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Draft Enhancing and Downdraft Inhibiting Characteristics of Chimney Caps

by

Andrew Martin Koski-Harja
B.Eng. (Aerospace), Carleton University

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
Ottawa-Carleton Institute
for Mechanical and Aerospace Engineering

Carleton University
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of Chimney Caps**

submitted by
Andrew Martin Koski-Harja, B.Eng.

in partial fulfilment of the requirements for
the degree of Master of Engineering

Chair, Department of Mechanical and Aerospace Engineering

Thesis Supervisor

Carleton University
December 1994

Abstract

This thesis presents the results obtained from wind tunnel testing of chimney caps. The performance of five chimney caps was evaluated in terms of enhancing draft and preventing downdraft in chimney systems and was measured using a modified version of a natural roof ventilator performance testing procedure developed by J. J. Wannenburg.

Based on results obtained from the performance testing procedure, it was found that two of the three initially tested chimney caps did not perform as expected as compared to a commercially available chimney cap design. The decreased draft enhancement was due to the chimney cap geometry and flue flow interaction with the passing wind tunnel flow, causing the wind tunnel flow to be deflected away from the chimney cap. This flow deflection was shown using flow visualization techniques.

Based on the results of the three initially tested chimney caps, two modified chimney caps were developed and shown to provide increased draft enhancement. The modification made to improve the chimney cap performance was the installation of eight equally spaced guide vanes to direct the wind tunnel flow over the suction pipe exit. This improved chimney cap design also performed equal to or better than most previously tested natural roof ventilators, which are closely related to chimney caps. The performance of the tested chimney caps is summarized graphically in performance charts.

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Nomenclature

A	discharge coefficient (Gonzales)
B	coefficient accounting for turbulent eddies over the ventilator exit due to sharp edges (Gonzales)
C	maximum static pressure difference coefficient (Gonzales)
$C_p _{disk}$	static pressure coefficient behind a circular flat plate normal to the flow
$C_p _v$	ventilator static pressure coefficient (Elger and McLam)
F, G	constants used to simplify the flow coefficient relationship
g	gravitational acceleration
K	total suction pipe resistance
K_c	chimney cap exit resistance
K_{fi}	flow interaction resistance
K_i	inlet resistance
K_p	suction pipe resistance
L, M, N	constants used in verification testing
n	coefficient accounting for turbulent eddies over the ventilator exit due to sharp edges (Gonzales)
P	static pressure
ΔP_{max}	maximum ventilator static pressure difference (Gonzales)
ΔP_{vent}	ventilator static pressure difference (Gonzales)
P_{c1}, P_{c2}	wind tunnel static pressures at points "c1" and "c2"
P_{∞}	static pressure in suction pipe when inlet section closed
q	wind dynamic pressure
q_{pipe}	suction pipe dynamic pressure
q_{wt}	wind tunnel dynamic pressure
TL	throat length

V	wind tunnel free stream velocity
V_a	velocity of ambient air
v_w	suction pipe air velocity
x	suction pipe flow variable
z	distance from some datum used to measure potential energy
α	proportionality coefficient in suction pipe flow relations
γ	roof angle
η	pressure coefficient
η_{max}	maximum value of the pressure coefficient
θ	wind elevation angle relative to the horizontal
θ'	wind angle relative to the exterior wall plane of chimney cap/ventilator face
λ	inlet section pressure coefficient (Schrenk)
λ^2	inlet section pressure coefficient
ξ	ventilator inlet static pressure coefficient (Gonzales)
ρ	density
σ	ventilator inlet dynamic pressure coefficient (Gonzales)
ψ	flow coefficient

Subscripts

1	refers to values at the inlet section
2	refers to values at the chimney cap inlet
3	refers to values in the chimney cap
a	refers to values at ambient conditions
c	refers to chimney cap values
corr	refers to corrected values

spd	refers to values due to static pressure difference between the ambient and wind tunnel static pressures
w	refers to suction pipe values
wt	refers to wind tunnel values

Superscripts

/	refers to values measured for the three inch diameter inlet section
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Chapter 1

Introduction

1.1 Objectives and Thesis Outline

The objectives of the research contained in this thesis are to study the effects of some design and operating parameters on the draft enhancing and downdraft inhibiting characteristics of chimney caps, and to explore the possibility of adapting a chimney cap type of device for use as a roof ventilator. The chimney cap of a chimney system serves the primary purpose of preventing precipitation from entering the various parts of the chimney system. Through careful design, the chimney cap can also serve other purposes such as those which form the major focus of this thesis, such as aiding in the removal of flue gases in draft deficient chimney systems.

There are two types of chimney caps which can be generalized as masonry and metal. Masonry chimney caps consist of a concrete cap that is set on top of a brick chimney stack. The masonry cap serves to prevent precipitation from entering the brick chimney stack, as illustrated in Figure 1.1. Precipitation in the brick chimney stack can cause deterioration of the stack which can lead to the structural failure of that stack. Some masonry chimney caps have a slab over top of the flue liner to prevent precipitation from entering the flue liner.

Masonry chimneys also often have part of the clay chimney flue liner protruding above the concrete cap. The height at which the clay flue liner protrudes is often dependent upon the region of the country in which the chimney is located [1]. The reason for the regional differences in clay flue liner protrusion height are likely due

purely to aesthetics and local construction practices [1].

Metal chimney caps, also known as rain, weather, or termination caps, are located on top of metal chimney flue liners, as shown in Figure 1.2. The chimney flue liner can be contained either in a brick or metal chimney stack. It is the metal chimney cap which is of interest in this thesis. Hereafter, the general term chimney cap will refer to metal chimney caps.

As stated earlier, chimney caps are primarily used to prevent or minimize entry of precipitation into the chimney system. In addition, chimney caps should also possess a number of characteristics which enhance its performance such as low flow resistance and the ability to not deflect contaminated air downwards [2]. From a practical viewpoint, chimney caps should also be inexpensive, of simple construction, and require little maintenance [2]. One final recommended feature of chimney caps is that they should prevent birds, insects, and small animals from entering the chimney system, and hence the building envelope [3]. This final point is often not regarded in chimney cap design.

Chimney caps can be designed such that their geometry is able to utilize the winds surrounding the building to aid in the removal of the combustion products. This is known as the aspiration effect. This aspect of chimney caps will be the major focus of this thesis.

Although the aspiration effect might eliminate downdraft, the downdraft diverter used in many gas fired appliances cannot be eliminated [4]. While the downdraft diverter is not used for the purpose for which its name implies, it is used to minimize the effects of fluctuating wind conditions which can remove flue gases before the gases have time to transfer their useful energy to where it can be utilized. The argument above also holds true for draft regulators in oil fired equipment.

Before progressing further into the study of the aspiration effect of chimney caps, a brief review of the physical principles behind the operation of chimneys would be beneficial to the reader. This review is contained in Section 1.2.

It should also be mentioned that there exists a relationship between metal chimney caps and natural roof ventilators, also known as attic ventilators. This relationship between the two devices, which basically operate following the same principles and require the same characteristics, allows for the use of research on ventilators to be examined within the framework of chimney caps. Previous research on both chimney caps and natural ventilators is discussed in Section 1.3.

Natural roof ventilators should not be confused with powered roof ventilators which use a fan to force air flow out of the space to be ventilated. In this thesis, the term ventilator refers exclusively to natural roof ventilators.

From the physical principles reviewed in Section 1.2 and the literature survey in Section 1.3, a theoretical basis for the experimental procedure was derived. The derived procedure, with appropriate modifications, is discussed in Chapter 2. However, due to the nature of the assumptions made in the derivation of the procedure to be followed, a set of verification measurements were required. These measurements are described in Section 3.2. Based on this verified procedure, the draft enhancing characteristics of five different chimney caps were evaluated. A discussion of the draft enhancement of these various chimney caps forms the bulk of Chapter 3. Conclusions and recommendations for further research are addressed in Chapter 4.

1.2 A Brief Review of Building and Chimney Physics

1.2.1 Building Physics

The rate of air flow into or out of a building depends upon the pressure difference which exists between the inside and outside of the building, and the resistance to air flow of openings in the building [5]. The pressure differences are created by two separate

phenomena. The first cause of the pressure difference is due to the dynamic pressure of the wind forces on and around the building, including the chimney top. The second pressure difference is caused by the density and temperature differences between inside and outside of the building, commonly known as the stack effect. This effect is also often known as the buoyancy, chimney, or Archimedes effect.

The pressure distribution around the building is a complex function of building geometry and its surroundings. Objects such as trees, hills, and other buildings will have a great influence on the dynamic pressure distribution. However, if a building of simple geometry and surroundings is considered, a general understanding of the pressure distributions can be realized. From the building configuration of Figure 1.3, it has been demonstrated numerous times [5] that the pressure distributions on the walls of the structure will be in the range of +0.5 to +0.9 times the wind dynamic pressure (q) for the windward walls, -0.3 to -0.6 times q for the leeward wall, and -0.1 to -0.9 times q for the remaining walls.

The pressure distribution on the roof of the simple building is a function of the roof geometry, wind angle relative to the horizontal and to the plane of the exterior walls, and location on roof with respect to the leading edge of the roof. For flat and low-pitched roofs with roof angles up to 30 degrees, pressures range from -0.2 to -0.8 times the wind dynamic pressure over the entire roof. In the case of high-pitched roofs, pressures of +0.2 to +0.3 times q for the windward side and -0.5 to -0.7 times q for the leeward side of the roof are common.

Pressure distributions inside buildings are determined by two factors. These factors are the amount of air flow into buildings through cracks and openings, known as infiltration, and the operation of any exhausting devices in the building such as fans, clothes dryers, and fireplaces [6].

Infiltration is a function of the wind angle relative to the wall plane, and the geometry and distribution of openings in the building envelope. For uniformly distributed openings, building pressures of plus or minus 0.2 times the wind dynamic pressure are

common [5]. However, if there exists a dominance of windward openings, pressures up to $+0.8$ times q can occur whereas a dominance of leeward openings can develop pressures of -0.2 to -0.4 times q or greater.

Exhausting devices can cause large amounts of air to be extracted from the building envelope. This results in a depressurization of the building, which in extreme cases can approach values that can negate chimney draft and reverse the flow in a chimney [6].

As stated earlier, temperature differences between inside and outside of the building cause pressure differences which also drive air flow into and out of buildings as demonstrated in Figures 1.4(a) and (b). If the temperature inside the building is higher than that of its outside surroundings and the average pressure inside the building is equal to that of the average outside pressure, lower than outside pressures and inflow will occur at levels of the house below some balance point, while above this balance point, higher than outside pressures and outflow will occur. The opposite effect is realized if the inside temperature is lower than the outside temperature. At the plane at which this balance point exists, no pressure difference occurs between outside and inside, considering only temperature induced pressures. This plane is called the neutral zone.

The location of the neutral zone within a building is dictated by the arrangement and flow resistance of cracks and openings. In typical residential homes, the neutral zone is approximately located much higher than the mid-height of the house [5]. The chimney system in a residential home has the effect of raising the neutral zone level with decreasing outdoor temperature.

Just as the pressure distribution around a building is a complex function of building geometry and surroundings, so too is the flow of air around buildings. Buildings act as bluff bodies to the air flowing past them and hence create turbulent eddies on and near the building [7,8]. Similarly, other nearby structures and topographical and geographical features can also create eddies and deflections in the air flow around the building and also near the chimney top. The formation of these eddies and air flow

deflections are shown in Figure 1.5.

The turbulent eddies and deflected air flow, in conjunction with the placement of the chimney top and chimney cap, can cause the air flow past the chimney top to be at some angle of elevation with respect to the horizontal. This wind elevation angle also has an important role in the chimney cap's aspiration effect.

Due to the influence of these turbulent eddies, building codes have been issued in order to attempt to have the tops of chimneys placed out of this area of influence. In the National Building Code of Canada 1990 [9], it is stated in Section 9.21.4.4 that a "*chimney flue* shall extend not less than 900 mm above the highest point at which the *chimney* comes in contact with the roof, and not less than 600 mm above the highest roof surface or structure within 3 m of the *chimney*."

These requirements are shown graphically in Figure 1.6. However, it appears that these requirements have not always been enforced, and even when they have been, the codes have not always ensured problem free operation. Therefore, a chimney cap which is relatively resistant to the eddies will aid in chimney performance and that is part of what is being examined in this thesis.

The chimney caps to be studied in this thesis would likely be utilized primarily for wood burning appliances. If the chimney caps were to be adapted for use with gas burning appliances, the chimney caps would be required to meet strict construction standards. However, these standards and codes were not considered in this thesis.

1.2.2 Chimney Physics

The air flow in a chimney is dependant on a number of factors [7,10]. One of the factors which determines the chimney air flow is the pressure difference between the pressure inside the building near the fuel burning appliance, and the outside pressure distribution surrounding the chimney top. How these two pressures vary was discussed

in the previous section.

The effect of the pressure distribution surrounding the chimney cap differs from the pressure distribution in the chimney cap since the latter is a function of the wind velocity, wind direction, and chimney cap geometry and location relative to the roof. The chimney cap geometry and location on the roof will alter the flow field in the cap itself and hence alter the pressure distribution within the cap. This pressure difference between the air surrounding the chimney cap and the air just inside of chimney cap is known as the aspiration effect. The aspiration effect is the subject to be investigated in this thesis.

Other factors affecting chimney flow include the temperature and density differences between the ambient outside air and the appliance combustion gases known as the buoyancy, stack, chimney, or Archimedes effect. In addition, the resistance to flow of the entire chimney system will affect the chimney operation, but will not be directly affected by the chimney cap location and geometry.

Natural ventilators, as stated earlier, are similar to metal chimney caps and hence operate in essentially the same manner. The major difference between the chimney cap and ventilator physics is that the buoyancy effect is much less in the ventilator because of the lack of hot combustion gases.

1.3 Literature Survey

As stated earlier, chimney caps and roof ventilators are closely related. Therefore, no attempt has been made to separate research into either of the two since the research can, with some modifications, be applied to the other device.

1.3.1 Natural Ventilation Using Wind

Natural ventilation techniques using the passing wind date back many centuries [11]. For example, windscoops were used in Pakistan to circulate air through homes, as shown in Figure 1.7. The movement of air in the windscoop, either upflow or downflow, is dependent upon the wind direction relative to the windscoop. If the wind is flowing directly into the windscoop, the air flow developed in the windscoop will be downwards. However, if the wind direction is opposite to the plane of the windscoop opening, the windscoop creates a zone of lower than ambient pressure which causes upwards flow in the windscoop stack. The Pakistani windscoops are still in use in some locations.

Another example of natural ventilation techniques using windscoops is in Iran, seen in Figure 1.8. The principle behind the Iranian windscoop is similar to that of the Pakistani windscoop but the geometry of the windscoop is different, resulting in less directional effects.

Another case of building geometry which aids in its ventilation is the Pantheon in Rome, Italy as shown in Figure 1.9. The Pantheon uses its shape to generate a zone of negative pressure at the top of the dome shaped structure. A hole in the roof at this point creates a flow of air out of the building independent of wind direction. Scholars are unsure whether this phenomena was designed specifically for this purpose or if it was purely accidental.

In more recent times, several individuals have also conducted studies in the use of wind for natural ventilation applications. For example, Aynsley [12] studied the effects of using wind to moderate the comfort level in homes located in tropical climates. Using wind tunnel techniques, Aynsley estimated the amount of wind generated air flow through the buildings. As with the centuries old windscoop, the amount of air flow through the buildings was dependent on the size and shape of the openings in the building.

There has been a large amount of research on natural ventilation in buildings due to openings in the building envelope. However, this thesis will examine natural

ventilation due only to the wind action on natural ventilators, since that is the area of natural ventilation that is closely related to chimney caps.

