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Factors Affecting Air Entrainment of Hydraulic Jumps within Closed Conduits

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FACTORS AFFECTING AIR ENTRAINMENT OF HYDRAULIC JUMPS WITHIN

CLOSED CONDUITS

by

Joshua D. Mortensen

A thesis submitted in partial fulfillment
of the requirements for the degree

of

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ABSTRACT

Factors Affecting Air Entrainment of Hydraulic Jumps Within Closed Conduits

by

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Utah State University, 2009

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While there has been a great deal of research on air entrainment at hydraulic jumps within closed conduits, very little of the research has specifically addressed size and temperature scale effects. Influences from jump location and changing length characteristics on air entrainment have also received little attention from past research. To determine the significance of size-scale effects of air entrained by hydraulic jumps in closed conduits, air flow measurements were taken in four different-sized circular pipe models with similar Froude numbers. Each of the pipe models sloped downward and created identical flow conditions that differed only in size. Additionally, specific measurements were taken in one of the pipe models with various water temperatures to identify any effects from changing fluid properties. To determine the significance of the effects of changed length characteristics on air demand, air flow measurements were taken with hydraulic jumps at multiple locations within a circular pipe with two different air release configurations at the end of the pipe.

Results showed that air demand was not affected by the size of the model. All together, the data from four different pipe models show that size-scale effects of air entrained into hydraulic jumps within closed conduits are negligible. However, it was determined that air entrainment was significantly affected by the water temperature. Water at higher temperatures entrained much less air than water at lower temperatures. Hydraulic jump location results showed that for both configurations the percentage of air entrainment significantly increased as the hydraulic jump occurred near the point of air release downstream. As the jump occurred nearer to the end of the pipe, its length characteristics were shortened and air demand increased. However, jump location was only a significant factor until the jump occurred some distance upstream where the length characteristics were not affected. Upstream of this location the air demand was dependent only on the Froude number immediately upstream of the jump.

(65 pages)

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LIST OF SYMBOLS AND ABBREVIATIONS

<u>List of Symbols</u>

β	Ratio of volumetric air flow to water flow (-)
Fr	Froude Number (-)
Re	Reynolds Number (-)
We	Weber Number (-)
g	Acceleration of gravity (ft/s^2 / m/s^2)
y_e	Effective hydraulic depth (ft / m)
La	Aeration length of hydraulic jump (pipe diameters)
Lj	Distance from jump toe to end of pipe (pipe diameters)
Lr	Roller length of hydraulic jump (pipe diameters)
V	Flow velocity (ft/s / m/s)
Q_{air}	Volumetric air flow rate (ft^3/s / m^3/s)
Q_{water}	Volumetric water flow rate (ft^3/s / m^3/s)

<u>List of Abbreviations</u>

GVF	Gradually Varied Flow
MWH	Montgomery Watson Harza
USBR	United States Bureau of Reclamation
UWRL	Utah Water Research Laboratory

CHAPTER I

INTRODUCTION

At a transition from subcritical to supercritical flow a hydraulic jump occurs which entrains air into the flow due to its high level of turbulence at the air-water interface. When a hydraulic jump occurs within a closed conduit and causes pressurized flow downstream, the air that is entrained may cause problems within the conduit. Pipelines with changing slopes, low-level outlet works of dams and other hydraulic conduits have experienced choked flow, blow-back, negative pressures and other similar problems due to air that was entrained through a hydraulic jump. Knowledge of the amount of air that is entrained by a hydraulic jump is important for proper venting and air release design.

Due to the many factors that may affect air entrainment, physical model studies are often necessary to predict the amount of air entrained by a hydraulic jump (or air demand of the jump). Great care must be taken when scaling results from models of two-phase flows as size-scale effects may exist. Various model sizes may be necessary to determine the significance of size-scale effects between the different sized structures.

An example of such a model study is a pipeline and air release system that was modeled at the Utah Water Research Laboratory for MWH Global. This circular pipeline was designed to transport treated effluent from the area of Las Vegas, Nevada to the bottom of Lake Mead. Due to the slope of the pipe and the hydraulic grade line at the lake surface, a hydraulic jump will always exist somewhere in the pipe. A passive air venting system requiring no manual operation or maintenance was designed to capture all

of the free air entrained by the jump. This design consisted of air capture chambers (short sections of larger diameter pipe with air vents near the top) placed in series down the length of the pipe. This design was necessary to prevent any free air to be released into the lake which could cause algae bloom and other environmental problems. Air demand data was taken at hydraulic jumps in different sized pipe models to determine the possibility and significance of size-scale effects between pipe sizes. Test results were useful in optimizing the air release design, assuring that no free air would be released into the lake.

This thesis studied size-scale, temperature and jump location effects of air entrained by hydraulic jumps using a very similar pipe and air release design as the MWH study. For size-scale effects, air entrainment rates were recorded in pipe sizes of 24-inch, 12-inch, 7-inch and 3-inch I.D. that were operated with common Froude numbers. For water temperature effects, similar tests were performed in the 3-inch pipe at four different water temperatures (55, 85, 120 and 145 °F). For the research on jump location effects, air flow measurements were taken with hydraulic jumps located at various distances from the pipe exit using two different air release structures at the end of the pipe. One structure was the air capture chamber used in the size-scale effects study and the other was an open tank. The roller and aeration lengths (characteristic lengths) of the jump were expected to change with distance from the end of the pipe, possibly affecting air demand.

Previous studies of air entrainment of hydraulic jumps were reviewed for guidance in this thesis. The research indicated that various factors may influence the air demand of hydraulic jumps such as upstream Froude number (Kalinske and Robertson,

1943), jump location from an upstream air intake (Sharma, 1976), flow and exit conditions as well as conduit geometry (Escarameia, 2007). Many studies of air entrainment of hydraulic jumps in open channels showed that viscous and surface tension effects can produce size-scale effects (Chanson, 2008a, 2008b, 2007, 2006, 1995). However, very little of the research specifically addressed size-scale, temperature or jump location effects of air entrainment of hydraulic jumps within circular closed conduits.

Specifics of the literature review, experimental set up, procedure and test results are documented in Chapters II and III of this document. Chapter II addresses size-scale effects from the four pipe sizes as well as temperature effects. Chapter III addresses effects from jump location and changed characteristic lengths. Both chapters are journal articles to be submitted to the Journal of Hydraulic Research.

In summary, the main objective of this thesis was to determine how air demand of hydraulic jumps in circular closed conduits is affected by the following factors:

- Size-scale effects

- Temperature effects

- Jump Location and altered length characteristics effects

Many articles of past research on air entrainment by hydraulic jumps in both closed conduit and open channel flows have been reviewed and have been found useful. However, results from these past studies do not specifically address the factors investigated in the current research. The results obtained from the physical model studies provide new insights into air entrainment processes of hydraulic jumps within closed

conduits. Hopefully, these results will be useful in future modeling processes and aid the

practicing engineer in predicting air entrainment rates for design purposes.

CHAPTER II

SCALE EFFECTS OF AIR ENTRAINED BY HYDRAULIC JUMPS WITHIN CLOSED CONDUITS[1]

ABSTRACT

While there has been a great deal of research in air entrainment at hydraulic jumps within closed conduits, very little of the research has specifically addressed size-scale effects. To determine the significance of size-scale effects of air entrained by hydraulic jumps in closed conduits, air flow measurements were taken in four different sized circular pipe models with similar Froude numbers. Additionally, specific measurements were taken in one of the models with various water temperatures to identify any effects from changing fluid properties. Results showed that the percentage of air entrainment was not affected by the size of the model. All together, the data from four different pipe models show that scale effects of air entrained into hydraulic jumps within closed conduits are negligible. However, it was determined that air entrainment was significantly affected by water temperature.

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[1] Coauthored by Steven L. Barfuss P.E. and Michael C. Johnson Ph.D., P.E

1 Introduction

A hydraulic jump which occurs at a transition from open channel flow to pressurized flow within a closed conduit will entrain air into the flow due to its high level of turbulence at the air-water interface. Knowledge of the amount of air entrained by a hydraulic jump is important for the proper design of pipelines, low-level outlet works of dams, and other such conveyance systems. Past studies have shown that the amount of air entrained and passed downstream by the jump within closed conduits is dependent on many factors, including; Froude number (Kalinske & Robertson, 1943), and jump location (Sharma, 1976). However, no studies were found that specifically addressed scale effects of air entrainment of hydraulic jumps within closed conduits. Extensive research by Chanson (2008a, 2008b, 2007) has shown that for open channel flows, scale effects of air entrainment exist between different sized jumps with a common Froude number. However, despite the many studies on air entrainment at hydraulic jumps performed by Chanson, scale effects of air entrained by hydraulic jumps within closed conduits have not been addressed.

The primary objective of this study was to investigate size-scale effects of air entrainment in circular closed conduits. To accomplish this, measurements of air flow were taken at hydraulic jumps in four different sized pipe models that were operated with common Froude numbers. A secondary objective of this research was to determine if air entrainment is dependent on water temperature. Tests were performed in one of the models by recording air flow measurements at four different water temperatures. The results of this study are important because the differences in conduit size and even water temperature are often significant between model and prototype. It is expected that these

findings will give greater insight into air entrainment processes and will be valuable for system design.

2 Literature Review

2.1 Closed Conduit Flow

Kalinske and Robertson (1943) conducted some of the very first experiments of air entrainment by measuring air entrainment rates at hydraulic jumps within a single circular pipe at various slopes from 0 to 16.7 degrees. Their results showed that air demand is dependent only on the Froude number immediately upstream of the jump and not the slope of the pipe. From their data they developed the following air demand relationship:

$$\beta = \frac{Q_{air}}{Q_{water}} = 0.0066(Fr-1)^{1.4} \tag{1}$$

In Eq. (1) β is the volumetric ratio of the air flow to water flow and Fr is the Froude number immediately upstream of the jump with Fr defined as follows:

$$Fr = \frac{V}{\sqrt{gy_e}} \tag{2}$$

In Eq. (2) g is the acceleration of gravity, V is the approach velocity and y_e, the effective depth, is the water cross-sectional flow area divided by the water surface width.

