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**THE ONSET OF SIGNIFICANT VOID
IN BOILING FLOWS OVER
A WIDE RANGE OF OPERATION CONDITIONS**

by

Jinghui Li

B.Eng., Tsinghua University, China, 1985

**A thesis submitted to the Faculty of Graduate
Studies and Research in partial fulfilment
of the requirements for the Degree of**

Master of Engineering

**Department of
Mechanical and Aerospace Engineering
Carleton University
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January , 1992

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ABSTRACT

The model of Rogers, Salcudean, et al, for the onset of significant void (OSV) in boiling flows, which was developed for low pressure, low velocity conditions in boiling water flows, has been modified for other conditions by correlating the empirical rough surface factor in the model with data from the literature which cover a wide range of pressures and velocities. The recommended form of the modified model gives better predictions of the OSV data over the range of pressures and velocities than do other models in the literature. Analysis and discussions of parameter effects on OSV are presented and recommendations for future work are made.

Dedication

To my husband

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Nomenclature

A	channel heated area
a	surface void fraction in the Griffith model
A_c	effective condensation area in the Griffith model
	channel cross-section area in the Rouhani model
B_0, B_1	constants in Griffith model
C, C'	empirical constants in Levy model
C_0, C_p, C_s	proportionality constants in Levy model
C_1, C_2, C_3	functions of the equilibrium contact angle in the Rogers model
C_d	bubble drag coefficient in the Rogers model
C_s	empirical correction factor for surface tension force in the Rogers model
C_{pl}	liquid specific heat
De	hydraulic or equivalent diameter
f	friction factor
f_l	friction factor for rough surface
f_s	friction factor for smooth surface
F_b, F_b	buoyancy force
F_d	drag force
F_f	wall shear force
F_s, F_s	surface tension force
F_l	rough surface factor

$Frou_b$	bubble Froude number
G	mass flow rate
g	acceleration of gravity
h	heat transfer coefficient in the Griffith and Rouhani models
h_0	heat transfer coefficient in the Rogers model
h_l	heat transfer coefficient for rough surface
h_s	heat transfer coefficient for smooth surface
H_{fg}	latent heat of evaporation
K_c	condensation coefficient in the Rouhani model
k_f	liquid thermal conductivity
M	total mass flow rate in the Rouhani model
m_s	vaporized mass per unit time per unit heated area in the Rouhani model
Nu	Nusselt number
P	pressure
P_c	critical pressure
P_f	liquid pressure
P_g	vapour pressure
P_H	channel heated perimeter
P_w	channel wetted perimeter
Pe	Peclet number
Pr	Prandtl number
Q	total heat
q'', q_v''	wall heat flux

r^*	nucleus radius
r_b	bubble radius at departure
Re	Reynolds number
Re_b	bubble Reynolds number
s	channel characteristic dimension
St	Stanton number
T	temperature
T^+	non-dimensional temperature
T_b^+	T^+ at bubble tip
T_l	liquid bulk temperature
T_s	superheated liquid temperature
T_w	wall temperature
T_{sat}	saturation temperature
ΔT_d	liquid subcooling at OSV
ΔT_{sub}	liquid subcooling
u^*	shear stress velocity
u^+	non-dimensional velocity
u_r	liquid velocity at y_r
V	average flow velocity at inlet
v_{fg}	specific volume change during evaporation
We_b	bubble Weber number
X_{eq}	equilibrium vapour quality
Y_b, y_b	distance from wall to bubble tip
Y_b^+, y_b^+	non-dimension form of Y_b, y_b
y_r	distance from wall to bubble centre
Z	channel length

Greek Symbols

α	void fraction
α_c	void fraction at OSV in Rouhani model
ε	heat flux ratio in Bowring model
θ_0	equilibrium contact angle
θ_a	advancing contact angle
θ_r	receding contact angle
θ_l	liquid subcooling in Rouhani model
μ_l	liquid dynamic viscosity
ρ_l	liquid density
ρ_g	vapour density
σ	surface tension
τ_w	wall shear stress
Φ	heat flux in Bowring model

Abbreviations

ONB	onset of nucleate boiling
OSV	onset of significant void

Chapter 1

INTRODUCTION

1.1 The Nuclear Reactor and Its Thermal-hydraulic Characteristics

In nuclear power reactors, water is often used as the coolant to remove generated heat from the fuel core. The thermal and hydrodynamic characteristics of the water flow, its temperatures, densities, flow rates and so on, are very important to the performance and safety of the reactors.

Since the power densities of most nuclear reactors are very high, the water flow is usually subjected to a very high heat flux and phase change phenomena may occur, for example in the CANDU (Canadian Deuterium Uranium Pressurized Heavy Water) reactor. Therefore two-phase flow, liquid and vapour, often exists in the system. The volumetric fraction of vapour phase, or void fraction, is an important parameter in reactor designs. The void fraction and its distribution depend to a great extent on the point at which the vapour volume begins to grow significantly. This point is generally called the position of Onset of Significant Void (OSV).

In boiling-type reactors, the change in phase is consciously designed into the system. The BWR (Boiling Water Reactor), for example, is operated under saturation conditions. The feedwater is directly changed into steam within the reactor vessel, and the void of the moderator-coolant

is used as a negative feedback to control power level [1]. That is, when the void is high, the lower water density makes neutron moderation less effective and, thus, decreases the reactivity, while lowering the void has the opposite effect. There is no doubt about the importance of OSV in this system.

In the CANDU reactor, both local or subcooled boiling and a small amount of bulk boiling (exit quality about 3% to 4%) occur. Subcooled boiling also occurs in the SES-10 (10 Megawatt Slowpoke Energy System) reactor. It is important to recognize that OSV can occur under subcooled conditions, particularly at lower pressures, because of boundary layer temperatures being above the saturation temperature. The knowledge of OSV in these reactors is also very important.

In non-boiling type reactors, such as the PWRs (Pressurized Water Reactors), phase change does not happen under normal operation conditions because of the very high operating pressure (about 15 MPa) and hence very high saturation temperature. But under accident conditions, such as a loss of coolant accident, boiling may occur. To predict the behaviour of the reactor under accident conditions, the knowledge of OSV is also needed.

Pressure drop is also an important parameter in all reactor systems, and void fraction plays a direct role in pressure drop characteristics through the effective density head and the acceleration components, as well as through a significant increase in friction factor. In addition, of course, the designers of a reactor must be able to predict critical heat flux conditions in the channel to avoid dry-out and overheating of the fuel

element cladding.

Details about the thermal-hydraulic characteristics and designs in nuclear reactor systems are discussed in [1]-[4].

1.2 Void Fraction in Subcooled boiling and OSV Point

1.2.1 Development of Two-phase Flow

The behaviour of the coolant in a nuclear reactor can be simplified as that of a liquid flow in a heated channel. The designers of reactors should be able to predict the void at different points along the channel to be able to predict the effects of void on reactivity and on core pressure drop as well as the transient behaviour which could lead to burnout. A diagram of flow pattern development, coolant and wall temperature profiles, and heat transfer regimes in a heated vertical channel with uniform axial power distribution is shown in Figure 1.1. OSV can occur in the subcooled boiling or saturated nucleate boiling regions of the bubbly flow.

Flow regimes in horizontal channels tend to be more complex than those in vertical channels because of the asymmetry of the phases resulting from the influence of gravity, which makes the heavier liquid accumulate at the bottom of the channel. But as far as the OSV point is concerned, the influence of gravity is very small because of the very low void fraction in this region. So the development of a horizontal flow before and at the

Figure 1.1 Development of Two-phase Flow in a Heated Vertical Channel (Ref.[5], Fig.4.13)

OSV point is similar to that in a vertical flow. The effect of the flow direction will be further discussed in Chapter 5.

The definitions and transitions of flow regimes, the general methods of two-phase flow calculations and other two-phase flow concerned problems are described in [5] and [6].

1.2.2 Subcooled Boiling and OSV

The topic of this thesis is the onset of significant void (OSV) in channels. As mentioned before, the accurate prediction of void fraction depends on the accuracy of the prediction of the OSV point.

In subcooled boiling region, the liquid bulk temperature T_f is still below the saturation temperature and the difference between the two temperatures is often called liquid subcooling. That is

$$\Delta T_{\text{sub}} = T_{\text{sat}} - T_f \quad (1.2.1)$$

Figure 1.2 shows the development of a flow in the subcooled boiling region with high uniform heat flux from the wall. Figure 1.2.(a) shows the void fraction profile and flow bulk temperature profile in the axial direction and Figure 1.2.(b) shows the flow temperature profiles in four typical radial cross-sections.

Before point A of Figure 1.2.(a), the flow bulk temperature T_f is far

below T_{sat} , so the flow is in single-phase and its radial temperature distribution is shown in Figure 1.2.(b)-(I). As the flow is heated, T_f rises and when the flow reaches point A, a superheat water sublayer is formed as shown in the shadow area of Figure 1.2.(b)-(II). In this sublayer, liquid temperature is higher than saturation temperature, and eventually there is enough energy to allow the initiation of vaporization. Point A is called the Onset of Nucleate Boiling (ONB).

Nucleate boiling is a process in which a small bubble or nucleus is formed and grows. There are two types of nuclei. One type is formed in a pure liquid such as a high energy molecular group, resulting from thermal fluctuations of liquid molecules. The nucleation in a pure liquid is called homogeneous nucleation. It can also be triggered by ionizing radiation, e.g., a cosmic ray or gamma ray. The other type of nuclei is formed on a foreign object such as a cavity on the heated wall or suspended foreign material with a non-wetted surface. This kind of nucleation is called heterogeneous nucleation.

The superheat required for bubble nucleation corresponds to the pressure difference in the equation below, which is derived by a force balance on a spherical nucleus forming under homogeneous conditions,

$$P_s - P_f = \frac{2\sigma}{r^*} \quad (1.2.2)$$

where P_g is the vapour pressure, P_f is the imposed liquid pressure corresponding to a constant saturation temperature T_{sat} , σ is the surface tension, and r^* is the nucleus radius. The Clausius-Clapeyron equation gives the relationship between the liquid superheat and the pressure difference as:

$$\frac{dP}{dT} = \frac{H_k}{v_k T_{sat}} \quad (1.2.3)$$

which can be approximated by

$$P_g - P_f = (T_g - T_{sat}) \frac{H_k}{v_k T_{sat}} \quad (1.2.4)$$

where T_g is the superheated liquid temperature, H_k is the latent heat of evaporation, v_k is the specific volume change during evaporation. By combining Equations (1.2.2) and (1.2.4), there is:

$$r^* = \frac{2 \sigma v_k T_{sat}}{(T_g - T_{sat}) H_k} \quad (1.2.5)$$

At a certain superheat, only those nuclei with the radii greater than r^* can grow and those with the radii smaller than r^* will condense and collapse. The higher the superheat, the smaller the critical r^* .

The above equations are derived for homogeneous nucleation. In practice, the probability of homogeneous nucleation is very small, while the heterogeneous nucleation, especially that from cavities capable of trapping vapour or a dissolved gas on heated walls, is very common. Equations (1.2.2) to (1.2.5) can be applied only approximately to heterogeneous nucleation, but they correctly describe the trends of the observed behaviour of heterogeneous nucleation. In heterogeneous nucleation from a cavity on a wall, r^* is related to the size of the cavity. So, as described in the last paragraph, bubble nucleation from large size cavities starts at a certain liquid superheat, which corresponds to the ONB point, and as the superheat increases, more and more bubbles can grow up from the cavities of smaller sizes. Besides the superheat and the cavity size, the nucleation is also related to the bubble contact angle and the shape of the cavity which decides the capability of trapping vapour or a gas. Please refer [5] for details.

After the ONB point, the flow develops in the subcooled boiling region AC. This region can be, once again, divided into two sub-regions. In the region AB of Figure 1.2.(a), liquid bulk temperature is very low. So, as the generated bubbles grow, they meet the colder liquid and collapse by condensation before detaching from the wall, although some of them may slide along the wall before collapse. Since the condensation rate is higher than that of vaporization, little net vapour is generated in this region and the void fraction values are very low so that they have little practical significance to the pressure drop and heat transfer rate. But they do have effects on the reactivity, especially on those reactors operated

under low pressures (e.g. Slowpoke, Maple, etc.).

In the region BC, the subcooling (shown in Figure 1.2.(b)-(III)) and hence the bubble collapse rate are lower so that bubbles can grow larger and depart into the bulk stream. Since lots of bubbles are formed on the cavities of the heated wall as discussed before, when these bubbles depart, a small amount of vapour will be trapped in the cavities by the liquid filling in, this amount of vapour becomes new nuclei and new bubbles will grow from them. So, as the result of the low condensation rate and the new bubbles generated and growing into the main flow continuously, significant vapour is generated and the void fraction increases rapidly along the wall. It is the transition point B of the two regions that is called as the point of Onset of Significant Void (OSV). In some references, this point is also called as the Initial Point of Net Vapour Generation (IPNVG) .

As the flow is further heated, T_f reaches saturation temperature (shown in Figure 1.2.(b)-(IV)) at point C, and bulk boiling occurs. After point C, condensation ceases and the flow develops in the bulk boiling region.

Figure 1.2 Development of Subcooled boiling flow

**(a). Void Fraction and Temperature Profiles
in Axial Direction**

(I). Before Point A.

(II). At Point A
(ONB).

(III). At Point B
(OSV).

(IV). At Point C.

Figure 1.2 Development of Subcooled boiling flow
(b) Temperature Profile in Three Typical
Radial Cross-sections.

1.2.3 Characteristics of Subcooled Boiling

Since the bulk temperature is below the saturation temperature as shown in Figure 1.2.(b), subcooled boiling is characterized by the fact that thermodynamic equilibrium does not exist. So general two-phase flow calculation methods, such as the homogeneous equilibrium model [5], are not suitable for subcooled boiling calculations. Here the concept of true vapour quality may be introduced as opposed to equilibrium vapour quality. True vapour quality is the actual vapour flow rate over the total flow rate. Equilibrium vapour quality is the local vapour weight fraction calculated from a heat balance by assuming thermal equilibrium. This can be defined by the equation below

$$X_{eq} = \frac{C_p (T_f - T_{sat})}{H_{fg}} \quad (1.2.6)$$

where C_p is the specific heat of liquid. It is zero when the liquid bulk temperature equals the saturation temperature, as shown at point C in Figure 1.2.(a). In the subcooled region, X_{eq} has a negative value and Equation (1.2.6) can be written as

$$X_{eq} = - \frac{C_{p,l} \Delta T_{sub}}{H_{fg}} \quad (1.2.7)$$

Even though it has no physical meaning, it is very useful in calculations by connecting void fraction and liquid subcooling. So both X_{eq} and ΔT_{sub} are used to represent the liquid bulk condition at the OSV point. The prediction of the OSV point means the prediction of X_{eq} or ΔT_{sub} at that point.

The onset of significant void depends on many parameters, such as the geometry, pressure, flow rate, heat flux, and fluid properties. The accurate prediction of the OSV point is very difficult because of the difficulty of exact measurements to the relative effects of nucleation, bubble growth, bubble condensation, etc, and to the effect of surface conditions on nucleation. Attempts at establishing mechanism models have been made since late 1950's. Some of these models are based on the analysis of forces acting on bubbles, some based on energy balance among vaporization, condensation, and convective heat transfer, but almost all these approaches ended with using at least two empirical constants to match the experimental data. Since the void fraction in subcooled boiling region is very difficult to measure, the experimental data themselves scatter a lot. It makes the prediction more difficult. So far there are few generally accepted models. Thus lots of different predictive models and the scatter of experimental data becomes another "characteristic" of subcooled boiling.

1.3 Objective of Thesis

During the contract work for Atomic Energy of Canada Ltd. in support

of the development of the low-power SLOWPOKE reactors [7] - [10], Rogers Salcudean, et al proposed an OSV prediction model [11]. Before that, most existing models applied to boiling flows at high pressures and high flow rates since the empirical constants in these models were obtained under such operating conditions. Rogers model was developed to predict OSV for low pressure and low velocity water flows. The single empirical constant in this model was obtained from the results of their experimental work described in [12], in which the experiments were conducted under the pressure of 155 kPa and flow velocities from 0.07 to 0.475 m/s .

To make this model applicable to a wide range of pressures and flow rates, some modification is needed, which is the main objective of this thesis. To do this modification, a wide range of existing experimental data has been analyzed and this is described in Chapter 2. Some important subcooled boiling models are introduced in Chapter 3. The Rogers model and its modification are discussed in Chapter 4. Comparisons are also made in Chapter 4 among the experimental data and the predicted values by some important models. In Chapter 5, the effects of some parameters on OSV are analyzed to try to get a better understanding of OSV mechanism. In the last chapter of this thesis, some conclusions and recommendations are given.

Chapter 2

ANALYSIS OF EXPERIMENTAL DATA

2.1 Collection of Void Fraction and OSV Data

Table 2.1 shows all the experimental data collected from available literature which contains void fraction and OSV information. The investigators, sources of references, geometries, and experimental conditions, such as the pressure, flow rate, and heat flux, are listed in the table. It includes some earlier data by P. Griffith, et al and R. A. Egen, et al in the late fifties and the most recent ones by Bibeau and Salcudean in 1990. Most of the early data are at high pressures up to 150 bar, and high velocity up to 8.19 m/s , while the new data are in the lower range of close to the atmosphere pressure and 0.1 m/s velocity. So these data cover a wide range of operation conditions and the amount of data is also very large.

Since most of these investigators used water as the working fluid, and only Dix used Freon-114, the modification of Rogers' model is based on the water data, and Dix's data are used to check the applicability of the modified model to different fluids.

Table 2.1 Collection of Experimental OSV Data ¹

Investigator [Ref.]	Geometry and size mm	Pressure bar	Velocity m/s	Heat flux $W/m^2 * 10^{-3}$
G.G.Bartolemei [13]	Tube D=15.4 , 24.0	15.0-45.0	1.00-1.14	0.38-0.80
G.G.Bartolemei [14]	Tube D = 12.0	30.0-147.9	0.54-3.50	0.34-2.21
E. L. Bibeau [15]	Annulus OD ² = 21.8, ID ³ = 12.7	1.55	0.22-0.46	0.30-0.98
H.Christensen [16]	Rectangular 44.4 x 11.1	27.6-68.9	0.77-1.15	0.21-0.50
J. Costa [17]	Rectangular 38x2 , 38x3.6 Tube , D=6.0	1.735-4.985	3.17-8.19	1.0-4.2
G. E. Dix [18]	Annulus OD = 18.64 ID = 9.50	3.14-8.48	0.07-0.16	0.004-0.03
Z. Edelman [19]	Tube d = 11.3	1.013	0.10-0.19	0.049- 0.096

¹ The fluid used by Dix is Freon-114 , all others used water.

² OD = Outside Diameter

³ ID = Internal Diameter

Table 2.1 (Continue)

Investigator Ref.	Geometry and size mm	Pressure bar	Velocity m/s	Heat flux w/m² *10⁻⁶
R.A. Egen [20]	Rectangular 25.4 x 2.62	138	0.63-1.31	0.25-1.58
R.Evangelisti [21]	Annulus OD = 13.0 , ID = 7.0	1.128	0.64-1.48	0.437- 0.885
P. Griffith [22]	Rectangular 12.7 x 12.7	82.7-137.9	0.63-1.38	0.31-1.91
D.A.Labuntsov [23]	Tube D = 12.1	20.0-70.0	1.00-4.00	0.58-1.16
R. Martin [24]	Rectangular 50x2 , 50x2.8	78.48	1.03-3.03	0.4-1.7
G.W. Maurer [25]	Rectangular 25.4 x2.21	85.5-142.5	0.79-7.66	0.306- 3.786
R. McLeod [12]	Annulus OD=22,25,30 ID=13.1	1.55	0.07-0.48	0.6-1.19
S.Z.Rouhani [26]	Annulus OD = 25.0 ID = 12.0	9.8-50.0	0.15-1.54	0.3-1.21
F. W. Staub [27]	Rectangular 76.2 x 7.62	1.117-3.083	0.34-2.93	0.308- 0.792

2.2 Void Fraction Measurement and Accuracy

Most of the above experimental studies of subcooled boiling were undertaken in test loops with variable operating conditions and uniform power supply to test sections. The test sections have different geometries such as the circular tube, rectangular channel, or annular channel. Parameters of pressure, heat flux, flow rate, inlet and outlet flow temperatures, wall temperatures were generally measured. Void fraction data at different positions along the axial direction or the radial direction were taken depending on the specific purposes of tests.

There are several methods to measure the void fraction and the onset of significant void. The simplest way is direct visual observation which gives qualitative results only. The earlier void fraction data were obtained by employing high speed photographic techniques, such as those of Griffith. Photos in the axial direction and radial directions were taken. Void fraction values were obtained by counting the number of bubbles in the pictures, measuring the bubble diameters, and dividing the vapour occupied area by the total flow area.

The development of the photographic techniques was reviewed by Hewitt and Whalley [28] and Delhayé [29]. They are still widely used today to observe the behaviour of the bubble sublayer, and the two-phase flow development and characteristics. Some new techniques such as the holographic interferometry is also used in this area [30].

Methods depending on the spatial distribution of radiation absorption are widely used now in void measurements, such as X-radiography, single

or multi-beam Gamma-ray densitometry and so on. These techniques are introduced in [31]-[33]. The main principle of these methods is that the vapour phase and the liquid phase have different absorptions of X-rays or Gamma rays. Radiation beams directed across a two-phase flow are partly absorbed and the intensity of the attenuated beams is measured by a detector on the other side of the flow duct from the source. The void fraction can be determined by calibrating the instrument using lucite inserts of different sizes to represent the liquid.

One of the most important things needed to be discussed here is the accuracy of the void fraction measurement. All methods mentioned above have their own limitations. There are two main problems in photographic methods. The first one is the influence of the complex interfacial structures that give multiple reflections, and the second one is the refraction effects that obscure the view. There are also two main problems in the measurements using radiation absorption techniques. One is the effects of void distribution, and the other is the fluctuations in void fraction with time. Another source of error with gamma ray methods is the counting error from low intensity source, particularly for transient measurements. In both photographic and radiation absorption methods, the problems become more severe when void fraction values are very low. According to Martin [24], when void fraction is greater than 0.5, the scatter of data is in the order of 10%, and when void fraction is less than 0.20, the error could reach 100%. Rogers also gives the measurement error at different void ranges under experimental condition of 155 kPa pressure and 0.07 - 0.475 m/s velocity [11]. The result is listed in Table 2.2.

Table 2.2 Estimated Errors in Void Fraction [11]

α	$\delta\alpha$	$\delta\alpha/\alpha$
0.05	± 0.027	± 0.54
0.10	± 0.027	± 0.27
0.20	± 0.028	± 0.14
0.30	± 0.028	± 0.093
0.40	± 0.029	± 0.073
0.50	± 0.030	± 0.060
0.60	± 0.031	± 0.052

The problems also become severe when using the method of directly taking cross-section average void fraction values. Such as taking pictures of whole cross-section in photography methods, or using single wide beam (as wide as the channel) in X-ray or Gamma-ray densitometry methods. Using the method of the chordal mean or local void measurement and getting the cross-section average void by integrating the chordal or local values may to some extent reduce the error. For example, when $\alpha = 0.10$, using local measurement can reduce the relative error from 50% to 20% as mentioned by Martin [24]. And the more important thing is that local void measurement can provide important information on the distribution of the void in the channel. Figure 2.1 shows a multi-beam X-ray system which can be used to take the chordal mean void values.

Outline A represents rigid detector support plate
 Outline B represents lead shielding box (cut away for beam entry)

Figure 2.1 Multi-beam X-ray System for Determination of Chordal Mean Void Fraction (Ref.[6], Fig.2.1.9).

The local void can be measured by using electrical, thermal or optical probes. The size of these probes is very small so they can be put at different positions of a cross-section to measure the time average void at those points. For example, Dix developed a hot wire anemometer based on the idea that when a vapour or a liquid passes by a hot wire probe, the

heat transfer rates are different. In operation, the probe temperature is controlled at a constant value so that the power to the probe varies as the heat transfer rate changes. By recording the power fluctuation, local void fraction values can be calculated [18].

