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**LA THÈSE A ÉTÉ
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INVESTIGATION OF SUBCOOLED VOID FRACTION GROWTH
IN WATER
UNDER LOW PRESSURE AND LOW FLOWRATE CONDITIONS

by

Ronald Daniel McLeod, B.Eng (Mech.)

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Engineering.

Department of Mechanical and Aeronautical Engineering

Carleton University.

Ottawa, Ontario

April 30, 1986

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Dr. J. J. Ryan
Thesis Supervisor

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ABSTRACT

The objective of this thesis was to investigate subcooled void fraction growth in water under low pressure (1.55×10^5 Pa) and low flowrate conditions (0.03 - 0.50 m/s). A number of experiments were done to determine void growth in a uniformly heated annular test section. Five models from the literature were compared to the experimental results, but none gave consistently good predictions. Two methods were developed to predict the void growth. One model was phenomenologically based while the other was determined using an empirical factor. Each of the models was applied to the test results and found to be good for various ranges of flow velocities.

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NOMENCLATURE

A	cross sectional area (m^2)
C_o	distribution factor
C_p	specific heat (J/KgC)
D_d	departure diameter of bubble (m)
D_H	hydraulic diameter (m)
D_i	inside diameter (m)
D_o	outside diameter (m)
f	friction factor
G	mass flow per unit area (Kg/m^2s)
g	gravitational acceleration (m/s^2)
h	convective heat transfer coefficient (W/m^2C)
h_{cv}	enthalpy of control volume (J/Kg)
h_f	enthalpy of saturated liquid (J/Kg)
h_{fg}	heat of vaporization (J/Kg)
h_g	enthalpy of vapor (J/Kg)
h_l	enthalpy of liquid (J/Kg)
h_{ld}	enthalpy of liquid at departure (J/Kg)
j	total local flux (m/s)
j_g	local flux of vapor phase (m/s)
j_l	local flux of liquid phase (m/s)
j_{gl}	drift flux of vapor with respect to the liquid (m/s)
j_{lg}	drift flux of liquid with respect to the vapor (m/s)

K_c	condensation factor (W/m C)
k	conductive heat transfer (W/m C)
L	length of heated section (m)
$\dot{m}$	mass flow (Kg/s)
$\dot{m}_f$	liquid mass flow (Kg/s)
$\dot{m}_g$	vapor mass flow (Kg/s)
$\dot{m}_s$	mass of liquid converted to steam per unit length (Kg/s)
N	number of counts (counts)
N'	reading from ratemeter (counts/sec)
n	number of samples (Chapter 2)
Nu	Nusselt number $(q/AD_H)/(K_i\Delta T)$
p	pressure (N/m ²)
Pe	Peclet number (Nu/St)
Pr	Prandtl number
P_H	heated perimeter (m)
q	local heat input (W)
$Q_b(Z)$	heat absorbed by boiling per unit time per unit length (W/m)
$Q_c(Z)$	heat released by condensation per unit time per unit length (W/m)
Re	Reynolds number
r	bubble radius (m)
R_i	inside radius of annulus (m)

R_o	outside radius of annulus (m)
S	slip factor (U_g/U_l)
St	Stanton number ($q/A / GC_p \Delta T$)
T	temperature (C)
T_l	liquid temperature (C)
T_b	bulk temperature (C)
T_{wall}	wall temperature (C)
T_{sat}	saturation temperature (C)
T_{in}	inlet temperature (C)
T_{osv}	temperature at onset of significant void (C)
ΔT	$(T_{sat} - T)$ (C)
ΔT_b	$(T_{sat} - T_b)$ (C)
ΔT_{in}	$(T_{sat} - T_{in})$ (C)
ΔT_l	$(T_{sat} - T_l)$ (C)
ΔT_{osv}	$(T_{sat} - T_{osv})$ (C)
T^+	dimensionless temperature
U	velocity (m/s)
U_{gj}	drift velocity of vapor with respect to the flux density (m/s)
U_{lj}	drift velocity of liquid with respect to flux density (m/s)
v	specific volume (m^3/Kg)
X_t	true quality (weight fraction)
X_{eq}	equilibrium quality

X_l	local empirical parameter (chapter 5)
Y_B	distance from wall to bubble tip (m)
Y_B^+	non-dimensional distance from wall
Z	distance along heated length (m)
Z_{osv}	distance to onset of significant void (m)
Z_d	distance to departure location (m)
Z^+	dimensionless distance
$\langle \rangle$	cross-sectional average
	weighted mean

Greek Symbols

ρ	density (Kg/m ³)
$\Delta\rho$	$\rho_l - \rho_g$ (Kg/m ³)
β	ρ_l / ρ_g
α	vapor volume fraction
α_b	free bubble void
α_{osv}	void fraction at onset of significant void
α_w	wall voidage
σ	surface tension (N/m), statistical error (eqno 2.4, Appendix B)

σ	standard deviation (Appendix B)
ϵ	channel roughness (m)
τ_w	wall shear stress (N/m ²)
μ	viscosity (Kg/ms)
κ	thermal diffusivity

Subscripts

0	zero percent void fraction
1	one hundred percent void fraction
<i>d</i>	departure
<i>l</i>	liquid
<i>g</i>	vapor
<i>in</i>	inlet to test section
<i>out</i>	outlet from test section
OSV	onset of significant void
ONB	onset of nucleate boiling

CHAPTER 1: INTRODUCTION

The objective of this research was to predict void fraction growth at low pressures and low flowrates so as to provide information for the evaluation of the negative void coefficient of the up-rated SLOWPOKE reactor.

1.1 SLOWPOKE Reactor

The SLOWPOKE (Safe LOW Power critical (K) Experiment) was developed by Atomic Energy of Canada Limited (AECL) as a low power (10 KW) research and experimental reactor. The SLOWPOKE is a pool type reactor cooled by natural convection. Features that characterize the reactor are low critical mass, inherent safety and unattended operation. The core is designed so that it has a negative temperature coefficient (1) to limit the power and fuel temperature to safe levels following a large reactivity insertion. Because of the inherent safety no electromechanical safety devices are required and therefore an operator need not always be present in the reactor room during operation. A further advantage is that no emergency cooling is required since the core is immersed in a pool and cooled by natural convection.

AECL has proposed to up-rate the SLOWPOKE to 2 to 10 megawatts to provide low-temperature industrial or space heating. A goal of this unit was, like the original design, to have inherent safety characteristics, so as to allow unattended operation. Because of the higher power rating the up-rated SLOWPOKE must also rely on a negative void coefficient (1) to provide the inherent safety against power excursions. A schematic of the SLOWPOKE is given in figure 1.1. The core is located near the bottom of a pool of water. Natural convection upward flow of water provides

the cooling. The system is not pressurized so that the pressure at the core exit results from the head of water above it. The arrangement is thus a low flow rate, low pressure system. Further information on the SLOWPOKE and the up-rated SLOWPOKE can be found in references 1, 2, 3 and 4.

1.2 Importance of Void Growth

The up-rated SLOWPOKE reactor experiencing a reactivity excursion causing increased boiling, results in a system reactivity decrease which limits the power excursion. When the coolant, which moderates the neutrons via scattering interactions is subject to boiling the effective density is reduced and the capacity for thermalization is decreased. Hence, the boiling effect produces a negative feedback on the system. The reactivity compensation suggested by Hilborn (1) is 13 mk for an average coolant void fraction of 5%.

To ensure that the negative void coefficient will provide the required inherent shut down mechanism without damage to the fuel the designer requires the prediction of the rapid growth of void fraction, as well as the critical heat flux, for any reactivity excursion over the anticipated range of operation.

Another important parameter required in subcooled two phase flow systems is the pressure drop. The pressure drop in two phase flow is composed of three components; friction, gravity and acceleration. The latter two are almost directly dependent on void fraction. Thus it has been suggested (5), that the void fraction could be utilized in correlating its prediction. Presently though, all work has been of an empirical nature independent of the void growth. A review of experimentally determined predictive methods is presented by Gollier (5). Values of subcooled two phase pressure losses were given, by Dormer and Bergles, to be up to ten times that

of single phase (similar unheated tube at the same velocity and inlet temperature), for water in a small diameter tube at low pressure. These high pressure losses are significant when determining pumping requirements or the circulation rate in natural-circulation systems. The variation in pressure along the channel can also be used to compute changing fluid properties although in general the effect on two phase flow analysis is minimal.

Collier proposed, in the slightly subcooled region, using a separated flow model that gives the total pressure gradient as a function of local quality and local void fraction. For highly subcooled regions, where the void is assumed attached to the wall, the surface roughness used in single phase pressure drop calculations is replaced by the time-averaged diameter of the growing bubble. This value has been suggested as 0.75 times the diameter of the bubble at departure.

It is therefore expected that a method to determine the pressure drop within the up-rated SLOWPOKE could be developed from the present study.

1.3 Void Fraction in Subcooled Boiling

For conditions in the up-rated SLOWPOKE the void fraction grows at a bulk fluid temperature less than the saturation, ie. subcooled boiling. The bubbles grow and depart from the wall once the wall temperature sufficiently surpasses the saturation temperature, the bulk temperature is high enough so that bubbles no longer collapse on the wall and the flow conditions are favorable (figure 1.2). The bubbles, once departed, collapse within the bulk fluid until the point where saturation conditions are reached. As boiling progresses distinct flow patterns develop as illustrated in figure 1.3. The two major patterns expected under the conditions of interest to this research were bubbly and slug flow.

The void growth along a heated section is illustrated in figure 1.2. Point A represents the onset of nucleate boiling (ONB), point B the onset of significant void (OSV) and point C the start of bulk boiling. The research is intended to provide a prediction of void growth for the segment from point B to C, representing the subcooled region.

Five models from the literature were tested : Lahey (6), Rouhani (7,8), Bowring (9), Levy (10) and Zuber et al (11,12). These models did not provide satisfactory results and hence further development was needed.

Two separate approaches were undertaken to predict the void growth. The first method originated from an experimentally observed trend. From this an empirical factor was obtained and incorporated into a mechanistic boiling-condensation model.

The second method employs a drift flux model. The analysis is centered on the determination of the distribution factor introduced by Zuber and Findlay (13). This value depends on flow and concentration profile development and therefore was formulated as a function of a local parameter. Both models were found to work well for certain ranges of flow velocities.

Figure 1.1 The up-rated SLOWPOKE reactor (Ref.3).

Figure 1.2 Void growth along the heated length (Ref.5, pg.179).

Figure 1.3 The major flow regimes encountered in vertical upward flow.

CHAPTER 2 : EXPERIMENTAL WORK

The test apparatus used for the experimental runs was designed and financed under a joint co-operative project of the Department of Mechanical and Aeronautical Engineering of Carleton University and the Department of Mechanical Engineering of Ottawa University. The apparatus is located at the University of Ottawa.

The components of the test apparatus can be divided into three main categories : the test loop, the test section, and instrumentation.

2.1 Test Loop

The test loop was designed to simulate the projected operating characteristics of the proposed up-rated SLOWPOKE. A detailed description of the test loop is provided in Appendix A. A brief description follows.

The loop consists of a closed system employing distilled water, with forced flow used to simulate the natural convection within the reactor core. This is justified since the chimney above the core provides a significant head which in effect gives forced flow through the core. A schematic diagram and a photograph of the system are presented in figures 2.1 and 2.2 respectively. The dotted line in figure 2.1 illustrates the path of the water.

The circulation through the loop was provided by a centrifugal pump. The flow through the test section was controlled by a valve at the inlet plenum. The pressure within the loop is maintained by a surge tank and filling pump that acts directly on the test section outlet. At several locations within the loop there are provisions for degassing. Preheaters are incorporated for maintaining temperatures within the loop and for initial heating of the water. Heat removal from the loop is by a one-shell 2-tube pass heat exchanger. At the outlet of the test section a condenser was

incorporated to collapse any remaining vapor. The condenser employed a single pass shell and tube counter flow scheme. Both heat exchangers used cold water from the main supply.

The only recent modifications were two components to dampen mechanical vibration and possible flow oscillations caused by void collapse. To dampen mechanical vibrations the orifice was effectively isolated from the loop by placing a section of plastic tubing before and after it. To dampen flow oscillations a small surge tank with a cushion of air was placed between the test section inlet and the orifice. The diameter of the surge tank was 8 cm, hence a small interface between the water and air.

2.2 Test Section

A photograph and a schematic of the test section are presented in figures 2.3 and 2.4 respectively. The basic design incorporates an electrically heated tube inside a pyrex glass tube, with an upward direction of water flow. The incorporation of a glass tube allows effective visual observation of void fraction and possible occurrence of critical heat flux. The heater element was constructed of Inconel 718 thin wall tube with 1.31 cm outer diameter connected to copper tubes at either end. Inconel was used since it has a fairly constant electrical resistivity over a wide temperature range. The wall thickness was constant so as to provide an even heat flux. The heater element was placed in tension so as to accommodate expansion and contraction without bending. This was achieved by securing the heater tube by the top electrical conductor and suspending the lower conductor before fastening to the heater element, thus allowing the conductor weight to provide the tension force. The conductor was then secured to the lower plate. Power is supplied to the heater element through the copper conductors which rest on insulators on the upper and

lower plates. Power supplied to the heater element is by a 64 KVA transformer. The potential across the test section can be varied between 0 and 32 V.

The inner diameter of the glass tubes tested were 2.2, 2.5, 3.0 cm. These diameters were selected to represent expected hydraulic diameters in the up-rated SLOWPOKE core. Two heater element lengths were tested, 48.0 and 60.0 cm. The 48.0 cm heater element corresponds to the length of the fuel element of the up-rated SLOWPOKE. The 60.0 cm heater element was used so that a more fully developed flow would occur at the exit.

2.3 Instrumentation and Data Acquisition

The instruments used are thermocouples and amplifiers to measure temperatures, an orifice and pressure transducer for the flow rate and a gamma densitometer to measure the void. The measured voltage across the test section is required for the determination of the dissipated power.

The test section inlet and outlet water temperatures are measured using K type thermocouples. The inlet thermocouple was located at the inlet plenum. The outlet thermocouple is located 30 cm down-stream of the outlet plenum, so as to allow the void to collapse. The collapse of the void is important so that the thermocouple will have a better thermal contact with the liquid phase and therefore give a better indication of the bulk liquid temperature. The signal from the thermocouple is sent to a ANALOG DEVICES AD521 amplifier with a gain of one thousand. This signal is then fed to the data processing system.

The flow rate through the test section was determined from the pressure drop across an orifice by a differential pressure transducer (CELESCO P7D) with a range of 0.5 psia. The signal was then converted to an analog signal (0-10 volts) by a carrier demodulator (Model CD-10DC) which is interfaced with the pressure

transducer. This signal was then sent directly to the data processing system. In order to achieve the desired accuracy five orifices are used to cover the flow rates corresponding to the velocities 0.03 to 0.5 m/s.

A pressure gage is located at the outlet plenum so as to measure the test section pressure.

The void fraction was measured with a gamma densitometer. The basic principle of this device is that gamma rays are attenuated to a greater extent in water than steam. The densitometer is located on a traversing table that allows measurements at axial locations along the heated element. For this study the densitometer was located at a position ninety percent of the heater element length from the inlet (figure 2.3) Previous work (Undergraduate Thesis of Zia Abdullah : Investigation of Onset of Significant Void Fraction Under Low Pressure and Low Velocities, University of Ottawa 1982.) indicated there was little difference in measuring the void fraction at the outlet of the test section as compared to along the length. The rays originate from a source (10 millicurie Cobalt 57), are collimated, pass through the test section and are detected by a photomultiplier tube on the other side. The void fraction is thus a function of the attenuation. The signals from the photomultiplier are fed to an amplifier (ORTEC 452 Spectroscopy Amplifier), discriminator (ORTEC 405A Single Channel Analyzer) and counter (ORTEC 9349 Ratemeter). The analog signal (0-10 volts) output from the counter was then sent to the data acquisition system. Further discussion on the densitometer is given in Appendix A.1.

The data processing system is the center of the instrumentation. The signals from all instruments converge here for processing into data to be displayed or stored in memory. The data processing system consists of a microcomputer interfaced with a floppy disk unit, a line printer and a C.R.T. with a keyboard. The system has

been interfaced with a scanner and an analog-to-digital converter. The signals from all instrumentation are fed to the scanner, where they are scanned one by one. The output from the scanner goes to the analog to digital converter where a digital signal is produced for the microcomputer. The signal is processed by the microprocessor using software written in FORTRAN (Appendix A.4). The program has a subroutine (written in 8080 machine language) which enables scanning of the input channels of the A/D converter to be done and 350 samples of each measurement to be taken. From these averages are determined and displayed. The parameters can be displayed on the screen, stored on the disks or printed on the line printer. A schematic of the data acquisition system is illustrated in figure 2.5. Further information on the data processing system is presented in Appendix A.2.

2.4 Experimental Investigation

A number of tests were conducted to determine void fraction growth. For each test a prescribed procedure was carried out. The results from each were tabulated. The uncertainties in measured values and errors in calculated values were determined. As well, a study was undertaken to ensure that low void readings ($< 10\%$) were vapor and not air.

2.4.1 Test Procedure

Each test undertaken was approximately three hours in duration. For each the following procedures were undertaken:

- 1) The loop was pressurized by activation of the filling pump, any air contained in the system was then released by the bleeder valves. The flow was then started by activation of the circulating pump.

2) For the determination of void, a maximum reading 100% (steam) and a minimum 0% (water) were required. To determine the maximum value the test section was isolated from the system and the water drained. The air having approximately the same attenuation as steam provided the 100% reading (N_1). The test section was then filled with water and flow established. The reading for 0% void was then taken (N_0). For each case, 4000 samples of the voltage from the ratemeter were taken in order to minimize the statistical error. A linear relationship was used for readings of void (N_α) during a test run (18);

$$\alpha = \frac{N_\alpha - N_0}{N_1 - N_0} \quad (2.1)$$

3) Zeros were set for the flow rate and the temperature reference (room temperature) was inputted to the microcomputer. The zeros refer to the condition of no flow through the test section. To obtain this the valve to the inlet of the test section was closed. The zero of the transducer was set by turning a knob on the carrier demodulator until the water flow rate reading on the microcomputer screen read approximately 'zero'. Opening the inlet valve will then provide the water flow rate on the microcomputer screen.

4) To begin the run a flow rate was induced and the required heat flux was applied. The desired flow rate and inlet temperature, at the prescribed pressure, were set. The data acquisition system was then activated for measurements. For the condition of single phase or low void (approximately < 5.0%) the heat balance across the heater element should close. This heat balance can be checked from comparison of the calculated outlet temperature and the measured value. If a discrepancy of greater than approximately 5.0% occurred the test was terminated and the problem investigated. The inlet temperature was allowed to rise slowly between readings to decrease the subcooling at the exit and therefore increase the void. At various times during a test, approximately every 30 minutes, the water was degasified via

the bleeder valves. The test was terminated when a visibly high void formation occurred that, at the discretion of the operator, could cause damage to either the glass tube or heater element. The termination of a run was often at a void of approximately 35.0%. At this point large vapor formations on the heater element occurred quite frequently and the probability of critical heat flux greatly increased. Tests were also halted due to excessive vibration caused by void collapse threatening to break the outer glass tube.

The parameters measured and tabulated for each test were :

- i) Mass flow: The mass flow of the water through the test section (kg/s).
- ii) Velocity: The velocity of the water through the test section (m/s), based on liquid density at saturation temperature.
- iii) T_{in} : The measured bulk temperature of the water at the inlet (C).
- iv) T_{out} : The measured bulk temperature of the water at the outlet (C).
- v) $T_{out,cal}$: The calculated outlet temperature, determined from a heat balance across the heater element (C);

$$T_{out} = \frac{q P_H L}{\dot{m} C_p} + T_{in} \quad (2.2)$$

- vi) Void fraction: The volume of steam measured at the location of the densitometer (%).
- vii) Equilibrium quality: Calculated at the position of the densitometer. The temperature at this location was determined from a heat balance from the inlet.

$$X_{eq} = \frac{C_p (T_b - T_{sat})}{h_{fg}} \quad (2.3)$$

A typical result is provided in table 2.1. The physical dimensions of the test section, for each experimental test, are presented in table 2.2, with the range of operating conditions given in table 2.3.

2.4.2 Error Analysis

The uncertainties in directly measured parameters were determined from manufacturer's data, calibration and judgment associated with scale discrimination. Errors in the directly measured quantities are presented in table 2.4.

The errors in calculated quantities were determined from the error in the measured parameters using standard methods for the propagation of errors. Errors in physical properties were considered negligible. The results of the analysis are presented in table 2.5. All errors are in relation to the probability of one standard deviation, with an uncertainty of 68 %. The detailed analysis is presented in Appendix B.

The densitometer was calibrated using various sized lucite inserts, as suggested by Evangelisti (16) and Chan (18), since the inserts have approximately the same attenuation as water. The air gap with no inserts was taken as the reading for vapor. The difference between the total gap area and that physically measured from the inserts was taken as the 'calculated void'. The densitometer was fitted with the glass tube (22 mm) and heater element (13.1 mm) and readings obtained for air (100%) and water (0%). The insert representing water was determined to have a 'calculated void' of 1.75% (this was due to the clearance required for inserting the block). To correct comparisons between the calculated void and that measured by the densitometer, the value of 1.75% was taken as a reference. This was then added to all values measured with the densitometer. Results are shown in table 2.6.

It is evident that the densitometer provided a more accurate reading for the high void region. But the absolute errors for each of the readings were approximately equivalent. Each of the readings were within 2% void and no larger than 5.0%.

To determine the error introduced by radial distribution of void, lucite inserts with the air gap next to the heater element and ones with approximately half the gap located at the heater element and the remaining portion at the outer glass tube, were tested. For the densitometer to provide accurate readings the attenuation indicated by void next to the heater element had to be equivalent to that distributed between the two extremes. It is observable from table 2.6, in cases 3 and 4 (7.5%) as well as 6 and 7 (30.0%) that the void measured on the heater element had an absolute error approximately equal to that measured on both sides, indicating that little to no error is introduced by radial distribution of void.

Measurements for zero percent void are shown in table 2.7. These readings were made at the beginning of a run before any heat was added to the water. It can be seen that the readings fluctuate between approximately $\pm 1.0\%$, hence making it extremely difficult in obtaining low void fractions (1-2%).

The accuracy of the densitometer was verified by determining the statistical error on the void fraction readings. Since the random nature of radioactive decay does not allow the determination of a true value, an error is associated with the number of events observed. Therefore the larger the number of events the more accurate the reading. The statistical error in radioactive work (18,19) is given as;

$$\sigma = \sqrt{N} \quad (2.4)$$

Where N is the number of counts from the ratemeter. This represents one standard deviation from the mean ie. a confidence level of 68%. Referring to equation 2.1, the linear relation for void fraction, the values of N_1 and N_0 are assumed to have no statistical error since they are averaged over a long period of

time (Section 2.4). The void fraction is then given as;

$$\alpha = \frac{N_a - N_0 \pm \sqrt{N_a}}{N_1 - N_0} \quad (2.5)$$

Considering typical values of the ratemeter from this study;

$$N'_0 : 12,000 \text{ counts/sec}$$

$$N'_1 : 19,000 \text{ counts/sec}$$

The time constant is set so as to discriminate transient conditions. For the test equipment the time constant was set at 0.03 seconds. The number of counts were therefore determined to be;

$$N_0 : 360 \text{ counts}$$

$$N_1 : 600 \text{ counts}$$

Therefore the statistical error on the void reading will be between approximately $\pm 11.0\%$ and 9.0% . The number of counts increase for higher void, since the attenuation decreases, and therefore the statistical error decreases.

There are three ways that this error can be reduced. Two of these methods increase the number of counts. Either going to a larger source, hence increasing the count rate (which represents an expensive alternative), or increase the time constant. Increasing the time constant, in many cases, will not allow accurate readings of transient conditions. The third approach, incorporated in this experiment, is to take a large number of samples and average the results. The errors calculated above are for a single reading. Considering a normal distribution of a number of samples these values will decrease with $1/\sqrt{n}$ where n is the sample space. As stated in Section 2.3 there are 350 samples taken from the ratemeter for each reading, from

which the average is displayed. The statistical error was therefore determined to be no larger than $\pm 0.5\%$ void.

From this analysis the conclusions drawn were;

1. The calibration error was no larger than $\pm 5\%$ void.
2. The statistical error of the void fraction reading is no larger than $\pm 0.5\%$ void.

It can be seen from these results that the statistical error does not make a large contribution to the total error. The error in void fraction readings is therefore primarily due to calibration. Hence, a calibration procedure should be conducted. Presently this has not been undertaken so that the conservative estimate of an error no larger than 5% void was assumed.

Other investigators have reported errors of the same magnitude as that found in this study. Schrock (20) indicated that when the system is well designed that "accurate void measurements, within 5% of the true value, can be achieved."¹ Edelman (17) incorporating the gamma attenuation method, presented void fraction data with error bars in the order of $\pm 5-10\%$ void. Although no overall error is specified by Evangelisti and Lupoli (16) a calibration error of approximately $\pm 5\%$ void can be deduced from calibration curves presented. Chan (18) calibrated the densitometer used in his experiments to an error no larger than $\pm 15\%$ void from which he concludes that fairly accurate readings can be obtained. The error in void fraction found in this study compares quite favorably with the above cited works providing confidence in the densitometer readings. Typical error bars are shown for both void fraction and equilibrium quality, in figure 2.6, for experiment No.1.

2.4.3 Dissolution of Air from System Water

To be convinced that low void readings ($< 10\%$) were not simply entrained air within the water a three fold investigation was undertaken;

1. Operation of loop for an extended period at low void.
2. Determination of possible air content.
3. Study of nucleation correlations.

The first approach was to run an extended degasification operation on the loop. Two methods of degassing were used by McAdams et al (21). First the pressure within the system was produced by boiling within the pressurizing tank. They could then blow off steam and air. This method was found to reduce the air content to 0.3 cc/l. The system was then further degasified by boiling the circulating water by their preheater, allowing any released air to be bled off. An idea similar to the latter was applied to the test loop used in this study. The first check undertaken was therefore to run the test loop at low voids ($< 10\%$) for an extended period of time. The system was run twice for a duration of approximately 10 hours each time, at 5-6% void. The void fraction was obtained by a low heat flux on the heater element with approximately constant inlet conditions controlled by the heat exchanger. At various times (approximately every 15 minutes) the system was bled at the high points as a degassing procedure. The results of the two tests are shown in figures 2.7 and 2.8. Approximately 400 test points were obtained, in each test, over the ten hour period. The values were time averaged and plotted every fifteen minutes. The line drawn through the points represents a least squares best fit. Considering the error in the void fraction a best fit through the data points could be a straight line. The fact that this condition was maintained for a long period of time, without

significant change in void fraction, verifies that the void is formed by vapor and not air.

The second point considered was the possible air content of the water. The loop was initially filled with distilled water in equilibrium with the atmosphere. The air content at room temperature and pressure (20°C , 101.1 kPa) was calculated to be 2.06% by volume and 1.206% at 100 C, assuming saturated conditions. Hence, raising the temperature of the water from 20 - 100 C results in a possible 0.854 % , by volume, air release (calculations of this are shown in Appendix C.1).

McAdams et al (21) did some testing with water that was pressurized by air, hence providing air-saturated water conditions at various pressures. With air pressurized systems they found that bubbles started to form at lower values of ΔT ($T_{\text{wall}} - T_b$) than for degasified systems. They also observed two effects of dissolved gases in that the stream of water was cloudy, and many small gas bubbles were carried out in the water leaving the test section. No quantitative observations were given for the vapor content when it first appeared or the values obtained when the cloudy flow was observed.

To check this effect and also whether the densitometer was reading air or void, a test was conducted and visual observations made. The flow was set and heat flux was increased in increments so that the vapor content could be observed and measured. Results are presented in table 2.8.

The following are the qualitative observations made during the run shown in table 2.8, the number shown corresponds directly to the test point within the table.

1. Small observable vapor which seemed to be only at the outlet.
2. Observable vapor at the exit portion of the heater element but little more than before.

- The flow was a bit milky.
- There were bubbles past the unheated length, which was most probably air.
- 3. Vapor was observable at the outlet of the heater element, small bubbles (approximately 1-2 mm) were growing and collapsing on the wall.
- 4. Vapor was definitely forming on the wall at the outlet.
- 5. More vapor formed on the wall, the flow was still observably milky.
- 6. Quite a bit of vapor on the wall but it seemed to condense once it departed from the wall.
- There was milky flow past the end.
- 7. Considerable vapor formed at the end of the heater element as well as further down the tube. a progressively lower void proceeding down the heater element from the exit) indicating void growth.
- More bubbles past the end, but now should also be due to un-condensed vapor.

It can be concluded that up to condition 3 the void measured was partially due to the air content, as can be seen from the calculated possible air content. The densitometer has problems distinguishing this low void.

The conditions noted by McAdams et al was observed here in the form of milky flow and bubbles past the heated length. But after condition 6 it was obvious that there was quite a bit of vapor formed (5-7%) and as shown by the calculations only a small amount of air released ($< 0.8\%$). The densitometer has no problems distinguishing this higher vapor content.

The third aspect investigated was the onset of nucleate boiling correlations proposed by Bergles and Rohsenow (22) and Davis and Anderson (23), based on thermodynamic considerations. The onset of nucleate boiling is the point where bubbles are first formed on the heated surface (point A, figure 1.2). It is postulated

that the bubbles form at cavities on the surface where some gas or vapor is present. When heat is added the vapor in the cavity grows by evaporation at the liquid-vapor interface near the wall. The bubble grows and departs trapping vapor in the cavity (possibly ones around it as well) which provides the seed for the next bubble. For a particular test when the velocity and inlet temperature are known, from their correlations, the heat flux where void should first appear could be ascertained. Any bubbles present before this condition would therefore be air. Bergles and Rohsenow's correlation (q/A is in Btu/hr ft², p is in lb_F/in² and the temperatures are in deg. F.) is given as;

$$\frac{q}{A} = 15.60 p^{1.156} (T_{wall} - T_{sat})^{2.3/p^{0.0234}} \quad (2.6)$$

while the correlation of Davis and Anderson (SI units) is;

$$\frac{q}{A} = \frac{K}{4B} (T_{wall} - T_{sat})^2 \quad (2.7)$$

with

$$B = \left(\frac{2\sigma T_{sat} v_{fg}}{h_{fg}} \right)$$

Three tests were undertaken to determine the ONB point. For each test the pressure, inlet water temperature and velocity were set and the heat flux, predicted to cause the onset of nucleate boiling, was applied to the heater element. The condition of each was;

Test Section:

$$D_o = 30.0 \text{ mm}$$

$$D_i = 13.1 \text{ mm}$$

$$\text{Pressure} = 22.5 \text{ psia } (1.55 \times 10^5 \text{ Pa})$$

1. $U = 0.0358 \text{ m/s}$ $G = 36.46 \text{ Kg/sm}^2$ $T_{in} = 20.0 \text{ C}$

- Rohsenow and Bergles = 4.13 W/cm^2
- Davis and Anderson = 4.06 W/cm^2

2. $U = 0.057 \text{ m/s}$ $G = 58.0 \text{ Kg/sm}^2$ $T_{in} = 20.0 \text{ C}$

- Rohsenow and Bergles = 5.81 W/cm^2
- Davis and Anderson = 5.68 W/cm^2

3. $U = 0.117 \text{ m/s}$ $G = 116.7 \text{ Kg/sm}^2$ $T_{in} = 22 \text{ C}$

- Rohsenow and Bergles = 6.99 W/cm^2
- Davis and Anderson = 6.83 W/cm^2

For each of the above conditions a test run was conducted with and without power on the heater element to show there was no difference in void measurements, as well visual observations were made. The results of the tests are shown in Appendix C.3. There were no bubbles formed at the heat fluxes predicted. None were measured by the densitometer, and nothing was observed other than the water movement near the heated wall caused by natural convection.

Bergles and Rohsenow suggest that the point of incipient boiling is dependent on velocity and subcooling. They state 'In commercially prepared surfaces a wide range of cavity sizes can be expected. Incipient boiling, then, should be independent of surface condition for most commercially finished surfaces. The present analysis should, therefore, be valid in most practical applications.'² They later state that they have shown their prediction to be valid for 'several commercially finished surfaces', which they feel have a wide range of cavity sizes (but none are mentioned). If surfaces do not have a sufficiently wide range of cavity sizes, the data will not agree. Such is the case in systems with low heat-transfer coefficients and low subcooling

as in natural convection boiling and in low velocity forced convection flows (range not given). Incipient boiling is then predicted at lower wall superheat than those at which it actually occurs. ³

2.5 Experimental Results and Observations

This section summarizes the results and presents observations from the experimental tests.

2.5.1 Experimental Results

The results from the experimental tests are presented in tables 1-66 of Appendix G. Plots of void growth (void versus equilibrium quality) obtained from the experimental data are illustrated in figures 1-66 of Appendix G (the velocity indicated is representative of that during the rapid growth). A void growth plot, for experiment No.3, is presented in figure 2.9.

2.5.2 Experimental Observations

The void growth profile exhibited an approximate "S" shape distribution, commencing from the OSV. Many researchers (10,11,14) emphasize the importance of an accurate determination of the OSV before attempting to predict the void growth, resulting in many empirical correlations. For this research values of OSV were obtained from the experimental void growth curves, at the point where a straight line drawn through the high void fractions intersected a straight line drawn through the approximately constant low void region. The void fraction at which OSV occurred was between 5.0-10.0%. The determination of the straight line fits is judgmental and therefore the equilibrium quality at OSV is estimated to have an uncertainty of approximately $\pm 5.0\%$ of the reading. A summary of the OSV values is given in table 2.9. The point of OSV exhibited a definite velocity dependence. It was ob-

served that for the same heat flux, pressure, and geometry the equilibrium quality at OSV decreased with increased velocity. At higher heat fluxes this dependence of OSV on velocity was determined to increase. Further work on this subject is presented by Salcudean and Rogers et al (15).

An interesting result observed was that the majority of the void profiles exhibited approximately equivalent rates of growth following OSV. Exceptions occurred for velocities larger than 0.4 m/s and lower than 0.045 m/s, for these cases the void growth was respectively lower and higher than the general result.

During experimental tests visual observations were made of the changing flow regimes. As the boiling process progressed the flow was seen to pass through the bubbly regime into a unsteady flow condition of large vapor growth and collapse, with no stable slug formation. This characterizes a transition regime between the ideal bubbly flow and slug flow. The transition to this regime was observed to occur at a void fraction of approximately 15-20%.

For low velocities (<0.04 m/s) a very rapid growth occurs in the void fraction, these tests were observed to exhibit characteristics of the churn turbulent regime from the point of OSV.

It was found that for the 60 cm heater element and 22 mm glass tube, a very sudden void jump occurred when imposing heat fluxes larger than approximately 77.8 W/cm^2 resulting in an insufficient number of data points. (increasing the velocity and/or decreasing the inlet temperature to their maximum and minimum values respectively could not solve the problem). For the glass diameters of 25 and 30 cm the vapor collapse rate, for heat flux greater than 60 W/cm^2 , caused considerable vibration in the glass tube at high void fractions ($>25\%$) which threatened to break it. Hence no tests were conducted for heat fluxes greater than 66 W/cm^2 .

The most significant observation, through-out the tests, was a very slow void growth before OSV. This produces what appears to be a region of approximately constant void fraction, of 5-6%, before the onset of significant void. This region can be seen in almost all runs, a test that clearly illustrates this is shown in figure 2.9. Rouhani (8) and Bowring (9) reviewed a large number of experimental investigations, but no reference was made to any low void region before OSV. Levy (10) also reviewed a number of experimental works one of which, Ferrell, did indicate a similar region ($\lesssim 10\%$ void). These experimental studies were done at high pressures, due to its significance in boiling water nuclear reactors. Some work has been conducted at low pressures (16,17) although not for the same physical conditions considered in this study. The work of Evangelisti and Lupoli (16) was for larger mass velocities, while both the heat flux and flow rates of Eldelman (17) were lower. This low void region was again evident in the work of Evangelisti and Lupoli, although no reference was made to it in the text. A summary of physical parameters for the various experimental investigators cited above is given in table 2.10.

2.6 Conclusions

Comparing the accuracy of the densitometer with that of other investigators instills confidence in the void fraction readings, still there is some degree of uncertainty in the readings. This uncertainty does not affect the densitometer's ability to discern the stability of the low void region, only its magnitude. The fact that the loop was run for an extended period of time at the equilibrium condition indicates that the readings must be vapor since the system would have been degasified. The possible air release was found to be insignificant (less than 0.85%) and therefore contributes little to void fraction error. The nucleation correlations of Rohsenow and Bergles, and Davis and Anderson predict a heat flux, for a set pressure, velocity

and inlet temperature, where no observable bubbles were formed. If any bubbles had been measured or observed before the predicted heat flux then they would have been classified as air.

The approximately constant low void region prior to OSV was not unique to this investigation, although no study of it has been made in the literature. Since vapor is forming in this region with no net vapor generation, implies a balance between the evaporation and condensation processes, hence a state of equilibrium.

TABLE 2.1 : Recorded Void Growth : Experiment No. 1

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.020	0.0820	25.7	87.4	88.5	5.779	-4.512
2	0.020	0.0798	27.5	92.8	92.0	6.217	-3.846
3	0.019	0.0772	27.7	97.2	94.5	5.958	-3.389
4	0.019	0.0755	28.1	99.5	96.4	7.954	-3.021
5	0.019	0.0758	28.4	100.1	96.4	6.833	-3.028
6	0.018	0.0745	28.6	100.6	97.8	8.971	-2.761
7	0.019	0.0750	28.8	100.1	97.6	7.725	-2.807
8	0.018	0.0725	29.2	100.3	100.3	6.385	-2.293
9	0.017	0.0698	29.6	103.4	103.4	8.659	-1.706
10	0.017	0.0700	29.3	105.3	102.9	10.148	-1.806
11	0.017	0.0691	29.7	105.3	104.2	12.684	-1.551
12	0.017	0.0689	29.8	106.2	104.5	10.151	-1.497
13	0.017	0.0686	29.5	108.1	104.5	16.192	-1.494
14	0.017	0.0684	29.7	108.1	105.0	19.046	-1.402
15	0.016	0.0663	29.8	108.8	107.6	28.543	-0.920

TEST PARAMETERS :

PRESSURE = 22.5 psia D_o = 22.0 mm D_i = 13.1 mm
 VOLTAGE = 9.0 volts HEAT FLUX = 29.7 W/cm**2
 HEATER ELEMENT = 48 cm

Test Case No.	Inside diameter (mm)	outside diameter (mm)	length of Heater Element (mm)
1 - 20	1.31	22.0	48.0
21 - 29	1.31	22.0	60.0
30 - 40	1.31	25.0	48.0
41 - 47	1.31	25.0	60.0
48 - 56	1.31	30.0	48.0
57 - 68	1.31	30.0	60.0

Table 2.2 : Physical dimensions of the test section for experimental runs.

heat flux	29.7 - 118.0 W/cm ²
pressure	1.55 x 10 ⁵ Pa (22.5 psia)
T _{in}	18 - 65 C
velocity	0.03 - 0.5 m/s
mass velocity	29.0 - 475 kg/s m ²

Table 2.3 : Range of experimental operating conditions

outlet pressure	$\pm 3.0 \%$
inlet temperature	$\pm 0.75 \%$
mass flow rate	$\pm 2.5 \%$
voltage across test section	1 - 15 volt range ± 0.15 volts 5 - 50 volt range ± 0.35 volts
test section current	± 1.1 ampère

Table 2.4 : Estimated errors in directly measured quantities

test section velocity	$\pm 2.5 \%$
heater element resistance	$\pm 1.7 \%$
heat flux at 29.9 W/cm^2	$\pm 2.9 \%$
heat flux at 118.0 W/cm^2	$\pm 3.2 \%$
$T_{out,at}^{**}$	$\pm 3.5 \%$
X_{eq}^{**}	$\pm 0.0056 - \pm 0.0069$ *

* values in quality

** determined from experiment 1

Table 2.5 : Estimated errors in calculated quantities.

Table 2.6 : Calibration of densitometer

#	calculated void %	#1 void %	error %	#2 void %	error %	#3 void %	error %	#4 void %	error %	location of air gap
1	3.89	3.59	7.7	3.23	16.9	2.02	48.1	3.52	9.5	both inside and out
2	5.25	3.72	29.1	6.48	23.4	2.21	57.9	3.00	42.9	inside
3	7.25	-	-	-	-	6.71	7.4	5.75	20.7	both inside and out
4	7.62	5.86	23.1	5.82	23.6	6.92	9.2	8.87	16.4	inside
5	11.04	9.05	18.0	9.11	17.5	6.30	42.9	7.29	33.9	both inside and out
6	28.41	-	-	-	-	25.61	9.9	25.98	8.6	inside and out
7	30.05	27.53	8.2	25.29	15.7	23.93	20.2	26.64	11.4	inside
8	49.11	45.02	8.3	45.12	8.1	43.68	11.1	43.71	10.9	both inside and outside
9	61.24	58.99	3.7	59.50	2.8	55.83	8.8	56.45	8.5	both inside and outside
10	70.81	73.16	3.3	72.30	2.1	68.39	3.4	71.44	1.0	both inside and outside

Test Section : $L_0 = 2.2$ cm

$D_1 = 1.31$ cm

Table 2.7 Calibration of densitometer; readings for 0.0% void

Reading	Measured Void
#	%
1	-0.462
2	-0.064
3	-0.125
4	0.269
5	0.456
6	-0.401
7	0.379
8	-0.807
9	-0.165
10	-1.083
11	0.623
12	0.848
13	0.749
14	-0.088
15	-0.039
16	-0.324
17	-0.479
18	-0.421
19	1.684
20	0.595

Table 2.8 : Test to study air release.

Point #	Heat Flux W/cm	Velocity m/s	T _{in} C	T _{out} C	Void %	Air content released % *
1	28.8	0.1173	23.0	39.8	0.936	0.52 @ 40 C
		0.1168	22.8	41.9	1.363	
2	38.5	0.1170	22.8	48.5	0.363	0.63 @ 50 C
		0.1173	21.6	44.2	0.242	
		0.1168	22.9	47.9	0.381	
		0.1169	23.1	49.0	0.049	
3	51.2	0.1167	23.4	57.4	2.496	0.71 @ 60 C
		0.1169	23.0	57.5	0.013	
		0.1174	23.2	56.6	1.993	
		0.1170	23.2	57.7	1.285	
4	65.8	0.1173	23.5	68.3	2.095	0.78 @ 70 C
		0.1173	23.3	68.0	2.089	
		0.1171	23.6	69.0	0.303	
		0.1178	23.3	66.4	2.921	
5	80.0	0.1175	23.9	76.8	1.194	0.81 @ 80 C
		0.1177	23.4	76.3	3.088	
		0.1181	24.3	77.1	0.163	
		0.1183	23.9	77.3	1.224	
		0.1183	23.9	77.0	1.981	

Table 2.8 continued.

6	91.1	0.1180	23.7	83.1	6.284	0.81 @ 80
		0.1170	25.0	85.1	3.183	
		0.1182	23.5	83.0	4.475	
		0.1180	23.7	81.1	2.598	
		0.1178	23.1	82.9	7.250	
		0.1180	24.4	82.9	4.166	
		0.1175	26.0	83.0	4.694	
7	102.8	0.1168	23.9	91.8	6.396	0.83 @ 80
		0.1158	25.5	91.2	5.168	
		0.1148	23.9	88.3	7.823	
		0.1140	25.3	95.3	6.919	

TEST PARAMETERS :

Pressure = 1.55×10 Pa Do = 30.0 mm D1 = 13.1 mm

*.The air content released was calculated by the difference between the saturated air content at room temperature and pressure, and at the outlet temperature indicated.

Table 2 9 : Experimentally determined OSV points.

Experimental test No.	Do (cm)	heater element (cm)	velocity (m/s)	heat flux (W/cm**2)	Xeq O.S.V. (%)	Void (%)
1	2.2	48.0	0.0660	29.7	-1.8	8.5
2	2.2	48.0	0.0750	29.7	-1.5	9.5
3	2.2	48.0	0.0691	29.7	-1.5	9.0
4	2.2	48.0	0.0810	29.7	-1.7	9.0
5	2.2	48.0	0.2506	60.5	-1.5	9.0
6	2.2	48.0	0.1517	61.0	-2.0	10.0
7	2.2	48.0	0.1798	74.2	-1.5	8.0
8	2.2	48.0	0.2871	74.2	-2.2	9.0
9	2.2	48.0	0.4247	74.2	-2.3	9.0
10	2.2	48.0	0.1774	77.0	-2.6	9.0
11	2.2	48.0	0.1818	77.4	-2.5	5.0
12	2.2	48.0	0.2385	77.4	-2.5	9.0
13	2.2	48.0	0.2330	97.5	-3.0	9.5
14	2.2	48.0	0.3175	97.5	-3.8	6.0
15	2.2	48.0	0.3047	97.3	-3.8	9.5
16	2.2	48.0	0.3011	118.6	-3.8	7.0
17	2.2	48.0	0.3726	118.6	-4.1	9.0
18	2.2	48.0	0.3867	118.7	-5.0	9.0
19	2.2	48.0	0.4076	118.6	-4.8	7.0
20	2.2	48.0	0.4752	118.6	-4.0	9.0
21	2.2	60.0	0.0611	27.7	-2.2	4.0
22	2.2	60.0	0.0805	27.7	-1.8	7.0
23	2.2	60.0	0.1617	60.1	-2.3	8.0
24	2.2	60.0	0.1943	60.6	-2.8	9.0
25	2.2	60.0	0.2235	60.1	-2.9	9.0
26	2.2	60.0	0.2027	73.9	-3.2	9.0
27	2.2	60.0	0.3327	73.9	-5.3	9.0
28	2.2	60.0	0.2569	77.8	-3.3	8.0
29	2.2	60.0	0.3600	77.8	-4.4	8.0

Table 2.9 continued.

30	2.5	48.0	0.0386	29.7	-1.4	8.0
31	2.5	48.0	0.0492	29.7	-2.3	7.0
32	2.5	48.0	0.0580	29.7	-1.8	7.0
33	2.5	48.0	0.1286	60.6	-2.0	9.0
34	2.5	48.0	0.1494	60.6	-1.7	9.0
35	2.5	48.0	0.0923	77.5	-1.4	8.0
36	2.5	48.0	0.1523	77.5	-2.3	8.0
37	2.5	48.0	0.1528	97.6	-3.3	8.0
38	2.5	48.0	0.1912	97.6	-3.2	8.0
39	2.5	48.0	0.1842	118.7	-3.0	7.0
40	2.5	48.0	0.1774	77.0	-3.7	8.0
41	2.5	60.0	0.0476	29.7	-2.3	9.0
42	2.5	60.0	0.0558	29.7	-3.3	9.0
43	2.5	60.0	0.0839	28.6	-1.8	9.0
44	2.5	60.0	0.1335	59.5	-3.3	7.0
45	2.5	60.0	0.1579	59.5	-4.0	8.0
46	2.5	60.0	0.2100	77.9	-6.0	9.0
47	2.5	60.0	0.2595	77.9	-7.0	7.0
48	3.0	48.0	0.0287	29.7	-2.3	7.5
49	3.0	48.0	0.0324	29.7	-1.8	8.5
50	3.0	48.0	0.0530	60.2	-2.3	8.5
51	3.0	48.0	0.0601	60.2	-2.2	8.0
52	3.0	48.0	0.0876	74.1	-2.5	9.0
53	3.0	48.0	0.1003	74.1	-3.2	9.0
54	3.0	48.0	0.0995	77.3	-3.0	9.0
55	3.0	48.0	0.1103	97.6	-2.8	8.0
56	3.0	48.0	0.1066	119.0	-1.8	6.0
57	3.0	48.0	0.1290	119.0	-3.0	7.0
58	3.0	60.0	0.0333	29.7	-2.6	8.0
59	3.0	60.0	0.0875	60.3	-2.4	10.0
60	3.0	60.0	0.1380	60.3	-3.5	9.5
61	3.0	60.0	0.0923	74.5	-3.3	8.0
62	3.0	60.0	0.0898	77.9	-1.5	9.0
63	3.0	60.0	0.1165	77.9	-2.8	10.0
64	3.0	60.0	0.0966	97.7	-3.0	9.0
65	3.0	60.0	0.1344	97.7	-3.2	9.0
66	3.0	60.0	0.0448	29.7	-2.3	10.0

Table 2.10 Experimental work on subcooled void fraction.

Source of data	Geometry	Flow Area		Pressure (bar)	q/A (W/cm)	G (Kg/sm)	Fluid
		Do (cm)	Di (cm)				
Evangelisti & Lupolia Ref. (16)	annular	1.3	0.7	1	44-89	607, 1413	water
Eldelman & Elias Ref. (17)	round tube	1.13	-	1	2-6	38-114	water
Ferrell Ref. (10)	no geometry given			4-16	24-68	529-1318	water
Poletavkin and Shapkin Ref. (9)	round tube	0.56	-	7, 16 41	0-290	vel. = .7 -11.5 m/s	water
Rouhani Ref. (8)	annular	2.5	1.2	19-50	60-120	130-1450	water
Christensen Ref. (8,9)	rectangular (1.11 X 4.44 cm)	-	-	27-69	27-69	637-914	water
Eklund et al. Ref. (8)	6-rod cluster	flow area 30.5 cm**2		32-51	47-65	1345-1607	water
Griffith et al. Ref. (9)	rectangular (1.3 x 1.3 or .45 or .23 cm)	-	-	34, 68 102	80-860	vel. = 6.0 - 9.0 m/s	water
Nylund et al. Ref. (8)	36-rod cluster	flow area 142.7 cm**2		50	22-64	1110-1159	water
Fogila et al., BMI Ref. (9)	rectangular (2.8 x .13 or .254 cm)	-	-	50-88	30-190	vel. = 2.0 - 5.0 m/s	water
Egen et al., BMI Ref. (8)	rectangular (0.26 x 2.54 cm)	-	-	138	19-0 126.1	9080-1165	water

Figure 2.1 Schematic of Test Loop.

Figure 2.2' The Test Loop.

Figure 2.3 The Test Section.