Kalinske and Robertson also found that for downward sloping pipes, multiple hydraulic jumps may occur in series with a pressurized air pocket between them and that the primary jump's ability to entrain air is dependent the hydraulic features beyond the jump (Estrada, 2007). Many others have built upon Kalinske and Robertson's pioneering work by performing similar air entrainment experiments of closed conduit flow.

Sharma (1976) collected air demand data in a high-head gated, rectangular conduit model for many different flow scenarios, including a hydraulic jump that fills the conduit. After comparing his results to prototype data he found that Kalinske and Robertson's equation (Eq. 1) underestimated the air entrained by the hydraulic jump in the prototype when the jump occurred at a considerable distance from the gate. He claimed that prototype air demand was larger due a "pre-entrained" hydraulic jump which pumps additional air that was entrained into the more turbulent upstream supercritical flow. Sharma's research indicates that jump location and water surface roughness upstream of the jump may contribute to scale effects and should be accounted for when measuring air entrainment rates. Despite the studies of Sharma and others, pipe size-scale effects on air entrained into hydraulic jumps within circular closed conduits has not been thoroughly investigated.

Escarameia (2007) measured rates of air entrainment into hydraulic jumps in a circular pipe and compared her results to those found by Kalinske and Robertson (1943), Wisner *et al*. (1975), Rajaratnam (1967), and Rabben *et al.* (1983). This comparison showed significant differences of air demand between the various experiments. She suggests that the different results may be due to differences in conduit geometry as well as downstream flow and exit conditions. The comparison of Escarameia's results with

other studies show that factors other than pipe size-scale effects may influence air

entrainment and great care should be taken to recognize the effect of each factor.

2.2 Open Channel Flow

Hager *et al.* (1989 and 1990) have conducted many studies on a classical

hydraulic jump within open channels and reported that in addition to the Froude number

the Reynolds number also influences jump characteristics. They also defined the length

from the toe to the surface stagnation point as the surface roller length. Their

observations indicate that air bubbles intensively rise at the downstream end of the roller.

Although the characteristics of a hydraulic jump in a closed pipe may differ, knowledge

of air bubble transport within hydraulic jumps is important.

Chanson (2008a, 2008b, 2007, 2006, 1995) has extensively studied scale effects

of air entrainment in hydraulic jumps in open channel flows. His work shows that scale

effects may exist between two systems that are not dynamically similar. Complete

dynamic similitude is achieved only when each dimensionless parameter (*Fr, Re, We*) is

the same in both model and prototype (D.O.I., 1980). When comparing two hydraulic

jumps of different flume widths using Froude similitude, he found greater air entrainment

within the larger jump. Chanson determined that this was due to the jump's greater

incoming velocities, Reynolds numbers and resulting turbulence. A visual comparison

clearly shows the greater turbulence of the jump in the larger flume as well as a

difference in air bubble size. Greater incoming velocities and turbulence cause more

breakup of the air bubbles, resulting in smaller bubble size and greater air entrainment

rates (Chanson, 2008b).

Chanson's results indicate numerically as well as visually that viscous and surface tension effects do influence air entrainment because of their effect on turbulence and bubble size. His results confirm that scale effects do exist for air entrainment of hydraulic jumps in open channel flows. However, to date, Chanson's research has not addressed air entrainment of hydraulic jumps in closed conduit flows.

3 Experimental Setup and Procedure

In order to investigate the specific influence of model size and fluid properties on air entrainment of hydraulic jumps in closed conduits, physical model studies were conducted to compare results. Air entrainment rates were measured in four similar circular pipe models with inside diameters of 7.62-cm, 17.7-cm, 30.0-cm and 59.1 cm and lengths of 106, 120, 80, and 53 pipe diameters, respectively. Pipe length and material varied due to space and visual constraints; each model was set at a 4% downward slope. Air entrainment rates were obtained in each model by using a model A031 Kanomax anemometer to measure air velocities through a 6.35 cm diameter air intake located immediately downstream of an acrylic flow nozzle at the upstream end of the pipe model. Pressure drop readings across the inlet of each air intake confirmed that it would not limit the air flow for the range of air velocities measured. Water flow rates were measured using a combination of calibrated magnetic, ultrasonic and venturi flow meters.

Water entered each model through a flow nozzle which forced an open channel flow condition with a smooth water surface. A gradually varied flow surface profile developed down the length of the pipe until a hydraulic jump occurred downstream. At

the end of the pipe the water flowed through a larger diameter air capture chamber with an air vent near the top to allow the free air to be released from the flow. A hydraulic jump was forced to occur at a desired location by adjusting a control valve downstream of the chamber. The air entrained by the jump was measured as it entered the system through the acrylic intake inserted just downstream of the nozzle (Fig. 1).
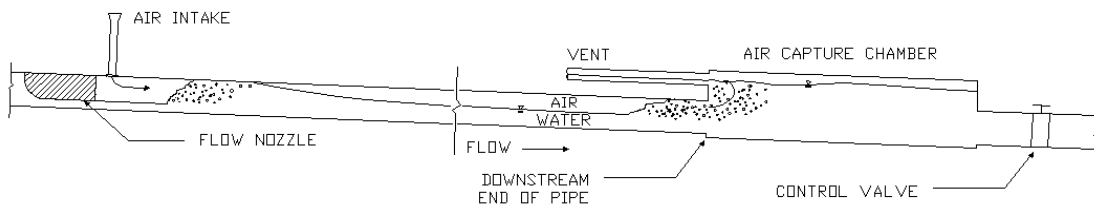
Figure 1 Profile of air and water flow through each model

3.1 Size-scale Effect Data Collection

For each model size, common Froude numbers (ranging 2.6 – 11.4) were obtained by measuring the depth and velocity of the supercritical flow upstream of the jump location. Due to the difficulty in acquiring an accurate depth measurement inside the pipe, calculated Gradually Varied Flow (GVF) profiles of the water surface were used to estimate the depth. Approximate visual measurements from the outside of the pipe were made for verification. Once the hydraulic jump stabilized at the desired location, the air entrainment for each run was quantified by averaging a three minute sample (180 velocity readings) of air velocity measurements and then calculating the volumetric air flow rate (Q_{air}). To ensure accuracy and repeatability, selected runs were repeated using two identical anemometers and allowing data to be collected for up to ten minutes (600 velocity readings). All tests were performed at a temperature of approximately 10° C.

Scale effects were investigated by plotting the percentage of air entrainment (Eq. 3) (air demand) versus the respective Froude number for each model on the same graph. Since the same range of Froude numbers was used for each model size, any existing scale effects could be readily identified.

$$\beta = \frac{Q_{air}}{Q_{water}}(100)$$ (3)

3.2 Temperature Scale Effect Data Collection

Additional air entrainment rates were recorded at four different water temperatures (12.8° C, 29.4° C, 48.9° C and 62.8° C) using the same procedure as the size-scale effect data collection. The air was at room temperature (approximately 21.1° C). The 7.62-cm I.D. model was used for the varied temperature tests. As with the size-scale data, selected runs from each temperature were repeated using two anemometers and allowing data to be collected for up to ten minutes (600 velocity readings).

Water was heated to a desired temperature in a 5 m^3 tank and then circulated through the system and pipe, then back into the tank as shown in Figure 2. Water temperature was measured as the water left the capture chamber using a digital thermometer and was kept within 2 degrees of the desired temperature during each test series. Temperature effects were illustrated by plotting the percent air entrainment versus the corresponding Froude number for each temperature on the same graph. Temperature effects could be identified since a common Froude range was used for each temperature.
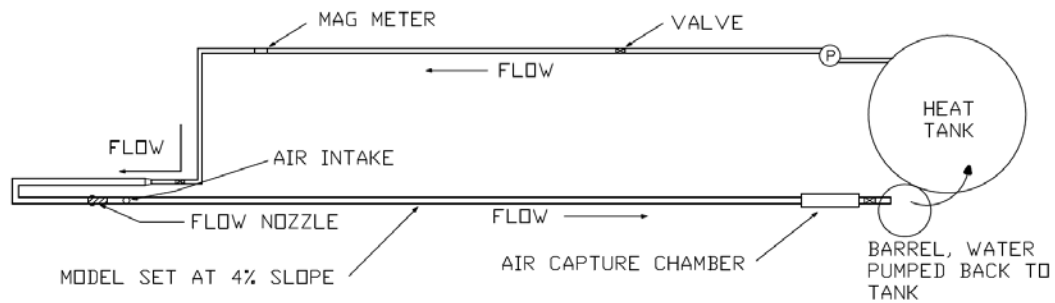
Figure 2 Plan view of the model used for data collection at various water temperatures