One of the newest methods for the local void measurement is using fibre-optics laser [34]. The laser probe signal is sensitive to the changes in the refractive index of the surrounding medium at the tip of the probe. If the tip of the probe is in water, the laser beam is deflected away, if it is in vapour, the laser beam is reflected back. The fluctuation in intensities of the reflected laser beam represents the alternation of the liquid or vapour phase passing by the laser probe. So the void fraction value at the probe position can be obtained by analyzing the fluctuation of the reflected beam.

Most of the data listed in Table 2.1 were collected using cross-section average radiation absorption methods, so the accuracies of these data were not very high. Edelman gave the absolute error of all his void fraction data as 0.05 void in the void range of 0 - 0.75. Egen gave the absolute error of his data as 0.045 void in the void range of 0 - 0.8. The error of the McLeod's data is as shown in Table 2.2, and the absolute error of the Bartolemei is 0.04 in the void range of 0 - 0.6. The void fraction at the OSV point is in the range of 0.04 to 0.10, the value is lower when the pressure is high and higher when the pressure is low. So the relative error in these measurements is in the range of 50% - 100%. Even though some references did not give the error analysis of their data, they should be in this range.

An additional source of error arises in establishing the OSV point, since there is no sharp demarcation in void fraction at point B of Figure 1.2. Different methods used to establish this point will be discussed in Section 2.3. In this thesis, the actual OSV data provided in a cited reference are directly used. In the cases where only void fraction profile curves are given in a reference, OSV values were determined by the method described in the next section.

2.3 Determination of Onset of Significant Void

There are several methods to determine the OSV point described in the literature. Most of them are graphical extrapolations. A typical void fraction profile curve is shown in Figure 2.2.(a). Generally, if the pressure is not very high, there will be a long flat tail before the rapid growth of the void. McLeod's OSV data were obtained by drawing a estimated best-fit line in the tail area and another one in the high quality area and taking the joint point as OSV, which is shown in Figure 2.2.(b). It is a good method in the low pressure region. Edelman extrapolated the data at higher void fraction towards the zero void fraction and got OSV data at the joint point with the quality axis [19]. This is shown in Figure 2.2.(c), and this method is good at high pressure. A similar method is described by Martin [24], in which a line tangent to the curve at the point of zero equilibrium quality is drawn and the interface point with quality axis is taken as OSV (Figure 2.2.(d)). In this thesis, OSV data are mostly found by the Martin method with compromises to other methods when the tangent line is difficult to draw

(a) Void Fraction Profile

(b) McLeod Method

(c) Edelman Method

(d) Martin Method

Figure 2.2 Methods of OSV Point Determination

or the result is not quite reasonable from the view of the concept that a rapid increase in the void fraction will occur after the OSV point.

The mathematical expression below can also be used to describe the OSV point [35].

$$\frac{d^2\alpha}{dX_{eq}^2} = 0 \quad (2.3.1)$$

where α is the void fraction and X_{eq} is the equilibrium vapour quality. The meaning of this equation is very clear. When the second order differential of α equals zero, its first order differential will be the maximum, i.e., the increasing rate of the void fraction with the equilibrium quality reaches its largest value. Even though it may best express the physical meaning of onset of significant void, most information of void fraction in literature is given in the form of profile curves so that it is difficult to use this method in practise.

As mentioned before, the uncertainty in decision of OSV point will cause some extra error in OSV values. But in thesis, some compromises are made to limit it to as small as possible. It can be said that the judgement error in determining the OSV points from void fraction curves is in the range of around 20% of equilibrium quality. Considering the large error in void fraction measurement in low quality region, this error is relatively small.

CHAPTER 3

VOID FRACTION AND OSV PREDICTION MODELS

3.1 Introduction

One of the earliest studies on the subcooled boiling mechanism was done by Griffith, Clark and Rohsenow in 1958 [22]. Griffith, et al. are the first ones to suggest that subcooled boiling could be divided into two regions. In the first region, no net vapour is generated, and in the second region, a bubble layer is formed and the void fraction increases rapidly. Then they assumed different heat transfer mechanisms and divided the total heat flux into different components in the two regions. By analyzing these components and applying the energy balance, they obtained the void fraction and liquid subcooling at OSV.

Bowring developed an important model in 1962 [36], which was quite different from Griffith's. He introduced the concept of bubble detachment. He suggested that the second region of the subcooled boiling was characterized by bubbles departing from the wall and moving into the bulk liquid stream. Bubble detachment allows new bubbles to be generated at the same nucleation site continuously; and the agitation caused by bubble detachment also causes great increase in the heat transfer rate. So these may result in a rapid increase in void fraction values. Then he proposed an empirical correlation of bubble detachment to predict the liquid

subcooling at OSV.

Griffith and Bowring's ideas are followed by most of the later studies; so the void fraction and OSV prediction models could generally be divided into two categories -- Energy balance types and Bubble detachment types. In the later part of this chapter, several important models of both types will be introduced. Since this thesis deals with the OSV problem only, models without OSV predictions are not included, even though they may have the same importance. For example, R. T. Lahey, Jr. proposed a mechanistic model to predict the void fraction in subcooled boiling region [37]. This model is thought to be the best mechanistic model up to now and is often used in practice.

3.2 Griffith Model

As mentioned before, two subcooled boiling regions were assumed in the Griffith model. In the first region, he assumed that wall heat flux could be divided into two components. One is the non-boiling component, which goes into the liquid in the same form as that of normal single phase heat transfer. Another is the boiling component, which goes to bubble generation. So, there are

$$\frac{Q}{A} = \left(\frac{Q}{A} \right)_{nb} + \left(\frac{Q}{A} \right)_b \quad (3.2.1)$$

where Q is the heat from the wall and A is the heated area, and where the subscript nb stands for non-boiling and b for boiling. The first term of the right hand side of the equation can be expressed in the form of single phase convective heat transfer, in which the wall temperature is assumed to be equal to the saturation temperature

$$\left(\frac{Q}{A} \right)_{nb} = h (T_{sat} - T_f) \quad (3.2.2)$$

where T_{sat} and T_f are the saturation temperature and liquid bulk temperature, respectively, and h is an appropriate film coefficient given by the equation below,

$$Nu = \frac{h D_e}{k_f} = 0.036 Re^{0.8} Pr^{\frac{1}{3}} \quad (3.2.3)$$

where Nu is Nusselt number, D_e is the hydraulic or equivalent diameter, k_f is liquid thermal conductivity, Re is the flow Reynolds number and Pr is the liquid Prandtl number.

Since the assumption of zero vapour generation in the first region, the boiling component of heat flux must be equal to the vapour condensation flux. So, for the second term of the right hand side in the Equation (3.2.1), there is

$$\left(\frac{Q}{A} \right)_b = \left(\frac{Q}{A} \right)_c \quad (3.2.4)$$

The expression of $(Q/A)_c$ was obtained by assuming a constant condensation heat transfer coefficient, an effective condensation area, and the liquid subcooling as driving potential. That is

$$\begin{aligned} \left(\frac{Q}{A} \right)_c &= h_c \frac{A_c}{A} (T_{\text{sat}} - T_f) \\ &= B_0 h \frac{A_c}{A} (T_{\text{sat}} - T_f) \end{aligned} \quad (3.2.5)$$

where B_0 is an empirical constant, A_c is the effective condensation area.

The pictures taken by Griffith in the first region of subcooled boiling show that the vapour is in the form of bubble strands near the heated surface. Both the effective condensation area (A_c/A) and the surface void fraction (α) are related to the strand sizes, where (α) is defined as $\alpha = a/s$, α is the void fraction and s is the characteristic dimension. The size of these strands depends on the thermal layer thickness and velocity layer thickness of the flow. By some assumptions made by Griffith, the thermal layer thickness is simplified to be proportional to k/h , and the velocity thickness to be proportional to $Pr \cdot k/h$. So the relationship between effective condensation area and the surface void fraction can be finally expressed as

$$\frac{A_c}{A} \propto \alpha \left(\frac{h}{k_f Pr} \right) \quad (3.2.6)$$

So equation (3.2.5) becomes

$$\left(\frac{Q}{A} \right)_c = \frac{B_1 a h^2 (T_{\text{sat}} - T_f)}{k_f Pr} \quad (3.2.7)$$

where B_1 is an empirical constant, which is found equal to 1.07 by correlating the experimental data.

From Equations (3.2.1), (3.2.4) and (3.2.7), the connection between void fraction and liquid subcooling can be obtained as

$$a = \frac{\left[\frac{Q}{A} - \left(\frac{Q}{A} \right)_{nb} \right] k_f Pr}{1.07 h^2 (T_{\text{sat}} - T_f)} \quad (3.2.8)$$

In the second region of subcooled boiling, Griffith assumed that all the heated surface was covered by a layer of bubbles and all the heat flux from the wall went into bubble generation. Heat transfer to the liquid core is by the means of bubble condensation. So the energy balance equation can be written as

$$\frac{Q}{A} = \left(\frac{Q}{A} \right)_b = \left(\frac{Q}{A} \right)_c + \left(\frac{Q}{A} \right)_v \quad (3.2.9)$$

where $(Q/A)_c$ is the condensation heat flux and $(Q/A)_v$ is the heat flux to the net vapour generation. Then, a constant condensation heat transfer rate is assumed, which is 5 times the rate of single phase heat transfer. So the condensation component of heat flux can be written as

$$\left(\frac{Q}{A} \right)_c = 5 h (T_{\text{sat}} - T_f) \quad (3.2.10)$$

Therefore, from Equation (3.2.9), the net heat flux to vapour generation $(Q/A)_v$. From $(Q/A)_v$, the true vapour quality can be found. After that, by assuming that the liquid phase and the vapour phase have the equal weighted mean velocities, the average void fraction can be predicted in this region.

At the interface of the first and second subcooled boiling regions, the heat flux to the net vapour generation is zero. So Equation (3.2.9) becomes

$$\frac{Q}{A} = \left(\frac{Q}{A} \right)_c \quad (3.2.11)$$

Substituting Equation (3.2.10), the liquid subcooling at the OSV point is

$$\Delta T_d = (T_{\text{sat}} - T_f)_{\text{osv}} = \frac{Q}{5 h A} \quad (3.2.12)$$

The void fraction value at OSV can be calculated by Equations (3.2.12) and (3.2.8).

The shortcoming of this model is obvious. Subcooled boiling is a very complicated phenomenon, the assumptions made by Griffith, such as in dividing heat transfer components, finding thermal and velocity layer thicknesses, the effective condensation area and condensation heat transfer rate, are too simple so that the model can not give good predictions, especially at low flow rate conditions. Besides, according to this model, single phase heat transfer exists in the first region and suddenly disappears in the second region, so there is also a discontinuity in the heat transfer mechanism.

3.3 Bowring Model

In the Griffith model, OSV was thought to be the point at which all heated surface is covered by a layer of bubbles. Unlike Griffith, Bowring suggested that the onset of significant void fraction corresponded to the point of the initial bubble detachment from the heated wall to the subcooled liquid core [36]. Bowring gave a good analysis of subcooled boiling heat transfer mechanisms and suggested that bubble detachment plays an important role in these mechanisms. As a bubble grows, it pushes superheated liquid in front of it into the subcooled bulk flow. When the bubble departs from the wall, it continues to push liquid away from the wall and meanwhile, allows colder liquid from the bulk flow to rush into the space it left. This greatly enhances the convection between the heated wall

and the liquid flow. Besides the convective heat transfer caused by bubble agitation (Φ_a), three other mechanisms were also suggested by Bowring, they were,

- (i). the latent heat content of bubbles (Φ_b),
- (ii). condensation at the top of the growing bubbles still attached to the wall (Φ_c), and
- (iii). single phase heat transfer between patches of bubbles (Φ_p).

Bowring thought the second one (Φ_c) was not important and could be neglected. So, the whole heat flux could be written as

$$\Phi = \Phi_a + \Phi_b + \Phi_p \quad (3.3.1)$$

From the analysis of bubble agitation, He assumed that Φ_a is directly related to Φ_c . So there is

$$e = \frac{\Phi_a}{\Phi_c} \quad (3.3.2)$$

where e is a constant obtained from experimental data. So the net heat flux to vapour generation is

$$\Phi_c = \frac{1}{1+e} (\Phi - \Phi_p) \quad (3.3.3)$$

Then, by replacing the whole flux in bulk boiling by the net heat to vapour generation, Bowring obtained an analogue of a bulk boiling equation to predict the vapour quality in the subcooled boiling region.

In the Bowring model, the transition criterion from the first region to the second region is quite different from the one in Griffith model. This criterion depends on the heat flux, pressure and mass flow rate. Based on the existing water void fraction data, Bowring proposed an empirical equation to predict liquid subcooling at OSV, that is

$$\Delta T_d = (14 + 0.1 P) \frac{\Phi}{V} \quad (3.3.4)$$

where the temperature is in the unit of °C, the heat flux in W/cm², the pressure in atmospheres, and the flow velocity in cm/s.

This is a very important correlation for OSV predictions since it is the first one to relate the liquid subcooling at OSV to the parameters like P, V and Φ , which play important roles in OSV mechanism. But this is also a very simple correlation and the geometric effects on the OSV is not taken into consideration. It is also dimension dependent, and is restricted to the data available at that time. It gives relatively good predictions at high velocities but very poor in low velocity region.

3.4 Rouhani Model

Like the Griffith model, Rouhani model is also a typical energy balance type of model, which is described in [38] and [39]. The heat transfer mechanism analysis in the Rouhani model is similar as that of Bowring's and three heat flux components are suggested in subcooled boiling region, they are,

- (i). single phase heat transfer $(Q/A)_{sb}$,
- (ii). steam generation $(Q/A)_b$,
- (iii). heating the amount of water which replaces the detached bubbles $(Q/A)_{pump}$, which is known as pump function.

So the energy balance equation can be written as

$$\frac{Q}{A} = \left(\frac{Q}{A} \right)_{sb} + \left(\frac{Q}{A} \right)_b + \left(\frac{Q}{A} \right)_{pump} \quad (3.4.1)$$

The single phase heat transfer area decreases as the void fraction increases, and becomes zero at the end of the first region where, like Griffith, he also assumed a bubble layer is formed and all heated surface is covered by bubbles. So, if T_s is assumed equal to T_{sat} , there is

$$\left(\frac{Q}{A} \right)_{sb} = \left(1 - \frac{\alpha}{\alpha_c} \right) h (T_{sat} - T_f) \quad (3.4.2)$$

Where h is the single phase heat transfer coefficient, α_c is the void fraction at OSV. The empirical formulation of α_c was given as

$$\alpha_c = 2.435 \times 10^{-3} P^{-0.237} \frac{P_H}{A_c} \quad (3.4.3)$$

where P is the flow pressure in N/m^2 , P_H is the heated perimeter in m , and A_c is the cross-section of the channel in m^2 .

The heat flux to steam generation is

$$\left(\frac{Q}{A}\right)_b = \dot{m}_s H_{fg} \quad (3.4.4)$$

where $\dot{m}_s$ is the vaporized mass per unit time per unit heated surface. H_{fg} is the latent heat of evaporation. The amount of water replacing the detached bubbles is $(\dot{m}_s/\rho_f)\rho_f$, so the heat flux to heat the amount of water to saturation temperature is

$$\left(\frac{Q}{A}\right)_{\text{temp}} = \frac{\dot{m}_s}{\rho_s} C_p \rho_f (T_{\text{sat}} - T_f) \quad (3.4.5)$$

where C_p is the specific heat, and ρ_g and ρ_f are the vapour and liquid density respectively. So Equation (3.4.1) can be written as

$$\frac{Q}{A} = h \theta_f \left(1 - \frac{\alpha}{\alpha_c} \right) + \dot{m}_s H_{fg} + \frac{\dot{m}_s}{\rho_s} C_{pf} \rho_f \theta_f \quad (3.4.6)$$

where $\theta_f = T_{sat} - T_f$. The first item in the right hand side is zero when $\alpha > \alpha_c$. This expression overcomes the discontinuity in heat transfer mechanism in the Griffith model.

From the above equation, the expression of the boiling heat transfer per unit time within the finite length dZ along the heated channel can be written as

$$dQ_b = \dot{m}_s H_{fg} P_H dZ$$

$$= \frac{\left(\frac{Q}{A} \right) - h \theta_f \left(1 - \frac{\alpha}{\alpha_c} \right)}{\rho_s H_{fg} + C_{pf} \rho_f \theta_f} \rho_s H_{fg} P_H dZ \quad (3.4.7)$$

The amount of heat which goes to the liquid core through the bubble condensation can be expressed as

$$dQ_c = K_c \theta_f dZ \quad (3.4.8)$$

where K_c is the condensation coefficient related to the fluid properties, mass velocity, heat flux, void and channel geometry. A correlation of K_c is given in [39].

The heat going to net vapour generation is $(dQ_b - dQ_c)$, and the finite change in the vapour fraction, i.e., the true vapour quality can be written as

$$dX = \frac{dQ_b - dQ_c}{M H_{fg}} \quad (3.4.9)$$

where M is the total mass flow rate. The finite change in the liquid subcooling is

$$d\theta_f = \frac{\left(\frac{Q}{A}\right) P_H dZ - (dQ_b - dQ_c)}{M C_{pf}} \quad (3.4.10)$$

By integrating above two equations, the true vapour quality and liquid subcooling can be obtained.

To calculate the void fraction by the true vapour quality, Rouhani assumed a slip velocity between the vapour and liquid phase and used a relationship given by Zuber and Findlay in their drift-flux model [40]. This is a big improvement compared with the Griffith model.

From Equation (3.4.3), the void fraction at the OSV point can be obtained. And by integrating Equation (3.4.10), the liquid subcooling at OSV can also be calculated. Since the result is very complicated and very hard to use to predict the OSV point in practice, it will not be introduced here.

3.5 Levy Model

Like Bowring, Levy also thought the onset of significant void is caused by the bubble detachment from the wall to the bulk flow. He made an attempt to describe the bubble departure point by analyzing the forces acting on the bubble [41] . As shown in Figure 3.1, Levy thought that there were mainly three forces acting on the bubble surface in the flow direction. They were the buoyancy force F_B and the wall shear force F_F , which act to detach the bubble from the wall, and the vertical component of the surface tension force F_S , which acts to hold the bubble on the wall. So the force balance equation was

$$F_B + F_F - F_S = 0 \quad (3.5.1)$$

Figure 3.1 Vapour Bubble Prior to Departure from Heated Surface. (Ref.[41], Fig.2)

The buoyant force F_b is given by

$$F_b = C_b g r_b^3 (\rho_f - \rho_g) \quad (3.5.2)$$

where C_b is a proportionality constant, g is the acceleration of gravity, r_b is the bubble radius, and ρ_f and ρ_g are the liquid and vapour density, respectively. The surface tension force F_s can be expressed as

$$F_s = C_s r_b \sigma \quad (3.5.3)$$

where C_s is a proportionality constant and σ is the surface tension. The frictional force F_f can be related to the pressure differential across the bubble which is proportional to $(-dp/dz)_f$, r_b and acts across an area proportional to r_b^2 , while the pressure drop per unit length $(-dp/dz)_f$ can be related to the wall shear stress τ_w and the hydraulic diameter D_e . So F_f can be expressed as

$$F_f = C_f \frac{\tau_w}{D_e} r_b^3 \quad (3.5.4)$$

where C_f is a proportionality constant, and D_e can be calculated by

$$D_e = \frac{4 A_c}{P_w} \quad (3.5.5)$$

where A_c is the cross-section area, and P_w is the wetted perimeter. Therefore, Equation (3.5.1) can be written as

$$C_B g r_b^3 (\rho_f - \rho_g) + C_F \frac{\tau_w}{D_c} r_b^3 - C_S r_b \sigma = 0 \quad (3.5.6)$$

And the bubble radius r_b could be obtained by solving this equation.

Then Levy suggested that the distance from the wall to the bubble tip Y_b is proportional to r_b , so the non-dimensional form of Y_b can be written as

$$Y_b^+ = C \frac{(\sigma D_c \rho_f)^{\frac{1}{2}}}{\mu_f} \left(1 + C' \frac{g (\rho_f - \rho_g) D_c}{\tau_w} \right)^{-\frac{1}{2}} \quad (3.5.7)$$

where

$$Y_b^+ = Y_b \frac{\rho_f}{\mu_f} \sqrt{\frac{\tau_w}{\rho_f}} \quad (3.5.8)$$

where μ_f is the liquid dynamic viscosity.

Finally, Levy assumed that the temperature distribution away from the wall was the same as that of the single phase fully developed turbulent flow, and the temperature at Y_b would at least equal the saturation temperature, then using the Martinelli temperature distribution equations

[42], he established the relationship between the liquid subcooling and flow conditions at OSV.

There are two empirical constants in Equation (3.5.7), C and C' , which were found by the experimental data as

$$C = 0.015, \quad \text{and} \quad C' = 0$$

The zero value of C' means that the buoyancy force plays no role in the force balance hence the bubble departure. The reason he got this result is that the data he used to find C and C' were mainly obtained under high pressure and high velocity operation conditions where the buoyancy force can be neglected. But this is not the truth at low flow conditions under which the buoyancy force becomes important. So this is a main limitation of the Levy model.

3.6 Zuber Model

Zuber proposed a simple, easy-to-use criterion for the OSV point [43]. Three non-dimensional parameters were used in his analysis, they were

(i). Stanton number, which is defined as

$$St = \frac{q_w''}{G C_p \Delta T_s} \quad (3.6.1)$$

where q_w'' is the heat flux and G is the mass flow rate.

(ii). Nusselt number, which is defined as

$$Nu = \frac{q_w'' D_e}{k_f \Delta T_d} \quad (3.6.2)$$

(iii). Peclet number, which is defined as the ratio of the Nusselt number and the Stanton number as below

$$Pe = \frac{Nu}{St} = \frac{G D_e C_p}{k_f} \quad (3.6.3)$$

Zuber correlated experimental data in terms of the Stanton number and the Peclet number, and obtained a result as shown in Figure 3.2.

There are two regions in the figure. Zuber called them the thermally controlled region where OSV was determined by a constant Nusselt number and the hydrodynamically controlled region where OSV is determined by a constant Stanton number. The first region usually represents the low flow rate region, and the second represents the high flow rate region.

Zuber assumed that bubble detachment from the wall was a necessary but not a sufficient condition for OSV. In the thermally controlled region, that is where Pe is less than 70,000, when the subcooling is too high, detached bubbles will immediately condense as moving to the liquid core, so

Figure 3.2 Stanton Number versus Peclet Number
at OSV Point. (Ref.[43], Fig.2)

there will be no rapid increase in the void fraction. The bubbles have to flow further along the wall until the liquid subcooling is reduced significantly so that the effect of vapour condensation is compensated by evaporation. From Figure 3.2, Zuber found this condition was satisfied when the local Nusselt number reached 455. In the second region where Pe is greater than 70,000, bubble detachment is the only condition to OSV, that is when Stanton number reaches 0.0065. From Figure 3.2, it can be noted that in this region, when $St = 0.0065$, Nusselt number has already reached 455. So the OSV criterion can be expressed as

$$Nu = \frac{q_w'' D_e}{k_f \Delta T_d} = 455 \quad , \quad \text{if } Pe \leq 70,000 \quad (3.6.4)$$

and

$$St = \frac{q_w''}{G C_{pf} \Delta T_d} = 0.0065 \quad , \quad \text{if } Pe > 70,000 \quad (3.6.5)$$

Hence, the liquid subcooling at OSV is

$$\Delta T_d = 0.0022 \frac{q_w'' D_e}{k_f} \quad , \quad \text{if } Pe \leq 70,000 \quad (3.6.6)$$

and

$$\Delta T_d = 154 \frac{q_w''}{G C_{pf}} \quad , \quad \text{if } Pe > 70,000 \quad (3.6.7)$$

One point may be argued in this model is that the constant Nusselt number at OSV in the first region means that flow velocity has no effect on the OSV point, while experiments show that it does have.