1.3.2 Chimney Cap and Ventilator Testing

In 1948, Schmitt and Engdahl [13] conducted a study of four different residential chimneys. The authors were interested in discovering information that was relevant to the performance characteristics of residential chimneys as a whole. As a part of the study, wind effects over the top of the chimney were simulated and examined. From the wind effect testing, they found that wind had an "undesirable effect" on the two chimneys examined. The effect that caused the most concern was the fact that the wind effect would cause the flow in the chimney to reverse at certain wind angles relative to the horizontal. Schmitt and Engdahl showed through experiment that a commercially available chimney cap, as seen in Figures 1.10(a) and (b), was able to reduce the wind effects on the chimney draft.

In Figure 1.10(b), it can be seen that when the wind elevation angle reaches a certain value, the open top chimney will begin to downdraft. The most likely reason for this is that as the wind elevation angle increases, the total pressure at the top of the chimney will increase, and will eventually exceed the static pressure of the chimney and the house and hence downdrafting will occur.

In order to combat the wind effects using a method other than chimney caps, Schmitt and Engdahl also tested the double-walled chimney proposed by a former project member P. C. Vyff. Vyff suggested that the air for combustion be obtained from the same plane at which the combustion products were exhausted. Vyff postulated that since the air inlet and the exhaust outlet were at the same level, the pressures would be equal and there would be no effect on the chimney caused by the wind since the wind would equally effect the inlet and exit flows. Schmitt and Engdahl found through experiment

that the double-walled chimney was no better at counteracting wind effects than a conventional chimney.

Wannenburg [14] based his 1957 ventilator testing method on improvements which he made to the 1932 procedure of Schrenk [15]. Wannenburg improved on Schrenk's approach for measuring the aspiration effect of natural ventilators while also providing equations by which to account for the stack and building interior-exterior pressure difference effects. In this method, a number of ventilator flow relations were derived, from which a nondimensional ventilator flow coefficient resulted. Wannenburg's method allowed for testing at various wind elevation angles.

In 1965, Ducar and Engholm [16] explored the use of ventilator caps as one factor in ventilating underground fallout shelters. The ventilators would be located on top of the inlet and exhaust pipes from an underground shelter and would use the wind to help ventilate the shelter. By revising theoretical flow equations with an empirical flow factor, the authors calculated the "minimum expected ventilation rates with various ventilator cap combinations and wind velocities" [16]. From their study, Ducar and Engholm concluded that, due to the uncertainties associated with natural ventilation and the low spring and summer ventilation rates, natural ventilation should not be employed in fallout shelters.

Gonzales [17] established a different testing method for ventilators in 1984. In this method, a nondimensionalized equation was created from the test data. The coefficients and exponents in this equation can be used to compare the performance of the various ventilators tested. Of the various ventilators tested, as shown in Figure 1.11, the ventilator which had the highest ventilation rate was Model 7. However, no allowance was made for the effects of testing the ventilator at wind elevation angles other than zero degrees.

In 1987, Scanada Consultants [18] tested a number of chimney caps which are shown in Figure 1.12. Scanada utilized testing apparatus similar to both Wannenburg [14] and Gonzales [17] for their testing program. From their results, Scanada concluded that the chimney cap performance was highly dependent upon wind elevation angle. For

example, of the chimney caps they investigated for wind elevation angles of zero degrees, the open masonry chimney cap provided the highest draft enhancement, whereas for positive wind elevation angles, the open masonry chimney cap tended to downdraft.

Carpenter [10] tested eight different clay chimney pots, seen in Figure 1.13, for their anti-downdraft characteristics in 1990. Using control volume analysis and worst case scenarios such as start-up conditions, which involve no flue gas density differences, and no pressure difference between the interior and exterior of the building, Carpenter stated that the static pressure at the top of the chimney cap should be lower than or equal to the static pressure of the surrounding air for no downdrafting to occur. Using the test procedure which he established, Carpenter was then able to evaluate and rank the various pot designs based on the static pressure differences between the pot interior and its surroundings. Of the chimney pots shown in Figure 1.13, the best draft enhancement based on Carpenter's test procedure was obtained by the H-pot chimney pot.

In 1990, Elger and McLam [19] developed yet another testing method for natural ventilators. Their method included the building envelope characteristics in the control volume analysis. Again, nondimensional ventilator flow and pressure coefficients were derived from existing theory. However, similar to Gonzales' paper, no account for wind elevation angles other than zero degrees was taken. From their research, they concluded that the ventilator pressure coefficient was equal to the pressure coefficient behind a flat circular plate when flow is normal to the plate plus a discharge pressure loss coefficient. Of the ventilators shown in Figure 1.14, the wind directional ventilator demonstrated the best ventilation enhancement.

The wind directional ventilator rotates to orient itself to the direction of the wind. The rotation implies that the wind directional ventilator must be maintained more rigorously than other designs because of its movement. If the movement is restricted by rusting or icing for example, the ventilator will not perform as desired.

Lapage and Irwin [20] examined in their paper of 1990 a technique for predicting natural ventilation rates in low-rise office buildings using roof vents. Four roof vent

designs, all with free standing walls to create negative pressure zones, were tested. Wind effects on the entire building were determined by measuring external pressures on a scale model in a boundary layer wind tunnel while the building stack effect was calculated mathematically. The resulting analyses provided an average air flow rate through the building as well as a relationship for the interior heat gain of the building envelope. These results, when combined with meteorological wind and temperature data, allowed for natural ventilation systems to be analyzed for a particular site. The results of the study showed that ventilation rates reach a maximum value for winds which are perpendicular to the long axis of the building, while minimum ventilation rates occur when the wind is parallel to the building's long axis.

In 1993, Dale and Ackerman [21] evaluated the performance of attic turbine ventilators, taking into account the soffits of the house as shown in Figure 1.15. Through a theoretical model, the authors estimated that with an attic turbine exit area and soffit area of approximately the same magnitude, the ventilation rate with the attic turbine ventilator would increase by only 34% over a model with soffits only. However, no method was established to take into account treating the attic ventilators as a wind-driven centrifugal fan.

1.3.3 Smoke Ventilators

Smoke ventilators operate in a manner similar to roof ventilators. The primary function of a smoke ventilator is to allow a path for smoke and other gases to escape from industrial buildings, as well as providing pressure relief for that building [22]. In general, the geometry of smoke ventilators is such that they are simply large open areas on the roof that are protected by some type of rain cover, as seen in Figure 1.16. Studies by Kandola [22] in 1990, Ghosh [23] in 1993, Kramer and Gerhardt [24] in 1993, and

Meessen [25] in 1993 show that wind flowing over buildings can be used to increase the flow through the smoke ventilator. However, due to the geometry of the smoke ventilators, these results cannot be adapted for use in residential chimney caps.

1.3.4 House Depressurization

Moffatt [6] investigated the level to which a home could be depressurized and still maintain safe venting of gas fired equipment in 1986. As homes become more air tight for energy conservation reasons, there will be less openings in the building envelope and therefore less air flow available for the chimney. If other appliances which exhaust air, such as clothes dryers, are in operation, then even less air flow is available for the chimney. Eventually, as the exhaust flows of the other appliances are increased, the air flow in the chimney will decrease, and at a point the exhausting appliances will negate the chimney draft and the flow in the chimney will reverse. Moffatt measured these house depressurization limits in Figure 1.17 and concluded that natural draft chimneys "will become a thing of the past" [6] as homes move toward tighter building envelopes.

In 1988, Timusk, Seskus, Selby, and Rinella [26] also examined house depressurization. Venting failures were induced by intentionally lowering the pressure in the house to a level at which the failure would occur. At the point at which the combustion gases could not reverse a downdrafting chimney, then a venting failure was said to have occurred. The authors studied the worst case scenario of having a chimney initially at the outside temperature which corresponds to start up conditions, and no aspiration effect at the chimney top. The results showed that chimney downdraft did not occur unless other appliances were operating, that the probability of venting failure was small, and that wind aided in removing combustion products.

From the literature survey, it can be seen that testing, using various methods, has been performed on chimney caps and ventilators of various geometries. However, it

appears that the geometries of interest in this thesis have not been previously tested or at least have not been reported. A schematic diagram of the chimney cap geometries to be considered in this thesis can be seen in Figure 1.18.

Chapter 2

Theoretical Basis of Experiment

2.1 Problem Statement

The problem to be solved in this thesis is whether or not certain design and operating parameters of chimney caps will enhance draft and inhibit downdraft, and to what extent the chimney flow will be affected. From the papers examined in the literature survey, it seems likely that the geometries under consideration in this thesis will induce an air flow in the chimney but to what extent is unknown since no similar geometries have been previously tested. The capability of a chimney cap to enhance draft and inhibit downdraft is important for a number of reasons.

Due to the air tightening of new homes, draft enhancement is becoming more important. As discussed earlier, as homes become tighter there is less air flow available, and therefore some form of draft augmentation is needed. Also, conversions from oil to natural gas furnaces affect chimney flows since the lower flue gas temperatures of the natural gas combustion products reduce the chimney effect and hence reduce the overall chimney flow. Oil to natural gas furnace conversions also often result in a downsizing of the furnace due to higher efficiency and eliminate the need for burner fans, which serve to further reduce the chimney flow available [6]. Powerful home exhaust systems such as clothes dryers and range hood fans can depressurize homes to an extent that they can affect chimney flows [6,26]. Finally, energy conservation trends such as lowering the overnight thermostat setting and added insulation result in reduced furnace operations which also effect chimney flows [26].

Downdraft prevention is needed in order to counteract spillage effects. Spillage is a term referring to the leakage of combustion gases back into the space being heated. Spillage of combustion products of natural gas and propane such as carbon monoxide (CO) and nitrogen oxide (NO₂) must be prevented because of their harmful and potentially fatal effects on humans. Reduction of spillage of carbon dioxide (CO₂) and water vapour would help reduce the effects of "stuffiness" and humidity in some homes [6].

However, if too much air flow is created by the chimney cap, the chimney can tend to exhaust large amounts of air and hence other systems such as gas fired hot water heaters could downdraft, thus causing more problems than were solved with the chimney cap. This thesis does not study these effects but instead focuses on the characteristics which enhance chimney draft with the hopes that the obtained results could be used by those interested in studying the effects of too much chimney cap aspiration.

2.2 A Brief Comparison of Published Testing Procedures

The theory behind the test procedure to be used in this thesis was developed by examining four papers which specifically describe the testing of chimney caps and/or ventilators. These four papers were those written by Wannenburg [14], Gonzales [17], Carpenter [10], and Elger and McLam [19].

2.2.1 Wannenburg Ventilator Performance Testing Procedure

The method developed by Wannenburg [14] involves using an open jet of air to test ventilators. The apparatus used by Wannenburg is shown in Figure 2.1. The

ventilator to be tested is attached to a suction pipe in which static pressure difference measurements are made. The static pressure difference measurements allow for the flow in the suction pipe to be determined. The flow can then be corrected for the case of "free inlet conditions", which is the case which would occur if no suction pipe were connected. The free inlet condition is the condition at which most roof ventilators operate.

This procedure also accounts for the wind angle relative to the horizontal. This is an important consideration since the effects of the building surroundings, ventilator placement on the roof, roof angle, and approaching turbulent eddies can be modelled simply by allowing the wind angle to change.

The results from the Wannenburg procedure, nondimensionalized with respect to the wind jet dynamic pressure, can be used to evaluate the ventilator performance at any value of wind speed, wind angle, and suction pipe resistance. The variation of suction pipe resistance is important because different chimney or ventilator systems have different system resistances. For example, a typical chimney system resistance is approximately 5.0 and a typical value for system resistance for a combined gas vent chimney system serving more than one appliance would be 7.5 [7].

A final note on this procedure is that there is no forced draft incorporated in it. Thus the test procedure examines only the aspiration effect of ventilators.

2.2.2 Gonzales Ventilator Performance Testing Procedure

In the test procedure described by Gonzales [17], an open circuit wind tunnel with an attached plenum chamber and forced draft fan is used to obtain ventilator performance data. The Gonzales test apparatus is shown in Figure 2.2. No wind angle effect is considered in this method.

By measuring the wind tunnel dynamic pressure, the flow in the suction pipe using a Venturi meter, and the pressure difference between the wind tunnel and the plenum

chamber, four characteristic parameters A, B, C, and n can be found which form the following ventilator performance equation.

$$\xi = \frac{\sigma}{A} + C + B\sigma^n$$

In the above equation, ξ is the nondimensionalized static pressure difference (ΔP_{vent}) at the ventilator inlet and σ is the nondimensionalized dynamic pressure (q_{pipe}) at the ventilator inlet. Both of these values are nondimensionalized with respect to the wind tunnel dynamic pressure (q_{wt}). Of the four characteristic parameters, A is the discharge coefficient, which is an inverse function of the ventilator exit resistance, C is the nondimensionalized maximum static pressure difference (ΔP_{max}) which corresponds to the case when there is no flow through the ventilator, and B and n are correction terms which account for eddies over the ventilator caused by flow separation from the sharp edges of the ventilator. Thus the previous equation can be rewritten as follows.

$$\frac{\Delta P_{vent}}{q_{wt}} = \frac{1}{A} \left(\frac{q_{pipe}}{q_{wt}} \right) + \frac{\Delta P_{max}}{q_{wt}} + B \left(\frac{q_{pipe}}{q_{wt}} \right)^n$$

The value which the characteristic parameters assume define the ventilation enhancing characteristics of the ventilator. The value of A should be as high as possible, implying a low resistance to flow. For a beneficial aspiration effect to occur over the ventilator, C must be less than zero. The value of B should be as close to zero as possible so that the eddy effects over the ventilator are eliminated. The exponent n should be near 0.5 since that value gives a small eddy correction term at values of σ less than one, and gives a large correction term when σ is greater than one at which the operation of the ventilator no longer is a strong function of the wind tunnel velocity and pressure. Comparisons of the values of the characteristic parameters allows for the ranking of various ventilators.

2.2.3 Carpenter Chimney Pot Performance Testing Procedure

As stated previously in Section 1.3.2, Carpenter [10] used a control volume analysis to develop his testing procedure. In the control volume analysis, Carpenter assumed worst case scenarios such as no flue gas density differences which corresponds to start up conditions, and no pressure difference between the inside and the outside of the house. From the above assumptions, Carpenter postulated that the static pressure at the top of the chimney must be less than or equal to static pressure of the surrounding ambient air for no downdrafting to occur.

Building aerodynamics were ignored in the control volume analysis. As a simplification to the analysis, Carpenter assumed that there always existed a zone of lower pressure air over the building. However, this is not always the case as was shown in Figure 1.3. Wind elevation angle was considered however.

No measurement of the amount of flow developed by the aspiration effect is possible with this procedure since one end of the chimney pot was sealed. Carpenter assumed that the flow developed in the chimney pot would be low and that little flow interaction at the chimney pot exit would occur. By placing the chimney pot in a wind tunnel and measuring the static pressure drop in the chimney pot, a nondimensional pressure coefficient could be developed. The lower this coefficient is in the negative direction, the better the chimney pot operates. Thus the various chimney pots tested could then be ranked on this basis.

2.2.4 Elger and McLam Ventilator Performance Testing Procedure

The procedure developed by Elger and McLam [19] is similar to that of Gonzales. Both procedures utilize forced draft fans to create ventilator pipe flows. The measured

quantities of ventilator suction pressure difference and vent pipe flow are also similar to those quantities measured in the Gonzales method. As with the Gonzales method, no wind angle effect is considered. The differences between the two methods are that Elger and McLam use a wind jet as opposed to a wind tunnel and they also use a different calculation procedure.