Figure 2.4 Schematic of Test Section.

21	L.E INSULATOR	2
20	10 TURNS POTENTIOMETER	1
19	BASE	4
18	BUSHING	4
17	LOWER PLATE	1
16	ELECTRICAL CABLE	8
15	PELNUM SUPPORT	2
14	INLET TUBE	1
13	GLASS TUBE	1
12	COUNTER WEIGHT	2
11	HEATING ELEMENT	1
10	BUSHING	4
9	COLLIMATOR AND DETECTOR HOUSING	1
8	SCREW	1
7	PELNUM	2
6	UPPER PLATE	1
5	BUSHING	4
4	BEARING	2
3	MOTOR	1
2	ELECTRICAL CONDUCTOR	2
1	RACK	1
PART NO	PART NAME	QTY
DRAWN BY JACK NAIN	SET UP FOR VERTICAL TWO - PHASE ANNULAR FLOW	DATE 12-1-68 PAGE 1

Figure 2.5 Schematic of Data Acquisition.

Figure 2.6 Void growth experiment No.1, with error bars.

Heat Flux = 29.7 W/cm**2

Velocity = 0.0667 m/s

XEQ(osv) = -1.80

OD. = 22.0 mm

Figure 2.7 Extended Operation of Test Apparatus Test No.1.

Heat Flux = 47.2 W/cm^2
 Average Velocity = 0.220 m/s
 OD. = 22.5 mm

Figure 2.8 Extended Operation of Test Apparatus Test No.2.

Heat Flux = 47.2 W/cm^2
 Average Velocity = 0.220 m/s
 OD. = 22.5 mm

Figure 2.9 Low void region prior to OSV, experiment No.3.

Heat Flux = 29.7 W/cm**2

Velocity = 0.0716 m/s

XEQ(osv) = -1.50

OD. = 22.0 mm

CHAPTER 3 SUBCOOLED VOID MODEL PREDICTIONS

3.1 Introduction

Five void growth models were compared to the experimental results. Two models, Lahey (6) and Rouhani (7,8), applied an evaporative-condensation technique, both approaches incorporating ideas introduced by Bowring (9). As well two empirically determined models, that of Levy (10) and Zuber et al (11,12), were considered. Each of the approaches were applied as stated in their descriptions. No model was derived for the conditions of this study, although some suggested their range of applicability would extend to it. The range of each model is summarized in table 3.1. A brief description of each follows with a detailed presentation in appendix D.

3.2 Lahey Model (6)(modified)

Lahey developed a mechanistic subcooled boiling model shown to be suitable for high pressures. The void growth was initiated at the point of bubble departure which he determined from a relation derived by Saha and Zuber (11). The true quality, following departure, was determined from an equation which was a function of a boiling heat flux and condensation term. The boiling heat flux was evaluated from the imposed heat flux and an effective single phase contribution. The condensation term was determined using an empirical value evaluated from considering representative subcooled boiling data which were not indicated. The void fraction was then determined from a relationship derived by Zuber and Findlay(13) with $C_o = 1.1$ although Lahey suggested the use of Dix's (35) variable C_o .

3.3 Rouhani Model (7,8)

Rouhani presented two papers (7,8) which provide a prediction of vapor growth for subcooled boiling conditions. The first paper (7) introduced a method of determining the onset of significant void and a growth model assuming no slip between phases. His second paper (8) develops a mechanistic approach to vapor growth. In the mechanistic model true quality is determined from the difference between the amount of heat which goes to steam generation and that released by steam bubble condensation. The steam generation term is derived from a heat balance on the heated surface while the condensation is determined from a condensation coefficient (similar dimensionally to that of single phase thermal conductivity) which was empirically derived. The vapor fraction was then determined from the Zuber and Findlay (13) relationship.

3.4 Bowring (9)

Bowring introduced a physical model to predict the void fraction in the subcooled region. Before the onset of significant void he assumed there was a small amount of void forming on the wall, which he determined from experimental results. The onset of significant void was empirically determined to be a function of heat flux, pressure and mass velocity. Following the onset the vapor weight fraction was determined using an analogy to bulk boiling, with the total heat flux replaced by an evaporative heat flux term. He defines the void fraction corresponding to this weight fraction as free void, which is separate from the wall voidage, which is determined from a mass balance between the phases. The total void fraction is then obtained from the sum of the wall voidage and that determined following the onset.

3.5 Levy (10)

Levy's model was developed to predict both the point of vapor bubble departure and the growth of void fraction, during forced convection subcooled boiling. The point of bubble departure was determined from considering both a force balance on the bubble and the single phase turbulent temperature distribution away from the heated wall. An empirically derived equation was proposed for the relationship between the true local vapor weight fraction and the corresponding equilibrium value. The vapor volumetric fraction was then determined from the relationship of Zuber and Findlay (13).

3.6 Zuber et al (11,12)

Zuber et al presented a model to predict the point of net vapor generation (11) and vapor void fraction for subcooled boiling (12). It was suggested that the onset of significant void is a function of local thermal and dynamic conditions. The thermal conditions are presumed to be dominant at low mass flow rates and dynamic effects at high. A relation was proposed for the determination of the true vapor weight fraction, following OSV, as a function of the local equilibrium quality. Knowing the equilibrium quality the vapor volumetric fraction can be determined from the relationship of Zuber and Findlay (13). A non-dimensional approach was also taken (12) for the determination of the true vapor weight fraction. The vapor volume was then determined by a relationship similar to that developed by Zuber and Findlay.

3.7 Conclusions

It was found that none of the models provided a satisfactory prediction for all cases. Results of the predictions for various tests covering the range of experimental conditions are illustrated in figures 3.1-3.12. Observations of the experimental results indicated a state of equilibrium between boiling and condensation before OSV, the development of a void growth model should therefore include the effects of vapor condensation. This idea was applied by Lahey and worked well for some cases, but he proposed an empirically determined condensation term, the calculation of which was not clearly defined. It was observed that initiating Lahey's model from the experimentally determined OSV point would provide a reasonable fit for some tests. Rouhani's model gave the best theoretical base to build upon, since the boiling processes were divided into evaporative and condensation terms that have general applicability.

Table : 3.1 Range of applicability of void growth models considered from the literature.

model	geometry	pressure (bar)	heat flux (W/cm**2)	mass velocity (Kg s m**2)
Lahey (6)	annular	19-50	60-120	130-1450
Rouhani (7,8)	annular, rectangular channels, rod clusters	19-138	18-120	130-9080
Bowring (9)	all	1-140	0-200	0-200 cm/s
Levy (10)	rectangular channels, annular	8-136	21-110	530-1440
Zuber et al (11,12)	rectangular channels, annular	1-49	2-121	400-1050

Figure 3.1 Comparison of void growth models : Experiment No.1.

□ : Experiment 1 — : Lahey ---- : Rouhani
 -- : Bowring --- : Levy ----- : Zuber

Heat Flux = 29.7 W/cm² D_o = 22.0 mm
 Velocity = 0.0067 m/s Heater Element = 48 cm

Figure 3.2 Comparison of void growth models : Experiment No.10.

□ : Experiment 10 — : Lahey ---- : Rouhani
 --- : Bowring ---- : Levy ---- : Zuber

Heat Flux = 77.0 W/cm² D_e = 22.0 mm
 Velocity = 0.1774 m/s Heater Element = 48 cm

Figure 3.3 Comparison of void growth models: Experiment No.20.

□ : Experiment 20 — : Lahey ---- : Rouhani
 — : Bowring ---- : Levy ---- : Zuber

Heat Flux = 112.6 W/cm² Do = 22.0 mm
 Velocity = 0.4758 m/s Heater Element = 48 cm

Figure 3.4 Comparison of void growth models : Experiment No.21.

□: Experiment 21 —: Lahey ----: Rouhani
 ---: Bowring ----: Levy ----: Zuber

Heat Flux = 27.7 W/cm² Do = 22.0 mm
 Velocity = 0.0611 m/s Heater Element = 60 cm

Figure 3.5 Comparison of void growth models : Experiment No.29.

o : Experiment 29 — : Lahey ---- : Rouhani

--- : Bowring ---- : Levy ---- : Zuber

Heat Flux = 77.5 W/cm² D_o = 22.0 mm
Velocity = 0.3800 m/s Heater Element = 60 cm

Figure 3.6 Comparison of void growth models : Experiment No.30.

□ : Experiment 30 — : Lahey ---- : Rouhani
 --- : Bowring - · - : Levy - - - : Zuber

Heat Flux = 20.7 W/cm² D_o = 20.0 mm
 Velocity = 0.0300 m/s Heater Element = 48 cm

Figure 3.7 Comparison of void growth models : Experiment No.39.

□ : Experiment 39 — : Lahey ----: Rouhani
 ---: Bowring -.-: Levy -.-: Zuber

Heat Flux = 118.7 W/cm² D_o = 25.0 mm
 Velocity = 0.1848 m/s Heater Element = 48 cm

Figure 3.8 Comparison of void growth models : Experiment No.41.

□ : Experiment 41 — : Lahey ---- : Rouhani
 -- : Bowring -.- : Levy -.-.- : Zuber

Heat Flux = 29.7 W/cm² D_e = 25.0 mm
 Velocity = 0.0476 m/s Heater Element = 60 cm

Figure 3.9 Comparison of void growth models : Experiment No.47.

□ : Experiment 47 — : Lahey ---- : Rouhani
 --- : Bowring ---- : Levy ---- : Zuber

Heat Flux = 77.9 W/cm² Do = 25.0 mm
 Velocity = 0.8595 m/s Heater Element = 60 cm

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Figure 3.10 Comparison of void growth models : Experiment No.48.

□ : Experiment 48 — : Lahey ---- : Rouhani

-- : Bowring --- : Levy -.- : Zuber

Heat Flux = 29.7 W/cm² De = 20.0 mm
Velocity = 0.9897 m/s Heater Element = 48 cm

Figure 3.11 Comparison of void growth models : Experiment No.58.

□ : Experiment 58 — : Lahey ---- : Rouhani
 --- : Bowring - - - : Levy - . - : Zuber

Heat Flux = 20.7 W/cm² D_o = 20.0 mm
 Velocity = 0.0033 m/s Heater Element = 60 cm

Figure 3.12 Comparison of void growth models : Experiment No.62.

□: Experiment 62 —: Lahey ----: Rouhani
 ---: Bowring ----: Levy ----: Zuber

Heat Flux = 77.0 W/cm² D_e = 30.0 mm
 Velocity = 0.0086 m/s Heater Element = 60 cm

CHAPTER 4 : EQUILIBRIUM MODEL

4.1 Introduction

The equilibrium model is based on observed experimental trends. As discussed in chapter 2 a region of low, approximately constant, void (5-6%) was observed before the onset of significant void. Since there was no net vapor generation, it was assumed that there was a state of equilibrium between the evaporation and condensation. This equilibrium indicated the potential for development of a mechanistic boiling-condensation model.

Rouhani's (8) approach is employed since he presented a model which accounted for the evaporation and condensation separately. From this a condensation coefficient is derived for the low void plateau and its use projected to the void growth region. The model is therefore empirically based on the assumed state of equilibrium in the boiling process before the onset of significant void.

4.2 Methodology

Various mechanisms of heat transfer to a boiling liquid have been suggested, a summary of these is presented by Engelberg-Forster and Greif (26), a brief description of each is given in Appendix E.1. Both Rouhani (7,8) and Bowring (9) proposed three major mechanisms of heat removal;

1. Single phase heat transfer, in relation to the degree that bubbles do not cover the heated surface.
2. Steam generation.

3. Heating of the water replacing the detached bubbles.

The condensation of vapor in the subcooled liquid provides a major contribution in the heat exchange between the generated steam and the bulk liquid.

A heat balance in the transverse direction on the heater surface can then be written as;

$$\frac{q}{A} = h\Delta T\left(1 - \frac{\alpha}{\alpha_{osv}}\right) + \dot{m}_s h_{fg} + \frac{\dot{m}_s}{\rho_g} C_p \rho_l \Delta T_b \quad (4.1)$$

The first term represents the single phase heat transfer effect. As the void fraction begins to form a portion of the heated surface is covered by bubbles and hence inaccessible to the single-phase liquid flow. This produces a decrease in the single phase heat transfer to the point where it reaches zero at OSV, where it is assumed the total surface is covered by bubbles. The single phase heat transfer should be defined by the temperature difference $T_{wall} - T_b$, since the value of T_{wall} is not known an approximation to ΔT is made by $T_{sat} - T_b$.

The second term represents the heat transfer by steam generation. The term $\dot{m}_s$ is defined by Rouhani as "the mass of liquid which is converted into steam per unit time per unit area of the heated surface." ⁴ It can also be defined as the number of bubbles formed per unit time per unit area of the heated surface multiplied by the mass of each. Considering the later definition, multiplying by the heat of vaporization, the steam generation term represents the energy required to produce a number of bubbles within a defined area for a prescribed amount of time.

The last term of equation 4.1 represents the heating of the mass of water replacing the detached bubbles. Considering the definition of $\dot{m}_s$, on a per bubble basis, it can be shown that the term represents the amount of heat required to raise a mass of water, equivalent to the volume of a departing bubble, to the saturation

temperature, multiplied by the number of departing bubbles.

The amount of heat which goes to steam generation per unit time per unit length of the heated section is calculated as;

$$Q_b(Z) = \dot{m}_s h_{fg} P_H \quad (4.2)$$

Solving for $\dot{m}_s$ from equation 4.1 and substituting into 4.2 gives;

$$Q_b(Z) = \left(\frac{\left(\frac{q}{A} - h \Delta T \left(1 - \frac{\alpha}{\alpha_{oss}} \right) \right)}{\rho_g h_{fg} + C_p \rho_l \Delta T_b} \right) \rho_g h_{fg} P_H \quad (4.3)$$

The amount of heat which goes to the subcooled liquid through condensation of vapor per unit time per unit length of the heated section is ;

$$Q_c(Z) = K_c \Delta T_b \quad (4.4)$$

In this equation K_c represents a condensation coefficient with the same dimensions as that of the thermal conductivity, although there is no direct physical comparison. Rouhani presented an empirical value of K_c for pressures ($p > 19$ bars), well above those of the present study;

$$K_c = 30 \frac{k_l}{Pr} \left(\frac{\rho_g}{\rho_l} \right)^2 A^{2/3} \alpha^{2/3} \frac{Re}{N_q^{0.5}} \quad (4.5)$$

with

$$N_q = \frac{\frac{q}{A} \mu_l}{h_{fg} (\rho_l - \rho_g) \sigma}$$

To derive a value pertaining to the test conditions of this study, the findings of a region of approximately constant void fraction before the OSV was incorporated. The assumption that there is an equilibrium between evaporation and condensation provided the method for obtaining a condensation factor;

$$Q_b(Z) = Q_c(Z) \quad \alpha < \alpha_{oss}$$

$$K_c = \left(\frac{\frac{q}{A} - h \Delta T (1 - \frac{\alpha}{\alpha_{sat}})}{\Delta T_b (\rho_g h_{fg} + C_p \rho_l \Delta T_b)} \right) \rho_g h_{fg} P_H \quad (4.6)$$

It was concluded from the above that K_c is a function of both heat flux and location ($\alpha, \Delta T_b$). Since the void is approximately constant the bulk temperature is the predominant local parameter. Hence it was expected that K_c would vary within the region before OSV. It was observed that to maintain equilibrium conditions within the region K_c must increase along the heated length to compensate for increasing $Q_b(Z)$ and decreasing ΔT_b . Before boiling begins there is no condensation hence the value of K_c must be equal to zero. Condensation also equals zero when the bulk temperature reaches the saturation temperature. Therefore, a maximum is reached some where between the two states. It was expected that within the equilibrium region the highest condensation rate would occur just before the OSV. The void fraction then develops as the values of $Q_b(Z)$ and $Q_c(Z)$ diverge (illustrated in figure 4.1). Therefore it was assumed that taking a value of K_c just prior to the experimentally determined OSV would give a 'worst effect' approach, that is the value would either give a good prediction indicating high condensation throughout the process or a prediction lower than the actual. Values of K_c for each experiment are presented in table 4.1. A comparison between the condensation factor determined by Rouhani and by the equilibrium model, for the region before OSV, is given in tables 4.2–4.7. It is observed that there is a considerable difference between the values (by a factor of 200–1500). The values determined by Rouhani are small enough to imply no condensation, which is the result proposed by Bowring for all subcooled boiling conditions. Rouhani's work at high pressure though indicated high values of K_c ; 214.9 and 793.1 for pressures of 19 and 50 bar respectively and 5% void (geometry as given in table 2.5, $G=1055$ and 665 $\text{Kg/m}^2\text{s}$, $q/A = 88$ and 60.7 W/cm^2 respectively). The results of Rouhani's work indicates a decreasing value of K_c with decreasing pressure, but no discussion was presented on extrapolating to atmospheric conditions resulting in no condensation.

The change in the true vapor weight fraction and bulk temperature are derived, in section 2 and 3 respectively of Appendix E , by considering the heat balance on the two phases separately;

$$dX_t = \frac{(Q_b(Z) - Q_c(Z)) dZ}{\dot{m} h_{fg}} \quad (4.7)$$

and

$$\frac{dT_b}{dz} = \frac{\left(\frac{q}{A} P_H - (Q_b(Z) - Q_c(Z)) \left(\frac{h_z}{h_{fg}} \right) \left(1 - \frac{C_p T_b}{h_{fg}} \right) \right)}{\dot{m} C_p (1 - X_t)} \quad (4.8)$$

The average local void fraction was calculated by the use of the Zuber and Findlay (13) correlation;

$$\alpha = \frac{X_t}{\rho_g} \left(C_o \left(\frac{X_t}{\rho_g} + \frac{1 - X_t}{\rho_l} \right) + \frac{1.18}{G} \left(\frac{\sigma g (\rho_l - \rho_g)}{\rho_l} \right)^{\frac{1}{4}} \right)^{-1} \quad (4.9)$$

The distribution factor, C_o , was taken as 1.1 as suggested (8,11,12) for most flow conditions. The point where OSV occurred ($T_{osv}, X_{eq...}$) was taken from the experimental tests. The Fortran program of the equilibrium model is presented in Appendix E.4. Plots of the equilibrium model, for a number of experimental tests covering the velocity range studied, are shown in figures 4.2–4.15.

4.3 Discussion of Results

The model provides good predictions of the void fraction growth in the medium velocity range of approximately 0.07–0.18 m/s (figure 4.2–4.7). For both the low (< 0.07 m/s) and high (> 0.18 m/s) velocities the prediction lies under the experimental (figures 4.8–4.11 and 4.12–4.15 respectfully). Thus, as suggested, assuming a condensation factor derived from the low void plateau gives predictions that are either situated on or beneath the experimental results.

For low velocities, following the OSV, the flow quickly developed into a transition region between the bubbly and slug flow. The larger vapor formation associated with this flow pattern corresponds to lower condensation, this is seen in the very rapid growth associated with this region. A better prediction occurred when no condensation was assumed (figures 4.16–4.18). This was accomplished by setting the condensation factor to zero.

At higher velocities (>0.18 m/s) the bubble size at departure decreases with increasing velocity, as predicted by Winterton (25). Due to the smaller bubble size and less coalescence the condensation was expected to be high. As can be seen from the results the predictions were not in agreement with the experiments, but the deviation was not as significant as that found for the low velocities. It was observed, for this case as well, that assuming no condensation produced a better result (figures 4.19–4.21). A possible explanation is that due to the higher velocities the bubbles are entrained closer to the wall. The condensation rate is reduced since the bubble effectively sees a temperature somewhere between the bulk and the wall. Therefore assuming no condensation provides a qualitative perception of this condition.

For both the low and high velocities the predictions using K_c derived from the low void plateau region and that assuming no condensation encompass the experimental points for void fractions less than approximately 20 percent. This indicates that the condensation process should lie somewhere between the two extremes. Outside of this the boiling curve rises more rapidly than either predict.

4.4 Conclusions

The model works well for the medium velocity range of 0.07–0.18 m/s indicating the possibility of assuming a condensation factor derived from the low void region. The value provides a prediction lower than the test results for velocities outside this range which is to be expected since the condensation factor is assumed constant after the equilibrium region where the highest condensation was presumed to occur. The model provides a convenient method of determining the void growth from a correlating parameter based on a physically observed phenomenon. The results although not all inclusive provides insight into the evaporative-condensation mechanism at low pressure and low velocities.

Table 4.1 : Condensation factors, Kc, for the experimental tests.

Experimental test No.	velocity (m/s)	heat flux (W/cm**2)	Xeq OSV (%)	Void OSV (%)	Xeq Kc (%)	Void Kc (%)	Kc (W/m C)
1	0.0660	29.7	-1.8	8.5	-2.293	6.385	38.25
2	0.0750	29.7	-1.5	9.5	-1.759	9.234	80.11
3	0.0691	29.7	-1.5	9.0	-1.501	6.592	77.39
4	0.0810	29.7	-1.7	9.0	-1.969	6.531	68.38
5	0.2506	60.5	-1.5	9.0	-1.538	8.978	172.21
6	0.1517	61.0	-2.0	10.0	-2.372	9.749	74.39
7	0.1798	74.2	-1.5	8.5	-1.871	8.426	91.04
8	0.2871	74.2	-2.2	9.0	-2.359	7.213	90.29
9	0.4247	74.2	-2.3	9.0	-2.425	6.916	84.75
10	0.1774	77.0	-2.6	9.0	-2.684	7.853	73.26
11	0.1818	77.4	-2.5	5.0	-2.779	4.939	66.94
12	0.2385	77.4	-2.5	9.5	-2.558	9.360	81.42
13	0.2330	97.5	-3.0	9.5	-2.936	9.155	66.04
14	0.3175	97.5	-3.8	6.0	-4.015	4.959	41.47
15	0.3047	97.3	-3.8	9.5	-4.455	9.425	34.25
16	0.3011	118.6	-3.8	7.0	-4.059	7.173	50.34
17	0.3726	118.6	-4.1	9.0	-4.227	8.307	46.02
18	0.3867	118.7	-5.0	9.0	-5.313	6.885	28.59
19	0.4076	118.6	-4.8	7.0	-4.978	6.626	33.32
20	0.4752	118.6	-4.0	9.0	-4.264	6.960	44.33
21	0.0611	27.7	-2.2	4.0	-2.568	3.684	28.80
22	0.0805	27.7	-1.8	7.0	-2.142	4.736	40.48
23	0.1617	60.1	-2.3	8.0	-2.425	5.942	69.24
24	0.1943	60.6	-2.8	9.0	-3.068	6.375	43.53
25	0.2235	60.1	-2.9	9.0	-3.052	7.268	43.90
26	0.2027	73.9	-3.2	9.0	-3.275	8.399	47.59
27	0.3327	73.9	-5.3	9.0	-5.487	8.537	17.06
28	0.2569	77.8	-3.3	8.0	-3.635	5.221	39.62
29	0.3600	77.8	-4.4	8.0	-4.489	7.475	26.73

Table 4.1 continued.

30	0.0386	29.7	-1.4	6.0	-2.651	5.189	29.00
31	0.0492	29.7	-2.3	7.0	-3.318	6.143	18.80
32	0.0580	29.7	-1.8	7.0	-2.138	7.551	44.61
33	0.1286	60.6	-2.0	9.0	-2.188	8.151	86.37
34	0.1494	60.6	-1.7	9.0	-1.857	7.392	118.68
35	0.0923	77.5	-1.4	8.0	-1.540	6.505	219.38
36	0.1523	77.5	-2.3	8.0	-2.463	7.972	87.89
37	0.1528	97.6	-3.3	6.0	-3.406	5.893	58.42
38	0.1912	97.6	-3.2	8.0	-3.307	6.329	61.30
39	0.1842	118.7	-3.0	7.0	-3.205	4.228	78.90
40	0.1774	77.0	-3.7	8.0	-3.856	7.483	35.93
41	0.0476	29.7	-2.3	9.0	-2.848	8.587	25.26
42	0.0558	29.7	-3.3	9.0	-3.456	8.493	16.86
43	0.0839	28.6	-1.8	9.0	-1.838	8.777	57.47
44	0.1335	59.5	-3.3	7.0	-3.746	6.400	29.36
45	0.1579	59.5	-4.0	8.0	-4.131	7.907	24.32
46	0.2100	77.9	-6.0	9.0	-6.173	8.861	14.35
47	0.2595	77.9	-7.0	7.0	-7.159	6.827	10.66
48	0.0287	29.7	-2.3	7.5	-2.376	7.032	36.09
49	0.0324	29.7	-1.8	8.5	-1.846	8.091	59.19
50	0.0530	60.2	-2.3	8.5	-2.339	8.042	75.48
51	0.0601	60.2	-2.2	8.0	-2.203	7.041	84.77
52	0.0876	74.1	-2.8	9.0	-2.952	7.794	58.62
53	0.1003	74.1	-3.2	9.0	-3.207	8.107	49.81
54	0.0995	77.3	-3.0	9.0	-3.027	8.893	58.41
55	0.1103	97.6	-2.8	8.0	-3.140	6.927	68.37
56	0.1066	119.0	-1.8	6.0	-2.189	4.904	169.59
57	0.1290	119.0	-3.0	7.0	-3.062	6.684	87.84
58	0.0333	29.7	-2.6	8.0	-2.869	7.655	24.92
59	0.0875	60.3	-2.4	10.0	-2.850	9.851	51.30
60	0.1380	60.3	-3.2	9.5	-3.456	9.347	35.06
61	0.0923	74.5	-3.3	8.0	-3.485	7.770	42.60
62	0.0898	77.9	-1.5	9.0	-1.598	8.823	205.80
63	0.1165	77.9	-2.8	10.0	-2.824	9.709	67.45
64	0.0966	97.7	-3.0	9.0	-3.174	8.836	67.24
65	0.1344	97.7	-3.2	9.0	-3.427	8.020	57.59
66	0.0448	29.7	-2.0	10.0	-2.097	9.841	46.16

* Refer to tables G.1 - G.66 for experimental parameters.

Table 4.2 : Comparison of Condensation factor calculated by the equilibrium model and Rouhani (8) : Experiment No.1.

POINT #	VELOCITY, m/s	VOID %	QUALITY Xeq %	EQUILIBRIUM Kc W/mC	ROUHANI Kc W/mC
1	0.0820	5.779	-4.512	9.75	0.025
2	0.0798	6.217	-3.846	13.54	0.026
3	0.0772	5.958	-3.389	17.42	0.024
4	0.0755	7.954	-3.021	22.34	0.030
5	0.0758	6.833	-3.028	26.44	0.027
6	0.0745	8.971	-2.761	26.04	0.032
7	0.0750	7.725	-2.807	25.78	0.029
8	0.0725	6.385	-2.293	38.25	0.024

TEST PARAMETERS :

Xeq (OSV) = -1.8%, Void (OSV) = 8.5%
 PRESSURE = 22.5 psia D_o = 22.0 mm D_i = 13.1 mm
 HEAT FLUX = 29.7 W/cm**2 HEATER ELEMENT = 48 cm

Table 4.3 : Comparison of Condensation factor calculated by the equilibrium model and Rouhani (8) : Experiment No.10

POINT #	VELOCITY m/s	VOID %	QUALITY Xeq %	EQUILIBRIUM Kc W/mC	ROUHANI Kc W/mC
3	0.2209	5.505	-4.663	23.72	0.041
4	0.2171	6.300	-4.408	26.85	0.044
5	0.2101	6.674	-3.899	34.50	0.045
6	0.2054	5.978	-3.417	44.66	0.040
7	0.2029	7.424	-3.190	51.84	0.047
8	0.1974	8.233	-2.842	65.56	0.049
9	0.1970	7.143	-2.809	66.59	0.044
10	0.1982	7.853	-2.684	73.26	0.048

TEST PARAMETERS :

Xeq (OSV) = -2.6%, Void (OSV) = 9.0%
 PRESSURE = 22.5 psia D_o = 22.0 mm D_i = 13.1 mm
 HEAT FLUX = 77.0 W/cm**2 HEATER ELEMENT = 48 cm

Table 4.4 : Comparison of Condensation factor calculated by the equilibrium model and Rouhani (8) : Experiment No.20

POINT #	VELOCITY m/s	VOID %	QUALITY Xeq %	EQUILIBRIUM Kc W/mC	ROUHANI Kc W mC
16	0.4891	7.042	-4.801	34.94	0.087
17	0.4900	4.504	-4.675	35.40	0.063
18	0.4890	7.744	-4.596	38.55	0.094
19	0.4896	6.960	-4.264	44.33	0.087

TEST PARAMETERS :

Xeq (OSV) = -4.0%, Void (OSV) = 9.0%
 PRESSURE = 22.5 psia $D_o = 22.0$ mm $D_i = 13.1$ mm
 HEAT FLUX = 118.6 W/cm**2 HEATER ELEMENT = 48 cm

Table 4.5 : Comparison of Condensation factor calculated by the equilibrium model and Rouhani (8) : Experiment No.39

POINT #	VELOCITY m/s	VOID %	QUALITY Xeq %	EQUILIBRIUM Kc W/mC	ROUHANI Kc W/mC
6	0.1946	3.337	-4.382	41.66	0.035
7	0.1941	2.906	-4.326	42.63	0.032
8	0.1943	3.500	-3.959	51.15	0.036
9	0.1942	4.103	-3.816	55.27	0.040
10	0.1943	4.193	-4.120	47.42	0.041
11	0.1912	5.688	-3.509	65.93	0.050
12	0.1886	4.228	-3.205	78.90	0.040

TEST PARAMETERS :

Xeq (OSV) = -3.0%, Void (OSV) = 7.0%
 PRESSURE = 22.5 psia $D_o = 25.0$ mm $D_i = 13.1$ mm
 HEAT FLUX = 118.6 W/cm**2 HEATER ELEMENT = 48 cm

Table 4.6 : Comparison of Condensation factor calculated by the equilibrium model and Rouhani (8) : Experiment No.50

POINT #	VELOCITY m/s	VOID %	QUALITY Xeq %	EQUILIBRIUM Kc W/mC	ROUHANI Kc W/mC
12	0.0557	4.845	-3.953	26.50	0.036
13	0.0558	4.726	-3.999	25.88	0.035
14	0.0560	5.367	-3.993	26.03	0.038
15	0.0554	4.977	-3.689	30.42	0.036
16	0.0546	4.824	-3.439	34.96	0.035
17	0.0549	4.688	-3.399	35.76	0.034
18	0.0547	5.752	-2.845	51.06	0.040
19	0.0561	5.670	-2.485	66.66	0.040
20	0.0564	7.320	-2.374	73.26	0.049
21	0.0545	7.601	-2.427	70.20	0.048
22	0.0314	8.042	-2.339	75.48	0.051

TEST PARAMETERS :

Xeq (OSV) = -2.3%, Void (OSV) = 8.5%
 PRESSURE = 22.5 psia D_o = 30.0 mm D_i = 13.1 mm
 HEAT FLUX = 60.2 W/cm**2 HEATER ELEMENT = 48 cm

Table 4.7 : Comparison of Condensation factor calculated by the equilibrium model and Rouhani (8) : Experiment No.57

POINT #	VELOCITY m/s	VOID %	QUALITY Xeq %	EQUILIBRIUM Kc W/mC	ROUHANI Kc W/mC
4	0.1446	4.592	-4.713	36.78	0.063
5	0.1445	4.073	-4.432	41.47	0.058
6	0.1444	4.463	-4.414	41.90	0.062
7	0.1447	4.411	-4.411	41.94	0.061
8	0.1447	4.637	-4.029	50.32	0.064
9	0.1446	6.177	-3.764	58.03	0.078
10	0.1441	5.201	-3.437	81.57	0.069
11	0.1432	7.178	-3.164	82.18	0.086
12	0.1429	6.684	-3.062	87.84	0.082

TEST PARAMETERS :

Xeq (OSV) = -3.0%, Void (OSV) = 7.0%
 PRESSURE = 22.5 psia D_o = 30.0 mm D_i = 13.1 mm
 HEAT FLUX = 119.0 W/cm**2 HEATER ELEMENT = 48 cm

Figure 4.1 Variation of Q_b and Q_c after OSV : Experiment No.1.

: Experimental 1 — : $Q_b(z)$ --- : $Q_c(z)$.
 Heat Flux₁ = 29.7 W/cm² Do = 22.0 mm
 Velocity = 0.0667 m/s Heater Element = 48 cm

2

1.0

1.1

1.25

1.4

1.6

1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0

2.8

2.5

3.2

2.2

3.6

2.0

4.0

1.8

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(ANSI and ISO TEST CHART No. 2)

Figure 4.2 Prediction of void growth, with equilibrium model, of experimental test 3: heat flux = 29.7 W/cm^2 $D_o = 2.2 \text{ cm}$, heater element = 48 cm, velocity = 0.0691 m/s.

Figure 4.3 Prediction of void growth, with equilibrium-model, of experimental test 33: heat flux = 60.6 W/cm^2 $D_o = 2.5 \text{ cm}$, heater element = 48 cm, velocity = 0.1286 m/s.

Figure 4.4 Prediction of void growth, with equilibrium model, of experimental test 57: heat flux= 119.0 W/cm^2 $D_o = 3.0 \text{ cm}$, heater element= 48 cm , velocity= 0.1290 m/s .

Figure 4.5 Prediction of void growth, with equilibrium model, of experimental test 6: heat flux= 61.0 W/cm^2 $D_o = 2.2 \text{ cm}$, heater element= 48 cm , velocity= 0.1517 m/s .

Figure 4.6 Prediction of void growth, with equilibrium model, of experimental test 10: heat flux= 77.0 W/cm² D_o = 2.2 cm, heater element= 48 cm, velocity= 0.1774 m/s.

Figure 4.7 Prediction of void growth, with equilibrium model, of experimental test 7: heat flux= 74.2 W/cm² D_o = 2.2 cm, heater element= 48 cm, velocity= 0.1798 m/s.

Figure 4.8 Prediction of void growth, with equilibrium model, of experimental test 31: heat flux= 29.7 W/cm² D_o = 2.5 cm, heater element= 48 cm, velocity= 0.0492 m/s.

Figure 4.9 Prediction of void growth, with equilibrium model, of experimental test 50: heat flux= 60.2 W/cm² D_o = 3.0 cm, heater element= 48 cm, velocity= 0.0530 m/s.

Figure 4.10 Prediction of void growth, with equilibrium model, of experimental test 32: heat flux = 29.7 W/cm^2 $D_o = 2.5 \text{ cm}$, heater element = 48 cm , velocity = 0.0580 m/s .

Figure 4.11 Prediction of void growth, with equilibrium model, of experimental test 1: heat flux = 29.7 W/cm^2 $D_o = 2.2 \text{ cm}$, heater element = 48 cm , velocity = 0.0660 m/s .

Figure 4.12 Prediction of void growth, with equilibrium model, of experimental test 39: heat flux = 118.7 W/cm^2 $D_o = 2.5 \text{ cm}$, heater element = 48 cm , velocity = 0.1842 m/s .

Figure 4.13 Prediction of void growth, with equilibrium model, of experimental test 14: heat flux = 97.5 W/cm^2 $D_o = 2.2 \text{ cm}$, heater element = 48 cm , velocity = 0.3175 m/s .

Figure 4.14 Prediction of void growth, with equilibrium model, of experimental test 17: heat flux= 118.6 W/cm^2 $D_o = 2.2 \text{ cm}$, heater element= 48 cm , velocity= 0.3726 m/s .

Figure 4.15 Prediction of void growth, with equilibrium model, of experimental test 20: heat flux= 118.6 W/cm^2 $D_o = 2.2 \text{ cm}$, heater element= 48 cm , velocity= 0.4752 m/s .

---: Equilibrium Model —: No Condensation □: Experimental 31

Figure 4.16 Prediction of void growth, with the equilibrium model and a model assuming no condensation, of experimental test 31: heat flux= 29.7 W/cm², D_o = 2.5 cm, heater element= 48 cm, velocity= 0.0492 m/s.

---: Equilibrium Model —: No Condensation □: Experimental 50

Figure 4.17 Prediction of void growth, with the equilibrium model and a model assuming no condensation, of experimental test 50: heat flux= 60.2 W/cm², D_o = 3.0 cm, heater element= 48 cm, velocity= 0.0530 m/s.

Figure 4.18 Prediction of void growth, with the equilibrium model and a model assuming no condensation, of experimental test 1: heat flux= 29.7 W/cm², D_o = 2.2 cm, heater element= 48 cm, velocity= 0.0660 m/s.

Figure 4.19 Prediction of void growth, with the equilibrium model and a model assuming no condensation, of experimental test 39: heat flux= 118.7 W/cm², D_o = 2.5 cm, heater element= 48 cm, velocity= 0.1842 m/s.

Figure 4.20 Prediction of void growth, with the equilibrium model and a model assuming no condensation, of experimental test 17: heat flux= 118.6 W/cm², D_o = 2.2 cm, heater element= 48 cm, velocity= 0.3726 m/s.

Figure 4.21 Prediction of void growth, with the equilibrium model and a model assuming no condensation, of experimental test 20: heat flux= 118.6 W/cm², D_o = 2.2 cm, heater element= 48 cm, velocity= 0.4752 m/s.

CHAPTER 5 : DRIFT FLUX MODEL

5.1 Introduction

5.1.1 Drift Flux Model

The drift flux model places emphasis on the relative motion of the phases rather than the individual flows. The approach is one-dimensional and provides a basis to extend the theory to flows where two and three dimensional effects, such as variation of concentration and velocity across the cross-section, are important. The drift flux model as stated by Wallis (27)⁵ has wide spread application to the bubbly, slug, and drop regimes of gas-liquid flow as well as to fluid-particle systems.⁵

The drift velocity is defined as the difference between the component velocities and the average. The drift velocity of the two phases are given as;

$$U_{gj} = U_g - j \quad (5.1)$$

and

$$U_{lj} = U_l - j \quad (5.2)$$

Where j , the total local flux, is the sum of the volumetric flux of the separate phases;

$$j = j_g + j_l \quad (5.3)$$

with

$$j_l = (1 - \alpha)U_l = \frac{G(1 - X_t)}{\rho_l} \quad (5.4)$$

and

$$j_g = \alpha U_g = \frac{GX_t}{\rho_g} \quad (5.5)$$

The drift flux is defined as the volumetric flux of a component relative to a surface moving at the average velocity. The drift flux of each phase is therefore given as;

$$j_{gl} = \alpha(U_g - j) = \alpha U_{gj} \quad (5.6)$$

and

$$j_{lg} = (1 - \alpha)(U_l - j) = (1 - \alpha)U_{lj} \quad (5.7)$$

Rearranging equation 5.6 gives;

$$j_g = \alpha j + j_{gl} \quad (5.8)$$

This equation is valid for one-dimensional flow.

Zuber and Findlay (13) applied the drift flux approach to obtain a general equation for the weighted mean velocity of the gas phase (Appendix F.1);

$$\overline{U}_g = \frac{\langle j_g \rangle}{\langle \alpha \rangle} = C_o \langle j \rangle + \frac{\langle \alpha U_{gj} \rangle}{\langle \alpha \rangle} \quad (5.9)$$

Where C_o is a distribution factor defined as;

$$C_o = \frac{\langle \alpha j \rangle}{\langle \alpha \rangle \langle j \rangle} \quad (5.10)$$

$\langle \rangle$ denotes an average over the cross-section, defined by the equation;

$$\langle F \rangle = \frac{\int F dA}{A} \quad (5.11)$$

and $\overline{}$ denotes a weighted mean value defined as;

$$\overline{F} = \frac{\langle \alpha F \rangle}{\langle \alpha \rangle} \quad (5.12)$$

Since the one dimensional theory does not take into account variations in the concentration and velocity profiles across the cross-section, the C_o factor was introduced to account for this. Generally, for two-phase flow the ratio of suitable

integrals are used to define parameters which are equal to unity for truly one dimensional flow and not far from one in the general case. The C_o term represents the ratio of the average of the product of flux and concentration to the product of the averages, this being equal to unity for the one dimensional case.

The important result of the analysis is that equation 5.9 provides a convenient method of analyzing experimental data. When this equation is plotted on a graph of $\langle j_g \rangle / \langle \alpha \rangle$ versus $\langle j \rangle$ it results in a straight line, the slope of which is the distribution factor and the intercept on the abscissa the weighted mean drift velocity.

5.1.2 Distribution Factor

The distribution factor C_o was introduced by Zuber and Findlay (13) for conditions of adiabatic, dispersed two-phase flow systems with fully established velocity and concentration profiles. They found this parameter to be a constant between 1.0-1.5 depending on the curvature of the flow and concentration profiles. For the condition of heat and/or mass addition or removal along a duct the velocity and concentration profiles change. Hence C_o does not remain constant but varies along the length. From their analysis they introduced an equation for the calculation of void fraction as a function of true quality, physical parameters, distribution factor and weighted mean drift velocity (equation 4.9).

Kroeger and Zuber (11) proposed that C_o would vary from approximately zero at the point where $\langle \alpha \rangle$ was zero, and increase to a value larger than unity within the bulk boiling region. They found that varying C_o , in an equation similar to that of Zuber and Findlay's, had little effect on the shape of the void growth curve in the subcooled region but had a pronounced effect in the bulk boiling region. They

suggested in the absence of experimental data on flow profiles a constant value of C_o should be assumed for the entire test section.

5.2 Application of Drift Flux Model

5.2.1 Introduction

For the experimental tests heat was added uniformly by the heater element, so that the concentration and volumetric flux profiles change along the heated length, resulting in changing values of C_o . Consequently, plots of an experimental test in the $\langle j_g \rangle / \langle \alpha \rangle - \langle j \rangle$ plane would result in a curvature effect. Since experimental measurements are made on a local basis an approach was undertaken to determine C_o as a function of a non-dimensional local parameter, defined as X_l , which could be correlated to all experimental tests. An appropriately chosen X_l term would then facilitate a straight line plot of local values of $\langle j_g \rangle / \langle \alpha \rangle$ and $\langle j \rangle$, determined from a range of experimental conditions. From each plot C_o and U_{gj} can be obtained for a corresponding local parameter and a relationship derived for C_o as a function of X_l .

5.2.2 Determination of Local Parameter

As a first approximation the void growth was assumed to be strictly a function of the volumetric concentration. Since void growth varies directly with the heat flux for an equivalent heated length (with constant velocity, pressure and equal T_{in}) it was speculated that the void fraction would give a direct indication of changing regimes. The local parameter was therefore defined by the true quality. Plots of $\langle j_g \rangle / \langle \alpha \rangle$ versus $\langle j \rangle$ for this parameter showed a large degree of scatter

and was consequently disregarded.

It has been shown that the void fraction does give an indication of changing regimes (28,29), where the transition from bubble to slug flow was suggested as approximately 25% (or as high as 52%), but the velocity of each phase is required to define the exact point of transition. A significant velocity effect is observed on the temperature at OSV (refer to Chapter 2.5.2) while the void fraction profiles following OSV, for the velocity range of 0.06–0.40 m/s, have relatively similar rates of growth. This was observed by superimposing the growth curves using the OSV as a reference. The local non-dimensional parameter was therefore proposed, at a location downstream of the OSV, where both the true and equilibrium qualities are known, to be;

$$X_l = \frac{X_t - X_{t_{osv}}}{X_{eq} - X_{eq_{osv}}} \quad (5.13)$$

The non-dimensional local parameter can be seen to be a straight line approximation of the void growth curve. Since the true quality before OSV was low (corresponding to a void fraction less than 10%) and approximately constant for all experiments, equation 5.13 was simplified to;

$$X_l = \frac{X_t}{X_{eq} - X_{eq_{osv}}} \quad (5.14)$$

The value of X_t was determined from the correlation proposed by Levy (10);

$$X_t = X_{eq} - X_{eq_{osv}} \exp \left(\frac{X_{eq}}{X_{eq_{osv}}} - 1 \right) \quad (5.15)$$

while the equilibrium quality at onset was determined from the experimental tests.

5.2.3 Methodology

The drift flux model was applied to the experimental tests by calculating $\langle j_g \rangle$, $\langle j_l \rangle$, $\langle j \rangle$, X_l and X_l at each point following OSV. The value of X_l was found in general, to increase along the heated length. A typical result is presented in table 5.1 for experimental test No.1. (the Fortran program to determine drift flux values and values of X_l is given in Appendix F.3). The lower and upper limits of X_l were determined to be approximately 0 and 0.30 respectively, while the majority were located in the range of 0.01 to 0.23. There was a tendency for X_l values to congregate around certain points (0.02, 0.05, 0.08, 0.10, 0.12, 0.15, 0.18, 0.20 and 0.22), these were therefore chosen as the correlating values for which to apply the drift flux model. For each chosen value of X_l values within ± 0.01 of the mean were included in the graphs. A least square fit was applied to each plot to arrive at the value of C_o and the drift velocity. The results from the drift flux approach are presented in figures 5.1-5.9 where it is observed a linear relationship was obtained in the $\langle j_g \rangle / \langle \alpha \rangle - \langle j \rangle$ plane for constant values of X_l . The scale of the plots was chosen to illustrate the relative dispersion of values within the plane for increasing values of X_l .

For values of X_l greater than 0.10, corresponding to higher void fractions, the drift velocity was seen to decrease. This drop can be explained by the fact that as void fraction increases the average velocity of the flow approaches that of the vapor phase, resulting in a decrease in the drift velocity of the vapor phase.

For values of X_l less than 0.10 the expected trend in C_o occurs, ie. decreasing in magnitude with decreasing X_l , but there seems to be no drift velocity. It was unlikely that the flow acted as a homogeneous mixture with no slip, since the drift velocity should be the highest within this region.

Collier (5) states that "the drift flux model is valuable only when the drift velocity is significant compared with the total volumetric flux (say $U_{gj} > 0.05j$). This limits its usefulness to bubbly, slug and churn flow patterns." ⁶ For $X_l < 0.10$ this condition was not met since the drift velocity was approximately zero while the values of j were as high as 0.5 m/s, hence the results may not be consistent for low values of X_l .

It was observed in the experimental tests that after approximately 15-20% void the boiling process had proceeded through the bubbly region into a highly unsteady flow. This regime was a transition between the bubbly and slug flow which Wallis (27) labeled churn-turbulent. Zuber and Findlay (13) suggested a drift velocity for this region;

$$U_{gj} = 1.18 \left(\frac{g\sigma\Delta\rho}{\rho_l^2} \right)^{1/4} \quad (5.16)$$

which was found to be 0.1846 m/s for the experimental conditions of this study. Various expressions for the drift velocity have been proposed (13,27,35) all of which are approximations resulting in similar values (Appendix F.2). Since the majority of the test data following OSV have void fractions higher than approximately 15% it was expected that assuming a constant value of the drift velocity, corresponding to the churn-turbulent value, should provide equivalent distribution factors. The drift flux plots were redone with the least square fit forced through the abscissa corresponding to the drift flux velocity. Approximately the same C_0 values were obtained for X_l greater than 0.10 (table 5.2). Results of the analysis are shown in figures 5.10-5.17.

5.2.4 Variable Distribution Factor

The variation of C_o was obtained by plotting the values determined from the drift flux model versus the corresponding local parameter. Since the plot (figure 5.18) outlines a parabolic shape a quadratic was fit through the points giving;

$$C_o = 25.7X_l - 64.8X_l^2 \quad (5.17)$$

This was determined by forcing the quadratic through the origin so as to satisfy the condition $C_o \approx 0$ at $\alpha = 0$. Since not enough data was available for the region $X_l > 0.22$ a constant value of 2.6 was assumed.

A void growth model was developed incorporating the variable C_o . The temperature (hence equilibrium quality) and void fraction at the OSV was assumed from the experimental results. A heat balance was applied from the onset position, from which the equilibrium quality at locations downstream of the OSV were obtained. The true quality at locations following the OSV was determined from equation 5.15. This equation requires the condition of zero quality at OSV. In this study void fractions of 5-10% were measured at OSV and thus a quality. Therefore to satisfy Levy's equation the quality was assumed to be zero and the void at OSV was subsequently added to all calculated values of void (using equation 4.9). For this study the boundary conditions of the void growth profiles were;

$$\left. \frac{dX_t}{dX_{eq}} \right|_{X_{eq...}} = 0 \quad X_t = C \quad \text{at} \quad X_{eq} = X_{eq...}$$

C being a constant value (corresponding to the void fraction at OSV). The equation for the true quality should therefore be;

$$X_t = X_{eq} - X_{eq...} \exp \left(\frac{X_{eq}}{X_{eq...}} - 1 \right) + C \quad (5.18)$$

This equation is the same as Levy's with the addition of the term accounting for the quality at OSV. Thus, the determination of void fraction should be as described above. The Fortran program for variable C_o is given in Appendix F.4. Testing the model with experimental conditions values of C_o , as expected, increased along the heated length (table 5.3).

5.3 Discussion of Results

5.3.1 Prediction of Void Growth with Variable Distribution Factor

The variable C_o approach was compared to the experimental results, figures 5.19–5.32, to determine its proficiency. The prediction provided good agreement for the velocity range of approximately 0.06–0.40 m/s (figures 5.19–5.28).

Below approximately 0.06 m/s the model was found to under predict the results, figures 5.29–5.31. This can be explained to be a result of high bubble coalescence and hence a lower condensation rate than the conditions for which C_o was obtained. The low condensation was evident in the low experimental velocities (<0.04 m/s) where a very rapid void growth resulted in a early development of the churn turbulent region.

For velocities greater than 0.40 m/s the model predicted higher void fractions than the experimental (figures 5.32). This result can also be explained by a condensation effect. Winterton (25) determined, for atmospheric pressure and a velocity range of 0–0.4 m/s, that the bubble diameter goes up exponentially as the velocity decreases. Inversely as the velocity increases the bubble diameter decreases as well turbulent forces act to break and disperse the gas phase, accordingly there is an increase in condensation due to the surface area effect. This results in a slower void

growth and therefore the reason for the poorer prediction.