4   Results

4.1 Size-scale Effects

Figure 3 shows air demand results of each pipe model compared to the Kalinske and Robertson (1943) curve (Eq. 1). This curve was adjusted to fit the x-axis of *Fr* instead of *Fr-1* as presented in their article. The overlapping data from each model shows that pipe size has very little effect on the percentage of air entrained by the hydraulic jump. Air entrainment was dependent on the Froude number immediately upstream of the jump, except when the hydraulic jump occurred near the air capture chamber where the air is released from the flow. When the jump was located too near the air capture chamber, the measured air entrainment increased. Jump lengths (from toe to point where all air bubbles rose to surface) varied from about 15 to 20 pipe diameters. Once the jump was more than about 20 pipe diameters upstream, the full length of the jump was contained in the pipe and the influence of the air capture chamber was not a factor.
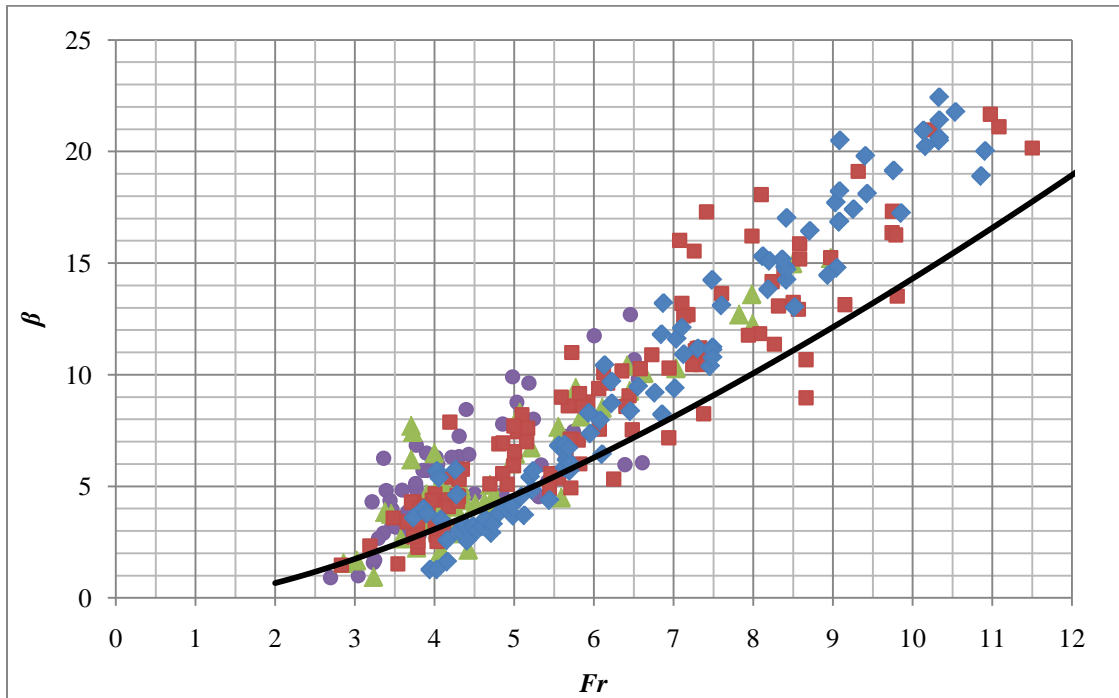
Figure 3 Air demand vs. Froude number for each model size; (♦) 7.62 cm, (■) 17.7 cm,

(▲) 30.0 cm and (●) 59.1 cm diameters

Flow conditions similar to Kalinske and Robertson's (1943) findings were observed in each pipe model where a primary hydraulic jump occurred followed by a pressurized air pocket followed by a secondary hydraulic jump downstream. This almost always occurred unless the primary jump was near the air capture chamber, and then only one jump would occur. For some conditions, usually with greater water flow rates, the air demand consistently oscillated. The primary hydraulic jump also oscillated about a mean location in phase with the air demand, moving downstream as the air demand increased and moved upstream as the air demand decreased. When this happened the vent pipe out of the air capture chamber would fill with water and then be blown out in phase with the oscillations of the air demand and hydraulic jump.

Figure 4 illustrates the difference in air entrainment at the hydraulic jump between pipe sizes when a single hydraulic jump occurred too near the air capture chamber. For this condition, jumps in the larger models entrained a greater amount of air. Figure 4 shows scale effects in air entrainment between the different model sizes for hydraulic jumps at locations between 6 and 10 pipe diameters upstream of the air capture chamber. It was determined that if the jump was further away from the air capture chamber than about 20 pipe diameters, the effects illustrated in Figure 4 would not occur.
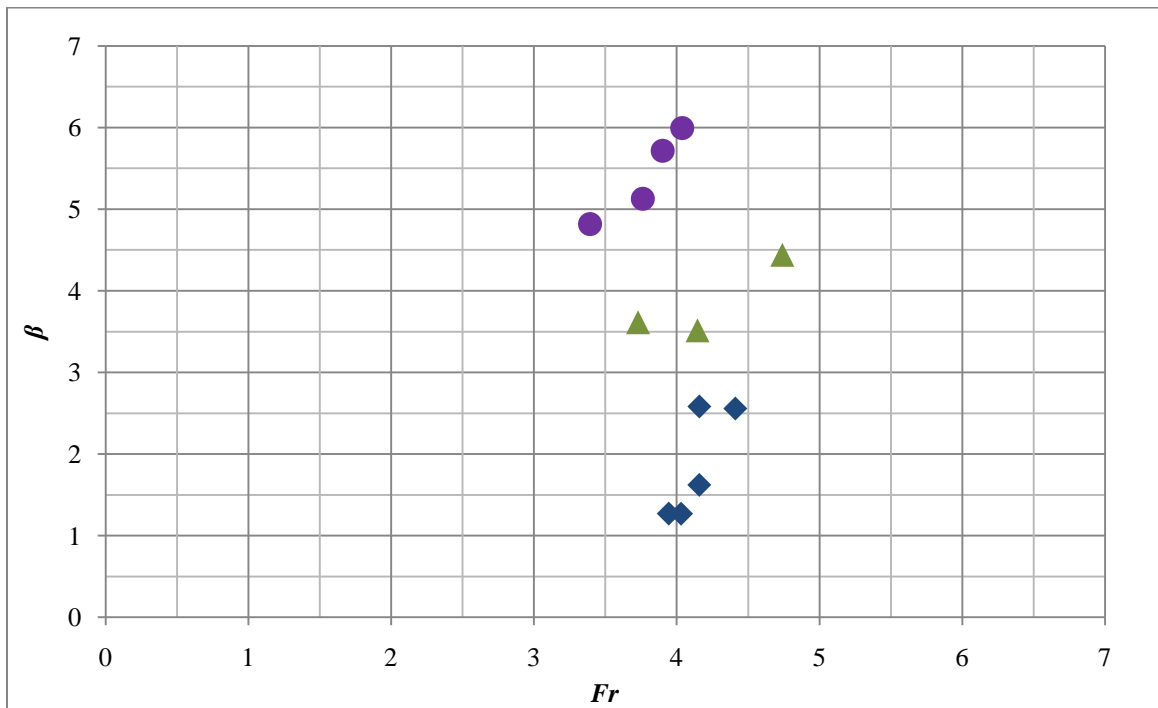
Figure 4 Scale effects due to jump location near point of air release: (♦) 7.62 cm, (▲) 30.0 cm and (●) 59.1 cm pipe diameters

4.2 Temperature Scale Effects

Results indicated that air entrainment is significantly affected by water

temperature. As the temperature of the water increased, the amount of air entrained by

the hydraulic jump decreased (Fig. 5). There is only a slight difference between results

of 12.8 °C and 29.4 °C, but the trend becomes more significant with higher temperatures.

Primary and secondary hydraulic jumps were observed to be similar for all temperatures,

similar to the flow conditions of the size-scale data. As noted previously, a primary

hydraulic jump oscillated about a mean location and a secondary hydraulic jump occurred

mostly near the inlet to the air capture chamber.
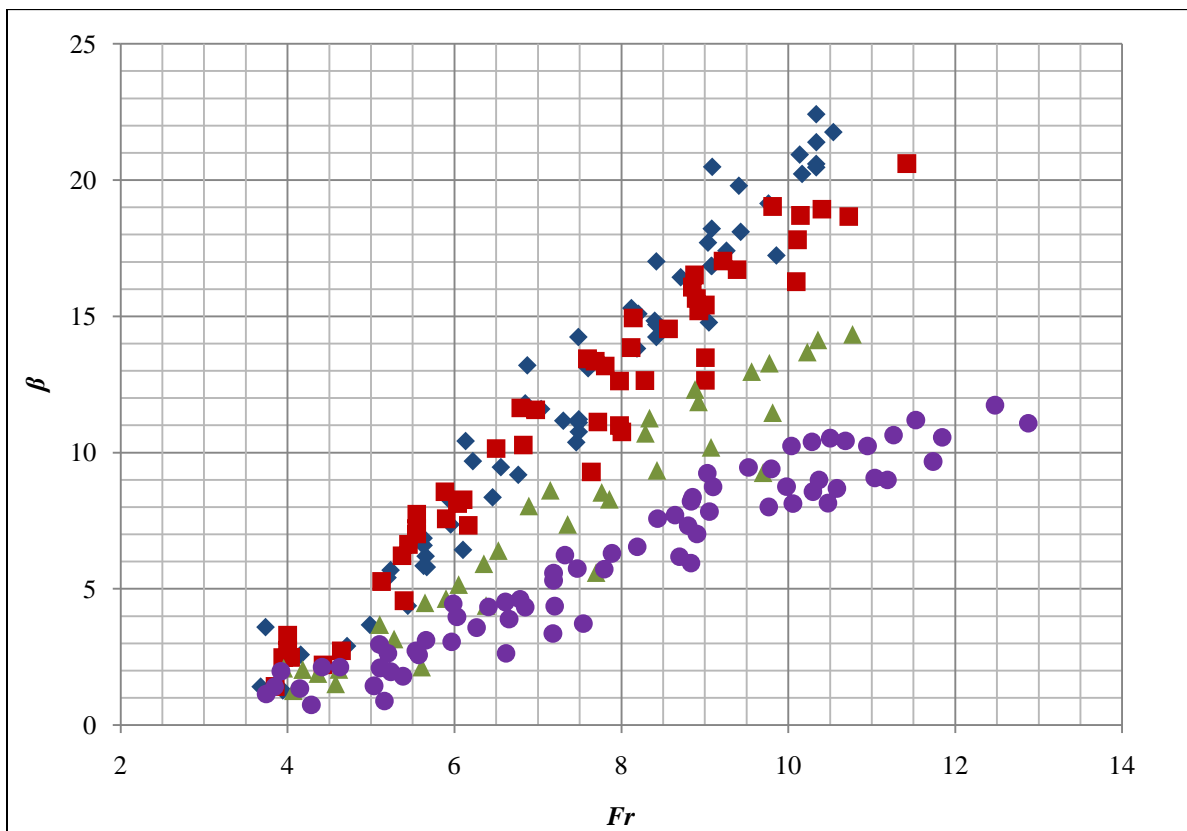
Figure 5 Air demand vs. Froude number for each water temperature where (♦) 12.8°C,