3.7 Rogers Model

The model proposed by Rogers, Salcudean, et al [11] (which will be

referred to subsequently, for convenience, as the Rogers model) is based on the investigation of Al-Hayes and Winterton [44] on the bubble detachment and their own experimental results [12] at low pressure and low flow rate conditions. It is a bubble detachment type model with only one empirical constant. This model will be introduced in detail in the next chapter where it will be modified to allow for higher pressures and velocities.

3.8 Other Models

There are also some other models in literature. Some of them are the energy balance type, such as the Ahmad model [45] which used an empirical correlation of the liquid phase heat transfer coefficient to predict heat flux to the net vapour generation and the subcooling at the OSV point. Larsen and Tong model [46], Costa model [17], Dix model [18], etc, also belong to this category. An example for the force balance type models is the Staub model [47], which is similar as the Levy model but with different forms of force expressions. Since they are more or less limited by their own data used to derived these models, there will be no detailed introduction of them here.

Chapter 4

ROGERS MODEL AND ITS MODIFICATION FOR HIGHER PRESSURES AND VELOCITIES

4.1 Rogers Model

Rogers, Salcudean, et al have developed an OSV prediction model based on the investigation of Al-Hayes and Winterton on the bubble detachment and the approach of Levy on the temperature distribution in predicting the liquid subcooling at the bubble detachment.

Al-Hayes and Winterton conducted an experimental study on bubble departure behaviour [44]. Their bubble detachment model was based on this experiment so it is more fundamental than the Levy model or others. The main difference in Winterton's model is that the force analysis is based on the distorted bubble shape caused by the forces acting on the bubble, which is closer to the real bubble shape than the spherical one assumed by Levy in his force analysis.

By using Winterton's analysis, three forces were assumed to be acting on the bubble in the flow direction in Rogers model. Two of them are the buoyant and drag force, which act as detaching forces; the other is the component of surface tension force in the flow direction, which acts as the holding force. Bubble departure occurs only when the detaching forces overcome the holding force.

Figure 4.1 Bubble Shapes Under the Acting Forces

The buoyant force was calculated by assuming that bubbles have the shape as shown in Figure 4.1.(a). The contact angle with the surface equals to the equilibrium contact angle θ_0 . So there is

$$F_b = \rho_f g \frac{\pi r_b^3}{3} (2 + 3\cos\theta_0 - \cos^3\theta_0) \quad (4.1.1)$$

where ρ_f is the liquid density, g is the acceleration of gravity, and r_b is the bubble radius.

The drag force is proportional to the projected area of the bubble which faces the flow. It is also proportional to the dynamic pressure of the flow at the position of bubble centre height. So there is

$$F_d = C_d \frac{\rho_f u_r^2}{2} r_b^2 (\pi - \theta_0 + \cos\theta_0 \sin\theta_0) \quad (4.1.2)$$

where u_r is the liquid velocity at the distance y_r , while

$$y_r = \frac{y_b}{2} = \frac{r_b}{2} (1 + \cos\theta_0) \quad (4.1.3)$$

The drag coefficient C_d in (4.1.2) was obtained from the experimental result of Winterton,

$$C_d = 1.22 \quad \text{for} \quad Re_b \geq 20 \quad (4.1.4)$$

$$C_d = \frac{24}{Re_b} \quad \text{for} \quad 4 < Re_b < 20 \quad (4.1.5)$$

where Re_b is the bubble Reynolds number defined as

$$Re_b = \frac{\rho_f u_r (2r_b)}{\mu_f} \quad (4.1.6)$$

where μ_f is the liquid dynamic viscosity.

Under the effects of the buoyant force and the drag force, the bubble undergoes a distortion as shown in Figure 4.1.(b). The contact angle at the upstream stagnation point becomes θ_a , which is called the advancing contact angle, and that at the downstream becomes θ_r , which is called the receding contact angle. From the experimental study of Winterton, the two angles have the values of

$$\theta_s = \theta_0 + 10^\circ \quad (4.1.7)$$

$$\theta_r = \theta_0 - 10^\circ \quad (4.1.8)$$

By assuming reasonable variations of the contact angle at intermediate points around the periphery of the contact line, the net surface tension force in the flow direction can be expressed as

$$F_s = C_s \frac{\pi}{2} r_b \sigma \sin \theta_0 (\cos \theta_r - \cos \theta_s) \quad (4.1.9)$$

where σ is the liquid surface tension, C_s is an empirical correction factor given by

$$C_s = \frac{58}{\theta_0 + 5} + 0.14 \quad (4.1.10)$$

where θ_0 is in degree.

The force balance equation at the bubble detachment point is

$$F_b + F_d - F_s = 0 \quad (4.1.11)$$

By substituting equations (4.1.1), (4.1.2) and (4.1.9) into the above equation, bubble radius at departing can be expressed as

$$r_b = \frac{3}{4\pi} \frac{C_2}{C_1} C_d \frac{u_r^2}{g} \left[\left(1 + \frac{8\pi^2}{3} \frac{C_1 C_s}{C_2^2} \frac{C_d}{C_d^2} \frac{g \sigma}{\rho_f u_r^4} \right)^{\frac{1}{2}} - 1 \right] \quad (4.1.12)$$

where

$$C_1 = 2 + 3 \cos \theta_0 - \cos^3 \theta_0 \quad (4.1.13)$$

$$C_2 = \pi - \theta_0 + \cos \theta_0 \sin \theta_0 \quad (4.1.14)$$

$$C_3 = \sin \theta_0 (\cos \theta_r - \cos \theta_a) \quad (4.1.15)$$

To calculate the velocity u_r at y_r at the departure point, two non-dimensional parameters are applied. One is the non-dimensional distance defined as in Equation (4.1.16), and the other is the non-dimensional velocity defined as in Equation (4.1.17).

$$y^* = y \frac{\rho_f}{\mu_f} \sqrt{\frac{\tau_w}{\rho_f}} \quad (4.1.16)$$

and

$$u^* = \frac{u}{u^*} = \frac{u}{\sqrt{\frac{\tau_w}{\rho_f}}} \quad (4.1.17)$$

where τ_w is the shear stress at the wall given by

$$\tau_w = \frac{1}{2} f \rho_f V^2 \quad (4.1.18)$$

where V is the velocity at the bubble departure point, which can be taken as the channel inlet velocity since the liquid is assumed incompressible and the void volume at OSV is very small. The friction factor f is calculated by the equation for the fully developed single phase turbulent flow over a hydraulic smooth surface, that is

$$f = 0.046 Re^{-0.2} \quad (4.1.19)$$

So, the non-dimensional distance from the wall to the bubble centre is

$$y_r^+ = \frac{1}{2} r_b (1 + \cos\theta_0) \frac{\rho_f}{\mu_f} \sqrt{\frac{\tau_w}{\rho_f}} \quad (4.1.20)$$

u^+ can be calculated by using the universal velocity distribution for turbulent flow on a hydraulic smooth surface, that is

In the viscous sublayer where $y^+ \leq 5.0$

$$u^+ = y^+ \quad (4.1.21)$$

In the buffer layer where $5.0 < y^+ \leq 30$

$$u^+ = 5.0 \ln y^+ - 3.08 \quad (4.1.22)$$

In the turbulent core where $y^+ > 30$

$$u^+ = 2.5 \ln y^+ + 5.5 \quad (4.1.23)$$

From equations (4.1.12), (4.1.20) and one of (4.1.21)-(4.1.23), the bubble radius at departure can be obtained, hence the distance from the wall to the bubble tip y_b which is equal to $2y_r$.

To calculate the liquid subcooling at OSV, Levy's approach is adopted. As mentioned in Chapter 1, if a bubble can depart from the wall without collapse immediately after departure, the liquid superheat at the bubble tip must exceed the value corresponded to the Equation (1.2.4). To simplify the calculation, it is assumed that the liquid temperature at the bubble tip is at least equal to the saturation temperature. Then the Martinelli Equations are used for the temperature distribution from the wall to bubble tip, that is

In the viscous sublayer where $y^+ \leq 5.0$

$$T^* = Pr_f y^+ \quad (4.1.24)$$

In the buffer layer where $5.0 < y^+ \leq 30$

$$T^* = 5 \left[Pr_f + \ln \left(1 + Pr_f \left(\frac{y^+}{5} - 1 \right) \right) \right] \quad (4.1.25)$$

In the turbulent core where $y^+ > 30$

$$T^* = 5 \left[Pr_f + \ln (1 + 5Pr_f) + 0.5 \ln \left(\frac{y^+}{30} \right) \right] \quad (4.1.26)$$

where Pr_f is the liquid Prandtl number, and T^* is defined as

$$T^* = \frac{C_H \rho_f u^*}{q''} (T_w - T) \quad (4.1.27)$$

At the bubble tip y_b , the temperature T_b is set equal to the saturation temperature. The relationship between the wall and bulk temperature is given by

$$T_w - T_f = \frac{q''}{h_0} \quad (4.1.28)$$

Here, the heat transfer coefficient in the first subcooled boiling region is assumed to be the same as that for fully-developed single-phase turbulent flow over a smooth surface, so h_0 is given by

$$\frac{h_0 De}{k_f} = 0.023 Re^{0.8} Pr_f^{0.4} \quad (4.1.29)$$

where De is the equivalent diameter given by Equation (3.5.5).

From Equation (4.1.27) and (4.1.28), the liquid subcooling at OSV can be expressed as

$$\Delta T_s = (T_w - T_f)_{OSV} = q'' \left(\frac{1}{h_0} - \frac{T_b^*}{C_H \rho_f u^*} \right) \quad (4.1.30)$$

In the above model, the friction factor, heat transfer coefficient, velocity and temperature distributions are based on relationships for the smooth surface. At the OSV point, a bubble layer is formed and it almost covers all the wall. The bubble-covered surface will act more like a rough than a smooth surface, so using the relationships for smooth surface at this situation will cause some error. The roughness of the surface will affect both terms in Equation (4.1.30), so a correction factor F_R , which is called the rough surface factor, is arbitrarily inserted into the first term, and Equation (4.1.30) becomes

$$\Delta T_d = q'' \left(\frac{1}{F_R h_0} - \frac{T_b^*}{C_H \rho_f u^*} \right) \quad (4.1.31)$$

From the experimental results of [12], the factor is found to be

$$F_R = 1.11 \pm 0.036 \quad \text{for } \theta_0 = 30^\circ \quad (4.1.32)$$

$$F_R = 1.06 \pm 0.022 \quad \text{for } \theta_0 = 80^\circ \quad (4.1.33)$$

Since this value is only good for the low pressure of 155 kPa and low flow velocities from 0.15 to 0.5 m/s, the correlation of F_R for all pressures and velocities is needed to make this model applicable to a wide range of operation conditions. The purpose of this thesis is to establish such a correlation.

4.2 Correlation of Rough Surface Factor

As mentioned in the last section, Equation (4.1.30) is derived by using some relationships for a smooth surface, while the existence of a bubble layer at the OSV point makes the channel wall behave more like a rough one. The surface roughness will effect both terms in Equation (4.1.30) by its effects on the heat transfer coefficient for the first term and on the friction factor, velocity profile and temperature profile for the second term.

Generally, the effect of surface roughness on the friction factor f is given by Moody curves [48]. The friction factor increases as the relative roughness goes up. The effect of this increase on the second term of Equation (4.1.30) can be analyzed as below. The increased friction factor will enlarge the wall shear stress τ_w calculated by Equation (4.1.18), and this will make the denominator of the second term of Equation (4.1.30) increase since it makes u^* increase as shown in Equation (4.1.17). The increase of τ_w also changes the velocity profile and temperature profile as shown in Equation (4.1.16) and equation groups of (4.1.21) - (4.1.23) and (4.1.24) - (4.1.26). This change will make the numerator of the second term of Equation (4.1.30) increase as well, but the order of this increase is lower than that in the denominator.

Surface roughness will increase the heat transfer coefficient h_0 , but the effect is less than that on the friction factor. The rough expression of Equation (4.2.1) can be used to predict the heat transfer coefficient for rough surface from the friction factor for the same surface under the same

dynamic conditions [49],

$$\frac{h_{0R}}{h_{0S}} = \left(\frac{f_R}{f_S} \right)^{\frac{1}{2}} \quad (4.2.1)$$

where the subscript R refers to the rough surface and S refers to the smooth surface. So the existence of the bubble layer also make the denominator of the first term of Equation (4.1.30) increase. By Equation (4.2.1), this change is in the same order as that in the second term denominator.

To represent the effect of the bubble layer or surface roughness on the friction factor and the heat transfer coefficient, a correlation factor F_f is arbitrarily inserted into the denominator of the first term of Equation (4.1.30). From above analysis, the factor should have the value of greater than 1.

The bubble layer varies with the operation conditions, so the roughness, hence the rough surface factor, will change as well. A correlation of F_f varying with operation conditions will be made in the rest of this section. As the first approach, the changes of F_f with the experimental conditions are calculated using the experimental results listed in Table 2.1. The operation conditions of each data point, its geometry, pressure, mass flow rate, heat flux, and the measured liquid subcooling at OSV are given in Appendix 1.

The correlation of F_f using experimental conditions and results will also account for the variation of the other empirical parameters in the

Rogers model as the pressure and velocity vary. These parameters are C_d and C_v , as well as θ_i and θ_r .

The calculation of F_b is done by substituting the experimental condition of each point into the Rogers model, rewriting equation (4.1.31) as

$$F_R = \frac{1}{h_0 \left(\frac{\Delta T_d}{q''} + \frac{T_b^*}{C_{p_f} \rho_f u^*} \right)} \quad (4.2.2)$$

and then taking the measured subcooling as ΔT_d and substituting it into this equation. The F_b values for each of experimental point are listed in Appendix 2. Figure 4.2 and Figure 4.3 show the changes of F_b with pressures at the bubble equilibrium contact angles of 30 and 80 degree, respectively. The literature research by Rogers [50] indicated that the bubble equilibrium contact angle at the departure point is in the range of 30 - 80 degree. In the later studies of this thesis, both limit angles, 30 and 80 degree, are used for the OSV evaluation. Figure 4.4 and Figure 4.5 show the changes of F_b with flow velocities. All the four figures show the trends that F_b rises with the increases of pressure and velocity. These trends can be roughly explained as below. As indicated by Moody curves [48], the increase of the friction factor with the relative roughness in high Reynolds number region is greater than that in low Reynolds number region, especially in the region of $10^4 \leq Re \leq 10^6$, the range of almost all the experimental data. So the influence of roughness, hence F_b , increases as the velocity goes up. As the pressure goes up, the saturation temperature,

at which the properties are evaluated, goes up as well, and this makes the properties change. For example, the dynamic viscosity decreases rapidly and this will increase the Reynolds number. So the influence of the pressure on F_1 is the same as that of the velocity.

According to the trends mentioned above, the correlation of F_1 is assumed to have the forms of

$$F_R = 1 + a P^n + b V^n \quad (4.2.3)$$

or

$$F_R = 1 + a P^n V^n \quad (4.2.4)$$

Then the least square method is used to solve for the coefficients in the equations to get the best fit lines. The maximum error and the standard deviation of these fittings are calculated and analyzed. The results show that the following equations have the simplest form and give relatively good fittings to F_1 data calculated by Equation (4.2.2).

$$F_R = 1 + 0.00338 P + 0.0808 V \quad \text{for } \theta_0 = 30^\circ \quad (4.2.5)$$

and

$$F_R = 1 + 0.00257 P + 0.0646 V \quad \text{for } \theta_0 = 80^\circ \quad (4.2.6)$$

where P is in units of bar, and V in units of m/s. The standard deviations of the two equations will be given in Table 4.1.

To eliminate the effect of dimensions, a non-dimensional form

$$F_R = 1 + a \frac{P}{P_c} + b Re \quad (4.2.7)$$

is assumed, where P_c is the critical pressure. By the least square method, the following equations are obtained

$$F_R = 1 + 0.469 \frac{P}{P_c} + 2.16 \times 10^{-6} Re \quad \text{for } \theta_0 = 30^\circ \quad (4.2.8)$$

and

$$F_R = 1 + 0.348 \frac{P}{P_c} + 1.72 \times 10^{-6} Re \quad \text{for } \theta_0 = 80^\circ \quad (4.2.9)$$

Their standard deviations will be given in Table 4.1 as well.

Since F_l is a factor related to the rough surface caused by the bubble layer, there must be more fundamental connections between F_l and bubble layer characteristics. So the relations between F_l and the bubble Reynolds number, Weber number and Froude number were studied. Here, bubble Reynolds number is the same as defined in Equation (4.1.6), that is

$$Re_b = \frac{\rho_f u_r (2 r_b)}{\mu_f} \quad (4.2.10)$$

Bubble Weber number is defined as

$$We_b = \frac{\text{Bubble dynamic force}}{\text{Bubble surface tension}}$$

$$= \frac{\rho_f u_r^2 (2 r_b)}{\sigma} \quad (4.2.11)$$

Bubble Froude number is defined as

$$Frou_b = \frac{\text{Bubble dynamic force}}{\text{Bubble buoyant force}}$$

$$= \frac{u_r^2}{g (2 r_b)} \quad (4.2.12)$$

These non-dimensional numbers for each experimental point were calculated and listed in Appendix 2. Figure 4.6 to Figure 4.10 show the relations between F_b and Re_b , We_b , $Frou_b$ respectively. A very interesting one among them is Figure 4.8, curves of F_b versus bubble Weber number. It shows that below a certain bubble Weber number, F_b remains essentially constant, while the bubble Weber number itself becomes constant at that value. It is obvious that in the second region, bubble Weber number cannot be used to correlate F_b . The meaning of this constant Weber number will be discussed in Chapter 5. The relations between F_b and bubble Reynolds number is more regular than that with Froude number. By analyzing Equation (4.2.10), it can be seen that bubble Reynolds number is

related to r_f which can represent the roughness of the surface, u_f which is affected by the velocity profile, and the properties ρ_f and μ_f which are affected by the pressure through the saturation temperature. So using bubble Reynolds number to correlate F_f seems to be a good approach.

According to the trends in Figure 4.6 and 4.7, the best fit line is assumed to have the form of

$$F_R = 1 + a (Re_b)^m \quad (4.2.13)$$

Once again, the coefficients are found by the least square method, and the final results are

$$F_R = 1 + 28.61 Re_b^{-1.0} \quad \text{for } \theta_0 = 30^\circ \quad (4.2.14)$$

and

$$F_R = 1 + 240.0 Re_b^{-1.31} \quad \text{for } \theta_0 = 80^\circ \quad (4.2.15)$$

Table 4.1 is the summary of the correlations and their maximum errors and standard deviations to the F_f data calculated from experimental results. The standard deviation shows that using bubble Reynolds number to do the correlation gives the best results. Since it is non-dimensional, theoretically speaking, it can be used for any liquid.

Table 4.1 The Correlations

Correlations	Maximum Error*	Standard Deviation**
For $\theta_0=30^\circ$:		
$F_R = 1 + 0.00338 P + 0.0808 V$	0.627	0.0935
$F_R = 1 + 0.469 \frac{P}{P_c} + 2.16 \times 10^{-6} Re$	0.850	0.1017
$F_R = 1 + 28.61 Re_b^{-1.0}$	0.543	0.0884
For $\theta_0=80^\circ$:		
$F_R = 1 + 0.00257 P + 0.0646 V$	0.550	0.0825
$F_R = 1 + 0.348 \frac{P}{P_c} + 1.72 \times 10^{-6} Re$	0.730	0.0917
$F_R = 1 + 240.0 Re_b^{-1.3}$	0.342	0.0848

$$* \text{ Maximum Error} = \max_{i=1}^n |F_{R_{cal}} - F_{R_{exp}}|_i$$

$$** \text{ Standard Deviation} = \sqrt{\frac{\sum_{i=1}^n \left(\frac{F_{R_{cal}} - F_{R_{exp}}}{F_{R_{cal}}} \right)^2}{n-1}}$$

Figure 4.2 F_l versus Pressure at $\theta_0 = 30^\circ$

Figure 4.3 F_l versus Pressure at $\theta_0 = 80^\circ$

Figure 4.4 F_r versus Velocity at $\theta_0 = 30^\circ$

Figure 4.5 F_r versus Velocity at $\theta_0 = 80^\circ$

Figure 4.6 F_l versus Bubble Reynolds No. at $\theta_0 = 30^\circ$

Figure 4.7 F_L versus Bubble Reynolds No. at $\theta_0 = 80^\circ$

Figure 4.8 F_r vs Bubble Weber No. at $\theta_0 = 30^\circ$ and $\theta_0 = 80^\circ$

Figure 4.9 F_1 vs Bubble Froude No. at $\theta_0 = 30^\circ$

Figure 4.10 F_1 vs Bubble Froude No. at $\theta_0 = 80^\circ$

4.3 Comparisons among Model Predictions and Experimental Data

The modification to the Rogers model can be made by using the F_1 correlations obtained in the last section in Equation (4.1.31). To evaluate the result of the modification, comparisons among some model predictions and experimental data were made. The Bowring model, Levy model, Zuber model, original Rogers model and two forms of the modified Rogers model are chosen to do the comparisons. One form of the modified Rogers model is denoted by the superscript 1, and it uses the F_1 correlation given by Equation (4.2.14) and (4.2.15), i.e., modifies the model by bubble Reynolds number. The other form is denoted by the superscript 2, and it uses the F_1 correlation given by Equation (4.2.5) and (4.2.6), i.e., modifies the model by the pressure and velocity.

Computer programs were written to use these models to calculate the liquid subcooling at the OSV point under each experimental condition. The computer codes are given in Appendix 3. The vapour properties in the models were evaluated at the saturation temperatures. The liquid properties should be evaluated at the bulk or film temperature, but to simplify the calculation, they were also evaluated at the saturation temperatures. This may cause some error, but the effect should not be too much. The property values at different saturation temperatures are obtained by linear interpolation using Table A.3 of [5]. The calculated results of model predictions are listed in Appendix 4. They are also plotted in Figures 4.11 to 4.19. According to the pressure, the data in these figures are divided into four groups and each group is denoted by a different symbol to observe whether a model gives a good prediction or not in a certain

pressure region. Table 4.2 shows the maximum and standard deviations of these model predictions to the experimental data.

Among these models, the Bowring model didn't predict well. It over predicted the liquid subcooling in most cases and the deviations are very large. The Levy model gives a good prediction in middle and high pressure regions, but it over predicts in most low pressure cases. It predicts some low pressure data well, such as the Costa data in the left bottom corner in Figure 4.12, this is because that though the Costa data are at low pressures, the flow velocities are very high. From Table 4.2, it can be seen that the Zuber model is better than Levy model, but from Figure 4.13 and Appendix 4, it is obvious that the Zuber model often gives a constant prediction in spite of the changes of operation conditions. The reasons why the above three models have deviation in predictions have been discussed in Chapter 3.

The best one among these models is the modified Rogers model¹ by bubble Reynolds number. Even so, there are some points at which the differences between predicted values and experimental data are very large. By studying Figures 4.16, 4.17, Appendix 2 and 4, it can be found that these points are mostly for the cases of very low pressures and the flow velocity less than 0.2 m/s, such as the Edelman data and part of the McLeod data. Velocities below 0.15 m/s were excluded from the original Rogers model since some of the assumptions in the model did not apply at very low velocity [11]. Some of the Rouhani data were also obtained at the velocities below 0.2 m/s but the pressures about 10 bar or higher. The modified Rogers model gives good predictions for these data. Further

investigation of the data showed that the Reynolds numbers for these Rouhani data are over 10^4 , while the data for which the modified Rogers model gives very poor predictions, such as the Edelman data and part of the McLeod data mentioned above, have the Reynolds numbers from 3,863 to 8,919. So a criterion for the validity of the modified Rogers model can be set as:

$$Re \geq 10^4 \quad (4.3.1)$$

For the flows of Reynolds number below 10^4 , the modified Rogers model¹ will not predict well. Since the criterion is non-dimensional, it should also be good to evaluate the studies using non-water fluids.