Elger and McLam, as stated earlier, found that the ventilator performance could be expressed as follows.

$$C_p|_v = C_p|_{disk} + (\text{discharge pressure loss coefficient})$$

In this equation, $C_p|_v$ is the ventilator pressure coefficient non-dimensionalized with respect to the wind tunnel dynamic pressure. The lower this value is in the negative direction, the better the ventilator will induce air flow. Elger and McLam found it easier to compare the performance of the ventilator to that of a flat circular plate when the flow is normal to that plate, represented by $C_p|_{disk}$.

2.2.5 Choice of Performance Testing Procedure

From the analysis of these papers, it was decided that the best procedure to follow was one very similar to that of Wannenburg [14], the only differences arising from modifications to the procedure due to the testing apparatus available for this thesis. The choice of this technique was based on a number of factors. The various aspects of each testing procedure are summarized in Table 2.1.

The first reason for the choice of the Wannenburg procedure was its completeness. The procedure allowed for wind angle variations from the horizontal plane, which is one of the areas to be examined in this thesis. The procedure also allowed for the creation of a performance chart such the one as in Figure 2.3. This performance chart provides a convenient manner in which to present the data. A designer can choose the anticipated

wind angle expected from roof geometry and other considerations (Point 1 in Figure 2.3), and using the system resistance (Point 2) and expected wind speed (Point 3), the flow coefficient can be obtained and hence the ventilator extraction rate can be determined (Point 4).

Another reason for the choice of the Wannenburg procedure is that the theory behind Carpenter's procedure [10] is wholly contained in Wannenburg's. This allows the chosen procedure to produce results similar to those contained in both papers. As well, the chosen procedure can be used to test both chimney caps and ventilators with no major difficulties.

The final reason for the choice of this procedure is based on the fact that, through manipulation of some of Wannenburg's equations, the results obtained in this thesis can be directly compared to the results obtained in the papers by Gonzales [17] and Elger and McLam [19].

2.3 Experimental Procedure

2.3.1 Chimney Flow Relationships

Wannenburg used an open wind jet in order to perform his experiments. For the experiments to be performed in this thesis, a conventional open circuit wind tunnel was used. This required that the procedure by Wannenburg be modified slightly. The modifications to the following procedure are discussed in Section 2.3.4.

Based on the schematic in Figure 2.4(a), the following parameters can be defined.

$P_1, P_2, P_3, P_a, P_{wt}$ = static pressure at points 1, 2, 3, a, and wt respectively

V = wind tunnel free stream velocity approaching the chimney cap

ρ_{wt} = wind tunnel free stream density

v_w = suction pipe airspeed

$$\Delta P_1 = P_a - P_1 = (P_a - P_{wt}) - (P_1 - P_{wt})$$

$$\Delta P_2 = P_a - P_2 = (P_a - P_{wt}) - (P_2 - P_{wt})$$

$$\Delta P_3 = P_a - P_3 = (P_a - P_{wt}) - (P_3 - P_{wt})$$

Flow and pressure coefficients, ψ and η respectively, can also be defined as follows.

$$\psi \equiv \frac{v_w}{V} \quad (2.1a)$$

$$\eta \equiv \frac{\Delta P_2 - \Delta P_1}{\frac{1}{2} \rho_w V^2} \quad (2.1b)$$

The flow coefficient will be used as a measure of the flow induced by the aspiration effect whereas the pressure coefficient η is a measure of the pressure difference in the suction pipe due to the aspiration effect.

We will also define another parameter λ^2 , the inlet section pressure coefficient.

$$\lambda^2 \equiv \frac{\Delta P_1}{\frac{1}{2} \rho_w V^2} \quad (2.2)$$

If we apply the steady flow energy equation [27, p.166] between points (a) and (1) in Figure 2.4(a),

$$\frac{P_a}{\rho_a} + \frac{1}{2} V_a^2 + g z_a = \frac{P_1}{\rho_1} + \frac{1}{2} V_1^2 + g z_1 + (\text{inlet loss})$$

Assuming the density between the two points is constant and can be written as ρ_w , and simplifying (i.e. $V_a = 0$, $V_1 = v_w$, $z_a = z_1$),

$$\therefore P_a - P_1 = \frac{1}{2} \rho_w v_w^2 + \rho_w (\text{inlet loss})$$

but, from [27, p. 333],

$$\text{inlet loss} = \frac{\Delta P_1}{\rho_w} = (K_i \frac{1}{2} \rho_w v_w^2) / \rho_w = K_i \frac{v_w^2}{2}$$

where K_i = inlet resistance, and
w refers to the suction pipe values

$$\therefore P_a - P_1 = \Delta P_1 = \frac{1}{2} \rho_w v_w^2 + K_i \frac{1}{2} \rho_w v_w^2$$

$$\Delta P_1 = (1 + K_i) \frac{1}{2} \rho_w v_w^2 \quad (2.3)$$

Substituting Equation (2.3) into Equation (2.2),

$$\lambda^2 = \frac{(1 + K_i) \frac{1}{2} \rho_w v_w^2}{\frac{1}{2} \rho_w V^2}$$

From Equation (2.1a), $\psi = v_w / V$.

$$\lambda^2 = (1 + K_i) \psi^2 \left(\frac{\rho_w}{\rho_{wt}} \right) \quad (2.4)$$

Similar to the development of Equation (2.3), the relationship for the pressure change across the chimney top can be defined as:

$$\Delta P_3 = (1 + K + K_c) \frac{1}{2} \rho_w v_w^2 \quad (2.5)$$

where K = total suction pipe resistance
= inlet resistance + pipe resistance
= $K_i + K_p$
 K_c = chimney top resistance

The change in pressure across the chimney cap cannot in general be measured directly because of the complex geometry of chimney cap and ventilators. One case in which the pressure differential can be directly measured is the case in which no flow is permitted through the chimney cap. This condition corresponds to the case in which the resistance of the suction pipe is infinite. This then gives $P_2 = P_3 = P_\infty$, or equivalently, $\Delta P_3 = \Delta P_\infty$.

If the value of total suction pipe resistance is changed to some finite value, flow develops in the suction pipe and the static pressure in the chimney cap will change from the infinite pressure value P_∞ to an associated finite pressure value of P_3 . If it is assumed that the difference between these two pressure values is a function of the dynamic pressure of the suction pipe flow, then the following relationship between the two pressures can be assumed.

$$\Delta P_3 = \Delta P_\infty - x \frac{1}{2} \rho_w v_w^2 \quad (2.6)$$

In this equation, x is a function of the free stream wind angle approaching the chimney cap, relative to the horizontal. It has been shown experimentally [10, 14, 17, 19] that the nondimensionalized results of chimney cap/ventilator performance tests are independent of Reynolds number based on the wind tunnel undisturbed velocity and the chimney flue diameter. Therefore, it is assumed that x is a function only of wind elevation angle and not Reynolds number. This must be verified for the chimney caps to be examined in this thesis.

Again, similar to the development of Equation (2.3), the pressure change between points (1) and (2) can be expressed in the following relation.

$$\Delta P_2 - \Delta P_1 = K_p \frac{1}{2} \rho_w v_w^2 \quad (2.7)$$

Also,

$$\Delta P_3 - \Delta P_2 = K_c \frac{1}{2} \rho_w v_w^2 \quad (2.8)$$

Dividing Equation (2.8) by the wind tunnel dynamic pressure ($\frac{1}{2}\rho_{wt}V^2$),

$$\frac{\Delta P_3 - \Delta P_2}{\frac{1}{2}\rho_{wt}V^2} = \frac{K_c \frac{1}{2}\rho_w v_w^2}{\frac{1}{2}\rho_{wt}V^2} \quad (2.9)$$

But from the definition of the pressure coefficient η (Equation (2.1b)),

$$\Delta P_2 = \eta(\frac{1}{2}\rho_{wt}V^2) + \Delta P_1 \quad (2.10)$$

Substituting Equation (2.10) into Equation (2.9) and simplifying using Equations (2.1a) and (2.2) yields

$$\frac{\Delta P_3}{\frac{1}{2}\rho_{wt}V^2} - \lambda^2 = \eta + K_c(\rho_w/\rho_{wt})\psi^2 \quad (2.11)$$

If Equation (2.6) is substituted into Equation (2.11), the following relationship results.

$$\frac{\Delta P_{\infty}}{\frac{1}{2}\rho_{wt}V^2} - \frac{x\frac{1}{2}\rho_w v_w^2}{\frac{1}{2}\rho_{wt}V^2} - \lambda^2 = \eta + K_c(\rho_w/\rho_{wt})\psi^2 \quad (2.12)$$

But $\Delta P_{\infty}/\frac{1}{2}\rho_{wt}V^2$ is the maximum value of η . Therefore the following function is defined.

$$\eta_{\max} \equiv \frac{\Delta P_{\infty}}{\frac{1}{2}\rho_{wt}V^2} \quad (2.13)$$

Substituting Equation (2.13) into Equation (2.12) and rearranging,

$$\eta_{\max} - \eta = \lambda^2 + \psi^2(x+K_c)(\rho_w/\rho_{wt}) \quad (2.14)$$

Recall from Equation (2.4) that

$$\lambda^2 = (1+K_p)\psi^2\left(\frac{\rho_w}{\rho_{wt}}\right)$$

or,

$$\psi^2 = \lambda^2 / [(1+K_p)(\rho_w/\rho_{wt})] \quad (2.15)$$

Substituting Equation (2.15) into Equation (2.14) and rearranging gives

$$\eta_{\max} - \eta = \lambda^2 [1 + (x+K_c)/(1+K_p)] \quad (2.16)$$

or

$$\lambda^2 = \alpha(\eta_{\max} - \eta) \quad (2.17)$$

where

$$\alpha = [1 + (x+K_c)/(1+K_p)]^{-1} \quad (2.18)$$

Equation (2.17) can be graphically represented as in Figure 2.4(b). Note that α can be determined in terms of values that are able to be measured separately. This implies that performance calculations are possible for any value of the suction pipe resistance. This allows the experimental results to be applicable to both chimney caps, with typical piping resistance values near 5.0 [7], and ventilators, with piping resistances near zero for free inlet (no suction pipe) conditions [14].

Now, consider Equation (2.7). This equation can be divided by the wind tunnel dynamic pressure $\frac{1}{2}\rho_{wt}V^2$ to obtain

$$\frac{\Delta P_2 - \Delta P_1}{\frac{1}{2}\rho_{wt}V^2} = \frac{K_p \frac{1}{2}\rho_w v_w^2}{\frac{1}{2}\rho_{wt}V^2}$$

By definition, the left side of the previous equation is equal to η from Equation (2.1b). Therefore,

$$\eta = K_p(\rho_w/\rho_{wt})\psi^2 \quad (2.19)$$

If Equations (2.19) and (2.4) are substituted into Equation (2.16) and simplified,

$$\psi^2 = [\eta_{\max}(\rho_{wt}/\rho_w)]/[1+x+K_i+K_p+K_c]$$

but $K = K_i + K_p$

$$\therefore \psi^2 = [\eta_{\max}(\rho_{wt}/\rho_w)]/[1+x+K+K_c] \quad (2.20)$$

Thus, by performing chimney cap tests, one with an open suction pipe and one with a closed suction pipe, the value of α in Equation (2.17) can be found. Since K_i and K_c are determined separately, Equation (2.18) can be solved for x . Substitution of the values of x and K_c into Equation (2.20) yields a relationship between ψ and K . That is,

$$\psi^2 = \frac{F}{K+G} \quad (2.21)$$

where $F = \eta_{\max}(\rho_{wt}/\rho_w)$, and

$$G = 1 + x + K_c$$

2.3.2 Inlet Resistance Relationship

Applying Equation (2.3) to this situation, the following equation is obtained.

$$\Delta P_1 = (1+K_i)\frac{1}{2}\rho_w v_w^2$$

Rearranging,

$$K_t = \frac{\Delta P_1}{\frac{1}{2}\rho_w v_w^2} - 1 \quad (2.22)$$

2.3.3 Chimney Cap Resistance Relationship

Applying the steady flow energy equation between points (c) and (a) of Figure 2.4(c), the following relationship is developed.

$$\frac{P_c}{\rho_c} + \frac{1}{2}v_w^2 + gz_1 = \frac{P_a}{\rho_a} + \frac{1}{2}V_a^2 + gz_a + (\text{exit loss})$$

Assuming constant density between the two points (a reasonable assumption for resistance testing), and V_a and $g\Delta z$ are zero for resistance testing purposes,

$$\therefore P_c - P_a = \rho_w(\text{exit loss}) - \frac{1}{2}\rho_w v_w^2$$

but, from [27, p. 333],

$$\text{exit loss} = \frac{\Delta P_c}{\rho_c} = (K_c \frac{1}{2}\rho_c V_w^2)/\rho_c = K_c \frac{v_w^2}{2}$$

where K_c = chimney top resistance

$$\therefore \Delta P_c = P_c - P_a = \frac{1}{2}\rho_w v_w^2(K_c - 1) \quad (2.23)$$

2.3.4 Modifications to the Experimental Procedure

Due to the equipment available for the experimental work in this thesis, some modifications to the above experimental procedure must be made. The first modification occurs from the fact that Wannenburg developed the procedure for use with an open jet, whereas the type of wind tunnel utilized in this thesis was an open circuit wind tunnel. Schematics of the two wind tunnels are shown in Figure 2.5.

The main difference between the two wind tunnels arises from the static pressures in the airstreams of the two. In the open jet, the static pressure is essentially equal to the atmospheric pressure, while in the open circuit wind tunnel, the wind tunnel static pressure is lower than the ambient pressure around the wind tunnel. The pressure difference in the open circuit wind tunnel will create a flow through the chimney cap and suction pipe system, just as a pressure difference between the inside and outside of a building would create a flow as discussed in Section 1.2. This flow will be in addition to the flow caused by the aspiration effect of the air flowing over the chimney cap. Therefore, the flow due to the static pressure difference must be considered so that the aspiration effects of the chimney caps can be studied.

In order to remove the effects of the flow due to the static pressure difference, it must be assumed that the flow due to the static pressure difference and the flow due to the aspiration effect are independent of each other. If this assumption is made, then the corrected flow, or equivalently the corrected flow coefficient $(\psi^2)_{corr}$, will simply be the measured flow in the system ψ^2 , minus the flow due to the static pressure difference, $(\psi^2)_{spd}$. Expressed mathematically,

$$(\psi^2)_{corr} = \psi^2 - (\psi^2)_{spd}$$

In the above equation, ψ^2 is the value of the flow coefficient obtained from Equation (2.21). The above equation is based on the argument that the total volume flow rate of a system squared is the sum of the squares of the individual flow rate that define

that system. The value of $(\psi^2)_{spd}$ can be derived in a manner similar to that of Equation (2.3).

By applying the steady flow energy equation between points (a) and (wt) in Figure 2.4(a), and assuming that the ambient air density and the wind tunnel air density are equal and can be expressed as ρ , the following relationship is obtained.

$$P_a - P_{wt} = \Delta P_{wt} = \frac{1}{2}\rho v_w^2(1+K_i+K_p+K_c+K_R) + \frac{1}{2}\rho V^2$$

In the above equation, K_R represents the flow loss due to the interaction of the suction pipe flow and the wind tunnel air flow passing through the chimney cap. This is essentially a measure of the interaction of the aspiration effect and the suction pipe flow due to the static pressure difference between the wind tunnel and the ambient conditions. Therefore the two flows are not necessarily independent of each other. Thus no attempt was made to separate these effects. Therefore, the value of ψ^2 obtained from the outlined procedure will be used to describe the draft enhancing characteristics of the chimney cap tested and to compare the enhancement capabilities of the tested chimney caps to those models previously tested.

This approach is valid since neither Gonzales [17] nor Elger and McLam [19] decoupled the effects of aspiration and forced flow. In the procedure described by Carpenter [10], there is no flow out of the chimney pot and therefore there is no need to correct for the coupling of the two effects.