(■) 29.4 °C, (▲) 48.9 °C and (●) 62.8 °C

It was noted that the size of the air bubbles entrained by the jump visually increased with temperature. Figure 6 illustrates the difference in air bubble size between hydraulic jumps with a common Froude number of 7.62. The air demand of each temperature was 12.5 (a), 12.1 (b), 7.5 (c) and 3.2 (d).
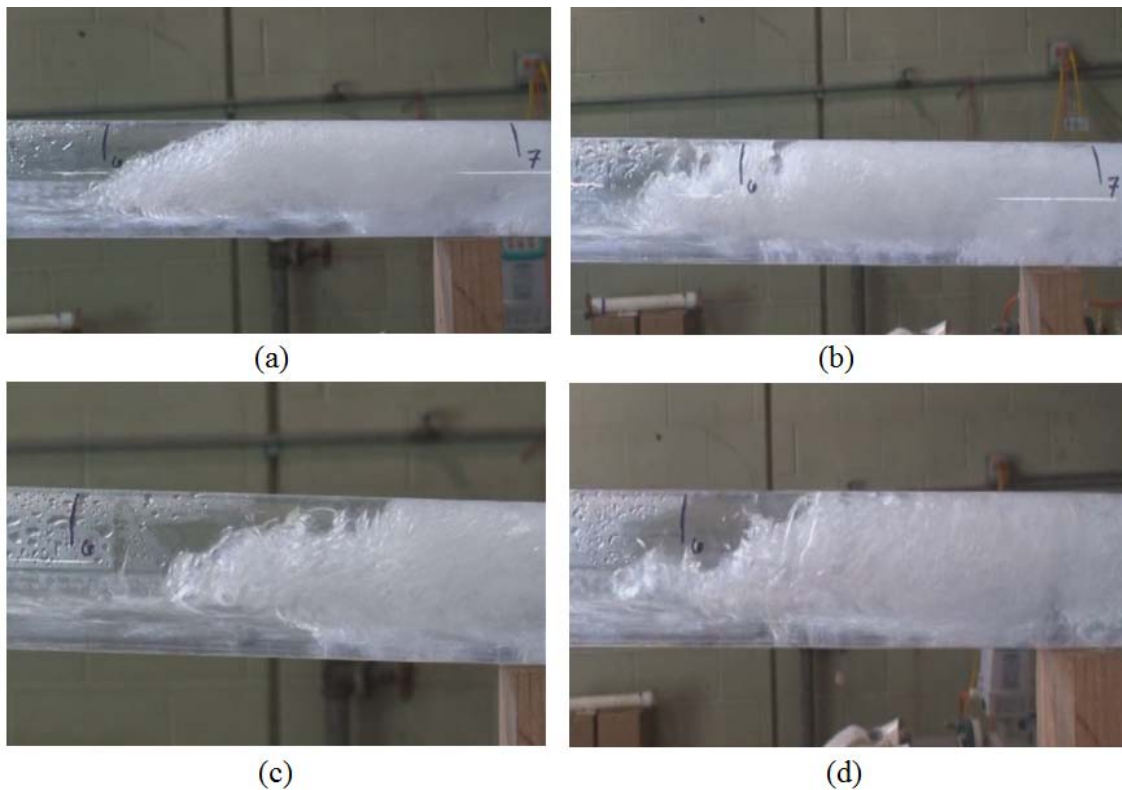
Figure 6 Difference in air bubble size between (a) 12.8°C, (b) 29.4 °C, (c) 48.9 °C and (d) 62.8 °C

Several factors may have contributed to the uncertainty and spread of the data. These factors come from natural and experimental causes. First, the natural process of air entrainment in a hydraulic jump is very unstable and erratic which is a significant cause of the spread of the data. Additional uncertainty was introduced by estimating the depth

of the supercritical flow calculating a GVF profile. Depths were not steady as also mentioned in Kalinske and Robertson's (1943) study which also showed spread in their data. Also, jump location and air demand oscillated about a mean value as previously mentioned. Data points that were repeated several times with two anemometers and a 10 minute average (average of 600 velocity readings) produced similar results as the 3 minute average. While the results were similar, some uncertainty due to the anemometer instrumentation was observed.

Despite the uncertainty of the data, definite trends and similarities were confirmed. Tests in which data was collected for a longer period of time showed no significant change of air demand or water depth over time. Data from these repeated runs added confidence that the measured average air demand and estimated Froude number are accurate representations of the actual values. They also showed that the air demand trends were repeatable and consistent, despite the erratic nature of air entrainment at hydraulic jumps which was the greatest source of uncertainty.

5   Discussion

5.1 Size-scale Effects

Results from the size-scale effect data show that for closed conduit flow, air demand is not affected by pipe size. The data suggest that the absence of scale effects between the different pipe model sizes was due to the confined flow downstream of the hydraulic jump in which the air could not be immediately released from the flow. This was true even when the downstream pipe was partially filled with air when multiple hydraulic jumps occurred in series, similar to Kalinske and Robertson's (1943) experiment. Also, a correlation was found of results from different pipe sizes to Kalinske

and Robertson's curve (Fig. 3). They did not indicate in their study where any of the

jumps occurred relative to the end of the pipe. The deviation from their curve,

particularly at lower Froude numbers, may be due to the close location of the hydraulic

jump to the end of the pipe. Also, Kalinske and Robertson did not indicate the

temperature of the water or if it was held constant for each run which may account for

slightly higher air demand results of this study in comparison to their curve.

The greater air demand that occurred when the hydraulic jump is located too near

the end of the pipe suggests that air entrainment is dependent on the extent that the

hydraulic jump is contained within the pipe. In other words, the jump's location relative

to the point of air release downstream. For jumps 15 – 20 pipe diameters or closer to the

end of the pipe, air entrainment was dominated by the jump not being fully contained in

the pipe, despite the relatively low Froude number for these tests. This may be due to

reducing the length characteristics of the jump, or allowing the downstream end of the

jump roller to occur within the air capture chamber which would allow more air to be

freely released from the flow (Hager *et al*., 1990). The presence of scale effects for

jumps near the chamber suggests that size scaling effects may exist when the air is freely

released from the jump. This finding is consistent with Chanson's (2008a, 2008b, 2007,

2006) work on scale effects of open channel hydraulic jumps in which the air can be

immediately released from the flow into the atmosphere.

5.2 Temperature Effects

Significant temperature effects on air entrainment were detected when water

temperature was varied (Fig. 5). Since greater Reynolds numbers result from higher

temperatures one would expect greater air entrainment rates due to the increased turbulence of the hydraulic jump as Chanson (2008b) described for open channel flow hydraulic jumps. However, the opposite occurred when the jump was confined in a closed conduit resulting in decreased air entrainment with increased water temperatures. This may be explained by a visual inspection of the air bubbles entrained into the hydraulic jump.

The bubbles within the air-water mixture expanded within the hydraulic jump and were visually larger as temperature increased. Consequently, there was less breakup of the larger air bubbles limiting the amount of air that could be entrained and passed downstream. This may have been because of greater surface tension due to the increased Weber number and surface area of the air bubbles. Also, the buoyant force is greater on a bubble with more surface area which would keep it up in the recirculation region of the jump roller, preventing it from being passed downstream. Also, air is less soluble in water at higher temperatures. However, the majority of the air did not go into solution but was passed downstream as air bubbles which rose to the pressurized air pocket at the crown of the pipe.

This trend of decreased air demand continued for rising temperatures even though Reynolds and Weber numbers increased and Froude numbers remained the same for each temperature. Photographs show a gradual increase of bubble size with temperature (Fig. 6). The visual inspection suggests that air entrained by a hydraulic jump is dependent on the size of the air bubbles entrained into the flow.

6 Summary and Conclusions

Measurements were taken of air entrainment rates into four different sized pipe models with similar Froude numbers and compared to identify any scaling effects. Additional air entrainment measurements were taken at different water temperatures to determine if changing water properties would affect the amount of air entrained into a hydraulic jump. Results showed that the percentage of air entrainment was not affected by the size of the pipe model. However, results from the model with different water temperatures showed that air entrainment decreases significantly with increasing temperatures.

From the comparison of air entrainment within the different sized models it may be concluded that when the air is not immediately released downstream of the hydraulic jump, the air demand is not dependent on the size of the conduit. Even though a larger jump has more turbulence, it cannot entrain a greater percentage of air because the air leaving the jump is not freely released and the fluid reaches a certain carrying capacity. It can further be concluded that air entrainment is dependent on the jump's location relative to the point of air release on the downstream side of the hydraulic jump. When the jump was near an air capture chamber, the air demand increased and scale effects were detected between the different models. This is possibly due to the air being more freely released from the hydraulic jump similar to open channel jumps which is in accordance with Chanson's work.

After visually inspecting the air demand of different water temperatures, it was concluded that air bubble size greatly affects the air demand of the hydraulic jump. Higher water temperatures caused the air-water mixture to expand, forming larger air

bubbles. Consequently, larger air bubbles led to less breakup of the entrained air, causing less air entrainment into the jump even though the Reynolds number had increased.

The findings from this study provide new insights into air entrainment processes of hydraulic jumps within closed conduits. The absence of size-scale effects of air entrained into hydraulic jumps in closed conduit flow should aid the practicing engineer in predicting air entrainment rates for design purposes. Also, in addition to the other factors that influence air entrainment, water temperature should be considered when predicting air entrainment of hydraulic jumps.