By eliminating the data of Reynolds number below 10^4 from the data file and re-correlating the rough surface factor F_R , the new correlations were obtained as below,

$$F_R = 1 + 17.58 Re_b^{-0.89} \quad \text{for } \theta_0 = 30^\circ \quad (4.3.2)$$

and

$$F_R = 1 + 58.86 Re_b^{-1.03} \quad \text{for } \theta_0 = 80^\circ \quad (4.3.3)$$

By using the new data file and the new correlations for the modified Rogers model¹ to re-calculate the maximum and standard deviations of model predictions, Table 4.3 was obtained. The comparisons between predicted values by the modified Rogers model¹ and experimental data within the valid boundary are plotted in Figures 4.20 and 4.21 for $\theta_0 = 30^\circ$ and $\theta_0 = 80^\circ$, respectively. From the two figures, as well as the Table 4.3, It can be seen that the deviations are greatly reduced.

From the above analysis, the conclusion is either Equation (4.3.2) or Equation (4.3.3) can be used as the final form of the F_1 correlation for the modification of the Rogers model if $\theta_0 = 30^\circ$ or $\theta_0 = 80^\circ$ is assumed in the model respectively. The valid region of the modified model is $Re \geq 10^4$. The standard deviation of the model prediction is about 35 % .

If other equilibrium contact angle than 30° or 80° is assumed in the model, the F_1 correlation will change. Appendix 5 gives a table of correlations for different equilibrium contact angles and their deviations of predictions in 5° interval. From this table, it can be seen that the accuracies of these predictions are about the same.

Table 4.2 The maximum deviations and the standard deviations of model predictions.

		Maximum deviation ¹	Standard deviation ²²
Levy Model		45	0.932
Zuber Model		47	0.819
Bowring Model		125	2.040
Rogers Model,	$\theta_b = 30^\circ$	42	1.141
	$\theta_b = 80^\circ$	48	1.110
Mod'd Rogers Model ¹ ,	$\theta_b = 30^\circ$	34	0.517
	$\theta_b = 80^\circ$	35	0.540
Mod'd Rogers Model ² ,	$\theta_b = 30^\circ$	101	1.365
	$\theta_b = 80^\circ$	83	1.057

$$\bullet \text{ Maximum Deviation} = \max_{i=1}^n \left| \left(\frac{\Delta T_d}{q''} \right)_{exp} - \left(\frac{\Delta T_d}{q''} \right)_{pre} \right|_i$$

$$\bullet\bullet \text{ Standard Deviation} = \sqrt{\frac{\sum_{i=1}^n \left(\frac{\left(\frac{\Delta T_d}{q''} \right)_{exp} - \left(\frac{\Delta T_d}{q''} \right)_{pre}}{\left(\frac{\Delta T_d}{q''} \right)_{exp}} \right)^2}{n-1}}$$

¹ Modified Rogers Model by Bubble Reynolds Number

² Modified Rogers Model by Pressure and Velocity

Table 4.3 The maximum deviations and the standard deviations of model predictions ($Re \geq 10^4$).

		Maximum deviation ¹	Standard deviation ²
Levy Model		24	0.578
Zuber Model		31	0.563
Bowring Model		81	0.717
Rogers Model,	$\theta_0 = 30^\circ$	28	1.142
	$\theta_0 = 80^\circ$	24	1.074
Mod'd Rogers Model ¹	$\theta_0 = 30^\circ$	23	0.360
	$\theta_0 = 80^\circ$	26	0.338
Mod'd Rogers Model ² ,	$\theta_0 = 30^\circ$	27	0.457
	$\theta_0 = 80^\circ$	33	0.360

$$* \text{ Maximum Deviation} = \max_{i=1}^n \left| \left(\frac{\Delta T_d}{q''} \right)_{exp} - \left(\frac{\Delta T_d}{q''} \right)_{pre} \right|_i$$

$$** \text{ Standard Deviation} = \sqrt{\frac{\sum_{i=1}^n \left(\frac{\left(\frac{\Delta T_d}{q''} \right)_{exp} - \left(\frac{\Delta T_d}{q''} \right)_{pre}}{\left(\frac{\Delta T_d}{q''} \right)_{exp}} \right)^2}{n-1}}$$

¹ Modified Rogers Model by Bubble Reynolds Number

² Modified Rogers Model by Pressure and Velocity

2

A resolution test chart featuring several groups of horizontal and vertical lines of varying thicknesses. Each group is accompanied by a numerical value indicating the resolution. The values include 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, 4.5, 5.0, 5.6, 6.3, 7.1, 8.0, 9.0, 10, 11.2, 12.5, 14, 16, 18, 20, 22.5, 25, 28, 32, 36, 40, 45, 50, 56, 63, 71, 80, 90, 100, 112, 125, 140, 160, 180, 200, 225, 250, 280, 320, 360, 400, 450, 500, 560, 630, 710, 800, 900, 1000, 1120, 1250, 1400, 1600, 1800, 2000, 2250, 2500, 2800, 3200, 3600, 4000, 4500, 5000, 5600, 6300, 7100, 8000, 9000, 10000.

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Figure 4.11 Comparison between experimental values and Bowring model predictions of $\Delta T_d/q''$.

$\Delta T_d - ^\circ\text{C}, \quad q'' - \text{W/m}^2$

Figure 4.12 Comparison between experimental values and Levy model predictions of $\Delta T_f/q''$.

$$\Delta T_f - ^{\circ}\text{C}, \quad q'' - \text{W}/\text{m}^2$$

Figure 4.13 Comparison between experimental values and Zuber model predictions of $\Delta T_d/q''$.

$$\Delta T_d - ^{\circ}\text{C}, \quad q'' - \text{W}/\text{m}^2$$

Figure 4.14 Comparison between experimental values and Rogers model predictions of $\Delta T_f/q''$ for $\theta_0 = 30^\circ$.
 ΔT_f - $^\circ\text{C}$, q'' - W/m^2

Figure 4.15 Comparison between experimental values and Rogers model predictions of $\Delta T_f/q''$ for $\theta_0 = 80^\circ$.
 ΔT_f - $^\circ\text{C}$, q'' - W/m^2

Figure 4.16 Comparison between experimental values and Modified Rogers model¹ predictions of $\Delta T_f/q''$ for $\theta_0 = 30^\circ$. ΔT_f - $^\circ\text{C}$, q'' - W/m^2

Figure 4.17 Comparison between experimental values and Modified Rogers model¹ predictions of $\Delta T_d/q''$ for $\theta_0 = 80^\circ$. ΔT_d - $^\circ\text{C}$, q'' - W/m^2

Figure 4.18 Comparison between experimental values and Modified Rogers model² predictions of $\Delta T_f/q''$ for $\theta_0 = 30^\circ$. ΔT_f - °C, q'' - W/m²

Figure 4.19 Comparison between experimental values and Modified Rogers model¹ predictions of $\Delta T_f/q''$ for $\theta_0 = 80^\circ$. $\Delta T_f - ^\circ\text{C}$, $q'' - \text{W/m}^2$

Figure 4.20 Comparison between experimental values and Modified Rogers model¹ predictions of $\Delta T_f/q''$ for $\theta_0 = 30^\circ$, and $Re \geq 10^4$.
 ΔT_f - $^\circ\text{C}$, q'' - W/m^2

Figure 4.21 Comparison between experimental values and Modified Rogers model¹ predictions of $\Delta T_f/q''$ for $\theta_f = 80^\circ$, and $Re \geq 10^4$.
 ΔT_f - $^\circ\text{C}$, q'' - W/m^2

Chapter 5

PARAMETER ANALYSIS AND DISCUSSIONS

In the last chapter, emphasis was put on the predictions of the liquid subcooling at OSV. In this chapter, analyses and discussions will be focused on the effects of some parameters on OSV, such as the pressure, flow velocity, heat flux, geometry and so on.

5.1 The Effects of Flow Velocity

Flow velocity is a very important parameter in subcooled boiling and OSV predictions. Figure 5.1 to Figure 5.7 show how velocity affects the magnitude of liquid subcooling at the OSV point by the predictions of the Bowring model, Levy model, Zuber model, original Rogers model and modified Rogers model¹. The equivalent diameter in these figures is arbitrarily chosen as 0.0089 m, which is from the experimental work of Rogers et al [11], and the effect of the equivalent diameter will be discussed later. These figures show that all the predictions give the same trend at high flow velocity region, that is when the flow rate goes up, the subcooling at OSV goes down. This trend is also consistent with the experimental data. The phenomenon can be explained as below. At the same heat flux, when the velocity increases, the flow becomes more turbulent

so that the heat transfer to the bulk flow increases. This makes the thermal boundary layer thinner and thus, reduces the energy accumulation in the superheated sublayer. This also changes the temperature distribution throughout the thermal boundary layer and reduces the temperature near the bubble tip. All of these inhibit the growth of bubbles and delay their departing. So, bubble detachment occurs later at higher flow bulk temperature hence the liquid subcooling at OSV is lower.

The low flow rate case is very complicated and different models give different predictions. The Bowring and Levy models give the same trends as for high velocities. The Zuber model predicts no effect of velocity. The Rogers and modified Rogers models predicts that subcooling decreases as velocity decreases at low pressures, contrary to the predictions of Bowring and Levy, but that subcooling increases as velocity decreases at high pressures in agreement with the Bowring and Levy models. The Levy model begins to show trends similar to the Rogers models at very low velocity but it is below the valid region of these models which will be discussed later in this section. Figure 5.8 gives the comparisons among the experimental results (McLeod and Bibeau data) and the model predictions in the low pressure and low velocity region. It shows that Rogers and modified Rogers models represent the test results well. The trends predicted by the two models are also supported by the data given in Table 6 of [11].

To find out what causes the changes of the subcooling at OSV with the flow rate, we can look into the Rogers model and analyze the effects of flow velocity on the drag force, buoyant force and the bubble radius at departure. As explained in [11], when the velocity increases, the drag

force goes up, and this makes the bubble detachment occur earlier, so the subcooling at OSV is higher. On the other hand, the increase of the flow rate also enhances the heat transfer as mentioned in the beginning of this section, and this makes the bubble departure occur later. But at low flow region, the effect of drag force is dominant, and the overall trend is that as velocity goes up, the liquid subcooling at OSV goes up as well. In contrast, at the high flow region, the effects of velocity on the thermal boundary thickness and the heat transfer rate become dominant, and this reverses the trend.

In the low velocity region, the role of the buoyant force becomes relatively more important than that in the high velocity region. Figure 5.9 shows the bubble radius at departure predicted by the Rogers models. It becomes larger at low velocities, so does the buoyant force as shown in Figure 5.10. The buoyant force contributes about 30% to bubble detachment forces at the 0.2 m/s velocity. But this contribution reduces very quickly so that it only remains 3% at the 0.5 m/s velocity, while when the velocity is over 1 m/s, the buoyant force is close to zero and the drag force becomes the only one to overcome the effect of the surface tension and make the bubble detach. So $F_b/F_s \approx 1$. This explains why the bubble Weber number, which represents the ratio of the dynamic force and surface tension acting on the bubble, becomes a constant beyond certain region as discussed in the Section 4.2. By above discussion, the neglect of the buoyant force in the Levy model is reasonable at higher velocities, but at the low velocity region, the neglect of the buoyant force will cause some error.

Figure 5.9 also shows the effect of the pressure. It can be seen that because bubble radii become smaller at higher pressures, the effect of the drag force is reduced as shown in Equation (4.1.2). Therefore, in the high pressure and low velocity region, the effect of the velocity on OSV is the same as that in the high velocity region.

One point should be mentioned is that at very low velocities thus, very low Reynolds numbers, all the models break down by giving very unreasonable high or low predictions except the Zuber model which predicts no effect of velocity in this region. The reason for the Bowring model's breaking down is that the empirical correlation of Equation (3.3.4) was obtained from the experimental data mostly in the high flow rate region and it does not hold when the velocity is very low. As shown in the equation, when the velocity approaches to zero, ΔT_d approaches to the infinite. The reason for the Levy model or the Rogers models' breaking down may be that in the very low velocity region, some ignored forces, such as vapour thrust, becomes more important [11]. Some relationships used for the fully development turbulent flow may not hold at very low velocity. A more accurate treatment may also be needed for the heat transfer coefficient and the temperature at which the properties are evaluated. The validity criterion for the modified Rogers model has been discussed in the Section 4.3, that is $Re \geq 10^4$.

Figure 5.1 The Effects of Flow Velocity on $\Delta T_f / q''$ by the Bowring Model.

ΔT_f - $^\circ\text{C}$, q'' - W/m^2

Figure 5.2 The Effects of Flow Velocity on $\Delta T_f/q''$
by the Levy Model.

$$\Delta T_f - ^\circ\text{C} , q'' - \text{W}/\text{m}^2$$

Figure 5.3 The Effects of Flow Velocity on $\Delta T_f/q''$ by the Zuber Model.

ΔT_f - °C , q'' - W/m²

Figure 5.4 The Effects of Flow Velocity on $\Delta T_f/q''$
 by the Rogers Model for $\theta_0 = 30^{\circ}$.
 ΔT_f - $^{\circ}\text{C}$, q'' - W/m^2

Figure 5.5 The Effects of Flow Velocity on $\Delta T_f/q''$
 by the Rogers Model for $\theta_i=80^{\circ}$.
 ΔT_f - $^{\circ}\text{C}$, q'' - W/m^2

Figure 5.6 The Effects of Flow Velocity on $\Delta T_f/q''$
 by the Modified Rogers Model, $\theta_i = 30^{\circ}$.
 ΔT_f - $^{\circ}\text{C}$, q'' - W/m^2

Figure 5.7 The Effects of Flow Velocity on $\Delta T_f/q''$
 by the Modified Rogers Model, $\theta_c = 80^{\circ}$.

ΔT_f - $^{\circ}\text{C}$, q'' - W/m^2

Figure 5.8 The Comparison of Experimental Data and Model Predictions at Low Flow Velocity Region.

**Figure 5.9 The Effects of Flow Velocity on Bubble Radius
at Departure by the Rogers Models.**

**Figure 5.10 The Effects of Velocity on Force Ratios
by the Rogers Models.**

5.2 The Effects of Pressure, Heat Flux and Geometry

5.2.1 The Effect of Pressure

The effect of pressure on OSV is represented by its effects on flow properties. Flows at different pressures will have different saturation temperatures, so the vapour and liquid properties will be different and this will affect the development of the velocity and thermal boundary layers and the heat transfer, hence the OSV point. Figure 5.11 and 5.12, which are in the same form as Figure 6.3 of Collier's book [5], show the trends of the liquid subcooling changing with the pressure at the OSV point by the predictions of the Levy model, Zuber model, and the modified Rogers model. The Bowring model gives the same trends as Levy's which is not included in the figures. The original Rogers model is only applicable to $P=155$ kPa, so it is not included in the figures, either. As shown in the two figures, the modified Rogers model gives the trends that ΔT_l increases as pressure increases in the low or middle pressure region, and that ΔT_l decreases rapidly as pressure increases in the high pressure region. The Levy model gives the opposite trends to those of the modified Rogers model. The Zuber model predicts very slight effect of pressure on ΔT_l in the low and middle pressure region, and gives the same trend as the modified Rogers model in the high pressure region. Figure 4.12 shows that the Levy model over predicts in the low pressure region, this means that the trend given by the Levy model is not likely correct. Table 5.1 also gives some experimental data, each group of which is measured under different

pressures but in the same geometries and at about the same velocities. These data show the same trends as the predictions of the modified Rogers model. But because of the scatter of experimental data and the large measurement error, not all of the data in Appendix 1 give the same trend. Figure 5.11 and 5.12 also shows the effect of velocity which has been discussed in the last section.

5.2.2 The Effect of Heat Flux

Heat flux has direct effect on the wall temperature and flow temperature distributions, so it directly affects the liquid subcooling at the OSV point. All the models discussed in this thesis give the prediction of the linear relationship between the heat flux and the liquid subcooling at the OSV, that is the higher the heat flux is, the earlier the significant void occurs. This is consistent with the experimental results as shown in Figure 5.13.

5.2.3 The Effect of Geometry

Channel geometries also have great effects on OSV. Figure 5.14 shows the changes of the liquid subcooling at OSV with the equivalent diameter by the predictions of the modified Rogers model, Levy model and Zuber model. (There is no consideration of the geometric effects on OSV in the Bowring model.) The general trend shown by this figure is that when the equivalent diameter increases, the liquid subcooling at OSV increases as

well except the Zuber model which gives a close to constant prediction in the large diameter region. This general trend can be explained as that when the equivalent diameter increases, the heat transfer coefficient decreases (as shown in the Equation 4.1.29), therefore, the heat transfer to the bulk flow is reduced and the energy accumulation in the thermal boundary layer increases. This makes the OSV occur earlier as analyzed in Section 5.1.

Besides the size, the geometrical shape may also have effects on OSV. For example, under the same operation conditions and the same equivalent diameter, the subcooling at OSV of a rectangular channel may be different from that of an annular channel or a circular tube. Since there are no particular experimental studies concentrated on this aspect, no direct comparisons can be made. In Table 2.1, there are some experimental studies using circular tubes and some using annuli. The deviation of the measured ΔT_f data for tubes from the models predictions and that of the measured ΔT_f data for annuli from the models prediction were compared. No distinctive trends were shown. So it is very hard to tell the effect of the geometric shape on the OSV. But there are some studies in literature focusing on effect of the means of heating the channel [23]. For instance, heating an annular channel by its internal tube or external tube or both can cause the difference on OSV. It is the same for the rectangular channel by heat its one side or two or all sides. So in some studies, the equivalent diameter is calculated by using the heated perimeter instead of the wetted perimeter in the Equation (3.5.5). Since the hydraulic aspect is very important for the thermal development of a flow hence the OSV, most studies in literature still use the wetted perimeter, so does this thesis.

Table 5.1 The Variations of Liquid Subcooling at OSV with Pressures.

Low Pressure Region (Costa data and Staub data)

Pressure, bar	Velocity, m/s	$\Delta T_d/q''$, °C/(w/m ²)*10 ⁶
1.735	3.17	6.77
2.985	3.22	6.66
2.985	3.22	7.25
4.985	3.28	7.25
4.985	3.28	7.89
1.735	4.19	5.92
1.735	4.20	5.69
2.985	4.29	6.27
2.985	4.32	6.31
4.985	4.26	6.80
1.740	5.26	6.96
2.985	5.26	7.64
4.985	5.26	8.79
1.740	7.39	5.25
2.985	7.40	6.57
2.985	7.51	6.46
4.985	7.59	7.00
1.131	0.335	33.23
1.145	0.335	32.25
3.083	0.366	36.65
1.186	1.433	17.59
1.193	1.463	20.04
3.083	1.463	22.48

Table 5.1 The Variations of Liquid Subcooling at OSV with Pressures
(Continue).

High Pressure Region (Bartolemei, Christensen, and Maurer data)

Pressure, bar	Velocity, m/s	$\Delta T_f/q''$, °C/(w/m ²)*10 ⁶
67.40	1.33	22.38
68.10	1.33	21.14
68.40	1.29	24.95
68.90	1.30	30.00
108.10	1.43	23.69
108.10	1.43	20.03
146.80	1.65	17.76
67.90	2.72	14.09
68.10	2.74	10.73
108.40	2.90	9.05
108.40	2.90	9.23
147.40	3.04	6.15
147.90	3.04	5.50
41.37	1.150	19.70
55.16	1.149	19.55
68.95	1.152	17.50
85.52	0.844	16.69
114.00	0.845	11.22
85.52	1.715	10.15
114.00	1.843	8.50
142.46	1.882	7.88

Figure 5.11 Variations of $\Delta T_f / q''$ with the Pressure by the Modified Rogers Model and Levy Model.

ΔT_f - $^{\circ}\text{C}$, q'' - W/m^2

Figure 5.12 Variations of $\Delta T_j / q''$ with the Pressure by the Modified Rogers Model and the Zuber Model.

$$\Delta T_j - ^{\circ}\text{C}, \quad q'' - \text{W}/\text{m}^2$$

Figure 5.13 Variations of ΔT_f with the Heat Flux.

Figure 5.14 Variations of $\Delta T_f/q''$ with the
 Equivalent Diameter.

5.3 Some Other Discussions

All the studies in this thesis are concentrated on the vertical upwards flow. The influence of gravity makes the case more complicated for the horizontal flow than that for the vertical flow. But as discussed in Chapter 1, the gravity influence is very small in the low void region especially in the region before the OSV. From the OSV point of view, the main difference between a vertical flow and a horizontal flow is the buoyant force. In a vertical upwards flow, the buoyant force exerts on the bubble in the flow direction and acts as a departure force. In a horizontal flow, it is in the direction perpendicular to the flow as shown in Figure 5.15.

Figure 5.15 Forces acted on the bubble in horizontal flow.

For the bubbles on the bottom wall, the buoyant force acts as the departure force by overcoming the component of the surface tension force

in the direction normal to wall, while for the bubbles on the top wall, it doesn't. So the force analysis becomes more complicated for a horizontal flow than that for a vertical flow. But as discussed in the Section 5.1, the buoyant force is not very important so that it can be ignored except in the very low velocity region. Therefore, in most cases, the treatment for the horizontal flow is the same as that for the vertical upwards flow. The case is the same for the vertical downwards flow where the buoyant force is in the direction opposite to the flow and contributes to the holding forces. In the low velocity region, Bibeau and Salcudean did some experimental comparisons between upwards and downwards flows [15]. They found that the OSV occurs at higher subcooling for the downwards flow than for the upwards flow. So they suggested that in the low velocity region, bubble detachment may not be the only criterion for OSV determination. Since the low velocity region is very complex as discussed before, more further mechanistic and experimental studies are needed to get a better understanding of this region.

The studies of this thesis are based on the experiments using water as the fluid. The available experimental data of non-water fluid are those of Dix's using Freon-114. A comparison between the Dix data and the predictions of the modified Rogers model has been made. The predicted values are far below the experimental ones, so the result is not satisfactory. One reason is that Dix data were obtained at very low velocities as shown in Appendix 1-A1.2, which gives the experimental data of Dix and the Reynolds number for each point as well. The Reynolds numbers for all the experimental points are below 10^4 , which are below the valid region of the modified Rogers model. Another reason may be that the

contact angles used in this model, such as θ_0 , θ_i and θ_r , are not applicable to Freon-114. θ_i and θ_r were obtained from the experimental studies of Winterton [44] who only used water as the fluid, and θ_0 is from the literature studies of Rogers [50], while in literature, most studies also used water. Different properties of different fluids may cause these angles to change significantly. So the present model is only recommended for the predictions of the water flow. Further studies are needed to use this model predicting the OSV of other fluids.

Chapter 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Rogers model is a relatively good and fundamental model which can be used to predict the liquid subcooling at the OSV point in the low velocity and low pressure region. A modification of this model has been made by correlating its rough surface factor based on the large amount and wide range of experimental data to make this model applicable to all pressures and velocities. A summary of the datum range is given in Table 6.1.

Table 6.1. Summary of Datum Range for F_1 Correlation.

Geometry	Tube, rectangular, annulus
Equivalent Diameter	0.0038 - 0.024 m
Pressure	112.8 - 14,790 kPa
Velocity	0.149 - 8.19 m/s
Heat Flux	211,400 - 4,200,000 W/m²

Bubble Reynolds number is introduced in the correlation. Since the

development of the bubble layer plays a key role in the OSV mechanism, using the bubble Reynolds number is more fundamental than using the pressure and velocity. Following equations are recommended for the rough surface factor for $\theta_0 = 30^\circ$ and $\theta_0 = 80^\circ$, respectively.

$$F_R = 1 + 17.58 Re_b^{-0.89} \quad \text{for } \theta_0 = 30^\circ$$

and

$$F_R = 1 + 58.86 Re_b^{-1.03} \quad \text{for } \theta_0 = 80^\circ$$

And if other equilibrium contact angles are assumed in the model, Appendix 5 is recommended.

By analyzing and comparing among different OSV prediction models, it is found that the modified Rogers model gives best predictions with the standard deviation around 35% .