5.3.2 Comparison of Constant and Variable Distribution Factor

To further investigate the effect of the distribution factor comparisons of void growth were made using both a variable and constant C_o . The constant value of C_o was assumed to be 1.1, as suggested in Chapter 4.2, to encompass most flow conditions. The same approach for calculation of void growth was applied as discussed in Section 5.2.4. Therefore at a position along the heated length where the quality is the same the resulting void will depend on the value of C_o . Comparison of the resulting void growth profiles are shown in figures 5.33–5.38, for the range of velocities studied. Overall the results for the variable C_o gave a much better prediction of the void growth than the constant value. But for void less than approximately 15% the prediction using a constant C_o was slightly better. Within this region the variable C_o is less than 1.1, as indicated in table 5.3. Since the void growth determined using a constant C_o under-predicted that using a variable value indicates that a high C_o is required following OSV. Assuming a high value of C_o would artificially produce a better result since it would suppress the void and give a better prediction. This is contrary to the expected trend, indicated by Zuber and Findlay and verified in this study, of increasing C_o along the length from $C_o \approx 0$ at $\langle \alpha \rangle = 0$. The fact that high C_o values are required to correlate the data, for low void (<15%), further strengthens the concept of a significant condensation effect.

5.4 Conclusions

The merit of the model lies in the determination of the local non-dimensional parameter X_l . The proposed value allows for the application of the drift flux model on a local basis, giving straight line plots in the $\langle j_g \rangle / \langle \alpha \rangle - \langle j \rangle$ plane and drift velocities in accordance with those found in the literature. This provided for a simple relationship between the distribution factor and the local parameter. Incorporation of the variable C_0 in a void growth model indicated good agreement within the velocity range 0.06–0.40 m/s. Discrepancies in the results for velocities outside this range is explained by an expected condensation effect.

Table 5.1 : Results of applying drift flux approach to experimental test No.1.

EXPERIMENTAL CONDITIONS, TEST NO.1

No	VELOCITY (m/s)	EQUILIBRIUM QUALITY (%)	VOID (%)
1	0.0691	-1.551	12.68
2	0.0689	-1.497	10.15
3	0.0686	-1.494	16.19
4	0.0684	-1.402	19.05
5	0.0663	-0.920	28.54

DRIIFT FLUX VALUES

	J (m/s)	JG/VOID (m/s)	X1
1	0.0815	0.0978	0.066083
2	0.0870	0.1786	0.079635
3	0.0870	0.1136	0.080380
4	0.0989	0.1602	0.102838
5	0.1988	0.4648	0.209038

TEST PARAMETERS :

$X_{eq} = -1.8 \%$ Void = 8.5 %
 PRESSURE = 22.5 psia $D_o = 22.0$ mm $D_i = 13.1$ mm
 VOLTAGE = 9.0 volts HEAT FLUX = 29.7 W/cm**2
 HEATER LENGTH = 48.0 cm

Table 5.2 Comparison of Co values with and without imposing a empirical drift velocity.

X	Co	drift velocity (m/s)	Co	imposed drift velocity (m/s)
0.05	1.10	-0.0136	0.33	0.1846
0.08	1.94	-0.0185	1.15	0.1846
0.10	2.03	0.0379	1.75	0.1846
0.12	2.05	0.2534	2.20	0.1846
0.15	1.97	0.2820	2.02	0.1846
0.18	2.61	0.1997	2.64	0.1846
0.20	2.59	0.0914	2.45	0.1846
0.22	2.59	0.0490	2.32	0.1846

Table 5.3 : Variation of Co along the heated length
: Experiment No. 6.

No.	Co	Z - Z _{osv} (m)	X _{eq} (%)	Void (%)
1	-	0.00000	-2.000	10.000
2	0.189	0.00100	-1.970	10.180
3	0.369	0.00200	-1.940	10.631
4	0.541	0.00300	-1.909	11.267
5	0.704	0.00400	-1.879	12.032
6	0.858	0.00500	-1.849	12.888
7	1.004	0.00600	-1.819	13.808
8	1.142	0.00700	-1.789	14.768
9	1.273	0.00800	-1.759	15.751
10	1.396	0.00900	-1.728	16.741
11	1.511	0.01000	-1.698	17.727
12	1.620	0.01100	-1.668	18.699
13	1.721	0.01200	-1.638	19.651
14	1.816	0.01300	-1.608	20.575
15	1.904	0.01400	-1.577	21.470
16	1.986	0.01500	-1.547	22.333
17	2.061	0.01600	-1.517	23.163
18	2.130	0.01700	-1.487	23.960
19	2.194	0.01800	-1.457	24.726
20	2.251	0.01900	-1.426	25.461
21	2.303	0.02000	-1.396	26.168
22	2.350	0.02100	-1.366	26.856
23	2.391	0.02200	-1.336	27.509
24	2.427	0.02300	-1.306	28.148
25	2.458	0.02400	-1.276	28.770
26	2.485	0.02500	-1.245	29.378
27	2.506	0.02600	-1.215	29.974
28	2.523	0.02700	-1.185	30.563
29	2.536	0.02800	-1.155	31.147
30	2.544	0.02900	-1.125	31.728
31	2.548	0.03000	-1.094	32.311
32	2.548	0.03100	-1.064	32.897
33	2.543	0.03200	-1.034	33.490
34	2.535	0.03300	-1.004	34.092
35	2.524	0.03400	-0.974	34.707

Table 5.3 continued.

36	2.600	0.03500	-0.943	34.544
37	2.600	0.03600	-0.913	35.001
38	2.600	0.03700	-0.883	35.438
39	2.600	0.03800	-0.853	35.855
40	2.600	0.03900	-0.823	36.254
41	2.600	0.04000	-0.793	36.636
42	2.600	0.04100	-0.762	37.001
43	2.500	0.04200	-0.732	37.350
44	2.600	0.04300	-0.702	37.683
45	2.600	0.04400	-0.672	38.003
46	2.600	0.04500	-0.642	38.309
47	2.600	0.04600	-0.611	38.602
48	2.600	0.04700	-0.581	38.883
49	2.600	0.04800	-0.551	39.152
50	2.600	0.04900	-0.521	39.409
51	2.600	0.05000	-0.491	39.657
52	2.600	0.05100	-0.461	39.894
53	2.600	0.05200	-0.430	40.122

TEST PARAMETERS :

$X_{eq} = -2.0\%$ Void = 10.0 %
 PRESSURE = 22.5 psia $D_o = 22.0$ mm $D_i = 13.1$ mm
 VOLTAGE = 12.9 volts HEAT FLUX = 61.0 W/cm**2
 HEATER LENGTH = 48.0 cm

$X_l = 0.02 \quad C_o = 0.32 \quad \text{Drift Vel.} = -0.0005 \text{ M/S}$

Figure 5.1 Determination of C_o and drift velocity for $X_l = 0.02$.

$X_l = 0.05 \quad C_o = 1.10 \quad \text{Drift Vel.} = -0.0136 \text{ M/S}$

Figure 5.2 Determination of C_o and drift velocity for $X_l = 0.05$.

Figure 5.3 Determination of C_o and drift velocity for $X_l = 0.08$.

Figure 5.4 Determination of C_o and drift velocity for $X_l = 0.10$.

Figure 5.5 Determination of C_o and drift velocity for $X_l = 0.12$.

Figure 5.6 Determination of C_o and drift velocity for $X_l = 0.15$.

$X_l = 0.18$ $C_o = 2.61$ Drift Vel. = 0.1997 M/S

Figure 5.7 Determination of C_o and drift velocity for $X_l = 0.18$.

$X_l = 0.20$ $C_o = 2.59$ Drift Vel. = 0.0914 M/S

Figure 5.8 Determination of C_o and drift velocity for $X_l = 0.20$

$X_l = 0.22$ $C_o = 2.59$ Drift Vel. = 0.0490 M/S

Figure 5.9 Determination of C_o and drift velocity for $X_l = 0.22$.

$X_l = 0.05$ $C_o = 0.33$ Drift Vel. = 0.1046 M/S

Figure 5.10 Determination of C_o , with fixed drift velocity, for $X_l = 0.05$.

$X_l = 0.08$ $C_o = 1.15$ Drift Vel. = 0.1846 M/S

Figure 5.11 Determination of C_o , with fixed drift velocity, for $X_l = 0.08$.

$X_l = 0.10$ $C_o = 1.75$ Drift Vel. = 0.1846 M/S

Figure 5.12 Determination of C_o , with fixed drift velocity, for $X_l = 0.10$.

$X_l = 0.12$ $Co = 2.20$ Drift Vel. = 0.1846 M/S

Figure 5.13 Determination of C_o , with fixed drift velocity, for $X_l = 0.12$.

$X_l = 0.15$ $Co = 2.02$ Drift Vel. = 0.1846 M/S

Figure 5.14 Determination of C_o , with fixed drift velocity, for $X_l = 0.15$.

$X_l = 0.18$ $C_o = 2.64$ Drift Vel. = 0.1846 M/S

Figure 5.15 Determination of C_o , with fixed drift velocity, for $X_l = 0.18$.

$X_l = 0.20$ $C_o = 2.45$ Drift Vel. = 0.1846 M/S

Figure 5.16 Determination of C_o , with fixed drift velocity, for $X_l = 0.20$.

$X_l = 0.22$ $Ca = 2.32$ Drift Vel. = 0.1846 M/S

Figure 5.17 Determination of C_o , with fixed drift velocity, for $X_l = 0.22$.

$$C_o = 25.7 \cdot X_l - 64.8 \cdot X_l^{0.2}$$

Figure 5.18 Evaluation of distribution factor as a function of the local parameter X_l .

--- : Variable C_o ■ : Experiment 2

Figure 5.19 Prediction of void growth; with variational C_o , of experimental test 2: heat flux= 29 W/cm², D_o = 2.2 cm, heater element= 48 cm, velocity= 0.0750 m/s.

--- : Variable C_o ■ : Experiment 43

Figure 5.20 Prediction of void growth, with variational C_o , of experimental test 43: heat flux= 28.6 W/cm², D_o = 2.5 cm, heater element= 60 cm, velocity= 0.0839 m/s.

--- : Variable C_o ■ : Experiment 33

Figure 5.21 Prediction of void growth, with variational C_o , of experimental test 33: heat flux= 60.6 W/cm², D_o = 2.5 cm, heater element= 48 cm, velocity= 0.1286 m/s.

--- : Variable C_o ● : Experiment 65

Figure 5.22 Prediction of void growth, with variational C_o , of experimental test 65: heat flux= 97.7 W/cm², D_o = 3.0 cm, heater element= 60 cm, velocity= 0.1344 m/s.

Figure 5.23 Prediction of void growth, with variational C_o , of experimental test 60: heat flux= 60.3 W/cm², D_o = 3.0 cm, heater element= 60 cm, velocity= 0.1380 m/s.

Figure 5.24 Prediction of void growth, with variational C_o , of experimental test 6: heat flux= 61.0 W/cm², D_o = 2.2 cm, heater element= 48 cm, velocity= 0.1517 m/s.

Figure 5.25 Prediction of void growth, with variational C_o , of experimental test 7: heat flux= 74.2 W/cm², D_o = 2.2 cm, heater element= 48 cm, velocity= 0.1798 m/s.

Figure 5.26 Prediction of void growth, with variational C_o , of experimental test 39: heat flux= 118.7 W/cm², D_o = 2.5 cm, heater element= 48 cm, velocity= 0.1842 m/s.

Figure 5.27 Prediction of void growth, with variational C_o , of experimental test 14: heat flux = 97.5 W/cm^2 , $D_o = 2.2 \text{ cm}$, heater element = 48 cm , velocity = 0.3175 m/s .

Figure 5.28 Prediction of void growth, with variational C_o , of experimental test 17: heat flux = 118.6 W/cm^2 , $D_o = 2.2 \text{ cm}$, heater element = 48 cm , velocity = 0.3726 m/s .

Figure 5.29 Prediction of void growth, with variational C_o , of experimental test 48: heat flux = 29.7 W/cm^2 , $D_o = 3.0 \text{ cm}$, heater element = 48 cm , velocity = 0.0287 m/s .

Figure 5.30 Prediction of void growth, with variational C_o , of experimental test 50: heat flux = 60.2 W/cm^2 , $D_o = 3.0 \text{ cm}$, heater element = 48 cm , velocity = 0.0530 m/s .

Figure 5.31 Prediction of void growth, with variational C_o , of experimental test 32: heat flux 29.7 W/cm^2 , $D_o = 2.5 \text{ cm}$, heater element = 48 cm, velocity = 0.0580 m/s .

Figure 5.32 Prediction of void growth, with variational C_o , of experimental test 19: heat flux 118.6 W/cm^2 , $D_o = 2.2 \text{ cm}$, heater element = 48 cm; velocity = 0.4076 m/s .

Figure 5.33 Prediction of void growth, with variational and constant C_o , of experimental test 50: heat flux= 60.2 W/cm², D_o = 3.0 cm, heater element= 48 cm, velocity= 0.0530 m/s.

Figure 5.34 Prediction of void growth, with variational and constant C_o , of experimental test 60: heat flux= 60.3 W/cm², D_o = 3.0 cm, heater element= 60 cm, velocity= 0.1380 m/s.

---: Variable C_o —: Constant C_o □: Experiment 6

Figure 5.35 Prediction of void growth, with variational and constant C_o , of experimental test :
heat flux= 61.0 W/cm², D_o = 2.2 cm, heater element= 48 cm, velocity= 0.1517 m/s

---: Variable C_o —: Constant C_o □: Experiment 39

Figure 5.36 Prediction of void growth, with variational and constant C_o , of experimental test :
heat flux= 118.7 W/cm², D_o = 2.5 cm, heater element= 48 cm, velocity= 0.1842 m/s

---: Variable C_o —: Constant C_o □: Experiment 14

Figure 5.37 Prediction of void growth, with variational and constant C_o , of experimental test 14:
heat flux = 97.5 W/cm², D_o = 2.2 cm, heater element = 48 cm, velocity = 0.3175 m/s.

---: Variable C_o —: Constant C_o □: Experiment 19

Figure 5.38 Prediction of void growth, with variational and constant C_o , of experimental test 19:
heat flux = 118.6 W/cm², D_o = 2.2 cm, heater element = 48 cm, velocity = 0.4752 m/s.

CHAPTER 6 : CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary of Investigation

A number of experimental tests were carried out to investigate subcooled void fraction growth in water under low pressure (1.55×10^5 Pa) and low flow rate conditions (0.03–0.50 m/s) in an internally heated annular test section. The growth curves illustrated the familiar "S" shape, with the OSV indicating a strong velocity dependence. The most significant outcome was a region of low void (5–6%) before OSV which was observed in all tests. This region appeared in two experimental studies found in the literature, indicating that this region was not unique to this study. Yet, no reference is made to this phenomenon. Error analysis on the void fraction (no larger than ± 5.0 %) indicates that the densitometer has the ability to discern the stability of the low region, but not the exact magnitude. Investigation of possible air content (0.854 % by volume) indicated that this introduced little to no error in the void fraction readings.

The five subcooled void growth models from the literature were derived for conditions outside the range of this study and hence did not provide good predictions. Although the method proposed by Rouhani (8) gave a good mechanistic approach to build upon by separately considering condensation and evaporation.

6.2 Final Remarks on the Equilibrium Model

A model to predict the void growth was developed from the observed equilibrium between evaporation and condensation in the low void region before OSV and Rouhani's mechanistic model.

This condition, of no net vapor growth, provided the means of obtaining a condensation factor for the region prior to OSV;

$$K_c = \left(\frac{\frac{q}{A} - h\Delta T (1 - \alpha/\alpha_{osv})}{\Delta T_b(\rho_g h_{fg} + C_p \rho_l \Delta T_b)} \right) \rho_g h_{fg} P_H$$

The value of K_c was determined at an experimental point just prior to OSV and employed throughout the boiling process. It was expected that the highest condensation would occur at this point. This was seen to be the case since the model gave good void growth predictions in the velocity range 0.07–0.15 m/s while under-predicted the results outside of this range. The approach provides a convenient method of determining the void growth from a correlating parameter based on a physically observed phenomenon.

6.3 Final Remarks on the Drift Flux Model

A drift flux model was applied on a local basis to the experimental tests. The non-dimensional local parameter determined to correlate the changing flow conditions was;

$$X_l = \frac{X_t - X_{t_{osv}}}{X_{eq} - X_{eq_{osv}}}$$

This parameter provided for straight line plots in the $\langle j_g \rangle / \langle \alpha \rangle - \langle j \rangle$ plane and thus allowed the determination of C_o and U_{gj} . The distribution factor was then determined to vary with the local parameter as;

$$C_o = 25.7X_l - 64.8X_l^2$$

The incorporation of the variable C_o in a void growth model provided good agreement in the velocity range 0.06–0.40 m/s. Discrepancies in the results for velocities outside this range is explained by an expected condensation effect. Limited experimental results were obtained in the low velocity (nine tests for $U < 0.06$ m/s) and high velocity range (two tests for $U > 0.40$ m/s). Additional studies in

these areas would provide a means to further assess the non-dimensional parameter X_l and thus the distribution factor. This model provided good predictions over a wider range of experimental conditions than the equilibrium model and thus must be considered as a more viable technique of obtaining void growth profiles.

6.4 Suggestions for Future Work

- A more thorough calibration of the densitometer should be undertaken. The uncertainty in the void fraction could be more clearly defined and therefore instill more confidence in low void readings ($< 5\%$).
- Further analytical work for the prediction of void growth should be on a per bubble basis. This allows for the study of the mechanism of evaporation and condensation on a single bubble which when a population is known would give the void fraction at a location.
- Further study is also required on the velocity, two phases temperature and concentration profiles. This would then provide a better understanding of the condensation effect which was observed to be very predominant throughout the tests. As well it would provide an analytical means of determining the concentration factor.
- Studies could also be done to determine a flow pattern map. The transition from bubbly to churn turbulent and possibly slug flow could therefore be determined.
- A modification to the experimental apparatus that would be very beneficial would be the installation of instrumentation for the determination of wall temperatures. Presently calculations are done assuming $T_{wall} = T_{sat}$. A means of obtaining T_{wall} was initiated although no final results were obtained.

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FOOTNOTES

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Appendix A : Experimental Equipment

A.1 Gamma Densitometer

The Gamma densitometer consists of a 10 millicurie Cobalt 57 Source, a lead shielded collimator tube, a photomultiplier tube, a signal counting, amplifying and processing unit, and a microcomputer for scanning and time averaging the signal.

The collimator is a lead shielded tube with a one inch inside diameter and six inch length. The Cobalt 57 source is placed at one end of the collimator tube and the annular test section at the other. The Gamma rays originating from the source are collimated by the collimator pass through the test section and are detected by a photomultiplier tube on the other side. The whole assembly is located on a traversing table, which allows scanning of the entire test section by means of a motor driven lead screw. The schematic of the collimator is presented in figure A.1.

The signals originating from the photomultiplier tube are fed directly to the amplifier, discriminator and counter. To reduce the problem of excessive heating of the photomultiplier magnetic shielding, caused by the A.C. magnetic field (from the high current passing through the heater element), a forced air cooling system, using the compressed air supply of the building, is used.

A.2 Data Processing System

The following information on the systems hardware was obtained from the Undergraduate Thesis of Zia Abdullah : Investigation of Onset of Significant Void Fraction Under Low Pressure and Low Velocities. University of Ottawa, 1982.

A.2.1 System Hardware

The center of the data processing system is an 8080 CPU interfaced with 64k bytes of RAM, a 2000 character CRT, an ASCII keyboard and dual double density diskette drives providing over 1 million bytes of on line data storage. The system has also been interfaced with an ISBC 711 Analog Input Board consisting of 8 differential or 16 single ended channel multiplexer, input protection circuit, programmable gain amplifier, sample and hold amplifier and 12 bit A/D converter. The system has also been interfaced with a Centronics 739 line printer, and an H.P. 7225A Plotter.

A.2.2 Software

The software incorporated in the data processing system is FORTRAN 80 (presented in Appendix A.4), while the subroutine to the control scanner is written in 8080 machine language. The main program used in the process of data acquisition calls a subroutine to scan the input channels of the A/D converter, to store the data and for calculations.

The flowrate is determined from the formula;

$$\text{Flowrate} = C \times \text{Transducer Voltage}$$

There is a constant C determined for each of the five orifices. The value of C was determined by calibrating the orifice by actual measurements of the flowrate and the transducer voltage. The value of C is changed in the program when a new orifice is used. The velocity is expressed in meters per second obtained from multiplying the mass flow reading by appropriate constants. The mass flow, velocity and the transducer voltage are displayed on the microcomputers screen. The transducer voltage is required for setting the zero reading before the run.

The signal from the thermocouple is converted to a reading of temperature by:

$$T(C) = \frac{\text{Temperature Signal}}{4} \times 100$$

Three temperatures are displayed on the microcomputer screen, the water temperature at the inlet and outlet and the room temperature.

The void signal is obtained from the ratemeter. This signal is sampled by the software; the number of which can easily be adjusted. Each sample is stored and the mean value taken. Presently the number of samples taken of the ratemeter per output is 350.

The program calculates the power by dividing the square of the R.M.S. voltage by the resistance of the heater element. The resistance of the heater element is determined from the voltmeter and ammeter, for the range of voltage 8 -18 volts, the average value is then used in the calculation.

A.3 Experimental Loop

A.3.1 Test Conditions

A detailed schematic of the test loop is shown in figure A.2, the path of the demineralized water is shown with a dotted line. Each of the test loop's components are numbered, description of each and positioning of valves during a test follows:

1. Pressure gage (Ashcroft) 0-60 psig, discrimination 1.0 psig; Indicates loop pressure.
2. Trip-off valve; activated when loop pressure exceeds 50 psi.

3. Gate valve - open; this allows pressure relief system to activate at 35 psi.
4. Trip-off valve; activated when loop pressure exceeds 35 psi. Overflow from both relief valves flows to the overflow tank.
5. Was a pressure relief valve; removed from system.
6. Degasification valve; used to degas loop.
7. Gate valve - opened for test; used to regulate pressure on surge tank from filling pump.
8. Gate valve - variable; controls overflow back to the reservoir which allows fine adjustment of loop pressure.
9. Upper valve to surge tank level.
10. Sight glass; measurement of surge tank level.
11. Lower valve to surge tank level.
12. Gate valve - closed; provides drainage from surge tank to overflow tank.
13. Gate valve - closed; allows pressurization at the inlet when opened and gate valve No. 29 closed.
14. Gate valve - closed; allows drainage of overflow tank.
15. Gate valve - open.
16. Gate valve - open; controls fluid flow to the test section.
17. Flow meter for test section - not in use.
18. Gate valve - variable; used to control fluid flow through the by-pass loop.
19. Flow meter for bypass loop - not in use.
20. Degasification valve; used to degas loop.

21. Inlet valve - varied; controls flow through the test section.
22. Valve - closed; allows drainage from the annular section.
23. Test section exit plenum.
24. Outlet valve - open; the outlet valve from the test section is open during all runs.
25. Annular test section; outer glass tube and internal heater element.
26. Heat exchanger; shell and tube , one pass.
27. Pneumatic regulation valve; not operational, always open.
28. Gate valve - open.
29. Gate valve - open; allows pressurization of test section outlet.
30. Centrifugal circulating pump (Pumps and Softeners ltd., serial No.8111)
31. Unidirectional valve - open.
32. Gate valve - variable; allows flow to be diverted from main flowrate.
33. Degasification valve; used to degas the loop.
34. Gate valve - variable; allows flow to be diverted from main flowrate.
35. Gate valve - open; inlet to preheater, always to be open.
36. Drain valve - closed; allows drainage of preheater during change of fluid.
37. Unidirectional valve - closed.
38. Gate valve - closed; allows flow from main flow loop to the overflow tank.
39. Gate valve - open; valve before mixing of the main loop flow and the bypass loop.

40. Gate valve - open; used in the isolation of the circulating pump.
41. Gate valve - closed; blocks direct flow to the heat exchanger.
42. Gate valve - closed; blocks returning fluid from the heat exchanger from mixing with flow entering the pump.
43. Valve to heat exchanger - closed for test; opened for cooling of fluid between runs.
44. Gate Valve - opened for normal operation; closed when heat exchanger used.
45. Valve from heat exchanger - closed for test; opened for cooling of fluid between runs.
- 46) Pressure gage (Superfrunt) 0-30 psig, discrimination 0.25 psig. psig.
47. Pressure gage (Superfrunt) 0-30 psig, discrimination 0.25 psig.
48. Degasification valve; used to degas loop.
49. Orifice.
50. Filling Pump (Monarch Industries Ltd. Model No.OE-33); used to fill the loop when fluid level decreases and to provide the required pressurization of the loop.
51. Degasification valve; used to degas the loop.
52. Surge tank; used to prevent flow oscillations from affecting the orifice.
53. Plastic tubing placed upstream and downstream of the orifice to isolate the orifice from the connecting piping and thereby reducing vibrations caused by the circulating pump.

A.3.2 Surge Tank

The purpose of the surge tank is to suppress pressure excursions in the loop and provide pressure at the test section outlet. The capacity of the tank is approximately

300 l. The degasification valve at the top of the tank provides for venting of any contained gas.

A.3.3 Pre-Heater

The preheater provides heat to the water so as to maintain inlet temperatures. The preheaters can raise the inlet temperature to approximately 80 C, by means of four 3 kW heaters immersed in the water. The volumetric capacity is approximately 300l.

A.3.4 Heat Exchanger

The heat exchanger can be employed to maintain a constant inlet temperature or cool the water between runs. The unit is a one-shell pass, two tube pass configuration utilizing the city main (approximately 15 C) for cooling. The heat exchanger is by-passed for the majority of tests.

A.3.5 Filling pump

The filling pump maintains the pressure on the surge tank and provides for filling of the loop. The pump is a centrifugal type drawing from a reservoir of demineralized water. The pressure is monitored by a gage located at the inlet of the surge tank. There is a by-pass loop which diverts excess flow back to the reservoir.

A.3.6 Overflow Tank

The main function of the overflow tank is to provide a reservoir for excess water caused by pressure excursions within the loop.

A.3.7 By-pass Loop

Water flowing through the loop which does not pass through the test section is diverted through the by-pass loop. The flows are then reunited at a point after the test section outlet, before entering the circulating pump.

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Figure A.1 Section of the gamma densitometer.

Figure A.2 Detailed schematic of test loop.

ISIS-II FORTRAN-80 V2.0 COMPILATION OF PROGRAM UNIT @MAIN
 OBJECT MODULE PLACED IN :F1:LOOP.OBJ
 COMPILER INVOKED BY: fort80 :F1:LOOP.ftn

```

1      DIMENSION V(20), VA(20), VS(2000),Z(10),T(10),VOID(50),ZZ(10)
2      CHARACTER*1 PRNT
3      CHARACTER*8 PRESG,DIAG,VOLTG,HEATG,VOIDG,XQEG
4      CHARACTER*20 L5
5      REAL MINFLO,MAXFLO
        C      The following array does not have to be changed when the
        C      channel scanning limits or the gain is changed.
6      INTEGER*1 IA(3)
channel)C      Gaussian integer*2 array of length equal to (last channel fur
        C      The converted data is returned to this array
7      INTEGER*2 ID(11)
8      OPEN(UNIT=7,FILE=':LP:')
9      OPEN(UNIT=3,FILE=':F1:DATES')
10     OPEN(UNIT=4,FILE=':F1:TRYEE')
11     OPEN(UNIT=2,FILE=':TO:')
        C      Ajuste les origine du plotter
12     PRINT 430
13     430  FORMAT('AJUSTE LES ORIGINES DU PLOTTER & PRESS RETURN')
14     READ 917,PRNT
        C      The setting of the suppression control on the rateneter is '1'
15     SUP=5.0
16     MINFLO=5.0
17     MAXPLO=0.0
18     K=15
        C      The number of samples of the signal is 'M'.
        C      PRINT 40
        C      40  FORMAT('PLEASE TYPE THE NUMBER OF SAMPLES TO BE TAKEN')
        C      READ 41,M
19     M=350
20     41  FORMAT(I4)
21     PRINT 42
22     42  FORMAT('PLEASE TYPE IN THE ROOM TEMPERATURE (C)')
23     READ 97,TTZERO
24     PRINT 50
25     50  FORMAT('PLEASE TYPE IN THE PRESSURE')
26     READ 51, PRSR
27     51  FORMAT(F4.1)
28     PRINT 52
29     52  FORMAT('PLEASE TYPE IN THE VOLTAGE')
30     READ 53, VLTG
31     53  FORMAT(F4.1)
        C      R IS THE MEASURED RESISTANCE OF THE ROD IN OHMS.
32     R=.0142312
        C      Q IS THE POWER SUPPLIED.
33     Q=(VLTG**2.0)/R
34     CP=4232
35     XEQ=0.0
        C      The number of times the average of the signal is taken is 'K'
36     MM=1
37     KNN=50
38     RS=6

```

```

39      97      FORMAT(F6.3)
40      PRINT 45
ON41    45      FORMAT('PLEASE TYPE VOIDMETER READING FOR AIR IN THE TEST SEC
42      READ 43,AIR
43      PRINT 46
TI0M') 46      FORMAT('PLEASE TYPE VOIDMETER READING FOR WATER IN THE TEST S
45      READ 43,WATER
46      43      FORMAT(F7.4)
47      STORE=0.0
48      PRINT 961
49      961     FORMAT('DO YOU WISH DATA TO BE PRINTED?')
50      READ 917,PRNT
51      917     FORMAT(A1)
52      IF(PRNT.EQ.'Y')THEN
53      READ(3,333)IDAY,IMONTH,IYEAR
54      WRITE(7,77)IDAY,IMONTH,IYEAR
55      333     FORMAT(I2,I2,I2)
56      77      FORMAT(34X,I2,'/',I2,'/',I2,/)
57      HF=Q/(48.*1.3*3.141593)
58      WRITE(7,765)('_ ',I=1,22),PRSR,VLTG,Q,HF,('_ ',I=1,22)
59      765     FORMAT(28X,22A1,/,28X,'| 30mm DIA |',/,28X,
        *'| ',F4.1,' P.S.I.A. |',/,28X,'| ',F4.1,' VOLTS |'
        *'/,28X,'| POWER= ',F7.1,' W |',/,28X,'| HEAT FLUX= ',F5.1,'
        *',/,28X,22A1)
60      WRITE(7,742) M, TTZERO, AIR, WATER,('_ ',I=1,22)
61      742     FORMAT(28X,'| # OF SAMPLES= ',I4,' |',/,28X,'| ROOM TEMP. =',
        *F6.3,' |',/,28X,'| AIR ZERO= ',F7.4,' |',/,28X,'| WTR ZERO =',
        *F7.4,' |',/,28X,22A1,/)
62      WRITE(7,444)
63      444     FORMAT(80('_ '),/)
64      WRITE(7,331)
65      331     FORMAT(' NO',1X,'VOLT',1X,'FLOW',1X,'VELO.', 'T in',1X,'T out'
        *,2X,'FLO1',2X,'FLO2',1X,' TOUT ', ' TOUT ',2X,
        *'VOID',4X,'T out',2X,'QUALITY',/,4X,'FLOW',
        *1X,'RATE',51X,'CALC.',/,1X,'*',7X,'Kg/s',1X,
        *'m/s',3X,'C',5X,'C',5X,'C',5X,'C',19X,'X',8X,'C',7X,'X')
66      WRITE(7,444)
67      ENDIF
C Transfer des constance sur le graph.
68      WRITE(4,435) PRSR,VLTG,HF
69      435     FORMAT(F4.1,F4.1,F5.1)
70      CLOSE(UNIT=4)
71      OPEN(UNIT=4,FILE=':F1:TRYEE')
72      READ(4,440)PRESG,VLTG,HEATG
73      DIAG='30'
74      440     FORMAT(A4,A4,A5)
75      CLOSE(UNIT=4)
76      WRITE(2,445)
77      445     FORMAT('SM;SC-1000,300,0,5500;SI.38,.54;DTM;')
78      WRITE(2,450) 'PA-550,5250;LB',DIAG,'mm;
79      450     FORMAT(' ',A20,A5,A6)
80      WRITE(2,450) 'DTA;PA-550,5000;LB',PRESG,'PSIA;
81      WRITE(2,450) 'DTS;PA-550,4750;LB',VLTG,'VOLTS;
82      WRITE(2,450) 'DT,;PA-550,4500;LB',HEATG,' ,;
83      455     PRINT 460
84      460     FORMAT('Ecrire le numero du graph?')
85      READ 470,IGRAP

```

```

86      470  FORMAT(I1)
87      IF(IGRAP.GT.4)GO TO 455
88      L5='SC-1000,300,'
89      IF(IGRAP.EQ.2)L5='SC-1000,-350,'
90      IF(IGRAP.EQ.3)L5='SC-350,300,'
91      IF(IGRAP.EQ.4)L5='SC-700,-50,'
92      WRITE(2,475)L5,'0,5500;SI;SM*;'
93      475  FORMAT(A20,A20)
94      PRINT 480
95      READ 470,IGRAP
96      480  FORMAT('PRESS RETURN POUR PARTIR(START)')
      C      smallest orifice (1).
      C      CORFI=.009205
      C      small orifice (1.5)
      C      CORFI=.02093
      C      medium orifice (2) own pipe
      C      CORFI=.03873
      C      large orifice (3)
97      CORFI=.07405
      C      largest orifice (4)
      C      CORFI=.2092
      C      The following DO LOOP repeats the averaging process.
98      DO 654 IMARC=1,1000
99      DO 1 KN=1,KNN
100     KS=RS-KN
101     IF(KS.NE.1)GO TO 110
102     RS=RS+5
      C      PAUSE 500
103     110  CONTINUE
      C      The following DO LOOP initializes V(J) and VA(J).
104     DO 2 J=1,20
105     V(J)=0
106     VA(J)=0
107     2    CONTINUE
108     FLOSUM=0.0
      C      The gain of the A/D converter is set by 'IA(1)'.
109     IA(1)=0
      C      The channel # on which the scanning starts = IA(2).
110     IA(2)=4
      C      The channel # on which the scanning stops = IA(3).
111     IA(3)=15
      C      The following do loop does the actual scanning.
112     DO 3 L=1,M
113     CALL ADSCAN(ID,IA)
      C      The following do loop transfers ID to V(J) and then
      C      converts V(J) to volts.
114     DO 4 J=4,K
115     JJ=J-3
116     V(J)=ID(JJ)
117     28    IF(V(J).LT.0)GO TO 22
118     IF(V(J).GT.0)GO TO 23
119     GO TO 25
120     22    V(J)=(10.0*((V(J)/32768.0)+1))
121     IF(J.NE.10)GO TO 25
122     FLOW=SQRT(V(10))*CORFI*1.00
      C      for the large (3) orifice the constant is *0.0865*
      C      For the small (2) orifice the constant is *0.03873*

```



```

C      For the largest (3+1) orifice the constant is 0.2092
C      For the smallest (1) orifice the constant is 0.009205*
C      For the medium (1.5) orifice the constant is 0.021490
123      FLOSUM=FLOSUM+FLOW
124      GO TO 25
125      23      V(J)=(10.0*((V(J)/32768.0)-1))
126      FLOW=0.0
127      25      CONTINUE
128      VA(J)=VA(J)+V(J)
129      CONTINUE
130      4      CONTINUE
131      VS(L)= V(K)
132      3      CONTINUE
C      The following DO LOOP calculates the average reading, VA(J)
133      DO 5 J=4,K
134      VA(J)=VA(J)/(L-1)
135      5      CONTINUE
136      FLORAB=FLOSUM/(L-1)
137      FLORAC=SQRT(VA(10))*CORFI
138      FLORAT=(FLORAB+FLORAC)/2.0
139      VOID(KN)=VA(14)
140      PRINT 26, MM, VA(10)
141      26      FORMAT(/,3X,I4,21X,'FLOWRATE TRANSDUCER = ',F10.4)
142      GO TO 33
143      33      CONTINUE
144      VEL=FLORAT*1.7418
145      IF(VEL.GT.MAXFLO)MAXFLO=VEL
146      IF(VEL.LT.MINFLO)MINFLO=VEL
147      VELF=VEL*3.278
148      PRINT 31, FLORAT,VEL,VELF
149      31      FORMAT(38X,'MASS FLOW = ',F10.4,' KG PER SEC',/,39X,
&      'VELOCITY = ',F10.4,' METER PER SEC',/,39X,'VELOCITY = ',
&      F10.4,' FT PER SEC')
150      SUM=0
151      DO 9 J=1,M
152      SUM=SUM+((VS(J)-VA(14))*X2)
153      9      CONTINUE
154      ST=SQRT(SUM/M)
155      STR=((ST/(VA(14)+SUP))*100)
156      PRINT 21,TTZERO
157      21      FORMAT(/,31X,'ROOM TEMPERATURE = ',F9.1,' C')
158      DO 30,J=8,9
159      T(J)=(VA(J)/4.04)*100.0
160      T(J)=T(J)+TTZERO
161      CONTINUE
162      30      CONTINUE
163      DO 314,J=12,15,3
164      T(J)=0.0-(VA(J)/4.37)*100.0-1.5
165      T(J)=T(J)+TTZERO
166      314      CONTINUE
167      IF(PRNT.NE.'Y')GO TO 964
168      964      PRINT 27, (T(J),J=8,9)
169      27      FORMAT(30X,'INLET TEMPERATURE = ',F9.1,' C',/
&      ,29X,'OUTLET TEMPERATURE = ',F9.1,' C')
170      PRINT 423, (T(J),J=12,15,3)
171      423      FORMAT(30X,'TEMP. AT 1.5"= ',F9.1,' C',/
&      ,29X,'TEMP. AT 3.5"= ',F9.1,' C')

```

```

172      VOLT=V(11)
173      PRESO=(VA(13))*500.0
174      PRINT 29,PRESO
175 29    FORMAT(34X,'PRESSURE DROP =',F9.3,' PSI X10**3')
176      PRINT 100, VA(14),ST,STR
177 100   FORMAT(/,11X,'AVERAGE READING OF THE DENSITOMETER
      & = ',F10.4,/,28X,'STANDARD DEVIATION = ',F10.4,
      & /,17X,'STANDARD DEVIATION PERCENTAGE = ',F10.4)
178 6    FORMAT(/,5F15.5)
179      CONTINUE
180      DIFRNC =AIR-WATER
181      PVOID=((VA(14)-WATER)/DIFRNC)*100
182      PRINT 47, PVOID
183 47    FORMAT(/,32X,'VOID PERCENTAGE = ',F10.4,' %')
184      PRESA=0.0
185      T1=T(8)
186      T2=T(9)
C THIS IS FOR 1.5 INCHES
187      TCAL=T(8)+Q*.9000/(FLORAT*CP)
C      TCAL=T(8)+Q/(FLORAT*CP)
188      TCAL2=T(9)-Q*(1.-.9254)/(FLORAT*CP)
C      XEQ=(TCAL-TSAT)*CP/HFG*100
189      T12CAL=T(8)+Q*1.000/(FLORAT*CP)
190      T15CAL=T(8)+Q*1.0000/(FLORAT*CP)
191      H12=HF/((T(12)-T12CAL)*1.0E-4)
192      H15=HF/((T(15)-T15CAL)*1.0E-4)
C XEQ is computed with Tout and not with Tcal
193      IF(PRSR.EQ.35.0) XEQ=(TCAL2-125.7)*.1912
194      IF(PRSR.EQ.28.0) XEQ=(TCAL2-119.0)*.1895
195      IF(PRSR.EQ.22.5) XEQ=(TCAL2-112.5)*.1879
196      PRINT 60, TCAL, XEQ
197 60    FORMAT(/,18X,'CALCULATED OUTLET TEMPERATURE = ',F9.1,' C',/,
      * 21X,'EQUILIBRIUM VAPOUR QUALITY = ',F10.4,' %')
198      IF(PRNT.EQ.'Y') WRITE(7,222) MM,VA(10).FLORAT,VEL,T(8),T(9),
      * FLORAB,FLORAC,T12CAL,T15CAL,PVOID,TCAL,XEQ
199 222   FORMAT(I4,1X,F3.1,F5.3,F6.4,1X,F4.1,1X,F5.1,1X,F5.3,1X,F5.3,
      * 1X,F6.1,1X,F6.1,1X,F8.4,1X,F5.1,2X,F7.4,/)
200      VVOID=VOID(KN)
201      MM=MM+1
202      IF (STORE .EQ.0.0)GO TO 223
203 101   CONTINUE
204      IF(PVOID.LE.10.0)M=350
205      IF(PVOID.GT.10.0)M=200
206 223   IVOID=INT(PVOID*100.)
207      IXEQ=INT(XEQ*100.)
208      OPEN(UNIT=4,FILE=' :F1:TRYEE')
209      WRITE(4,221)IVOID,IXEQ
210      CLOSE(UNIT=4)
211 221   FORMAT(I5,I5)
212      OPEN(UNIT=4,FILE=' :F1:TRYEE')
213      READ(4,486)VOIDG,XEQG
214 486   FORMAT(A5,A5)
215      CLOSE(UNIT=4)
216      WRITE(2,487)'PA',XEQG,',',',',VOIDG,',;'
217 487   FORMAT(5A5)
218      1   CONTINUE
219 654   CONTINUE

```

```
220      WRITE(7,478)MINFLO,MAXFLO
221      478  FORMAT(///,15X,'VELOCITY RANGE IS: ',F5.4,' TO ',F5.4,' m/s')
222      STOP
223      END
```

MODULE INFORMATION:

```
CODE AREA SIZE      = 1CB0H    7344D
VARIABLE AREA SIZE  = 2276H    8822D
MAXIMUM STACK SIZE  = 000AH     10D
283 LINES READ
```

0 PROGRAM ERROR(S) IN PROGRAM UNIT @MAIN

0 TOTAL PROGRAM ERROR(S)
END OF FORTRAN COMPILATION

Appendix B : Error Analysis

B.1 Equipment error

All errors given in this section are in relation to the probability of one standard deviation, with an uncertainty of 68%.

B.1.1 Temperature Readings

K-type thermocouple has an error in the temperature reading of $\pm 0.75\%$, as suggested by the manufacture (Omega Engineering Inc.).

B.1.2 Power Measurements

Power dissipated across the heater element is calculated from values of voltage and current. The readings are obtained from single measurement needle type meters. The voltage can be read from one of two meters;

- Low range 1-15 volts discrimination of 0.2 volt. General Electric model No. 3602-117.
- High range 5-50 volts, discrimination of 1 volt. General Electric model No. 2902-117.

The current is obtained from a single meter.

- Range 25-300 amperes , discrimination of 5 amperes. General Electric model No. 4604-07.

When the experiment was built calibration of the voltage and current was undertaken by Zia Abdullah, one of the original technicians. The voltmeter was calibrated to an error no greater than ± 0.1 volts. The ammeter was calibrated to an error no larger than ± 0.1 ampere. The voltage and current are taken as single measurements with a reading error associated with the scale discrimination. The reading error for the volt-meters were estimated to be ± 0.05 volts for the low range and ± 0.25 volts for the high range. The percent reading error for the volt meters from the highest to the lowest reading (20-1 volts) is approximately 0.05-5.0 %. The ammeter has a estimated reading error of ± 1.0 amp, corresponding to a percent error of 0.04-4.0% from the highest to lowest reading (300-25 ampere). The cumulative error is approximated to be;

Voltmeter :

- low range ± 0.15 volts
- high range ± 0.35 volts

Ammeter :

- ± 1.1 ampere

B.1.3 Heater Element Resistance

The statistical error on the heater element resistance, assuming a normal distribution of ten experimental determined values ($R = \frac{V}{I}$), was determined to be approximately $\pm 1.7\%$.

When the experiment was built calibration of the voltage and current was undertaken by Zia Abdullah, one of the original technicians. The voltmeter was calibrated to an error no greater than ± 0.1 volts. The ammeter was calibrated to an error no larger than ± 0.1 ampere. The voltage and current are taken as single measurements with a reading error associated with the scale discrimination. The reading error for the volt-meters were estimated to be ± 0.05 volts for the low range and ± 0.25 volts for the high range. The percent reading error for the volt meters from the highest to the lowest reading (20-1 volts) is approximately 0.05-5.0 %. The ammeter has a estimated reading error of ± 1.0 amp, corresponding to a percent error of 0.04-4.0% from the highest to lowest reading (300-25 ampere). The cumulative error is approximated to be;

Voltmeter :

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- high range ± 0.35 volts

Ammeter :

- ± 1.1 ampere

B.1.3 Heater Element Resistance

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B.1.4 Flowrate Measurement

To determine the statistical error on the flowrate, 'known' flowrates (independent variable) were plotted versus measured flowrates (dependent variable). The 'known' flowrate was determined by measuring a large volume of water (20 l for $\dot{m} < 0.1$ Kg/s, 40 l for $\dot{m} > 0.1$ Kg/s) over a long period of time, thereby reducing the measuring error to a value assumed to be negligible. The result of the calibration is shown in figure B.1. The error on the measured flowrate was determined to be no larger than approximately ± 2.5 % for flowrates less than 0.11 kg/s (highest value used in study).

B.1.5 Dimensional Measurements

The error associated with the location of the densitometer from the test section inlet (0.9 of the heater element length from the inlet) is approximated to be ± 0.1 cm, this is due to the estimate of the central position of the densitometer. The location error can therefore be expressed as ± 0.23 %.

The heater element outside diameter and the glass tube inside diameter were measured with calipers having discrimination of 0.002 cm, the reading error was estimated to be ± 0.0002 cm, or ± 0.015 %.

B.1.4 Flowrate Measurement

To determine the statistical error on the flowrate, 'known' flowrates (independent variable) were plotted versus measured flowrates (dependent variable). The 'known' flowrate was determined by measuring a large volume of water (20 l for $\dot{m} < 0.1$ Kg/s, 40 l for $\dot{m} > 0.1$ Kg/s) over a long period of time, thereby reducing the measuring error to a value assumed to be negligible. The result of the calibration is shown in figure B.1. The error on the measured flowrate was determined to be no larger than approximately ± 2.5 % for flowrates less than 0.11 kg/s (highest value used in study).

B.1.5 Dimensional Measurements

The error associated with the location of the densitometer from the test section inlet (0.9 of the heater element length from the inlet) is approximated to be ± 0.1 cm, this is due to the estimate of the central position of the densitometer. The location error can therefore be expressed as ± 0.23 %.

The heater element outside diameter and the glass tube inside diameter were measured with calipers having discrimination of 0.002 cm, the reading error was estimated to be ± 0.0002 cm, or ± 0.015 %.

B.2 Error Propagation

When it is required to calculate the error on some quantity Z which is given as a function of several variables;

$$Z = Z(A, B, \dots, N) \quad (B.1)$$

There is a propagation of error resulting from the errors of the associated quantities. The formula for the error on quantity Z is given as (30,31);

$$\sigma_Z^2 = \left(\frac{\partial Z}{\partial A} \sigma_A \right)^2 + \left(\frac{\partial Z}{\partial B} \sigma_B \right)^2 + \dots + \left(\frac{\partial Z}{\partial N} \sigma_N \right)^2 \quad (B.2)$$

For addition or subtraction;

$$Z = A - B + \dots$$

The error in Z is;

$$\sigma_Z^2 = (1)^2 \sigma_A^2 + (-1)^2 \sigma_B^2 + \dots \quad (B.3)$$

For multiplication, division and exponentiation;

$$Z = A^n B^q C^{-p} \dots$$

giving an error;

$$\left(\frac{\sigma_Z}{Z} \right)^2 = n^2 \left(\frac{\sigma_A}{A} \right)^2 + q^2 \left(\frac{\sigma_B}{B} \right)^2 + p^2 \left(\frac{\sigma_C}{C} \right)^2 + \dots \quad (B.4)$$

B.3 Error on Equilibrium Quality

The value of the equilibrium quality is calculated from the relation;

$$X_{eq} = \frac{C_p(T_b - T_{sat})}{h_{fg}} \quad (B.5)$$

The values of C_p , h_{fg} and T_{sat} are taken from standard tables (32) and are assumed to have no associated error.

The value of T_b at the position of the densitometer is determined from a heat balance from the inlet to the location;

$$\dot{m}C_p(T_b - T_{in})\Delta T = \frac{q}{A}P_H L$$

giving

$$T_b = T_{in} + \frac{\frac{q}{A}(P_H L)}{\dot{m}C_p} \quad (B.6)$$

letting;

$$U = \frac{\frac{V^2}{R}(P_H L)}{\dot{m}C_p} = \frac{V^2 R^{-1} P_H L \dot{m}^{-1}}{C_p} \quad (B.7)$$

Thus the error on U can be determined by applying equation (B.4);

$$\left(\frac{\sigma_U}{U}\right)^2 = 2\left(\frac{\sigma_V}{V}\right)^2 + \left(\frac{\sigma_R}{R}\right)^2 + \left(\frac{\sigma_{P_H}}{P_H}\right)^2 + \left(\frac{\sigma_{\dot{m}}}{\dot{m}}\right)^2 \quad (B.8)$$

Then applying the addition equation (B.3) to obtain the error on the bulk temperature and therefore on the equilibrium quality.

$$\sigma_{T_b}^2 = \sigma_{T_{in}}^2 + \sigma_U^2 \quad (B.9)$$

Consider experiment No.1 as an example;

$$\frac{\sigma_U}{U} = \sqrt{2\left(\frac{0.15}{9.0}\right)^2 + 0.017^2 + 0.00015^2 + 0.0023^2 + 0.025^2} = 0.0344$$

Therefore the error on the bulk temperature is;

$$\frac{\sigma_{T_b}}{T_b} = \sqrt{0.0075^2 + 0.0344^2} = 0.0352$$

Considering the first value with $X_{e,q} = -4.512\%$ and $T_b = 88.0\text{ C}$

$$\sigma_{X_{e,q}} = \frac{(0.0352 \times T_b) C_p}{h_{fg}}$$

$$= \frac{(0.0317 \times 88) C_p}{h_{fg}}$$

$$= 0.0056$$

The error in the equilibrium quality for experiment No.1, has a range of ± 0.0056 - 0.0069 , the resulting error bars are shown in figure 2.6.

Figure R1 Calibration of mass flow rate.

Appendix C : Calculation of Air Content and Nucleation Point

C.1 To Calculate Possible Air Content

The solubility of air in water is;

Solubility of O_2 in water at 20 C = $1.4 \cdot 10^{-3}$ mole/l (Ref.33).

Solubility of N_2 in water at 20 C = $6.9 \cdot 10^{-4}$ mole/l (Ref.33).