CHAPTER III

THE EFFECTS OF HYDRAULIC JUMP LOCATION ON AIR ENTRAINMENT IN

CLOSED CONDUITS[2]

ABSTRACT

While there has been a great deal of research on air entrainment at hydraulic

jumps within closed conduits, very little of the research has specifically addressed how

the jump's location from the point of downstream air release may influence the amount of

air it can entrain. To determine the significance of the effects of jump location on air

entrained by hydraulic jumps in closed conduits, air flow measurements were taken in a

7.62-cm circular pipe with two different air release configurations at the end of the pipe.

Results showed that for both configurations the percentage of air entrainment was

significantly affected by the hydraulic jump's proximity to the point of air release

downstream. As the hydraulic jump occurred closer to the air release at the end of the

pipe air entrainment increased because characteristic lengths of the jump were shortened

allowing more air to be freely released. However, this was only a significant factor until

the jump occurred some distance upstream where it was then dependent only on the

Froude number immediately upstream of the jump.

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[2] Coauthored by Steven L. Barfuss, P.E., and Blake P. Tullis, Ph.D., P.E.

1 Introduction

Often in closed water conveyance systems a hydraulic jump will occur at a transition from open channel to pressurized flow due to elevation changes or other occurrences which cause the hydraulic grade line to be greater than the pipe diameter. A hydraulic jump will entrain air into the flow due to its high level of turbulence at the air-water interface. Knowledge of the amount of air entrained by a hydraulic jump is important for the proper design of pipelines, dam low-level outlet works, and other such conveyance systems requiring air venting. Past studies have shown that the rate of air entrained and passed downstream by the hydraulic jump, or air demand of the jump within closed conduits is dependent on many factors, including; Froude number, flow and exit conditions, jump and conduit geometry and jump location relative to the air supply. However, no studies were found that specifically addressed how the location of the jump in closed conduits relative to the point of air release downstream influences the rate of air entrainment. It is suspected that the location of the hydraulic jump relative to the point of downstream air release may affect the characteristics lengths of the jump which may also influence the air demand of the jump.

The objective of this study was to investigate how air entrainment rates are influenced by changing a hydraulic jump's characteristic lengths due to its proximity to the point where the air is released from the flow. To accomplish this, air flow measurements were made in conjunction with hydraulic jumps that completely fill the conduit (open to pressurized flow) located at various positions within a circular pipe. The measurements were made with two different air release structures at the end of the pipe, one a pipe expansion with an air vent and the other an open tank to determine if

vented or free air release influences the amount of air entrained. Jump location was

defined by the distance from the jump toe to the end of pipe for each air release test

configuration. The results from this study are important because length characteristics

are suspected to influence air entrainment within a hydraulic jump and specific studies

are not found in the literature. It is expected that these findings will give greater insight

into air entrainment processes and will be valuable for system design.

2   Literature Review

Kalinske and Robertson (1943) conducted some of the very first experiments of

air entrainment within circular pipes by measuring air entrainment rates at hydraulic

jumps at open channel to pressurized flow at various slopes from 0 to 16.7 degrees. Their

results showed that air demand varied only with the Froude number immediately

upstream of the jump. Additionally they found that air demand was not dependent on the

slope of the pipe. From their data they developed the following air demand relationship

$$\beta = \frac{Q_{air}}{Q_{water}} = 0.0066(Fr - 1)^{1.4} \tag{1}$$

In Eq. (1) β is the volumetric ratio of the air flow to water flow and Fr is the Froude

number immediately upstream of the jump with Fr defined as follows

$$Fr = \frac{V}{\sqrt{gy_e}} \tag{2}$$

In Eq. (2) g is the acceleration of gravity, V is the approach velocity and y_e, the effective

depth, is the water area divide by the surface width upstream of the jump.

Others have built upon Kalinske and Robertson's pioneering work by performing

similar air entrainment experiments of closed conduit flow. Sharma (1976) collected air

demand data in a lab-scale rectangular conduit model with a vertical gate under high

upstream head conditions for many different flow scenarios, including a hydraulic jump

that fills the conduit. After comparing his results to prototype data he determined that

Kalinske and Robertson's equation (Eq. 1) underestimated the air entrained by a

hydraulic jump in the prototype when the jump occurred at a considerable distance from

the gate. He claimed that prototype air demand was larger due a "pre-entrained"

hydraulic jump which pumps additional air that was entrained into the more turbulent

upstream supercritical flow. Sharma's research indicates that distance to a jump and

water surface roughness upstream of the jump may influence air entrainment and should

be accounted for when measuring air entrainment rates.

Wisner *et al.* (1975), Rajaratnam (1967), and Rabben *et al.* (1983) also developed

air demand relationships for hydraulic jumps. Escarameia (2007) compared the air

demand relationship from her results to those found by Kalinske and Robertson (1943),

Wisner *et al.*, Rajaratnam, and Rabben *et al.*. This comparison showed significant

differences of air demand between the various experiments which may be due to

differences in conduit geometry as well as downstream flow and exit conditions.

Escarameia's comparison with other studies shows that many factors may influence air

entrainment and great care should be taken to recognize the effect of each factor.

For hydraulic jumps in open channel flows Chanson (2008a, 2008b, 2007, 1995) has extensively studied air entrainment. Chanson showed that in addition to *Fr*, *Re* and *We* numbers also significantly influence air entrainment rates of hydraulic jumps. Chanson's studies may also be helpful in understanding air entrainment of closed conduit hydraulic jumps.

Hager *et al.* (1989, 1990) studied characteristics of a classical hydraulic jump in a rectangular channel and observed a turbulent recirculation region in which unsteady flow reversals occurred. This region from the toe to the stagnation point was defined as the surface roller length (*Lr*). It was observed that air bubbles intensively rise at the downstream end of the roller. Hager also defined the aeration length (*La*) of an open channel hydraulic jump (Fig. 7) as the length from the toe to the point where all the air bubbles have risen to the surface (Chanson, 1995). Later Stahl and Hager (1999) observed that in a circular pipe when the upstream depth is greater than 1/3 of the pipe diameter, a hydraulic jump is similar to the classical hydraulic jump with a turbulent surface roller. While these definitions do not address rates of air entrainment, they may be helpful to understand characteristics lengths and air entrainment or detrainment processes of a hydraulic jump that completely fills a closed conduit.
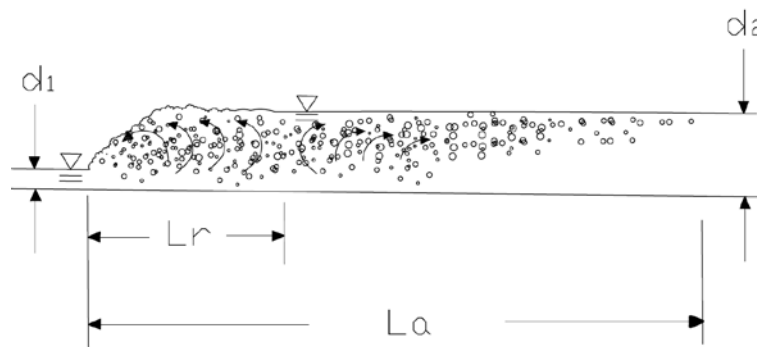

Figure 7 Schematic of open channel hydraulic jump roller (*Lr*) and aeration (*La*) lengths

3   Experimental Setup and Procedure

An experimental study was conducted in order to investigate the specific influence of altered hydraulic jump characteristic lengths due to location on air entrainment of jumps in closed conduits. Air entrainment rates were measured in an acrylic circular pipe with an inside diameter of 7.62 cm and a length of 8 m. The model was set at a 4% downward slope. Air entrainment rates were obtained using a model A031 Kanomax hot-wire anemometer to measure air velocities through a 6.35 cm diameter air intake located at the upstream end of the pipe (Fig. 8). Pressure drop readings across the inlet of the air intake confirmed that it was sufficiently large to not limit the air flow. Water flow rates approaching the pipe model were measured using a calibrated Siemens magnetic flow meter.