Parameter effects on the OSV are also analyzed. Flow velocity has great effects. In the low velocity region, liquid subcooling at OSV increases as the velocity increases. And in this region, the buoyant force is relatively important. In the high velocity region, liquid subcooling at OSV decreases as the velocity increases. The buoyant force is not important and can be ignored in this region.

Pressure also has great effects on OSV. By the prediction of the modified Rogers model, the liquid subcooling at OSV increases as the pressure increases in the low and middle pressure region, and in the high

pressure region, the liquid subcooling decreases rapidly as the pressure increases.

The higher the heat flux is, the higher the liquid subcooling at the OSV. The geometries of channels also have influence on OSV. Larger geometric size makes the OSV occur earlier.

The valid region of the modified Rogers model is for flows of the Reynolds number greater than 10^4 . The model is applicable to water flows only.

6.2 Recommendations

If it is possible to establish accurate relationships among the effects of the surface roughness on the friction factor, heat transfer coefficient, temperature profile and velocity profile, the rough surface factor would finally be eliminated from the model, which will make the model more fundamental and give better predictions. The valid region of the present model can be enlarged to lower Reynolds numbers if the relationships for laminar flows are applied in the model as well.

The large scatter of experimental data gives a lot of uncertainties in OSV model predictions. Therefore, to develop a good OSV prediction model, more accurate measurements of the void fraction and the identification of the OSV are needed.

The mechanism of the OSV in the low velocity region, such as the

ignored forces, should be studied. More experimental studies in this very low velocity region are also needed. Only based on these, modifications of the present model can be made to predict the OSV more accurately in this region.

A more accurate treatment of properties, such as using the bulk or film temperature instead of the saturation temperature to evaluate the liquid properties, or using more accurate interpolation instead of the linear one, may improve the predictions of present model.

The experimental studies on bubble detachment with more fluids should also be done to make the present model applicable to these fluids as well.

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APPENDIX 1

EXPERIMENTAL DATA

A1.1 DATA OF WATER

G.G.BARTOLEMEI DATA (1) [13]

No.	De, m	P, kPa	$\rho V, \text{kg/m}^2\text{s}$	$q'', \text{W/m}^2$	$X_{eq}, \%$	$\Delta T_d, ^\circ\text{C}$
1	.0154	1500.0	900.	380000.	-3.8	16.50
2	.0240	1500.0	900.	380000.	-3.9	16.93
3	.0240	1500.0	900.	780000.	-7.0	30.40
4	.0154	3000.0	900.	380000.	-3.5	13.33
5	.0154	3000.0	900.	800000.	-6.4	24.36
6	.0240	3000.0	900.	380000.	-3.4	12.94
7	.0240	3000.0	900.	780000.	-5.6	21.32
8	.0154	4500.0	900.	380000.	-3.2	10.83
9	.0154	4500.0	900.	800000.	-5.8	19.62
10	.0240	4500.0	900.	380000.	-3.0	10.15
11	.0240	4500.0	900.	780000.	-4.7	13.55

G.G.BARTOLOMEI DATA (2) [14]

No.	De, m	P, kPa	$\rho V, \text{kg/m}^2\text{s}$	$q'', \text{W/m}^2$	$X_{eq}, \%$	$\Delta T_d, ^\circ\text{C}$
1	.0120	3010.0	990	980000.	-6.0	22.84
2	.0120	6740.0	988	1700000.	-13.5	38.05
3	.0120	6840.0	961	1130000.	-10.0	28.19
4	.0120	6810.0	988	440000.	-3.3	9.30
5	.0120	6890.0	405	790000.	-15.2	42.85
6	.0120	6890.0	965	780000.	-8.3	23.40
7	.0120	6790.0	2024	780000.	-3.9	10.99
8	.0120	6810.0	2037	1130000.	-4.3	12.12
9	.0120	10810.0	966	1130000.	-13.6	26.77
10	.0120	10840.0	1959	1130000.	-5.2	10.23
11	.0120	10810.0	966	1130000.	-11.5	22.63
12	.0120	10840.0	1959	1130000.	-5.3	10.43
13	.0120	11020.0	503	990000.	-17.0	33.40
14	.0120	14750.0	2123	1130000.	-6.6	8.03
15	.0120	14990.0	2012	2210000.	-14.2	17.27
16	.0120	14700.0	2014	1720000.	-11.1	13.50
17	.0120	14750.0	2123	1130000.	-7.4	9.00
18	.0120	14740.0	1847	770000.	-3.9	4.74
19	.0120	14790.0	1878	420000.	-1.9	2.31
20	.0120	14680.0	1000	1130000.	-16.5	20.07

E.L.BIBEAU DATA [15]

No.	De, m	P, kPa	V, m/s	q'', W/m ²	X _{eq} , %	ΔT _d , °C
1	.0091	155.0	.260	980000.	-2.3	12.08
2	.0091	155.0	.370	980000.	-3.2	16.81
3	.0091	155.0	.460	980000.	-3.3	17.34
4	.0091	155.0	.230	600000.	-3.2	16.81
5	.0091	155.0	.220	300000.	-1.8	9.46

H.CHRISTENSEN DATA ¹

No.	De, m	P, kPa	ρV, kg/m ² s	q'', W/m ²	X _{eq} , %	ΔT _d , °C
1	.0178	2757.9	638.0	211400.	-1.6	6.21
2	.0178	4136.9	916.3	353400.	-2.0	6.96
3	.0178	5515.8	882.3	495300.	-3.1	9.68
4	.0178	6894.8	855.2	495300.	-3.1	8.67

J.COSTA DATA [17]

No.	De, m	P, kPa	ρV, kg/m ² s	q'', W/m ²	ΔT _d , °C
1	.0038	298.5	7450	3140000.	14.1
2	.0038	298.5	5000	3140000.	18.1
3	.0038	298.5	5000	2180000.	12.1
4	.0038	498.5	7500	3100000.	13.6
5	.0066	298.5	4550	2200000.	13.1
6	.0066	298.5	3000	2220000.	16.1
7	.0066	298.5	5000	2870000.	17.1
8	.0066	298.5	4030	2870000.	18.1
9	.0066	298.5	4000	2250000.	14.1
10	.0066	298.5	3000	2870000.	19.1
11	.0066	498.5	3900	2840000.	19.3
12	.0066	498.5	3000	2840000.	20.6
13	.0066	498.5	3000	2230000.	17.6
14	.0066	173.5	4970	2930000.	15.5

¹ Data were taken from [41].

J.COSTA DATA (continue)

No.	De, m	P, kPa	$\rho V, \text{kg/m}^2\text{s}$	$q'', \text{W/m}^2$	$\Delta T_d, ^\circ\text{C}$
15	.0066	173.5	5020	2290000.	11.5
16	.0066	173.5	3970	2280000.	13.5
17	.0066	173.5	3000	2290000.	15.5
18	.0066	173.5	3980	2900000.	16.5
19	.0066	173.5	6000	2900000.	14.5
20	.0060	298.5	5200	3600000.	28.1
21	.0060	298.5	6900	4200000.	27.6
22	.0060	298.5	4900	4200000.	32.1
23	.0060	298.5	5000	2800000.	23.1
24	.0060	298.5	7000	2800000.	18.1
25	.0060	298.5	7000	2000000.	13.1
26	.0060	298.5	5000	2000000.	16.1
27	.0060	298.5	3000	2000000.	19.1
28	.0060	298.5	4950	1000000.	8.6
29	.0060	298.5	7000	4200000.	28.1
30	.0060	298.5	7000	4200000.	28.1
31	.0060	298.5	3000	1000000.	10.6
32	.0060	498.5	6950	2800000.	19.6
33	.0060	498.5	4980	2800000.	24.6
34	.0060	498.5	7000	4200000.	26.6
35	.0060	498.5	5000	4200000.	29.6
36	.0060	174.0	6950	4160000.	29.5
37	.0060	174.0	6950	2800000.	18.7
38	.0060	174.0	6950	2800000.	19.7
39	.0060	174.0	4980	2800000.	19.5
40	.0060	174.0	7000	2000000.	10.5
41	.0060	174.0	5000	2000000.	17.5
42	.0060	174.0	3000	2000000.	20.5
43	.0060	174.0	3000	1000000.	9.5

Z.EDELMAN DATA [19]

No.	De, m	P, kPa	$\rho V, \text{kg/m}^2\text{s}$	$q'', \text{W/m}^2$	$X_{eq}, \%$	$\Delta T_d, ^\circ\text{C}$
1	.0113	101.3	97.	49150.	-.34	37.01
2	.0113	101.3	114.	60625.	-.40	35.30
3	.0113	101.3	135.	70400.	-.58	44.08
4	.0113	101.3	153.	78000.	-.65	44.59
5	.0113	101.3	169.	86650.	-.70	43.23
6	.0113	101.3	185.	95500.	-.73	40.90

R.A.EGEN DATA ¹

No.	De, m	P, kPa	$\rho V, \text{kg/m}^2\text{s}$	$q'', \text{W/m}^2$	$\Delta T_d, ^\circ\text{C}$
1	.00475	13790.0	912.8	252000.	4.4
2	.00475	13790.0	549.2	473000.	9.4
3	.00475	13790.0	897.8	946000.	12.8
4	.00475	13790.0	886.9	1262000.	17.8
5	.00475	13790.0	1139.2	946000.	13.9
6	.00475	13790.0	1144.7	1262000.	21.1
7	.00475	13790.0	1144.7	1577000.	17.2

R.EVANGELISTI DATA [21]

No.	De, m	P, kPa	$\rho V, \text{kg/m}^2\text{s}$	$q'', \text{W/m}^2$	$\Delta T_d, ^\circ\text{C}$
1	.0060	112.8	1410	437000.	12.7
2	.0060	112.8	608	446000.	17.7
3	.0060	112.8	1416	885000.	21.5

P.GRIFFITH DATA ¹

No.	De, m	P, kPa	$\rho V, \text{kg/m}^2\text{s}$	$q'', \text{W/m}^2$	$\Delta T_d, ^\circ\text{C}$
1	.0127	8274.0	768.9	1892000.	47.1
2	.0127	8274.0	1173.3	1911000.	28.9
3	.0127	8274.0	568.3	624000.	18.9
4	.0127	8274.0	1221.9	1899000.	20.0
5	.0127	8274.0	603.6	306000.	6.1
6	.0127	8274.0	797.5	1091000.	17.8
7	.0127	11032.0	553.3	309000.	8.9
8	.0127	11032.0	805.6	621000.	12.8
9	.0127	11032.0	805.6	943000.	20.0
10	.0127	11032.0	1220.6	785000.	10.0
11	.0127	13790.0	918.3	959000.	18.9
12	.0127	13790.0	1160.8	956000.	16.1

¹ Data were taken from [41].

D.A.LABUNTSOV DATA [23]

No.	De, m	P, kPa	V, m/s	q", W/m ²	X _{eq} , %	ΔT _d , °C
1	.0121	2000.0	4.000	1160000.	-2.5	10.36
2	.0121	7000.0	1.000	580000.	-5.8	16.08
3	.0121	7000.0	4.000	1160000.	-4.0	11.09

R.MARTIN DATA [24]

No.	De, m	P, kPa	ρV, kg/m ² s	q", W/m ²	X _{eq} , %	ΔT _d , °C
1	.0056	7848.0	750	400000.	-5.0	12.92
2	.0056	7848.0	750	750000.	-5.9	15.23
3	.0056	7848.0	1500	750000.	-4.1	11.02
4	.0056	7848.0	2200	750000.	-2.8	7.23
5	.0056	7848.0	1500	400000.	-2.3	5.94
6	.0056	7848.0	1500	750000.	-3.3	8.52
7	.0056	7848.0	1500	1100000.	-5.8	14.98
8	.0056	7848.0	1500	1700000.	-10.8	27.89

G.W.MAURER DATA ¹

No.	De, m	P, kPa	ρV, kg/m ² s	q", W/m ²	X _{eq} , %	ΔT _d , °C
1	.0041	8552.0	766	1884000.	-13.7	33.31
2	.0041	8552.0	1169	1907000.	-11.1	27.00
3	.0041	8552.0	564	624000.	-5.4	13.13
4	.0041	8552.0	1223	1891000.	-7.9	19.22
5	.0041	8552.0	602	306000.	-2.1	5.10
6	.0041	8552.0	799	1093000.	-6.3	15.32
7	.0041	11400.0	3230	2525000.	-4.3	7.96
8	.0041	11400.0	5097	3786000.	-2.5	4.63
9	.0041	11400.0	555	306000.	-3.0	5.55
10	.0041	11400.0	562	545000.	-3.3	6.11
11	.0041	11400.0	807	621000.	-5.1	9.44
12	.0041	11400.0	810	942000.	-7.3	13.52
13	.0041	11400.0	1226	785000.	-3.6	6.66
14	.0041	14246.0	915	958000.	-7.6	10.01
15	.0041	14246.0	1161	954000.	-5.7	7.51

¹ Data were taken from [51].

R.D.MCLEOD DATA [12]

No.	De, m	P, kPa	V, m/s	q", W/m ²	X _{eq} , %	ΔT _d , °C
1	.0089	155.0	.251	605000.	-1.5	7.88
2	.0089	155.0	.152	610000.	-2.0	10.51
3	.0089	155.0	.180	742000.	-1.5	7.88
4	.0089	155.0	.287	742000.	-2.2	11.56
5	.0089	155.0	.425	742000.	-2.3	12.08
6	.0089	155.0	.177	770000.	-2.6	13.66
7	.0089	155.0	.182	774000.	-2.5	13.13
8	.0089	155.0	.238	774000.	-2.5	13.13
9	.0089	155.0	.233	975000.	-3.0	15.76
10	.0089	155.0	.317	975000.	-3.8	19.96
11	.0089	155.0	.305	973000.	-3.8	19.96
12	.0089	155.0	.301	1186000.	-3.8	19.96
13	.0089	155.0	.373	1186000.	-4.1	21.54
14	.0089	155.0	.387	1187000.	-5.0	26.27
15	.0089	155.0	.408	1186000.	-4.8	25.22
16	.0089	155.0	.475	1186000.	-4.0	21.01
17	.0089	155.0	.162	601000.	-2.3	12.08
18	.0089	155.0	.194	606000.	-2.8	14.71
19	.0089	155.0	.223	601000.	-2.9	15.24
20	.0089	155.0	.203	739000.	-3.2	16.81
21	.0089	155.0	.333	739000.	-5.3	27.84
22	.0089	155.0	.257	778000.	-3.3	17.34
23	.0089	155.0	.360	778000.	-4.4	23.12
24	.0120	155.0	.129	606000.	-2.0	10.51
25	.0120	155.0	.149	606000.	-1.7	8.93
26	.0120	155.0	.152	775000.	-2.3	12.08
27	.0120	155.0	.153	976000.	-3.3	17.34
28	.0120	155.0	.191	976000.	-3.2	16.81
29	.0120	155.0	.184	1187000.	-3.0	15.76
30	.0120	155.0	.177	770000.	-3.7	19.44
31	.0120	155.0	.133	595000.	-3.3	17.34
32	.0120	155.0	.158	595000.	-4.0	21.01
33	.0120	155.0	.210	779000.	-6.0	31.52
34	.0120	155.0	.259	779000.	-7.0	36.78
35	.0170	155.0	.100	741000.	-3.2	16.81
36	.0170	155.0	.110	976000.	-2.8	14.71
37	.0170	155.0	.107	1190000.	-1.8	9.46
38	.0170	155.0	.129	1190000.	-3.0	15.76
39	.0170	155.0	.138	603000.	-3.5	18.39
40	.0170	155.0	.116	779000.	-2.8	14.71
41	.0170	155.0	.134	977000.	-3.2	16.81

S.Z.ROUHANI DATA [26]

No.	De, m	P, kPa	$\rho V, \text{kg/m}^2\text{s}$	$q'', \text{W/m}^2$	$\Delta T_d, ^\circ\text{C}$
1	.0130	979.1	131.9	300070.	11.11
2	.0130	979.1	132.1	590000.	18.89
3	.0130	979.1	1016.2	590000.	15.56
4	.0130	979.1	1016.2	889700.	20.56
5	.0130	979.1	1371.0	590000.	11.67
6	.0130	979.1	530.8	933900.	21.11
7	.0130	2930.3	132.1	300700.	11.67
8	.0130	2930.3	132.1	590000.	22.22
9	.0130	2930.3	132.1	892900.	32.22
10	.0130	4998.7	132.1	590000.	17.78
11	.0130	4998.7	132.1	892900.	27.78
12	.0130	5000.0	665.0	880000.	17.00
13	.0130	5000.0	665.0	1210000.	23.00
14	.0130	1980.0	1055.0	607000.	19.00
15	.0130	1980.0	1060.0	1180000.	28.00
16	.0130	2950.0	1043.0	920000.	15.00

F.W.STAUB DATA [27]

No.	De, m	P, kPa	V, m/s	$q'', \text{W/m}^2$	$\Delta T_d/q'', ^\circ\text{C}/(\text{W/m}^2)*10^6$
1	.0140	113.1	.335	386000.	33.230
2	.0140	114.5	.335	369000.	32.250
3	.0140	111.7	.914	308000.	27.860
4	.0140	118.6	1.372	369000.	18.570
5	.0140	118.6	1.433	715000.	17.590
6	.0140	119.3	1.463	368000.	20.040
7	.0140	148.3	2.896	772000.	12.220
8	.0140	308.3	.366	373000.	36.650
9	.0140	308.3	1.463	378000.	22.480
10	.0140	308.3	2.926	785000.	10.750
11	.0140	308.3	2.926	792000.	11.730

Al.2 Data of Freon-114

G. E. DIX DATA [18]

$D_e = 0.00914 \text{ m}$

No.	P, kPa	$\rho V, \text{kg/m}^2\text{s}$	V, m/s	$q'', \text{W/m}^2$	$X_{eq}, \%$	$\Delta T_d, ^\circ\text{C}$	Re
1	315.8	205.33	.145	10474.	-3.19	3.56	6264.00
2	315.8	205.60	.145	11956.	-2.66	2.97	6272.24
3	315.8	205.60	.145	13471.	-3.90	4.35	6272.24
4	315.8	205.74	.145	14953.	-4.34	4.84	6276.51
5	317.8	103.48	.073	5994.	-1.85	2.08	3164.49
6	317.8	102.39	.072	6720.	-2.44	2.74	3131.16
7	315.8	102.33	.072	10474.	-2.67	2.98	3121.78
8	315.8	103.07	.073	11956.	-4.08	4.55	3144.36
9	848.1	202.48	.159	5395.	-20.72	18.34	8859.06
10	847.4	206.69	.162	29938.	-13.92	12.32	9040.10
11	847.4	207.10	.162	3596.	-13.59	12.03	9058.03
12	847.4	207.50	.163	3596.	-15.65	13.85	9075.53
13	318.5	206.69	.146	10474.	-2.21	2.49	6326.07
14	318.5	207.04	.146	11956.	-3.24	3.65	6336.78
15	318.5	206.69	.146	13471.	-3.03	3.41	6326.07
16	318.5	206.69	.146	14953.	-3.42	3.85	6326.07
17	318.5	207.50	.147	17950.	-3.48	3.92	6350.86
18	318.5	103.19	.073	6720.	-1.76	1.98	3158.29
19	317.8	103.40	.073	7477.	-2.16	2.43	3162.04
20	317.8	103.67	.073	8991.	-2.61	2.93	3170.30
21	318.5	103.17	.073	10474.	-3.06	3.45	3157.68
22	316.5	103.79	.073	11956.	-1.58	1.77	3168.99
23	316.5	103.79	.073	13471.	-2.89	3.23	3168.99
24	315.1	103.36	.073	14953.	-4.04	4.49	3150.55
25	315.8	103.79	.073	16468.	-3.47	3.87	3166.32
26	317.8	206.82	.146	20947.	-6.44	7.23	6324.70
27	317.2	207.23	.147	23944.	-5.77	6.47	6332.65
28	317.2	206.96	.146	26941.	-7.12	7.98	6324.40
29	315.1	207.10	.146	29875.	-6.88	7.65	6312.68
30	315.8	206.15	.146	22746.	-5.13	5.72	6289.02
31	848.1	205.20	.161	4133.	-15.40	13.63	8978.06
32	315.1	103.29	.073	14953.	-3.00	3.34	3148.41
33	315.1	103.91	.073	14953.	-3.01	3.35	3167.31
34	315.1	103.75	.073	14953.	-2.92	3.25	3162.43
35	315.1	103.59	.073	14953.	-2.82	3.14	3157.56

G. E. DIX DATA (continue)

No.	P, kPa	$\rho V, \text{kg/m}^2\text{s}$	V, m/s	$q'', \text{W/m}^2$	$X_{eq}, \%$	$\Delta T_d, ^\circ\text{C}$	Re
36	313.7	207.10	.146	29938.	-8.63	9.55	6302.05
37	313.7	207.10	.146	29938.	-8.84	9.79	6302.05
38	313.7	207.23	.146	29938.	-8.90	9.85	6306.01
39	313.7	207.10	.146	29938.	-8.71	9.64	6302.05
40	848.1	206.15	.162	5521.	-19.33	17.11	9019.63
41	848.1	205.74	.161	5521.	-19.19	16.98	9001.69
42	848.1	206.28	.162	5521.	-19.19	16.98	9025.32
43	848.1	206.15	.162	5521.	-19.15	16.95	9019.63
44	848.1	102.82	.081	28424.	-10.96	9.70	4498.66
45	848.1	103.21	.081	28424.	-10.65	9.43	4515.72
46	848.1	102.99	.081	28424.	-10.83	9.58	4506.10
47	848.1	102.56	.080	28424.	-10.48	9.27	4487.28

APPENDIX 2

Re, Re_b, We_b, Frou_b, and F_R of Experimental Points

A2.1 $\theta_0 = 30^\circ$

G.G. BARTOLEMEI DATA (1)

No.	P, kPa	V, m/s	Re	Re _b	We _b	Frou _b	F _R
1	1500.	1.000	98777.	182.49	.262	240.52	1.022
2	1500.	1.000	153938.	188.09	.262	210.75	1.071
3	1500.	1.000	153938.	188.71	.262	211.77	1.129
4	3000.	1.095	119733.	162.95	.262	325.35	1.119
5	3000.	1.095	119733.	162.69	.262	324.55	1.183
6	3000.	1.095	186597.	168.19	.262	285.99	1.198
7	3000.	1.095	186597.	167.99	.262	285.48	1.297
8	4500.	1.142	130939.	146.52	.263	370.79	1.225
9	4500.	1.142	130939.	146.06	.263	368.98	1.293
10	4500.	1.142	204060.	151.20	.262	326.20	1.324
11	4500.	1.142	204060.	150.80	.262	324.89	1.442

G.G. BARTOLEMEI DATA (2)

No.	P, kPa	V, m/s	Re	Re _b	We _b	Frou _b	F _R
1	3010.	1.200	102288.	150.89	.263	444.08	1.250
2	6810.	1.330	123377.	112.96	.263	582.45	1.311
3	6810.	1.290	119666.	115.18	.263	539.01	1.263
4	6810.	1.330	123377.	113.60	.263	587.92	1.336
5	6810.	.540	50093.	200.43	.258	56.39	1.051
6	6810.	1.300	120594.	114.85	.263	551.59	1.171
7	6810.	2.720	252320.	72.87	.263	3535.26	1.414
8	6810.	2.740	254175.	72.81	.263	3623.88	1.577
9	10840.	1.430	136712.	81.72	.263	663.12	1.308
10	10840.	2.900	277247.	52.68	.263	3704.51	1.717
11	10840.	1.430	136712.	81.16	.263	654.97	1.396
12	10840.	2.900	277247.	52.70	.263	3707.82	1.704
13	10840.	.750	71702.	121.79	.261	129.79	1.242
14	14750.	3.500	340387.	33.85	.263	5121.96	1.875
15	14750.	3.310	321909.	34.15	.263	4263.02	1.832
16	14750.	3.320	322882.	33.98	.263	4266.44	1.829
17	14750.	3.500	340387.	32.84	.263	4820.07	1.809
18	14750.	3.040	295651.	36.70	.263	3626.00	1.983
19	14750.	3.090	300513.	35.65	.263	3627.76	2.055
20	14750.	1.650	160468.	52.07	.263	809.49	1.475