The loop was in equilibrium with air at atmospheric pressure.

Therefore:

partial pressure of oxygen = 0.21 atm.

partial pressure of nitrogen = 0.79 atm.

Applying Henry's law at the two pressure ratios;

$$\frac{\text{concentration } O_2 \text{ at } 0.21\text{atm}}{\text{concentration } O_2 \text{ at } 1.0\text{atm}} = \frac{0.21}{1.00}$$

The same is done for nitrogen.

Therefore:

concentration of O_2 at 0.21 atm = $2.940 \cdot 10^{-4}$ mole/l.

concentration of N_2 at 0.79 atm = $5.451 \cdot 10^{-4}$ mole/l.

Now considering 1l of water;

gives;

$$2.94 \times 10^{-4} \text{ moles of } O_2$$

$$5.45 \times 10^{-4} \text{ moles of } N_2$$

Therefore:

$$\# \text{ of grams of } O_2 \text{ is } 32 \text{ g/mole} \times 2.94 \times 10^{-4} \text{ moles}$$

$$= 9.41 \times 10^{-3} g$$

$$\# \text{ of grams of } N_2 \text{ is } 28 \text{ g/mole} \times 5.45 \times 10^{-4} \text{ moles}$$

$$= 1.53 \times 10^{-2} g$$

Now the concentration can be determined on a volume basis ; For O_2

$$9.41 \times 10^{-3} g \times 1 / (1.300 Kg/m^3 \times 1000 g/Kg) = 7.23 \times 10^{-6} m^3/l$$

For N_2

$$1.53 \times 10^{-3} g \times 1 / (1.1421 \times 1000) = 1.33 \times 10^{-5} m^3/l$$

$$= 2.060 \times 10^{-5} m^3/l = 20.6 cc/l$$

Therefore we have 2.06% by volume (since 1l = 0.001 m³) of dissolved air in water saturated by air.

Now consider the conditions at 100 C ;

Solubility of O_2 in water at 100 C = 7.6×10^{-4} moles/l (Ref.33).

Solubility of N_2 in water at 100 C = 4.2×10^{-4} moles/l (Ref.33).

It can then be determined;

$$\# \text{ grams of } O_2 = 5.107 \times 10^{-3} \text{ g}$$

$$\# \text{ grams of } N_2 = 9.290 \times 10^{-3} \text{ g}$$

$$\text{volume} = 5.107 \times 10^{-3} \times 1/(1.3007 \times 1000) + 9.2 \times 10^{-3} \times 1/(1.142 \times 1000) \text{ giving}$$

$$= 1.206 \times 10^{-5} m^3/l$$

or

$$= 12.06 \text{ cc/l} = 1.206\%$$

Therefore maximum air content that could be released is;

$$2.06 - 1.206 = 0.854\%$$

By the time the water reaches 100 C the maximum percentage of air that could be released is 0.854. The corresponding void fraction is not measurable by the densitometer.

C.2 Incipience of Nucleate Boiling

An iterative technique was applied to determine, for initial conditions of T_{in} and velocity, the heat flux where bubbles first appear on the wall. The test apparatus was then set at these initial conditions and the heat flux was raised to the value determined for inception, and observations made.

Three equations are required for the determination of the heat flux for inception:

- 1) The convective heat transfer equation rearranged to the form;

$$T_{wall} = \frac{q}{h} + T_b \quad (C.2.1)$$

- 2) The two equations for predicting ONB;

Bergles and Rohsenow (22) (imperial units);

$$\frac{q}{A}/_{ONB} = 15.6 p^{1.156} (T_{wall} - T_{sat})_{ONB}^{2.3/p^{0.0234}} \quad (C.2.2)$$

Davis and Anderson (23);

$$\frac{q}{A}/_{ONB} = \frac{k}{4B} (T_{wall} - T_{sat})_{ONB}^2 \quad (C.2.3)$$

with

$$B = \frac{2\sigma T_{sat} v_{fg}}{h_{fg}}$$

- 3) The heat balance expressed as;

$$T_b = T_{in} + \frac{q LP_H}{C_p} \quad (C.2.4)$$

The steps taken to solve for the inception point;

- Guess an initial heat flux.
- Since the likelihood of void formation would be at the outlet, ie. location of densitometer, T_b was calculated from equation C.2.4.
- The wall temperature was then calculated using equation C.2.1. Three different convective heat transfer coefficients were used;

i) Dittus Boelter (32);

$$\frac{hD_i}{k} = 0.023 Re_d^{0.8} Pr^{0.4} \quad (C.2.5)$$

For fully developed turbulent flow in smooth tubes. Properties are evaluated at the fluid bulk temperature.

ii) Nusselt (32);

$$\frac{hD_i}{k} = 0.036 Re_d^{0.8} Pr^{1/3} \left(\frac{D_H}{L} \right)^{0.055} \quad (C.2.6)$$

Used for entrance regions in a tube, $10 < L/D_H < 400$.

iii) Stein and Begell (34);

$$St Pr^{2/3} Re^{0.2} \left(\frac{D_o}{D_i} \right)^{1/2} = 0.0244 \quad (C.2.7)$$

For annuli test sections, developed from experimental work (heat flux = 12.6–354 W/m², velocity = 1.21–13.7 m/s).

Values of the heat transfer coefficients were within $\pm 10\%$ of each other, therefore the equation of Dittus Boelter was used due to its general acceptance.

- The heat flux for ONB was calculated from either equation C.2.2 or C.2.3.

- Iteration was required if there was not agreement with the guessed value.

The test apparatus was then set to the determined heat flux and the results observed.

C.3 Check of Rohsenow (22) and Anderson (23) Theory

C.3.1 Test Case One

Test Conditions :

$$D_o = 30 \text{ mm } D_i = 13.1 \text{ mm } p = 1.55 \times 10^5 \text{ Pa}$$

$$\text{Vel.} = 0.0358 \text{ m/s } T_{in} = 20.0 \text{ C } G = 36.46 \text{ Kg/m}^2\text{s}$$

Theoretically determined heat flux at ONB;

- Rohsenow and Bergles = 4.13 W/cm^2 $T_b = 28.15 \text{ C}$
- Davis and Anderson = 4.06 W/cm^2 $T_b = 27.99 \text{ C}$

Observations;

- As a reference for void fraction, readings of the densitometer were made with no heat, ie no void (Table C.1).
- The heat flux corresponding to the predicted value was set on the test section, the resulting void fraction readings are presented in table C.2.
- No void was physically observed.
- No void was measured with the densitometer.

C.3.2 Test Case Two

Test Conditions :

$$D_o = 30 \text{ mm } D_i = 13.1 \text{ mm } p = 1.55 \times 10^5 \text{ Pa}$$

$$\text{Vel.} = 0.0570 \text{ m/s } T_{in} = 20.0 \text{ C } G = 58.00 \text{ Kg/m}^2\text{s}$$

Theoretically determined heat flux at ONB;

- Rohsenow and Bergles = 5.81 W/cm^2 $T_b = 27.55 \text{ C}$
- Davis and Anderson = 5.68 W/cm^2 $T_b = 27.39 \text{ C}$

Observations;

- No vapor bubbles were observed or measured, results are given in table C.3.

C.3.3 Test Case Three

Test Conditions :

$$D_o = 30 \text{ mm } D_i = 13.1 \text{ mm } p = 1.55 \times 10^5 \text{ Pa}$$

$$\text{Vel.} = 0.1170 \text{ m/s } T_{in} = 22.0 \text{ C } G = 116.70 \text{ Kg/m}^2\text{s}$$

Theoretically determined heat flux at ONB;

- Rohsenow and Bergles = 6.99 W/cm^2 $T_b = 26.45 \text{ C}$
- Davis and Anderson = 6.83 W/cm^2 $T_b = 26.35 \text{ C}$

Observations;

- No vapor bubbles were observed or measured, results are shown in table C.4.

Table C.1 : Recording of zero void (no heat flux).

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.021	0.0357	18.9	20.1	-	-0.482	-
2	0.021	0.0358	18.8	20.0	-	-0.064	-
3	0.021	0.0357	18.7	19.9	-	-0.126	-
4	0.021	0.0357	18.7	19.9	-	0.269	-
5	0.021	0.0358	18.7	19.9	-	0.456	-
6	0.021	0.0358	18.7	19.8	-	-0.401	-
7	0.021	0.0358	18.7	19.8	-	0.379	-
8	0.021	0.0358	18.7	19.8	-	-0.807	-
9	0.021	0.0358	18.7	19.8	-	-0.165	-
10	0.021	0.0357	18.7	19.8	-	-1.083	-

TEST PARAMETERS :

PRESSURE = 22.2 psia

D_o = 30.0 mm

D_i = 13.1 mm

VOLTAGE = - volts

HEAT FLUX = -

W/cm**2

TABLE C.2 : Verification of Rohsenow and Anderson theory;
test case No.1.

POINT	MASS	VELOCITY	T _{in}	T _{out}	T _{out} cal.	VOID	QUALITY
#	Kg/s	m/s	C	C	C	%	X _{eq} %
1	0.021	0.0357	19.3	28.9	29.3	0.623	-
2	0.021	0.0358	19.5	29.7	29.4	0.848	-
3	0.021	0.0358	19.4	30.3	29.4	0.749	-
4	0.021	0.0358	19.9	29.9	29.8	-0.088	-
5	0.021	0.0358	20.3	30.0	30.2	-0.039	-
6	0.021	0.0359	20.4	30.1	30.3	-0.324	-
7	0.021	0.0358	20.3	30.1	30.2	-0.479	-
8	0.021	0.0358	20.2	30.3	30.1	-0.421	-
9	0.021	0.0359	20.3	30.0	30.2	1.684	-
10	0.021	0.0358	20.3	30.0	31.3	0.027	-

TEST PARAMETERS :

PRESSURE = 22.2 psia D_o = 30.0 mm D_i = 13.1 mm
VOLTAGE = 3.7 volts HEAT FLUX = 4.9 W/cm**2

Table C.3 : Verification of Rohsenow and Anderson theory,
test case No.2.

POINT	MASS	VELOCITY	T _{in}	T _{out}	T _{out} cal.	VOID	QUALITY
#	Kg/s	m/s	C	C	C	%	X _{eq} %
1	0.031	0.0568	20.9	26.8	29.1	1.426	-
2	0.031	0.0568	21.0	27.1	29.3	-0.089	-
3	0.031	0.0567	21.1	27.3	29.3	0.831	-
4	0.031	0.0567	21.2	27.3	29.4	0.853	-
5	0.031	0.0569	21.2	27.2	29.4	0.015	-
6	0.031	0.0568	21.2	27.2	29.5	1.328	-
7	0.031	0.0575	21.3	27.3	29.4	1.014	-
8	0.031	0.0571	21.3	27.4	29.5	0.307	-
9	0.031	0.0567	21.3	27.4	29.6	0.625	-
10	0.031	0.0566	21.4	27.6	29.7	0.299	-

TEST PARAMETERS :

PRESSURE = 22.2 psia D_o = 30.0 mm D_i = 13.1 mm
VOLTAGE = 4.1 volts HEAT FLUX = 6.0 W/cm²

Table C.4 : Verification of Rohsenow and Anderson theory,
test case No.3.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.064	0.1170	21.6	25.2	26.4	1.010	-
2	0.064	0.1168	21.7	25.5	26.6	0.533	-
3	0.064	0.1170	22.0	25.5	26.8	1.012	-
4	0.064	0.1169	22.0	25.8	26.9	0.853	-
5	0.064	0.1170	22.2	25.8	27.0	0.865	-
6	0.064	0.1171	22.4	25.8	27.2	0.172	-
7	0.064	0.1171	22.4	25.8	27.2	0.172	-
8	0.064	0.1170	22.3	26.0	27.2	0.933	-
9	0.064	0.1170	22.5	26.0	27.3	0.740	-
10	0.064	0.1170	22.5	26.2	27.3	1.678	-

TEST PARAMETERS.:

PRESSURE = 22.2 psia D_o = 30.0 mm D_i = 13.1 mm
VOLTAGE = 4.5 volts HEAT FLUX = 7.2 W/cm²

C.5 Computer Program to Calculate Bubble Departure Point for Bergles and Rohsenow (22) and Davis and Anderson (23).

\$JOB

C

C====>THIS PROGRAM DETERMINES THE HEAT FLUX FOR ONB IE.

C THE POINT WHERE THE BUBBLES FIRST LEAVE THE HEATED

C SURFACE. TWO CORRELATIONS ARE USED;

C 1) BERGLES @ ROHSENOW 2) AND DAVIS @ ANDERSON.

C THE VALUE OF HEAT FLUX IS DETERMINED FROM EXPERIMENTAL

C VELOCITY AND BULK TEMPERATURE.

C

TSAT=112.5

SURF=0.0566

P=22.5

HFG=2226.0E+3

DENG=0.863

PI=3.1415927

DO=0.030

DI=0.0131

DE=DO-DI

ZL=.48

READ(5,1)TIN,VEL,GUESS

1 FORMAT(F6.2,1X,F6.4,1X,F6.2)

WRITE(6,*)TIN,VEL

CALL WATER(TIN,DEN,VISC,CP,PR,XK)

HOLD=GUESS

A=PI*(DO**2-DI**2)/4

XM=VEL*DEN*A

G=XM/A

REL=DEN*VEL*DE/VISC

H=(XK/DE)*0.023*(REL**0.8)*(PR**0.4)

C H=(XK/DE)*0.036*(REL**0.8)*(PR**(1./3.))*(DE/ZL)**0.055

C H=(DEN*CP*VEL*0.0244)/((PR**2./3.)*(REL**.2)*(DI/DO)**.5)

SUM=0.0

5 CONTINUE

FLUX=GUESS*10000

T=TIN+FLUX*PI*DI*0.9*ZL/(XM*CP)

TWALL=T+FLUX/H

IF(TWALL.LE.TSAT)GO TO 4

GO TO 3

4 CONTINUE

GUESS=GUESS+2.

GO TO 5

3 CONTINUE

C

C====>Bergles @ Rohsenow

C

TWALLF=TWALL*1.8+32.

TSATF=TSAT*1.8+32.

XA=(2.3)/(P**(0.0234))

XB=P**1.156


```

XC=(TWALLF-TSATF)
FLUBR=15.6*XB*(XC)**XA
FLUX2=FLUBR*(1./317)/10000.
ERR=100.*(GUESS-FLUX2)/GUESS
IF(ABS(ERR).LE.0.50)GO TO 6
IF(ERR.GT.0.0)GUESS=GUESS+0.01
IF(ERR.LT.0.0)GUESS=GUESS-0.01
SUM=SUM+1
IF(SUM.GT.25000)GO TO 6
GO TO 5
6 CONTINUE
RB=FLUX/10000.0
WRITE(6,*)XM,CP,DEN,A
WRITE(6,*)ERR
WRITE(6,*)'REL =' ,REL,'H =' ,H
WRITE(6,*)'TB =' ,T,'ITTER =' ,SUM
WRITE(6,*)'TWALL =' ,TWALL,' G =' ,G
WRITE(6,*)'ROHSENOW @ BERGLES =' ,RB

```

C
C===>Davis and Anderson
C

```

SUP=0.0
10 CONTINUE
FLUXX=HOLD*10000
T=TIN+FLUXX*PI*DI*0.9*ZL/(XM*CP)
TWALLX=T+FLUXX/H
IF(TWALLX.LE.TSAT)GO TO 11
GO TO 12
11 CONTINUE
HOLD=HOLD+2.
GO TO 10
12 CONTINUE
VFG=(1./DENG-1./DEN)
B=2*SURF*TSAT*VFG/HFG
FLUXDA=(XK*(TWALLX-TSAT)**2)/(4*B)
FLUX3=FLUXDA*(1./317)/10000.
ERRX=100.*(HOLD-FLUX3)/HOLD
IF(ABS(ERRX).LE.0.50)GO TO 14
IF(ERRX.GT.0.0)HOLD=HOLD+0.01
IF(ERRX.LT.0.0)HOLD=HOLD-0.01
SUP=SUP+1
IF(SUP.GT.25000)GO TO 14
GO TO 10
14 CONTINUE
DA=FLUXX/10000.0
WRITE(6,*)ERRX
WRITE(6,*)'TB =' ,T,'ITTER =' ,SUP
WRITE(6,*)'TWALL =' ,TWALLX,' G =' ,G
WRITE(6,*)'DAVIS AND ANDERSON =' ,DA
STOP
END

```

C
C===>SUBROUTINE TO DETERMINE LOCAL PROPERTIES OF WATER.
C

```

SUBROUTINE WATER(T,DEN,VISC,CP,PR,XK)
REAL TX(16),CPX(16),DENX(16),VISX(16),XKX(16),PRX(16)
DO 1 J=1,16
  READ(5,2)TX(J),CPX(J),DENX(J),VISX(J),XKX(J),PRX(J)
1 CONTINUE
DO 3 JX=1,15
  M=JX
  IF(T.GE.TX(M).AND.T.LE.TX(M+1))GO TO 4
3 CONTINUE
4 CONTINUE
XINTER=(T-TX(M))/(TX(M+1)-TX(M))
WRITE(6,*)XINTER
CP=XINTER*(CPX(M+1)-CPX(M))+CPX(M)
DEN=XINTER*(DENX(M+1)-DENX(M))+DENX(M)
VISC=XINTER*(VISX(M+1)-VISX(M))+VISX(M)
XK=XINTER*(XKX(M+1)-XKX(M))+XKX(M)
PR=XINTER*(PRX(M+1)-PRX(M))+PRX(M)
2 FORMAT(F6.2,1X,F6.1,1X,F5.1,1X,F8.6,1X,F5.3,1X,F4.2)
RETURN
END

```

\$ENTRY.

022.00	0.1170	010.00				
21.11	4179.8	997.4	0.000980	0.604	6.78	
26.67	4179.0	995.8	0.000860	0.614	5.85	
32.22	4174.0	994.9	0.000765	0.623	5.12	
37.78	4174.0	993.0	0.000682	0.630	4.53	
43.33	4174.0	990.6	0.000616	0.637	4.04	
48.89	4179.0	988.8	0.000562	0.644	3.64	
54.44	4179.0	985.7	0.000513	0.649	3.30	
60.00	4179.0	983.3	0.000471	0.654	3.01	
65.55	4183.0	980.3	0.000430	0.659	2.73	
71.11	4186.0	977.3	0.000401	0.665	2.53	
76.67	4191.0	973.7	0.000372	0.668	2.33	
82.22	4195.0	970.2	0.000347	0.673	2.16	
87.78	4199.0	966.7	0.000327	0.675	2.03	
93.33	4204.0	963.2	0.000306	0.678	1.90	
104.40	4216.0	955.1	0.000267	0.684	1.66	
115.60	4229.0	946.7	0.000244	0.685	1.51	

Appendix D : Void Growth Models

A detailed description of the five subcooled void growth models, from the literature, is presented.

D.1 Lahey Model (Ref. 6).

Lahey developed a mechanistic subcooled boiling model. He stated that no mechanistic model can be uniquely determined, due to lack of understanding. No range of applicability was stated, though he applied his technique to results of Rouhani (8) at high pressures (29.5, 50 bars).

The energy flux at the surface was arbitrarily divided into three forms ;

- i) The evaporative heat flux.

$$q_{evap} = \dot{v}_B \rho_g h_{fg} \quad (D.1.1)$$

with $\dot{v}_B$ (m^3 / s) being the volumetric rate of vapor formation per unit heated area.

- ii) Single phase heat transfer.

$$q_{10} \approx h(T_{wall} - T_l) \quad (D.1.2)$$

- iii) A term which was labeled liquid agitation or pumping.

$$q_{pump} = \dot{v}_B (\rho_l(h_{cv} - h_l) + \rho_g(h_f - h_{cv})) \quad (D.1.3)$$

The first term being the energy flux required to raise the enthalpy of the liquid leaving the control volume (due to displacement by bubble formation) from the av-

average core enthalpy (h_l) to the average enthalpy of the control volume (h_{cv}) bounded by the bubble layer and the heated surface. The second term represents the energy flux to raise the mass of liquid which evaporates to the saturation temperature.

An empirical constant ϵ was introduced;

$$\epsilon = \frac{\text{heat flux due to pumping}}{\text{heat flux which causes bubble formation}} \quad (D.1.4)$$

$$= \frac{\rho_l(h_{cv} - h_l) + \rho_g(h_f - h_{cv})}{\rho_g h_{fg}} \quad (D.1.5)$$

If the liquid leaving the control were saturated;

$$\epsilon = \frac{\rho_l(h_f - h_l)}{\rho_g h_{fg}} \quad (D.1.6)$$

For the mechanistic model the equation derived was determined from the energy equation of the two-phase mixture;

$$G(1 - \langle X_t \rangle) \frac{dh_l}{dZ} + G(\langle X_t \rangle) \frac{dh_g}{dZ} = \frac{qP_H}{A} - \Gamma(h_g - h_l) \quad (D.1.7)$$

From continuity for vapor phase;

$$\Gamma = G \frac{d\langle X_t \rangle}{dZ} \quad (D.1.8)$$

This was integrated to give;

$$\langle X_t(Z) \rangle = \frac{\langle h(Z) \rangle - h_l(Z)}{h_g - h_l(Z)} \quad (D.1.9)$$

Considering the process of vapor generation at the wall and condensation within the subcooled fluid;

$$\frac{qP_H}{GA} = \frac{P_H}{GA} ((q_{evap} - q_{cond}) + (q_{10} + q_{pump} + q_{cond})) \quad (D.1.10)$$

Comparing equations D.1.7 and D.1.10, and assuming dh_g/dz negligible the portion of energy that goes to the formation of vapor may be arbitrarily partitioned as;

$$\frac{P_H}{GA} (q_{evap} - q_{cond}) = h_{fg} \frac{d \langle X_t \rangle}{dZ} \quad (D.1.11)$$

rearranging gives;

$$\frac{d \langle X_t(Z) \rangle}{dZ} = \frac{P_H}{GA h_{fg}} \left(\frac{q_b(Z)}{(1 + \epsilon(Z))} - q_{cond}(Z) \right) \quad (D.1.12)$$

Where the boiling heat flux, q_b , is defined as;

$$q_b = q_{evap} + q_{pump} \quad (D.1.13)$$

Then equation D.1.12 can be integrated from some critical location Z_o to any axial position downstream. He recommended that the critical point be taken as the point of bubble departure, Z_d ;

$$\langle X_t(Z) \rangle = \frac{1}{GA h_{fg}} \left(\int_{Z_o}^Z \frac{P_H q_b(Z) dZ}{(1 + \epsilon(Z))} - \int_{Z_o}^Z P_H q_{cond}(Z) dZ \right) \quad (D.1.14)$$

The point of departure, Z_d , is calculated from;

$$Z_d = \frac{1}{\frac{q}{\lambda} P_H} (\dot{m} C_p (T_{osv} - T_{in})) \quad (D.1.15)$$

with T_{osv} determined from the relations of Saha and Zuber (11) (see section D.5).

Lahey assumed that at the point of departure, $Z_o = Z_d$, the void was approximately zero. Hence, q_b must be equal to zero before the onset point.

In order to assure the above condition, Lahey proposed an effective single phase contribution for $h_l > h_{l,d}$;

$$q_{10,eff}(Z) = q(Z) \left(\frac{h_f - h_l(Z)}{h_f - h_{l,d}(Z)} \right) \quad (D.1.16)$$

Then the net boiling heat flux can be defined as;

$$q_b(Z) = 0.0 \quad h_l \leq h_{ld} \quad (D.1.17)$$

$$\begin{aligned} q_b(Z) &= q(Z) - q_{10,ff}(Z) \\ &= q(Z) \left(1 - \left(\frac{h_f - h_l(Z)}{h_f - h_{ld}(Z)} \right) \right) \quad h_l > h_{ld} \end{aligned} \quad (D.1.18)$$

$$q_b(Z) = q(Z) \quad h_l = h_f \quad (D.1.19)$$

Lahey proposed an empirically determined function for the condensation heat transfer process, as found by Levenspiel;

$$P_H q_{cond} = \frac{H_o h_{fg}}{v_{fg}} A < \alpha > (T_{sat} - T_l) \quad (D.1.20)$$

Then comparing his model to some 'representative' subcooled boiling data indicated that;

$$H_o = 0.075(sK)^{-1} \quad (D.1.21)$$

To obtain the void fraction Zuber and Findlay's (13) model was incorporated with $C_o = 1.1$, although Lahey suggested the use of Dix's variable C_o . Finally no indication was given as to an axial temperature distribution, so a heat balance was used to obtain a value upstream of the departure point. A fortran program of Lahey's model (assuming a constant C_o) is presented in Appendix D.6.

D.2 Rouhani (Ref. 7,8)

Rouhani presented two papers for the vapor growth under subcooled conditions. The first (7) presented a method to determine the onset position as well as a growth model, ignoring slip. His second paper (8) developed a mechanistic model incorporating slip. To form a complete model the onset conditions from the first paper and the growth from the second are used.

The void at onset was given by;

$$\alpha_{osv} = 2.435 \times 10^{-3} p^{-0.237} \frac{P_H}{A} \quad (D.2.1)$$

The temperature at this point was then required. From a heat balance;

$$\Delta T_l = \Delta T_{in} - \frac{\int_0^Z P_H \frac{q}{A} dz - Q_s}{\dot{m} C_p} \quad (D.2.2)$$

with

$$Q_s = X_t \dot{m} h_{fg}$$

Q_s being the heat carried by steam bubbles and X_t the steam quality determined from equal velocities;

$$X_t \alpha \rho_g + X_t (1 - \alpha) \rho_l = \alpha \rho_g \quad (D.2.3)$$

giving

$$X_t = \frac{\alpha}{\alpha + (1 - \alpha) \frac{\rho_l}{\rho_g}} \quad (D.2.4)$$

Differentiating and rearranging equation D.2.2 gives;

$$dZ = - \frac{\dot{m} C_p}{P_H \frac{q}{A}} \left(d(\Delta T_l) - \frac{dQ_s}{\dot{m} C_p} \right) \quad (D.2.5)$$

He then neglects $\frac{dQ_s}{\dot{m} C_p}$.

The heat balance on the heated surface is;

$$\frac{q}{A} = h\Delta T_l + \dot{m}_s h_{fg} + \frac{\dot{m}_s}{\rho_g} C_p \rho_l \Delta T_l \quad (D.2.6)$$

Where $\dot{m}_s$ is the mass of liquid converted into steam per unit length per unit time per unit area of the heated surface. Then the amount of heat which goes to steam generation per unit time within an element of the channel dZ is;

$$dQ_b = \dot{m}_s h_{fg} P_H dZ = \frac{\frac{q}{A} - h\Delta T_l}{\rho_g h_{fg} + C_p \rho_l \Delta T_l} \rho_g h_{fg} P_H dZ \quad (D.2.7)$$

The amount of heat which will be removed from steam bubbles by condensation per unit time within an element of height dZ is ;

$$dQ_c = K_c (T_{sat} - T_l) dZ \quad (D.2.8)$$

Now considering the flow of steam into and out of a small section of the channel AdZ ;

$$\text{Energy in steam flow out} - \text{Energy in steam flow in} = dQ_b - dQ_c.$$

with

$$\text{out :} \quad A((U + dU)(\alpha + d\alpha)) \rho_g h_{fg} \quad (D.2.9)$$

and

$$\text{in :} \quad A(U\alpha) \rho_g h_{fg} \quad (D.2.10)$$

gives

$$A((U + dU)(\alpha + d\alpha) - U\alpha) \rho_g h_{fg} = dQ_b - dQ_c \quad (D.2.11)$$

Neglecting the relative velocity of vapor with respect to the liquid;

$$U = \frac{\dot{m}}{A\rho} = \frac{\dot{m}}{A(\alpha\rho_g + (1 - \alpha)\rho_l)} \quad (D.2.12)$$

differentiating

$$dU = \frac{\dot{m}}{A} \left(\frac{(\rho_l - \rho_g) d\alpha}{(\alpha \rho_g + (1 - \alpha) \rho_l)^2} \right) \quad (D.2.13)$$

Substituting into equation D.2.13 values for dU , dQ_b , dQ_c and dZ gives;

$$\frac{d\alpha}{\left(1 - \alpha(1 - \frac{1}{\beta})\right)^2} \approx -\frac{C_p \rho_l}{\frac{q}{A}} \left(\frac{\frac{q}{A} - h \Delta T_l}{h_{fg} \rho_g + C_p \rho_l \Delta T_l} - \frac{K_c \Delta T_l}{P_H h_{fg} \rho_g} \right) d(\Delta T_l) \quad (D.2.14)$$

This was then integrated from the inlet to any point before OSV to obtain;

$$\begin{aligned} \frac{1}{1 - \alpha} - 1 &= \frac{1}{\frac{q}{A}} \left(\left(\frac{q}{A} + \frac{h h_{fg} \rho_g}{C_p \rho_l} \right) \ln \left(\frac{h_{fg} \rho_g + C_p \rho_l \Delta T_{in}}{h_{fg} \rho_g + C_p \rho_l \Delta T_l} \right) \right. \\ &\quad \left. - \frac{1}{\frac{q}{A}} \left(h(\Delta T_{in} - \Delta T_l) + \frac{\phi_1 C_p \rho_l}{P_H h_{fg} \rho_g} \right) \right) \end{aligned} \quad (D.2.15)$$

in which;

$$\phi_1 = \int_{\Delta T_{in}}^{\Delta T_l} K_c \Delta T_l d(\Delta T_l) \quad (D.2.16)$$

From which he experimentally obtained;

$$\phi_1 = a_1 \frac{k_l}{P_r} \beta^{-1} Re N_q^{0.25} A^{2/3} \alpha^{2/3} (0.6 \Delta T_{in} + \Delta T_l) (\Delta T_{in} - \Delta T_l) \quad (D.2.17)$$

where

$$a_1 = 3.5 \times 10^{-3} \quad (m^{-4/3}) \quad (D.2.18)$$

and

$$N_q = \frac{\frac{q}{A} \mu_l}{h_{fg} \rho_l \sigma g_c} \quad (D.2.19)$$

The void fraction before OSV was calculated from the approximation;

$$\alpha = \left(\frac{\Delta T_{in} - \Delta T_l}{\Delta T_{in} - \Delta T_{osv}} \right) \alpha_{osv} \quad (D.2.20)$$

Integration of equation D.2.2 gives the location where the void departs;

$$Z_{osv} = \frac{\dot{m}}{P_H \frac{q}{A}} \left(\frac{\alpha_{osv} h_{fg}}{\alpha_{osv} + (1 - \alpha_{osv}) \beta} + (\Delta T_{in} - \Delta T_{osv}) C_p \right) \quad (D.2.21)$$

Knowing α_{osv} (from D.2.1) and substituting into equations D.2.15 and D.2.17 the value of ΔT_{osv} can be found by iteration.

To determine α and ΔT_l before the departure point the procedure followed was

1. require $\Delta T_{in}, \Delta T_{osv}, \alpha_{osv}$.
2. guess ΔT_l , determine α from equation D.2.20.
3. put α into equation D.2.2 determine ΔT_l .
4. modify ΔT_l as required.
5. check to see if Z past Z_{osv} .

After OSV;

He assumes three modes of heat removal;

1. Single phase heat transfer which will be partially effective as long as the heated surface is not covered with bubbles.
2. Steam generation.
3. Heating of the mass of water which replaced the detached bubbles.

The heat balance on the heated surface;

$$\frac{q}{A} = h\Delta T_l \left(1 - \frac{\alpha}{\alpha_{osv}}\right) + \dot{m}_s h_{fg} + \frac{\dot{m}_s}{\rho_g} C_p \rho_l \Delta T_l \quad (D.2.22)$$

The relation for h was given by Colburn's;

$$h = \frac{0.023}{Re^{0.2}} GC_p Pr^{1/3} \quad (D.2.23)$$

The single phase term contributes only to the onset point.

3

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dQ_b and dQ_c are determined as previously stated.

The condensation factor was determined experimentally to be;

$$K_c = 30.0 \frac{k_l}{Pr} \left(\frac{\rho_g}{\rho_l} \right)^2 A^{2/3} \alpha^{2/3} \frac{Re_l}{N_q^{0.5}} \quad (D.2.24)$$

The change in the true vapor quality;

$$dX_t = \frac{dQ_b - dQ_c}{\dot{m} h_{fg}} \quad (D.2.25)$$

The change in liquid subcooling;

$$d\Delta T_l = \frac{\frac{q}{A} P_H dz - (dQ_b - dQ_c)}{\dot{m} C_p} \quad (D.2.26)$$

For the determination of average local void from steam quality the derivation of Zuber and Findlay (13) was incorporated;

$$\alpha = \frac{X_t}{\rho_g} C_o \left(\frac{X_t}{\rho_g} + \frac{1 - X_t}{\rho_l} \right) + \frac{1.18}{G} \left(\frac{\sigma g (\rho_l - \rho_g)}{\rho_l^2} \right)^{1/4} \quad (D.2.27)$$

The value of C_o arrived at by Rouhani for the flow conditions studied was;

$$C_o = 1.54 \quad (D.2.28)$$

The problem can be solved two ways. Either by taking small dZ values or integration by numerical means;

A numerical technique was applied for the determination of X_t and ΔT ;

$$\int_{Z_1}^{Z_2} dZ = \int_{X_{t1}}^{X_{t2}} \left(\frac{\dot{m} h_{fg}}{\left(\frac{\frac{q}{A} \rho_g h_{fg} P_H}{\rho_g h_{fg} + C_p \rho_l \Delta T_l} - \frac{30 k_l \left(\frac{\rho_g}{\rho_l} \right)^2 A^{2/3} \alpha^{2/3} Re \Delta T_l}{Pr N_q^{0.5}} \right)} \right) dX_t \quad (D.2.29)$$

which can be written in a simplified manner;

$$\int_{Z_1}^{Z_2} dZ = \int_{X_{t1}}^{X_{t2}} f(X_t) dX_t \quad (D.2.30)$$

then

$$Z_2 - Z_1 = \left| \frac{f(X_{t_1}) - f(X_{t_2})}{2} + f(X_{t_2}) \right| |X_{t_1} - X_{t_2}| \quad (D.2.31)$$

Since X_{t_1} , Z_1 and Z_2 are known X_{t_2} can be solved for.

A similar approach was applied to the change in bulk temperature;

$$\int_{Z_1}^{Z_2} dZ = \int_{\Delta T_1}^{\Delta T_2} \frac{\dot{m}C_p}{\left(\frac{2}{A}P_H dZ - \left(\frac{2}{A}\rho_g h_{fg}P_H - K_c\Delta T_l \right) \right)} d\Delta T_l \quad (D.2.32)$$

Both methods of solution were compared for accuracy. It was found there was negligible difference in the results, but using small increments in size (dZ) saved considerable computational time. Hence this method was incorporated. The fortran program of both methods are given in Appendix D.7 and D.8.

D.3 Bowring Model (Ref. 9)

The approach was that of a physical model to predict the void fraction in the subcooled region of a heated channel. It was developed upon experimentally observed detachment of bubbles at low degrees of subcooling. The subcooled void fraction within this region was treated essentially as a bulk fluid effect.

The point of bubble departure was considered the onset of significant void. The temperature at the initial point of departure was experimentally determined to be;

$$T_{osv} = T_{sat} - (14.0 + 0.1p) \frac{\Delta}{GU_l} \cdot 10^{-6} \quad (D.3.1)$$

The void fraction at the onset point was taken to be the wall voidage;

$$\alpha_w = \frac{P_H 0.066 r_d}{A} \quad (D.3.2)$$

The radius of departure, r_d , was taken to be 2.25 mm as determined from a plot of r_d verses pressure (at 22.5 psia).

The heat balance was determined from;

$$\phi = \phi_e + \phi_{sp} + \phi_a \quad (D.3.3)$$

where;

ϕ_e evaporative heat flux.

ϕ_{sp} single phase heat flux, $h(T_{sat} - T_l)$.

ϕ_a agitation heat flux. Convection caused by bubble agitation of the boundary layer.

He then introduced an empirical parameter;

$$\epsilon = \frac{\phi_a}{\phi_e} = \left(\frac{\rho_l C_p}{\rho_g h_{fg}} \right) \tau \quad (D.3.4)$$

τ : An effective temperature difference ; temperature that cold water drawn to the wall is heated through before being pushed out by the bubble.

For pressure $1 < p < 9.5$ bars, he defines a term;

$$(1 + \epsilon) = 1 + 3.2 \left(\frac{\rho_l C_p}{\rho_g h_{fg}} \right) \quad (D.3.5)$$

He defines two regions one at high subcooling where the voidage was small, and second where it grows rapidly with decreasing subcooling. The second starts from the wall voidage. the total voidage being the sum of the wall voidage (α_w) and the free bubble voidage (α_b).

The mass balance for both the subcooled and bulk boiling regions relating the void fraction to the weight fraction;

$$\frac{\alpha}{1 - \alpha} = \frac{X_t}{\frac{\rho_l}{\rho_t} S(1 - X_t)} \quad (D.3.6)$$

The rise in weight fraction for the slightly subcooled region was assumed analogous to the bulk boiling. For the bulk boiling the total heat flux goes to the increase of quality, while the subcooled region only the evaporative heat flux term applies;

$$X_t = \frac{P_H}{\rho_l A U h_{fg}} \int_{Z_d}^Z \phi_e dZ \quad (D.3.7)$$

substituting equation D.3.3 and D.3.4 into D.3.7 gives;

$$X_t = \frac{P_H}{\rho_l A U h_{fg}} \int_{Z_d}^Z \frac{(\phi - \phi_{sp})}{(1 + \epsilon)} dZ \quad (D.3.8)$$

letting

$$\phi_{scb} = \phi - \phi_{sp} \quad (D.3.9)$$

and defining;

$$\overline{\phi_{scb}} = \frac{1}{Z - Z_d} \int_{Z_d}^Z \phi_{scb} dZ \quad (D.3.10)$$

gives

$$X_t = \frac{P_H}{\rho_l A U h_{fg} (1 + \epsilon)} \overline{\phi_{scb}} (Z - Z_d) \quad (D.3.11)$$

An approximation of X_t , for $\Delta T_l > \Delta T_{l,n}$ and assuming $\phi_n = \phi - h \Delta T_l$, can be determined from;

$$X_{t,n+1} - X_{t,n} = \frac{P_H}{A h_{fg} \rho_l (1 + \epsilon) U} (Z_{n+1} - Z_n) 0.5 (\phi_n + \phi_{n+1}) \quad (D.3.12)$$

with

$$X_t = 0 \quad \text{at} \quad Z = Z_d$$

Then from equation D.3.6 the void can be determined;

$$\frac{\alpha_b}{1 - \alpha_b} (1 - X_t) = \frac{P_H}{\rho_g A U h_{fg} S} \int_{Z_d}^Z \frac{\phi - \phi_{sp}}{(1 + \epsilon)} dZ \quad (D.3.13)$$

or

$$\frac{\alpha_b}{(1 - \alpha_b)} = \frac{X_t}{S \frac{\rho_g}{\rho_l} (1 - X_t)} \quad (D.3.14)$$

once α_b is determined;

$$\alpha = \alpha_{wall} + \alpha_b \quad (D.3.15)$$

The slip factor S was taken to be 1.5. Throughout the paper various values were used from 1.2-2.0. The temperature at each location was determined from a heat balance. A fortran program of the method is presented in Appendix D.9.

D.4 Levy Model (Ref. 10)

Levy's model was developed to predict the vapor volumetric fraction during forced convection subcooled boiling. The model was determined by incorporating three steps : First the point of the bubble departure was determined from a bubble force balance and the single phase liquid turbulent temperature distribution away from the heated wall. An empirical equation was used for the relationship between the true local vapor weight fraction and the corresponding equilibrium value. Finally the vapor volumetric fraction was obtained from the true local vapor weight fraction used in Zuber and Findlay (13) relationship.

The force balance;

The buoyancy force;

$$F_B = C_B r^3 (\rho_l - \rho_g) g \quad (D.4.1)$$

The surface tension;

$$F_S = C_S r \sigma \quad (D.4.2)$$

The friction force was given by;

$$F_F = C_F \tau_w \frac{r^3}{D_H} \quad (D.4.3)$$

C_b , C_s , and C_f are proportionality constants for their respective equations.

Now balancing the forces;

$$F_S = F_B + F_F \quad (D.4.4)$$

therefore

$$C_B r^3 (\rho_l - \rho_g) \frac{g}{g_c} + \frac{C_F \tau_w r^3}{D_H} - C_S r \sigma = 0 \quad (D.4.5)$$

Solving for the bubble radius;

$$r = \left(\frac{C_S \sigma}{\left(C_B \frac{g}{g_c} (\rho_l - \rho_g) + C_F \frac{\tau_w}{D_H} \right)} \right)^{1/2} \quad (D.4.6)$$

Assuming that the distance Y_B to the tip of the bubble was proportional to r then;

$$Y_B = C \left(\frac{\sigma D_H}{\tau_w} \right)^{1/2} \left(1 + \frac{C' g (\rho_l - \rho_g) D_H}{g_c \tau_w} \right)^{-1/2} \quad (D.4.7)$$

A non-dimensional distance term Y_B^+ was given by;

$$Y_B^+ = Y_B \left(\frac{\tau_w g_c}{\rho_l} \right)^{1/2} \frac{\rho_l}{\mu_l} = C \left(\frac{\sigma g_c D_H \rho_l}{\mu_l} \right)^{1/2} \left(1 + C' \frac{g (\rho_l - \rho_g) D_H}{g_c \tau_w} \right)^{-1/2} \quad (D.4.8)$$

It was found experimentally $C = 0.015$ while $C' = 0$.

Once Y_B^+ was known the temperature at departure could be determined from Martinelli's temperature profile.

If

$$0 \leq Y_B^+ \leq 5$$

then

$$T_b = T_{sat} - \frac{q/A}{h} + Q Pr Y_B^+ \quad (D.4.9)$$

If

$$5 \leq Y_B^+ \leq 30$$

then

$$T_b = T_{sat} - \frac{q/A}{h} + 5Q \left(Pr + \ln \left(1 + Pr \left(\frac{Y_B^+}{5} - 1 \right) \right) \right) \quad (D.4.10)$$

If

$$Y_B^+ > 30$$

then

$$T_b = T_{sat} - \frac{q/A}{h} + 5Q \left(0.5 \ln \left(\frac{Y_B^+}{30} \right) + Pr + \ln(1 + 5Pr) \right) \quad (D.4.11)$$

with

$$Q = \frac{\frac{q}{A}}{\left(\rho_l C_p \left(\frac{\tau_w g_c}{\rho_l} \right)^{1/2} \right)} \quad (D.4.12)$$

The wall shear stress was determined from;

$$\tau_w = \frac{f}{8} \frac{1}{\rho_l} \frac{G^2}{g_c} \quad (D.4.13)$$

The friction factor f , was obtained as;

$$f = 0.0055 \left(1 + \left(20,000 \left(\frac{\epsilon}{D_H} \right) + \frac{10^6}{\left(\frac{G D_H}{\mu} \right)} \right)^{1/3} \right) \quad (D.4.14)$$

$\frac{\epsilon}{D_H}$ was taken as 10^{-4} for that of drawn tubing.

At each location along the heated section following departure a heat balance was used to obtain the local bulk temperature. From this the thermodynamic quality could be determined;

$$X_{eq} = \frac{C_p \Delta T}{h_{fg}} \quad (D.4.15)$$

Levy then presented an equation that determined X_t from X_{eq} and $X_{eq_{\infty}}$. This equation satisfies the criteria;

$$\left. \frac{dX_t}{dz} \right|_{z_s} = \left. \frac{dX_t}{dX_{eq}} \right|_{X_{eq_{\infty}}} = 0 \quad (D.4.16)$$

ie. bubble motion was absent at the point of bubble departure, and most of the heat was being transferred to the liquid.

Also as X_{eq} increases and becomes positive and large, non-thermal equilibrium conditions no longer exist;

$$X_t \rightarrow X_{eq} \quad \text{for } X_t \gg |X_{eq_{\infty}}| \quad (D.4.17)$$

The equation proposed to satisfy the above conditions was;

$$X_t = X_{eq} - X_{eq_{\infty}} \exp \left(\frac{X_{eq}}{X_{eq_{\infty}}} - 1 \right) \quad (D.4.18)$$

To calculate the void the relationship proposed by Zuber and Findlay (13) was used. A value of 1.13 was used for the distribution factor (C_0). A fortran program of the Levy model is presented in Appendix D.10.

D.5 Zuber et al Model (Ref. 11,12)

Zuber presented a method to predict the point of net vapor generation (11) and vapor void fraction (12). It was deduced that the point of net vapor generation depends on local thermal and dynamic conditions. Thermal conditions for low mass flow and dynamic affects for high mass flows. A simple relation was proposed for the determination of the void as a function of local parameters.

Considering a wide range of data (different fluids, system pressures, mass flow rate, heat flux and various channel geometries) a plot of Stanton versus Peclet ($\frac{Nu}{St}$) number was considered. Two distinct regions were found;

$$Nu = \frac{\frac{q}{A} D_H}{k(T_{sat} - T_{osv})} = 455 \quad Pe \leq 70,000 \quad (D.5.1)$$

and

$$St = \frac{\frac{q}{A}}{GC_p(T_{sat} - T_{osv})} = 0.0065 \quad Pe > 70,000 \quad (D.5.2)$$

The first equation (D.5.1) was assumed to represent a thermally controlled region, for low mass flow rates. The second represents a dynamically controlled region, for high mass flow rates. From this, the temperature at the onset was determined. At each subsequent location the temperature was determined from a heat balance.

Two non-dimensional terms were introduced (12) to define the temperature and location;

$$T^+ = \frac{T_l - T_{osv}}{T_{sat} - T_{osv}} \quad (D.5.3)$$

and

$$Z^+ = -\ln(1 - T^+) \quad (D.5.4)$$

Two methods were introduced to determine the true quality.

i) From Kroeger and Zuber (12);

$$X_t = \frac{C_p \Delta T_l (Z^+ - T^+)}{h_{fg} + C_p \Delta T_l (1 - T^+)} \quad (D.5.5)$$

i) From Saha and Zuber (11);

$$X_t = \frac{X_{eq} - X_{eq_{\infty}} \exp\left(\frac{X_{eq}}{X_{eq_{\infty}}} - 1\right)}{1 - X_{eq_{\infty}} \exp\left(\frac{X_{eq}}{X_{eq_{\infty}}} - 1\right)} \quad (D.5.6)$$

The first method was incorporated for the determination of true quality. The void was calculated from Zuber and Findlay (13) with the distribution factor taken as $C_o = 1.13$. A fortran program of Zuber et al is presented in Appendix D.11.