The other modification to the theory which must be considered stems from the fact that the flow relations were written for a pipe of constant diameter. Since the diameter of the chimney cap models was fixed at six inches, and an existing hole in the floor of the wind tunnel was three inches in diameter and could not be enlarged, the suction pipe could therefore not be of constant diameter. Thus, the inlet section diameter was kept at three inches in diameter to reduce losses in the system.

In the chimney flow equations, ΔP_1 and ΔP_2 are based on a pipe of constant diameter. Thus, one of the pressure differences must be changed into the equivalent

pressure difference with respect to the other's pipe diameter. Since the chimney cap diameter is six inches, the appropriate modification would be to change ΔP_1 based on the three inch diameter inlet section to the equivalent pressure drop in a six inch diameter inlet section.

In order to achieve this static pressure difference correction, recall from Equation (2.22) that

$$K_i = \frac{\Delta P_1}{\frac{1}{2}\rho_w v_w^2} - 1$$

If it is assumed that the inlet resistance remains unchanged when moving from a three inch diameter inlet section to a six inch diameter inlet section, and renaming the quantities referenced to the three inch diameter inlet section as primed (') quantities, then the following relation can be written.

$$\frac{\Delta P_1}{\frac{1}{2}\rho_w v_w^2} - 1 = \frac{\Delta P_1'}{(\frac{1}{2}\rho_w v_w^2)'} - 1$$

or,

$$\frac{\Delta P_1}{\frac{1}{2}\rho_w v_w^2} = \frac{\Delta P_1'}{\frac{1}{2}\rho_w (v_w')^2}$$

The six inch diameter section has an area four times the area of the three inch diameter section. Thus, from the continuity equation assuming constant density flow at the inlet, the velocity developed in the three inch diameter section will be four times that of the velocity in the six inch diameter section.

$$\therefore \frac{\Delta P_1}{\frac{1}{2}\rho_w v_w^2} = \frac{\Delta P'_1}{\frac{1}{2}\rho_w (4v_w)^2}$$

or.

$$\Delta P_1 = \frac{\Delta P'_1}{16} \quad (2.24)$$

Therefore, the quantity measured in the experimental work, $\Delta P'_1$, is sixteen times higher than the desired static pressure difference, ΔP_1 . This correction will thus permit the use of the Wannenburg test procedure although the testing conditions are not exactly similar. The assumptions made concerning the constant inlet resistance will need to be verified experimentally, as is further addressed in Section 3.1.

2.3.5 Wind Modelling

In order to test the desired chimney caps at conditions in which they are most likely to face, the average wind velocities for a number of Canadian cities were found [28]. Since in most locations the wind velocity rarely falls below half the average wind velocity for more than a few hours per month [5], the chimney caps should be tested at half of the average wind velocity for Canada. The average wind velocity is approximately 5 metres per second, usually measured at a height of 10 metres above ground level [28]. Thus the chimney caps should be tested at a wind velocity of 2.5 m/s. However, the wind tunnel to be used for the experimental work is not capable of providing a 2.5 m/s wind velocity since at the lowest fan speed the wind velocity available is approximately 4 m/s. Thus, the average wind velocity of 5 m/s, was used to conduct the wind tunnel tests on the chimney caps.

The wind elevation angle was also required to be modelled. As discussed in Section 1.2.1, the air flow around buildings can be deflected by surrounding structures and objects, causing the air flow to be at some angle of elevation with respect to the horizontal. Typically, the elevation angle will not be greater than ± 30 degrees. However, in order to observe performance at extreme conditions, the chimney caps in this thesis will be tested over a wind elevation angle range of ± 60 degrees.

Another condition that should be considered is the effect of the atmospheric boundary layer on the building and chimney system. The atmospheric boundary layer is divided into two sections, the interfacial layer near the ground and the Ekman layer above it. The interfacial layer height is determined by the average height of the objects in the region in which the wind is blowing. In most suburbs, this implies that the building height is the defining height of the interfacial layer. This is demonstrated in Figure 2.6. In the interfacial layer, the flow will be in several directions due to the obstructions in this layer and hence the net overall flow is zero [29]. Thus by changing the angle that the chimney cap sees, the local flow near the chimney cap in the interfacial layer can be modelled to some extent.

In relatively open rural areas, the interfacial layer could be below the roof top of a typical home and thus the chimney cap will be in the Ekman layer. In the Ekman layer, wind velocity changes with height. However, the amount that the wind velocity would change over the height of a residential chimney cap is negligible due to the fact that the atmospheric boundary layer is several hundreds of meters in height. Thus the average wind speed can be used, regardless of whether the chimney top is in the interfacial or the Ekman layer.

2.4 Chimney Cap Models and Experimental Apparatus

Three basic chimney cap models were initially considered for testing purposes. Model A, shown in Figure 2.7, is a conventional chimney cap which is commercially available. Models B and C are experimental chimney cap models that were expected to induce greater chimney flows due to their geometries, as seen in Figure 2.8. In theory, Models B and C operate using the Venturi effect, that is the constriction near the chimney flue exit forces the wind flowing past it to increase in velocity, hence decreasing the static pressure at the constriction. This decrease in static pressure is the aspiration effect and is the driving force resulting in increased chimney flows. The distance between the two halves of Models B and C could be varied in order to determine what effect the changing distance would have on the chimney cap performance.

However, if the proposed Models B and C were found not to enhance draft, then measures would need to be taken to determine why draft was not enhanced. Flow visualization techniques could be needed to determine flow patterns near the chimney caps. Based on the flow visualization results, new chimney cap models may need to be designed and tested for their draft enhancing characteristics.

It should be noted that chimney flue pipes with no chimney caps were not tested. The reason for this is that this thesis is partly concerned with the effects of wind elevation angles. Thus any positive wind elevation angle, as defined in Figure 1.5, could cause downdrafting. This would be in conflict with the objectives of this thesis.

In order to conduct the required tests on the chimney caps, a wind tunnel test rig was required to be designed. The rig needed to support the chimney cap as well as having the capacity to rotate the chimney cap such that the wind elevation angle could be changed. The wind tunnel test rig developed is presented in Figure 2.9. An important feature of the test rig was that it allowed the angle of the chimney cap relative to the wind velocity to be changed from outside of the wind tunnel using a control rod while the wind tunnel was in operation.

In accordance with the experimental procedure mentioned above, a suction pipe was required in order to determine the flow which would develop within it. This suction pipe had to extend from the wind tunnel working section to the ambient room conditions. However, due to the constraints of the three inch diameter hole in the floor of the wind tunnel, part of the suction pipe was required to be three inches in diameter. In addition, the suction pipe was required to be flexible so that the test rig and chimney cap could be rotated to simulate the wind angles upon it. The above concerns were addressed by using three inch diameter dryer ducting connected to a three inch diameter to six inch diameter diffuser as the suction pipe, as seen in Figure 2.9.

The introduction of the three inch to six inch diffuser would likely cause non-uniform velocity profiles and swirl effects at the suction pipe exit which could affect the draft enhancing characteristics of the chimney caps tested [30]. However, these aspects are not addressed in this thesis.

As part of the performance formulations outlined in Section 2.3, the inlet and chimney cap exit resistances were required to be determined. In order to measure these quantities, the test rig shown in Figure 2.10 was developed. The test rig pipe contained a damper to vary the pipe air flow and a flow straightener to filter out any swirling effects caused by the fans. The constant speed fans could be mounted to give either inflow or outflow conditions. A Pitot-static tube was used to measure the dynamic pressure of the air in the pipe. The Pitot-static tube is seen in Figure 2.11.

All static pressure differences were measured with the water manometer shown in Figure 2.12. The resolution of each side of the manometer was approximately ± 0.001 inches of water (± 0.249 Pa). The static pressure taps used were 1 mm in diameter. The "ideal" static pressure tap would have a diameter less than $\frac{1}{4}$ mm and would be drilled perpendicular to the surface of the pressure to be measured [31]. According to Shaw [32], a 1 mm static pressure tap hole with a nonperpendicularity of up to 45 degrees will introduce an error of less than 1% of the dynamic pressure. Therefore the arrangement in this thesis will give small errors due to the static pressure taps.

Three inlet sections were designed for this thesis. These configurations are shown in Figure 2.13 and were used to verify the inlet resistance testing procedure which was previously developed.

The wind tunnel used in this thesis was the Low Speed Boundary Layer Wind Tunnel located in the Department of Mechanical and Aerospace Engineering of Carleton University, Ottawa. However, the boundary layer capabilities were not utilized.

Chapter 3

Results and Discussion

3.1 Inlet and Chimney Cap Resistance Testing

In order to utilize the procedure established in Section 2.3.1, the values of the inlet section resistance K_i and the chimney cap exit resistance K_e must first be found experimentally. Equations relating the resistances to measurable quantities were given in Sections 2.3.2 and 2.3.3, specifically Equations (2.22) and (2.23), to find K_i and K_e respectively. As can be seen from the two equations, by changing the flow through the inlet or the chimney cap, the static pressure difference will also change.

The apparatus used to measure the flow resistances is shown in Figure 2.10. To measure the flow in the apparatus, a Pitot-static tube (Figure 2.11) was inserted into the test rig near the inlet or the chimney cap being tested. This Pitot-static tube gave the dynamic pressure of the flow in the apparatus. Four static pressure taps attached to a pressure averager were used to obtain the static pressure change across the inlet or chimney cap.

The flow through the test rig was changed and the corresponding pressure change was also measured. A plot of dynamic pressure versus static pressure difference should give a linear relationship between the two, according to Equations (2.22) and (2.23). To test this procedure, a three inch diameter inlet section without a plate, seen in Figure 2.13, was used. The theoretical inlet resistance of such a geometry is K_i equals 1.0 [27]. The tests on this inlet model showed that the inlet resistance was found to be 1.26. Appendix A1 outlines how this value was obtained. This higher value of inlet resistance is to be

expected since the theoretical resistance assumes a perfectly round inlet section with no imperfections. The inlet section tested contained a seam which could account for the higher inlet resistance. Figure 3.1 shows the linear relationship between the dynamic pressure and the static pressure difference.

The same inlet resistance test was also conducted on a four inch diameter inlet section without a plate to verify that the actual resistance was higher than the theoretical resistance. The four inch diameter inlet section also served the purpose of verifying the assumption made in obtaining Equation (2.24), that is that $\Delta P_1 = \Delta P_1'/16$ which was derived from the assumption that K_i is constant for scaled geometries.

The value of K_i obtained for the four inch diameter section was found to be 1.40. Although this value may seem far off from the value for the three inch diameter section, it is actually within the error of the manometer readings. This is because, from Appendix A1, the slope of the line for the three inch diameter section is 2.26 while the slope of the line is 2.40 for the four inch diameter section. These values are within 10% of each other, which corresponds well to the possible reading error of 10% for the manometer. This source of error is discussed in more detail in Section 3.6. Thus it seems reasonable to assume that K_i will remain constant from the three inch diameter inlet section to the four inch diameter inlet section and hence assuming K_i is also constant for the six inch diameter inlet section would also seem reasonable.

Since the procedure was verified using the inlet section with no plate, the same procedure was used to determine the resistance of an inlet section with a plate (Figure 2.13). Figure 3.1 also shows the results of the tests, which gave an inlet resistance K_i of 0.37. The radius of the seam joining the inlet pipe to the plate was approximately 1/32 of an inch, which gives a ratio of seam radius over pipe diameter of approximately 0.01. Thus, from Figure 3.2 [27], a value of inlet resistance of 0.37 for the inlet section with plate is reasonable. The inlet section resistances are summarized in Table 3.4.

With the fans on the test apparatus now mounted to give a flow out of the apparatus, the chimney cap exit resistances could be measured. Figures 3.3 through 3.6

show the relationship between the dynamic pressure and the static pressure difference for the various models in their various configurations. The resistances of the models and configurations tested are summarized in Table 3.20, as well as in Figure 3.7. The resistances were obtained in a method similar to that of Appendix A1. As expected, as the distance between the two halves of Models B and C was decreased, the exit resistance increased. The distance between the two halves will hereafter be referred to as the throat length, as was shown in Figure 1.18.

With the resistances of the inlet section and the various chimney cap models with their various throat lengths now determined, the next step in the test method was to verify the test procedure developed in Section 2.3.

3.2 Verification of Theoretical Basis of Experiment

In the development of the experimental procedure, many assumptions were made about the nature of the air flow through the suction pipe system. Thus, before conducting performance tests of the chimney cap models, the assumptions made must be verified.

The first assumption involved the relationships between the static pressure differences in the chimney cap and suction pipe, and the dynamic pressure in the wind tunnel. The relationship was assumed to be linear and therefore values such as $(\Delta P_2 - \Delta P_1)/\frac{1}{2}\rho_{wt}V^2$, which was defined as η , would be constant for a given chimney cap geometry, wind elevation angle, and suction pipe resistance.

In order to confirm this relationship, values of $\Delta P_1'$, ΔP_2 , and ΔP_{∞} were measured against various wind tunnel speeds and for various chimney cap angles. The results can be seen in Figures 3.8 through 3.14. From these figures, it can be seen that the relationship is linear and hence values such as λ^2 and η_{max} will be constant for the given geometries, wind elevation angles, and suction pipe resistances.

Note that $\Delta P_1'$ is plotted as opposed to ΔP_1 . The relationship for ΔP_1 will still be linear since ΔP_1 is a scalar function of $\Delta P_1'$. The values of $\Delta P_1'$ are plotted in order that all of the static pressure differences can be shown on the same figure.

It should also be noted that the wind tunnel dynamic pressure was required to be corrected according to the following relationship, which has been calibrated experimentally for the wind tunnel used in this thesis [33].

$$\frac{1}{2}\rho_{wt}V^2 = 0.85(P_{c1} - P_{c2})$$

In the above equation, P_{c1} and P_{c2} are the static pressures at two static taps in the wind tunnel and 0.85 is the wind tunnel calibration factor based on the location of the two static taps. P_{c1} and P_{c2} were measured with a manometer similar to the one shown in Figure 2.12.

Also considered was the effect of the orientation of the posts of the chimney cap models on the measured pressures. This is important to consider since the wind approaching the chimney cap is not always from the same direction. For example, winter winds may come from the north while spring winds may come from the west. From Figure 3.15, no effect is observed due to the orientation of the posts for Model A. There will therefore be no effect due to post orientation for Models B and C since their posts are much smaller than the posts on Model A.

It should also be noted that more complete verification testing was done on Model A and less for the other two models. This was due to the fact that similar trends were seen in the verification tests of the other models. Conducting verification testing on the other models to the same degree that they were conducted on Model A would have provided no new observations at the cost of unnecessary repetition.

Wannenburg [14] also used the above verification method for the same assumptions. However, he found that the linear relationship between the static pressure differences and the wind jet dynamic pressures did not hold true for wind jet or wind

tunnel velocities lower than 2 to 3 miles per hour. Wannenburg felt the reason for this nonlinearity was due to the flow not being fully turbulent. This nonlinearity was not observed in the verification tests conducted for this thesis since the lowest wind tunnel velocity available was approximately 4 metres per second, or roughly 9 miles per hour.

Another assumption made was the validity of the modification proposed by Wannenburg on the relationship between static pressure differences and chimney flow developed by Schrenk [15]. Recall from Equation (2.17) that

$$\lambda^2 = \alpha(\eta_{\max} - \eta) \quad (\text{Wannenburg})$$

The Schrenk relation upon which the above equation is based has the following form.

$$\lambda = \alpha(\eta_{\max} - \eta) \quad (\text{Schrenk})$$

By conducting tests at various values of suction pipe resistance K_p , different values of λ and η could be found. These values of λ and η were taken from the slopes of Figures 3.16 through 3.19, as outlined in Appendix A2. The resulting values of λ and η are plotted in Figures 3.20 and 3.21. As can be seen from the previous two figures, the experimental points agree more closely to the Wannenburg formulation (λ^2) than they would according to the Schrenk formulation (λ). Also note that Model C followed more closely to Wannenburg's formulation than did Model A. This could be due to the presence of turbulent eddies over the exit of Model A due to the sharp edges of that model, whereas the edges near the exit of Model C were somewhat less sharp and would therefore produce smaller turbulent eddies.