E.L.BIBEAU DATA

No.	P, kPa	V, m/s	Re	Re _b	We _b	Frou _b	F _R
1	155.	.260	8994.	305.58	.218	5.28	1.117
2	155.	.370	12799.	262.18	.244	13.66	1.147
3	155.	.460	15912.	232.42	.252	24.47	1.174
4	155.	.230	7956.	315.92	.204	3.79	1.052
5	155.	.220	7610.	318.60	.198	3.36	1.039

H.CHRISTENSEN DATA

No.	P, kPa	V, m/s	Re	Re _b	We _b	Frou _b	F _R
1	2758.	.770	96297.	208.79	.261	122.67	1.238
2	4137.	1.150	151076.	150.41	.263	361.08	1.399
3	5516.	1.149	155362.	138.82	.263	362.69	1.426
4	6895.	1.152	158656.	127.23	.263	363.98	1.495

J.COSTA DATA

No.	P, kPa	V, m/s	Re	Re _b	We _b	Frou _b	F _R
1	299.	7.990	137602.	41.29	.263	48662.57	1.518
2	299.	5.360	92309.	52.93	.263	18999.42	1.457
3	299.	5.360	92309.	52.94	.263	19009.11	1.477
4	499.	8.190	160160.	43.87	.263	60511.96	1.524
5	299.	4.880	145968.	57.08	.263	12467.56	1.561
6	299.	3.220	96315.	73.75	.263	4552.91	1.509
7	299.	5.360	160326.	53.64	.263	15442.15	1.546
8	299.	4.320	129218.	62.26	.263	9522.10	1.544
9	299.	4.290	128320.	61.81	.263	9157.26	1.551
10	299.	3.220	96315.	73.77	.263	4555.13	1.544
11	499.	4.260	144690.	66.40	.263	10315.08	1.517
12	499.	3.280	111405.	77.13	.263	5321.50	1.519
13	499.	3.280	111405.	77.93	.263	5423.67	1.477
14	174.	5.250	135673.	51.34	.263	13409.27	1.596
15	174.	5.300	136965.	51.16	.263	13781.03	1.620
16	174.	4.190	108280.	58.94	.263	7732.84	1.562
17	174.	3.170	81921.	68.99	.263	3830.83	1.522
18	174.	4.200	108538.	58.14	.263	7591.15	1.582

J.COSTA DATA (CONTINUE)

No.	P, kPa	V, m/s	Re	Re _b	We _b	Frou _b	F _R
19	174.	6.430	166167.	44.66	.263	21060.25	1.603
20	299.	5.580	151733.	52.34	.263	17887.23	1.365
21	299.	7.400	201223.	43.76	.263	34546.69	1.391
22	299.	5.260	143032.	55.29	.263	15923.66	1.387
23	299.	5.360	145751.	53.47	.263	15937.27	1.342
24	299.	7.510	204214.	43.79	.263	36473.40	1.395
25	299.	7.510	204214.	44.43	.263	37538.55	1.383
26	299.	5.360	145751.	53.46	.263	15937.27	1.357
27	299.	3.220	87559.	73.05	.263	4647.67	1.370
28	299.	5.310	144391.	53.63	.263	15506.39	1.321
29	299.	7.510	204214.	44.31	.263	37350.49	1.370
30	299.	7.510	204214.	43.37	.264	35773.36	1.375
31	299.	3.220	87559.	73.07	.263	4648.83	1.320
32	499.	7.590	234357.	46.09	.264	42262.65	1.333
33	499.	5.440	167971.	56.99	.263	19224.77	1.294
34	499.	7.650	236210.	45.55	.263	42503.60	1.400
35	499.	5.460	168589.	56.93	.263	19435.25	1.427
36	174.	7.340	172580.	42.01	.263	31167.23	1.345
37	174.	7.340	172580.	42.01	.263	31167.23	1.382
38	174.	7.340	172580.	42.02	.263	31193.31	1.350
39	174.	5.260	123675.	50.12	.263	13370.79	1.443
40	174.	7.390	173756.	40.77	.263	30085.60	1.531
41	174.	5.280	124145.	50.13	.263	13555.54	1.317
42	174.	3.170	74534.	69.15	.263	3997.54	1.334
43	174.	3.170	74534.	68.48	.263	3924.35	1.369

Z.EDELMAN DATA

No.	P, kPa	V, m/s	Re	Re _b	We _b	Frou _b	F _R
1	101.	.101	3863.	217.18	.063	.35	1.079
2	101.	.119	4552.	247.18	.087	.55	1.066
3	101.	.141	5393.	272.45	.116	.87	1.040
4	101.	.160	6120.	285.63	.138	1.23	1.034
5	101.	.176	6732.	291.76	.155	1.59	1.036
6	101.	.193	7382.	294.39	.171	2.04	1.041

R.A.EGEN DATA

No.	P, kPa	V, m/s	Re	Re _b	We _b	Frou _b	F _R
1	13790.	1.048	40188.	71.50	.263	359.69	1.370
2	13790.	.630	24159.	97.68	.261	101.57	1.335
3	13790.	1.030	39498.	72.63	.263	348.05	1.468
4	13790.	1.018	39037.	72.67	.263	334.02	1.456
5	13790.	1.307	50120.	62.32	.263	613.06	1.429
6	13790.	1.314	50388.	62.76	.263	633.56	1.368
7	13790.	1.314	50388.	62.71	.263	632.53	1.547

R.EVANGELISTI DATA

No.	P, kPa	V, m/s	Re	Re _b	We _b	Frou _b	F _R
1	113.	1.474	30715.	103.67	.263	532.20	1.021
2	113.	.636	13253.	175.71	.259	60.92	1.001
3	113.	1.481	30861.	103.04	.263	535.75	1.088

P.GRIFFITH DATA

No.	P, kPa	V, m/s	Re	Re _b	We _b	Frou _b	F _R
1	8274.	.859	85468.	136.04	.262	186.15	1.382
2	8274.	1.310	130341.	103.94	.263	544.11	1.523
3	8274.	.635	63181.	164.43	.260	84.87	1.275
4	8274.	1.364	135714.	101.86	.263	607.86	1.664
5	8274.	.674	67061.	158.40	.260	99.15	1.405
6	8274.	.890	88552.	133.02	.262	203.96	1.485
7	11032.	.627	63512.	134.15	.260	80.10	1.320
8	11032.	.913	92482.	106.17	.262	209.17	1.434
9	11032.	.913	92482.	106.44	.262	210.07	1.422
10	11032.	1.383	140091.	81.84	.263	590.08	1.619
11	13790.	1.054	108065.	76.49	.262	280.90	1.486
12	13790.	1.332	136567.	66.39	.263	500.05	1.536

D.A.LABUNTSOV DATA

No.	P, kPa	V, m/s	Re	Re _b	We _b	Frou _b	F _R
1	2000.	4.000	324783.	74.40	.263	9209.28	1.522
2	7000.	1.000	93723.	134.43	.262	282.06	1.253
3	7000.	4.000	374894.	57.26	.263	9077.00	1.560

R.MARTIN DATA

No.	P, kPa	V, m/s	Re	Re _b	We _b	Frou _b	F _R
1	7848.	1.034	45208.	117.89	.263	380.90	1.081
2	7848.	1.034	45208.	117.61	.263	379.37	1.275
3	7848.	2.068	90416.	76.49	.263	2171.65	1.354
4	7848.	3.034	132651.	61.09	.263	5646.22	1.487
5	7848.	2.068	90416.	75.98	.263	2145.06	1.329
6	7848.	2.068	90416.	76.58	.263	2176.34	1.466
7	7848.	2.068	90416.	76.43	.263	2168.50	1.373
8	7848.	2.068	90416.	75.81	.263	2136.46	1.276

G.W.MAURER DATA

No.	P, kPa	V, m/s	Re	Re _b	We _b	Frou _b	F _R
1	8552.	1.074	34493.	107.11	.263	454.45	1.290
2	8552.	1.640	52671.	81.68	.263	1297.89	1.350
3	8552.	.791	25404.	129.68	.262	207.71	1.238
4	8552.	1.715	55080.	80.09	.263	1471.16	1.492
5	8552.	.884	28391.	120.83	.262	275.94	1.314
6	8552.	1.120	35971.	103.58	.263	499.23	1.377
7	11400.	4.856	158742.	35.33	.263	17558.66	2.034
8	11400.	7.664	250535.	25.62	.263	47727.97	2.632
9	11400.	.834	27263.	100.68	.262	227.01	1.309
10	11400.	.845	27623.	100.18	.262	235.90	1.446
11	11400.	1.213	39653.	79.74	.263	577.98	1.362
12	11400.	1.218	39816.	79.40	.263	582.07	1.385
13	11400.	1.843	60247.	61.42	.263	1595.48	1.584
14	14246.	1.483	49030.	55.28	.263	869.68	1.540
15	14246.	1.882	62221.	47.98	.263	1564.45	1.654

R.D.MCLEOD DATA

No.	P, kPa	V, m/s	Re	Re _b	We _b	Frou _b	F _R
1	155.	.251	8478.	308.85	.214	4.81	1.107
2	155.	.152	5132.	313.40	.139	1.24	1.057
3	155.	.180	6083.	322.57	.168	1.96	1.080
4	155.	.287	9713.	294.59	.227	6.94	1.115
5	155.	.425	14368.	243.05	.249	19.91	1.169
6	155.	.177	6002.	322.18	.166	1.89	1.061
7	155.	.182	6150.	322.77	.170	2.02	1.064
8	155.	.238	8069.	313.08	.208	4.21	1.087
9	155.	.233	7883.	314.73	.206	3.95	1.088
10	155.	.317	10741.	282.24	.235	9.11	1.108
11	155.	.305	10308.	287.38	.232	8.15	1.103
12	155.	.301	10186.	288.80	.231	7.89	1.117
13	155.	.373	12605.	260.95	.244	14.02	1.140
14	155.	.387	13082.	255.84	.246	15.48	1.124
15	155.	.408	13789.	248.62	.248	17.83	1.135
16	155.	.475	16076.	227.79	.253	26.88	1.176
17	155.	.162	5470.	318.21	.150	1.47	1.052
18	155.	.194	6573.	322.86	.180	2.42	1.049
19	155.	.223	7561.	317.61	.200	3.53	1.055
20	155.	.203	6857.	321.91	.187	2.71	1.056
21	155.	.333	11255.	276.21	.238	10.34	1.041
22	155.	.257	8691.	306.46	.217	5.14	1.077
23	155.	.360	12179.	265.57	.242	12.77	1.080
24	155.	.129	5866.	288.62	.104	.73	1.094
25	155.	.149	6815.	308.77	.130	1.09	1.097
26	155.	.152	6947.	310.77	.134	1.15	1.096
27	155.	.153	6970.	311.06	.134	1.16	1.091
28	155.	.191	8721.	322.94	.173	2.12	1.101
29	155.	.184	8402.	322.27	.167	1.91	1.109
30	155.	.177	8092.	321.20	.160	1.73	1.077
31	155.	.133	6090.	294.25	.110	.80	1.070
32	155.	.158	7203.	314.11	.140	1.26	1.053
33	155.	.210	9579.	321.90	.187	2.73	1.043
34	155.	.259	11837.	308.69	.214	4.83	1.030
35	155.	.100	6481.	233.92	.061	.33	1.151
36	155.	.110	7128.	253.59	.074	.43	1.154
37	155.	.107	6889.	246.57	.069	.39	1.169
38	155.	.129	8336.	282.80	.098	.66	1.147
39	155.	.138	8918.	293.53	.110	.79	1.110
40	155.	.116	7528.	264.25	.082	.50	1.143
41	155.	.134	8685.	289.48	.105	.74	1.138

S.Z.ROUHANI DATA

No.	P, kPa	V, m/s	Re	Re _b	We _b	Frou _b	F _r
1	979.	.149	11507.	421.86	.148	1.42	1.073
2	979.	.149	11507.	421.71	.148	1.42	1.085
3	979.	1.144	88347.	164.65	.263	339.42	1.181
4	979.	1.144	88347.	165.28	.263	341.36	1.231
5	979.	1.544	119238.	136.21	.263	742.23	1.267
6	979.	.598	46181.	250.45	.259	61.24	1.226
7	2930.	.160	14726.	419.58	.168	1.95	1.095
8	2930.	.160	14726.	419.42	.168	1.95	1.097
9	2930.	.160	14726.	419.48	.168	1.95	1.101
10	4999.	.170	16626.	377.64	.180	2.41	1.138
11	4999.	.170	16626.	377.51	.180	2.41	1.135
12	5000.	.855	83619.	169.11	.262	183.62	1.372
13	5000.	.855	83619.	168.99	.262	183.41	1.378
14	1980.	1.240	108021.	155.07	.263	456.65	1.108
15	1980.	1.250	108892.	153.83	.263	464.20	1.229
16	2950.	1.270	116982.	146.74	.263	502.05	1.401

P.W.STAUB DATA

No.	P, kPa	V, m/s	Re	Re _b	We _b	Frou _b	F _r
1	116.	.335	16408.	266.45	.233	8.67	1.113
2	116.	.335	16408.	266.36	.233	8.66	1.118
3	116.	.914	44766.	148.97	.261	123.20	1.191
4	116.	1.372	67198.	115.27	.263	350.04	1.305
5	116.	1.433	70185.	112.16	.263	391.08	1.321
6	116.	1.463	71655.	111.00	.263	414.02	1.276
7	148.	2.896	152510.	75.68	.263	2442.31	1.407
8	308.	.366	23404.	302.36	.243	13.28	1.098
9	308.	1.463	93553.	128.76	.263	516.92	1.229
10	308.	2.926	187105.	83.20	.263	2974.76	1.471
11	308.	2.926	187105.	82.74	.263	2945.63	1.430

A2.2 $\theta_0 = 80^\circ$

G.G. BARTOLEMEI DATA (1)

No.	P, kPa	V, m/s	Re	Re _b	We _b	Frou _b	F _R
1	1500.	1.000	98777.	442.82	.739	155.23	.956
2	1500.	1.000	153938.	457.85	.738	136.09	1.001
3	1500.	1.000	153938.	457.01	.738	135.76	1.052
4	3000.	1.095	119733.	394.22	.740	212.29	1.042
5	3000.	1.095	119733.	394.27	.740	212.32	1.096
6	3000.	1.095	186597.	407.23	.740	186.04	1.113
7	3000.	1.095	186597.	407.26	.740	186.06	1.197
8	4500.	1.142	130939.	353.26	.741	244.39	1.136
9	4500.	1.142	130939.	353.42	.741	244.54	1.194
10	4500.	1.142	204060.	364.89	.741	214.38	1.224
11	4500.	1.142	204060.	364.98	.741	214.46	1.323

G.G. BARTOLEMEI DATA (2)

No.	P, kPa	V, m/s	Re	Re _b	We _b	Frou _b	F _R
1	3010.	1.200	102288.	364.21	.742	291.86	1.154
2	6810.	1.330	123377.	271.89	.742	398.04	1.214
3	6810.	1.290	119666.	277.03	.742	366.89	1.173
4	6810.	1.330	123377.	271.94	.742	398.16	1.237
5	6810.	.540	50093.	485.00	.722	36.12	.976
6	6810.	1.300	120594.	275.79	.742	374.67	1.093
7	6810.	2.720	252320.	172.32	.744	2522.97	1.322
8	6810.	2.740	254175.	170.57	.744	2546.23	1.466
9	10840.	1.430	136712.	193.92	.743	467.07	1.224
10	10840.	2.900	277247.	124.12	.744	2749.15	1.594
11	10840.	1.430	136712.	193.86	.743	466.61	1.299
12	10840.	2.900	277247.	124.13	.744	2749.54	1.583
13	10840.	.750	71702.	291.41	.735	87.19	1.155
14	14750.	3.500	340387.	78.55	.744	3860.47	1.746
15	14750.	3.310	321909.	79.97	.744	3273.30	1.706
16	14750.	3.320	322882.	80.81	.744	3378.23	1.699
17	14750.	3.500	340387.	77.13	.744	3721.48	1.685
18	14750.	3.040	295651.	84.47	.744	2688.59	1.842
19	14750.	3.090	300513.	84.29	.744	2839.07	1.893
20	14750.	1.650	160468.	123.33	.743	607.93	1.382

E.L.BIBEAU DATA

No.	P, kPa	V, m/s	Re	Re _b	We _b	Frou _b	F _r
1	155.	.260	8994.	693.83	.553	3.26	1.072
2	155.	.370	12799.	621.18	.658	8.53	1.082
3	155.	.460	15912.	557.54	.694	15.44	1.095
4	155.	.230	7956.	701.36	.503	2.34	1.017
5	155.	.220	7610.	701.01	.483	2.08	1.006

H.CHRISTENSEN DATA

No.	P, kPa	V, m/s	Re	Re _b	We _b	Frou _b	F _r
1	2758.	.770	96297.	507.65	.734	78.17	1.138
2	4137.	1.150	151076.	362.97	.741	237.40	1.284
3	5516.	1.149	155362.	334.04	.741	240.28	1.311
4	6895.	1.152	158656.	305.11	.741	243.07	1.373

J.COSTA DATA

No.	P, kPa	V, m/s	Re	Re _b	We _b	Frou _b	F _r
1	299.	7.990	137602.	95.50	.744	35873.98	1.424
2	299.	5.360	92309.	122.45	.744	13621.44	1.365
3	299.	5.360	92309.	123.40	.744	13815.52	1.381
4	499.	8.190	160160.	99.02	.745	42341.54	1.435
5	299.	4.880	145968.	134.77	.744	9266.01	1.456
6	299.	3.220	96315.	176.17	.744	3297.84	1.400
7	299.	5.360	160326.	126.92	.744	11660.08	1.444
8	299.	4.320	129218.	145.49	.744	6843.33	1.441
9	299.	4.290	128320.	147.00	.744	6795.38	1.442
10	299.	3.220	96315.	175.04	.744	3262.58	1.431
11	499.	4.260	144690.	156.69	.744	7455.78	1.412
12	499.	3.280	111405.	184.18	.744	3823.02	1.406
13	499.	3.280	111405.	183.21	.744	3789.70	1.373
14	174.	5.250	135673.	119.22	.744	9730.92	1.493
15	174.	5.300	136965.	119.46	.744	10105.35	1.513
16	174.	4.190	108280.	137.28	.744	5577.82	1.460

J.COSTA DATA (CONTINUE)

No.	P, kPa	V, m/s	Re	Re _b	We _b	Frou _b	F _f
17	174.	3.170	81921.	164.41	.744	2797.10	1.416
18	174.	4.200	108538.	137.81	.744	5664.70	1.474
19	174.	6.430	166167.	104.99	.744	15914.42	1.499
20	299.	5.580	151733.	122.90	.744	13202.94	1.285
21	299.	7.400	201223.	103.42	.744	26423.21	1.310
22	299.	5.260	143032.	127.45	.744	11403.42	1.309
23	299.	5.360	145751.	127.38	.744	12193.96	1.263
24	299.	7.510	204214.	103.58	.744	27946.43	1.314
25	299.	7.510	204214.	102.00	.744	27143.98	1.309
26	299.	5.360	145751.	126.25	.744	11996.68	1.278
27	299.	3.220	87559.	174.17	.744	3361.12	1.279
28	299.	5.310	144391.	126.83	.744	11696.14	1.245
29	299.	7.510	204214.	103.90	.744	28112.64	1.293
30	299.	7.510	204214.	103.72	.744	28029.29	1.294
31	299.	3.220	87559.	174.84	.744	3382.76	1.235
32	499.	7.590	234357.	109.43	.744	32456.06	1.258
33	499.	5.440	167971.	131.88	.744	13790.33	1.224
34	499.	7.650	236210.	108.51	.745	32850.82	1.317
35	499.	5.460	168589.	131.54	.744	13912.09	1.342
36	174.	7.340	172580.	96.08	.744	22453.62	1.276
37	174.	7.340	172580.	96.27	.744	22533.90	1.309
38	174.	7.340	172580.	96.39	.744	22587.74	1.280
39	174.	5.260	123675.	119.56	.744	10231.10	1.352
40	174.	7.390	173756.	97.06	.744	23471.02	1.433
41	174.	5.280	124145.	117.93	.744	10113.45	1.244
42	174.	3.170	74534.	162.73	.744	2855.36	1.253
43	174.	3.170	74534.	163.38	.744	2874.44	1.281

Z.EDELMAN DATA

No.	P, kPa	V, m/s	Re	Re _b	We _b	Frou _b	F _f
1	101.	.101	3863.	400.30	.123	.22	1.051
2	101.	.119	4552.	468.12	.175	.35	1.034
3	101.	.141	5393.	534.29	.244	.55	1.004
4	101.	.160	6120.	576.70	.302	.77	1.000
5	101.	.176	6732.	602.60	.349	.99	1.002
6	101.	.193	7382.	621.64	.395	1.27	1.007

R.A.EGEN DATA

No.	P, kPa	V, m/s	Re	Re _b	We _b	Frou _b	F _l
1	13790.	1.048	40188.	169.94	.741	260.09	1.273
2	13790.	.630	24159.	233.26	.733	70.46	1.233
3	13790.	1.030	39498.	171.31	.741	247.76	1.359
4	13790.	1.018	39037.	172.54	.741	240.44	1.347
5	13790.	1.307	50120.	147.97	.743	453.32	1.329
6	13790.	1.314	50388.	146.92	.743	456.39	1.279
7	13790.	1.314	50388.	147.15	.743	457.65	1.433

R.EVANGELISTI DATA

No.	P, kPa	V, m/s	Re	Re _b	We _b	Frou _b	F _l
1	113.	1.474	30715.	247.81	.742	364.80	.968
2	113.	.636	13253.	423.57	.724	39.47	.942
3	113.	1.481	30861.	247.04	.742	369.29	1.027

P.GRIFFITH DATA

No.	P, kPa	V, m/s	Re	Re _b	We _b	Frou _b	F _l
1	8274.	.859	85468.	326.69	.738	123.53	1.271
2	8274.	1.310	130341.	249.21	.742	374.57	1.400
3	8274.	.635	63181.	396.58	.730	55.36	1.174
4	8274.	1.364	135714.	242.97	.742	416.44	1.521
5	8274.	.674	67061.	381.84	.732	64.90	1.284
6	8274.	.890	88552.	319.68	.738	135.89	1.359
7	11032.	.627	63512.	322.17	.729	53.48	1.219
8	11032.	.913	92482.	254.35	.739	143.57	1.323
9	11032.	.913	92482.	254.01	.739	143.27	1.314
10	11032.	1.383	140091.	195.08	.742	418.62	1.491
11	13790.	1.054	108065.	180.72	.740	198.85	1.383
12	13790.	1.332	136567.	155.92	.742	358.83	1.432

D.A.LABUNTSOV DATA

No.	P, kPa	V, m/s	Re	Re _b	We _b	Frou _b	F _R
1	2000.	4.000	324783.	175.21	.744	6503.27	1.418
2	7000.	1.000	93723.	323.07	.740	187.49	1.161
3	7000.	4.000	374894.	132.93	.744	6542.65	1.463

R.MARTIN DATA

No.	P, kPa	V, m/s	Re	Re _b	We _b	Frou _b	F _R
1	7848.	1.034	45208.	281.84	.741	256.10	1.009
2	7848.	1.034	45208.	282.29	.741	256.72	1.176
3	7848.	2.068	90416.	181.11	.744	1540.49	1.260
4	7848.	3.034	132651.	141.71	.744	4020.05	1.388
5	7848.	2.068	90416.	181.19	.744	1541.62	1.237
6	7848.	2.068	90416.	180.20	.744	1527.57	1.358
7	7848.	2.068	90416.	180.61	.744	1533.38	1.277
8	7848.	2.068	90416.	181.02	.744	1539.24	1.190