D.6 Computer Program for Calculating Lahey Model (6)

```

C
C==> PROGRAM TO DETERMINE VOID PROFILE, INCORPORATING R. T. LAHEY JR.'S
C      MECHANISTIC SUBCOOLED CHARACTERISTIC MODEL.
C
      REAL T(100),VOID(100),XEQ(100),X(100),TX(11),HLX(11),
      *QC(100),QB(100),VOIDI(100),XEQX(100),VOIDX(100)
      DATA PI/3.14159/,CSF/0.013/,TSAT/112.5/,DENG/0.876/
      DATA HG/2697.0E+3/,DO/0.022/,XLENG/0.48/,SUR/0.0566/,DI/0.0131/
      DATA HFG/2250.0E+3/,VISC/2.48E-4/,PR/1.53/,CP/4232.0/,COND/.685/
      DATA DENL/950.0/,HF/468.0E+3/,PRESS/1.53/,VG/1.1386/,VL/0.00105/
      COMMON /AAA/TX,HLX
C
C==> EXPERIMENT NO.1
C
      HFLUX=29.7
      VEL=0.066
      DZ=0.00050
      AREA=PI*(DO**2-DI**2)/4.
      XM=DENL*VEL*AREA
      G=XM/AREA
      DH=DO-DI
      ALPA=COND/(DENL*CP)
      FLUX=HFLUX*10000
C
C==> USING SAHA ZUBER FOR THE STARTING LOCATION.
C      HE IGNORES THE INITIAL HIGH SUBCOOLED REGION.
C
      T(1)=TSAT-FLUX*DH/(455.*CP*ALPA*DENL)
      X(1)=0.0
      VOID(1)=0.0
      C=1.1
C
C==> LIQUID ENTHALPY FOR LOCAL TEMPERATURES.
C
      DO 7 J=1,11
        READ(5,12)TX(J),HLX(J)
      7 CONTINUE
      12 FORMAT(F6.2,1X,F8.1)
      XEQ(1)=CP*(T(1)-TSAT)/HFG
      CALL WATER(T(1),HOSV)
      BH=PI*DI
      HO=0.075
      VFG=VG-VL
C
C==> QB IS EQUAL TO ZERO BEFORE THE ONSET LOCATION. SINCE NO HIGH
C      SUBCOOLED REGION IE. VOID EQUAL TO ZERO AT THE START QC ALSO
C      EQUALS ZERO.
C
      QB(1)=0.0
      QC(1)=HO*HFG*AREA*VOID(1)*(TSAT-T(1))/(VFG*PH)

```

```
DZZ=DZ
DO 100 IU=2,100
```

```
C
C==> NO TEMPERATURE PROFILE SUGGESTED SO A HEAT BALANCE WAS APPLIED.
C
```

```
T(IU)=T(1)+(FLUX*PH*DZ)/(XM*CP)
XEQ(IU)=CP*(T(IU)-TSAT)/HFG
CALL WATER(T(IU),HL)
E=(DENL*(HF-HL))/(DENG*HFG)
QB(IU)=(FLUX*(1.-(HF-HL)/(HF-HOSV)))/(1.+E)
CONST=(PH/(G*AREA*HFG))
A=QB(IU)-QB(1)
X(IU)=CONST*(A)*DZ
```

```
C
C==> VOID CALCULATED FROM ZUBER AND FINDLAY.
C
```

```
AA=C*(X(IU)/DENG+(1-X(IU))/DENL)
BB=(1.18/G)*(SUR*9.81*(DENL-DENG)/DENL**2)**0.25
VOID(IU)=(X(IU)/DENG)*(1./(AA+BB))
WRITE(6,*)X(IU),VOID(IU)
10 CONTINUE
E=(DENL*(HF-HL))/(DENG*HFG)
QB(IU)=(FLUX*(1.-(HF-HL)/(HF-HOSV)))/(1.+E)
QC(IU)=HO*HFG*AREA*VOID(IU)*(TSAT-T(IU))/(VFG*PH)
CONST=(PH/(G*AREA*HFG))
```

```
C
C==> INTEGRATION FROM ZO TO SOME LOCATION Z.
C
```

```
A=QB(IU)-QB(1)
B=QC(IU)-QC(1)
X(IU)=CONST*(A-B)*DZ
```

```
C
C==> ITERATION IS REQUIRED SINCE VOLUME FRACTION IS REQUIRED IN
C THE CONDENSING TERM.
C
```

```
AA=C*(X(IU)/DENG+(1-X(IU))/DENL)
BB=(1.18/G)*(SUR*9.81*(DENL-DENG)/DENL**2)**0.25
VOIDI(IU)=(X(IU)/DENG)*(1./(AA+BB))
ERROR=(VOIDI(IU)-VOID(IU))/VOIDI(IU)
WRITE(6,*)X(IU),VOIDI(IU),ERROR
IF(ABS(ERROR).GT.0.01)VOID(IU)=VOIDI(IU)
IF(ABS(ERROR).GT.0.01)GO TO 10
WRITE(6,*)XEQ(IU),VOID(IU)
DZ=DZ+DZZ
IF(VOID(IU).GT.0.40)GO TO 119
```

```
100 CONTINUE
```

```
C WRITE(6,11)
```

```
C 11 FORMAT(2X,'XEQ',8X,'TEMP',7X,'VOID',7X,'XTRUE',8X,'Z')
```

```
119 CONTINUE
```

```
DZZ=0.0
```

```
DO 4 II=1,100
```

```
IF(VOID(II).GT.0.40)GO TO 120
```

```
VOIDX(II)=VOID(II)*100.
```

```
XEQX(II)=100.*XEQ(II)
```

```

C      WRITE(6,*)XEQX(II),VOIDX(II)
      WRITE(6,101)XEQX(II),VOIDX(II)
      DZZ=DZZ+0.0100
    4   CONTINUE
101   FORMAT(F7.3,1X,F6.3)
120   CONTINUE
      STOP
      END

```

```

C
C====>SUBROUTINE TO DETERMINE LOCAL ENTHALPY OF WATER.
C

```

```

      SUBROUTINE WATER(T,HL)
      REAL TX(11),HEX(11)
      COMMON /AAA/TX,HEX
C      WRITE(6,*)T
      DO 3 JX=1,10
        M=JX
        IF(T.GE.TX(M).AND.T.LE.TX(M+1))GO TO 4
    3   CONTINUE
    4   CONTINUE
      XINTER=(T-TX(M))/(TX(M+1)-TX(M))
      HL=XINTER*(HEX(M+1)-HEX(M))+HEX(M)
      RETURN
      END

```


2

D.7 Computer Program for Calculating Rouhani Model (7,8)
Using Small Increments Along the Heated Length

```

C
C==> THE FOLLOWING PROGRAM IMPLIMENTS ROUHANI'S MODEL FOR VOID GROWTH
C USING SMALL INCREMENTS IN DZ.
C
DATA PI/3.14159/,TSAT/112.0/,DENG/0.876/,DENL/950.0/
DATA DO/0.022/,XLENG/0.48/,SURF/0.0566/,DI/0.013/
DATA HEG/2250.9E+3/,VISC/2.48E-4/,PR/1.53/,CP/4232.0/,COND/.685/
C
C==> EXPERIMENT NO.1
C
TIN=29.8
VEL=0.066
FLUX=29.7
DZ=0.0060
C WRITE(6,7)'TIN =',TIN,'VELOCITY =',VEL
C WRITE(6,*)'FLUX =',FLUX
DTIN=TSAT-TIN
DE=DO-DI
P=1.53E+5
AREA=PI*(DO**2-DI**2)/4.
XM=DENL*VEL*AREA
FLUX=FLUX*10000.0
PH=PI*DI
REL=VEL*DENL*(DO-DI)/VISC
GG=XM/AREA
DTC=DTIN
REL=VEL*DENL*(DO-DI)/VISC
H=(0.023/(REL**0.2))*GG*CP*PR**(-2/3)
VOIDC=0.002435*P**(-.237)*PH/AREA
XNQ=(FLUX*VISC/(HEG*SURF*DENL))**.25
A=3500.*COND*DENG*REL*XNQ*AREA**(.667)*VOIDC**(.667)/(PR*DENL)
DO 1 J=1,10000
C
C==> THIS LOOP IS USED TO FIND THE TEMPERATURE AT ONSET, FROM THE
C FIRST POINT.
C
B=(.6*DTIN+DTC)*(DTIN-DTC)
PHI=A*B
XLS=1./(1.-VOIDC)-1.
C=FLUX*(H*HEG*DENG)/(CP*DENL)
D=ALOG((HEG*DENG+CP*DENL*DTIN)/(HEG*DENG+CP*DENL*DTC))
E=-H*(DTIN-DTC)
F=(PHI*CP*DENL)/(PH*HEG*DENG)
G=E-F
RS=(1./FLUX)*(C*D+G)
ERR=(RS-XLS)/XLS
IF(ABS(ERR).LE.0.01)GO TO 3
IF(ERR.GT.0.0)DTC=DTC+.001
IF(ERR.LT.0.0)DTC=DTC-.001

```

```

1 CONTINUE
3 CONTINUE
WRITE(6,*)'NUMBER OF ITERATIONS ARE',J,'DTC=',DTC
TBC=TSAT-DTC
XEQOSV=-1.*CP*DTC/HFG
DTL=DTIN
BETA=DENL/DENG
AA=(VOIDC*HFG)/(VOIDC+(1-VOIDC)*BETA)
BB=CP*(DTIN-DTC)

```

```

C
C==> ZC: THE HEATED LENGTH FOR THE FIRST REGION IE. TO THE POINT WHERE
C      THE ONSET BEGINS, ALSO TAKEN FROM 1ST PAPER.
C

```

```

      ZC=(XM/(PH*FLUX))*(AA+BB)
      ZE=ZC/DZ
      Z=0.0
8 CONTINUE
      Z=Z+DZ

```

```

C
C==> THIS LOOP DETERMINES, STARTING AT THE BEGINING, UP TO THE OSV
C      LOCATION THE VOID AND TEMPERATURE (REGION I). AGAIN FROM 1ST

```

```

88 CONTINUE
VOID=((DTIN-DTL)/(DTIN-DTC))*VOIDC
DTLL=DTIN-FLUX*PH*Z/(XM*CP)+VOID*HFG/((VOID+(1.-VOID)*BETA)*CP)
ER=(DTL-DTLL)/DTLL
IF(ABS(ER).LT.0.001)GO TO 7
DTL=DTLL
GO TO 88
7 CONTINUE

```

```

C==> USING A LINEAR RELATION FOR REGION I TAKEN FROM 1ST PAPER.
C

```

```

      XI=VOID/(VOID+(1.-VOID)*BETA)
      XEQI=(CP*DTLL*(-1.))/HFG
      IF(IP.EQ.25)GO TO 50
      GO TO 51
C 50 CONTINUE
      TB=TSAT-DTLL
      XEQE=XEQI*100.
      VOIDE=VOID*100.
      WRITE(6,19)XEQE,VOIDE
19 FORMAT(F7.3,F6.3)

```

```

C
C==> EXITS LOOP IF REACHED END OF FIRST REGION.
C

```

```

      IF(Z.GT.ZC)GO TO 9
      Z=Z+DZ
      GO TO 8
9 CONTINUE
VOIDCC=100.*VOIDC
XEQOS=100.*XEQOSV
WRITE(6,90)VOIDCC,TBC,XEQOS
90 FORMAT('      OSV =',F6.3,5X,'TBC =',F6.2,5X,'XEQ AT ONSET =',F8.3)

```

```

C
C==> TO CONTINUE THE CALCULATIONS X AT OSV IS DETERMINED FROM THE
C RELATION FROM THE 1ST PAPER.
C
C      X=VOIDC/(VOIDC+(1-VOIDC)*BETA)
C      WRITE(6,*)X
C      X=0.0
C      DTL=(TSAT-TBC)
C      C=1.54
C
C==> THE FOLLOWING LOOP SOLVES FOR THE VOID GROWTH BY THE USE OF
C ROUHANI'S SECOND PAPER. THE EQUATIONS WERE SOLVED BY USING
C SMALL INCREMENTS IN DZ RATHER THEN INTEGRATION.
C
      DO 4 JJ=1,100
        XZ=DENG*HFG+CP*DENL*DTL
        DQB=((FLUX-H*DTL*(1-VOID/VOIDC))*DENG*HFG*PH*DZ)/XZ
        IF(VOID.GT.VOIDC)DQB=FLUX*DENG*HFG*PH*DZ/XZ
        REL=(GG*(DO-DI))/((1.-VOID)*VISC)
        XXNQ=(FLUX*VISC)/(HFG*(DENL-DENG)*SURF)
        ZZ=PR*XXNQ**.5
        CONK=30.*COND*((DENG/DENL)**2)*(AREA**.667)*(VOID**.667)*REL/ZZ
        DQC=CONK*DTL*DZ
        DX=(DQB-DQC)/(XM*HFG)
        X=X+DX
        DTT=(FLUX*PH*DZ-(DQB-DQC))/(XM*CP)
        TB=TB+DTT
        DTL=DTL-DTT
        AO=C*(X/DENG+(1-X)/DENL)
        BO=(1.18/GG)*((SURF*9.81*(DENL-DENG))/DENL**2)**(0.25)
        VOID=(X/DENG)*(1./(AO+BO))+VOIDC
        XEQ=CP*(TB-TSAT)/HFG
        TTT=TSAT-TB
        Z=Z+DZ
        XEQW=100.*XEQ
        VOIDW=100.*VOID
        IF(VOIDW.GT.40.0)GO TO 119
        WRITE(6,99)XEQW,VOIDW
99      FORMAT(F7.3,1X,F6.3)
4      CONTINUE
119     CONTINUE
        STOP
        END

```

D.8 Computer Program for Calculating Rouhani Model (7,8)
Using a Numerical Solution

```

C
C==> ROUHANI'S VOID GROWTH PREDICTION USING A NUMERICAL SOLUTION.
C
$JOB
REAL X(5),V(5),FX(2),XX(1000),VOIDX(1000),DT(4),FT(4),DTX(1000),
*XXEQ(1000),TY(1000)
DATA PI/3.14159/,TSAT/112.0/,DENG/0.876/,DENL/950.0/
DATA DO/0.022/,XLENG/0.48/,SURF/0.0566/,DI/0.013/
DATA HFG/2250.0E+3/,VISC/2.48E-4/,PR/1.53/,CP/4232.0/,COND.635.
READ(5,2)TIN,VEL,FLUX,DZ,NO
2  FORMAT(F5.1,1X,F6.4,1X,F6.2,1X,F7.5,1X,I4)
WRITE(6,2)TIN,VEL,FLUX,DZ,NO
DTIN=TSAT-TIN
P=1.53E+5
AREA=PI*(DO**2-DI**2)/4
XM=DENL*VEL*AREA
FLUX=FLUX*10000.0
PH=PI*DI
DE=DO-DI
REL=VEL*DENL*(DO-DI)/VISC
XG=XM/AREA
DTC=DTIN
H=(0.023/(REL**0.2))*XG*CP*PR**(-2/3)
VOIDC=0.002435*P**(-.237)*PH/AREA
WRITE(6,*)VOIDC
XNQ=(FLUX*VISC/(HFG*SURF*DENL))**.25
A=3500.*COND*DENG*REL*XNQ*AREA**(.667)*VOIDC**(.667)/(PR*DENL)
DO 1 J=1,50000
B=(.6*DTIN+DTC)*(DTIN-DTC)
PHI=A*B
XLS=1./(1.-VOIDC)-1.
C=FLUX+(H*HFG*DENG)/(CP*DENL)
D=ALOG((HFG*DENG+CP*DENL*DTIN)/(HFG*DENG+CP*DENL*DTC))
E=-H*(DTIN-DTC)
F=(PHI*CP*DENL)/(PH*HFG*DENG)
G=E-F
RS=(1./FLUX)*(C*D+G)
ERR=RS-XLS
IF(ABS(ERR).LE.0.00001)GO TO 3
IF(ERR.GT.0.0)DTC=DTC+.001
IF(ERR.LT.0.0)DTC=DTC-.001
1 CONTINUE
3 CONTINUE
TBC=TSAT-DTC
WRITE(6,*)'NUMBER OF ITTERATIONS ARE',J,'TBC=',TBC
XEQ=(TBC-TSAT)*CP/HFG
WRITE(6,*)'EQUILIBRIUM QULAITY =',XEQ
DTL=DTIN
BETA=DENL/DENG

```

```

AA=(VOIDC*HFG)/(VOIDC+(1-VOIDC)*BETA)
BB=CP*(DTIN-DTC)
ZC=(XM/(PH*FLUX))*(AA+BB)
ZE=ZC/DZ
Z=0.0
VOID=0.0
WRITE(6,*)Z,VOID
8 CONTINUE
Z=Z+DZ
88 CONTINUE
VOID=(DTIN-DTL)/(DTIN-DTC)*VOIDC
DTLL=DTIN-FLUX*PH*Z/(XM*CP)+VOID*HFG/((VOID+(1.-VOID)*BETA)*CP)
ER=(DTLL-DTL)/DTLL
IF(ABS(ER).LT.0.01)GO TO 7
DTL=DTLL
GO TO 88
7 CONTINUE
XI=VOID/(VOID+(1.-VOID)*BETA)
XEQI=(CP*DTLL*(-1.))/HFG
WRITE(6,*)XI,XEQI,VOID,Z
IF(Z.GT.ZC)GO TO 9
DTL=DTIN
GO TO 8
9 CONTINUE
X(1)=VOIDC/(VOIDC+(1.-VOIDC)*BETA)
GUESS=X(1)+0.000001
GUES=DTL+0.0001
WRITE(6,*)X(1)
XC=1.12
DTT=DTL
JI=1
DO 100 I=1,NO
    J=0
10 CONTINUE
    J=J+1
11 CONTINUE
    X(2)=GUESS
    UA=XC*(X(J)/DENG+(1-X(J))/DENL)
    UB=(1.18/XG)*(SURF*9.81*(DENL-DENG)/DENL**2)**0.25
    V(J)=(X(J)/DENG)*(1./(UA+UB))
    REL=(XG*DE)/((1.-V(J))*VISC)
    XNQ=PR*(FLUX*VISC/(HFG*SURF*DENL))*0.5
    BETAX=DENG/DENL
    UC=30.*COND*(BETAX**2)*(AREA**0.667)*(V(J)**.667)*REL*DTT/XNQ
    UD=(FLUX*DENG*HFG*PH)/(DENG*HFG+CP*DENL*DTT)
    FX(J)=XM*HFG/(UD-UC)
    IF(J.EQ.1)GO TO 10
    XRS=ABS((FX(1)-FX(2))/2.+FX(2))*ABS(X(1)-X(2))
    XLS=DZ
    ER=(XRS-XLS)/XLS
    IF(ABS(ER).LE.0.01)GO TO 12
    IF(ER.LE.0.0)GUESS=GUESS+0.00000010
    IF(ER.GT.0.0)GUESS=GUESS-0.00000010
    WRITE(6,*)FX(1),FX(2)

```

```

C      WRITE(6,*)ER,GUESS,XRS
      GO TO 11
12     CONTINUE
      XX(I)=X(1)
      XX(I+1)=X(2)
      VOIDX(I)=V(1)
C      VOIDX(I+1)=V(2)
      X(1)=X(2)
      GUESS=X(2)+0.000001
      DT(1)=DTT
      K=0
14     CONTINUE
      K=K+1
15     CONTINUE
      DT(2)=GUES
      UC=30.*COND*(BETAX**2)*(AREA**0.667)*(V(K)**.667)*REL*DT(K)/XNQ
      UD=(FLUX*DENG*HFG*PH)/(DENG*HFG+CP*DENL*DT(K))
      FT(K)=(XM*CP)/(FLUX*PH-(UD-UC))
      IF(K.EQ.1)GO TO 14
      XLSS=DZ
      XRSS=ABS((FT(1)-FT(2))/2.+FT(2))*ABS(DT(1)-DT(2))
      UER=(XRSS-XLSS)/XLSS
      IF(ABS(UER).LE.0.010)GO TO 16
      IF(UER.LE.0.0)GUES=GUES-0.00050
      IF(UER.GT.0.0)GUES=GUES+0.00050
C      WRITE(6,*)UC,UD,FT(1),FT(2)
C      WRITE(6,*)I,UER,GUES,XRSS
      GO TO 15
16     CONTINUE
      DTX(I)=DT(1)
      DTX(I+1)=DT(2)
      XSEQ(I)=(CP*DT(1)*(-1.))/HFG
      XSEQ(I+1)=(CP*DT(2)*(-1.))/HFG
      TY(I)=DT(1)
      TY(I+1)=DT(2)
      DTT=DT(2)
      GUES=DT(2)+0.001
C      IF(VOIDX(I).GT.0.50)GO TO 120
      JI=JI+1
100    CONTINUE
120    CONTINUE
      WRITE(6,*)'          XTRUE          XEQ          VOID'
      DO 20 LO=1,JI
      XEQW=100.*XSEQ(LO)
      UA=XC*(XX(LO)/DENG+(1-XX(LO))/DENL)
      UB=(1.18/XG)*(SURF*9.81*(DENL-DENG)/DENL**2)**0.25
      VOIDX(LO)=100.*(XX(LO)/DENG)*(1./((UA+UB)))
C      WRITE(6,*)XX(LO),XSEQ(LO),VOIDX(LO),Z
      WRITE(6,*)XEQW,VOIDX(LO),Z
      Z=Z+DZ
20    CONTINUE
      STOP
      END
$ENTRY

```

D.9 Computer Program for Calculating Bowring Model (9)

```

C
C==> PROGRAM TO DETERMINE VOID PROFILE, INCORPORATING BOWRING'S MODEL
C MECHANISTIC SUBCOOLED CHARACTERISTIC MODEL.
C
  REAL T(100),VOID(100),XEQ(100),X(100),TX(11),HLX(11),
  *QB(100),DTN(100),VOIDO(100)
  DATA PI/3.14159/,CSF/0.013/,TSAT/112.0/,DENG/0.876/
  DATA HG/2697.0E+3/,DO/0.022/,XLENG/0.48/,SUR/0.0566/,DI/0.013/
  DATA HFG/2250.0E+3/,VISC/2.48E-4/,PR/1.53/,CP/4232.0/,COND/.685/
  DATA DENL/950.0/,HF/468.0E+3/,PRESS/1.53/,VG/1.1386/,VL/0.00105/
  COMMON /AAA/TX,HLX
C
C==> EXPERIMENT NO.1
C
  FLUX=29.7
  TIN=29.8
  AREA=PI*(DO**2-DI**2)/4.
  VEL=0.0663
  XM=DENL*VEL*AREA
  DZ=0.00035
  DH=DO-DI
  ALPA=COND/(DENL*CP)
  FLUX=FLUX*10000
  PH=PI*DI
  G=XM/AREA
  P=22.5/14.7
  REL=DENL*VEL*DH/VISC
  H=.023*G*CP*PR**(-0.667)/REL**0.2
C
C==> THE INITIAL POINT WAS TAKEN AS THE POINT OF DEPARTURE.
C
  T(1)=TSAT-(14.0+0.1*P)*DENL*FLUX*1.0E-6/G
C
C==> THE VOLUME AT DEPARTURE IS TAKEN AS THE WALL VOIDAGE.
C RD IS THE DEPARTURE RADIUS AS TAKEN FROM ROUHANI'S PAPER.
C THE TRUE QUALITY IS TAKEN AS 0.0.
C
  RD=0.00225
  VOID(1)=PH*0.066*RD/AREA
  VOIDO(1)=PH*0.066*RD/AREA
  X(1)=0.0
  XEQ(1)=100*CP*(T(1)-TSAT)/HFG
C
C==> DISTANCE FOR BULK BOILING TO BEGIN.
C
  XZ=XM*CP*(TSAT-TIN)/(FLUX*PH)
C
C==> RATIO OF HEATED LENGTH TO WHERE BOILING STARTS.
C
  XMM=XZ/XLENG

```

```

C
C==> THE POSITION WHERE OSV BEGINS.
C
  ZR=XMM*XLENG*(1.-(TSAT-T(1))/(TSAT-TIN))
C
  WRITE(6,*)XZ,XMM,ZR,H
  Z=ZR
  ZZ=0.0
  S=1.5
  DTN(1)=(TSAT-TIN)*(1.-Z/(XMM*XLENG))
  IF(DTN(1).LT.0.0)DTN(1)=0.0
  QB(1)=(FLUX-H*DTN(1))
  DO 100 JO=2,100

C
C==> A HEAT BALANCE IS USED TO DETERMINE THE LOCAL TEMPERATURES.
C
  Z=Z+DZ
  ZZ=ZZ+DZ
  T(JO)=T(1)+(FLUX*PH*ZZ)/(XM*CP)
  E=3.2*(DENL*CP)/(DENG*HFG)

C
C==> THIS VALUE FOR QB IS FROM BOWERING'S MODEL.
C
  DTN(JO)=(TSAT-TIN)*(1.-Z/(XMM*XLENG))
  IF(DTN(JO).LT.0.0)DTN(JO)=0.0

C
C==> SHOWS THAT S.P. IS EFFECTIVE UP TO THE BULK BOILING REGION.
C
  QB(JO)=(FLUX-H*DTN(JO))
  CONST=PH/((G*AREA*HFG)*(1.+E))
  X(JO)=X(JO-1)+CONST*DZ*0.5*(QB(JO)+QB(JO-1))

C
C==> USING BOWRING'S VOID CORRELATION.
C
  SLIP IS INCORPORATED AS S=1.5. THIS VALUE IS USED IN VARIOUS
C
  CALCULATIONS WITHIN THE PAPER, ALTHOUGH A VALUE OF 1.2-2.0
C
  WAS FOUND IN VARIOUS MEASUREMENTS.
C
  CCOST=(PH*(QB(JO)+QB(1))*0.5*ZZ)/(DENG*AREA*VEL*HFG*(1.+E))
  CCOST=X(JO)*DENL/(DENG*(1-X(JO))*S)
  VOID(JO)=CCOST/(1.+CCOST)
  XEQ(JO)=100.*CP*(T(JO)-TSAT)/HFG
  AA=1.1*(X(JO)/DENG+(1.-X(JO))/DENL)
  BB=(1.18/G)*(SUR*9.81*(DENL-DENG)/DENL**2)**0.25
  VOIDO(JO)=(X(JO)/DENG)*(1./(AA+BB))
  VOID(JO)=VOID(JO)+VOID(1)
  VOIDO(JO)=VOIDQ(JO)+VOIDO(1)
100 CONTINUE
  DZZ=ZR
  DO 4 II=1,100
    IF(VOID(II).GE.0.40)GO TO 109
    V=100.*VOID(II)
    V2=100.*VOIDO(II)
    WRITE(6,101)XEQ(II),V
    DZZ=DZZ+DZ
4 CONTINUE

```


101 FORMAT(F7.3,1X,F6.3,1X,F6.3)
109 CONTINUE
 STOP
 END

D.10 Computer Program for Calculating Levy Model (10)

```

C
C==> LEVY'S MODEL FOR THE PREDICTION OF VAPOUR GROWTH.
C
      REAL XEQ(100),T(100),VOID(100)
      DATA PI/3.14159/,TSAT/112.0/,DENG/0.876/,DENL/950.0/
      DATA DO/0.022/,XLENG/0.48/,SURF/0.0566/,DI/0.013/
      DATA HFG/2250.9E+3/,VISC/2.48E-4/,PR/1.53/,CP/4232.0/,COND/.685/
C
C==> EXPERIMENT NO.1
C
      FLUX=29.7
      DZ=0.00055
      VEL=0.066
      FLUX=FLUX*10000
      PH=DI*PI
      AREA=PI*(DO**2-DI**2)/4.
      XM=AREA*VEL*DENL
      P=22.5/14.7
      DH=DO-DI
      G=VEL*DENL
      H=COND*0.023*((G*DH/VISC)**0.8)*(PR**0.4)/DH
C
C==> FOLLOWING THE FORCE BALANCE PRESENTED, WHERE THE POINT
C      OF DEPARTURE IS DEFINED AS THE POINT OF RAPID RISE.
C
      ROUGH=1.0E-4
      F=0.0055*(1.+(20000.*ROUGH+1.0E6/(G*DH/VISC))**0.333)
      TW=(F*G**2)/(8.0*DENL)
      C=0.015
C
C==> C' IS TAKEN AS ZERO, ASSUMING NO BOUY. AFFECT.
C
      Q=FLUX/(DENL*CP*(TW/DENL)**0.5)
      YPLUS=C*((SURF*DH*DENL)**0.5)/VISC
      IF(YPLUS.GE.0.0.AND.YPLUS.LE.5.0)
      *T(1)=TSAT-FLUX/H+Q*PR*YPLUS
      IF(YPLUS.GT.5.0.AND.YPLUS.LE.30.)
      *T(1)=TSAT-FLUX/H+5*Q*(PR+ALOG(1+PR*(YPLUS/5.-1.)))
      QB=0.5*ALOG(YPLUS/30.)
      QA=PR+ALOG(1.+5*PR)
      IF(YPLUS.GT.30.)
      *T(1)=TSAT-FLUX/H+5*Q*(QB+QA)
      XEQ(1)=CP*(T(1)-TSAT)/HFG
      VOID(1)=0.0
      Z=0.0
      DO 7 J=2,100
        Z=Z+DZ
C
C==> A HEAT BALANCE WAS USED TO DETERMINE THE TEMPERATURE PROFILE.
C

```

```

T(J)=FLUX*DZ*PI*DI/(XM*CP)+T(J-1)
XEQ(J)=(T(J)-TSAT)*CP/HFG
X=XEQ(J)-XEQ(1)*EXP(XEQ(J)/XEQ(1)-1.)
AA=1.13*(X/DENG+(1.-X)/DENL)
BB=(1.18/G)*(((SURF*9.81*(DENL-DENG))/DENL**2)**.25)
VOID(J)=(X/DENG)*(1./(AA+BB))
7  CONTINUE
DO 8  JU=1,100
    XEQL=100.*XEQ(JU)
    VOIDL=100.*VOID(JU)
    WRITE(6,9)XEQL,VOIDL
    IF(VOIDL.GE.40.0)GO TO 19
8  CONTINUE
19  CONTINUE
9  FORMAT(F7.3,1X,F6.3)
    STOP
    END

```

D.11 Computer Program for Calculating Zuber et al Model (11,12)

```

C
C==> ZUBER ET AL VOID GROWTH MODEL
C
      REAL T(100),XEQ(100),VOID(100)
      DATA PI/3.14159/,TSAT/112.0/,DENG/0.876/,DENL/950.0/
      DATA DO/0.022/,KLENG/0.48/,SURF/0.0566/,DI/0.013/
      DATA HFG/2250.9E+3/,VISC/2.48E-4/,PR/1.53/,CP/4232.0/,COND/.685
C
C==> EXPERIMENT NO.1
C
      TIN=29.8
      VEL=0.066
      FLUX=29.7
      DZ=0.000345
      FLUX=FLUX*10000
      PH=DI*PI
      AREA=PI*(DO**2-DI**2)/4.
      XM=DENL*VEL*AREA
      P=22.5/14.7
      DH=DO-DI
      G=VEL*DENL
      DTIN=TSAT-TIN
      A=G*CP*DH/4.0
      H=COND*0.023*((G*DH/VISC)**0.8)*(PR**0.4)/DH
C
C==> USING BOWERINGS DEPARTURE POINT AS THE STARTING POINT.
C
      ZO=A*(DTIN/FLUX-((14.+0.1*P)*1.0E-6)/(G*VEL))
      T(1)=TIN+FLUX*PH*ZO/(XM*CP)
C
C==> USING SAHA AND ZUBER ONSET POINT
C
      ALPA=COND/(DENL*CP)
      T(1)=TSAT-FLUX*DH/(455.*CP*ALPA*DENL)
      DTO=TSAT-T(1)
      XEQ(1)=(T(1)-TSAT)*CP/HFG
      VOID(1)=0.0
      DO 2 J=2,100
C
C==> HEAT BALANCE USED FOR DETERMINATION OF TEMPERATURE PROFILE.
C
      T(J)=T(J-1)+FLUX*PH*DZ/(XM*CP)
      XEQ(J)=(T(J)-TSAT)*CP/HFG
C
C==> DIMENSIONLESS TEMP AND LOCATION.
C
      TSTAR=(T(J)-T(1))/(TSAT-T(1))
      ZPLUS=-ALOG(1-TSTAR)
      X=(CP*DTO)*(ZPLUS-TSTAR)/(HFG*CP*DTO*(1.-TSTAR))
      AA=1.13*(DENL-DENG)*X/DENL

```

```

      VGJ=1.41*(SURF*9.81*(DENL-DENG)/DENL**2)**0.25
      BB=(1.13+VGJ/VEL)*DENG/DENL
      VOID(J)=X/(AA+BB)
2    CONTINUE
      DO 3 JJ=1,100
        XEQQ=XEQ(JJ)*100.
        VOIDD=VOID(JJ)*100.
        WRITE(6,4)XEQQ,VOIDD
        IF(VOIDD.GT.40.0)GO TO 19
3    CONTINUE
4    FORMAT(F7.3,1X,F6.3)
19   CONTINUE
      STOP
      END

```

Appendix E : Boiling Heat Transfer

E.1 Heat Transfer Mechanisms

There are four possible heat transfer mechanisms presented by Engelberg - Forster and Grief (26).

1. Micro-convection in the sublayer.
 2. The bubbles act in the manner of surface roughness.
 3. Latent heat transport by bubbles.
 4. Vapor-liquid exchange action.
-
1. For this process the heat path leads from the heated surface to the liquid between the bubbles. There are large convective velocities, caused by bubble growth, which facilitates the high heat transfer process. The driving force was assumed to be $T_w - T_b$ and therefore the heat flux should be a function of this temperature difference. But, according to experimental findings no dependence on the temperature of the liquid is observed. It has been found for the same superheat ($T_{wall} - T_{sat}$), the heat flux in nucleate-boiling remains essentially unaffected while the subcooling may increase substantially. Thus this method must be rejected since it is incompatible with experimental findings.
 2. Bubbles formed on the heated surface increase the turbulent exchange of liquid between the heating surface and the bulk liquid. for this case the heat flux would have to depend on the ratio of mean bubble diameter to pipe diameter. Thus, due to the dependence of the friction coefficient on the ratio of the mean size of roughness to pipe diameter, the heat transfer coefficient must be similarly

affected in accordance with Reynold's analogy. It has been found that doubling the pipe diameter has no affect on the heat flux, thereby questioning the validity of the hypothesis.

3. This process is simply a transfer of latent heat absorbed while the bubble grows, which is deposited in the bulk fluid as it collapses. It has been shown that this method accounts for approximately two percent of the total heat flux. This method, insufficient by itself, could be supplemented by additional heat flux through the bubbles by mass transfer.
4. This method incorporates method three as well as assuming that the bubble transfers heat during growth by pushing a quantity of hot liquid from the heating surface into the stream. It has been shown that about 100 times more heat is transferred by the vapor-liquid exchange than by the latent-heat transport. Since the latent-heat transport accounts for a few percent of the total heat flux the vapor-liquid mechanism is by itself sufficient to account for the heat flux in nucleate boiling.

E.2 Heat Balance for Vapor Phase

The equation describing the heat exchange for the vapor phase, for an incremental length of the heated section, is;

$$\dot{m}_g h_g + (Q_b(Z) - Q_c(Z))dZ + \frac{-d\dot{m}_f}{dZ}dZ h_f = \dot{m}_g h_g + \frac{d\dot{m}_g}{dZ}dZ h_g \quad (E.2.1)$$

knowing;

$$-\frac{d\dot{m}_f}{dZ} = \frac{d\dot{m}_g}{dZ} \quad (E.2.2)$$

equation (E.2.1) reduces to;

$$\frac{d\dot{m}_g}{dZ}(h_g - h_f) = Q_b(Z) - Q_c(Z) \quad (E.2.3)$$

with the relation;

$$\dot{m}_g = \dot{m} X_t \quad (E.2.4)$$

$$\frac{d\dot{m}_g}{dZ} = \dot{m} \frac{dX_t}{dZ} \quad (E.2.5)$$

Substituting equation E.2.5 into E.2.3 gives the true quality as;

$$dX_t = \frac{(Q_b(Z) - Q_c(Z))dZ}{\dot{m} h_{fg}} \quad (E.2.6)$$

E.3 Heat Balance for Liquid phase

A similar equation to that of E.2.1 can be written for the liquid phase;

$$\dot{m}_f C_p T_b + \left(\frac{q}{A} P_H dZ - Q_b(Z) dZ \right) + Q_c(Z) dZ = \dot{m}_f C_p T_b + \frac{d(\dot{m}_f C_p T_b)}{dZ} dZ - \frac{d(\dot{m}_f h_f)}{dZ} dZ \quad (E.3.1)$$

From continuity we can write;

$$\frac{d\dot{m}_f}{dZ} = -\frac{d\dot{m}_g}{dZ} = -\dot{m} \frac{dX_t}{dZ} \quad (E.3.2)$$

rearranging gives;

$$\frac{q}{A} P_H dZ = (Q_b(Z) - Q_c(Z)) dZ + C_p \left(T_b \frac{d\dot{m}_f}{dZ} + \dot{m}_f \frac{dT_b}{dZ} \right) dZ - h_f \frac{d\dot{m}_f}{dZ} dZ \quad (E.3.3)$$

or

$$C_p \dot{m}_f \frac{dT_b}{dZ} = \frac{q}{A} P_H - (Q_b(Z) - Q_c(Z)) - C_p T_b \frac{d\dot{m}_f}{dZ} + h_f \frac{d\dot{m}_f}{dZ} \quad (E.3.4)$$

$$\frac{dT_b}{dZ} = \frac{\frac{q}{A} P_H - (Q_b(Z) - Q_c(Z)) - C_p T_b \frac{d\dot{m}_f}{dZ} + h_f \frac{d\dot{m}_f}{dZ}}{\dot{C}_p (1 - X_t) \dot{m}} \quad (E.3.5)$$

from equation E.2.6;

$$Q_b(Z) - Q_c(Z) = \dot{m} h_{fg} \frac{dX_t}{dZ} \quad (E.3.6)$$

Substituting E.3.6 into E.3.5 gives;

$$\begin{aligned} \frac{dT_b}{dZ} &= \frac{\frac{q}{A} P_H - \dot{m} h_{fg} \frac{dX_t}{dZ} - (C_p T_b - h_f) \left(-\frac{\dot{m} dX_t}{dZ} \right)}{\dot{m} C_p (1 - X_t)} \\ &= \frac{\frac{q}{A} P_H - \dot{m} (h_{fg} - C_p T_b) \frac{dX_t}{dZ}}{\dot{m} C_p (1 - X_t)} \\ &= \frac{\frac{q}{A} P_H - (Q_b(Z) - Q_c(Z)) + (h_f - C_p T_b) \frac{d\dot{m}_f}{dZ}}{\dot{m} C_p (1 - X_t)} \end{aligned} \quad (E.3.7)$$

Again from a continuity standpoint, and rearrangement of equation E.3.6 gives;

$$(C_p T_b - h_f) \frac{d\dot{m}_f}{dZ} = -(C_p T_b - h_f) \frac{d\dot{m}_g}{dZ} \quad (E.3.8)$$

$$= -(C_p T_b - h_f) \frac{Q_b(Z) - Q_c(Z)}{h_{fg}} \quad (E.3.9)$$

Substituting equation E.3.9 into E.3.7 gives the final form of the differential change in the bulk temperature;

$$\begin{aligned} \frac{dT_b}{dZ} &= \frac{\frac{q}{A} P_H - (Q_b(Z) - Q_c(Z)) + (C_p T_b - h_f) \left(\frac{Q_b(Z) - Q_c(Z)}{h_{fg}} \right)}{\dot{m} C_p (1 - X_t)} \\ &= \frac{\frac{q}{A} P_H - (Q_b(Z) - Q_c(Z)) \left(1 - \frac{(C_p T_b + h_f)}{h_{fg}} \right)}{\dot{m} C_p (1 - X_t)} \\ &= \frac{\frac{q}{A} P_H - (Q_b(Z) - Q_c(Z)) \left(\frac{h_{fg}}{h_{fg}} \right) \left(1 - \frac{C_p T_b}{h_{fg}} \right)}{\dot{m} C_p (1 - X_t)} \quad (E.3.10) \end{aligned}$$

This equation is not the same as the equation for $\frac{dT_b}{dZ}$ given by Rouhani (8).

Appendix E.4 Program to calculate void growth using the equilibrium model.

```

C
C==> PROGRAM TO CALCULATE THE VOID GROWTH USING THE EQUILIBRIUM
C MODEL. THE APPROACH IS SIMILAR TO ROUHANI EXCEPT THAT A
C CONDENSATION FACTOR IS DETERMINED FROM THE EXPERIMENTAL
C RESULTS.
C
DATA PI/3.14159/, TSAT/112.5/, DENG/0.876/, DENL/950.0/
DATA DO/0.030/, XLENG/0.48/, SURF/0.0566/, DI/0.0131/
DATA HFG/2250.0E+3/, VISC/2.48E-4/, PR/1.53/, CP/4232.0/, COND/.685/
DATA HG/2697.0E+3/, HF/468.0E+3/
C
C==> EXPERIMENT NO.1
C
XSTART=-0.034270
VEL=0.1344
FLUX=97.7
DZ=0.00100
XOSV=-0.032
VOID=0.080202
VOIDC=0.09
TSTART=XSTART*HFG/CP+TSAT
TOSV=XOSV*HFG/CP+TSAT
P=1.53E+5
AREA=PI*(DO**2-DI**2)/4
XM=DENL*VEL*AREA
FLUX=FLUX*10000.0
PH=PI*DI
DE=DO-DI
REL=VEL*DENL*(DO-DI)/VISC
XG=XM/AREA
H=(0.023/(REL**0.2))*XG*CP*PR**(-2/3)
TWALL=TSAT
C
C==> CALCULATION OF CONDENSATION FACTOR
C
TOP=(FLUX-H*(TWALL-TSTART))*(1-VOID/VOIDC))*DENG*HFG*PH
BOTTOM=(TWALL-TSTART)*(DENG*HFG+CP*DENL*(TWALL-TSTART))
CONKC=TOP/BOTTOM
CONKC=0.0
WRITE(6,*)CONKC,TWALL
CO=1.1
TB=TOSV
DTL=TSAT-TB
DTLL=TWALL-TB
Z=DZ
C
C==> TRUE QUALITY ASSUMED EQUAL TO ZERO BEFORE THE ONSET.
C THE VALUE OF VOID AT ONSET IS THEN ADDED TO THE VALUE
C CALCULATED.

```

C

X=0.0.

C

C==> THE FOLLOWING LOOP SOLVES FOR THE VOID GROWTH BY THE USE OF
C ROUHANI APPROACH ASSUMING SMALL INCREMENTS IN DZ RATHER
C THEN A NUMERICAL SOLUTION.
C

DO 4 JJ=1,100

XZ=DENG*HFG+CP*DENL*DTL

DQB=((FLUX-H*DTLL*(1-VOID/VOIDC))*DENG*HFG*PH*DZ)/XZ

IF(VOID.GT.VOIDC)DQB=FLUX*DENG*HFG*PH*DZ/XZ

REL=(XG*(DO-DI))/((1.-VOID)*VISC)

XXNQ=(FLUX*VISC)/(HFG*(DENL-DENG)*SURF)

C

C==> CALCULATION OF ROUHANI'S CONDENSATION FACTOR.

C

C

ZZ=PR*XXNQ**.5

C

CONKC=3Q.*COND*((DENG/DENL)**2)*(AREA**.667)*(VOID**.667)*REL/ZZ

DQC=CONKC*DTL*DZ

DX=(DQB-DQC)/(XM*HFG)

X=X+DX

DTT=(FLUX*PH*DZ-(DQB-DQC)*(HG/HFG)*(1.-CP*TB/HG))/((XM*CP)*(1-

TB=TB+DTT

XEQ=CP*(TB-TSAT)/HFG

DTLL=DTLL-DTT

DTL=DTL-DTT

AO=CO*(X/DENG+(1-X)/DENL)

BO=(1.18/XG)*((SURF*9.81*(DENL-DENG))/DENL**2)**(0.25)

VOID=(X/DENG)*(1./(AO+BO))+VOIDC

Z=Z+DZ

XEQW=100.*XEQ

VOIDW=100.*VOID

IF(VOID.GT.0.40)GO TO 19

WRITE(6,99)XEQW,VOIDW

99 FORMAT(F7.3,1X,E6.3)

4 CONTINUE

19 CONTINUE

STOP

END

Appendix F : Drift flux Model

F.1 Two Dimensional Flow

The one dimensional drift flux model can be extended to include velocity and concentration variations across the flow area using an empirical value depending on the above mentioned profiles. This approach suggested by Zuber and Findlay (13), is summarized in the following section.

The volumetric flux densities of each phase is given by;

$$j_g = \alpha U_g \quad (F.1.1)$$

and

$$j_l = (1 - \alpha) U_l \quad (F.1.2)$$

The total volumetric flux of the mixture is given as;

$$j = j_l + j_g \quad (F.1.3)$$

The diffusion or drift velocities, with respect to the volumetric flux density, are given by;

$$U_{gj} = U_g - j \quad (F.1.4)$$

and

$$U_{lj} = U_l - j \quad (F.1.5)$$

From which the drift flux can be determined for each phase to be;

$$j_{gl} = \alpha(U_g - j) \quad (F.1.6)$$

and

$$j_{lg} = (1 - \alpha)(U_l - j) \quad (F.1.7)$$

Zuber and Findlay (13) incorporated an average value defined by:

$$\langle F \rangle = \frac{1}{A} \int_A F dA \quad (F.1.8)$$

$\langle F \rangle$ being the average of F over a cross-section area of the duct. This was done so as to facilitate data which are mainly average rather than local values.

Applying equation F.1.8 to U_g ;

$$\langle U_g \rangle = \left\langle \frac{j_g}{\alpha} \right\rangle = \langle j \rangle + \langle U_{gj} \rangle \quad (F.1.9)$$

Giving $\langle U_g \rangle$ the average gas velocity across the cross-sectional area of the duct.

The average volumetric flux density is therefore defined as;

$$\langle j_g \rangle = \langle \alpha U_g \rangle \quad (F.1.10)$$

Now considering a weighted mean of a value F defined as;

$$\overline{F} = \frac{\langle \alpha F \rangle}{\langle \alpha \rangle} = \frac{\frac{1}{A} \int_A \alpha F dA}{\frac{1}{A} \int_A \alpha dA} \quad (F.1.11)$$

The weighted mean velocity, $\overline{U}_g$, of the gas phase is therefore;

$$\overline{U}_g = \frac{\langle U_g \alpha \rangle}{\langle \alpha \rangle} = \frac{\langle j_g \rangle}{\langle \alpha \rangle} \quad (F.1.12)$$

or

$$\overline{U}_g = \frac{\langle \alpha j \rangle}{\langle \alpha \rangle} + \frac{\langle \alpha U_{gj} \rangle}{\langle \alpha \rangle} \quad (F.1.13)$$

Multiplying the first term on the right hand side by $\langle j \rangle / \langle j \rangle$;

$$\overline{U}_g = \frac{\langle j_g \rangle}{\langle \alpha \rangle} = C_o \langle j \rangle + \frac{\langle \alpha U_{gj} \rangle}{\langle \alpha \rangle} \quad (F.1.14)$$

where;

$$C_o = \frac{\langle \alpha j \rangle}{\langle \alpha \rangle \langle j \rangle} \quad (F.1.15)$$

Plotting $\langle j_g \rangle / \langle \alpha \rangle$ versus $\langle j \rangle$ produces a straight line with a slope of C_0 and an intercept of weighted mean drift velocity.

F.2 Empirical Drift Velocities

Drift velocities for the churn turbulent flow and slug flow regimes are presented below. All property values are taken at a pressure of 1.55×10^5 Pa and the corresponding T_{sat} .

1. Churn Turbulent (35)

$$\begin{aligned} U_{gj} &= 2.9 \left(\frac{g\sigma\Delta\rho}{\rho_l^2} \right)^{1/4} \\ &= 0.4536 \text{ m/s} \end{aligned}$$

2. Churn Turbulent (Bubbly) (13)

$$\begin{aligned} U_{gj} &= 1.18 \left(\frac{g\sigma\Delta\rho}{\rho_l^2} \right)^{1/4} \\ &= 0.1846 \text{ m/s} \end{aligned}$$

3. Churn Turbulent (Bubbly) (13)

$$\begin{aligned} U_{gj} &= 1.53 \left(\frac{g\sigma\Delta\rho}{\rho_l^2} \right)^{1/4} \\ &= 0.2394 \text{ m/s} \end{aligned}$$

4. Slug Flow (27)

$$U_{gj} = K_1 \left(\frac{g D_o \Delta \rho}{\rho_l} \right)^{1/2} \\ = 0.1763 \text{ m/s}$$

with

$$\frac{D_i}{D_o} = \frac{1.31 \text{ cm}}{2.20 \text{ cm}} \simeq 0.6 \Rightarrow K_1 = 0.38$$

F3: Computer program to calculate values of <j>, <jg>/void,
and Xl for drift flux model.

```

C
C==> PROGRAM TO CALCULATE RELEVANT VALUES FOR THE
C    DRIFT FLUX MODEL.
C
    REAL T(30),VEL(30),VOID(30),XL(30),XJ(30),Y(30),XEQ(30)
    COMMON TX(15),CPX(15),DENX(15),VISX(15),XKX(15),PRX(15)
    TSAT=112.5
    DENG=0.876
    CP=4230.0
    HFG=2250.E+3
C
C==> READ THE EQUILIBRIUM QUALITY AT OSV, AND THE NUMBER
C    OF DATA POINTS CORRESPONDING TO A SPECIFIC RUN OF
C    CONSTANT HEAT FLUX.
C
    READ(5,1)XEQO,N
    WRITE(6,91)XEQO,N
    1  FORMAT(F9.6,1X,I2)
    91  FORMAT(1X,F9.6,1X,I2)
C
C==> THE CONDITION FOR EACH POINT IS NOW READ, IE. THE LOCAL
C    VALUE OF VELOCITY, TEMPERATURE, AND VOID. THIS ENSURES
C    THAT ALL CALCULATIONS ARE PERFORMED AT LOCAL CONDITIONS.
C
    WRITE(6,191)
    191  FORMAT(5X,'EXPERIMENTAL CONDITIONS, TEST NO.1',///,
    *3X,'VELOCITY',2X,'EQUILIBRIUM QUALITY',3X,'VOID',/)
    DO 2 I=1,N
        READ(5,3)VEL(I),XEQ(I),VOID(I)
        WRITE(6,33)I,VEL(I),XEQ(I),VOID(I)
    2  CONTINUE
    3  FORMAT(F6.4,1X,F9.6,1X,F6.4)
    33  FORMAT(1X,I2,2X,F6.4,6X,F9.6,9X,F6.4)
    DO 11 J=1,14
        READ(5,22)TX(J),CPX(J),DENX(J),VISX(J),XKX(J),PRX(J)
        WRITE(6,22)TX(J),CPX(J),DENX(J),VISX(J),XKX(J),PRX(J)
    11  CONTINUE
    22  FORMAT(F6.2,1X,F6.1,1X,F5.1,1X,F8.6,1X,F5.3,1X,F4.2)
C
C==>FOR THE CONDITION AT ONSET THE LOCAL PHYSICAL VALUES ARE
C    DETERMINED PROPERTIES OF WATER ARE AT SATURATED CONDITIONS.
C
    TOSV=TSAT+(XEQO*HFG)/CP
    CALL WATER(TOSV,DENL,VISC,CP,PR,XK)
    DO 4 NA=1,N
C
C==> AT A LOCAL POINT PHYSICAL VALUES ARE DETERMINED.
C
    T(NA)=TSAT+(XEQ(NA)*HFG)/CP

```

```

      CALL WATER(T(NA),DENL,VISC,CP,PR,XK)
      G=DENL*VEL(NA)

```

```

C
C==> XTRUE DETERMINED FROM LEVY'S MODEL.

```

```

      XTRUE=XEQ(NA)-XEQO*EXP(XEQ(NA)/XEQO-1.)

```

```

C
C==> THE FOUR FOLLOWING VALUES XL,XJG,XJF,XJ; CORRESPONDS
C     TO X1 Jg,Jf AND J RESPECTFULLY. THE VALUE OF Y IS THE
C     VERTICAL AXIS Jg/VOID.

```

```

      XL(NA)=XTRUE
      XL(NA)=XTRUE/(XEQ(NA)-XEQO)
      XJG=G*XTRUE/DENG
      XJF=G*(1.-XTRUE)/DENL
      XJ(NA)=XJG+XJF
      Y(NA)=XJG/VOID(NA)

```

```

4    CONTINUE
      WRITE(6,12)

```

```

C
C==> THE VALUE OF J, Jg/VOID AND XL IS NOW PRINTED FOR
C     EACH OF THE LOCAL POINTS CONSIDERED.

```

```

12   FORMAT(/,,,11X,'DRIFT FLUX VALUES',,,,
*    11X,'J',8X,'JG/VOID',9X,'XL',/)
      DO 5 K=1,N
        WRITE(6,19)K,XJ(K),Y(K),XL(K)
5    CONTINUE
19   FORMAT(1X,12,5X,F7.4,5X,F7.4,5X,F9.6)
      STOP
      END

```

```

C
C==>SUBROUTINE TO DETERMINE LOCAL PROPERTIES OF WATER.