The final assumption made was that of Equation (2.6), which stated that

$$\Delta P_3 = \Delta P_{\infty} - x \frac{1}{2} \rho_w v_w^2$$

If both sides of this equation are divided by the wind tunnel dynamic pressure, the equation becomes

$$\frac{\Delta P_3}{\frac{1}{2}\rho_{wt}V^2} = \frac{\Delta P_{\infty}}{\frac{1}{2}\rho_{wt}V^2} - x \frac{\frac{1}{2}\rho_w v_w^2}{\frac{1}{2}\rho_{wt}V^2}$$

Recall from Equations (2.1a) and (2.13) that

$$\psi \equiv \frac{v_w}{V}$$

and,

$$\eta_{\max} \equiv \frac{\Delta P_{\infty}}{\frac{1}{2}\rho_{wt}V^2}$$

Assuming constant density, the following relation between ΔP_3 and ΔP_{∞} is therefore obtained.

$$\frac{\Delta P_3}{\frac{1}{2}\rho_{wt}V^2} = \eta_{\max} - x\psi^2$$

From Figure 3.22, it can be seen that ψ is constant for a selected chimney cap orientation and geometry, and also for a given suction pipe resistance. This is due to the fact that v_w depends on $(\Delta P_2 - \Delta P_1)$ which is also a function of chimney cap geometry, wind elevation angle θ , and suction pipe resistance K_p as was previously verified. By the same argument, the left hand side of the above equation is also constant, and the equation can be rewritten as below.

$$L = M - xN$$

In the previous equation, L , M , and N are all constants and dependent only on chimney cap geometry, θ and K_p . Therefore x must also be a function of chimney cap geometry, θ and K_p . All assumptions have now been validated.

3.3 Chimney Cap Performance

Performance testing, as outlined in the previous chapter, was initially conducted on chimney cap Models A, B, and C. The tests were conducted at a wind speed of approximately 5 m/s and the wind angle was varied by ± 60 degrees. In order to compare the performance of the various models and their various throat length configurations, the values of flow coefficient ψ and the maximum static pressure coefficient $\eta_{\max}$ were compared at a wind elevation angle of zero degrees and a suction pipe resistance of zero. This comparison is graphically demonstrated in Figure 3.23. The experimental values of ψ for $\theta = 0^\circ$ and $K_p = 0$ are summarized as follows.

$$\psi_{\text{Model A}} = 0.404$$

$$\psi_{\text{Model B}} = 0.263 \text{ (highest value, throat length} = 3 \text{ inches)}$$

$$\psi_{\text{Model C}} = 0.233 \text{ (highest value, throat length} = 3\frac{1}{4} \text{ inches)}$$

From the above results and the ψ bars in Figure 3.23, it can be seen that Model A has the better draft enhancing characteristics since it develops the highest value of ψ . The best value of ψ for the other models were obtained for a value of throat lengths around three inches, but these values of ψ are still nowhere near those of the flow coefficient developed by Model A. Therefore, Models B and C did not enhance draft as much as expected.

To determine why Models B and C did not perform as expected, flow visualization techniques were used. The flow visualization method employed was one which used tufts of yarn attached to the surfaces of the chimney cap Model B. The movement of the yarn

tufts would show what was happening to the flow through the chimney cap. The results of the flow visualization are shown in Figures 3.24(a) and 3.24(b).

In Figure 3.24(a), the inlet section of the suction pipe was closed off, creating the infinite resistance condition and hence no flow was passing through the suction pipe and into the chimney cap. As can be seen from the figure, most of the tufts of yarn are parallel to the undisturbed wind tunnel wind velocity. Note that the tufts immediately downstream of the chimney cap exit are not parallel to the undisturbed wind tunnel wind velocity. This is because these tufts are in a region of separated flow.

When the inlet section was opened, flow developed in the suction pipe and flowed through the chimney cap. The interaction of the flow out of the chimney cap and the wind tunnel air flow past the chimney cap caused part of the wind tunnel air flow to be deflected away from the chimney cap as demonstrated by the deflected yarn tufts in Figure 3.24(b). Thus, with the oncoming wind tunnel air flow partially deflected, less wind tunnel air flow passed directly over the chimney cap exit. From the continuity equation, less air flow implies a lower velocity for the same given area and density. According to the steady flow energy equation, this decrease in velocity gives an increase in static pressure at the chimney cap exit, and hence the flow in the suction pipe will be reduced.

The flow visualization method also helped to explain the trends observed in the $\eta_{\max}$ bars of Figure 3.23. According to Carpenter [10], the value of $\eta_{\max}$ is a measure of the amount of air flow a chimney cap can develop. Therefore, according to Carpenter, the trends in the $\eta_{\max}$ bars should follow those of the ψ bars. From Figure 3.23, it can be seen that this is not the case at all. The reason for the discrepancy lies in the fact that Carpenter assumed that there was very little flow interaction over the chimney pots which he tested. This assumption is realistic for the chimney pots which he tested since those chimney pots had no top plate over the chimney pot exits, as seen in Figure 1.13. This assumption is not valid for chimney cap Models B and C because of the large flow interaction which they cause, as demonstrated with the flow visualization method used.

Once the reason for the lower than expected flow coefficient for Models B and C was determined, a method of correcting this situation was required to be developed. In order to modify the flow over the chimney cap so that the flow was not deflected to as great an extent, eight equally spaced guide vanes were added to Model B. This new model was renamed Model D and is shown in Figure 3.25.

The purpose of Model D was to serve as a concept model to show what effect the vanes had on the performance of the chimney cap. Since Model D was purely a demonstration model, the vanes were constructed of cardboard, providing a quick and inexpensive method by which to test the concept.

The introduction of the vanes created a situation in which the chimney cap performance was now dependent on its vane orientation, unlike the independence of post orientation of Models A, B, and C. Thus, performance testing must be done at different vane orientations with respect to the wind tunnel flow. As was shown graphically in Figure 3.15, the term "inline" refers to the first vane encountered by the wind tunnel flow being parallel to the approaching flow while the term "open" refers to the centreline of the first space in between the vanes encountered by the wind tunnel flow being parallel to the oncoming flow.

Testing was done on Model D for throat lengths of 3 5/8 inches and 2 inches and a wind angle of zero degrees. The values of the chimney cap resistances for Model D were assumed to be the same as those of Model B for the corresponding throat length. The experimental values of ψ obtained for Model D, with zero suction pipe resistance, are summarized below.

$$\begin{aligned}\psi_{\text{Model D}} &= 0.519 \text{ (inline configuration, throat length = 3 5/8 inches)} \\ &= 0.363 \text{ (open configuration, throat length = 3 5/8 inches)} \\ &= 0.910 \text{ (inline configuration, throat length = 2 inches)} \\ &= 0.616 \text{ (open configuration, throat length = 2 inches)}\end{aligned}$$

As can be seen from these results, Model D did provide higher values of ψ than any of the other models and thus showed improved draft enhancing characteristics over

the other models. The performance of Model D with a throat length of two inches also performed much better than Model A. Thus the vane concept does improve chimney cap draft enhancement but it also introduces a dependence of chimney cap vane orientation to the oncoming wind.

It should also be noted that the values of $\eta_{\max}$ for Model D, which were in the range of 1.5, were less than the value for $\eta_{\max}$ for Model A which was 1.846. The most probable cause of this was plane turbulent mixing [34]. Due to the orientation of the vanes, the velocity of the flow through the space between one set of vanes will not necessarily be the same as the velocity through the neighbouring space. The velocity difference arises since the area of the space between the vanes normal to the oncoming flow is not the same for neighbouring spaces. From the continuity equation the area difference causes a velocity difference, assuming relatively constant density. The velocity difference between the two spaces causes a turbulent mixing layer, as seen in Figure 3.26. The complex interaction of this mixing layer with the flow passing through the chimney cap and the geometry of the chimney cap could account for the lower value of $\eta_{\max}$.

Since it has been demonstrated that the concept behind Model D is viable, a more appropriate model based on Model D should be developed. However, a design similar to Model D already exists and has been patented [35]. The only significant difference between the patented model and Model D is the number of guide vanes, twelve for the patented model versus eight for Model D. Therefore a change in the geometry of Model D was used to create a new model, Model E, which has the potential to be patented. The modification made to the geometry involved replacing the shaped top and bottom shells of Model D with the flat plates of Model E, as seen in Figure 3.27.

Tests were conducted on Model E at $\theta = 0^\circ$ for throat lengths of three and two inches. A throat length of three inches was chosen since both Models B and C performed best at those throat length values. Testing was also done for a two inch throat length to observe the effect of decreased throat length on draft enhancement. Model E exit resistances were measured in the same manner as the other chimney cap models tested.

The results of the exit resistance testing can be seen in Figure 3.28. From the resistance testing, the values of K_c were found to be 1.45 for the three inch throat length and 1.99 for the two inch throat length. The results of the performance testing on Model E are summarized below, for a wind elevation angle of zero degrees and a suction pipe resistance of zero.

$$\begin{aligned}\Psi_{\text{Model E}} &= 0.856 \text{ (inline configuration, throat length = 3 inches)} \\ &= 0.681 \text{ (open configuration, throat length = 3 inches)} \\ &= 0.853 \text{ (inline configuration, throat length = 2 inches)} \\ &= 0.511 \text{ (inline configuration, throat length = 2 inches)}\end{aligned}$$

The above results show that Model E still provides better draft enhancement than Models A, B, and C. Model E still shows dependence on guide vane orientation but to a lesser extent than Model D, since Model E has a smaller difference between the inline and open configuration values of ψ than does Model D.

Since Model E with a three inch throat length performed better than the two inch throat length configuration, full performance testing was done on the three inch throat length model for the range of wind elevation angles desired. During the performance testing, Model E was mounted in the open configuration, which gave less draft enhancement than the inline configuration did. The open condition was considered to be the worst case at which the chimney cap would operate. Performance charts for both Models A and E can be seen in Figures 3.29 and 3.30.

3.3.1 Wind Tunnel Blockage Corrections

When a test object is placed in a wind tunnel, it creates an obstruction to the wind tunnel air flow. This blockage will tend to increase the local velocities around the test object because the same amount of air flow now must flow through a smaller area. The increased local flow velocity will also cause a local decrease in static pressures, which

leads to an increase in ΔP . Thus the measured local velocities and static pressures will not be the true values that would be measured if no blockage effects existed.

Using the quasi-streamlined flow method suggested by ESDU [36] for the blockage effects caused by the chimney cap models tested, the increase in ΔP was roughly calculated for the maximum flow blockage. The maximum flow blockage occurred for Models B and C at a wind elevation angle of +60 degrees. This resulted in a blockage of approximately 10% of the wind tunnel cross sectional area. This blockage resulted in an increased ΔP of approximately 8%. However, performance tests conducted on Models B and C showed poor draft enhancement and correcting for the blockage would only make the performance worse. Model D showed improved performance but there was no need to correct for blockage since Model D was only used to demonstrate and validate the guide vane concept.

The maximum blockage for Models A and E also occurred at a wind elevation angle of +60 degrees. The value of this blockage was roughly 5%, which resulted in a ΔP increase of approximately 3%. This value is less than the expected error of the performance testing measurements made, which is to be discussed in Section 3.6.

Since the blockages will be similar for Models A and E for all wind elevation angles, the blockage corrections will also be similar. Therefore no blockage corrections are done on the performance testing results.

3.4 Comparison of Results to Previously Published Data

As stated in Section 2.2.5, one of the reasons for the choice of the Wannenburg procedure was that, with some manipulations to the performance testing results obtained, these results could be compared to the results contained in the other three papers.

3.4.1 Comparison of Results to Those of Gonzales

Recall from Section 2.2.2 that the following equation was developed by Gonzales [17] for ventilator performance testing.

$$\xi = \frac{\sigma}{A} + C + B\sigma^n$$

Also recall that ξ is the static pressure difference at the ventilator inlet nondimensionalized with respect to the wind tunnel dynamic pressure. This is equivalent to $\Delta P_2 / \frac{1}{2} \rho_{wt} V^2$ in the notation given by Wannenburg. Similarly, σ was defined as the dynamic pressure at the ventilator inlet nondimensionalized with respect to the wind tunnel dynamic pressure, which is the same as ψ^2 . C is the nondimensionalized maximum static pressure difference which corresponds to η_{max} . A is the discharge coefficient and is measured when the value of σ approaches infinity, i.e. when the flow in the wind tunnel is zero. Thus, A is equal to the inverse of the ventilator resistance K_c . The values of B and n account for eddies over the ventilator exit and have no equivalent Wannenburg variables. Thus the Gonzales performance equation can be rewritten as follows.

$$\frac{\Delta P_2}{\frac{1}{2} \rho_{wt} V^2} = \frac{\psi^2}{(1/K_c)} + \eta_{max} + B\psi^{2n}$$

Therefore, if forced draft were used to vary the flow through the chimney caps tested, a performance line similar to those seen in Figures 3.31 through 3.33 could be created. However, the performance testing in this thesis did not involve any forced draft and thus we can only obtain a point on the charts in Figures 3.31 through 3.33. This point is still useful in that the performance of chimney caps tested can be compared to the performance obtained by Gonzales. If the point is above the line given by Gonzales, then the chimney cap performance is better than the Gonzales chimney cap/ventilator

since a higher flow coefficient ψ is developed. It should be noted that the wind angle elevation in Figures 3.31 through 3.33 was zero degrees.

From the comparison of results shown in Figures 3.31 through 3.33, it can be seen that Model E (open configuration, three inch throat length) performs better than or equal to Models 1 through 5. Sketches of the models tested by Gonzales can be seen in Figure 1.11.

The performance of Model E is on the other hand worse than that of Models 6 and 7. The reason for the worsened performance can be seen from the performance charts of Figures 3.29 and 3.30. At high wind elevation angles, the top plate of Models A and E create a wake, causing increased suction behind the plate. Essentially, Models 6 and 7 have a section perpendicular to the flow and hence create a larger wake effect, while still having a plate to protect the flue pipe from precipitation entry.

3.4.2 Comparison of Results to Those of Carpenter

Comparison of the performance of Model E to those of Carpenter [10] would not be valid since the chimney pots tested by Carpenter did not have any cover plates and hence would have little flow interaction between the wind tunnel flow and the suction pipe flow. Due to this low flow interaction, Carpenter stated that the value of $\eta_{\max}$ would be a means to rank the performance of the chimney caps tested. However, as demonstrated in Section 3.3 and in Figure 3.23, this was not true in the case of the chimney caps tested in this thesis because of large flow interactions which resulted in the deflected flow of Models B and C and the plane turbulent mixing of Models D and E.

3.4.3 Comparison of Results to Those of Elger and McLam

Similar to the method of Gonzales, the ventilator test procedure developed by Elger and McLam [19] employed a performance equation to generate a performance curve from measured data. Forced draft is required to produce this curve. However, the performance testing on Model E (open configuration, 3 inch throat length) can be plotted as a point on the curves generated by Elger and McLam.

On the curves created by Elger and McLam, seen in Figures 3.34 and 3.35, the value of C_p is the same as $C_{p|_v}$ which was defined in Section 2.2.4 as the ventilator pressure coefficient nondimensionalized with respect to wind tunnel dynamic pressure. This is equivalent to $\Delta P_2 / \frac{1}{2} \rho_{wt} V^2$ for the notation used in this thesis. Also the value of V/U_{∞} in Figures 3.34 and 3.35 is equivalent to ψ . Thus the performance of Model E can be plotted and compared to the ventilator tested by Elger and McLam, which are shown in Figure 1.14. As can be seen in Figures 3.34 and 3.35, Model E performed equal to or better than all the ventilators tested by Elger and McLam.