G.W.MAURER DATA

No.	P, kPa	V, m/s	Re	Re _b	We _b	Frou _b	F _R
1	8552.	1.074	34493.	255.71	.742	309.38	1.190
2	8552.	1.640	52671.	195.54	.743	927.09	1.249
3	8552.	.791	25404.	311.40	.738	138.74	1.139
4	8552.	1.715	55080.	190.00	.744	1038.83	1.372
5	8552.	.884	28391.	289.89	.740	185.91	1.205
6	8552.	1.120	35971.	249.00	.742	345.26	1.262
7	11400.	4.856	158742.	81.23	.744	12989.79	1.873
8	11400.	7.664	250535.	62.63	.744	39927.20	2.338
9	11400.	.834	27263.	241.03	.739	156.91	1.206
10	11400.	.845	27623.	238.94	.739	162.23	1.323
11	11400.	1.213	39653.	189.75	.742	410.68	1.260
12	11400.	1.218	39816.	189.03	.742	414.19	1.280
13	11400.	1.843	60247.	145.61	.744	1178.90	1.460
14	14246.	1.483	49030.	129.12	.743	638.21	1.431
15	14246.	1.882	62221.	110.95	.744	1137.45	1.535

R.D.MCLEOD DATA

No.	P, kPa	V, m/s	Re	Re _b	We _b	Frou _b	F _R
1	155.	.251	8478.	697.11	.540	2.97	1.065
2	155.	.152	5132.	632.76	.303	.77	1.028
3	155.	.180	6083.	678.42	.386	1.22	1.049
4	155.	.287	9713.	679.47	.590	4.30	1.066
5	155.	.425	14368.	580.73	.683	12.50	1.095
6	155.	.177	6002.	675.48	.380	1.17	1.031
7	155.	.182	6150.	680.61	.392	1.25	1.034
8	155.	.238	8069.	700.41	.519	2.60	1.048
9	155.	.233	7883.	701.00	.509	2.44	1.049
10	155.	.317	10741.	659.29	.621	5.66	1.055
11	155.	.305	10308.	668.00	.609	5.06	1.052
12	155.	.301	10186.	670.38	.605	4.89	1.065
13	155.	.373	12605.	618.53	.659	8.75	1.076
14	155.	.387	13082.	608.16	.667	9.69	1.059
15	155.	.408	13789.	592.95	.676	11.18	1.066
16	155.	.475	16076.	546.94	.698	16.97	1.095
17	155.	.162	5470.	652.38	.334	.92	1.023
18	155.	.194	6573.	691.42	.425	1.50	1.019
19	155.	.223	7561.	701.49	.491	2.18	1.021
20	155.	.203	6857.	696.17	.445	1.68	1.024
21	155.	.333	11255.	648.22	.633	6.43	.992
22	155.	.257	8691.	694.83	.550	3.18	1.036
23	155.	.360	12179.	627.97	.652	7.97	1.023
24	155.	.129	5866.	557.03	.214	.46	1.059
25	155.	.149	6815.	616.22	.280	.68	1.066
26	155.	.152	6947.	622.99	.289	.71	1.065
27	155.	.153	6970.	624.14	.290	.72	1.061
28	155.	.191	8721.	683.78	.400	1.31	1.069
29	155.	.184	8402.	676.46	.382	1.19	1.077
30	155.	.177	8092.	668.02	.363	1.07	1.047
31	155.	.133	6090.	572.64	.230	.50	1.038
32	155.	.158	7203.	635.14	.306	.79	1.025
33	155.	.210	9579.	696.52	.446	1.69	1.013
34	155.	.259	11837.	697.08	.540	2.99	.995
35	155.	.100	6481.	429.37	.117	.21	1.119
36	155.	.110	7128.	472.21	.145	.27	1.119
37	155.	.107	6889.	456.71	.134	.25	1.135
38	155.	.129	8336.	541.90	.200	.41	1.108
39	155.	.138	8918.	570.44	.227	.50	1.076
40	155.	.116	7528.	496.73	.163	.31	1.106
41	155.	.134	8685.	559.41	.216	.46	1.101

S.Z.ROUHANI DATA

No.	P, kPa	V, m/s	Re	Re _b	We _b	Frou _b	F _r
1	979.	.149	11507.	859.69	.325	.87	1.044
2	979.	.149	11507.	859.87	.325	.87	1.055
3	979.	1.144	88347.	399.41	.741	221.94	1.096
4	979.	1.144	88347.	399.58	.741	222.07	1.139
5	979.	1.544	119238.	327.55	.743	492.27	1.176
6	979.	.598	46181.	608.97	.723	38.35	1.138
7	2930.	.160	14726.	880.23	.383	1.19	1.059
8	2930.	.160	14726.	880.34	.383	1.19	1.061
9	2930.	.160	14726.	880.31	.383	1.19	1.065
10	4999.	.170	16626.	808.09	.423	1.48	1.098
11	4999.	.170	16626.	807.92	.423	1.48	1.095
12	5000.	.855	83619.	409.61	.737	119.55	1.253
13	5000.	.855	83619.	408.91	.737	119.27	1.258
14	1980.	1.240	108021.	374.68	.742	299.35	1.033
15	1980.	1.250	108892.	372.58	.742	305.70	1.137
16	2950.	1.270	116982.	353.90	.742	330.85	1.285

F.W.STAUB DATA

No.	P, kPa	V, m/s	Re	Re _b	We _b	Frou _b	F _r
1	116.	.335	16408.	620.58	.616	5.41	1.059
2	116.	.335	16408.	620.51	.616	5.41	1.063
3	116.	.914	44766.	359.20	.734	81.28	1.118
4	116.	1.372	67198.	276.80	.741	237.78	1.222
5	116.	1.433	70185.	269.25	.741	266.61	1.237
6	116.	1.463	71655.	265.63	.741	281.37	1.199
7	148.	2.896	152510.	178.91	.744	1731.09	1.322
8	308.	.366	23404.	716.94	.654	8.19	1.050
9	308.	1.463	93553.	308.95	.742	344.69	1.149
10	308.	2.926	187105.	197.82	.744	2054.59	1.373
11	308.	2.926	187105.	197.04	.744	2081.11	1.337

APPENDIX 3

COMPUTER PROGRAMS

A3.1 LEVY MODEL

```
PROGRAM LEVY
REAL MUF, KF, MUF1, MUF2, KF1, KF2
DIMENSION PS(40), TTS(40), V(140)
C ----- M IS THE NUMBER OF POINTS WANTED TO CALCULATE
C ----- P-PRESSUR, V-AVERAGE VELOCITY
C ----- Q-HEAT FLUX, De-EQUIVALENT DIAMETER
OPEN(3, FILE='PQV.DAT')
READ(3, *) M, P, DE, Q
II=1
DO 2 I=1, M
2 READ(3, *) V(I)
CLOSE(3)

C -----
C ----- CALCULATE PROPERTIES AT Ps, Ts
C -----
C ----- ROUF-DENSITY, MUF-VISCOSITY, PRF-PRANDTL NUMBER
C ----- KF-THERMAL CONDUCTIVITY, SM-SURFACE TENSION
C ----- TS-SATURATION TEMP. , CPF-SPECIFIC HEAT
OPEN(1, FILE='DATA.1')
READ(1, *) PS(1), TTS(1)
DO 10 I=1, 40
READ(1, *) PS(I+1), TTS(I+1)
IF(P.GT.PS(I).AND.P.LE.PS(I+1)) THEN
DP=(P-PS(I))/(PS(I+1)-PS(I))
TS=TTS(I)+DP*(TTS(I+1)-TTS(I))
DT=(TS-TTS(I))/(TTS(I+1)-TTS(I))
GOTO 20
END IF
10 CONTINUE
20 CONTINUE
OPEN(2, FILE='DATA.2')
DO 30 J=1, 6*(I-1)
30 READ(2, *) X
READ(2, *) ROUF1, CPF1, SM1, MUF1, KF1, PRF1
READ(2, *) ROUF2, CPF2, SM2, MUF2, KF2, PRF2
ROUF1=ROUF1/1000.0
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```

ROUF2=ROUF2/1000.0
ROUF=1./ROUF1+DT*(1./ROUF2-1./ROUF1)
CPF=CPF1+DT*(CPF2-CPF1)
SM=(SM1+DT*(SM2-SM1))/1000.0
MUF=(MUF1+DT*(MUF2-MUF1))/1000000.0
KF=KF1+DT*(KF2-KF1)
PRF=PRF1+DT*(PRF2-PRF1)
CLOSE(1)
CLOSE(2)

```

```

C -----
C          CALCULATE RE,TAUW
C -----
C ----- RE-REYNOLDS NUMBER,  F-FRICTION FACTOR
C ----- TAUW-SHEAR STRESS AT THE WALL
300 RE=ROUF*V(II)*DE/MUF
    F=.0055*(1.+(2.+1000000./RE)**(1./3.))
    TAUW=1./8.*F*ROUF*V(II)*V(II)

C -----
C          CALCULATE QP,H,YBP,DTD
C -----
C ----- YBP--NON-DIMENSIONAL DISTANCE FROM THE WALL TO THE
C ----- TIP OF THE BUBBLE AT DEPARTURE
C ----- DTD-LIQUID SUB-COOLING AT OSV
QP=1./CPF/(TAUW*ROUF)**.5
H=.023*RE**.8*PRF**.4*KF/DE
YBP=.015*(SM*DE*ROUF)**.5/MUF
IF(YBP.LE.5.) THEN
    DTD=1./H-QP*PRF*YBP
ELSE IF(YBP.GT.30.) THEN
    DTD=1./H-5.*QP*(PRF+LOG(1.+5.*PRF)+.5*LOG(YBP/30.))
ELSE
    DTD=1./H-5.*QP*(PRF+LOG(1.+PRF*(YBP/5.-1.)))
END IF
WRITE(4,*)DTD*1000000.
II=II+1
IF(II.LE.M) THEN
    GOTO 300
END IF
CLOSE(4)
STOP
END

```

A3.2 ZUBER MODEL

```

PROGRAM ZUBER
REAL MUF, KF,MUF1,MUF2,KF1,KF2
DIMENSION PS(40),TTS(40),V(140)
C ----- M IS THE NUMBER OF POINTS WANTED TO CALCULATE
C ----- P-PRESSUR, V-AVERAGE VELOCITY
C ----- Q-HEAT FLUX, De-EQUIVALENT DIAMETER
OPEN(3,FILE='PQV.DAT')
READ(3,*)M,P,DE,Q
II=1
DO 2 I=1,M
2 READ(3,*)V(I)
CLOSE(3)

C -----
C ----- CALCULATE PROPERTIES AT Ps,Ts
C -----
C -----ROUF-DENSITY, MUF-VISCOSITY, PRF-PRANDTL NUMBER
C -----KF-THERMAL CONDUCTIVITY, SM-SURFACE TENSION
C -----TS-SATURATION TEMP. , CPF-SPECIFIC HEAT
OPEN(1,FILE='DATA.1')
READ(1,*)PS(1),TTS(1)
DO 10 I=1,40
READ(1,*)PS(I+1),TTS(I+1)
IF(P.GT.PS(I).AND.P.LE.PS(I+1)) THEN
DP=(P-PS(I))/(PS(I+1)-PS(I))
TS=TTS(I)+DP*(TTS(I+1)-TTS(I))
DT=(TS-TTS(I))/(TTS(I+1)-TTS(I))
GOTO 20
END IF
10 CONTINUE
20 CONTINUE
OPEN(2,FILE='DATA.2')
DO 30 J=1,6*(I-1)
30 READ(2,*) X
READ(2,*)ROUF1,CPF1,SM1,MUF1,KF1,PRF1
READ(2,*)ROUF2,CPF2,SM2,MUF2,KF2,PRF2
ROUF1=ROUF1/1000.0
ROUF2=ROUF2/1000.0
ROUF=1./ROUF1+DT*(1./ROUF2-1./ROUF1)
CPF=CPF1+DT*(CPF2-CPF1)
MUF=(MUF1+DT*(MUF2-MUF1))/1000000.0
KF=KF1+DT*(KF2-KF1)
PRF=PRF1+DT*(PRF2-PRF1)

```

```

CLOSE(1)
CLOSE(2)
C -----
C           CALCULATE Re,Pe and DTd/Q
C -----
C ----- RE-REYNOLDS NUMBER, PE-PECLET NUMBER
C ----- DTD-LIQUID SUB-COOLING AT OSV
300 RE=ROUF*V(II)*DE/MUF
    PE=RE*PRF
    IF(PE.LE.70000.) THEN
        DTD=DE/KF/455.
    ELSE
        DTD=1./(.0065*ROUF*V(II)*CPF)
    END IF
    WRITE(4,*)DTD*1000000.0
    II=II+1
    IF(II.LE.M) THEN
        GOTO 300
    END IF
    CLOSE(4)
    STOP
    END

```

A3.3 MODIFIED ROGERS MODEL

```

PROGRAM ROGERS
REAL MUF, KF,MUF1,MUF2,KF1,KF2
DIMENSION PS(40),TTS(40),V(140)
C ----- M IS THE NUMBER OF POINTS WANTED TO CALCULATE
C ----- P-PRESSUR, V-AVERAGE VELOCITY, Q-HEAT FLUX
C ----- De-EQUIVALENT DIAMETER, A-EQUILIBRIUM CONTACT ANGEL
C ----- Rb-BUBBLE RADIUS, Fr-ROUGH SURFACE FACTOR
C ----- ERM=MAX(ABS(RB1-RB)), ITERATION ERROR
OPEN(3,FILE='PQV.DAT')
READ(3,*)M,P,DE,Q
II=1
DO 2 I=1,M
2 READ(3,*)V(I)
CLOSE(3)
OPEN(11,FILE='DATA.11';
READ(11,*)A,RB,ERM
CLOSE(11)

C -----
C ----- CALCULATE C1,C2,C3,CS
C -----
A=3.1415926*A/180.
C1=2.+3.*COS(A)-(COS(A))**3
C2=3.1415926-A+COS(A)*SIN(A)
AA=A+10.*3.1415926/180.
AR=A-10.*3.1415926/180.
C3=SIN(A)*(COS(AR)-COS(AA))
CS=58./(A*180./3.1415926+5.+.14

C -----
C ----- CALCULATE PROPERTIES AT Ps,Ts
C -----
C -----ROUF-DENSITY, MUF-VISCOSITY, PRF-PRANDTL NUMBER
C -----KF-THERMAL CONDUCTIVITY, SM-SURFACE TENSION
C -----TS-SATURATION TEMP. , CPF-SPECIFIC HEAT
OPEN(1,FILE='DATA.1')
READ(1,*)PS(1),TTS(1)
DO 10 I=1,40
READ(1,*)PS(I+1),TTS(I+1)
IF(P.GT.PS(I).AND.P.LE.PS(I+1)) THEN
DP=(P-PS(I))/(PS(I+1)-PS(I))
TS=TTS(I)+DP*(TTS(I+1)-TTS(I))
DT=(TS-TTS(I))/(TTS(I+1)-TTS(I))
GOTO 20
END IF
10 CONTINUE
20 CONTINUE

```

```

OPEN(2,FILE='DATA.2')
DO 30 J=1,6*(I-1)
30 READ(2,*) X
  READ(2,*) ROUF1,CPF1,SM1,MUF1,KF1,PRF1
  READ(2,*) ROUF2,CPF2,SM2,MUF2,KF2,PRF2
  ROUF1=ROUF1/1000.0
  ROUF2=ROUF2/1000.0
  ROUF=1./ROUF1+DT*(1./ROUF2-1./ROUF1)
  CPF=CPF1+DT*(CPF2-CPF1)
  SM=(SM1+DT*(SM2-SM1))/1000.0
  MUF=(MUF1+DT*(MUF2-MUF1))/1000000.0
  KF=KF1+DT*(KF2-KF1)
  PRF=PRF1+DT*(PRF2-PRF1)
  CLOSE(1)
  CLOSE(2)

C -----
C          CALCULATE RE,TAUW,USTAR
C -----
C          RE-REYNOLDS NUMBER,  F-FRICTION FACTOR
C          TAUW-SHEAR STRESS AT THE WALL
C          USTAR-SHEAR STRESS VELOCITY
300 RE=ROUF*V(II)*DE/MUF
    F=.046*RE**(-.2)
    TAUW=.5*F*ROUF*V(II)*V(II)
    USTAR=SQRT(TAUW/ROUF)

C -----
C          CALCULATE YRP,URP,UR
C -----
C          YRP--NON-DIMENSIONAL DISTANCE FROM THE WALL TO THE
C          TIP OF THE BUBBLE AT DEPARTURE
C          URP--NON-DIMENSIONAL VELOCITY AT YRP
C          UR  --LIQUID VELOCITY AT YR
100 YRP=.5*RB*(1.+COS(A))*ROUF*USTAR/MUF
    IF(YRP.LE.5.) THEN
      URP=YRP
    ELSE IF(YRP.GT.30.) THEN
      URP=2.5*LOG(YRP)+5.5
    ELSE
      URP=5.*LOG(YRP)-3.08
    END IF
    UR=URP*USTAR

C -----
C          CALCULATE REB,CD
C -----
C          REB--BUBBLE REYNOLDS NUMBER
C          CD  --BUBBLE DRAG COEFFICIENT

```

```

REB=ROUF*UR*2.*RB/MUF
IF(REB.GT.20.) CD=1.22
IF(REB.GE.4..AND.REB.LE.20.) CD=24./REB

```

```

C -----
C          CALCULATE RB
C -----

```

```

G=9.81
X1=1.+8.*3.1416**2/3*C1*C3/C2/C2*CS/CD/CD*G*SM/ROUF/UR**4
RB1=3./4./3.1415926*C2*CD/C1*UR*UR/G*(SQRT(X1)-1.)
ERR=ABS(RB1-RB)
IF(ERR.LT.ERM) THEN
GOTO 200
ELSE
RB=RB+.5*(RB1-RB)
N=N+1
GOTO 100
END IF
200 RB=RB1

```

```

C -----
C          CALAULATE TBP,DTD
C -----
C ----- DTD-LIQUID SUB-COOLING AT OSV
C ----- TBP-NON-DIMENSIONAL TEMP. DIFFERENCE BETWEEN THE WALL
C          AND LIQUID AT THE BUBBLE TIP

```

```

YBP=2.*YRP
IF(YBP.LE.5.) THEN
TBP=PRF*YBP
ELSE IF(YBP.GT.30.) THEN
TBP=5.*(PRF+LOG(1.+5.*PRF)+.5*LOG(YBP/30.))
ELSE
TBP=5.*(PRF+LOG(1.+PRF*(YBP/5.-1.)))
END IF
IF(A.LT.79.*3.14159/180.) THEN
FR=1.+28.61/REB
ELSE
FR=1.+240.0/(REB**1.31)
END IF
H0=.023*RE**.8*PRF**.4*KF/DE
DTD=(1./FR/H0-TBP/CPF/ROUF/USTAR)
WRITE(4,*)DTD*1000000.
II=II+1
IF(II.LE.M) THEN
GOTO 300
END IF
CLOSE(4)
STOP
END

```


APPENDIX 4

EXPERIMENTAL AND MODELS PREDICTED LIQUID

SUBCOOLING ($\Delta T_s/Q$, °C/(W/m²)*10⁴)

G.C.BARTOLEMI (1)

No.	Exp't data	Levy model	Zuber model	Bowring model	Rogers model		Modi'd R. model ¹		Modi'd R. model ²	
					$\theta_0=30^\circ$	$\theta_0=80^\circ$	$\theta_0=30^\circ$	$\theta_0=80^\circ$	$\theta_0=30^\circ$	$\theta_0=80^\circ$
1	43.41	21.48	39.57	15.48	36.10	32.55	31.39	30.53	33.43	28.66
2	44.55	24.67	39.57	15.48	41.76	38.14	37.03	36.28	38.85	33.89
3	38.98	24.67	39.57	15.48	41.71	38.18	37.01	36.30	38.79	33.92
4	35.07	21.27	36.23	15.49	36.59	33.50	30.42	30.53	29.93	26.49
5	30.45	21.27	36.23	15.49	36.62	33.49	30.93	30.53	29.95	26.48
6	34.05	24.42	36.23	15.49	41.95	38.82	36.18	35.94	34.66	31.16
7	27.33	24.42	36.23	15.49	41.97	38.82	36.18	35.94	34.68	31.16
8	28.50	21.57	34.51	16.15	37.27	34.46	30.44	30.44	27.32	24.78
9	24.50	21.57	34.51	16.15	37.31	34.46	30.44	30.44	27.36	24.77
10	26.70	24.78	34.51	16.15	42.56	39.74	35.54	35.73	31.69	29.16
11	20.38	24.78	34.51	16.15	42.60	39.73	35.54	35.72	31.73	29.15

G.C.BARTOLEMI DATA (2)

No.	Exp't data	Levy model	Zuber model	Bowring model	Rogers model		Modi'd R. model ¹		Modi'd R. model ²	
					$\theta_0=30^\circ$	$\theta_0=80^\circ$	$\theta_0=30^\circ$	$\theta_0=80^\circ$	$\theta_0=30^\circ$	$\theta_0=80^\circ$
1	23.31	19.10	33.06	14.14	32.66	29.93	26.78	26.57	26.23	23.27
2	22.38	20.17	28.87	15.58	34.14	32.04	25.20	25.77	21.14	19.94
3	24.95	20.46	29.76	16.06	34.64	32.46	25.73	26.27	21.46	20.19
4	21.14	20.17	28.87	15.58	34.08	32.04	25.20	25.77	21.08	19.93
5	54.24	30.01	46.44	38.37	47.30	40.88	41.68	39.02	26.76	21.52
6	30.00	20.39	29.53	15.94	34.49	32.35	25.60	26.15	21.36	20.12
7	14.09	14.14	14.11	7.62	23.27	22.59	14.60	15.16	13.31	13.36
8	10.73	14.09	14.01	7.56	23.16	22.53	14.52	15.04	13.21	13.33
9	23.69	21.41	24.70	17.27	34.86	33.45	21.85	22.78	16.76	16.92
10	9.05	14.76	12.18	8.52	23.38	22.91	11.93	12.12	10.90	11.45
11	20.03	21.41	24.70	17.27	34.93	33.46	21.82	22.78	16.82	16.92
12	9.23	14.76	12.18	8.52	23.38	22.91	11.93	12.12	10.90	11.45
13	33.74	29.43	47.09	32.93	47.24	43.81	34.39	35.06	20.27	19.23
14	7.11	14.36	8.65	8.16	21.27	21.09	7.44	6.58	8.16	9.01
15	7.81	14.83	9.15	8.63	22.13	21.89	7.75	6.95	8.62	9.45
16	7.85	14.81	9.12	8.60	22.11	21.80	7.71	7.03	8.61	9.38
17	7.96	14.36	8.65	8.16	21.40	21.16	7.27	6.43	8.29	9.08
18	6.16	15.57	9.96	9.39	23.24	23.05	8.60	7.80	9.07	10.03
19	5.50	15.43	9.80	9.24	23.09	22.79	8.34	7.71	9.05	9.88
20	17.76	21.96	18.36	17.31	33.66	32.89	15.52	15.84	13.27	14.29

B.L.BIBEAU DATA

No.	Exp't data	Levy model	Zuber model	Bowring model	Rogers model $\theta_0=30^\circ$ $\theta_0=80^\circ$		Modi'd R. model ¹ $\theta_0=30^\circ$ $\theta_0=80^\circ$		Modi'd R. model ² $\theta_0=30^\circ$ $\theta_0=80^\circ$	
1	12.33	39.89	29.21	54.43	16.91	15.95	18.68	20.31	38.68	28.03
2	17.16	35.18	29.21	38.25	26.45	22.01	24.58	23.67	40.76	29.42
3	17.69	32.28	29.21	30.77	29.86	24.12	25.92	24.00	40.46	29.18
4	28.02	41.46	29.21	61.53	12.67	13.20	15.58	18.22	37.54	27.21
5	31.52	42.01	29.21	64.33	11.10	12.16	14.35	17.35	37.16	26.91