```

```

      SUBROUTINE WATER(TB,DEN,VISC,CP,PR,XK)
      COMMON TX(15),CPX(15),DENX(15),VISX(15),XKX(15),PRX(15)
      WRITE(6,*)TB
      DO 3 JX=1,15
        M=JX
        IF(TB.GE.TX(M).AND.TB.LE.TX(M+1))GO TO 4
3    CONTINUE
4    CONTINUE
      XINTER=(TB-TX(M))/(TX(M+1)-TX(M))
      WRITE(6,*)XINTER
      CP=XINTER*(CPX(M+1)-CPX(M))+CPX(M)
      DEN=XINTER*(DENX(M+1)-DENX(M))+DENX(M)
      VISC=XINTER*(VISX(M+1)-VISX(M))+VISX(M)
      XK=XINTER*(XKX(M+1)-XKX(M))+XKX(M)
      PR=XINTER*(PRX(M+1)-PRX(M))+PRX(M)
C    2 FORMAT(F6.2,1X,F6.1,1X,F5.1,1X,F8.6,1X,F5.3,1X,F4.2)
      RETURN
      END

```

F4: PROGRAM TO CALCULATE VOID GROWTH ASSUMING A VARIABLE CO.

C
C==> PROGRAM TO CALCULATE VOID GROWTH WITH VARIABLE CO.
C

```
REAL XEQ(100), T(100), VOID(100), CO(100)
DATA PI/3.14159/, TSAT/112.0/, DENG/0.876/, DENL/950.0/
DATA DO/0.022/, XLENG/0.48/, SURF/0.0566/, DI/0.013/
DATA HFG/2250.9E+3/, VISC/2.48E-4/, PR/1.53/, CP/4232.0/, COND/.685/
```

C==> EXPERIMENT NO.6
C

```
FLUX=61.0
DZ=0.0010
VEL=0.1560
FLUX=FLUX*10000
PH=DI*PI
AREA=PI*(DO**2-DI**2)/4.
XM=AREA*VEL*DENL
P=22.5/14.7
DH=DO-DI
G=VEL*DENL
XEQ(1)=-0.020
VOID(1)=0.10
T(1)=XEQ(1)*HFG/CP+112
Z=0.0
DO 7 J=2, 100
  Z=Z+DZ
```

C
C==> A HEAT BALANCE WAS USED TO DETERMINE THE TEMPERATURE PROFILE.
C

```
T(J)=FLUX*DZ*PI*DI/(XM*CP)+T(J-1)
XEQ(J)=(T(J)-TSAT)*CP/HFG
X=XEQ(J)-XEQ(1)*EXP(XEQ(J)/XEQ(1)-1.)
XL=(X/(XEQ(J)-XEQ(1)))
CO(J)=(25.7*XL)-(64.8*XL**2.0)
IF(XL.GT.0.22)CO(J)=2.6
AA=CO(J)*(X/DENG+(1.-X)/DENL)
BB=(1.18/G)*(((SURF*9.81*(DENL-DENG))/DENL**2)**.25)
VOID(J)=(X/DENG)*(1./(AA+BB))+VOID(1)
```

7 CONTINUE

```
ULENG=0.0
```

```
DO 8 JU=1, 100
```

```
  XEQL=100.*XEQ(JU)
```

```
  VOIDL=100.*VOID(JU)
```

```
  WRITE(6,9)JU, CO(JU), ULENG, XEQL, VOIDL
```

```
  ULENG=ULENG+DZ
```

```
  IF(VOIDL.GT.40.0)GO TO 100
```

8 CONTINUE

9 FORMAT(1X, I3, 3X, F6.3, 3X, F7.5, 3X, F7.3, 3X, F7.3)

100 CONTINUE

```
STOP
```

```
END
```

Table G.1 Recorded Void Growth : Experiment No. 1.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.020	0.0820	25.7	87.4	88.5	5.779	-4.11
2	0.020	0.0798	27.5	92.8	92.0	6.217	-3.44
3	0.019	0.0772	27.7	97.2	94.5	5.958	-3.34
4	0.019	0.0755	28.1	99.5	96.4	7.954	-3.31
5	0.019	0.0733	28.4	100.1	96.4	6.833	-3.02
6	0.018	0.0745	28.6	100.6	97.8	8.971	-2.76
7	0.019	0.0750	28.8	100.1	97.6	7.725	-2.80
8	0.018	0.0725	29.2	100.3	100.3	6.385	-2.29
9	0.017	0.0698	29.6	103.4	103.4	8.659	-1.70
10	0.017	0.0700	29.3	105.3	102.9	10.148	-1.80
11	0.017	0.0691	29.7	105.3	104.2	12.684	-1.55
12	0.017	0.0689	29.8	106.2	104.5	10.151	-1.49
13	0.017	0.0686	29.5	108.1	104.5	16.192	-1.49
14	0.017	0.0684	29.7	108.1	105.0	19.046	-1.40
15	0.016	0.0663	29.8	108.8	107.6	28.543	-0.92

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 22.0 mm ID = 13.1 mm
 VOLTAGE = 9.0 volts HEAT FLUX = 29.7 W/cm²
 HEATER ELEMENT = 48 cm

Table G.2 Recorded Void Growth : Experiment No. 2.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.022	0.0906	37.2	84.9	94.1	7.614	-3.458
2	0.022	0.0893	38.0	94.3	95.7	7.345	-3.160
3	0.022	0.0884	38.2	96.0	96.5	7.384	-3.002
4	0.021	0.0865	38.2	97.4	97.7	6.703	-2.773
5	0.021	0.0846	38.3	99.1	99.3	6.195	-2.482
6	0.020	0.0826	38.3	100.0	100.7	8.825	-2.208
7	0.020	0.0818	38.8	101.0	101.8	7.097	-2.003
8	0.020	0.0803	39.0	102.9	103.1	9.234	-1.759
9	0.020	0.0792	39.0	104.0	104.1	9.404	-1.581
10	0.019	0.0779	38.9	105.7	105.0	11.830	-1.410
11	0.019	0.0764	39.4	106.9	106.9	11.859	-1.061
12	0.019	0.0758	39.7	108.1	107.7	13.624	-0.906
13	0.019	0.0763	40.0	109.0	107.5	13.857	-0.936
14	0.019	0.0757	40.5	108.7	108.6	18.956	-0.736
15	0.019	0.0756	40.4	108.7	108.6	23.419	-0.725
16	0.019	0.0752	40.3	109.4	108.8	30.224	-0.698

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 22.0 mm ID = 13.1 mm
 VOLTAGE = 9.0 volts HEAT FLUX = 29.7 W/cm**2
 HEATER ELEMENT = 48 cm

Table G.3 Recorded Void Growth : Experiment No. 3.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.024	0.0965	23.7	68.1	77.1	4.591	-6.647
2	0.024	0.0951	26.7	79.5	80.9	5.796	-5.940
3	0.023	0.0926	28.8	84.7	84.4	7.273	-5.271
4	0.023	0.0919	29.7	86.6	85.8	5.169	-5.025
5	0.022	0.0909	30.3	87.7	87.0	4.715	-4.797
6	0.022	0.0901	30.6	88.2	87.8	3.197	-4.640
7	0.022	0.0882	30.8	90.1	89.2	5.013	-4.373
8	0.022	0.0871	31.1	90.1	90.3	6.765	-4.166
9	0.021	0.0849	31.2	91.3	91.9	6.146	-3.878
10	0.021	0.0830	31.8	92.7	93.9	6.770	-3.495
11	0.020	0.0808	31.9	94.0	95.6	5.203	-3.167
12	0.020	0.0796	31.7	95.5	96.4	7.744	-3.021
13	0.019	0.0769	32.7	97.5	99.7	8.022	-2.396
14	0.019	0.0768	32.8	98.3	99.9	5.967	-2.367
15	0.019	0.0764	32.9	98.5	100.4	8.872	-2.274
16	0.019	0.0748	33.1	99.6	102.0	6.531	-1.969
17	0.018	0.0730	33.4	101.8	104.0	6.592	-1.601
18	0.018	0.0716	33.8	104.4	105.8	9.511	-1.264
19	0.017	0.0707	33.8	105.3	106.7	12.198	-1.090
20	0.018	0.0710	34.1	107.5	106.6	13.098	-1.104
21	0.017	0.0697	34.2	108.2	108.1	20.510	-0.819
22	0.017	0.0691	34.6	108.4	109.1	32.620	-0.638

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 22.0 mm ID = 13.1 mm
 VOLTAGE = 9.0 volts HEAT FLUX = 29.7 W/cm**2
 HEATER ELEMENT = 48 cm

Table G.4 Recorded Void Growth : Experiment No. 4.

POINT	MASS	VELOCITY	T _{in}	T _{out}	T _{out} cal.	VOID	QUALITY
#	Kg/s	m/s	C	C	C	%	X _{eq} %
1	0.024	0.0958	41.4	84.9	95.2	5.618	-3.255
2	0.023	0.0928	42.1	97.4	97.6	4.562	-2.791
3	0.023	0.0920	41.9	99.1	97.9	5.634	-2.736
4	0.023	0.0913	42.5	99.9	99.0	8.685	-2.541
5	0.022	0.0903	42.3	100.6	99.4	7.329	-2.461
6	0.022	0.0890	42.7	101.9	100.6	8.158	-2.242
7	0.022	0.0885	42.3	102.7	100.5	7.112	-2.249
8	0.022	0.0877	42.7	103.3	101.5	2.529	-2.072
9	0.022	0.0873	42.7	103.2	101.7	2.489	-2.028
10	0.021	0.0869	43.1	103.9	102.4	5.828	-1.891
11	0.021	0.0858	43.3	104.8	103.4	8.088	-1.711
12	0.021	0.0857	43.5	105.1	103.6	9.431	-1.669
13	0.021	0.0852	44.0	105.8	104.4	9.648	-1.513
14	0.021	0.0850	43.7	106.1	104.4	10.596	-1.530
15	0.021	0.0844	44.1	107.3	105.2	15.152	-1.372
16	0.021	0.0843	44.9	107.7	106.0	14.007	-1.224
17	0.021	0.0832	44.9	108.0	106.8	16.202	-1.079
18	0.021	0.0852	44.0	105.8	104.4	9.648	-1.513
19	0.021	0.0830	45.1	108.0	107.2	10.129	-0.995
20	0.020	0.0818	45.1	108.5	108.7	23.090	-0.713
21	0.020	0.0810	45.4	109.0	109.1	26.792	-0.648

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 22.0 mm ID = 13.1 mm
 VOLTAGE = 9.0 volts HEAT FLUX = 29.7 W/cm**2
 HEATER ELEMENT = 48 cm

Table G.5 Recorded Void Growth : Experiment No. 5.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.064	0.2567	57.2	98.2	98.1	4.361	-2.699
2	0.063	0.2539	57.3	98.7	98.7	5.769	-2.600
3	0.063	0.2533	57.3	98.8	98.8	4.838	-2.570
4	0.063	0.2529	57.8	99.5	99.4	5.061	-2.466
5	0.062	0.2512	58.6	99.8	100.5	3.301	-2.263
6	0.062	0.2516	58.5	99.9	100.3	6.824	-2.297
7	0.062	0.2521	59.0	100.2	100.7	3.289	-2.213
8	0.062	0.2524	59.2	99.8	100.8	5.401	-2.195
9	0.062	0.2517	59.1	100.6	100.8	5.587	-2.191
10	0.063	0.2532	59.7	100.7	101.1	6.428	-2.115
11	0.062	0.2508	60.1	101.5	102.0	8.320	-1.978
12	0.062	0.2519	60.6	101.2	102.4	8.444	-1.905
13	0.062	0.2522	60.8	102.0	102.4	8.424	-1.888
14	0.063	0.2530	61.6	102.0	103.2	5.911	-1.755
15	0.062	0.2515	61.5	102.8	103.2	4.304	-1.739
16	0.062	0.2520	62.1	103.0	103.8	5.205	-1.632
17	0.063	0.2529	62.0	103.2	103.6	7.607	-1.675
18	0.062	0.2523	62.7	103.4	104.4	6.377	-1.523
19	0.063	0.2528	62.7	103.6	104.5	8.978	-1.538
20	0.062	0.2518	63.3	104.9	105.0	10.958	-1.408
21	0.063	0.2532	63.7	106.0	105.2	16.253	-1.380
22	0.063	0.2532	63.8	106.2	105.3	15.515	-1.355
23	0.063	0.2548	64.2	106.4	105.5	18.107	-1.323
24	0.062	0.2520	64.4	107.0	106.1	17.144	-1.195
25	0.063	0.2529	65.0	107.1	106.6	19.875	-1.114
26	0.063	0.2530	65.0	107.3	106.5	20.585	-1.124
27	0.062	0.2501	65.3	107.3	107.4	22.012	-0.966
28	0.063	0.2527	65.3	107.4	106.8	23.135	-1.063
29	0.063	0.2529	65.6	107.8	107.2	21.638	-0.996
30	0.062	0.2510	65.2	107.8	107.0	26.571	-1.025
31	0.062	0.2506	65.4	108.4	107.8	29.224	-0.951

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 22.0 mm ID = 13.1 mm
VOLTAGE = 13.0 volts HEAT FLUX = 60.5 W/cm**2
HEATER ELEMENT = 48 cm

Table G.6 Recorded Void Growth : Experiment No. 6.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.042	0.1678	31.2	91.9	94.3	8.455	-3.425
2	0.041	0.1641	31.4	93.4	95.9	6.865	-3.123
3	0.040	0.1610	31.6	94.6	97.4	7.117	-2.846
4	0.040	0.1601	31.2	96.4	97.3	8.899	-2.859
5	0.039	0.1588	32.6	96.3	99.3	8.528	-2.484
6	0.039	0.1593	33.8	96.0	100.2	8.338	-2.304
7	0.040	0.1601	34.7	95.5	100.9	5.947	-2.184
8	0.039	0.1583	34.2	96.6	101.0	9.769	-2.153
9	0.039	0.1565	32.2	99.0	99.9	9.749	-2.372
10	0.039	0.1560	34.7	98.0	102.6	12.319	-1.868
11	0.038	0.1520	34.8	100.8	104.4	12.441	-1.512
12	0.038	0.1526	34.5	100.7	103.9	12.359	-1.625
13	0.038	0.1524	34.6	101.7	104.1	15.254	-1.585
14	0.038	0.1536	35.0	101.4	103.9	12.401	-1.608
15	0.038	0.1548	35.5	100.7	103.9	10.894	-1.612
16	0.038	0.1545	36.2	100.7	104.7	14.999	-1.470
17	0.038	0.1542	35.8	101.4	104.4	12.010	-1.517
18	0.038	0.1545	36.7	101.8	105.2	16.499	-1.369
19	0.038	0.1520	37.0	103.4	106.7	19.623	-1.096
20	0.037	0.1510	36.7	103.4	106.8	20.357	-1.067
21	0.037	0.1509	36.9	103.4	107.0	20.332	-1.030
22	0.038	0.1539	37.5	104.2	106.2	20.882	-1.177
23	0.038	0.1538	38.1	104.6	106.9	24.384	-1.044
24	0.038	0.1539	37.1	106.1	105.9	24.675	-1.246
25	0.038	0.1517	38.3	106.1	108.1	30.055	-1.246

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 22.0 mm ID = 13.1 mm
 VOLTAGE = 12.9 volts HEAT FLUX = 61.0 W/cm**2
 HEATER ELEMENT = 48 cm

Table G.7 Recorded Void Growth : Experiment No. 7.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.054	0.2196	26.6	87.3	87.8	5.779	-4.512
2	0.054	0.2190	29.0	87.5	88.6	6.427	-4.494
3	0.054	0.2173	30.0	88.1	90.1	4.967	-4.216
4	0.054	0.2168	30.7	88.7	90.9	3.978	-4.052
5	0.053	0.2157	31.1	89.4	91.6	6.745	-3.925
6	0.053	0.2131	31.4	90.4	92.6	9.228	-3.736
7	0.052	0.2115	32.1	91.7	93.8	8.046	-3.508
8	0.052	0.2093	33.1	92.7	95.5	5.064	-3.189
9	0.051	0.2069	33.1	93.9	96.2	7.793	-3.061
10	0.051	0.2056	34.2	95.0	97.7	4.718	-2.779
11	0.050	0.2040	35.0	95.9	99.0	6.927	-2.530
12	0.050	0.2015	35.1	97.2	99.9	7.703	-2.368
13	0.049	0.1975	36.4	99.3	102.5	8.426	-1.871
14	0.048	0.1938	37.3	101.3	104.6	7.666	-1.481
15	0.046	0.1871	37.2	104.4	106.9	16.152	-1.046
16	0.046	0.1873	37.4	106.4	107.1	20.437	-1.023
17	0.046	0.1861	38.0	107.1	108.1	21.936	-0.821
18	0.045	0.1814	38.1	107.9	110.1	24.303	-0.458
19	0.045	0.1803	39.0	108.3	111.4	26.528	-0.205
20	0.044	0.1798	39.7	108.7	112.3	29.144	-0.030

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 22.0 mm ID = 13.1 mm
 VOLTAGE = 14.4 volts HEAT FLUX = 74.2 W/cm**2
 HEATER ELEMENT = 48 cm

Table G.8 Recorded Void Growth : Experiment No. 8.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.085	0.3448	42.4	81.5	80.2	2.033	-6.060
2	0.086	0.3456	43.9	82.1	81.7	3.792	-5.789
3	0.086	0.3471	46.0	82.5	83.6	4.444	-5.430
4	0.086	0.3458	46.0	84.0	83.8	3.681	-5.397
5	0.085	0.3450	47.1	85.1	85.0	5.344	-5.173
6	0.085	0.3445	47.9	86.0	85.8	4.117	-5.018
7	0.085	0.3446	49.3	86.7	87.2	3.340	-4.749
8	0.085	0.3440	49.9	87.9	87.8	4.434	-4.639
9	0.085	0.3434	51.1	88.9	89.1	3.542	-4.402
10	0.085	0.3426	51.5	89.9	89.6	4.695	-4.308
11	0.085	0.3418	52.8	90.9	90.9	5.015	-4.051
12	0.084	0.3411	53.6	91.7	91.9	5.122	-3.871
13	0.084	0.3407	54.0	92.6	92.3	6.010	-3.793
14	0.084	0.3390	54.9	93.6	93.5	6.189	-3.578
15	0.084	0.3394	55.8	94.5	94.3	7.639	-3.421
16	0.084	0.3391	56.5	95.2	95.0	5.830	-3.285
17	0.084	0.3408	57.2	96.3	95.5	5.439	-3.201
18	0.085	0.3419	58.6	96.8	96.8	4.215	-2.948
19	0.084	0.3401	58.6	97.9	97.0	6.672	-2.921
20	0.084	0.3377	60.6	98.6	99.3	6.182	-2.486
21	0.083	0.3353	61.0	99.9	99.9	7.213	-2.359
22	0.083	0.3361	62.0	100.5	100.8	8.500	-2.199
23	0.083	0.3351	62.7	101.7	101.7	9.412	-2.031
24	0.081	0.3286	62.8	103.3	102.5	9.252	-1.877
25	0.078	0.3157	64.7	105.4	106.0	21.218	-1.217
26	0.075	0.3042	64.7	107.8	107.6	30.347	-0.928
27	0.071	0.2871	66.4	109.3	111.9	45.758	-0.115

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 22.0 mm ID = 13.1 mm
 VOLTAGE = 14.4 volts HEAT FLUX = 74.2 W/cm**2
 HEATER ELEMENT = 48 cm

Table G.9 Recorded Void Growth : Experiment No. 9.

POINT	MASS	VELOCITY	T _{in}	T _{out}	T _{out} cal.	VOID	QUALITY
#	Kg/s	m/s	C	C	C	%	X _{eq} %
1	0.110	0.4442	48.1	78.2	77.5	6.206	-6.577
2	0.110	0.4429	48.6	78.5	78.1	5.451	-6.461
3	0.109	0.4419	48.4	78.8	78.0	4.753	-6.487
4	0.109	0.4407	48.8	78.8	78.4	4.702	-6.402
5	0.109	0.4411	49.4	79.6	79.0	5.871	-6.302
6	0.109	0.4406	49.9	80.4	79.5	4.253	-6.192
7	0.109	0.4406	51.2	81.3	80.8	5.033	-5.954
8	0.109	0.4404	52.0	82.2	81.6	3.736	-5.801
9	0.109	0.4404	53.0	83.1	82.6	4.860	-5.615
10	0.109	0.4396	53.5	83.7	83.2	4.584	-5.505
11	0.109	0.4397	54.6	84.8	84.2	4.428	-5.309
12	0.109	0.4388	55.6	85.8	85.4	8.132	-5.091
13	0.108	0.4382	56.6	86.1	86.4	5.440	-4.909
14	0.108	0.4390	57.5	86.6	87.3	6.104	-4.744
15	0.108	0.4381	58.2	88.5	88.0	6.344	-4.597
16	0.108	0.4373	59.6	89.2	89.4	7.021	-4.338
17	0.108	0.4371	60.3	90.6	90.2	6.553	-4.196
18	0.108	0.4375	60.8	91.4	90.7	6.373	-4.103
19	0.108	0.4382	61.7	92.2	91.5	7.611	-3.944
20	0.108	0.4372	62.6	93.0	92.4	4.975	-3.769
21	0.108	0.4366	64.2	94.3	94.1	7.317	-3.451
22	0.108	0.4351	64.7	94.6	94.7	7.387	-3.349
23	0.107	0.4341	64.9	95.6	95.0	4.513	-3.295
24	0.108	0.4352	65.5	96.3	95.5	7.531	-3.191
25	0.108	0.4346	66.7	96.9	96.8	4.341	-2.952

Experiment No. 9 Continued

26	0.107	0.4340	67.3	97.7	97.4	7.417	-2.839
27	0.108	0.4355	68.2	98.4	98.1	7.963	-2.699
28	0.108	0.4350	68.1	99.4	98.1	9.843	-2.698
29	0.107	0.4334	69.5	99.4	99.6	6.916	-2.425
30	0.107	0.4318	70.4	100.2	100.7	9.349	-2.221
31	0.107	0.4345	71.4	101.0	101.4	8.929	-2.082
32	0.107	0.4331	71.8	101.9	102.0	10.489	-1.977
33	0.106	0.4297	72.2	102.8	102.8	15.245	-1.869
34	0.106	0.4287	72.7	103.7	103.1	16.985	-1.759
35	0.105	0.4260	74.0	104.3	104.7	20.691	-1.470
36	0.106	0.4267	74.3	105.0	104.9	25.504	-1.433
37	0.105	0.4247	75.5	106.0	106.2	33.009	-1.182

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 22.0 mm ID = 13.1 mm
 VOLTAGE = 14.4 volts HEAT FLUX = 74.2 W/cm**2
 HEATER ELEMENT = 48 cm

Table G.10 : Recorded Void Growth : Experiment No. 10

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.057	0.2295	26.3	85.5	84.6	3.421	-5.250
2	0.056	0.2252	26.5	87.4	85.9	3.268	-4.994
3	0.055	0.2209	27.1	88.1	87.7	5.505	-4.663
4	0.054	0.2171	27.4	88.4	89.0	6.300	-4.408
5	0.052	0.2101	28.1	90.4	91.7	6.674	-3.899
6	0.051	0.2054	29.2	93.0	94.3	5.978	-3.417
7	0.050	0.2029	29.6	93.3	95.5	7.424	-3.190
8	0.049	0.1974	29.6	96.8	97.4	8.233	-2.842
9	0.049	0.1970	29.6	97.4	97.5	7.143	-2.809
10	0.049	0.1982	30.7	97.1	98.2	7.853	-2.684
11	0.049	0.1969	30.4	98.2	98.4	10.384	-2.658
12	0.049	0.1968	31.5	98.2	99.4	10.675	-2.454
13	0.048	0.1959	32.1	98.4	100.4	13.249	-2.266
14	0.049	0.1994	31.7	98.7	98.7	12.583	-2.587
15	0.049	0.1961	31.8	100.0	100.1	15.493	-2.339
16	0.048	0.1954	32.5	101.8	101.0	18.107	-2.161
17	0.048	0.1958	34.2	100.7	102.5	22.574	-1.869
18	0.046	0.1875	34.4	103.8	105.7	29.028	-1.276
19	0.046	0.1841	33.9	104.8	106.6	29.385	-1.115
20	0.044	0.1774	34.6	106.4	110.0	41.734	-0.472

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 22.0 mm ID = 13.1 mm
 VOLTAGE = 14.5 volts HEAT FLUX = 77.0 W/cm**2
 HEATER ELEMENT = 48 cm

Table G.11 Recorded Void Growth : Experiment No. 11.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.055	0.2243	23.6	82.8	84.2	1.898	-5.311
2	0.055	0.2208	24.2	84.2	84.2	1.104	-5.008
3	0.054	0.2175	23.9	85.8	86.4	2.119	-4.906
4	0.053	0.2149	22.8	86.5	86.1	3.615	-4.965
5	0.053	0.2141	24.1	86.6	87.7	2.614	-4.667
6	0.053	0.2127	22.3	87.4	86.2	1.446	-4.936
7	0.052	0.2121	24.6	87.7	88.7	2.164	-4.466
8	0.052	0.2108	24.0	89.1	88.5	2.489	-4.513
9	0.051	0.2078	21.8	90.8	87.3	2.115	-4.735
10	0.051	0.2075	23.7	91.1	89.3	3.831	-4.358
11	0.051	0.2050	22.6	92.5	89.0	3.409	-4.412
12	0.050	0.2026	22.4	93.8	89.4	3.196	-4.311
13	0.050	0.2017	22.6	94.8	90.1	3.844	-4.218
14	0.050	0.2002	22.8	95.6	90.8	1.502	-4.077
15	0.049	0.1972	23.7	97.8	92.7	6.053	-3.726
16	0.048	0.1940	24.7	99.1	94.8	4.181	-3.330
17	0.047	0.1907	26.4	100.7	97.7	4.939	-2.779
18	0.048	0.1944	26.4	100.8	96.4	4.972	-3.022
19	0.048	0.1921	26.8	102.0	97.6	3.641	-2.805
20	0.046	0.1877	27.4	104.8	99.9	7.356	-2.376
21	0.046	0.1855	28.1	107.6	101.4	9.409	-2.077
22	0.046	0.1855	29.8	111.0	103.1	16.201	-1.760
23	0.046	0.1869	32.2	110.5	105.0	17.699	-1.405
24	0.044	0.1791	30.8	111.9	106.7	19.104	-1.084
25	0.045	0.1815	33.0	111.8	107.9	25.341	-0.862
26	0.045	0.1819	34.7	111.6	109.5	32.526	-0.568
27	0.045	0.1818	34.1	111.8	108.9	36.325	-0.678

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 22.0 mm ID = 13.1 mm
 VOLTAGE = 14.7 volts HEAT FLUX = 77.4 W/cm**2
 HEATER ELEMENT = 48 cm

Table G.12 Recorded Void Growth : Experiment No. 12.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.069	0.2800	32.6	79.9	80.6	4.572	-5.989
2	0.069	0.2792	33.4	81.6	81.5	6.185	-5.821
3	0.069	0.2797	34.4	82.1	82.4	6.587	-5.654
4	0.069	0.2803	35.6	82.5	83.6	3.786	-5.434
5	0.069	0.2794	36.6	83.3	84.7	3.921	-5.232
6	0.069	0.2797	37.0	84.5	85.1	5.227	-5.151
7	0.069	0.2799	38.1	85.3	86.1	5.949	-4.966
8	0.069	0.2793	38.2	85.7	86.3	6.346	-4.921
9	0.069	0.2786	39.9	86.9	88.1	7.034	-4.575
10	0.069	0.2804	40.5	87.5	88.4	6.517	-4.532
11	0.070	0.2821	41.9	88.3	89.6	6.734	-4.312
12	0.070	0.2821	42.2	89.8	89.9	6.157	-4.252
13	0.069	0.2806	43.4	90.6	91.3	7.279	-3.992
14	0.069	0.2794	43.9	91.4	92.0	6.253	-3.861
15	0.068	0.2749	44.8	93.5	93.7	6.009	-3.534
16	0.067	0.2708	46.0	95.3	95.7	7.319	-3.166
17	0.065	0.2632	46.7	96.6	97.8	9.165	-2.770
18	0.064	0.2583	46.9	98.9	98.9	9.360	-2.558
19	0.063	0.2566	48.0	100.1	100.3	10.417	-2.290
20	0.064	0.2572	48.4	100.9	100.7	14.544	-2.221
21	0.063	0.2566	49.5	101.7	101.8	16.380	-2.004
22	0.063	0.2560	50.1	102.0	102.6	16.536	-1.866
23	0.063	0.2556	50.5	102.6	103.0	20.042	-1.777
24	0.063	0.2539	50.9	102.9	103.8	22.610	-1.627
25	0.062	0.2501	51.2	103.4	104.9	24.527	-1.427
26	0.059	0.2385	51.6	105.8	108.0	37.548	-0.850

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 22.0 mm ID = 13.1 mm
 VOLTAGE = 14.7 volts HEAT FLUX = 77.4 W/cm**2
 HEATER ELEMENT = 48 cm

Table G.13 Recorded Void Growth : Experiment No. 13.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.067	0.2693	26.6	90.0	90.3	7.056	-4.176
2	0.067	0.2694	27.2	91.6	90.8	6.321	-4.069
3	0.066	0.2675	26.9	92.6	91.0	7.694	-4.038
4	0.066	0.2669	27.3	93.1	91.6	7.966	-3.936
5	0.066	0.2664	27.1	93.7	91.4	7.388	-3.960
6	0.066	0.2660	28.1	94.5	92.5	5.899	-3.752
7	0.066	0.2650	28.4	94.7	93.1	8.359	-3.646
8	0.065	0.2641	29.4	95.6	94.3	7.011	-3.413
9	0.065	0.2612	29.8	96.9	95.5	9.444	-3.200
10	0.064	0.2584	30.5	98.0	96.9	9.155	-2.936
11	0.064	0.2483	31.4	101.3	100.4	17.366	-2.267
12	0.059	0.2399	32.6	103.8	104.0	26.344	-1.593
13	0.058	0.2330	33.3	106.6	106.8	32.820	-1.068

TEST PARAMETERS :

PRESSURE = 22.5 psia OD= 22.0 mm ID = 13.1 mm
 VOLTAGE = 16.5 volts HEAT FLUX = 97.5 W/cm**2
 HEATER ELEMENT = 48 cm

Table G.14 Recorded Void Growth : Experiment No. 14.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.084	0.3381	30.3	80.9	81.0	5.115	-5.918
2	0.084	0.3382	32.3	81.5	83.0	3.706	-5.540
3	0.084	0.3376	32.1	81.8	82.9	4.437	-5.565
4	0.084	0.3377	31.7	82.7	82.5	3.041	-5.645
5	0.083	0.3373	32.7	83.2	83.5	3.638	-5.454
6	0.084	0.3382	33.6	84.6	84.3	4.466	-5.302
7	0.084	0.3380	34.9	85.2	85.6	4.158	-5.052
8	0.084	0.3381	35.2	86.3	85.9	4.735	-4.998
9	0.083	0.3372	36.6	87.0	87.5	3.902	-4.706
10	0.083	0.3373	37.2	88.0	88.0	6.287	-4.599
11	0.083	0.3367	38.1	88.8	89.0	3.985	-4.414
12	0.083	0.3367	38.3	89.8	89.2	5.085	-4.386
13	0.083	0.3364	39.3	90.8	90.3	4.826	-4.173
14	0.083	0.3365	40.2	91.7	91.1	4.959	-4.015
15	0.083	0.3362	41.2	92.7	92.2	6.087	-3.819
16	0.083	0.3355	41.6	93.8	92.7	8.521	-3.717
17	0.081	0.3279	42.8	95.5	95.1	18.088	-3.267
13	0.081	0.3275	44.4	97.0	96.7	19.341	-2.970
18	0.079	0.3213	45.4	98.3	98.7	29.554	-2.589
19	0.079	0.3175	45.4	98.3	98.7	31.892	-2.469

TEST PARAMETERS :

PRESSURE = 22.5 psia OD= 22.0 mm ID = 13.1 mm
 VOLTAGE = 16.5 volts HEAT FLUX = 97.5 W/cm**2
 HEATER ELEMENT = 48 cm

Table G.15 Recorded Void Growth : Experiment No. 15.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.084	0.3403	25.4	77.5	75.0	6.085	-7.037
2	0.084	0.3393	25.4	78.0	75.2	6.029	-7.005
3	0.084	0.3402	25.6	79.0	75.3	6.359	-6.987
4	0.083	0.3375	27.4	82.6	77.5	5.394	-6.582
5	0.084	0.3386	29.4	82.8	79.3	7.042	-6.238
6	0.083	0.3365	29.5	84.5	79.8	7.831	-6.152
7	0.083	0.3354	31.3	84.8	81.7	8.102	-5.795
8	0.083	0.3369	32.2	85.5	82.4	5.872	-5.654
9	0.083	0.3349	33.3	85.5	83.7	7.401	-5.404
10	0.083	0.3351	33.4	87.1	83.9	13.710	-5.383
11	0.082	0.3316	34.0	88.8	85.0	8.313	-5.174
12	0.082	0.3316	37.8	88.7	88.8	9.425	-4.455
13	0.081	0.3272	40.0	90.2	91.7	10.248	-3.912
14	0.079	0.3176	40.4	93.8	93.6	13.287	-3.554
15	0.077	0.3092	40.6	96.6	95.2	22.202	-3.242
16	0.076	0.3059	42.5	97.5	97.8	27.323	-2.764
17	0.075	0.3047	42.6	99.1	98.1	32.249	-2.701

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 22.0 mm ID = 13.1 mm
 VOLTAGE = 16.3 volts HEAT FLUX = 97.3 W/cm²
 HEATER ELEMENT = 48 cm

Table G.16 Recorded Void Growth : Experiment No. 16.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.082	0.3278	26.2	93.3	88.5	3.311	-4.507
2	0.084	0.3375	25.1	91.7	86.2	4.713	-4.948
3	0.085	0.3419	26.0	91.3	86.2	2.803	-4.939
4	0.085	0.3438	27.8	91.4	87.7	3.673	-4.654
5	0.085	0.3433	27.0	92.7	87.0	2.536	-4.797
6	0.085	0.3435	28.6	93.7	88.6	4.182	-4.182
7	0.085	0.3432	29.3	93.9	89.3	5.193	-4.365
8	0.085	0.3421	29.1	96.2	89.3	3.223	-4.349
9	0.085	0.3422	30.7	96.9	90.9	7.173	-4.059
10	0.084	0.3377	32.2	96.7	93.2	6.277	-3.622
11	0.083	0.3348	32.3	98.4	93.8	13.433	-3.517
12	0.082	0.3321	33.9	99.6	95.9	14.916	-3.124
13	0.082	0.3322	34.2	101.2	96.2	19.722	-3.071
14	0.081	0.3262	32.9	103.7	96.1	28.820	-3.087
15	0.074	0.3011	37.4	108.5	105.8	49.930	-1.253

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 22.0 mm ID = 13.1 mm
 VOLTAGE = 18.2 volts HEAT FLUX = 118.6 W/cm**2
 HEATER ELEMENT = 48 cm

Table G.17 Recorded Void Growth : Experiment No. 17.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.097	0.3908	25.6	84.0	78.3	5.483	-6.424
2	0.096	0.3898	25.6	82.6	78.4	5.571	-6.399
3	0.097	0.3912	25.8	82.8	78.4	8.036	-6.400
4	0.097	0.3913	26.9	83.0	79.5	9.093	-6.198
5	0.097	0.3901	28.5	85.1	81.3	5.890	-5.866
6	0.096	0.3891	30.2	86.5	83.1	6.253	-5.524
7	0.096	0.3884	31.1	88.1	84.1	7.301	-5.339
8	0.096	0.3884	31.3	88.7	84.4	6.130	-5.289
9	0.097	0.3903	33.1	88.8	85.9	9.165	-4.999
10	0.096	0.3886	34.2	88.9	87.2	6.817	-4.760
11	0.097	0.3904	35.0	89.7	87.8	9.228	-4.647
12	0.096	0.3894	35.3	90.6	88.2	8.667	-4.559
13	0.096	0.3883	37.0	92.3	90.0	8.307	-4.227
14	0.096	0.3880	37.7	93.2	90.8	10.794	-4.072
15	0.096	0.3878	38.6	93.0	91.7	11.190	-3.911
16	0.094	0.3786	38.6	95.2	93.0	16.483	-3.658
17	0.093	0.3755	40.1	96.4	94.9	22.000	-3.303
18	0.093	0.3746	40.8	96.8	95.8	24.962	-3.144
19	0.092	0.3746	40.8	97.8	97.1	31.397	-3.144

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 22.0 mm ID = 13.1 mm
 VOLTAGE = 18.2 volts HEAT FLUX = 118.6 W/cm**2
 HEATER ELEMENT = 48 cm

Table G.18 Recorded Void Growth : Experiment No. 18.

POINT	MASS	VELOCITY	T _{in}	T _{out}	T _{out} cal.	VOID	QUALITY
#	Kg/s	m/s	C	C	C	%	X _{eq} %
1	0.097	0.3906	21.9	76.6	74.7	1.724	-7.098
2	0.097	0.3912	21.8	78.1	74.5	4.949	-7.142
3	0.097	0.3923	22.8	79.5	75.4	1.900	-6.980
4	0.097	0.3924	24.6	79.5	77.2	5.948	-6.640
5	0.097	0.3907	25.5	80.2	78.3	6.350	-6.435
6	0.097	0.3925	27.6	79.2	80.1	4.877	-6.091
7	0.097	0.3907	28.8	81.6	81.6	6.463	-5.809
8	0.097	0.3907	30.9	83.8	83.7	8.440	-5.416
9	0.096	0.3892	29.1	87.1	82.1	6.669	-5.718
10	0.097	0.3902	31.4	87.8	84.2	6.885	-5.313
11	0.096	0.3898	35.1	88.4	88.0	8.444	-4.602
12	0.096	0.3875	34.7	89.5	87.9	11.553	-4.614
13	0.095	0.3848	34.5	93.6	88.1	17.066	-4.581
14	0.095	0.3845	34.4	96.3	88.0	20.541	-4.603
15	0.095	0.3859	40.2	93.8	93.6	25.151	-3.550
16	0.096	0.3867	41.7	94.9	95.0	31.769	-3.294

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 22.0 mm ID = 13.1 mm
 VOLTAGE = 18.0 volts HEAT FLUX = 118.7 W/cm**2
 HEATER ELEMENT = 48 cm

Table G.19 Recorded Void Growth : Experiment No. 19

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.112	0.4523	24.4	71.3	70.5	2.794	-7.897
2	0.112	0.4520	27.3	72.1	73.5	4.143	-7.331
3	0.112	0.4526	27.3	73.1	73.4	3.315	-7.350
4	0.112	0.4535	26.6	73.9	72.6	3.669	-7.492
5	0.112	0.4536	27.8	75.4	73.8	2.756	-7.281
6	0.112	0.4532	28.7	76.5	74.7	3.457	-7.100
7	0.112	0.4540	30.1	76.7	76.1	3.598	-6.848
8	0.112	0.4533	30.7	78.0	76.7	5.649	-6.722
9	0.112	0.4541	31.7	78.6	77.6	4.979	-6.562
10	0.112	0.4545	32.5	79.8	78.4	3.752	-6.408
11	0.112	0.4541	32.3	80.8	78.2	5.069	-6.441
12	0.112	0.4542	34.0	82.3	79.9	5.433	-6.123
13	0.112	0.4547	35.7	82.8	81.5	4.807	-5.817
14	0.112	0.4538	36.7	83.7	82.7	4.669	-5.602
15	0.113	0.4554	37.0	85.0	82.8	5.103	-5.574
16	0.112	0.4542	38.4	86.0	84.3	5.906	-5.304
17	0.112	0.4538	40.1	86.6	86.0	6.626	-4.978
18	0.112	0.4540	41.3	88.1	87.2	8.377	-4.746
19	0.112	0.4525	42.0	89.2	88.1	5.521	-4.581
14	0.110	0.4436	43.1	90.6	90.1	11.711	-4.216
15	0.109	0.4423	44.0	91.5	91.2	13.176	-4.004
16	0.106	0.4295	45.3	93.3	93.8	19.984	-3.505
17	0.101	0.4076	46.0	93.3	97.2	27.754	-2.873

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 22.0 mm ID = 13.1 mm
 VOLTAGE = 18.2 volts HEAT FLUX = 118.6 W/cm**2
 HEATER ELEMENT = 48 cm

Table G.20 Recorded Void Growth : Experiment No. 20.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.121	0.4909	30.0	70.9	71.9	2.595	-7.619
2	0.121	0.4904	30.9	71.6	72.9	3.757	-7.439
3	0.121	0.4906	31.1	73.3	73.1	3.466	-7.408
4	0.121	0.4899	31.5	76.2	73.6	2.864	-7.315
5	0.121	0.4899	31.9	76.2	74.0	1.183	-7.241
6	0.121	0.4896	33.3	77.2	75.4	3.332	-6.974
7	0.121	0.4901	35.3	77.7	77.3	3.716	-6.609
8	0.121	0.4895	35.4	78.1	77.5	2.239	-6.583
9	0.121	0.4898	36.8	80.0	78.9	2.866	-6.312
10	0.121	0.4899	38.2	80.3	80.2	2.229	-6.069
11	0.121	0.4903	39.3	82.1	81.3	2.913	-5.858
12	0.121	0.4900	40.6	82.9	82.6	4.267	-5.611
13	0.121	0.4898	41.1	84.0	83.2	5.723	-5.505
14	0.121	0.4895	42.7	85.1	84.7	3.483	-5.215
15	0.121	0.4903	44.1	85.9	86.1	3.686	-4.963
16	0.121	0.4891	44.8	87.4	86.9	7.042	-4.801
17	0.121	0.4900	45.6	88.1	87.6	4.504	-4.675
18	0.121	0.4890	45.9	89.6	88.0	7.744	-4.596
19	0.121	0.4896	47.4	90.2	89.8	6.960	-4.264
20	0.121	0.4899	49.4	91.4	91.4	8.494	-3.959
21	0.121	0.4892	49.4	92.2	91.5	8.540	-3.949
22	0.121	0.4879	50.6	94.5	92.8	7.040	-3.697
23	0.120	0.4856	51.8	94.8	94.2	11.841	-3.445
24	0.119	0.4796	53.3	94.7	96.2	20.071	-3.059
25	0.118	0.4779	52.7	96.2	95.8	26.888	-3.143
26	0.118	0.4752	54.7	96.8	98.0	36.195	-2.716

TEST PARAMETERS :

PRESSURE = 22.2 psia OD = 22.0 mm ID = 13.1 mm
 VOLTAGE = 18.2 volts HEAT FLUX = 118.6 W/cm**2
 HEATER ELEMENT = 48

Table G.21 Recorded Void Growth : Experiment No. 21.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.018	0.0734	20.1	90.2	99.8	3.706	-5.422
2	0.018	0.0735	19.6	99.9	99.2	5.739	-3.606
3	0.018	0.0716	19.7	102.2	101.3	4.401	-3.213
4	0.017	0.0687	20.1	105.9	105.2	3.684	-2.568
5	0.016	0.0661	20.8	108.1	109.2	6.694	-2.205
6	0.015	0.0621	19.4	110.9	113.5	19.250	-1.768
7	0.015	0.0616	19.4	111.2	114.3	23.254	-1.730
8	0.015	0.0611	19.5	111.6	115.3	33.250	-1.661

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 22.0 mm ID = 13.1 mm
 VOLTAGE = 11.1 volts HEAT FLUX = 27.7 W/cm**2
 HEATER ELEMENT = 60 cm

Table G.22 Recorded Void Growth : Experiment No. 22.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.023	0.0930	27.8	91.9	90.7	4.165	-4.843
2	0.023	0.0912	27.5	98.3	91.6	3.824	-3.671
3	0.022	0.0886	27.6	100.1	93.5	4.464	-3.349
4	0.021	0.0863	27.7	101.7	95.4	4.265	-3.084
5	0.022	0.0872	27.9	102.5	94.9	6.265	-2.927
6	0.022	0.0880	27.8	100.8	94.2	5.436	-3.229
7	0.021	0.0846	28.0	102.9	97.2	1.890	-2.873
8	0.023	0.0929	28.6	99.5	91.5	3.431	-3.431
9	0.023	0.0920	28.7	97.6	92.3	5.228	-3.785
10	0.023	0.0949	28.9	96.1	90.5	5.046	-4.041
11	0.023	0.0924	29.5	96.6	92.8	5.385	-3.972
12	0.023	0.0915	29.9	97.9	93.8	5.470	-3.744
13	0.023	0.0910	30.6	98.7	94.8	6.997	-3.597
14	0.022	0.0906	31.0	99.5	95.5	4.278	-3.456
15	0.022	0.0904	31.6	99.9	96.2	8.108	-3.382
16	0.022	0.0901	32.3	100.9	97.2	6.837	-3.186
17	0.022	0.0902	32.6	101.3	97.4	6.318	-3.105
18	0.023	0.0919	33.1	101.4	96.7	6.466	-3.068
19	0.024	0.0954	33.6	99.1	94.9	5.789	-3.482
20	0.024	0.0958	34.3	99.5	95.3	7.028	-3.397
21	0.023	0.0914	34.7	102.5	98.7	7.246	-2.871
22	0.022	0.0898	35.8	104.8	100.9	5.669	-2.459
23	0.022	0.0892	36.2	106.5	101.8	4.736	-2.142
24	0.022	0.0881	36.9	107.8	103.3	8.185	-1.912
25	0.022	0.0875	37.5	108.1	104.3	8.076	-1.869
26	0.021	0.0847	37.9	109.5	106.9	7.648	-1.645
27	0.021	0.0842	38.1	110.2	107.5	7.517	-1.521
28	0.021	0.0842	38.1	110.2	107.5	7.517	-1.521
29	0.020	0.0822	38.8	110.3	109.9	10.579	-1.519
30	0.021	0.0829	39.6	111.1	110.0	16.312	-1.364
31	0.020	0.0826	39.3	111.4	110.0	16.492	-1.310
32	0.020	0.0819	39.6	111.0	111.0	17.449	-1.395
33	0.020	0.0828	39.9	110.7	110.5	23.912	-1.441
34	0.020	0.0805	39.7	111.0	112.3	36.941	-1.408

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 22.0 mm ID = 13.1 mm
 VOLTAGE = 11.1 volts HEAT FLUX = 27.7 W/cm**2
 HEATER ELEMENT = 60 cm

Table G.23 Recorded Void Growth : Experiment No. 23.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.045	0.1818	24.2	89.6	93.9	2.183	-5.387
2	0.045	0.1800	24.6	96.5	94.9	1.698	-4.095
3	0.044	0.1782	24.6	97.6	95.7	3.711	-3.898
4	0.044	0.1767	24.6	97.7	96.3	5.812	-3.891
5	0.043	0.1755	25.6	99.0	97.7	5.441	-3.659
6	0.043	0.1742	25.6	99.7	98.3	4.073	-3.547
7	0.042	0.1712	25.7	101.1	99.7	3.576	-3.297
8	0.042	0.1693	26.2	104.2	101.0	6.121	-2.716
9	0.041	0.1674	26.6	104.0	102.3	5.789	-2.770
10	0.041	0.1672	26.6	104.8	102.3	6.356	-2.624
11	0.041	0.1655	26.6	106.4	103.1	5.727	-2.336
12	0.041	0.1654	26.7	104.4	103.3	8.385	-2.723
13	0.041	0.1650	27.0	106.0	103.7	5.942	-2.425
14	0.041	0.1649	27.4	106.4	104.3	8.378	-2.351
15	0.041	0.1660	28.1	106.8	104.4	7.442	-2.259
16	0.040	0.1623	30.5	107.4	108.6	10.955	-2.179
17	0.041	0.1639	30.5	108.3	107.7	12.740	-1.988
18	0.040	0.1631	29.6	110.3	107.3	12.417	-1.627
19	0.040	0.1619	29.4	109.3	107.6	19.219	-1.824
20	0.039	0.1588	30.1	109.9	109.9	26.107	-1.739
21	0.040	0.1617	29.9	109.4	108.3	27.504	-1.796

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 22.0 mm ID = 13.1 mm

VOLTAGE = 16.0 volts HEAT FLUX = 60.1 W/cm**2

HEATER ELEMENT = 60 cm

Table G.24 Recorded Void Growth : Experiment No. 24.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.057	0.2296	26.1	91.2	81.1	4.964	-4.854
2	0.056	0.2268	25.9	93.1	81.6	4.926	-4.512
3	0.055	0.2234	25.5	94.3	82.0	4.972	-4.307
4	0.054	0.2197	26.4	95.7	83.9	2.370	-4.057
5	0.053	0.2152	26.3	97.5	85.0	7.468	-3.727
6	0.052	0.2098	27.0	99.2	87.3	5.836	-3.443
7	0.051	0.2078	28.1	99.9	88.9	7.834	-3.319
8	0.051	0.2064	28.0	101.2	89.2	6.375	-3.068
9	0.050	0.2039	28.3	102.5	90.2	10.287	-2.841
10	0.050	0.2029	28.9	103.8	91.2	12.128	-2.595
11	0.050	0.2018	29.7	104.8	92.3	12.031	-2.426
12	0.050	0.2038	29.2	105.7	91.1	10.275	-2.252
13	0.050	0.2033	31.2	106.3	93.4	8.285	-2.128
14	0.050	0.2026	30.3	106.9	92.7	13.898	-2.021
15	0.049	0.1994	30.1	102.7	93.4	9.122	-2.828
16	0.049	0.1969	30.7	105.6	94.8	11.234	-2.290
17	0.050	0.2040	31.8	106.2	93.8	11.667	-2.155
18	0.054	0.2164	31.1	106.7	89.5	14.655	-1.991
19	0.054	0.2163	32.4	106.2	90.8	16.674	-1.991
20	0.049	0.1998	32.4	107.1	95.6	20.978	-2.007
21	0.049	0.1980	31.3	106.7	95.1	20.895	-2.078
22	0.048	0.1955	31.7	107.3	96.3	28.091	-1.987
23	0.048	0.1933	33.3	106.1	98.6	34.303	-2.217
24	0.048	0.1943	31.8	107.2	96.8	34.815	-2.016

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 22.0 mm ID = 13.1 mm
 VOLTAGE = 16.4 volts HEAT FLUX = 60.0 W/cm**2
 HEATER ELEMENT = 60 cm