3.5 Use of Metal Chimney Caps as Roof Ventilators

Thus far there has been no evidence to suggest that metal chimney caps and roof ventilators should perform any differently from each other. As long as the appropriate value of total suction pipe resistance K is chosen, performance charts such as those shown in Figures 3.29 and 3.30 can be used to establish the flow rate which will be developed by the chimney cap/ventilator. Appropriate values of K would be $K = 0$ for roof ventilators, $K = 5$ for gas vent chimney systems, and $K = 7.5$ for gas vent chimney systems serving more than one appliance [7, 14]. These values are given to serve as a

rough estimate of the different system resistances encountered in chimney and ventilator systems design.

However, chimney caps must be made of a material which must withstand the flue exhaust gas temperatures whereas this is not a requirement for roof ventilators. Therefore, roof ventilators could possibly be made from less expensive materials.

3.6 Sources of Error

The major source of error encountered in this thesis was the reading error of the manometers used, both the one shown in Figure 2.12 for measuring static pressure differences, and a similar one for measuring the wind tunnel dynamic pressure.

For the static pressure differences, the reading error for each side of the manometer was ± 0.001 inches of water. After an initial and final reading, the accumulated error was ± 0.002 inches of water for each side of the manometer, giving a total error on measurements of static pressure difference of ± 0.004 inches of water. For an average static pressure difference value of 0.080 inches of water, the error translated into an uncertainty of approximately 5%.

The manometer used for measuring the wind tunnel dynamic pressure had a potential reading error of approximately ± 0.002 inches of water due to imperfections in the manometer cylinders. Thus the potential total error on the dynamic pressure readings was ± 0.008 inches of water, which for an average dynamic pressure reading of 0.080 inches of water gave a possible uncertainty of approximately 10%.

However, through careful measurement, the errors on the flow coefficient ψ could be limited to an uncertainty of 5% to 10%, which was shown previously in Figure 3.22.

Other small possible sources of error included the diameter of the static pressure taps, which was discussed in Section 2.4 and was equal to less than 1% of the suction pipe dynamic pressure. Also the time lag of the manometer could have caused some

small errors since the manometer may not have reached its steady state value when a measurement was taken. This error was significantly reduced by recording measurements only when the manometer readings had not changed for at least a two minute time period.

From the above arguments, it can be concluded that the error on the performance results of the chimney caps is approximately 5% to 10%.

Chapter 4

Conclusions and Recommendations

The objective of this thesis was to examine the effects of design and operating parameters on the draft enhancing and downdraft inhibiting characteristics of chimney caps, and to explore the possibility of adapting chimney caps for use as roof ventilators. For this purpose, an experimental procedure was developed and utilized to initially obtain performance characteristics of three different chimney caps.

From the performance testing, it was found that two of the chimney cap models did not perform as expected as compared to a commercially available chimney cap. This was because the geometry and the flow interaction of the two chimney caps caused flow to be deflected away from the chimney cap exits. Thus the Venturi effect which was expected to increase draft was not fully realized.

In order to improve the draft enhancement of the two deficient chimney caps, modifications were made to one of the models and greatly improved performance resulted. These modifications consisted of adding eight equally spaced guide vanes to direct the flow over the chimney cap exit as a test of the guide vane concept. A fifth chimney cap model was designed and tested. The performance of the modified fifth chimney cap and the commercially available chimney cap were plotted on performance charts.

The modified chimney cap model performed better than the commercially available chimney cap, that is it developed a higher flow coefficient ψ . The performance of the modified chimney cap was compared to data on the performance of other chimney cap/ventilator designs previously tested, specifically those tested by Gonzales [17] and Elger and McLam [19]. From this comparison, it was found that the chimney cap

developed in this thesis performed equal to or better than all but two of the previously tested chimney cap/ventilators. The models that the modified chimney cap did not perform better than were two tested by Gonzales. The reason for the better performance of the two Gonzales models is because the two Gonzales models had parts of the chimney cap/ventilator perpendicular to the flow, creating a separated zone of lower than ambient static pressure. This effect was also observed on all the models tested in this thesis but only at high values of wind elevation angle, when parts of the chimney caps tested caused these same separated flow zones.

During the literature survey and the chimney cap testing, no evidence was found to suggest that chimney caps could not be used as roof ventilators. Roof ventilators can be used as chimney caps, provided that the ventilator would be able to withstand the flue exhaust gas temperature and corrosive elements of the flue exhaust gases encountered.

Future work in this area should focus on the optimization of the modified chimney cap design established in this thesis. Areas of optimization could include examining more closely the effects of throat length, while also attempting to find the optimum length and the optimum number of guide vanes. The performance of the optimized design should then be compared to the previously published chimney cap/ventilator performance studies.

In addition, studies on the distortion of the velocity profile and the swirl which were possibly introduced due to the three inch to six inch diffuser used in the experimental apparatus should be examined. Also, the effects of animal, bird, and insect screens should be examined as to their effects on draft enhancement as well as their possible susceptance to icing and the effects which that icing would cause.

Other topics to consider for future study on this area could include adapting the modified chimney cap design to large industrial chimneys and studying the dispersal patterns of the exhaust gases after they have left the chimney cap.

References

- 1) Primeau R.J., Morstead H. 1981, *Chimney Retrofits Due to Fuel Changeover*, Ontario Ministry of Municipal Affairs and Housing, Toronto.
- 2) Hama G.M., Downing D.A. 1963, "The Characteristics of Weather Caps", *Air Engineering*, Nov. 1963, pp. 34-37.
- 3) Wendes C.W., Pannkoke T. 1981, "Roof Ventilators: Workhorses of the Industry", *Heating, Piping & Air Conditioning*, Oct. 1981, pp. 79-86.
- 4) Gelert G.R. 1948, "Pertinent Facts on Natural Ventilation", *Sheet Metal Worker*, v39, n9, pp. 34-37.
- 5) ASHRAE 1992, *ASHRAE Handbook - 1992 Systems and Equipment Handbook*, Chapter 19: Infiltration and Natural Ventilation, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta.
- 6) Moffatt S. 1986, "Backdrafting Woes", *Progressive Builder*, Dec. 1986, pp. 25-36.
- 7) ASHRAE 1992, *ASHRAE Handbook - 1992 Systems and Equipment Handbook*, Chapter 31: Chimney, Gas Vent, and Fireplace Systems, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta.
- 8) Aynsley R.M., Melbourne W., Vickery B.J. 1977, *Architectural Aerodynamics*, Applied Science Publishers Ltd., London.
- 9) *National Building Code of Canada 1990*, issued by the Associate Committee on the National Building Code, National Research Council of Canada, Ottawa.
- 10) Carpenter C.J. 1990, "The Effectiveness of Anti-Downdraught Domestic Chimney Pots in Preventing Smoke Blow-Back", *Journal of Wind Engineering and Industrial Aerodynamics*, v34, n2, pp. 147-168.
- 11) Melaragno, M. 1982, *Wind in Architectural and Environmental Design*, Von Nostrand Reinhold Company, New York.
- 12) Aynsley R.M. 1979, "Wind Generated Natural Ventilation of Housing for Thermal Comfort in Hot Humid Climates", *Wind Engineering, Proceedings of the Fifth International Conference of Wind Engineering*, Fort Collins, CO, USA, pp. 243-254.

- 13) Schmitt L.B., Engdahl R.B. 1948, "Performance of Residential Chimneys", *Heating, Piping & Air Conditioning*, Nov. 1948, pp. 111-118.
- 14) Wannenburg J.J. 1957, "Performance Testing of Roof Ventilators", *Heating, Piping & Air Conditioning*, v29, n3, pp. 147-154.
- 15) Wannenburg J.J. 1957, with reference to Schrenk, O. 1932, "Untersuchungen von Dachluftern", *Ergebnisse der Aerodynamischen Versuchsanstalt Gottingen*.
- 16) Ducar G.J., Engholm G. 1965, "Natural Ventilation of Underground Fallout Shelters", *ASHRAE Journal*, v7, n8, pp. 91-92.
- 17) Gonzales M.A. 1984, "On the Aerodynamics of Natural Ventilators", *Building and Environment*, v19, n3, pp. 179-189.
- 18) Scanada Consultants Limited, Scanada Sheltair Consortium Inc. 1987, *The Influence of Termination Configuration on the Flow Performance of Flues*, prepared for Canada Mortgage and Housing Corporation, Ottawa.
- 19) Elger D.F., McLam E.T. 1990, "Rating of Gravity Roof Ventilator Draft", *ASHRAE Transactions Part 2, 1990 Annual Meeting of ASHRAE, Technical and Symposium Papers*, pp. 356-360.
- 20) Lepage M.F., Irwin P.A. 1990, "Scale Model and Analytical Methods to Improve Natural Ventilation of an Office", *Journal of Wind Engineering and Industrial Aerodynamics*, v36, pp. 469-479.
- 21) Dale J.D., Ackerman M.Y. 1990, "Evaluation of the Performance of Attic Turbine Ventilators", *ASHRAE Transactions*, v99, part 1, pp. 14-22.
- 22) Kandola B.S. 1990, "Effects of Atmospheric Wind on Flows Through Natural Convection Roof Vents", *Fire Technology*, v26, n2, pp. 106-120.
- 23) Ghosh B.K. 1993, "Some Effects of Crosswind on Ventilators", *Journal of Wind Engineering and Industrial Aerodynamics*, v45, n3, pp. 247-270.
- 24) Kramer C., Gerhardt H.J. 1993, "Aerodynamic Efficiency of Smoke Ventilators - Comparison of Measurements on Full Scale and Model Ventilators", *Journal of Wind Engineering and Industrial Aerodynamics*, v45, n3, pp. 313-323.

- 25) Meessen H. 1993, "Der VdS-Ringversuch. Die Überprüfung des Prüfstandeinflusses auf die aerodynamische Wirksamkeit von RA", *Journal of Wind Engineering and Industrial Aerodynamics*, v45, n3, pp. 291-307. Extended summary by Gerhardt H.J. 1993, *Journal of Wind Engineering and Industrial Aerodynamics*, v45, n3, pp.309-312.
- 26) Timusk J., Seskus A.L., Selby K.A., Rinella J. 1988, "Chimney Venting Performance Study", *Journal of Testing and Evaluation*, v16, n2, pp. 158-177.
- 27) White F.M. 1986, *Fluid Mechanics*, second edition, McGraw-Hill Book Company, New York.
- 28) ASHRAE 1993, *ASHRAE Handbook - 1993 Fundamentals Handbook*, Chapter 24: Weather Data, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, pp. 24.16-24.17.
- 29) Cook N.J. 1985, *The Designer's Guide to Wind Loading of Building Structures Part I*, Butterworths, London.
- 30) White, J.H., Personal communications, December 1994.
- 31) Goldstein, R.J. 1983, *Fluid Mechanics Measurements*, Hemisphere Publishing Corp., Washington.
- 32) Shaw, R. 1960, "The Influence of Hole Dimensions on Static Pressure Measurements", *Journal of Fluid Mechanics*, v.7, pp. 550-569.
- 33) Carleton University, Department of Mechanical and Aerospace Engineering 1992, *88.491A Mechanical Engineering Laboratory II Course Manual*, Issue No. 11, Ottawa.
- 34) Cebeci, T., Bradshaw, P. 1977, *Momentum Transfer in Boundary Layers*, Hemisphere Publishing Corp., Washington.
- 35) Topp, W. 1971, *Canadian Patent No. 884102: Cowls for Vent Air Pipes*, Ottawa.
- 36) ESDU 1980, *Blockage Corrections for Bluff Bodies in Confined Flows*, Item No. 80024, Engineering Sciences Data Unit, London.

Tables

Table 2.1: Comparison of Published Chimney Cap/Natural Ventilator Testing Procedures

	Wannenburg [14]	Gonzales [17]	Carpenter [10]	Elger and McLam [19]
Applicable to Chimney Caps to be Tested	✓	✓	✓	✓
Wind Angle Relative to Horizontal Considered	✓		✓	
Ranking of Chimney Caps Possible	✓	✓	✓	✓
Amount of Flow Produced Measurable	✓	✓		✓
Forced Draft Considered		✓		✓

Table 3.1: Sample of Raw Data from Inlet Resistance Testing of Three Inch Diameter Inlet Section Without Plate

	Fan/ Damper	R _{I1}	R _{I2}	R _{F1}	R _{F2}	ΔR_1	ΔR_F	ΔR
Pitot-Static Tube	2F/DO	436	530	469	561	33	31	64
	1F/DO	437	530	459	552	22	22	44
	1F/DH	437	530	457	550	20	20	40
	2F/DH	437	530	466	559	29	29	58
	2F/DC	437	529	447	540	10	11	21
	1F/DC	438	529	445	537	7	8	15
Static Taps	2F/DO	436	530	512	603	76	73	149
	1F/DO	437	530	487	578	50	48	98
	1F/DH	437	530	481	574	44	44	88
	2F/DH	437	530	502	594	65	64	129
	2F/DC	437	529	459	553	22	24	46
	1F/DC	438	529	455	548	17	19	36

Note: 1) All values in thousandths of an inch of water (0.001" H₂O = 0.249 Pa).

2) Fan/Damper configurations:

1F = one fan operating
 2F = two fans operating
 DO = damper open
 DH = damper half open
 DC = damper closed

3) Reading (R) subscripts:

1 = reading on vacuum side of manometer
 2 = reading on pressure side of manometer
 I = initial reading
 F = final reading

4) For Pitot-static tube, ΔR = dynamic pressure, q_w .

5) For static taps, ΔR = static pressure difference, ΔP_1 .

Table 3.2: Inlet Resistance Testing Data for Four Inch Diameter Inlet Section Without Plate

Fan/ Damper	q_w	ΔP_1
2F/DO	64	159
1F/DO	31	71
1F/DH	26	59
2F/DH	40	98
2F/DC	6	14

Table 3.3: Inlet Resistance Testing Data for Three Inch Diameter Inlet Section With Plate

Fan/ Damper	q_w	ΔP_1
2F/DO	64	88
1F/DO	44	57
1F/DH	38	53
2F/DH	55	74
2F/DC	22	31
1F/DC	14	21

Note: 1) All values in thousandths of an inch of water (0.001" H₂O = 0.249 Pa).

2) Fan/Damper configurations:

1F = one fan operating
2F = two fans operating
DO = damper open
DH = damper half open
DC = damper closed

Table 3.4: Summary of Inlet Resistances

Section	K_i
3" diam. section without plate	1.26
4" diam. section without plate	1.40
3" diam. section with plate	0.37

Table 3.5: Sample of Raw Data from Chimney Cap Exit Resistance Testing for Model A

	Fan/ Damper	R_{i1}	R_{i2}	R_{f1}	R_{f2}	ΔR_i	ΔR_f	ΔR
Pitot- Static Tube	2F/DO	432	532	455	555	23	23	46
	1F/DO	432	532	441	541	9	9	18
	2F/DH	432	532	442	542	10	10	20
	HF/DO	432	532	446	546	14	14	28
Static Taps	2F/DO	432	532	440	540	8	8	16
	1F/DO	432	532	435	535	3	3	6
	2F/DH	432	532	435	535	3	3	6
	HF/DO	432	532	437	537	5	5	10

Note: 1) All values in thousandths of an inch of water ($0.001'' \text{ H}_2\text{O} = 0.249 \text{ Pa}$).