Water entered the conduit test section through a flow nozzle which created an open channel flow condition with a smooth water surface (Fig 8). Primarily, the flow nozzle eliminated the possibility for air entrainment near an upstream control valve or slide gate which would create spray and disturb flow at the upstream end. Downstream of the flow nozzle a gradually varied flow surface profile formed until a hydraulic jump occurred downstream. At the end of the pipe the water flowed through a larger diameter cylindrical air capture chamber with an air vent near the upstream top to allow the free air to be released from the flow (Fig. 8a). A hydraulic jump was forced to occur at a desired location by adjusting a control valve downstream of the chamber. Tests were repeated using an open rectangular tank at the end of the pipe with a slide gate to control the jump location (Fig. 8b). The air entrained by the jump was measured as it entered the system through the acrylic intake inserted just downstream of the flow nozzle.
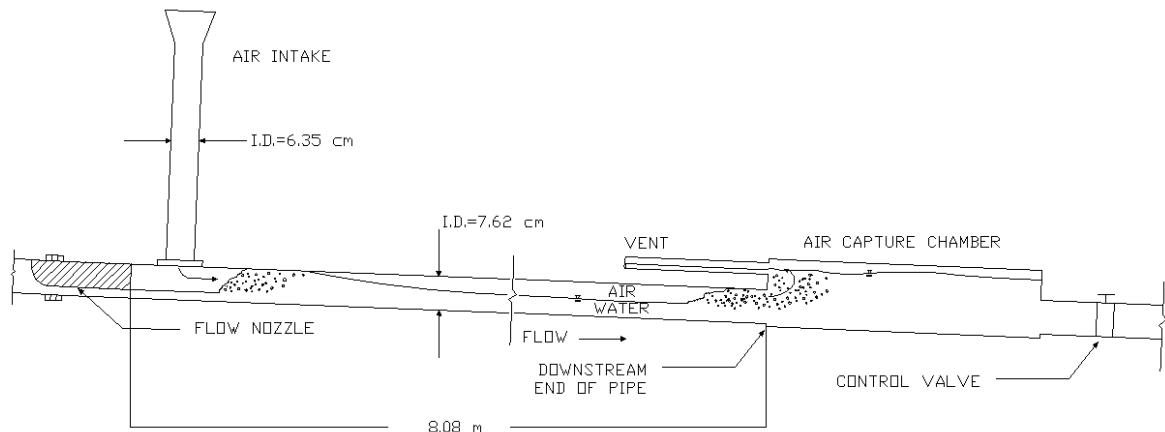
(a)
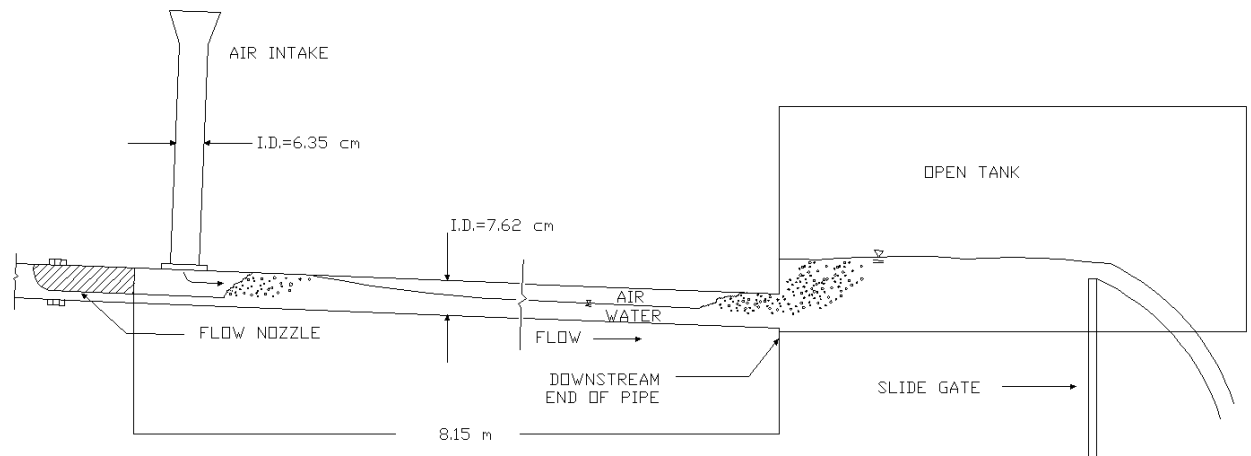
(b)

Figure 8 Cylindrical Air Capture Chamber (a) and Open Tank (b) air release
configurations

Froude numbers immediately upstream of the jump were obtained by measuring
the depth and velocity of the upstream supercritical flow. Due to the difficulty in
acquiring an accurate depth measurement inside the pipe, Gradually Varied Flow (GVF)
profiles of the open water surface were used to estimate the depth. Approximate visual
measurements from the outside of the pipe were also made to validate this method.

Velocities were obtained by conservation of mass using the known flow rate and water surface depth.

Once the hydraulic jump stabilized at the desired location, the air entrainment for each run was quantified by averaging a three minute sample (180 readings) of air velocity at the air intake and then calculating the volumetric air flow rate (Q_{air}). The volumetric ratio of air to water, or air demand, was then calculated (Eq. 5) and compared to the upstream Froude number. The location of the hydraulic jump was defined by the distance from the toe of the jump to the downstream end of the pipe.

$$\beta = \frac{Q_{air}}{Q_{water}}(100)$$ (5)

To ensure accuracy and repeatability, selected runs were repeated using two identical anemometers and allowing data to be collected for up to ten minutes (600 readings). Also, to determine if a rough upstream water surface would increase air demand by causing a pre-entrained hydraulic jump as described by Sharma (1976), selected runs were repeated using a roughened flow nozzle.

4 Results

Figure 9 is a comparison to Kalinske and Robertson's (1943) study which shows air demand of a hydraulic jump vs. the upstream Froude number. It includes results from both air release structures and shows that the air demand was dependent only on Froude number except when the jump occurred too near the end of the pipe. For this particular pipe and GVF profile, the Froude numbers decreased as the flow approached the pipe exit. The largest aeration length observed was about 17 pipe diameters. When the jump

toe occurred closer than 17 pipe diameters from the end of the pipe, the downstream end

of the jump was not contained in the pipe and air entrainment increased despite the

Froude number, causing the vertical trend. When the jump toe occurred further upstream

than 17 pipe diameters the full length of the jump was contained in the pipe and flow

conditions similar to Kalinske and Robertson's findings were observed. No significant

differences in air demand results were found between the air capture chamber and open

tank except when a jump occurred within 2 diameters of the end of the pipe at which

point a greater amount of air was entrained into the open tank configuration. A turbulent

roller was observed within the hydraulic jumps where much of the air was rising within

the jump at the downstream end of the roller, similar to Hager's (1990) description.
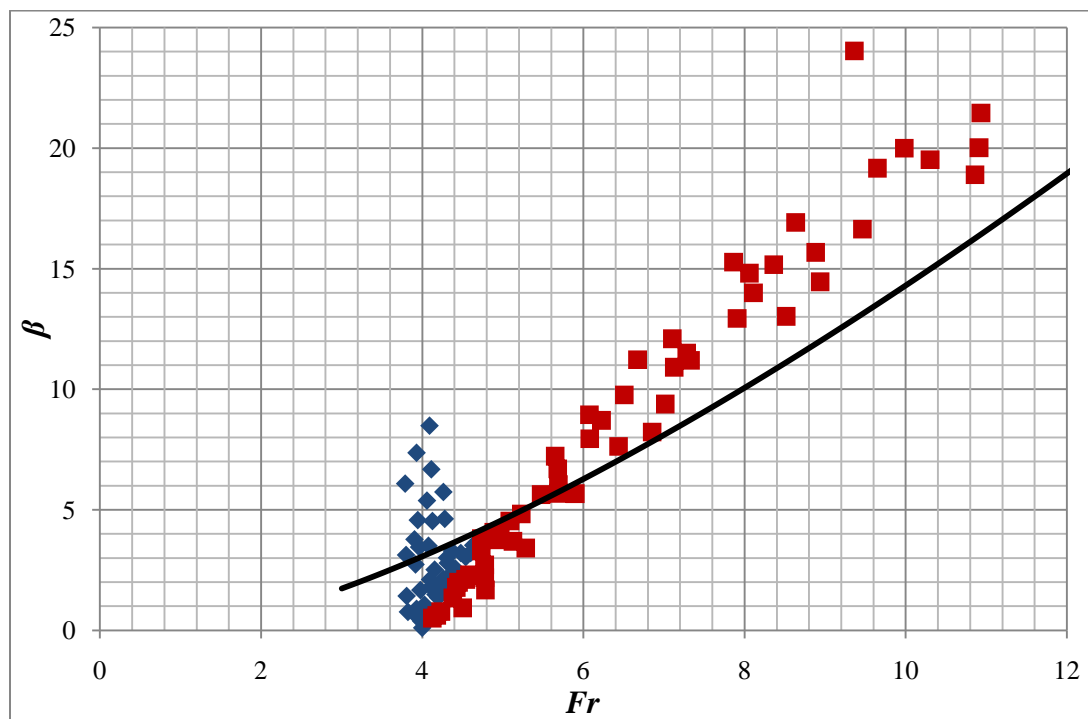

Figure 9 Air demand vs. Froude of jumps located less than 17 diameters (♦), greater than

17 diameters (■) from the end of the pipe and Kalinske and Robertson's curve (solid line)

Roller lengths (Lr) of 4 to 5 pipe diameters were observed as well as aeration lengths (La) of 13 to 17 pipe diameters depending on the Froude number. Lr and La had similar hydraulic characteristics as the classical open channel hydraulic jump but differed in length. Results showed that altered characteristic lengths directly influenced the jump's air demand.

Three separate cases of altered jump characteristic lengths were identified as well as their specific influence on the air demand of the hydraulic jump. Each case is illustrated in Figure 10 which defines Lj as the distance from the jump toe to the end of the pipe, La as the original (undisturbed) aeration length, and Lr as the original (undisturbed) jump roller length.

Case 1: $Lj > La$; the full length of the hydraulic jump is fully contained within the conduit. Characteristic lengths are unchanged and air demand is dependent on Froude number only.

Case 2: $La > Lj > Lr$; the actual aeration length is shortened by the end of the pipe. Air entrainment increases despite Froude number.

Case 3: $Lr > Lj$; the actual roller length is shortened by the end of the pipe. Air demand greatly increases and is dominated by this feature. Froude number is not significant.
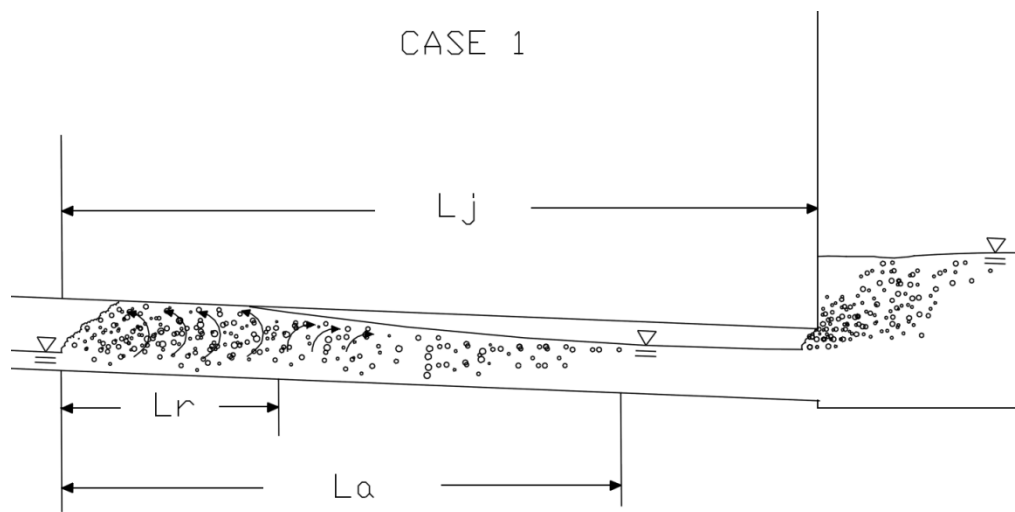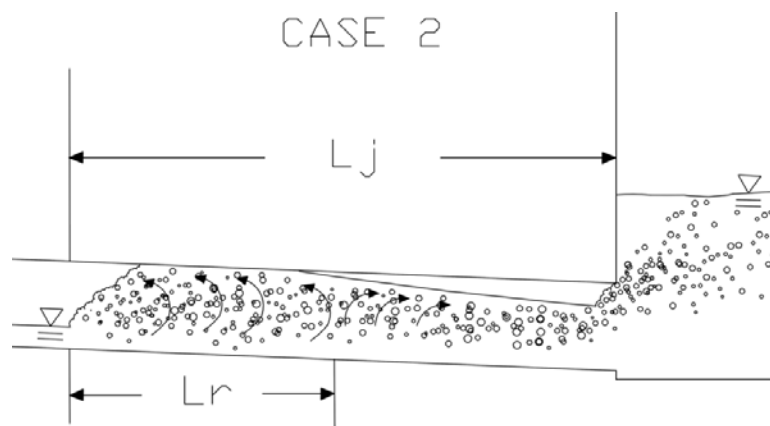
Figure 10 Cases of altered characteristic lengths; Case 1 (a), Case 2 (b), and Case 3 (c)