H.CHRISTENSEN DATA

No.	Exp't data	Levy model	Zuber model	Bowring model	Rogers model $\theta_0=30^\circ$ $\theta_0=80^\circ$		Modi'd R. model ¹ $\theta_0=30^\circ$ $\theta_0=80^\circ$		Modi'd R. model ² $\theta_0=30^\circ$ $\theta_0=80^\circ$	
1	29.38	24.96	51.55	21.72	42.80	37.93	38.89	36.93	37.07	31.18
2	19.70	22.16	34.36	15.72	38.41	35.58	31.77	31.78	28.98	26.30
3	19.55	23.14	33.96	16.92	39.75	37.08	31.99	32.28	27.37	25.33
4	17.50	24.23	33.29	18.06	41.01	38.54	31.95	32.56	25.85	24.42

J.COSTA DATA

No.	Exp't data	Levy model	Zuber model	Bowring model	Rogers model $\theta_0=30^\circ$ $\theta_0=80^\circ$		Modi'd R. model ¹ $\theta_0=30^\circ$ $\theta_0=80^\circ$		Modi'd R. model ² $\theta_0=30^\circ$ $\theta_0=80^\circ$	
1	4.49	5.61	4.84	1.79	8.71	8.55	3.34	3.11	3.56	3.71
2	5.76	7.05	7.21	2.67	10.93	10.66	4.90	4.86	5.91	5.90
3	5.55	7.05	7.21	2.67	10.93	10.63	4.90	4.89	5.91	5.88
4	4.39	5.34	4.76	1.77	8.39	8.28	3.59	3.36	3.44	3.63
5	5.95	8.64	7.92	2.93	13.45	13.11	6.66	6.86	7.94	7.88
6	7.25	10.82	12.01	4.44	16.84	16.16	9.50	9.99	12.10	11.46
7	5.96	8.21	7.21	2.67	12.76	12.46	6.10	6.25	7.16	7.16
8	6.31	9.24	8.95	3.31	14.35	13.99	7.46	7.71	9.02	8.87
9	6.27	9.27	9.01	3.33	14.45	14.02	7.47	7.78	9.13	8.90
10	6.66	10.82	12.01	4.44	16.84	16.20	9.50	9.96	12.09	11.49
11	6.80	8.94	9.15	3.40	14.23	13.80	7.98	8.28	9.05	8.83
12	7.25	10.27	11.89	4.42	16.44	15.75	9.86	10.30	11.72	11.10
13	7.89	10.27	11.89	4.42	16.40	15.78	9.89	10.28	11.67	11.13
14	5.29	8.71	7.30	2.70	13.17	12.93	5.73	5.75	7.32	7.37
15	5.02	8.66	7.24	2.67	13.10	12.84	5.69	5.73	7.23	7.28
16	5.92	9.86	9.15	3.39	14.90	14.56	7.02	7.25	9.38	9.24
17	6.77	11.48	12.10	4.47	17.30	16.67	8.86	9.39	12.43	11.81
18	5.69	9.85	9.13	3.37	14.93	14.52	6.96	7.26	9.40	9.20

J.COSTA DATA (continue)

No.	Exp't data	Levy model	Zuber model	Bowring model	Rogers model		Modi'd R. model ¹		Modi'd R. model ²	
					$\theta_0=30^\circ$	$\theta_0=80^\circ$	$\theta_0=30^\circ$	$\theta_0=80^\circ$	$\theta_0=30^\circ$	$\theta_0=80^\circ$
19	5.00	7.78	5.96	2.20	11.77	11.56	4.67	4.58	5.76	5.89
20	7.81	7.81	6.93	2.56	12.15	11.87	5.69	5.75	6.62	6.64
21	6.57	6.67	5.23	1.93	10.30	10.11	4.33	4.25	4.66	4.80
22	7.64	8.07	7.35	2.72	12.50	12.26	6.04	6.10	7.02	7.07
23	8.25	7.99	7.21	2.67	12.42	12.11	5.88	6.03	6.93	6.90
24	6.46	6.62	5.15	1.90	10.19	10.00	4.29	4.21	4.55	4.69
25	6.55	6.62	5.15	1.90	10.16	10.03	4.33	4.16	4.52	4.72
26	8.05	7.99	7.21	2.67	12.42	12.13	5.88	6.00	6.93	6.93
27	9.55	10.55	12.01	4.44	16.40	15.72	9.12	9.57	11.74	11.11
28	8.60	8.03	7.28	2.69	12.50	12.20	5.92	6.05	7.01	7.00
29	6.69	6.62	5.15	1.90	10.17	9.99	4.32	4.22	4.53	4.69
30	6.69	6.62	5.15	1.90	10.22	10.00	4.26	4.22	4.57	4.69
31	10.60	10.55	12.01	4.44	16.39	15.70	9.12	9.58	11.74	11.09
32	7.00	6.33	5.14	1.91	9.92	9.73	4.56	4.54	4.49	4.61
33	8.79	7.62	7.17	2.66	12.06	11.82	6.23	6.31	6.72	6.77
34	6.33	6.31	5.10	1.89	9.89	9.69	4.51	4.49	4.46	4.58
35	7.05	7.60	7.14	2.65	12.03	11.80	6.21	6.29	6.69	6.75
36	7.09	7.01	5.22	1.93	10.56	10.44	3.99	3.72	4.62	4.85
37	6.68	7.01	5.22	1.93	10.56	10.43	3.99	3.73	4.62	4.84
38	7.04	7.01	5.22	1.93	10.56	10.43	3.99	3.73	4.62	4.84
39	6.96	8.45	7.29	2.69	12.87	12.53	5.43	5.53	7.12	7.08
40	5.25	6.98	5.19	1.92	10.58	10.36	3.89	3.75	4.64	4.78
41	8.75	8.44	7.26	2.68	12.83	12.54	5.41	5.45	7.09	7.09
42	10.25	11.17	12.10	4.47	16.77	16.20	8.51	8.96	11.99	11.43
43	9.50	11.17	12.10	4.47	16.82	16.18	8.48	8.98	12.04	11.41

Z.EDELMAN DATA

No.	Exp't data	Levy model	Zuber model	Bowring model	Rogers model		Modi'd R. model ¹		Modi'd R. model ²	
					$\theta_0=30^\circ$	$\theta_0=80^\circ$	$\theta_0=30^\circ$	$\theta_0=80^\circ$	$\theta_0=30^\circ$	$\theta_0=80^\circ$
1	37.01	57.32	36.47	139.60	23.24	30.49	3.42	7.95	85.12	67.53
2	35.30	56.22	36.47	118.49	15.46	18.85	6.72	9.14	68.76	50.56
3	44.08	54.53	36.47	100.00	12.84	12.53	10.40	10.37	58.35	39.38
4	44.59	53.00	36.47	88.12	13.46	14.37	13.40	15.33	53.79	37.99
5	43.23	51.72	36.47	80.11	14.94	15.98	15.76	18.32	51.68	37.36
6	40.90	50.42	36.47	73.06	16.95	17.62	18.05	20.71	50.47	36.99

R.A. EGEN DATA

No.	Exp't data	Levy model	Zuber model	Bowring model	Rogers model		Modi'd R. model ¹		Modi'd R. model ²	
					$\theta_o=30^\circ$	$\theta_o=80^\circ$	$\theta_o=30^\circ$	$\theta_o=80^\circ$	$\theta_o=30^\circ$	$\theta_o=80^\circ$
1	17.62	22.74	22.20	26.35	32.41	30.66	16.33	16.91	10.60	10.84
2	19.96	30.42	22.20	43.82	39.77	36.38	22.96	23.62	8.79	8.30
3	13.53	22.96	22.20	26.81	32.61	30.91	16.58	17.12	10.55	10.86
4	14.10	23.12	22.20	27.12	32.86	31.06	16.68	17.27	10.63	10.85
5	14.69	20.00	22.20	21.12	29.17	27.87	13.70	14.07	10.30	10.70
6	16.73	19.94	22.20	21.01	29.00	27.84	13.70	13.97	10.20	10.73
7	10.91	19.94	22.20	21.01	29.00	27.83	13.70	13.98	10.20	10.71

R. BYANGLISTI DATA

No.	Exp't data	Levy model	Zuber model	Bowring model	Rogers model		Modi'd R. model ¹		Modi'd R. model ²	
					$\theta_o=30^\circ$	$\theta_o=80^\circ$	$\theta_o=30^\circ$	$\theta_o=80^\circ$	$\theta_o=30^\circ$	$\theta_o=80^\circ$
1	29.06	17.66	19.34	9.57	23.50	21.90	13.54	14.54	22.03	19.29
2	39.69	26.84	19.34	22.19	25.66	21.23	18.02	17.59	31.67	23.48
3	24.29	17.62	19.34	9.53	23.50	21.87	13.49	14.50	22.00	19.25

P. GRIFFITH DATA

No.	Exp't data	Levy model	Zuber model	Bowring model	Rogers model		Modi'd R. model ¹		Modi'd R. model ²	
					$\theta_o=30^\circ$	$\theta_o=80^\circ$	$\theta_o=30^\circ$	$\theta_o=80^\circ$	$\theta_o=30^\circ$	$\theta_o=80^\circ$
1	22.04	26.56	43.63	25.80	43.70	40.33	34.04	34.24	24.12	22.27
2	15.12	21.73	28.61	16.92	36.13	34.17	25.73	26.55	20.54	19.82
3	30.29	30.44	51.15	34.91	48.84	43.89	40.34	39.45	25.41	22.25
4	10.53	21.31	27.47	16.25	35.35	33.56	25.01	25.83	20.07	19.49
5	19.97	29.65	51.15	32.89	47.88	43.28	39.10	38.48	25.29	22.42
6	16.32	26.13	42.11	24.91	43.07	39.83	33.31	33.60	23.86	22.13
7	28.77	32.49	55.09	39.69	51.70	47.39	38.88	39.23	20.47	18.95
8	20.61	27.20	38.49	27.26	44.28	41.61	30.71	31.73	19.91	19.39
9	21.21	27.20	38.49	27.26	44.24	41.63	30.72	31.72	19.86	19.42
10	12.74	22.15	25.41	18.00	36.14	34.65	22.65	23.66	17.23	17.39
11	19.71	27.83	30.12	26.20	43.31	41.74	25.19	26.45	16.87	17.71
12	16.84	24.57	23.83	20.73	38.22	37.16	20.79	21.67	15.53	16.50

D.A.LABUNTSOV DATA

No.	Exp't data	Levy model	Zuber model	Bowring model	Rogers model		Modi'd R. model ¹		Modi'd R. model ²	
					$\theta_o=30^\circ$	$\theta_o=80^\circ$	$\theta_o=30^\circ$	$\theta_o=80^\circ$	$\theta_o=30^\circ$	$\theta_o=80^\circ$
1	8.93	10.53	9.91	3.99	17.22	16.77	11.08	11.51	10.97	10.85
2	27.73	23.23	38.29	20.91	38.99	36.03	30.42	30.59	23.77	21.84
3	9.56	11.63	9.57	5.23	18.53	18.25	10.43	10.64	9.57	9.95

R.MARTIN DATA

No.	Exp't data	Levy model	Zuber model	Bowring model	Rogers model		Modi'd R. model ¹		Modi'd R. model ²	
					$\theta_o=30^\circ$	$\theta_o=80^\circ$	$\theta_o=30^\circ$	$\theta_o=80^\circ$	$\theta_o=30^\circ$	$\theta_o=80^\circ$
1	32.28	19.78	22.30	21.03	30.89	28.24	22.01	22.07	16.61	15.04
2	20.32	19.78	22.30	21.03	30.92	28.22	22.01	22.07	16.65	15.02
3	14.12	13.71	18.26	10.52	22.46	21.45	13.60	13.99	12.15	11.94
4	9.64	11.12	12.45	7.17	18.15	17.66	9.94	10.08	9.26	9.46
5	14.85	13.71	18.26	10.52	22.51	21.45	13.58	13.99	12.19	11.94
6	11.36	13.71	18.26	10.52	22.46	21.49	13.61	13.97	12.14	11.98
7	13.62	13.71	18.26	10.52	22.54	21.47	13.56	13.98	12.23	11.96
8	16.40	13.71	18.26	10.52	22.52	21.45	13.58	13.99	12.21	11.94

G.W.MAURER DATA

No.	Exp't data	Levy model	Zuber model	Bowring model	Rogers model		Modi'd R. model ¹		Modi'd R. model ²	
					$\theta_o=30^\circ$	$\theta_o=80^\circ$	$\theta_o=30^\circ$	$\theta_o=80^\circ$	$\theta_o=30^\circ$	$\theta_o=80^\circ$
1	17.69	18.79	16.60	20.89	28.14	25.72	18.80	18.91	13.94	12.65
2	14.15	14.89	16.60	13.68	23.50	22.07	14.15	14.49	12.08	11.56
3	21.05	22.15	16.60	28.37	31.15	27.54	22.21	21.73	14.23	11.97
4	10.15	14.53	16.60	13.08	22.94	21.66	13.71	14.03	11.76	11.38
5	16.69	20.87	16.60	25.38	30.15	27.00	21.00	20.78	14.30	12.41
6	14.01	18.37	16.60	20.04	27.77	25.40	18.32	18.48	13.89	12.63
7	3.16	8.24	7.16	5.20	12.95	12.76	4.59	3.99	4.82	5.23
8	1.22	6.29	4.54	3.29	9.83	9.61	2.73	2.15	3.15	3.36
9	18.15	22.41	17.92	30.28	32.05	29.12	19.55	19.79	10.87	9.84
10	11.22	22.26	17.92	29.88	31.86	29.03	19.41	19.66	10.86	9.91
11	15.22	18.24	17.92	20.82	27.66	25.88	15.35	15.74	10.95	10.65
12	14.35	18.20	17.92	20.73	27.63	25.86	15.30	15.69	10.96	10.66
13	8.50	14.42	17.92	13.70	22.64	21.65	11.10	11.29	9.55	9.68
14	10.46	18.91	19.35	18.92	26.21	25.29	11.05	11.04	8.96	9.57
15	7.88	16.36	16.54	14.91	23.13	22.49	8.97	8.58	8.25	8.91

R.D.MCLBOD DATA

No.	Exp't data	Levy model	Zuber model	Bowring model	Rogers Model θo=30°	Rogers Model θo=80°	Modi'd R. model ¹ θo=30°	Modi'd R. model ¹ θo=80°	Modi'd R. model ² θo=30°	Modi'd R. model ² θo=80°
1	13.03	40.19	28.57	56.48	14.99	14.41	17.09	18.96	37.56	26.99
2	17.23	45.95	28.57	93.30	-1.68	2.10	2.04	6.06	35.96	24.06
3	10.62	44.22	28.57	78.72	3.13	6.26	7.35	11.53	35.01	24.64
4	15.58	38.41	28.57	49.30	19.44	17.29	20.18	20.94	38.83	27.89
5	16.29	33.17	28.57	33.32	28.34	22.99	25.12	23.49	40.19	28.85
6	17.74	44.36	28.57	79.78	2.72	5.93	6.94	11.15	35.02	24.58
7	16.97	44.09	28.57	77.85	3.50	6.54	7.70	11.84	35.02	24.70
8	16.97	40.83	28.57	59.34	13.24	13.26	15.80	18.09	37.06	26.62
9	16.17	41.12	28.57	60.74	12.43	12.72	15.18	17.66	36.84	26.46
10	20.48	37.06	28.57	44.58	22.32	19.15	22.01	22.03	39.55	28.39
11	20.52	37.61	28.57	46.45	21.20	18.42	21.31	21.62	39.29	28.21
12	16.83	37.77	28.57	47.00	20.87	18.21	21.10	21.50	39.22	28.15
13	18.16	34.92	28.57	37.98	26.07	21.55	24.11	23.13	40.19	28.84
14	22.13	34.42	28.57	36.60	26.79	22.00	24.46	23.28	40.24	28.87
15	21.26	33.72	28.57	34.72	27.71	22.58	24.87	23.43	40.25	28.88
16	17.72	31.69	28.57	29.78	29.77	23.86	25.54	23.47	39.82	28.59
17	20.11	45.33	28.57	87.53	-0.09	3.63	4.01	8.28	35.29	24.19
18	24.27	43.34	28.57	72.84	5.80	8.22	9.79	13.62	35.28	25.12
19	25.35	41.65	28.57	63.32	10.90	11.71	14.01	16.83	36.41	26.13
20	22.75	42.84	28.57	69.82	7.34	9.30	11.11	14.66	35.58	25.42
21	37.68	36.44	28.57	42.54	23.52	19.92	22.72	22.43	39.81	28.57
22	22.28	39.87	28.57	55.09	15.85	14.96	17.71	19.37	37.81	27.17
23	29.71	35.38	28.57	39.31	25.36	21.09	23.75	22.96	40.12	28.78
24	17.34	49.39	38.52	110.05	14.39	16.88	14.86	16.50	61.11	44.38
25	14.74	48.40	38.52	94.73	13.60	17.87	16.97	21.23	54.15	41.55
26	15.59	48.25	38.52	92.93	13.71	18.06	17.30	21.73	53.51	41.27
27	17.76	48.22	38.52	92.62	13.75	18.09	17.36	21.81	53.42	41.22
28	17.23	46.05	38.52	74.02	17.46	20.85	21.76	26.38	49.27	39.11
29	13.28	46.45	38.52	76.83	16.64	20.34	21.00	25.75	49.67	39.35
30	25.25	46.84	38.52	79.78	15.85	19.83	20.22	25.07	50.14	39.63
31	29.14	49.18	38.52	106.01	13.93	17.05	15.33	17.84	59.04	43.56
32	35.32	47.95	38.52	89.63	14.03	18.42	17.94	22.62	52.47	40.79
33	40.47	44.98	38.52	67.40	19.82	22.22	23.71	27.77	48.72	38.66
34	47.21	42.35	38.52	54.54	25.52	25.31	27.68	30.01	48.58	38.11
35	22.69	52.80	54.57	141.11	55.17	62.99	40.58	45.16	118.07	100.41
36	15.07	53.03	54.57	128.31	46.83	52.30	39.00	42.20	104.54	86.51
37	7.95	52.98	54.57	132.77	49.58	55.88	39.55	43.26	109.11	91.21
38	13.24	52.80	54.57	109.71	37.90	40.44	37.29	38.73	87.84	69.84
39	30.49	52.51	54.57	102.56	35.59	39.46	36.92	40.12	82.46	66.96
40	18.88	53.03	54.57	121.48	43.14	47.27	38.29	40.61	98.02	79.73
41	17.21	52.64	54.57	105.30	36.40	39.82	37.04	39.62	84.46	68.05

S.Z.ROUHANI DATA

No.	Exp't data	Levy model	Zuber model	Bowring model	Rogers model		Modi'd R. model ¹		Modi'd R. model ²	
					$\theta_0=30^\circ$	$\theta_0=80^\circ$	$\theta_0=30^\circ$	$\theta_0=80^\circ$	$\theta_0=30^\circ$	$\theta_0=80^\circ$
1	36.95	32.25	42.18	100.44	26.17	29.96	39.21	41.08	48.88	40.90
2	32.02	32.25	42.18	100.44	26.18	29.95	39.22	41.08	48.90	40.89
3	26.37	19.61	34.42	13.08	32.21	29.24	26.89	26.52	30.28	26.11
4	23.11	19.61	34.42	13.08	32.15	29.23	26.88	26.52	30.23	26.11
5	19.78	17.21	25.51	9.69	28.58	26.61	22.52	22.81	25.25	22.62
6	15.60	25.24	42.18	25.03	37.23	32.71	35.42	33.55	39.68	32.18
7	14.31	33.30	44.90	105.57	36.57	38.09	48.41	48.73	32.29	28.35
8	17.66	33.30	44.90	105.57	36.58	38.08	48.42	48.73	32.31	28.34
9	16.08	33.30	44.90	105.57	36.58	38.08	48.41	48.73	32.30	28.34
10	30.14	37.77	47.80	111.37	42.92	43.84	51.53	52.51	16.25	16.24
11	31.11	37.77	47.80	111.37	42.94	43.85	51.54	52.52	16.27	16.25
12	19.32	23.65	45.88	22.15	40.11	36.11	33.92	33.04	28.42	24.74
13	19.01	23.65	45.88	22.15	40.12	36.14	33.92	33.05	28.44	24.77
14	31.31	18.66	31.98	12.87	31.89	29.21	26.37	26.15	27.44	24.17
15	23.73	18.60	31.72	12.76	31.83	29.15	26.25	26.05	27.35	24.09
16	16.30	18.96	31.24	13.32	32.59	30.04	26.57	26.51	26.14	23.40

P.W.STAUB DATA

No.	Exp't data	Levy model	Zuber model	Bowring model	Rogers model		Modi'd R. model ¹		Modi'd R. model ²	
					$\theta_0=30^\circ$	$\theta_0=80^\circ$	$\theta_0=30^\circ$	$\theta_0=80^\circ$	$\theta_0=30^\circ$	$\theta_0=80^\circ$
1	33.23	43.12	45.11	42.13	36.63	33.08	34.78	35.10	55.32	43.09
2	32.25	43.12	45.11	42.13	36.64	33.08	34.78	35.10	55.33	43.09
3	27.86	28.24	41.71	15.44	37.46	34.58	27.80	28.97	40.04	34.33
4	18.57	23.25	27.79	10.29	32.76	31.04	22.03	23.57	31.56	28.32
5	17.59	22.76	26.60	9.85	32.20	30.58	21.42	22.96	30.66	27.64
6	20.04	22.53	26.06	9.65	31.90	30.36	21.14	22.67	30.21	27.31
7	12.22	15.36	13.21	4.88	22.74	22.15	13.02	13.92	17.33	16.65
8	36.65	35.15	44.72	39.08	36.28	34.25	37.43	38.05	49.76	40.94
9	22.48	19.99	26.44	9.78	30.56	28.68	22.85	23.63	28.60	25.60
10	10.75	14.23	13.22	4.89	21.93	21.22	13.89	14.69	16.71	15.96
11	11.73	14.23	13.22	4.89	21.96	21.25	13.87	14.68	16.74	15.99

APPENDIX 5

CORRELATIONS FOR DIFFERENT θ_0

Table A5.1 Correlations for Different θ_0 and Deviations of Model Predictions
Using These Correlations ($Re \geq 10^4$).

θ_0	Correlations	Maximum deviation	Standard deviation**
30	$F_R = 1 + 17.58 Re_b^{-0.89}$	23.4	0.360
35	$F_R = 1 + 22.38 Re_b^{-0.94}$	24.4	0.364
40	$F_R = 1 + 28.94 Re_b^{-0.98}$	24.4	0.345
45	$F_R = 1 + 44.15 Re_b^{-1.06}$	23.5	0.340
50	$F_R = 1 + 27.68 Re_b^{-0.95}$	26.5	0.347
55	$F_R = 1 + 32.61 Re_b^{-0.97}$	26.6	0.377
60	$F_R = 1 + 38.02 Re_b^{-0.99}$	26.3	0.340
65	$F_R = 1 + 43.80 Re_b^{-1.01}$	25.9	0.337
70	$F_R = 1 + 49.50 Re_b^{-1.02}$	26.1	0.332
75	$F_R = 1 + 54.96 Re_b^{-1.03}$	25.9	0.336
80	$F_R = 1 + 58.86 Re_b^{-1.07}$	25.8	0.339

$$* \text{ Maximum Deviation} = \max_{i=1}^n \left| \left(\frac{\Delta T_d}{q''} \right)_{exp} - \left(\frac{\Delta T_d}{q''} \right)_{pre} \right|_i$$

$$** \text{ Standard Deviation} = \sqrt{\frac{\sum_{i=1}^n \left(\frac{\left(\frac{\Delta T_d}{q''} \right)_{exp} - \left(\frac{\Delta T_d}{q''} \right)_{pre}}{\left(\frac{\Delta T_d}{q''} \right)_{exp}} \right)^2}{n-1}}$$

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