2) Fan/Damper configurations:

1F = one fan operating

2F = two fans operating

HF = two fans operating, one fan partially obstructed

DO = damper open

DH = damper half open

3) Reading (R) subscripts:

1 = reading on vacuum side of manometer

2 = reading on pressure side of manometer

I = initial reading, F = final reading

4) For Pitot-static tube, ΔR = dynamic pressure, q_w .

5) For static taps, ΔR = static pressure difference, ΔP_s .

**Table 3.6: Chimney Cap Exit Resistance Testing Data for Model B,
Throat Length = 1 inch**

Fan/ Damper	q_w	ΔP_c
2F/DO	30	88
1F/DO	14	41
2F/DH	14	44
HF/DO	20	58

**Table 3.7: Chimney Cap Exit Resistance Testing Data for Model B,
Throat Length = 1½ inches**

Fan/ Damper	q_w	ΔP_c
2F/DO	38	50
1F/DO	16	20
2F/DH	17	20
HF/DO	26	30

Note: 1) All values in thousandths of an inch of water (0.001" H₂O = 0.249 Pa).

2) Fan/Damper configurations:

1F = one fan operating

2F = two fans operating

HF = two fans operating, one fan partially obstructed

DO = damper open

DH = damper half open

**Table 3.8: Chimney Cap Exit Resistance Testing Data for Model B,
Throat Length = 2 inches**

Fan/ Damper	q_w	ΔP_c
2F/DO	46	29
1F/DO	16	10
2F/DH	21	14
HF/DO	26	16

**Table 3.9: Chimney Cap Exit Resistance Testing Data for Model B,
Throat Length = 2½ inches**

Fan/ Damper	q_w	ΔP_c
2F/DO	49	18
1F/DO	19	7
2F/DH	20	8
HF/DO	26	10

Note: 1) All values in thousandths of an inch of water (0.001" H₂O = 0.249 Pa).

2) Fan/Damper configurations:

1F = one fan operating

2F = two fans operating

HF = two fans operating, one fan partially obstructed

DO = damper open

DH = damper half open

**Table 3.10: Chimney Cap Exit Resistance Testing Data for Model B,
Throat Length = 3 inches**

Fan/ Damper	q_w	ΔP_c
2F/DO	47	10
1F/DO	18	4
2F/DH	16	4
HF/DO	26	6

**Table 3.11: Chimney Cap Exit Resistance Testing Data for Model B,
Throat Length = 3½ inches**

Fan/ Damper	q_w	ΔP_c
2F/DO	53	10
1F/DO	19	2
2F/DH	16	2
HF/DO	26	4

Note: 1) All values in thousandths of an inch of water (0.001" H₂O = 0.249 Pa).

2) Fan/Damper configurations:

1F = one fan operating

2F = two fans operating

HF = two fans operating, one fan partially obstructed

DO = damper open

DH = damper half open

**Table 3.12: Chimney Cap Exit Resistance Testing Data for Model B,
Throat Length = 3 5/8 inches**

Fan/ Damper	q_w	ΔP_c
2F/DO	50	6
1F/DO	20	2
2F/DH	34	3
HF/DO	26	4

**Table 3.13: Chimney Cap Exit Resistance Testing Data for Model C,
Throat Length = 1 3/4 inches**

Fan/ Damper	q_w	ΔP_c
2F/DO	38	40
1F/DO	14	16
2F/DH	22	20
HF/DO	24	22

Note: 1) All values in thousandths of an inch of water (0.001" H₂O = 0.249 Pa).

2) Fan/Damper configurations:

1F = one fan operating

2F = two fans operating

HF = two fans operating, one fan partially obstructed

DO = damper open

DH = damper half open

**Table 3.14: Chimney Cap Exit Resistance Testing Data for Model C,
Throat Length = 2¼ inches**

Fan/ Damper	q_w	ΔP_c
2F/DO	46	28
1F/DO	16	10
2F/DH	18	12
HF/DO	20	14

**Table 3.15: Chimney Cap Exit Resistance Testing Data for Model C,
Throat Length = 2¼ inches**

Fan/ Damper	q_w	ΔP_c
2F/DO	50	16
1F/DO	18	6
2F/DH	22	8
HF/DO	26	8

Note: 1) All values in thousandths of an inch of water (0.001" H₂O = 0.249 Pa).

2) Fan/Damper configurations:

1F = one fan operating

2F = two fans operating

HF = two fans operating, one fan partially obstructed

DO = damper open

DH = damper half open

**Table 3.16: Chimney Cap Exit Resistance Testing Data for Model C,
Throat Length = 3¼ inches**

Fan/ Damper	q_w	ΔP_c
2F/DO	52	14
1F/DO	18	6
2F/DH	20	6
HF/DO	28	8

**Table 3.17: Chimney Cap Exit Resistance Testing Data for Model C,
Throat Length = 3 5/8 inches**

Fan/ Damper	q_w	ΔP_c
2F/DO	46	12
1F/DO	19	6
2F/DH	23	6
HF/DO	28	8

Note: 1) All values in thousandths of an inch of water (0.001" H₂O = 0.249 Pa).

2) Fan/Damper configurations:

1F = one fan operating

2F = two fans operating

HF = two fans operating, one fan partially obstructed

DO = damper open

DH = damper half open

**Table 3.18: Chimney Cap Exit Resistance Testing Data for Model E,
Throat Length = 2 inches**

Fan/ Damper	q_w	ΔP_c
2F/DO	43	41
1F/DO	17	16
2F/DH	24	26
HF/DO	22	22

**Table 3.19: Chimney Cap Exit Resistance Testing Data for Model E,
Throat Length = 3 inches**

Fan/ Damper	q_w	ΔP_c
2F/DO	47	21
1F/DO	18	7
2F/DH	41	19
HF/DO	26	12

Note: 1) All values in thousandths of an inch of water (0.001" H₂O = 0.249 Pa).

2) Fan/Damper configurations:

1F = one fan operating

2F = two fans operating

HF = two fans operating, one fan partially obstructed

DO = damper open

DH = damper half open

Table 3.20: Summary of Exit Resistances for Models A, B, and C

Model	Exit Resistance K_e
A (3 5/8" throat length)	1.33
B (1" throat length)	3.96
B (1½" throat length)	2.24
B (2" throat length)	1.63
B (2½" throat length)	1.38
B (3" throat length)	1.22
B (3½" throat length)	1.16
B (3 5/8" throat length)	1.12
C (1¾" throat length)	2.00
C (2¼" throat length)	1.64
C (2¾" throat length)	1.33
C (3¼" throat length)	1.29
C (3 5/8" throat length)	1.28

Table 3.21: Summary of Exit Resistances for Model E

Throat Length (inches)	Exit Resistance K_e
2	1.45
3	1.99

Table 3.22: Verification Testing Data for Model A, $\theta = 0$ degrees, Open Post Configuration

Suction Pipe Resistance	Wind Tunnel Dynamic Pressure q_{wt}	$(P_a - P_{wt})$	$(P_1 - P_{wt})'$	$(P_2 - P_{wt})$	$(P_{\infty} - P_{wt})$
Standard Suction Pipe Setup	38	57	42	-14	-19
	88	129	82	-29	-47
	170	242	150	-66	-102
	250	340	205	-102	-156
	284	382	223	-136	-210
Shortest Possible Flexible Duct	71	114	73	-28	
	129	194	120	-50	
	177	263	163	-74	
	229	335	204	-94	
Added 16" Duct With Approx. 40% Blockage	78	123	92	-38	
	126	194	142	-62	
	166	254	184	-82	
	218	319	230	-105	

Note: 1) All values in thousandths of an inch of water ($0.001'' \text{ H}_2\text{O} = 0.249 \text{ Pa}$).
2) q_{wt} is the uncorrected wind tunnel dynamic pressure.

Table 3.23: Verification Testing Data for Model A, $\theta = 0$ degrees, Inline Post Configuration

Wind Tunnel Dynamic Pressure q_{wt}	$(P_a - P_{wt})$	$(P_{\infty} - P_{wt})$
70	102	-41
121	164	-83
176	260	-115
243	326	-158
303	407	-198

Table 3.24: Verification Testing Data for Model A, $\theta = +20$ degrees, Standard Suction Pipe Setup

q_{wt}	$(P_a - P_{wt})$	$(P_1 - P_{wt})'$	$(P_2 - P_{wt})$	$(P_{\infty} - P_{wt})$
77	112	86	-39	-56
123	174	127	-68	-94
174	238	170	-99	-128
242	326	235	-138	-181
306	421	293	-173	-226

Note: 1) All values in thousandths of an inch of water (0.001" H₂O = 0.249 Pa).
 2) q_{wt} is the uncorrected wind tunnel dynamic pressure.

Table 3.25: Verification Testing Data for Model A, $\theta = -20$ degrees, Standard Suction Pipe Setup

q_{wt}	$(P_a - P_{wt})$	$(P_1 - P_{wt})'$	$(P_2 - P_{wt})$	$(P_{\infty} - P_{wt})$
70	98	70	-22	-34
127	181	134	-35	-66
189	257	187	-56	-93
249	335	246	-89	-123
335	441	325	-108	-166

Table 3.26: Verification Testing Data for Model B, $\theta = 0$ degrees, Standard Suction Pipe Setup, Throat Length = 3 5/8 inches

q_{wt}	$(P_a - P_{wt})$	$(P_1 - P_{wt})'$	$(P_2 - P_{wt})$	$(P_{\infty} - P_{wt})$
76	106	68	-27	-82
123	172	108	-45	-138
190	258	160	-64	-219
266	356	215	-91	-323
285	381	237	-101	-357

Note: 1) All values in thousandths of an inch of water (0.001" H₂O = 0.249 Pa).
 2) q_{wt} is the uncorrected wind tunnel dynamic pressure.

Table 3.27: Verification Testing Data for Model B, $\theta = +20$ degrees, Standard Suction Pipe Setup, Throat Length = 3 5/8 inches

q_{wt}	$(P_a - P_{wt})$	$(P_1 - P_{wt})'$	$(P_2 - P_{wt})$	$(P_{\infty} - P_{wt})$
122	173	122	-57	-168
140	188	140	-62	-183
201	278	203	-92	-263
264	358	261	-123	-351

Table 3.28: Verification Testing Data for Model B, $\theta = -20$ degrees, Standard Suction Pipe Setup, Throat Length = 3 5/8 inches

q_{wt}	$(P_a - P_{wt})$	$(P_1 - P_{wt})'$	$(P_2 - P_{wt})$	$(P_{\infty} - P_{wt})$
122	173	122	-52	-188
162	226	159	-74	-249
226	310	219	-101	-353
288	388	262	-129	-439

Note: 1) All values in thousandths of an inch of water (0.001" H₂O = 0.249 Pa).
 2) q_{wt} is the uncorrected wind tunnel dynamic pressure.

Table 3.29: Verification Testing Data for Model C, $\theta = 0$ degrees, Throat Length = 3 5/8 inches

Suction Pipe Resistance	Wind Tunnel Dynamic Pressure q_{wt}	$(P_a - P_{wt})$	$(P_1 - P_{wt})'$	$(P_2 - P_{wt})$	$(P_{\infty} - P_{wt})$
Standard Suction Pipe Setup	79	112	70	-24	-87
	148	205	128	-44	-168
	217	297	185	-64	-252
	294	392	245	-90	-332
Added 16" Duct With Approx. 40% Blockage	75	120	87	-33	
	128	192	138	-51	
	177	261	190	-68	
	228	333	241	-83	

Note: 1) All values in thousandths of an inch of water (0.001" H₂O = 0.249 Pa).
 2) q_{wt} is the uncorrected wind tunnel dynamic pressure.

Table 3.30: Performance Testing Data for Model A

Wind Elevation Angle, θ (degrees)	$(P_1 - P_{wt})'$	$(P_2 - P_{wt})$	$(P_{\infty} - P_{wt})$
60	105	-60	-63
50	101	-59	-62
40	103	-59	-65
30	97	-64	-74
20	97	-50	-71
10	87	-43	-65
0	87	-37	-60
-10	89	-34	-56
-20	99	-27	-45
-30	106	-26	-38
-40	109	-11	-17
-50	114	-3	-8
-60	115	8	0
q_{wt}		90	
$P_a - P_{wt}$		136	

Note: 1) All values in thousandths of an inch of water (0.001" H₂O = 0.249 Pa).
2) q_{wt} is the uncorrected wind tunnel dynamic pressure.
3) Standard suction pipe setup used.

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**Table 3.31: Performance Testing Data for Model B, Throat
Length = 3 5/8 inches**

Wind Elevation Angle, θ (degrees)	$(P_1 - P_{wt})'$	$(P_2 - P_{wt})$	$(P_{\infty} - P_{wt})$
60	76	-90	-117
50	79	-64	-115
40	84	-40	-94
30	81	-36	-95
20	79	-34	-90
10	70	-32	-89
0	69	-27	-87
-10	70	-27	-87
-20	78	-36	-116
-30	81	-50	-114
-40	85	-48	-101
-50	81	-53	-102
-60	83	-76	-84
q_{wt}	74		
$P_a - P_{wt}$	108		

Note: 1) All values in thousandths of an inch of water (0.001" H₂O = 0.249 Pa).
 2) q_{wt} is the uncorrected wind tunnel dynamic pressure.
 3) Standard suction pipe setup used.

Table 3.32: Performance Testing Data for Model B, Throat Length = 3 inches

Wind Elevation Angle, θ (degrees)	$(P_1 - P_{wt})'$	$(P_2 - P_{wt})$	$(P_\infty - P_{wt})$
60	92	-82	-104
50	87	-69	-120
40	91	-38	-101
30	89	-30	-99
20	86	-27	-82
10	79	-27	-85
0	76	-22	-88
-10	78	-24	-85
-20	87	-23	-121
-30	89	-41	-123
-40	90	-46	-115
-50	91	-52	-111
-60	89	-59	-79
q_{wt}	75		
$P_s - P_{wt}$	120		

Note: 1) All values in thousandths of an inch of water (0.001" H₂O = 0.249 Pa).
2) q_{wt} is the uncorrected wind tunnel dynamic pressure.
3) Standard suction pipe setup used.

Table 3.33: Performance Testing Data for Model B, Throat Length = 2½ inches

Wind Elevation Angle, θ (degrees)	$(P_1 - P_{wt})'$	$(P_2 - P_{wt})$	$(P_{\infty} - P_{wt})$
60			
50	82	-39	-96
40	82	-36	-92
30	81	-31	-97
20	78	-18	-99
10	72	-16	-91
0	69	-17	-89
-10	71	-18	-91
-20	78	-24	-92
-30	82	-23	-91
-40	83	-30	-89
-50	82	-42	-107
-60			
q_{wt}		66	
$P_a - P_{wt}$		108	

Note: 1) All values in thousandths of an inch of water (0.001" H₂O = 0.249 Pa).
 2) q_{wt} is the uncorrected wind tunnel dynamic pressure.
 3) Standard suction pipe setup used.

**Table 3.34: Performance Testing Data for Model B, Throat
Length = 2 inches**

Wind Elevation Angle, θ (degrees)	$(P_1 - P_{wt})'$	$(P_2 - P_{wt})$	$(P_\infty - P_{wt})$
60	85	-57	-105
50	87	-44	-120
40	87	-33	-98
30	86	-28	-104
20	80	-24	-104
10	75	-22	-105
0	73	-16	-99
-10	74	-20	-111
-20	81	-22	-117
-30	82	-37	-123
-40	84	-44	-111
-50	82	-51	-120
-60	85	-51	-77
q_{wt}	78		
$P_s - P_{wt}$	109		

Note: 1) All values in thousandths of an inch of water ($0.001'' \text{ H}_2\text{O} = 0.249 \text{ Pa}$).
 2) q_{wt} is the uncorrected wind tunnel dynamic pressure.
 3) Standard suction pipe setup used.