Figure 11 illustrates how air demand was influenced by the distance (*Lj/La*) of the jump toe from the end of the pipe. The three data sets are different water flow rates that were tested. The greater flow rates naturally have higher Froude numbers which correlate to greater air entrainment which is most apparent in Case 1. The alignment of flow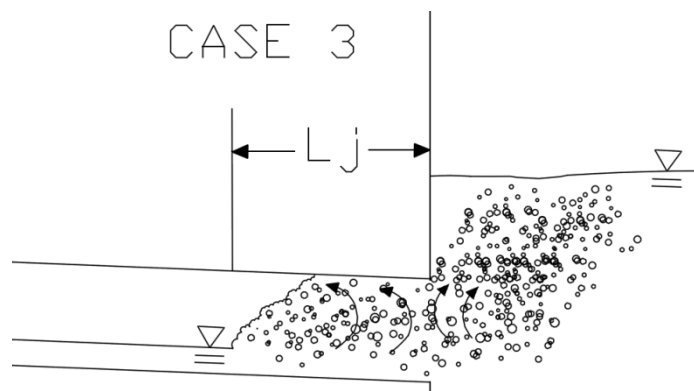 rate trends as the jump moves closer to the end of the pipe (right to left) indicates that the Froude number is no longer a significant influence because the characteristic lengths of the jump have been shortened. There is no significant change in air demand until Case 3 which shows a drastic increase of air demand as the jump occurred closer to the pipe exit. The line separating Case 3 and Case 2 corresponds to the original roller lengths of the jumps tested. Similarly, the line between Case 2 and Case 1 corresponds to the original aeration lengths.
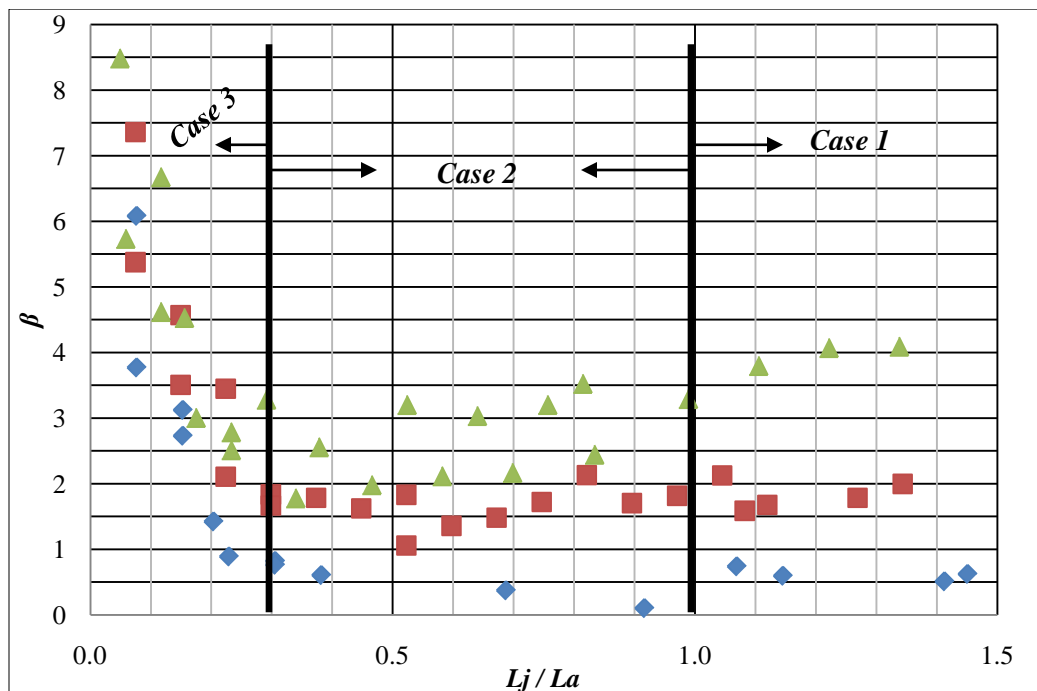
Figure 11 Air demand vs. distance of the jump from the end of the pipe for (▲) 5.0 l/s, (■) 4.4 l/s, and (◆) 3.8 l/s

Figure 12 is a visual illustration of Cases 2 and 3. For Case 2 (Fig. 12a), the jump toe occurred 10 diameters from the end of the pipe which allowed the full roller to form. However, since a fully formed aeration length would be about 17 diameters for this condition, it was cut short by the end of the pipe causing slightly increased air demand. For Case 3 (Fig. 12a), the roller length, which is about 4-5 diameters when fully developed, was cut short and the increase in air demand was even more significant. Air demand continued to increase as the toe of the jump occurred closer to the end of the pipe.
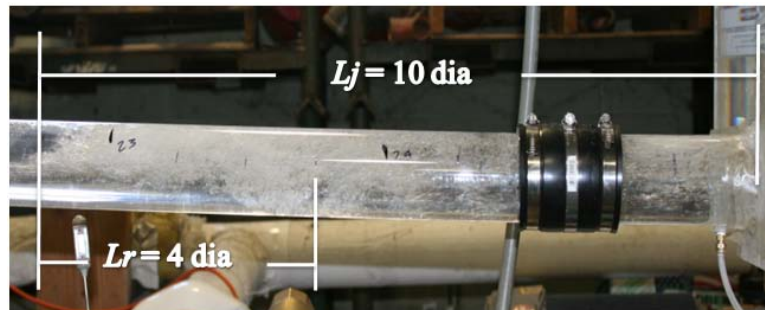
(a)
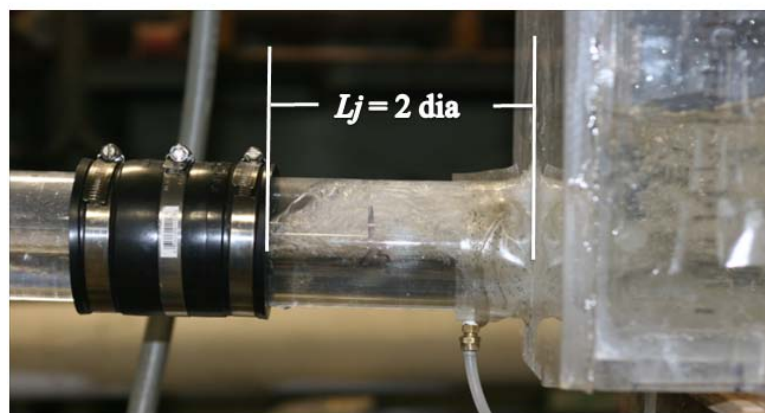
(b)

Figure 12 Photographs of hydraulic jump Case 2 (a) and Case 3 (b)

Using the roughened flow nozzle, there was no significant difference in air demand results. The supercritical flow upstream was visually roughened but air entrainment rates were similar to the runs using the smooth flow nozzle. This indicates that the hydraulic jump itself dominated the air entrainment rate and that the roughened water surface entrained very little air in comparison.

Several factors may have contributed to the uncertainty and spread of the data. These factors come from natural and experimental causes. First, the natural process of air entrainment in a hydraulic jump is very unstable and erratic which is a significant cause of the spread of the data. Additional uncertainty was introduced by estimating the depth of the supercritical flow calculating a GVF profile. Depths were not steady as also mentioned in Kalinske and Robertson's (1943) study which also showed spread in their data. Also, jump location and air demand oscillated about a mean value as previously mentioned. Data points that were repeated several times with two anemometers and a 10 minute average (average of 600 velocity readings) produced similar results as the 3 minute average. While the results were similar, some uncertainty due to the anemometer instrumentation was observed.

Despite the uncertainty of the data, definite trends and similarities were confirmed. Tests in which data was collected for a longer period of time showed no significant change of air demand or water depth over time. Data from these repeated runs added confidence that the measured average air demand and estimated Froude number are accurate representations of the actual values. They also showed that the air demand trends were repeatable and consistent, despite the erratic nature of air entrainment at hydraulic jumps which was the greatest source of uncertainty.

5   Discussion

For both air release configurations results of air demand vs. Froude number correlated with Kalinske and Robertson's (1943) results when the hydraulic jump was greater than 17 diameters from the end of the pipe. It is not indicated in the Kalinske study the location of hydraulic jumps in relation to the end of the pipe or if the jump's characteristic lengths were changed. Although the Kalinske data does indicate a greater spread at lower Froude numbers, the spread in the present data at lower Froude numbers is due to the changing of the hydraulic jump's characteristic lengths because of its location near the end of the pipe.