Table G.25 Recorded Void Growth : Experiment No. 25.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.064	0.2570	30.3	83.2	79.6	4.694	-6.276
2	0.064	0.2576	29.3	84.8	78.5	3.111	-5.977
3	0.064	0.2581	30.6	83.8	79.6	6.670	-6.162
4	0.064	0.2578	30.9	84.8	80.0	5.441	-5.963
5	0.063	0.2566	31.2	86.7	80.6	3.925	-5.615
6	0.063	0.2547	34.7	85.7	84.4	3.653	-5.812
7	0.062	0.2522	34.9	87.4	85.2	7.555	-5.502
8	0.061	0.2483	35.1	89.1	86.1	7.209	-5.185
9	0.058	0.2352	35.9	92.3	89.8	4.449	-4.627
10	0.058	0.2327	38.0	93.7	92.5	9.244	-4.384
11	0.058	0.2345	37.2	93.7	91.2	8.369	-4.369
12	0.058	0.2326	40.0	94.7	94.5	4.785	-4.193
13	0.057	0.2310	38.9	96.4	93.7	6.248	-3.878
14	0.057	0.2300	40.0	97.3	95.1	8.382	-3.705
15	0.056	0.2256	41.1	98.6	97.2	8.357	-3.487
16	0.056	0.2255	41.9	100.1	98.1	6.992	-3.201
17	0.056	0.2258	41.8	100.4	97.9	11.459	-3.152
18	0.056	0.2260	42.1	100.6	98.1	7.181	-3.112
19	0.056	0.2248	42.4	100.6	98.8	7.798	-3.118
20	0.056	0.2244	43.2	100.9	99.7	7.268	-3.052
21	0.055	0.2235	43.0	101.5	99.7	10.769	-2.954
22	0.056	0.2257	42.8	100.8	99.0	9.282	-3.079
23	0.056	0.2256	42.9	101.1	99.1	8.334	-3.015
24	0.055	0.2225	42.0	102.0	98.9	10.420	-2.863
25	0.055	0.2213	44.5	102.2	101.7	9.999	-2.821
26	0.054	0.2202	44.9	102.9	102.4	7.764	-2.699
27	0.055	0.2207	43.7	104.3	101.0	11.819	-2.442
28	0.055	0.2208	44.3	104.7	101.7	16.458	-2.363
29	0.055	0.2225	46.3	104.7	103.3	12.933	-2.354
30	0.058	0.2361	46.0	105.8	99.6	19.192	-2.089
31	0.060	0.2418	46.0	107.5	98.4	24.029	-1.760

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 22.0 mm ID = 13.1 mm
 VOLTAGE = 16.0 volts HEAT FLUX = 60.1 W/cm**2
 HEATER ELEMENT = 60 cm

Table G.26 Recorded Void Growth : Experiment No. 26.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID	QUALITY X _{eq} %
1	0.062	0.2489	7.5	77.3	70.0	6.828	-7.586
2	0.061	0.2457	11.6	78.3	74.9	4.849	-7.412
3	0.061	0.2464	8.2	77.3	71.3	6.332	-7.598
4	0.060	0.2438	9.5	78.6	73.3	4.399	-7.364
5	0.059	0.2398	10.3	80.7	75.2	6.010	-6.993
6	0.058	0.2338	12.5	83.0	79.1	2.793	-6.572
7	0.058	0.2336	12.8	85.6	79.4	7.059	-6.091
8	0.057	0.2317	14.9	89.5	82.1	5.544	-5.598
9	0.057	0.2292	15.8	91.5	83.7	5.509	-4.996
10	0.056	0.2263	16.6	93.8	85.3	5.625	-4.582
11	0.055	0.2239	16.9	95.5	86.3	6.779	-4.271
12	0.055	0.2209	16.8	97.1	87.2	8.833	-3.985
13	0.053	0.2147	18.5	99.0	90.9	8.994	-3.662
14	0.052	0.2120	18.6	101.2	92.0	8.399	-3.275
15	0.052	0.2116	19.3	101.7	92.9	8.423	-3.184
16	0.052	0.2109	19.7	101.8	93.5	14.103	-3.155
17	0.052	0.2106	20.0	103.4	93.9	13.370	-2.859
18	0.053	0.2127	21.6	103.5	94.8	11.928	-2.835
19	0.053	0.2134	21.3	103.2	94.2	11.178	-2.878
20	0.053	0.2128	22.0	104.0	95.1	17.329	-2.743
21	0.054	0.2170	22.5	104.8	94.2	17.509	-2.555
22	0.054	0.2179	24.0	106.1	95.4	18.552	-2.319
23	0.057	0.2315	25.1	107.1	92.3	22.137	-2.059
24	0.058	0.2333	24.9	106.6	91.6	26.959	-2.139
25	0.056	0.2271	25.8	107.0	94.3	27.891	-2.093
26	0.051	0.2066	26.1	109.4	101.4	41.305	-1.763
25	0.050	0.2027	26.3	108.6	103.1	38.832	-1.921

TEST PARAMETERS :

PRESSURE = 22.5 psia OD= 22.0 mm ID = 13.1 mm
 VOLTAGE = 18.2 volts HEAT FLUX = 73.9 W/cm**2
 HEATER ELEMENT = 60 cm

Table G.27 Recorded Void Growth : Experiment No. 27.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.089	0.3584	28.1	78.8	71.4	4.961	-6.999
2	0.083	0.3374	28.6	79.3	74.7	3.708	-6.962
3	0.090	0.2624	29.4	80.3	72.3	2.344	-6.716
4	0.089	0.3614	30.1	80.0	73.2	6.068	-6.777
5	0.090	0.3621	32.2	80.0	75.1	3.827	-6.769
6	0.090	0.3619	31.4	82.4	74.4	4.919	-6.331
7	0.090	0.3624	32.9	81.5	75.9	6.899	-6.492
8	0.090	0.3623	34.1	81.8	77.0	5.741	-6.440
9	0.090	0.3621	34.9	82.4	77.9	6.197	-6.318
10	0.089	0.3618	34.0	83.3	77.1	7.582	-6.152
11	0.089	0.3617	36.2	84.1	79.2	9.378	-6.005
12	0.090	0.3625	37.2	84.3	80.1	6.504	-5.973
13	0.090	0.3618	36.6	84.4	79.6	7.594	-5.583
14	0.089	0.3617	38.0	86.9	81.0	8.537	-5.487
15	0.090	0.3619	39.0	88.1	82.0	9.557	-5.257
16	0.088	0.3573	40.3	89.3	83.9	12.689	-5.030
17	0.089	0.3588	41.3	89.2	84.7	14.721	-5.060
18	0.088	0.3568	40.9	90.6	84.5	20.158	-4.795
19	0.089	0.3579	43.0	91.9	86.5	22.409	-4.553
20	0.088	0.3559	43.1	91.8	86.8	22.362	-4.570
21	0.087	0.3514	45.1	93.2	89.3	28.479	-4.316
22	0.083	0.3353	44.9	95.6	91.3	43.775	-3.907
23	0.082	0.3327	44.1	97.3	90.9	43.442	-3.578

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 22.0 mm ID = 13.1 mm
 VOLTAGE = 18.2 volts HEAT FLUX = 73.9 W/cm**2
 HEATER ELEMENT = 60 cm

Table G.28 Recorded Void Growth : Experiment No. 28.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.067	0.2724	29.7	94.5	88.6	7.590	-4.303
2	0.067	0.2721	30.6	96.4	89.5	4.714	-3.944
3	0.067	0.2725	31.6	94.9	90.4	6.723	-4.227
4	0.067	0.2709	31.9	96.8	91.1	3.093	-3.864
5	0.066	0.2675	35.0	95.5	94.9	5.131	-4.133
6	0.066	0.2644	33.7	96.5	94.3	7.147	-3.951
7	0.065	0.2613	35.5	98.2	96.9	5.221	-3.635
8	0.064	0.2582	35.0	99.7	97.1	10.359	-3.380
9	0.064	0.2569	36.8	99.8	99.2	5.901	-3.362
10	0.063	0.2557	35.5	101.4	98.2	6.398	-3.061
11	0.063	0.2554	36.0	101.3	98.8	8.168	-3.076
12	0.063	0.2560	37.1	100.7	99.8	12.464	-3.186
13	0.064	0.2577	37.0	101.3	99.3	10.407	-3.071
14	0.064	0.2574	38.3	101.3	100.6	11.866	-3.071
15	0.064	0.2567	38.1	102.0	100.6	15.380	-2.945
16	0.063	0.2548	37.5	104.2	100.4	17.942	-2.544
17	0.063	0.2547	38.7	103.9	101.6	15.646	-2.603
18	0.063	0.2542	39.4	104.7	102.5	22.348	-2.444
19	0.063	0.2544	38.9	104.7	101.9	22.429	-2.452
20	0.064	0.2567	39.0	104.0	101.4	17.432	-2.575
21	0.063	0.2555	38.7	104.7	101.5	20.507	-2.447
22	0.063	0.2556	39.5	104.9	102.3	24.467	-2.404
23	0.064	0.2569	39.6	105.6	102.0	25.462	-2.263
24	0.063	0.2566	40.9	105.5	103.4	27.419	-2.294
25	0.064	0.2592	41.4	106.9	103.4	26.720	-2.022

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 22.0 mm ID = 13.1 mm
 VOLTAGE = 14.4 volts HEAT FLUX = 74.2 W/cm**2
 HEATER ELEMENT = 60 cm

Table 29 Recorded Void Growth : Experiment No. 29.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.090	0.3653	30.9	80.2	75.8	4.849	-5.761
2	0.090	0.3644	31.9	81.2	76.9	6.635	-6.579
3	0.090	0.3645	33.0	81.4	78.0	3.608	-6.542
4	0.090	0.3656	34.5	80.0	79.3	4.425	-6.807
5	0.090	0.3656	33.0	81.8	77.8	5.152	-6.459
6	0.090	0.3651	34.5	83.0	79.4	4.981	-6.238
7	0.090	0.3653	35.4	83.1	80.3	3.217	-6.232
8	0.090	0.3656	36.3	82.8	81.2	3.714	-6.284
9	0.090	0.3653	35.6	84.5	85.5	4.228	-5.954
10	0.091	0.3661	37.0	83.7	81.8	4.872	-6.111
11	0.090	0.3653	38.7	83.8	83.6	2.950	-6.094
12	0.090	0.3647	38.2	85.5	83.2	5.515	-5.773
13	0.090	0.3648	38.9	86.2	83.9	5.912	-5.644
14	0.090	0.3656	40.3	86.9	85.1	5.393	-5.506
15	0.090	0.3656	41.8	87.6	91.6	3.152	-5.385
16	0.090	0.3657	40.8	88.1	85.6	6.821	-5.278
17	0.090	0.3657	41.8	88.4	86.6	6.929	-5.229
18	0.090	0.3648	41.9	89.4	86.9	8.572	-5.039
19	0.090	0.3648	43.8	90.6	88.8	5.550	-4.822
20	0.090	0.3653	44.3	90.8	89.2	7.716	-4.778
21	0.090	0.3636	45.2	92.5	90.3	6.964	-4.451
22	0.090	0.3636	46.2	92.3	91.3	7.475	-4.489
23	0.090	0.3642	45.6	93.7	90.6	6.571	-4.240
24	0.090	0.3641	47.2	93.9	92.2	12.852	-4.196
25	0.090	0.3632	48.2	94.7	93.3	15.156	-4.046
26	0.090	0.3619	49.6	95.6	94.9	18.069	-3.881
27	0.089	0.3616	49.1	96.6	94.4	21.475	-3.695
28	0.089	0.3615	49.3	97.0	94.7	21.713	-3.613
29	0.089	0.3600	50.1	98.7	95.6	32.657	-3.309

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 22.0 mm ID = 13.1 mm
 VOLTAGE = 18.2 volts HEAT FLUX = 77.8 W/cm**2
 HEATER ELEMENT = 60 cm

Table G.30 Recorded Void Growth : Experiment No. 30.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.016	0.0448	23.4	80.4	100.5	4.958	-7.232
2	0.016	0.0449	23.4	98.7	100.2	5.356	-3.786
3	0.016	0.0448	23.4	100.5	100.6	5.688	-3.458
4	0.016	0.0446	23.6	102.3	101.0	4.846	-3.114
5	0.016	0.0443	23.4	102.2	101.3	3.825	-3.156
6	0.016	0.0442	23.5	102.6	101.6	5.587	-3.083
7	0.016	0.0442	23.5	103.6	101.7	4.117	-2.884
8	0.016	0.0439	23.5	103.7	102.3	5.602	-2.887
9	0.016	0.0438	23.3	104.1	102.3	3.833	-2.806
10	0.015	0.0413	23.4	105.3	107.1	5.189	-2.651
11	0.014	0.0386	23.9	113.1	113.5	14.403	-1.291
12	0.014	0.0392	24.1	113.5	112.2	28.493	-1.178
13	0.014	0.0390	24.4	114.0	113.1	35.099	-1.091
14	0.014	0.0400	24.1	113.5	110.5	40.272	-1.166

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 25.0 mm ID = 13.1 mm
 VOLTAGE = 9.1 volts HEAT FLUX = 29.7 W/cm**2
 HEATER LENGTH = 48 cm

Table G.31 : Recorded Void Growth : Experiment No. 31

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.022	0.0609	26.7	85.5	83.5	4.871	-5.949
2	0.022	0.0608	27.5	86.3	84.3	4.747	-5.814
3	0.022	0.0602	28.3	86.8	85.7	4.994	-5.720
4	0.021	0.0595	28.3	87.7	86.3	6.082	-5.555
5	0.021	0.0587	29.0	89.2	87.8	4.565	-5.293
6	0.021	0.0579	29.8	91.2	89.5	4.939	-4.935
7	0.020	0.0570	29.9	91.5	90.5	4.664	-4.880
8	0.020	0.0554	30.4	93.6	92.8	6.709	-4.522
9	0.019	0.0526	31.2	96.7	96.9	4.258	-3.997
10	0.018	0.0503	31.5	100.5	100.2	6.143	-3.318
11	0.017	0.0484	32.2	103.7	103.7	7.417	-2.758
12	0.019	0.0529	32.6	104.2	98.0	5.350	-2.350
13	0.021	0.0579	32.9	96.0	92.6	4.794	-4.031
14	0.019	0.0540	33.2	96.2	97.2	5.441	-4.050
15	0.018	0.0505	33.8	100.5	102.1	6.912	-3.320
16	0.017	0.0476	34.4	107.6	107.0	11.084	-2.059
17	0.017	0.0487	34.3	108.6	105.3	15.410	-1.843
18	0.017	0.0487	34.2	109.0	105.2	14.332	-1.758
19	0.017	0.0487	34.7	109.6	105.7	17.778	-1.653
20	0.017	0.0481	34.1	109.1	105.9	20.018	-1.766
21	0.018	0.0492	35.0	109.8	105.1	34.794	-1.602

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 25.0 mm ID = 13.1 mm

VOLTAGE = 9.1 volts HEAT FLUX = 29.7 W/cm**2

HEATER LENGTH = 48 cm

Table G.32 : Recorded Void Growth : Experiment No. 32

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.027	0.0762	44.6	93.3	90.0	3.628	-4.306
2	0.028	0.0778	44.9	90.0	94.2	5.045	-4.915
3	0.028	0.0769	45.8	90.3	90.7	4.841	-4.864
4	0.027	0.0756	46.6	91.8	97.3	4.254	-4.593
5	0.027	0.0743	46.7	92.8	93.2	6.360	-4.424
6	0.026	0.0730	47.2	94.3	94.6	5.668	-4.149
7	0.026	0.0725	48.0	96.7	95.6	4.795	-3.717
8	0.026	0.0722	48.2	96.9	96.0	5.308	-3.676
9	0.027	0.0765	49.0	95.5	94.1	5.473	-3.895
10	0.027	0.0761	48.8	94.5	94.2	6.163	-4.091
11	0.027	0.0749	49.3	95.8	95.5	6.081	-3.857
12	0.026	0.0728	52.1	99.5	99.6	6.483	-3.189
13	0.025	0.0712	52.5	100.7	101.0	5.953	-2.980
14	0.024	0.0682	52.9	103.0	103.6	7.266	-2.568
11	0.023	0.0648	53.0	105.5	106.3	7.551	-2.138
12	0.021	0.0599	52.8	110.5	110.5	18.634	-1.283
13	0.021	0.0580	52.7	100.9	112.2	33.174	-1.235

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 25.0 mm ID = 13.1 mm
 VOLTAGE = 9.1 volts HEAT FLUX = 29.7 W/cm**2
 HEATER LENGTH = 48 cm

Table G.33 Recorded Void Growth : Experiment No. 33.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.049	0.1369	45.2	95.7	96.7	4.971	-3.954
2	0.049	0.1365	45.9	96.7	97.5	4.575	-3.775
3	0.049	0.1357	46.4	97.1	98.4	2.833	-3.708
4	0.048	0.1354	46.7	97.3	98.8	5.885	-3.666
5	0.049	0.1358	46.6	98.0	98.5	4.767	-3.526
6	0.048	0.1354	46.7	98.6	98.8	5.333	-3.416
7	0.048	0.1353	46.9	98.8	99.0	5.702	-3.382
8	0.048	0.1349	47.6	100.1	99.8	6.797	-3.139
9	0.048	0.1352	47.6	100.6	99.8	5.526	-3.044
10	0.048	0.1350	47.9	100.6	100.1	5.162	-3.059
11	0.048	0.1347	47.7	100.2	100.1	6.896	-3.119
12	0.048	0.1350	48.2	101.2	100.4	4.823	-2.946
13	0.048	0.1332	48.1	101.7	101.0	5.598	-2.858
14	0.048	0.1335	48.2	101.5	101.0	5.440	-2.889
15	0.048	0.1334	48.3	101.4	101.2	5.011	-2.902
16	0.048	0.1335	48.6	101.6	101.4	5.321	-2.872
17	0.048	0.1336	49.0	102.8	101.8	7.125	-2.644
13	0.048	0.1336	48.7	101.5	101.4	7.415	-2.882
18	0.048	0.1329	49.4	102.6	102.4	5.513	-2.688
19	0.048	0.1327	48.9	103.4	102.1	6.512	-2.528
20	0.047	0.1314	49.7	104.7	103.3	8.688	-2.306
21	0.047	0.1314	50.2	105.3	103.9	8.151	-2.188
22	0.047	0.1316	50.3	106.4	103.9	7.594	-1.987
23	0.044	0.1236	50.6	107.3	107.7	11.803	-1.864
24	0.044	0.1242	51.0	107.7	107.8	10.673	-1.796
25	0.045	0.1251	50.8	107.1	107.2	11.322	-1.893
26	0.045	0.1250	51.7	108.3	108.1	11.129	-1.667
29	0.045	0.1267	51.0	107.8	106.7	10.963	-1.745
30	0.046	0.1283	51.0	107.7	106.0	11.124	-1.761

Experiment No.33 Continued

31	0.046	0.1282	51.3	108.7	106.4	12.025	-1.566
32	0.046	0.1283	51.4	107.6	106.4	10.992	-1.769
33	0.046	0.1285	51.1	108.2	106.0	12.109	-1.666
34	0.046	0.1273	51.8	107.7	107.2	10.697	-1.760
35	0.046	0.1283	52.3	108.3	107.2	11.625	-1.644
36	0.046	0.1278	52.2	108.1	107.4	10.923	-1.682
37	0.046	0.1283	52.0	108.3	107.0	11.991	-1.651
38	0.046	0.1286	51.9	108.2	106.8	11.653	-1.666
39	0.046	0.1287	52.4	108.8	107.2	14.795	-1.549
40	0.046	0.1294	52.8	109.1	107.3	15.648	-1.492
41	0.046	0.1291	52.9	108.8	107.6	16.211	-1.551
42	0.047	0.1299	52.6	108.8	106.9	18.467	-1.547
43	0.046	0.1297	53.4	109.0	107.8	18.703	-1.509
44	0.046	0.1296	54.3	110.3	108.7	22.049	-1.254
45	0.046	0.1287	54.2	109.8	108.9	25.394	-1.356
46	0.046	0.1297	55.2	109.9	109.5	21.157	-1.329
47	0.046	0.1294	54.9	109.0	109.4	27.647	-1.506
48	0.046	0.1294	55.7	109.0	110.2	27.547	-1.506
49	0.046	0.1286	56.3	109.0	111.1	31.355	-1.505

TEST PARAMETERS :

PRESSURE = 22.5 psia OD= 25.0 mm ID = 13.1 mm
VOLTAGE = 13.0 volts HEAT FLUX = 60.6 W/cm**2
HEATER LENGTH = 48 cm

Table G.34 Recorded Void Growth : Experiment No. 34.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.061	0.1715	61.2	102.9	102.3	7.194	-2.437
2	0.061	0.1689	61.9	104.6	103.7	6.313	-2.133
3	0.060	0.1673	62.1	104.3	104.3	7.232	-2.047
4	0.059	0.1658	62.3	105.8	104.8	6.198	-1.927
5	0.057	0.1597	62.7	107.3	106.8	8.385	-1.664
6	0.057	0.1593	62.3	107.0	106.6	8.816	-1.719
7	0.057	0.1594	62.8	106.4	107.0	7.840	-1.836
8	0.057	0.1591	63.1	106.7	107.4	8.207	-1.773
9	0.057	0.1589	62.7	106.3	107.1	7.392	-1.857
10	0.057	0.1583	62.8	107.0	107.3	8.304	-1.731
11	0.056	0.1576	63.2	107.4	108.0	7.967	-1.662
12	0.056	0.1574	63.2	107.2	108.0	10.746	-1.686
13	0.057	0.1579	63.6	108.2	108.3	8.936	-1.511
14	0.055	0.1525	64.2	108.7	110.4	12.107	-1.428
15	0.053	0.1490	64.8	110.8	112.1	18.070	-1.064
16	0.053	0.1494	64.7	110.9	111.9	22.522	-1.028
17	0.053	0.1493	64.8	110.7	112.0	25.597	-1.076
18	0.053	0.1488	65.5	110.5	112.8	29.353	-1.119
19	0.053	0.1494	65.6	110.7	112.8	29.621	-1.079

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 25.0 mm ID = 13.1 mm
 VOLTAGE = 13.0 volts HEAT FLUX = 60.6 W/cm**2
 HEATER LENGTH = 48 cm

Table G.35 Recorded Void Growth : Experiment No. 35.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.037	0.1045	18.5	100.5	104.9	1.813	-3.608
2	0.036	0.1019	18.5	101.9	107.0	3.211	-3.367
3	0.037	0.1023	19.3	102.8	107.5	2.932	-3.198
4	0.037	0.1027	19.5	102.9	107.3	3.869	-3.168
5	0.036	0.1017	19.8	103.1	108.4	4.187	-3.145
6	0.035	0.0991	21.3	106.5	112.4	5.028	-2.551
7	0.035	0.0986	21.2	107.2	112.7	4.938	-2.394
8	0.035	0.0976	21.6	108.2	114.0	5.807	-2.243
9	0.035	0.0977	21.7	110.0	113.9	6.873	-1.897
10	0.036	0.0993	23.0	111.8	113.8	6.505	-1.540
11	0.035	0.0975	23.5	113.2	116.0	8.415	-1.300
12	0.035	0.0985	24.0	113.1	115.6	7.328	-1.314
13	0.035	0.0966	23.5	113.4	116.9	11.377	-1.282
14	0.034	0.0941	24.2	114.7	120.0	19.565	-1.082
15	0.034	0.0947	24.6	114.6	119.9	24.988	-1.096
16	0.033	0.0923	25.4	114.8	123.2	30.400	-1.086

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 25.0 mm ID = 13.1 mm
 VOLTAGE = 14.7 volts HEAT FLUX = 77.5 W/cm**2
 HEATER LENGTH = 48 cm

Table G.36 Recorded Void Growth : Experiment No. 36.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.058	0.1607	33.9	91.2	90.1	4.271	-4.868
2	0.057	0.1603	34.8	92.6	91.1	3.845	-4.606
3	0.057	0.1598	35.5	94.1	91.9	4.545	-4.328
4	0.057	0.1591	36.2	94.8	92.9	3.982	-4.216
5	0.056	0.1565	37.1	96.4	94.8	4.932	-3.927
6	0.056	0.1562	38.8	98.3	95.7	4.984	-3.524
7	0.056	0.1559	38.5	98.4	96.3	4.899	-3.546
8	0.056	0.1560	39.6	99.6	97.5	5.569	-3.325
9	0.055	0.1542	40.2	100.9	98.7	6.774	-3.092
10	0.055	0.1548	40.6	101.6	98.8	5.431	-2.955
11	0.055	0.1540	41.9	101.9	100.5	6.674	-2.907
12	0.055	0.1533	42.9	102.7	101.7	6.997	-2.749
13	0.055	0.1531	43.5	104.3	102.4	7.972	-2.463
14	0.054	0.1516	44.4	104.6	103.9	8.549	-2.412
15	0.054	0.1511	44.9	105.6	104.6	9.546	-2.232
16	0.059	0.1656	45.5	106.6	99.9	9.504	-1.961
17	0.057	0.1595	46.2	107.3	102.7	13.225	-1.853
18	0.054	0.1499	45.8	108.5	106.0	19.228	-1.681
19	0.054	0.1516	47.3	109.0	106.7	20.227	-1.593
20	0.054	0.1519	47.4	108.4	106.7	24.639	-1.698
21	0.054	0.1507	47.9	108.8	107.7	26.906	-1.626
22	0.055	0.1523	48.8	109.0	108.0	29.189	-1.579

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 25.0 mm ID = 13.1 mm
 VOLTAGE = 14.7 volts HEAT FLUX = 77.5 W/cm**2
 HEATER LENGTH = 48 cm

Table G.37 Recorded Void Growth : Experiment No. 37.

POINT	MASS	VELOCITY	T _{in}	T _{out}	T _{out} cal.	VOID	QUALITY
#	Kg/s	m/s	C	C	C	%	X _{eq} %
1	0.061	0.1695	22.2	91.7	89.1	2.223	-4.956
2	0.060	0.1685	22.0	93.3	89.4	2.574	-4.663
3	0.059	0.1641	22.2	94.6	91.4	2.856	-4.445
4	0.058	0.1631	23.5	96.5	93.2	3.158	-4.089
5	0.058	0.1621	24.2	97.7	94.2	4.422	-3.879
6	0.057	0.1600	24.1	98.9	95.1	4.729	-3.665
7	0.057	0.1590	24.3	99.8	95.8	6.077	-3.505
8	0.057	0.1583	24.9	100.0	96.0	4.094	-3.468
9	0.057	0.1595	24.8	100.3	96.0	5.893	-3.406
10	0.057	0.1591	24.7	100.8	96.1	7.414	-3.320
11	0.057	0.1582	25.6	102.6	97.4	7.039	-2.979
12	0.057	0.1583	25.6	101.8	97.4	8.303	-3.137
13	0.056	0.1576	26.0	100.6	98.1	8.516	-3.360
14	0.056	0.1569	27.7	102.6	100.1	9.816	-2.980
15	0.058	0.1630	27.6	103.3	105.0	9.986	-2.816
16	0.060	0.1664	29.6	105.7	97.8	13.165	-2.346
17	0.057	0.1605	29.6	106.1	100.4	14.690	-2.307
18	0.056	0.1567	29.3	106.6	101.8	18.819	-2.232
19	0.055	0.1541	30.5	106.0	104.2	28.900	-2.364
20	0.055	0.1528	30.8	106.2	105.1	30.526	-2.346

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 25.0 mm ID = 13.1 mm
 VOLTAGE = 16.5 volts HEAT FLUX = 97.6 W/cm**2
 HEATER LENGTH = 48 cm

Table G.38 Recorded Void Growth : Experiment No. 38.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal: C	VOID %	QUALITY X _{eq} %
1	0.082	0.2290	34.0	85.5	83.7	3.353	-5.843
2	0.081	0.2248	32.9	85.9	83.4	4.317	-5.780
3	0.080	0.2245	33.6	86.3	84.2	5.633	-5.711
4	0.080	0.2235	35.6	87.6	86.4	4.724	-5.466
5	0.080	0.2243	36.2	88.0	86.9	3.108	-5.389
6	0.080	0.2247	36.4	88.7	87.0	4.947	-5.256
7	0.076	0.2133	37.0	90.8	90.2	7.051	-4.905
8	0.073	0.2046	36.9	93.7	92.4	7.136	-4.393
9	0.073	0.2045	37.3	94.1	92.9	5.797	-4.324
10	0.073	0.2043	38.6	95.6	94.2	7.852	-4.041
11	0.073	0.2039	39.5	96.1	95.2	5.847	-3.946
12	0.073	0.2033	40.1	97.3	96.0	6.838	-3.727
13	0.071	0.1991	40.4	99.6	97.5	6.329	-3.307
14	0.070	0.1968	41.6	100.6	99.3	9.170	-3.139
15	0.070	0.1957	41.1	101.6	99.2	9.626	-2.943
16	0.070	0.1955	41.7	102.6	99.8	10.683	-2.757
17	0.069	0.1939	43.0	103.5	101.5	11.972	-2.606
18	0.069	0.1936	42.2	104.0	100.9	12.737	-2.512
19	0.069	0.1938	42.9	105.0	101.6	14.757	-2.330
14	0.069	0.1995	43.8	106.0	100.8	15.739	-2.107
15	0.071	0.1983	45.3	107.1	102.5	17.280	-1.908
16	0.070	0.1968	45.0	106.3	102.7	20.272	-2.072
17	0.068	0.1912	44.9	107.9	107.9	27.538	-1.793

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 22.0 mm ID = 13.1 mm
 VOLTAGE = 16.5 volts HEAT FLUX = 97.6 W/cm**2
 HEATER LENGTH = 48 cm

Table G.39 Recorded Void Growth : Experiment No. 39.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.078	0.2187	13.5	89.9	85.1	2.108	-5.333
2	0.070	0.1942	15.8	92.1	94.8	2.804	-4.949
3	0.070	0.1949	15.6	91.8	86.6	3.807	-4.993
4	0.070	0.1965	15.6	90.7	86.0	4.009	-5.193
5	0.070	0.1956	17.7	93.2	88.3	3.020	-3.019
6	0.070	0.1946	19.8	95.1	90.8	3.337	-4.382
7	0.070	0.1941	19.7	95.4	90.9	2.906	-4.326
8	0.070	0.1943	20.6	97.3	91.7	3.500	-3.959
9	0.070	0.1942	20.9	98.1	92.1	4.103	-3.816
10	0.069	0.1933	21.0	96.5	92.5	4.193	-4.120
11	0.068	0.1912	23.4	99.8	95.7	5.688	-3.509
12	0.068	0.1886	24.5	101.5	97.8	4.228	-3.205
13	0.067	0.1864	24.8	102.9	98.9	6.913	-2.964
14	0.067	0.1859	25.5	104.9	99.9	10.285	-2.594
15	0.066	0.1851	26.8	106.3	101.4	12.533	-2.337
16	0.067	0.1864	26.3	106.6	100.4	13.997	-2.259
17	0.068	0.1900	26.9	105.6	99.6	17.984	-2.435
18	0.069	0.1921	25.5	106.1	97.5	21.508	-2.315
19	0.068	0.1903	25.5	106.8	98.1	23.565	-2.197
20	0.066	0.1842	26.6	108.1	101.6	34.252	-1.987

TEST PARAMETERS :

PRESSURE = 22.5 psia OD= 25.0 mm ID = 13.1 mm
 VOLTAGE = 18.2 volts HEAT FLUX = 118.6 W/cm**2
 HEATER LENGTH = 48 cm

Table G.40 Recorded Void Growth : Experiment No. 40.

POINT	MASS	VELOCITY	T _{in}	T _{out}	T _{out} cal.	VOID	QUALITY
#	Kg/s	m/s	C	C	C	%	X _{eq} %
1	0.081	0.2274	26.5	87.3	94.4	4.883	-4.355
2	0.082	0.2276	27.5	95.8	88.2	4.153	-4.080
3	0.081	0.2274	27.9	96.0	88.6	4.614	-4.048
4	0.082	0.2277	30.1	95.4	90.8	5.826	-4.164
5	0.081	0.2267	31.0	96.3	92.0	5.414	-3.996
6	0.081	0.2261	32.0	95.6	93.1	5.194	-4.120
7	0.081	0.2258	31.6	96.4	92.8	6.225	-3.977
8	0.081	0.2259	32.6	97.1	93.8	7.483	-3.856
9	0.081	0.2257	34.0	98.6	95.2	8.247	-3.576
10	0.080	0.2247	33.2	97.1	94.7	11.187	-3.845
11	0.081	0.2250	35.5	99.3	96.9	10.989	-3.433
12	0.079	0.2217	36.9	102.7	99.2	13.941	-2.813
13	0.078	0.2190	37.0	102.8	100.1	18.609	-2.809
14	0.080	0.2239	37.6	102.7	99.3	20.371	-2.809
15	0.079	0.2199	39.1	104.7	102.0	27.702	-2.435

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 25.0 mm ID = 13.1 mm
 VOLTAGE = 18.2 volts HEAT FLUX = 118.7 W/cm**2
 HEATER ELEMENT = 60 cm

Table G.41 Recorded Void Growth : Experiment No. 41.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.022	0.0625	17.3	92.1	86.5	4.682	-4.918
2	0.021	0.0598	18.3	92.4	90.5	5.523	-4.904
3	0.021	0.0579	18.2	95.5	92.9	6.945	-4.356
4	0.020	0.0546	18.8	99.7	97.9	4.728	-3.636
5	0.023	0.0633	19.5	96.0	87.7	4.203	-4.155
6	0.022	0.0625	17.9	90.3	87.0	5.374	-5.246
7	0.022	0.0614	17.4	90.6	87.7	5.505	-5.207
8	0.022	0.0608	17.5	89.6	88.6	4.516	-5.416
9	0.021	0.0596	18.2	91.3	90.7	5.882	-5.112
10	0.021	0.0583	19.4	94.3	93.5	4.141	-4.572
11	0.021	0.0577	19.9	95.4	94.8	5.824	-4.375
12	0.020	0.0561	19.9	97.3	97.0	5.201	-4.058
13	0.020	0.0550	20.0	98.9	98.6	6.602	-3.775
14	0.019	0.0525	20.5	101.3	102.7	7.641	-3.388
15	0.018	0.0515	21.2	104.3	105.0	8.587	-2.848
16	0.018	0.0504	21.6	108.1	107.3	10.038	-2.160
17	0.018	0.0502	21.5	108.4	107.6	10.769	-2.109
18	0.018	0.0493	21.7	108.3	109.3	15.289	-2.146
19	0.017	0.0488	21.8	108.4	110.4	25.174	-2.149
20	0.017	0.0475	22.0	108.6	112.8	39.533	-2.150

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 25.0 mm ID = 13.1 mm
 VOLTAGE = 11.3 volts HEAT FLUX = 29.7 W/cm**2
 HEATER ELEMENT = 60 cm

Table G.42 Recorded Void Growth : Experiment No. 42.

POINT - #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.024	0.0664	22.4	86.2	87.4	6.004	-5.949
2	0.024	0.0659	22.1	86.3	87.7	6.866	-5.938
3	0.024	0.0657	23.7	88.4	89.5	5.948	-5.559
4	0.023	0.0654	24.1	89.0	90.2	5.653	-5.437
5	0.023	0.0654	24.5	90.2	90.5	5.689	-5.223
6	0.023	0.0650	24.8	90.9	91.3	7.174	-5.092
7	0.023	0.0646	25.8	92.6	92.7	6.314	-4.780
8	0.023	0.0640	25.7	93.7	93.2	6.638	-4.576
9	0.023	0.0634	26.3	95.1	94.4	7.450	-4.332
10	0.023	0.0633	27.1	95.0	95.3	7.082	-4.353
11	0.022	0.0626	27.9	95.7	96.9	6.661	-4.240
12	0.022	0.0612	27.7	96.2	98.3	8.685	-4.164
13	0.022	0.0603	28.5	98.1	100.2	7.329	-3.813
14	0.021	0.0592	29.2	100.1	102.2	8.539	-3.459
15	0.021	0.0593	29.2	100.1	102.0	8.493	-3.456
16	0.021	0.0599	29.6	101.0	101.8	10.336	-3.277
17	0.021	0.0595	29.9	101.7	102.5	9.567	-3.157
18	0.021	0.0590	30.4	102.4	103.7	8.395	-3.047
19	0.021	0.0585	30.4	102.0	104.3	10.667	-3.116
20	0.021	0.0581	31.0	102.9	105.3	12.702	-2.962
21	0.021	0.0576	30.7	102.2	105.7	14.600	-3.106
22	0.021	0.0574	31.2	102.8	106.4	13.326	-3.001
23	0.021	0.0578	31.8	103.1	106.5	12.089	-2.931
21	0.021	0.0574	31.2	102.3	106.6	14.340	-3.084
22	0.020	0.0572	31.3	102.0	106.9	14.400	-3.154
23	0.020	0.0567	31.9	102.9	108.1	16.475	-2.993
24	0.020	0.0568	31.6	102.4	107.6	19.223	-3.078
25	0.020	0.0558	31.5	102.7	109.0	24.212	-3.052
26	0.020	0.0558	31.3	102.4	109.0	29.819	-3.113

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 25.0 mm ID = 13.1 mm
 VOLTAGE = 11.3 volts HEAT FLUX = 29.7 W/cm²
 HEATER ELEMENT = 60 cm

Table G.43 Recorded Void Growth : Experiment No. 43.

POINT	MASS	VELOCITY	T _{in}	T _{out}	T _{out} cal.	VOID	QUALITY
#	Kg/s	m/s	C	C	C	%	X _{eq} %
1	0.030	0.0841	47.3	93.3	96.9	5.158	-4.384
2	0.030	0.0843	47.7	96.0	97.1	5.627	-3.868
3	0.029	0.0814	47.8	97.5	99.0	5.178	-3.623
4	0.029	0.0806	47.6	98.7	99.3	6.370	-3.391
5	0.029	0.0796	47.4	99.0	99.7	7.084	-3.349
6	0.028	0.0784	47.5	100.0	100.7	6.222	-3.178
7	0.028	0.0779	46.9	99.4	100.4	6.568	-3.294
8	0.028	0.0772	47.1	99.9	101.1	6.517	-3.216
9	0.028	0.0776	47.4	100.7	101.1	6.899	-3.048
10	0.027	0.0762	47.7	101.1	102.4	5.651	-2.986
11	0.027	0.0764	47.1	101.3	101.3	6.537	-2.964
12	0.027	0.0759	47.6	101.8	102.6	7.042	-2.862
13	0.027	0.0754	46.9	101.4	101.4	6.556	-2.953
14	0.027	0.0759	47.1	102.1	102.0	5.478	-2.810
15	0.027	0.0750	47.7	102.8	103.3	5.640	-2.687
16	0.027	0.0756	47.8	103.0	102.9	5.993	-2.636
17	0.027	0.0761	48.1	103.5	102.9	6.761	-2.552
13	0.029	0.0802	48.9	104.5	100.8	6.243	-2.304
18	0.028	0.0772	49.0	104.0	103.0	7.163	-2.436
19	0.028	0.0793	49.5	104.5	102.0	7.594	-2.321
20	0.028	0.0786	49.5	105.3	105.3	7.289	-2.175
21	0.028	0.0796	50.3	107.1	102.7	8.777	-1.838
22	0.029	0.0820	50.2	107.3	101.1	9.311	-1.769
23	0.030	0.0839	50.6	108.5	100.3	9.759	-1.526
24	0.029	0.0808	50.5	108.3	102.1	11.099	-1.601
25	0.028	0.0776	51.2	109.1	104.9	13.707	-1.473
26	0.029	0.0818	51.6	109.0	102.6	18.582	-1.456
29	0.029	0.0816	51.4	109.4	102.5	20.531	-1.374
30	0.035	0.0980	51.9	109.3	94.4	31.198	-1.261

TEST PARAMETERS:

PRESSURE = 22.5 psia OD = 25.0 mm ID = 13.1 mm
 VOLTAGE = 11.1 volts HEAT FLUX = 28.6 W/cm**2
 HEATER ELEMENT = 60 cm

• Table G.44 Recorded Void Growth : Experiment No. 44.

POINT	MASS	VELOCITY	T _{in}	T _{out}	T _{out} cal.	VOID	QUALITY
#	Kg/s	m/s	C	°C	C	%	X _{eq} %
1	0.051	0.1431	26.1	91.3	86.7	3.188	-4.925
2	0.052	0.1446	27.0	91.1	86.9	3.626	-4.959
3	0.051	0.1428	28.0	91.7	88.6	3.621	-4.861
4	0.051	0.1425	28.9	92.2	89.7	3.119	-4.766
5	0.051	0.1425	29.6	93.2	90.3	5.207	-4.575
6	0.050	0.1402	29.6	93.9	91.4	5.089	-4.453
7	0.050	0.1385	31.4	97.7	93.9	6.400	-3.746
8	0.049	0.1372	33.3	100.1	96.4	8.236	-3.320
9	0.049	0.1361	33.9	100.6	97.5	7.285	-3.234
10	0.049	0.1361	34.4	102.4	98.0	11.438	-2.894
11	0.049	0.1354	34.5	102.4	98.5	10.319	-2.898
12	0.048	0.1353	34.8	102.7	98.8	14.911	-2.830
13	0.048	0.1342	35.6	104.6	100.1	15.103	-2.482
14	0.048	0.1330	35.0	104.6	100.1	22.564	-2.503
15	0.048	0.1333	35.7	105.7	100.6	23.307	-2.284
16	0.048	0.1339	35.9	105.4	100.6	24.648	-2.336
17	0.048	0.1334	36.6	106.5	101.6	25.251	-2.137
18	0.048	0.1335	36.8	106.3	106.3	26.660	-2.177

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 25.0 mm ID = 13.1 mm
 VOLTAGE = 16.0 volts HEAT FLUX = 59.5 W/cm²
 HEATER ELEMENT = 60 cm

Table G.45 Recorded Void Growth : Experiment No. 45.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.061	0.1710	30.8	85.9	81.5	4.788	-5.791
2	0.060	0.1681	31.5	88.5	83.0	4.070	-5.304
3	0.059	0.1656	32.4	89.7	84.7	5.178	-5.101
4	0.059	0.1654	33.6	91.2	86.0	5.945	-4.815
5	0.060	0.1667	34.1	91.5	86.0	5.810	-4.762
6	0.060	0.1671	34.9	91.7	86.7	4.818	-4.717
7	0.060	0.1674	36.4	92.7	88.1	4.750	-4.529
8	0.061	0.1690	36.6	92.4	87.8	5.482	-4.579
9	0.060	0.1685	37.7	93.1	89.1	5.945	-4.455
10	0.060	0.1668	38.1	93.6	90.1	6.255	-4.360
11	0.059	0.1644	38.5	94.9	91.2	7.907	-4.131
12	0.059	0.1653	39.7	95.7	92.1	7.682	-3.967
13	0.059	0.1646	39.8	96.2	92.4	8.789	-3.874
14	0.059	0.1640	40.4	97.1	93.2	9.574	-3.718
15	0.059	0.1638	40.6	97.0	93.5	10.968	-3.743
16	0.058	0.1620	41.1	97.8	94.6	12.112	-3.591
17	0.059	0.1634	41.2	97.6	94.2	11.202	-3.626
18	0.057	0.1603	41.8	98.9	95.8	15.864	-3.394
19	0.058	0.1616	41.6	98.4	95.2	19.075	-3.491
20	0.057	0.1586	41.8	98.9	96.4	15.441	-3.411
21	0.057	0.1590	42.2	99.4	96.6	18.348	-3.361
22	0.057	0.1590	42.5	99.5	97.0	16.109	-3.298
23	0.057	0.1591	42.8	99.7	97.2	18.088	-3.260
24	0.057	0.1602	43.6	99.7	97.7	18.745	-3.244
25	0.058	0.1612	43.4	99.1	97.1	18.419	-3.354

Experiment No.45 Continued

26	0.057	0.1601	43.6	99.9	97.7	21.240	-3.207
27	0.058	0.1623	43.9	99.5	97.3	19.230	-3.283
28	0.058	0.1629	44.5	99.6	97.7	21.142	-3.250
29	0.058	0.1621	44.5	99.9	98.0	22.434	-3.200
30	0.058	0.1629	44.9	99.5	98.1	21.221	-3.280
31	0.058	0.1609	44.5	98.7	98.4	22.696	-3.430
32	0.058	0.1620	45.8	99.8	99.2	20.263	-3.215
33	0.058	0.1624	45.5	99.5	98.8	24.351	-3.264
34	0.059	0.1635	46.0	99.9	99.0	22.958	-3.202
35	0.057	0.1584	46.2	101.0	100.9	27.329	-3.006
36	0.058	0.1612	46.2	100.5	99.9	28.086	-3.090
37	0.057	0.1579	47.2	101.7	102.1	26.717	-2.889

TEST PARAMETERS :

PRESSURE = 22.5 psia OD= 25.0 mm ID = 13.1 mm
VOLTAGE = 16.0 volts HEAT FLUX = 59.5 W/cm**2
HEATER ELEMENT = 60 cm

Table G.46 Recorded Void Growth : Experiment No. 46.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.077	0.2141	23.2	82.0	76.1	6.509	-6.564
2	0.074	0.2071	23.6	83.4	78.3	7.741	-6.328
3	0.073	0.2038	24.4	84.3	80.0	8.861	-6.173
4	0.074	0.2060	24.9	85.0	79.9	9.229	-6.015
5	0.073	0.2048	25.2	85.4	80.5	11.439	-5.951
6	0.074	0.2069	24.8	84.9	79.5	14.415	-6.037
7	0.074	0.2066	25.4	85.2	80.2	12.549	-5.985
8	0.074	0.2070	26.3	86.5	81.0	15.721	-5.746
9	0.074	0.2063	27.3	87.1	82.2	16.156	-5.634
10	0.074	0.2070	28.3	88.1	83.1	14.493	-5.445
11	0.074	0.2067	28.9	88.1	83.8	22.631	-5.432
12	0.074	0.2072	29.8	88.8	84.5	22.691	-5.311
13	0.074	0.2071	30.2	89.7	84.9	23.322	-5.127
14	0.075	0.2100	30.9	90.2	84.8	26.615	-5.022

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 25.0 mm ID = 13.1 mm
 VOLTAGE = 18.3 volts HEAT FLUX = 77.9 W/cm**2
 HEATER ELEMENT = 60 cm

Table G.47 Recorded Void Growth : Experiment No. 47.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.101	0.2831	23.3	67.6	63.3	2.430	-9.056
2	0.100	0.2805	24.6	70.1	65.0	0.983	-8.597
3	0.100	0.2796	25.2	69.8	65.7	3.771	-8.646
4	0.100	0.2797	25.9	71.2	66.5	4.105	-8.398
5	0.100	0.2796	26.5	71.9	67.1	3.378	-8.268
6	0.100	0.2799	28.1	73.2	68.6	3.309	-8.023
7	0.100	0.2796	29.2	74.4	69.8	1.590	-7.781
8	0.100	0.2798	30.4	75.8	70.9	5.305	-7.529
9	0.100	0.2789	31.8	76.4	72.4	4.251	-7.410
10	0.100	0.2784	32.5	77.5	73.2	6.137	-7.202
11	0.099	0.2763	33.4	77.8	74.4	6.827	-7.159
12	0.099	0.2752	34.8	79.4	76.0	9.026	-6.870
13	0.095	0.2666	35.9	81.8	78.4	13.576	-6.436
14	0.095	0.2639	36.3	82.4	79.3	18.343	-6.322
15	0.095	0.2642	37.7	84.1	85.3	15.866	-6.002
16	0.095	0.2642	37.7	84.1	80.6	15.866	-6.002
17	0.092	0.2570	39.0	85.9	83.0	18.682	-5.681
18	0.093	0.2607	39.0	86.3	82.5	20.514	-5.604
19	0.093	0.2595	40.2	86.8	83.8	21.331	-5.505

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 25.0 mm ID = 13.1 mm
 VOLTAGE = 18.3 volts HEAT FLUX = 77.9 W/cm**2
 HEATER ELEMENT = 60 cm

Table G.48 Recorded Void Growth : Experiment No. 48.