Table 3.35: Performance Testing Data for Model C, Throat Length = 3 5/8 inches

Wind Elevation Angle, θ (degrees)	$(P_1 - P_{wt})'$	$(P_2 - P_{wt})$	$(P_s - P_{wt})$
60	76	-72	-99
50	76	-82	-100
40	75	-40	-83
30	74	-30	-79
20	72	-23	-76
10	67	-19	-79
0	67	-16	-77
-10	71	-18	-79
-20	75	-24	-84
-30	75	-30	-89
-40	84	-30	-52
-50	77	-59	-64
-60	78	-62	-66
q_{wt}	70		
$P_s - P_{wt}$	100		

Note: 1) All values in thousandths of an inch of water (0.001" H₂O = 0.249 Pa).
 2) q_{wt} is the uncorrected wind tunnel dynamic pressure.
 3) Standard suction pipe setup used.

**Table 3.36: Performance Testing Data for Model C, Throat
Length = 3¾ inches**

Wind Elevation Angle, θ (degrees)	$(P_1 - P_{wt})'$	$(P_2 - P_{wt})$	$(P_{\infty} - P_{wt})$
60	82	-57	-88
50	82	-46	-98
40	82	-33	-97
30	87	-25	-91
20	83	-19	-82
10	77	-15	-81
0	72	-17	-81
-10	73	-19	-86
-20	82	-25	-101
-30	85	-27	-101
-40	85	-34	-99
-50	84	-25	-59
-60	82	-50	-61
q_{wt}	71		
$P_a - P_{wt}$	112		

Note: 1) All values in thousandths of an inch of water (0.001" H₂O = 0.249 Pa).
 2) q_{wt} is the uncorrected wind tunnel dynamic pressure.
 3) Standard suction pipe setup used.

**Table 3.37: Partial Performance Testing Data for Model C,
 $\theta = 0$ degrees, Various Throat Lengths**

Configuration	q_{wt}	$(P_s - P_{wt})$	$(P_1 - P_{wt})'$	$(P_2 - P_{wt})$	$(P_\infty - P_{wt})$
3¼" throat length	71	116	74	-20	-84
2¾" throat length	71	116	76	-20	-85
2¼" throat length	71	116	74	-17	-86
2¾" throat length	71	116	73	-15	-82

Note: 1) All values in thousandths of an inch of water (0.001" H₂O = 0.249 Pa).
 2) q_{wt} is the uncorrected wind tunnel dynamic pressure.
 3) Standard suction pipe setup used.

**Table 3.38: Partial Performance Testing Data for Model D,
 $\theta = 0$ degrees, Various Throat Lengths**

Configuration	q_{wt}	$(P_a - P_{wt})$	$(P_1 - P_{wt})'$	$(P_2 - P_{wt})$	$(P_\infty - P_{wt})$
3 5/8" throat length, inline	78	120	71	-36	-49
3 5/8" throat length, open	93	130	90	-9	-16
2" throat length, open	74	106	74	-5	-11
2" throat length, inline	66	107	59	-43	-46

Note: 1) All values in thousandths of an inch of water (0.001" H₂O = 0.249 Pa).
 2) q_{wt} is the uncorrected wind tunnel dynamic pressure.
 3) Standard suction pipe setup used.

**Table 3.39: Partial Performance Testing Data for Model E,
 $\theta = 0$ degrees, Various Throat Lengths**

Configuration	q_{wt}	$(P_s - P_{wt})$	$(P_1 - P_{wt})'$	$(P_2 - P_{wt})$	$(P_{\infty} - P_{wt})$
2" throat length, inline	70	116	76	-8	-10
2" throat length, open	70	116	79	0	-8
3" throat length, inline	70	116	76	-9	-11
3" throat length, open	70	116	78	-7	-11

Note: 1) All values in thousandths of an inch of water ($0.001'' \text{ H}_2\text{O} = 0.249 \text{ Pa}$).
 2) q_{wt} is the uncorrected wind tunnel dynamic pressure.
 3) Standard suction pipe setup used.

Table 3.40: Performance Testing Data for Model E, Open Configuration, Throat Length = 3 inches

Wind Elevation Angle, θ (degrees)	$(P_1 - P_{wt})'$	$(P_2 - P_{wt})$	$(P_s - P_{wt})$
60	97	-53	-58
50	98	-54	-60
40	100	-31	-39
30	100	-11	-23
20	99	0	-12
10	90	-7	-9
0	82	-11	-13
-10	89	-15	-21
-20	97	-13	-17
-30	101	-13	-17
-40	100	-23	-23
-50	98	-45	-46
-60	97	-52	-53
q_{wt}	75		
$P_s - P_{wt}$	121		

Note: 1) All values in thousandths of an inch of water ($0.001'' \text{ H}_2\text{O} = 0.249 \text{ Pa}$).
 2) q_{wt} is the uncorrected wind tunnel dynamic pressure.
 3) Standard suction pipe setup used.

Figures

Figure 1.1: Masonry Chimney Cap and Surrounding Structure [1]

Figure 1.2: Metal Chimney Cap and Surrounding Structure [7]

Figure 1.3: Pressure Distribution on the Outside of a Building of Simple Geometry

Figure 1.4 (a): Schematic Diagram Demonstrating the Concept of the Neutral Zone

Figure 1.4 (b): Distribution of Inside and Outside Pressures Over the Height of a Building [5]

Figure 1.5: Wind Elevation Angle Variation on Chimney Caps

Figure 1.6: National Building Code of Canada 1990 Section 9.21.4.4 Requirements for Chimneys [9]

Figure 1.7: Windscoop Schematic Representation (Hyderabad, Pakistan) [11]

Figure 1.8: Windscoop Schematic Representation (Iran) [11]

Figure 1.9: Natural Ventilation of the Pantheon (Rome, Italy) [11]

Figure 1.10 (a): Chimney Cap Tested by Schmitt and Engdahl [13]

Figure 1.10 (b): Results of Schmitt and Engdahl Chimney Cap Test [13]

Figure 1.11: Ventilator Configurations Tested by Gonzales [17]

Figure 1.12: Chimney Cap Configurations Tested by Scanada Consultants [18]

Figure 1.13: Chimney Pot Configurations Tested by Carpenter [10]

Figure 1.14: Ventilator Configurations Tested by Elger and McLam [19]

Figure 1.15: Schematic of Attic Turbine Ventilator Testing by Dale and Ackerman [21]

- (a) single-flap lightdome-type ventilator with wind deflector
- (h) double-flap ventilator
- (c) single-flap lightdome-type ventilator with large opening angle and small sidewind deflector and a wind spoiler fitted at the hinge side
- (d) louvre-type ventilator
- (e) ridge-type ventilator
- (f) ventilator for shed-type lightstreets

Figure 1.16: Smoke Ventilator Configurations Tested by Meessen [25]

Figure 1.17: Allowable Total Exhaust Flows for Houses with Different Leakage Areas and House Depressurization Limits [6]

Model A

Model B/C

Chimney cap posts not shown for reasons of clarity.

Figure 1.18: Schematic Diagram of Chimney Cap Models to be Tested

Figure 2.1: Wannenburg Apparatus for Ventilator Testing [14]

Figure 2.2: Gonzales Apparatus for Ventilator Testing [17]

Figure 2.4 (b): Graphical Representation of Equation (2.17)

Figure 2.4 (c): Schematic Diagram of the Chimney Cap

Figure 2.5: Schematic Diagrams of an Open Jet and Open Circuit Wind Tunnel

Figure 2.6: Schematic Diagram Showing the Ekman and Interfacial Layers of the Atmospheric Boundary Layer

Figure 2.7: Chimney Cap Model A

Figure 2.8: Chimney Cap Models B and C

Figure 2.9: Chimney Cap Wind Tunnel Test Rig

Figure 2.10: Resistance Testing Rig

Figure 2.11: Pitot-Static Tube Used for Resistance Testing Rig Dynamic Pressure Measurements

Figure 2.12: Manometer Used for Measurements of Static Pressure Differences, Resolution of ± 0.001 inches of water

- (a) inlet sections without plates
(both 3" and 4" pipe diameter designs similar)

static pressure taps
(four equally spaced)

- (b) inlet section with plate (3" diameter)

Figure 2.13: Inlet Sections

Figure 3.1 Inlet Resistance Testing of Various Inlet Sections

Figure 3.2: Entrance Loss Coefficients for Rounded and Bevelled Inlets [27] (● represents resistance of inlet section with plate)

Figure 3.3: Exit Resistance Testing (Model A)

Figure 3.4: Exit Resistance Testing (Model B, throat lengths of 1", 1½", 2", and 2½")

Figure 3.5: Exit Resistance Testing (Model B, throat lengths of 3", 3½", and 3 5/8")

Figure 3.6: Exit Resistance Testing (Model C)

Figure 3.7: Throat Length versus Exit Resistance for Various Chimney Cap Models

Figure 3.8: Verification Testing on Model A, Static Pressure Difference versus Wind Tunnel Dynamic Pressure ($\theta = 0$ degrees)

Figure 3.9: Verification Testing on Model A, Static Pressure Difference versus Wind Tunnel Dynamic Pressure ($\theta = +20$ degrees)

Figure 3.10: Verification Testing on Model A, Static Pressure Difference versus Wind Tunnel Dynamic Pressure ($\theta = -20$ degrees)

Figure 3.11: Verification Testing on Model B, Static Pressure Difference versus Wind Tunnel Dynamic Pressure ($\theta = 0$ degrees)

Figure 3.12: Verification Testing on Model B, Static Pressure Difference versus Wind Tunnel Dynamic Pressure ($\theta = +20$ degrees)

Figure 3.13: Verification Testing on Model B, Static Pressure Difference versus Wind Tunnel Dynamic Pressure ($\theta = -20$ degrees)

Figure 3.14: Verification Testing on Model C, Static Pressure Difference versus Wind Tunnel Dynamic Pressure ($\theta = 0$ degrees)

Figure 3.15: Verification Testing on Model A, Effects of Post Orientation on Static Pressure Difference versus Wind Tunnel Dynamic Pressure Relationship ($\theta = 0$ degrees)

Figure 3.16: Verification Testing on Model A, Effect of Suction Pipe Resistance on Static Pressure Difference ΔP_1 versus Wind Tunnel Dynamic Pressure ($\theta = 0$ degrees)

Figure 3.17: Verification Testing on Model A, Effect of Suction Pipe Resistance on Static Pressure Difference ΔP_2 versus Wind Tunnel Dynamic Pressure ($\theta = 0$ degrees)

Figure 3.18: Verification Testing on Model C, Effect of Suction Pipe Resistance on Static Pressure Difference ΔP_1 versus Wind Tunnel Dynamic Pressure ($\theta = 0$ degrees)

Figure 3.19: Verification Testing on Model C, Effect of Suction Pipe Resistance on Static Pressure Difference ΔP_2 versus Wind Tunnel Dynamic Pressure ($\theta = 0$ degrees)

Figure 3.20: Verification Testing on Model A, λ and λ^2 versus η ($\theta = 0$ degrees)

Figure 3.21: Verification Testing on Model C, λ and λ^2 versus η ($\theta = 0$ degrees)

Figure 3.22: Verification Testing on Model A, ψ versus Wind Tunnel Dynamic Pressure for Various Total Suction Pipe Resistances ($\theta = 0$ degrees)

Figure 3.23: ψ and η_{max} for Various Chimney Cap Models Tested ($\theta = 0$ degrees, $K = 0$)

Figure 3.24: Flow Visualization Using Yarn Tufts for Model B, Two Inch Throat Length: (a) Inlet Section Closed, (b) Inlet Section Open

Figure 3.25: Chimney Cap Model D

Figure 3.26: Schematic of the Turbulent Mixing Layer

Figure 3.27: Chimney Cap Model E

Figure 3.28: Exit Resistance Testing (Model E)

Figure 3.29: Performance Chart for Chimney Cap Model A

Figure 3.30: Performance Chart for Chimney Cap Model E
(three inch throat length, open configuration)

Figure 3.31: Comparison of Results to those of Gonzales Model 1 [17] (● represents the performance of Model E, three inch throat length, open configuration)

Figure 3.32: Comparison of Results to Those of Gonzales Model 2 [17] (● represents the performance of Model E, three inch throat length, open configuration)

Figure 3.33: Comparison of Results to Those of Gonzales Models 3 through 7 [17] (● represents the performance of Model E, three inch throat length, open configuration)

Wind Directional Model

Caddicap Model

Figure 3.34: Comparison of Results to Those of Elger and McLam Wind Directional and Caddicap Models [19] (● represents the performance of Model E, three inch throat length, open configuration)

Figure 3.35: Comparison of Results to Those of Elger and McLam Vacuum Cap Model [19] (● represents the performance of Model E, three inch throat length, open configuration)

Appendix A

Appendix A

A1: Obtaining Inlet Resistance from Experimental Data

Recall from Equation (2.22) that

$$K_i = \frac{\Delta P_i}{\frac{1}{2}\rho_w v_w^2} - 1 \quad (2.22)$$

In the above equation, ΔP_i is static pressure difference across the inlet and $(\frac{1}{2}\rho_w v_w^2)$ is the dynamic pressure of the air flow at the inlet. These values were measured and plotted in Figure 3.1. Note that the value of $\Delta P_i/(\frac{1}{2}\rho_w v_w^2)$ is the slope of the line drawn through the points.

In order to draw a linear best fit line through the data, a linear least squares method was used. Since the best fit line must pass through the origin, the linear least squares method reduces to the following relationship for the obtained data.

$$slope = \frac{\sum (\Delta P_i)_j}{\sum (\frac{1}{2}\rho_w v_w^2)_j}$$

The above value for the slope can be substituted into Equation (2.22) to give the following relationship.

$$K_i = slope - 1$$

$$\therefore K_i = \frac{\sum (\Delta P_i)_j}{\sum (\frac{1}{2}\rho_w v_w^2)_j} - 1$$

A2: Obtaining η , $\eta_{\max}$, λ and λ^2 from Experimental Data for Verification of Assumptions

Recall from the definitions of Equations (2.1b), (2.2), and (2.13) that

$$\eta = \frac{\Delta P_2 - \Delta P_1}{\frac{1}{2}\rho_{wt}V^2} = \frac{\Delta P_2}{\frac{1}{2}\rho_{wt}V^2} - \frac{\Delta P_1}{\frac{1}{2}\rho_{wt}V^2} \quad (2.1b)$$

$$\lambda^2 = \frac{\Delta P_1}{\frac{1}{2}\rho_{wt}V^2} \quad (2.2)$$

$$\eta_{\max} = \frac{\Delta P_a}{\frac{1}{2}\rho_{wt}V^2} \quad (2.13)$$

Similar to the method described in Appendix A1, the values on the right side of the above equations are the slopes of the best fit lines through the experimental data points in Figures 3.16 to 3.19. Using the linear least squares method discussed in Appendix A1, the values of η , λ , λ^2 , and $\eta_{\max}$ can be obtained for the experimental data as follows.

$$\eta = \frac{\Sigma(\Delta P_2)_j}{\Sigma(\frac{1}{2}\rho_{wt}V^2)_j} - \frac{\Sigma(\Delta P_1)_j}{\Sigma(\frac{1}{2}\rho_{wt}V^2)_j}$$

$$\lambda = \sqrt{\frac{\Sigma(\Delta P_1)_j}{\Sigma(\frac{1}{2}\rho_{wt}V^2)_j}}$$

$$\lambda^2 = \frac{\Sigma(\Delta P_1)_j}{\Sigma(1/2\rho_{wr}V^2)_j}$$

$$\eta_{\max} = \frac{\Sigma(\Delta P_2)_j}{\Sigma(1/2\rho_{wr}V^2)_j}$$

For each line through the data points, the above equations will give one point on the λ and λ^2 versus η curves shown in Figures 3.20 and 3.21.

END

3 1 - 0 5 - 9 5

FIN