POINT #	MASS Kg/s	VELOCITY m/s	Tip C	Tout C	Tout cal. C	VOID %	QUALITY Xeq %
1	0.018	0.0318	22.6	95.4	90.5	3.404	-4.271
2	0.018	0.0314	23.8	97.1	92.5	2.780	-3.962
3	0.018	0.0312	24.1	98.3	93.3	3.924	-3.740
4	0.018	0.0308	24.4	98.6	94.4	3.771	-3.701
5	0.018	0.0305	24.6	99.2	95.3	3.784	-3.595
6	0.017	0.0304	24.7	99.2	95.6	4.244	-3.608
7	0.017	0.0303	24.9	99.9	96.0	3.507	-3.485
8	0.017	0.0302	24.9	100.1	96.6	3.385	-3.439
9	0.017	0.0300	25.1	100.3	96.8	4.539	-3.407
10	0.017	0.0301	25.3	99.4	96.9	4.199	-3.580
11	0.017	0.0298	25.7	99.6	97.9	4.669	-3.540
12	0.017	0.0295	25.8	99.9	99.0	4.737	-3.499
13	0.017	0.0278	25.5	99.8	103.1	5.623	-3.596
14	0.016	0.0284	26.1	102.5	102.1	5.510	-3.055
15	0.016	0.0275	26.4	105.1	104.7	5.516	-2.619
16	0.016	0.0282	27.3	107.2	103.6	6.259	-2.182
17	0.016	0.0284	28.0	107.2	103.8	7.886	-2.177
18	0.016	0.0284	27.9	106.1	103.6	7.032	-2.376
19	0.016	0.0287	28.9	107.6	104.1	9.781	-2.096
20	0.017	0.0293	29.1	107.5	102.6	11.285	-2.079
21	0.017	0.0294	29.8	107.7	103.1	12.435	-2.039
22	0.017	0.0294	30.1	107.4	103.3	14.899	-2.092
23	0.017	0.0291	30.4	107.2	104.5	16.557	-2.145
24	0.017	0.0293	31.0	107.9	104.6	18.802	-2.007
25	0.017	0.0292	31.4	107.7	105.3	21.843	-2.045
26	0.017	0.0292	31.7	107.6	105.6	23.891	-2.071
27	0.017	0.0296	32.2	107.8	105.1	25.604	-2.010
28	0.017	0.0293	32.6	107.5	106.3	26.301	-2.087
29	0.017	0.0298	32.9	108.0	105.3	28.853	-1.971
30	0.017	0.0289	33.2	108.3	107.8	31.269	-1.954

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 30.0 mm ID = 13.1 mm
 VOLTAGE = 9.1 volts HEAT FLUX = 29.7 W/cm**2
 HEATER ELEMENT = 48 cm

Table G.49 Recorded Void Growth : Experiment No. 49.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.020	0.0354	37.1	96.7	97.9	5.282	-3.909
2	0.020	0.0351	37.9	101.0	99.2	5.237	-3.117
3	0.019	0.0334	38.2	102.1	102.8	4.901	-2.956
4	0.019	0.0331	38.5	104.6	103.6	6.212	-2.491
5	0.019	0.0331	38.5	106.3	103.7	4.783	-2.175
6	0.019	0.0330	38.7	107.0	104.1	6.183	-2.057
7	0.019	0.0328	38.8	107.5	104.6	5.859	-1.967
8	0.019	0.0322	38.8	108.0	105.6	6.054	-1.889
9	0.019	0.0326	38.8	105.8	104.9	5.017	-2.286
10	0.018	0.0321	38.9	107.5	105.2	6.971	-1.992
11	0.019	0.0326	39.1	108.2	105.2	6.971	-1.846
12	0.019	0.0327	39.3	108.7	105.2	6.182	-1.745
13	0.019	0.0327	39.2	108.2	105.2	6.116	-1.838
14	0.019	0.0326	39.2	108.6	105.4	7.228	-1.766
15	0.019	0.0323	39.4	108.4	106.2	7.510	-1.807
16	0.019	0.0323	39.4	108.3	106.1	8.350	-1.825
17	0.019	0.0325	39.4	108.2	105.6	8.589	-1.839
18	0.019	0.0324	39.5	108.2	106.0	8.091	-1.846
19	0.018	0.0321	39.6	108.5	106.7	8.784	-1.803
20	0.019	0.0327	40.0	108.4	105.8	10.336	-1.792
21	0.019	0.0327	40.3	107.7	106.2	13.885	-1.919
22	0.019	0.0326	40.6	109.2	106.8	16.252	-1.661
23	0.019	0.0324	41.0	108.2	107.6	16.919	-1.848
24	0.019	0.0327	41.4	109.0	107.3	19.032	-1.679
25	0.019	0.0325	41.6	108.8	108.0	20.298	-1.723
26	0.019	0.0327	41.9	108.9	107.8	23.810	-1.708
27	0.019	0.0325	42.3	109.5	108.6	25.766	-1.638
28	0.019	0.0328	42.6	109.1	108.4	30.008	-1.667
29	0.019	0.0326	43.1	109.6	109.1	30.537	-1.580
30	0.019	0.0324	43.3	109.7	109.8	32.650	-1.559

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 30.0 mm ID = 13.1 mm
 VOLTAGE = 9.1 volts HEAT FLUX = 29.7 W/cm**2
 HEATER ELEMENT = 48 cm

Table G.50 Recorded Void Growth : Experiment No. 50.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.034	0.0587	20.4	88.9	94.9	4.051	-5.594
2	0.034	0.0584	21.2	91.1	96.1	2.537	-5.194
3	0.033	0.0580	21.2	90.2	96.6	3.187	-5.359
4	0.033	0.0580	21.6	91.8	96.9	3.485	-5.064
5	0.033	0.0577	21.9	91.6	97.6	3.479	-5.115
6	0.033	0.0570	22.7	93.5	99.4	2.897	-4.768
7	0.033	0.0573	23.1	94.7	99.4	3.066	-4.534
8	0.033	0.0572	24.2	96.8	100.7	3.841	-4.135
9	0.032	0.0559	24.4	97.2	102.5	4.512	-4.086
10	0.032	0.0559	24.9	98.1	103.0	3.337	-3.923
11	0.032	0.0553	25.5	99.9	104.4	3.919	-3.604
12	0.032	0.0557	25.5	98.0	104.0	4.845	-3.953
13	0.032	0.0558	26.0	97.7	104.4	4.726	-3.999
14	0.032	0.0560	26.1	97.7	104.2	5.367	-3.993
15	0.032	0.0554	27.4	99.4	106.2	4.977	-3.689
16	0.031	0.0546	27.9	100.8	107.9	4.824	-3.439
17	0.031	0.0549	28.6	101.0	108.3	4.688	-3.399
18	0.031	0.0547	29.9	104.0	109.8	5.752	-2.845
19	0.032	0.0561	30.7	105.7	108.6	5.670	-2.485
20	0.032	0.0564	31.2	106.3	108.7	7.320	-2.374
21	0.031	0.0545	31.5	106.2	111.7	7.601	-2.427
22	0.031	0.0548	32.4	106.7	112.1	8.042	-2.339
23	0.031	0.0537	32.9	107.5	114.4	10.085	-2.202
24	0.030	0.0528	33.6	107.3	116.3	13.982	-2.271
25	0.030	0.0522	34.1	107.1	117.8	19.101	-2.314
26	0.030	0.0530	34.5	107.4	116.9	24.605	-2.213
22	0.030	0.0530	35.1	106.4	117.5	28.624	-2.426

TEST PARAMETERS :

PRESSURE = 22.5 psia OD= 30.0 mm ID = 13.1 mm
 VOLTAGE = 12.8 volts HEAT FLUX = 60.2 W/cm**2
 HEATER ELEMENT = 48 cm

Table G.51 Recorded Void Growth : Experiment No. 51.

POINT	MASS	VELOCITY	T _{in}	T _{out}	T _{out} cal.	VOID	QUALITY
#	Kg/s	m/s	C	C	C	%	X _{eq} %
1	0.038	0.0656	38.7	99.2	105.3	5.131	-3.545
2	0.038	0.0658	39.2	100.5	105.7	5.623	-3.294
3	0.038	0.0655	39.2	100.6	106.0	6.327	-3.271
4	0.038	0.0657	39.1	100.9	105.6	4.810	-3.209
5	0.037	0.0649	39.4	101.9	106.8	5.116	-3.045
6	0.037	0.0647	39.7	102.5	107.3	4.419	-2.941
7	0.037	0.0646	39.7	102.5	107.4	5.527	-2.929
8	0.037	0.0648	39.6	102.5	107.1	5.438	-2.934
9	0.037	0.0641	40.2	103.3	108.4	5.518	-2.785
10	0.037	0.0637	40.3	103.4	108.9	5.207	-2.785
11	0.037	0.0645	40.4	104.1	108.2	5.623	-2.636
12	0.037	0.0643	40.7	104.8	108.7	6.369	-2.505
13	0.037	0.0649	40.9	105.1	108.2	6.497	-2.446
14	0.038	0.0658	41.2	105.7	105.7	6.576	-2.305
15	0.038	0.0655	41.7	106.5	108.5	7.642	-2.166
16	0.037	0.0646	41.7	106.5	109.4	7.086	-2.189
17	0.037	0.0638	42.2	106.4	110.7	8.546	-2.208
18	0.037	0.0646	42.5	106.4	110.2	7.041	-2.203
19	0.036	0.0619	42.8	107.1	113.4	9.474	-2.120
20	0.035	0.0609	43.1	107.1	114.8	12.472	-2.135
21	0.035	0.0613	43.5	107.3	114.8	14.696	-2.082
22	0.035	0.0614	43.8	107.0	114.7	15.479	-2.141
23	0.035	0.0609	43.8	106.5	115.5	17.093	-2.245
24	0.035	0.0608	44.1	107.1	116.0	20.038	-2.138
25	0.035	0.0605	44.4	107.0	116.7	23.168	-2.166
26	0.034	0.0601	44.8	107.5	117.5	26.637	-2.166

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 30.0 mm ID = 13.1 mm
 VOLTAGE = 12.8 volts HEAT FLUX = 60.2 W/cm**2
 HEATER ELEMENT = 48 cm

Table G.52 Recorded Void Growth : Experiment No. 52.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.055	0.0954	29.9	85.3	86.3	5.215	-5.989
2	0.054	0.0947	31.1	86.6	87.8	5.159	-5.744
3	0.054	0.0946	31.6	87.7	88.5	4.440	-5.544
4	0.054	0.0943	32.8	89.6	89.8	4.870	-5.191
5	0.054	0.0937	33.6	90.2	91.0	5.747	-5.089
6	0.053	0.0928	34.4	91.0	92.4	6.179	-4.950
7	0.053	0.0920	35.3	92.8	93.8	6.386	-4.621
8	0.053	0.0918	36.0	93.2	94.6	4.932	-4.548
9	0.052	0.0912	36.9	94.5	95.9	4.217	-4.294
10	0.052	0.0903	37.7	96.0	97.3	6.031	-4.019
11	0.052	0.0903	38.2	97.0	97.8	7.196	-3.850
12	0.051	0.0897	39.0	96.9	99.0	7.077	-3.857
13	0.051	0.0892	39.9	97.5	100.2	7.940	-3.759
14	0.051	0.0893	40.4	98.6	100.7	7.048	-3.557
15	0.051	0.0889	41.3	99.7	101.8	8.793	-3.341
16	0.051	0.0894	41.9	101.4	102.1	9.221	-3.023
17	0.052	0.0904	42.8	101.4	102.3	8.009	-3.017
18	0.052	0.0909	43.4	100.7	102.5	8.369	-3.148
19	0.052	0.0906	44.1	101.7	101.7	7.794	-2.952
20	0.053	0.0916	44.6	102.8	103.3	9.314	-2.740
21	0.063	0.1091	45.0	103.3	94.3	11.289	-2.504
22	0.060	0.1048	45.8	104.0	97.1	12.333	-2.405
23	0.052	0.0900	46.4	106.1	106.2	17.447	-2.135
24	0.053	0.0922	46.9	105.2	105.2	19.487	-2.285
25	0.052	0.0914	47.2	105.5	106.1	20.947	-2.229
26	0.052	0.0912	47.8	105.5	106.7	22.698	-2.243
27	0.053	0.0916	48.4	105.6	107.1	24.117	-2.215
28	0.051	0.0890	48.5	105.4	109.0	28.559	-2.267
29	0.051	0.0887	49.0	104.5	109.6	29.249	-2.448
30	0.051	0.0897	49.2	104.6	109.2	30.285	-2.423
31	0.051	0.0893	49.7	104.9	109.9	31.100	-2.358
32	0.050	0.0876	50.0	105.0	111.4	32.123	-2.369

TEST PARAMETERS :

PRESSURE = 22.2 psia OD = 22.0 mm ID = 13.1 mm
 VOLTAGE = 14.25volts HEAT FLUX = 74.1 W/cm**2
 HEATER ELEMENT = 48 cm.

Table G.53 Recorded Void Growth : Experiment No. 53.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.066	0.1150	47.5	95.2	94.3	7.785	-3.973
2	0.065	0.1129	47.5	95.4	95.1	8.281	-3.956
3	0.063	0.1103	47.5	96.9	96.2	8.691	-3.683
4	0.062	0.1085	47.8	97.9	97.4	7.860	-3.523
5	0.062	0.1073	47.9	97.5	98.0	8.369	-3.603
6	0.061	0.1067	48.4	98.6	98.9	9.285	-3.404
7	0.061	0.1061	48.8	99.3	99.5	9.314	-3.278
8	0.061	0.1056	48.9	99.5	99.9	9.844	-3.245
9	0.061	0.1058	48.9	99.1	99.8	9.886	-3.307
10	0.061	0.1058	49.1	99.4	100.0	9.439	-3.251
11	0.061	0.1058	49.3	99.6	100.2	8.107	-3.207
12	0.061	0.1059	49.7	99.8	100.4	9.514	-3.179
13	0.061	0.1057	49.8	100.1	100.7	10.792	-3.115
14	0.061	0.1061	49.7	100.0	100.5	9.651	-3.144
15	0.060	0.1045	50.1	100.2	101.6	10.277	-3.107
16	0.061	0.1058	50.2	100.8	101.0	10.191	-2.991
17	0.061	0.1066	50.6	101.4	101.1	10.988	-2.875
18	0.061	0.1061	50.8	100.8	101.4	11.067	-2.996
19	0.061	0.1062	50.9	101.2	101.6	11.350	-2.906
20	0.061	0.1059	51.3	101.1	102.1	10.687	-2.934
21	0.061	0.1061	51.4	101.3	102.0	11.072	-2.900
22	0.060	0.1040	51.4	102.5	103.1	12.111	-2.678
23	0.060	0.1044	51.9	102.6	103.4	12.959	-2.668
24	0.059	0.1035	52.2	102.9	104.2	12.785	-2.619
25	0.065	0.1128	52.3	103.6	100.0	13.893	-2.405
26	0.067	0.1166	52.7	104.8	98.8	13.450	-2.158

Experiment No.53 Continued

27	0.064	0.1112	52.9	104.7	101.2	16.143	-2.219
28	0.061	0.1063	53.0	105.8	103.6	17.442	-2.046
29	0.060	0.1037	53.0	105.7	104.9	19.110	-2.077
30	0.058	0.1011	53.4	106.0	106.6	22.846	-2.054
31	0.058	0.1005	53.4	105.5	106.9	24.029	-2.139
32	0.057	0.0999	53.8	106.0	107.6	25.584	-2.059
33	0.057	0.0997	53.9	106.0	107.8	25.167	-2.055
34	0.058	0.1006	53.9	105.5	107.3	27.240	-2.150
35	0.058	0.1003	54.2	105.5	105.5	26.873	-2.157

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 30.0 mm ID = 13.1 mm
VOLTAGE = 14.2 volts HEAT FLUX = 74.1 W/cm**2
HEATER ELEMENT = 48 cm

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MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS
STANDARD REFERENCE MATERIAL 1010a
(ANSI and ISO TEST CHART No. 2)

Table G.54 Recorded Void Growth : Experiment No. 54.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.051	0.0896	29.8	91.8	92.4	6.127	-4.858
2	0.051	0.0892	31.1	93.8	94.0	7.212	-4.495
3	0.051	0.0885	31.9	94.7	95.2	7.829	-4.332
4	0.051	0.0885	33.1	96.8	96.4	7.444	-3.932
5	0.051	0.0882	34.1	97.9	97.7	8.033	-3.741
6	0.051	0.0882	34.7	98.2	98.3	7.413	-3.678
7	0.050	0.0875	35.6	99.2	99.7	8.326	-3.506
8	0.050	0.0870	36.4	100.2	100.9	8.588	-3.381
9	0.050	0.0867	36.9	100.8	101.6	9.469	-3.215
10	0.050	0.0867	37.6	101.8	102.3	8.893	-3.027
11	0.049	0.0861	38.5	103.1	103.6	9.961	-2.791
12	0.055	0.0958	38.8	104.9	97.3	11.436	-2.335
13	0.052	0.0902	39.5	106.4	101.7	13.450	-2.112
14	0.052	0.0913	40.0	106.6	101.5	12.938	-2.069
15	0.053	0.0931	40.3	106.5	100.6	12.625	-2.073
16	0.051	0.0895	40.9	106.9	103.6	13.394	-2.033
17	0.051	0.0895	41.1	106.4	103.8	14.677	-2.128
18	0.052	0.0899	41.9	107.1	104.2	14.732	-1.985
19	0.051	0.0890	42.4	107.2	105.4	16.315	-1.974
20	0.052	0.0897	42.7	106.8	105.2	19.159	-2.047
21	0.051	0.0891	43.2	106.6	106.2	19.718	-2.095
22	0.052	0.0898	43.8	106.9	106.3	23.702	-2.025
23	0.051	0.0892	44.5	107.4	107.3	23.523	-1.945
24	0.052	0.0908	44.6	106.6	106.4	19.943	-2.072
25	0.052	0.0908	45.6	107.3	107.4	19.704	-1.938
26	0.052	0.0906	45.9	106.5	107.7	22.651	-2.089
27	0.052	0.0903	46.6	106.8	108.8	25.797	-2.039
28	0.051	0.0895	47.0	106.1	109.7	35.189	-2.186

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 30.0 mm ID = 13.1 mm
 VOLTAGE = 14.5 volts HEAT FLUX = 77.2 W/cm**2
 HEATER ELEMENT = 48 cm

Table G.55 Recorded Void Growth : Experiment No. 55.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.065	0.1134	27.8	94.0	90.3	4.489	-4.451
2	0.064	0.1121	30.1	94.3	93.3	4.764	-4.409
3	0.064	0.1114	31.1	95.5	94.7	5.151	-4.179
4	0.064	0.1116	32.3	95.8	95.8	5.048	-4.124
5	0.064	0.1117	33.0	97.3	96.5	5.190	-3.847
6	0.064	0.1121	33.8	97.1	97.1	5.707	-3.878
7	0.064	0.1113	34.8	99.1	98.5	6.659	-3.512
8	0.064	0.1106	36.1	100.1	100.2	6.080	-3.328
9	0.064	0.1110	36.8	101.1	100.6	6.927	-3.140
10	0.063	0.1103	37.9	103.3	102.2	9.359	-2.733
11	0.064	0.1118	38.5	103.0	101.9	9.487	-2.773
12	0.064	0.1120	39.4	104.1	102.7	10.692	-2.573
13	0.065	0.1126	40.0	103.3	102.9	13.483	-2.717
14	0.064	0.1112	41.3	105.1	105.0	14.981	-2.379
15	0.064	0.1120	42.1	105.4	105.3	16.989	-2.312
16	0.064	0.1119	42.5	105.2	105.8	19.688	-2.352
17	0.064	0.1121	43.4	105.1	106.6	23.512	-2.373
18	0.064	0.1123	44.3	105.4	107.4	25.441	-2.313
19	0.064	0.1118	45.2	105.3	108.6	30.050	-2.339
20	0.065	0.1132	45.9	105.6	108.5	32.351	-2.277

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 30.0 mm ID = 13.1 mm
 VOLTAGE = 16.3 volts HEAT FLUX = 97.6 W/cm**2
 HEATER ELEMENT = 48 cm

Table G.56 Recorded Void Growth : Experiment No. 56.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.067	0.1165	22.1	101.4	96.3	4.853	-3.250
2	0.067	0.1162	22.5	101.7	96.8	4.202	-3.178
3	0.066	0.1156	23.1	102.8	97.9	3.771	-2.985
4	0.066	0.1143	24.2	104.5	99.8	5.005	-2.677
5	0.064	0.1116	25.5	106.8	102.9	4.842	-2.273
6	0.063	0.1098	26.2	107.4	104.9	4.904	-2.189
7	0.061	0.1066	26.7	110.4	107.8	7.978	-1.659
8	0.063	0.1093	27.2	111.5	106.3	11.912	-1.415
9	0.062	0.1081	26.5	110.1	106.4	15.516	-1.688
10	0.062	0.1086	26.4	110.8	106.0	17.389	-1.558
11	0.063	0.1091	26.8	110.6	106.0	19.139	-1.588
12	0.063	0.1089	27.4	110.3	106.8	21.613	-1.646
13	0.062	0.1080	29.0	110.9	109.1	23.797	-1.547
14	0.062	0.1074	28.5	110.5	109.0	29.329	-1.637
15	0.061	0.1067	29.7	110.0	110.7	32.789	-1.729

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 30.0 mm ID = 13.1 mm
 VOLTAGE = 18.0 volts HEAT FLUX = 119.0 W/cm**2
 HEATER ELEMENT = 48 cm

Table G.57 Recorded Void Growth : Experiment No. 57.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.083	0.1452	26.7	90.1	86.2	3.371	-5.130
2	0.083	0.1448	26.8	90.5	86.5	3.558	-5.072
3	0.083	0.1449	27.2	90.2	86.8	3.696	-5.127
4	0.083	0.1446	28.0	92.4	87.8	4.592	-4.713
5	0.083	0.1445	30.1	93.9	89.9	4.073	-4.432
6	0.083	0.1444	32.0	94.0	91.9	4.463	-4.414
7	0.083	0.1447	32.8	94.0	92.6	4.411	-4.411
8	0.083	0.1447	34.0	96.0	93.7	4.637	-4.029
9	0.083	0.1446	35.2	97.4	95.0	6.177	-3.764
10	0.083	0.1441	36.2	99.2	96.2	5.201	-3.437
11	0.082	0.1432	37.3	100.7	97.7	7.178	-3.164
12	0.082	0.1429	38.0	101.2	98.5	6.684	-3.062
13	0.080	0.1390	39.8	104.1	102.0	10.732	-2.556
14	0.078	0.1353	40.5	106.0	104.4	13.561	-2.214
15	0.077	0.1345	41.1	107.8	105.3	17.806	-1.888
16	0.076	0.1329	42.3	109.3	107.3	22.873	-1.616
17	0.075	0.1310	42.6	108.9	108.6	30.984	-1.709
18	0.074	0.1290	44.0	108.9	110.9	37.864	-1.708

TEST PARAMETERS :

PRESSURE = 22.5 psia OD= 30.0 mm ID = 13.1 mm
 VOLTAGE = 18.0 volts HEAT FLUX = 119.0 W/cm**2
 HEATER ELEMENT = 48 cm

Table G.58 Recorded Void Growth : Experiment No. 58.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.025	0.0431	29.2	94.3	89.5	2.815	-4.352
2	0.024	0.0415	29.7	96.3	92.4	5.084	-4.016
3	0.022	0.0391	30.0	99.8	96.6	6.345	-3.426
4	0.021	0.0358	30.1	103.3	102.8	7.655	-2.869
5	0.020	0.0353	30.3	107.4	104.0	10.749	-2.098
6	0.020	0.0352	30.5	107.1	104.4	11.919	-2.158
7	0.020	0.0349	30.3	106.8	104.8	14.229	-2.240
8	0.020	0.0346	30.2	106.5	105.4	17.746	-2.295
9	0.020	0.0343	30.4	106.6	106.2	19.478	-2.287
10	0.020	0.0346	30.4	106.2	105.6	23.098	-2.359
11	0.019	0.0333	30.7	106.7	108.8	32.630	-2.306

TEST PARAMETERS :

PRESSURE = 22.5 psia OD= 30.0 mm ID = 13.1 mm
 VOLTAGE = 11.3 volts HEAT FLUX = 29.7 W/cm**2
 HEATER ELEMENT = 60 cm

Table G.59 Recorded Void Growth : Experiment No. 59.

POINT	MASS	VELOCITY	T _{in}	T _{out}	T _{out} cal.	VOID	QUALITY
#	Kg/s	m/s	C	C	C	%	X _{eq} %
1	0.053	0.0922	31.0	91.8	90.3	5.719	-4.806
2	0.053	0.0919	31.4	93.0	91.0	4.628	-4.591
3	0.052	0.0906	32.2	94.6	92.5	5.436	-4.299
4	0.052	0.0903	33.5	95.5	94.1	5.180	-4.133
5	0.050	0.0875	35.5	99.8	98.0	8.574	-3.362
6	0.050	0.0873	37.0	102.0	99.6	9.225	-2.953
7	0.051	0.0895	37.3	102.4	98.4	9.851	-2.850
8	0.061	0.1059	37.7	104.1	89.3	8.737	-2.378
9	0.059	0.1023	37.7	103.9	91.1	10.127	-2.456
10	0.056	0.0972	38.1	104.2	94.4	11.186	-2.434
11	0.053	0.0915	38.5	105.2	98.2	14.694	-2.307
12	0.054	0.0937	38.8	104.4	97.2	15.533	-2.429
13	0.053	0.0927	39.6	104.3	98.6	16.306	-2.453
14	0.052	0.0913	40.2	104.8	100.1	18.766	-2.387
15	0.053	0.0919	40.6	105.0	100.1	20.705	-2.342
16	0.051	0.0896	41.5	105.1	102.5	24.613	-2.342
17	0.052	0.0905	42.5	105.7	103.0	26.444	-2.225
18	0.053	0.0921	42.4	104.3	101.8	29.679	-2.464
19	0.052	0.0900	43.6	105.0	104.4	31.748	-2.354

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 30.0 mm ID = 13.1 mm
 VOLTAGE = 16.3 volts HEAT FLUX = 60.3 W/cm**2
 HEATER ELEMENT = 60 cm

Table G.60 Recorded Void Growth : Experiment No. 60.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.093	0.1621	48.2	83.0	82.0	4.843	-6.096
2	0.093	0.1625	49.4	83.4	83.0	4.767	-5.986
3	0.093	0.1628	49.9	83.9	83.6	4.803	-5.904
4	0.093	0.1623	50.6	85.4	84.3	5.206	-5.613
5	0.093	0.1620	51.4	86.4	85.2	4.799	-5.425
6	0.092	0.1610	52.8	87.4	86.8	5.051	-5.242
7	0.093	0.1612	53.3	88.0	87.2	6.024	-5.126
8	0.093	0.1613	54.2	89.3	88.1	3.298	-4.884
9	0.093	0.1612	55.2	90.4	89.2	6.345	-4.689
10	0.093	0.1618	55.8	89.9	89.6	5.325	-4.765
11	0.093	0.1614	56.6	92.2	90.5	5.737	-4.338
12	0.092	0.1605	57.1	93.0	91.2	6.736	-4.205
13	0.092	0.1600	58.4	93.8	92.6	6.387	-4.049
14	0.091	0.1593	59.2	94.4	93.5	7.310	-3.939
15	0.090	0.1571	59.8	95.4	94.7	6.283	-3.761
16	0.089	0.1557	60.3	96.5	95.4	8.034	-3.562
17	0.088	0.1538	61.4	97.1	97.0	9.347	-3.456
18	0.082	0.1431	62.1	100.6	100.4	12.937	-2.832
19	0.081	0.1406	62.7	102.1	101.6	18.388	-2.557
20	0.081	0.1415	63.5	102.1	102.1	19.215	-2.549
21	0.081	0.1416	63.7	103.0	102.4	22.136	-2.394
22	0.080	0.1395	64.5	103.6	103.7	26.026	-2.285
23	0.078	0.1363	64.5	103.6	104.6	32.433	-2.292
24	0.079	0.1372	64.8	103.6	104.6	33.267	-2.285
25	0.079	0.1380	65.2	103.6	104.9	34.320	-2.289

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 30.0 mm ID = 13.1 mm
 VOLTAGE = 16.1 volts HEAT FLUX = 60.3 W/cm**2
 HEATER ELEMENT = 60 cm

Table G.61 Recorded Void Growth : Experiment No. 61.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.070	0.1212	30.5	85.4	86.3	5.324	-5.953
2	0.069	0.1200	31.1	87.3	87.5	6.073	-5.615
3	0.069	0.1197	31.2	86.9	87.7	5.219	-5.685
4	0.069	0.1197	32.4	87.6	88.9	4.854	-5.580
5	0.069	0.1197	33.9	88.7	90.4	4.966	-5.346
6	0.069	0.1194	34.9	89.9	91.5	5.107	-5.120
7	0.068	0.1184	35.3	90.8	92.5	5.383	-4.976
8	0.066	0.1151	36.5	93.6	95.3	5.107	-4.474
9	0.060	0.1046	37.7	99.3	102.4	7.770	-3.485
10	0.053	0.0923	38.5	106.7	111.8	27.164	-2.229
11	0.045	0.0780	39.2	106.8	125.9	60.425	-2.423

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 30.0 mm ID = 13.1 mm
 VOLTAGE = 12.8 volts HEAT FLUX = 60.2 W/cm**2
 HEATER ELEMENT = 60 cm

Table G.62 Recorded Void Growth : Experiment No. 62.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.063	0.1099	14.0	82.1	78.3	3.912	-6.709
2	0.064	0.1107	12.9	81.5	76.7	3.416	-6.817
3	0.057	0.0995	13.6	90.8	84.7	3.516	-5.175
4	0.056	0.0983	13.9	92.1	85.8	4.225	-4.957
5	0.056	0.0978	14.5	93.7	86.8	5.206	-4.665
6	0.055	0.0966	15.1	94.9	88.3	4.385	-4.439
7	0.055	0.0964	15.4	96.1	88.7	4.787	-4.217
8	0.055	0.0957	16.2	96.9	90.1	5.473	-4.074
9	0.054	0.0945	16.7	98.9	91.5	5.352	-3.714
10	0.054	0.0942	17.5	99.1	92.5	6.162	-3.687
11	0.054	0.0935	18.3	100.8	93.8	5.494	-3.381
12	0.053	0.0923	19.6	103.4	96.1	6.026	-2.911
13	0.053	0.0919	20.2	103.8	97.0	6.067	-2.839
14	0.053	0.0915	21.0	105.5	98.2	6.477	-2.515
15	0.052	0.0912	21.4	106.9	98.9	7.563	-2.258
16	0.052	0.0914	22.0	107.8	99.3	9.004	-2.081
17	0.060	0.1049	22.9	109.6	90.2	8.823	-1.598
18	0.056	0.0973	23.3	110.6	96.0	11.208	-1.485
19	0.054	0.0938	23.5	110.5	98.8	12.463	-1.553
20	0.053	0.0929	23.5	109.8	99.6	18.309	-1.684
21	0.052	0.0909	24.4	111.3	102.1	19.530	-1.439
22	0.053	0.0926	24.6	110.5	100.9	19.588	-1.556
23	0.052	0.0905	24.4	109.4	102.5	23.048	-0.799
24	0.052	0.0898	24.9	110.2	103.6	25.756	-1.658

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 30.0 mm ID = 13.1 mm
 VOLTAGE = 18.3 volts HEAT FLUX = 77.9 W/cm**2
 HEATER ELEMENT = 60 cm

Table G.63 Recorded Void Growth : Experiment No. 63.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.066	0.1143	25.5	95.2	87.3	5.009	-4.209
2	0.065	0.1130	25.5	96.2	88.1	5.093	-4.042
3	0.067	0.1161	25.7	95.1	86.6	4.988	-4.219
4	0.067	0.1174	25.7	93.6	85.9	4.319	-4.483
5	0.068	0.1183	25.7	92.4	85.5	5.390	-4.716
6	0.068	0.1184	26.3	92.3	85.9	4.340	-4.725
7	0.067	0.1170	26.9	92.5	87.3	4.355	-4.698
8	0.067	0.1170	27.8	93.6	88.2	6.016	-4.490
9	0.067	0.1159	28.0	94.4	89.0	4.759	-4.343
10	0.066	0.1158	28.6	94.8	89.6	6.875	-4.272
11	0.067	0.1165	29.2	96.0	89.8	5.449	-4.037
12	0.067	0.1164	29.8	96.2	90.5	6.322	-4.011
13	0.067	0.1170	30.7	97.3	91.1	7.115	-3.804
14	0.067	0.1165	31.6	98.8	92.3	6.689	-3.527
15	0.067	0.1159	32.5	99.6	93.5	7.393	-3.377
16	0.067	0.1166	33.1	100.4	93.8	8.891	-3.225
17	0.067	0.1167	33.4	100.1	94.0	7.952	-3.272
18	0.067	0.1171	34.3	101.1	94.7	9.301	-3.078
19	0.067	0.1165	35.0	102.5	95.7	9.709	-2.824
20	0.068	0.1184	35.8	103.9	95.5	11.795	-2.555
21	0.072	0.1254	36.5	104.3	92.9	12.388	-2.425
22	0.068	0.1189	37.0	104.9	96.4	14.103	-2.352
23	0.067	0.1173	37.6	105.0	97.8	19.263	-2.338
24	0.067	0.1174	38.2	105.2	98.4	21.017	-2.315
25	0.067	0.1174	38.7	105.5	98.9	22.755	-2.249
26	0.067	0.1172	39.5	105.4	99.8	25.886	-2.278
27	0.068	0.1176	40.2	105.2	100.3	26.387	-2.313

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 30.0 mm ID = 13.1 mm
 VOLTAGE = 18.3 volts HEAT FLUX = 77.9 W/cm**2
 HEATER ELEMENT = 60 cm

Table G.64 Recorded Void Growth : Experiment No. 64.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.085	0.1476	10.2	73.5	77.0	3.220	-8.268
2	0.070	0.1216	11.2	83.7	84.2	4.326	-6.554
3	0.066	0.1144	10.2	90.0	87.8	5.014	-5.426
4	0.065	0.1134	11.8	91.3	90.0	5.232	-5.204
5	0.068	0.1106	13.4	95.5	93.6	4.758	-4.447
6	0.063	0.1093	12.0	95.2	93.1	6.012	-4.523
7	0.062	0.1074	13.2	99.3	95.8	7.233	-3.772
8	0.060	0.1046	14.8	102.6	99.6	8.836	-3.174
9	0.057	0.0999	16.1	107.0	105.0	15.561	-2.418
10	0.058	0.1014	16.8	106.8	104.2	14.060	-2.434
11	0.059	0.1027	17.4	108.8	103.8	16.271	-2.047
12	0.058	0.1013	18.5	108.7	106.0	19.531	-2.069
13	0.058	0.1014	20.4	111.4	107.9	21.251	-1.576
14	0.055	0.0966	21.0	111.6	112.9	34.059	-1.601

TEST PARAMETERS :

PRESSURE = 22.5 psia OD= 30.0 mm ID = 13.1 mm
 VOLTAGE = 20.5 volts HEAT FLUX = 97.7 W/cm**2
 HEATER ELEMENT = 60 cm

Table G.65 Recorded Void Growth : Experiment No. 65.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _{eq} %
1	0.081	0.1417	28.6	96.3	91.2	6.291	-4.023
2	0.082	0.1420	29.2	96.4	91.6	5.640	-4.004
3	0.081	0.1415	30.4	96.2	93.1	6.227	-4.036
4	0.081	0.1417	30.6	95.1	93.1	6.638	-4.237
5	0.081	0.1418	31.6	97.2	94.1	6.640	-3.849
6	0.081	0.1411	32.7	98.4	95.6	7.961	-3.634
7	0.079	0.1382	33.3	99.6	97.5	8.020	-3.427
8	0.079	0.1373	34.1	101.6	98.8	10.397	-3.061
9	0.078	0.1367	34.9	101.9	99.8	12.654	-3.000
10	0.078	0.1363	35.6	103.7	100.7	13.738	-2.664
11	0.078	0.1362	36.0	103.4	101.1	16.521	-2.721
12	0.078	0.1355	37.0	105.0	102.4	18.947	-2.425
13	0.078	0.1360	37.8	105.5	103.1	24.032	-2.326
14	0.077	0.1344	38.7	106.5	104.6	28.393	-2.161

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 30.0 mm ID = 13.1 mm
VOLTAGE = 20.5 volts HEAT FLUX = 97.7 W/cm**2
HEATER ELEMENT = 60 cm

Table G.66 Recorded Void Growth : Experiment No. 66.

POINT #	MASS Kg/s	VELOCITY m/s	T _{in} C	T _{out} C	T _{out} cal. C	VOID %	QUALITY X _e %
1	0.027	0.0478	44.7	99.5	101.1	5.993	-3.313
2	0.027	0.0462	45.0	100.4	103.3	5.088	-3.177
3	0.027	0.0462	45.3	101.5	103.7	5.819	-2.972
4	0.027	0.0463	45.5	102.1	103.7	5.544	-2.867
5	0.027	0.0465	46.1	102.2	102.2	6.537	-2.836
6	0.027	0.0463	46.1	103.2	103.2	6.426	-2.662
7	0.027	0.0463	46.7	103.7	103.7	6.310	-2.566
8	0.027	0.0464	46.8	103.8	104.9	6.109	-2.539
9	0.026	0.0460	47.3	104.7	105.9	6.793	-2.371
10	0.027	0.0462	47.6	104.6	106.0	6.755	-2.386
11	0.027	0.0465	48.1	104.3	106.0	5.992	-2.438
12	0.026	0.0454	48.5	105.5	107.8	7.033	-2.233
13	0.026	0.0458	48.8	106.1	107.6	7.575	-2.119
14	0.026	0.0453	49.0	106.2	108.4	7.163	-2.114
15	0.026	0.0455	49.2	106.3	108.4	8.922	-2.090
16	0.026	0.0452	49.5	106.3	109.1	9.841	-2.097
17	0.026	0.0454	50.0	106.7	109.4	10.267	-2.015
18	0.026	0.0457	50.1	106.9	109.0	11.346	-1.978
19	0.026	0.0461	50.2	106.9	108.7	11.791	-1.972
20	0.026	0.0457	50.7	106.5	109.7	11.926	-2.041
21	0.026	0.0456	51.0	106.6	110.1	11.139	-2.023
22	0.025	0.0442	51.4	106.3	112.4	13.566	-2.113
23	0.025	0.0441	51.2	106.4	112.3	17.182	-2.089
24	0.025	0.0435	51.5	106.1	113.4	19.723	-2.172
25	0.025	0.0430	51.4	105.9	114.2	23.672	-2.217
26	0.025	0.0431	51.9	106.9	114.4	26.219	-2.031
27	0.026	0.0448	51.9	104.4	112.0	32.846	-2.451

TEST PARAMETERS :

PRESSURE = 22.5 psia OD = 30.0 mm ID = 13.1 mm
 VOLTAGE = 11.3 volts HEAT FLUX = 29.7 W/cm**2
 HEATER ELEMENT = 60 cm

Figure G.1 Void Growth : Experiment No.1.

Heat Flux = 29.7 W/cm**2

Velocity = 0.0667 m/s

XEQ(osv) = -1.80

OD. = 22.0 mm

Figure G.2 Void Growth : Experiment No.2.

Heat Flux = 29.7 W/cm**2

Velocity = 0.075 m/s

XEQ(osv) = -1.50

OD. = 22.0 mm

Figure G.3 Void Growth : Experiment No.3.

Heat Flux = 29.7 W/cm²

Velocity = 0.0716 m/s

$X_{EQ(osv)} = -1.50$

OD. = 22.0 mm

Figure G.4 Void Growth : Experiment No.4.

Heat Flux = 29.7 W/cm**2

Velocity = 0.0810 m/s

XEQ(osv) = -1.70

OD. = 22.0 mm

Figure G.5 Void Growth : Experiment No.5.

Heat Flux = 60.5 W/cm**2

Velocity = 0.2506 m/s

XEQ(osv) = -1.50

OD. = 22.0 mm

Figure G.6 Void Growth : Experiment No.6.

Heat Flux = 61.0 W/cm**2

Velocity = 0.1560 m/s

XEQ(osv) = -2.00

OD. = 22.0 mm

Figure G.7 Void Growth : Experiment No.7.

Heat Flux = 74.2 W/cm**2

Velocity = 0.1798 m/s

XEQ(osv) = -1.50

OD. = 22.0 mm

Figure G.8 Void Growth : Experiment No.8.

Heat Flux = 74.2 W/cm**2

Velocity = 0.2871 m/s

XEQ(osv) = -2.20

OD. = 22.0 mm

Figure G.9 Void Growth : Experiment No.9.

Heat Flux = 74.2 W/cm^2

Velocity = 0.4247 m/s

$XEQ(osv) = -2.25$

OD. = 22.0 mm

Figure G.10 Void Growth : Experiment No.10.

Heat Flux = 74.2 W/cm**2

Velocity = 0.4247 m/s

XEQ(osv) = -2.60

OD. = 22.0 mm

Figure G.11 Void Growth : Experiment No.11.

Heat Flux = 77.4 W/cm**2

Velocity = 0.1818 m/s

XEQ(osv) = -2.50

OD. = 22.0 mm

Figure G.12 Void Growth : Experiment No.12.

Heat Flux = 77.4 W/cm**2

Velocity = 0.2385 m/s

XEQ(osv) = -2.50

OD. = 22.0 mm

Figure G.13 Void Growth : Experiment No.13.

Heat Flux = 97.5 W/cm**2

Velocity = 0.2330 m/s

XEQ(osv) = -3.00

OD. = 22.0 mm

Figure G.14 Void Growth : Experiment No.14.

Heat Flux = 97.5 W/cm**2

Velocity = 0.3175 m/s

XEQ(osv) = -3.80

OD. = 22.0 mm

Figure G.15 Void Growth : Experiment No.15.

Heat Flux = 97.3 W/cm**2

Velocity = 0.3047 m/s

Xeq(OSV) = -3.8

Do = 22.0 mm

Figure G.16 Void Growth : Experiment No.16.

Heat Flux = 118.6 W/cm**2

Velocity = 0.3011 m/s

XEQ(osv) = -3.75

OD. = 22.0 mm

Figure G.17 Void Growth : Experiment No.17.

Heat Flux = 118.6 W/cm**2

Velocity = 0.3726 m/s

XEQ(osv) = -4.10

OD. = 22.0 mm

Figure G.18 Void Growth : Experiment No.18.

Heat Flux = 118.7 W/cm**2

Velocity = 0.3867 m/s

XEQ(osv) = -5.00

OD. = 22.0 mm

Figure G.19 Void Growth : Experiment No.19.

Heat Flux = 118.6 W/cm**2

Velocity = 0.4076 m/s

XEQ(osv) = -4.80

OD. = 22.0 mm

Figure G.20 Void Growth : Experiment No.20.

Heat Flux = 118.6 W/cm**2

Velocity = 0.4752 m/s

XEQ(osv) = -4.00

OD. = 22.0 mm

Figure G.21 Void Growth : Experiment No.21.

Heat Flux = 27.7 W/cm**2

Velocity = 0.0611 m/s

XEQ(osv) = -2.20

OD. = 22.0 mm

Figure G.22 Void Growth : Experiment No.22.

Heat Flux = 27.7 W/cm**2

Velocity = 0.0805 m/s

XEQ(osv) = -1.75

OD. = 22.0 mm

Figure G.23 Void Growth : Experiment No.23.

Heat Flux = 60.1 W/cm**2

Velocity = 0.1617 m/s

XEQ(osv) = -2.25

OD. = 22.0 mm

Figure G.24 Void Growth : Experiment No.24.

Heat Flux = 60.0 W/cm**2

Velocity = 0.1943 m/s

XEQ(osv) = -2.80

OD. = 22.0 mm

Figure G.25 Void Growth : Experiment No.25.

Heat Flux = 60.1 W/cm**2

Velocity = 0.2235 m/s

XEQ(osv) = -2.90

OD. = 22.0 mm

Figure G.26 Void Growth : Experiment No.26.

Heat Flux = 73.9 W/cm**2
Velocity = 0.2027 m/s.
XEQ(osv) = -3.20
OD. = 22.0 mm

Figure G.27 Void Growth : Experiment No.27.

Heat Flux = 73.9 W/cm**2

Velocity = 0.3327 m/s

XEQ(osv) = -5.30

OD. = 22.0 mm

Figure G.28 Void Growth : Experiment No.28.

Heat Flux = 76.8 W/cm**2

Velocity = 0.2569 m/s

XEQ(osv) = -3.25

OD. = 22.0 mm

Figure G.29 Void Growth : Experiment No.29.

Heat Flux = 77.8 W/cm**2

Velocity = 0.3600 m/s

XEQ(osv) = -4.40

OD. = 22.0 mm

Figure G.30 Void Growth : Experiment No.30.

Heat Flux = 29.7 W/cm**2

Velocity = 0.0432 m/s

XEQ(osv) = -1.40

OD. = 25.0 mm

Figure G.31 Void Growth : Experiment No.31.

Heat Flux = 29.7 W/cm**2

Velocity = 0.0492 m/s

XEQ(osv) = -2.25

OD. = 25.0 mm

Figure G.32 Void Growth : Experiment No.32.

Heat Flux = 29.7 W/cm²

Velocity = 0.0580 m/s

XEQ(osv) = -1.80

OD. = 25.0 mm

Figure G.33 Void Growth : Experiment No.33.

Heat Flux = 60.6 W/cm**2

Velocity = 0.1286 m/s

XEQ(osv) = -2.00

OD. = 25.0 mm

Figure G.34 Void Growth : Experiment No.34.

Heat Flux = 60.6 W/cm**2

Velocity = 0.1494 m/s

XEQ(osv) = -1.70

OD. = 25.0 mm

Figure G.35 Void Growth : Experiment No.35.

Heat Flux = 77.5 W/cm**2

Velocity = 0.0923 m/s

XEQ(osv) = -1.40

OD. = 25.0 mm

Figure G.36 Void Growth : Experiment No.36.

Heat Flux = 77.5 W/cm**2

Velocity = 0.1523 m/s

XEQ(osv) = -2.25

OD. = 25.0 mm

Figure G.37 Void Growth : Experiment No.37.

Heat Flux = 97.6 W/cm**2

Velocity = 0.1528 m/s

XEQ(osv) = -3.25

OD. = 25.0 mm

Figure G.38 Void Growth : Experiment No.38.

Heat Flux = 97.6 W/cm**2

Velocity = 0.1912 m/s

XEQ(osv) = -3.20

OD. = 25.0 mm

Figure G.39 Void Growth : Experiment No.39.

Heat Flux = 118.7 W/cm**2

Velocity = 0.1842 m/s

XEQ(osv) = -3.00

OD. = 25.0 mm

Figure G.40 Void Growth : Experiment No 40.

Heat Flux = 118.7 W/cm**2

Velocity = 0.2199 m/s

XEQ(osv) = -3.70

OD. = 25.0 mm

Figure G.41 Void Growth : Experiment No.41.

Heat Flux = 29.7 W/cm²

Velocity = 0.0476 m/s

XEQ(osv) = -2.25

OD. = 25.0 mm

Figure G.42 Void Growth : Experiment No.42.

Heat Flux = 29.7 W/cm²

Velocity = 0.0558 m/s

XEQ(osv) = -3.30

OD. = 25.0 mm

Figure G.43 Void Growth : Experiment No.43.

Heat Flux = 28.6 W/cm**2

Velocity = 0.0839 m/s

XEQ(osv) = -1.80

OD. = 25.0 mm

Figure G.44 Void Growth : Experiment No.44.

Heat Flux = 59.5 W/cm**2

Velocity = 0.1335 m/s

XEQ(osv) = -3.30

OD. = 25.0 mm

Figure G.45 Void Growth : Experiment No.45.

Heat Flux = 59.5 W/cm**2

Velocity = 0.1579 m/s

XEQ(osv) = -4.00

OD. = 25.0 mm

Figure G.46 Void Growth : Experiment No.46.

Heat Flux = 77.9 W/cm**2

Velocity = 0.2595 m/s

XEQ(osv) = -6.00

OD. = 25.0 mm

Figure G.47 Void Growth : Experiment No.47.

Heat Flux = 77.9 W/cm**2

Velocity = 0.2595 m/s

XEQ(osv) = -7.00

OD. = 25.0 mm

Figure G.48 Void Growth : Experiment No.48.

Heat Flux = 29.7 W/cm**2

Velocity = 0.0287 m/s

XEQ(osv) = -2.30

OD. = 30.0 mm

Figure G.49 Void Growth : Experiment No.49.

Heat Flux = 29.7 W/cm**2

Velocity = 0.0324 m/s

XEQ(osv) = -1.80

OD. = 30.0 mm

Figure G.50 Void Growth : Experiment No.50.

Heat Flux = 60.2 W/cm**2

Velocity = 0.0530 m/s

XEQ(osv) = -2.30

OD. = 30.0 mm

Figure G.51 Void Growth : Experiment No.51.

Heat Flux = 60.2 W/cm**2

Velocity = 0.0601 m/s

XEQ(osv) = -2.20

OD. = 30.0 mm

Figure G.52 Void Growth : Experiment No.52.

Heat Flux = 74.1 W/cm²

Velocity = 0.0876 m/s

XEQ(osv) = -2.50

OD. = 30.0 mm

Figure G.53 Void Growth : Experiment No.53.

Heat Flux = 74.1 W/cm**2
Velocity = 0.1003 m/s
XEQ(osv) = -3.20
OD. = 30.0 mm

Figure G.54 Void Growth : Experiment No.54.

Heat Flux = 77.3 W/cm**2

Velocity = 0.0895 m/s

XEQ(osv) = -3.00

OD. = 30.0 mm

Figure G.55 Void Growth : Experiment No.55.

Heat Flux = 97.6 W/cm**2

Velocity = 0.1103 m/s

XEQ(osv) = -2.80

OD. = 30.0 mm

Figure G.56 Void Growth : Experiment No.56.

Heat Flux = 119.0 W/cm**2

Velocity = 0.1066 m/s

XEQ(osv) = -1.80

OD. = 30.0 mm

Figure G.57 Void Growth : Experiment No.57.

Heat Flux = 119.0 W/cm**2

Velocity = 0.1290 m/s

XEQ(osv) = -3.00

OD. = 30.0 mm

Figure G.58 Void Growth : Experiment No.58.

Heat Flux = 29.7 W/cm**2

Velocity = 0.0333 m/s

XEQ(osv) = -2.60

OD. = 30.0 mm

Figure G.59 Void Growth : Experiment No.59.

Heat Flux = 60.3 W/cm**2

Velocity = 0.0875 m/s

$X_{EQ(ov)} = -2.40$

OD. = 30.0 mm

Figure G.60 Void Growth: Experiment No.60.

Heat Flux = 60.3 W/cm**2

Velocity = 0.1380 m/s

XEQ(osv) = -3.50

OD. = 30.0 mm

Figure G.61 Void Growth : Experiment No.61.

Heat Flux = 74.5 W/cm²

Velocity = 0.0923 m/s

XEQ(osv) = -3.25

OD. = 30.0 mm

Figure G.62 Void Growth : Experiment No.62.

Heat Flux = 77.9 W/cm**2

Velocity = 0.0898 m/s

XEQ(osv) = -1.50

OD. = 30.0 mm

Figure G.63 Void Growth : Experiment No.63.

Heat Flux = 77.9 W/cm**2

Velocity = 0.1165 m/s

XEQ(osv) = -2.80

OD. = 30.0 mm

Figure G.64 Void Growth : Experiment No.64.

Heat Flux = 97.7 W/cm²

Velocity = 0.0966 m/s

XEQ(osv) = -3.00

OD. = 30.0 mm

Figure G.65 Void Growth : Experiment No.65.

Heat Flux = 97.7 W/cm**2

Velocity = 0.1344 m/s

XEQ(osv) = -3.20

OD. = 30.0 mm

Figure G.66 Void Growth : Experiment No.66.

Heat Flux = 29.7 W/cm²

Velocity = 0.0464 m/s

$x_{EQ(ov)}$ = -2.25

OD. = 30.0 mm

END

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