As shown in Figures 10 and 11, three separate cases of altered characteristic lengths were identified. In Case 1 the characteristic lengths of the jump were allowed to fully form and are completely contained within the pipe. For this case, the flow reached a certain carrying capacity due to the pressurized air pocket that formed at the crown of the pipe. Air demand was dependent on the Froude number only. For Case 2, La was cut short and less air downstream of the jump was confined to the pressurized air pocket at the crown of the pipe. This may have caused the slight increase in air demand for this condition. However, there was not a significant difference of air demand in Cases 1 and 2.

Case 3 was the most interesting because of the drastic increase of air demand compared to Cases 1 and 2. Due to Lr being shortened, the portion of air that was normally re-circulated by the reversed velocities within the roller was instead passed downstream. Since a great deal of air bubbles rise at the downstream end of the roller as described by Hager *et al.* (1990), this caused a significant increase in air demand despite

the low Froude number. The closer the jump toe occurred to the end of the pipe, the greater amount of air was allowed to short-cut through the jump and was released at the end of the pipe. The characteristic lengths of each jump were estimated by observation only. To date, there is no mathematical relationship that can accurately predict these lengths for the specific case of a hydraulic jump that completely fills a circular conduit. The definition of such a relationship may be a source of future research.

There was no significant increase in air demand during the tests with a roughened upstream water surface, which is not consistent with the results from Sharma's study. This may be due to pipe scale size, upstream approach length differences and/or physical disturbances near the upstream control gate. Again, this study installed a hydraulically smooth nozzle at the upstream end to eliminate all disturbed flow allowing for the relationship of hydraulic jump characteristics and location to air demand to be much more accurately understood.

6   Summary and Conclusions

Measurements were taken of air entrainment rates into a circular pipe with two different air release configurations at the end of the pipe. The results of both air release configurations showed that air entrainment rates were greatly influenced by altered jump length characteristics due to the jump's location to the downstream air release point. Three cases or conditions were identified to show how characteristic lengths were altered by the location of the jump relative to the end of the pipe.

The first case was when the jump occurred far enough away from the end of the pipe that the length characteristics were not affected. For this condition, the air demand of the jump was dependent only on the Froude number as shown by Kalinske and

Robertson (1943). In the second case the jump occurred close enough to the end of the pipe to shorten the aeration length of the jump. For this specific study, this occurred if the jump toe was closer than 17 pipe diameters from the end of the pipe. In this condition not all of the air downstream of the jump was confined to the air pocket at the crown of the pipe and air demand slightly increased despite the Froude number.

The third case occurred when the jump was close enough to the end of the pipe to shorten the jump roller. For this condition the air that was normally re-circulated within the jump roller was passed downstream and the air demand increased significantly. Since the downstream end of the roller was no longer confined within the pipe the air was freely released from the jump. These results correspond with Hager's (1990) observations of air bubbles intensively rising at the downstream end of the jump roller.

The findings from this study provide new insights into additional factors which influence air entrainment of hydraulic jumps within closed conduits. Understanding how a hydraulic jump's length characteristics are affected by the location to a downstream air release and its effect on air demand should aid the practicing engineer in predicting air entrainment rates for design purposes.

CHAPTER IV

SUMMARY AND CONCLUSIONS

In order to predict air entrainment rates of hydraulic jumps within a future prototype pipeline, the Utah Water Research Laboratory performed a physical model study to obtain results from four different sized circular pipes. The data from these tests helped determine the significance of size-scale effects and use the air demand prediction to optimize the design of the prototype air release structure. Additional research was conducted to determine the significance of water temperature effects on air entrainment of hydraulic jumps. Hydraulic jump location from the air release point and its effects on jump characteristic lengths and air demand was also investigated by obtaining data from a circular pipe with two different air release structures. Test results for each of these factors were obtained and conclusions made.

Results from the size-scale effect data showed that air demand was not affected by the size of the pipe. This was true as long as the jump occurred far enough upstream from the air release structure so the free air would not be immediately released from the flow. From the comparison of data from different sized pipes it may be concluded that when the air is not immediately released downstream of the hydraulic jump, the air demand is not dependent on the size of the conduit. Even though a larger jump has more turbulence, it cannot entrain a greater percentage of air because the air leaving the jump is not freely released and the fluid reaches a certain carrying capacity.

Temperature results showed that the air demand was significantly affected by the water temperature. The data confirmed that the jump was able to entrain less air with

higher water temperatures. After visually inspecting the air demand of different temperatures, it was concluded that air bubble size greatly affects the air demand of the hydraulic jump. Higher water temperatures caused the air-water mixture to expand, forming larger air bubbles. Consequently, larger air bubbles led to less breakup of the entrained air, causing less air to be entrained into the jump even though the Reynolds and Weber numbers had increased. Surface tension and buoyancy of the larger bubbles may have also influenced how air was passed downstream through the jump.

Data from various hydraulic jump locations showed that air demand significantly increased when the jump occurred close enough to the end of the pipe to change its hydraulic length characteristics. If the toe of the jump occurred at a distance less than its roller length (Lr) air demand drastically increased (Case 3). Visual observations suggest this increase was due to the downstream end of the roller, where much of the air rises to the surface, being cut short by the end of the pipe which allowed the air to be immediately released from the flow. Similarly, if the jump occurred at a distance less the aeration length of the jump (La) the increase in air demand was significant but not as drastic (Case 2). It was concluded that this was due to the aeration length of the jump being shortened by the end of the pipe where the air bubbles were still rising and were not confined by the downstream flow. If the jump occurred further upstream than its aeration length, the free air that rose to the surface was confined to a pressurized air pocket and the air demand became a function of the Froude number only (Case 1). It may be concluded that air entrainment rates increase as the free air is more immediately released from the flow.

Again, the main objective of this thesis was to determine how air demand of hydraulic jumps in circular closed conduits is affected by the following factors:

- Size-scale effects

- Temperature effects

- Location and altered length characteristic effects

For this purpose physical model studies have been conducted and results documented to provide new insights into air entrainment processes of hydraulic jumps within closed conduits.   It is expected that these results will be useful in aiding the practicing engineer in predicting air entrainment rates and will be valuable for system design.

CHAPTER V

FUTURE RESEARCH

Due to the unstable and erratic nature of air entrainment at hydraulic jumps there is still much that is unknown. Additional research is needed to better understand the processes of air entrained by hydraulic jumps and the factors that influence those processes. Specifically, for the case of a hydraulic jump at a transition from open channel to pressurized flow, additional studies could include the following:

- Comparison of air demand data from prototypes to model results for the same flow conditions, air release structure and pipe geometry as it becomes available

- Additional data from a greater range of temperatures (less than 40 ˚F and greater than 145 ˚F)

- Specific definitions and predictions of hydraulic jump length characteristics (*Lr* and *La*) for jumps that completely fill a circular conduit

- Air release/detrainment mechanisms and processes within a hydraulic jump with pressurized downstream flow

- Dynamics of released air flow through various air removal structures and their impact, if any, on air demand of upstream hydraulic jumps

These suggestions of future studies are related to components that directly influence air entrainment processes through closed conduit hydraulic jumps but were not addressed in the current research. Any insights provided from future research, especially information of how model results compare to prototype results, would be of great value for pipe system design.

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APPENDICES

Appendix A: Photographs of pipe models and air release structures

Figure 13 24-inch pipe model

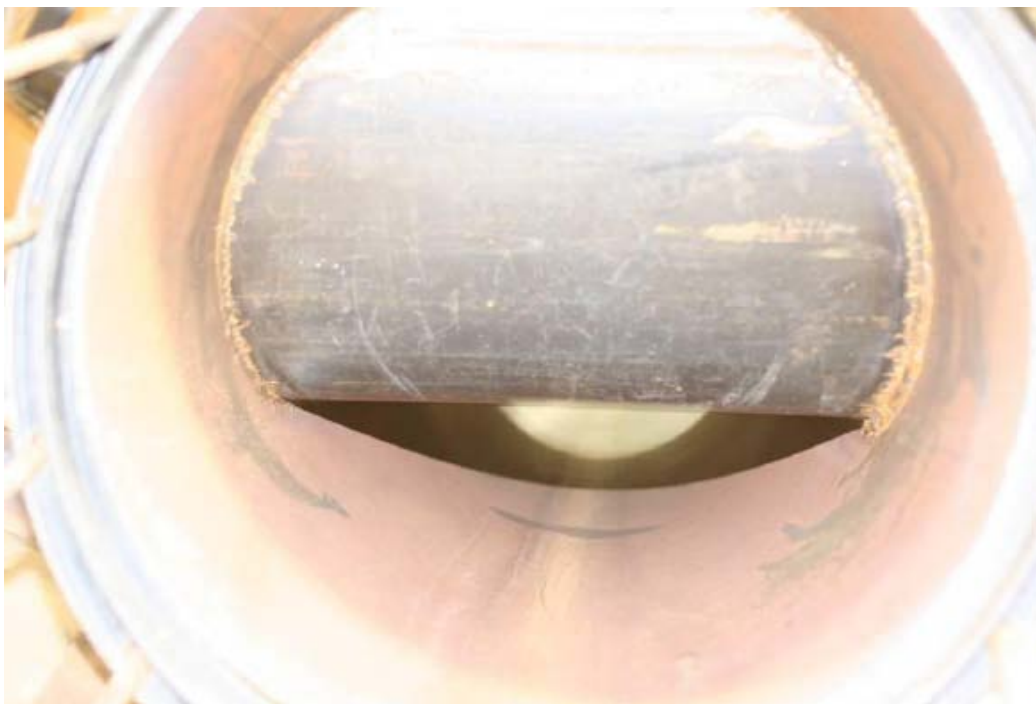Figure 14 24-inch model with air capture chamber and vent

Figure 15 Flow nozzle in the 24-inch pipe model

Figure 16 12-inch pipe model

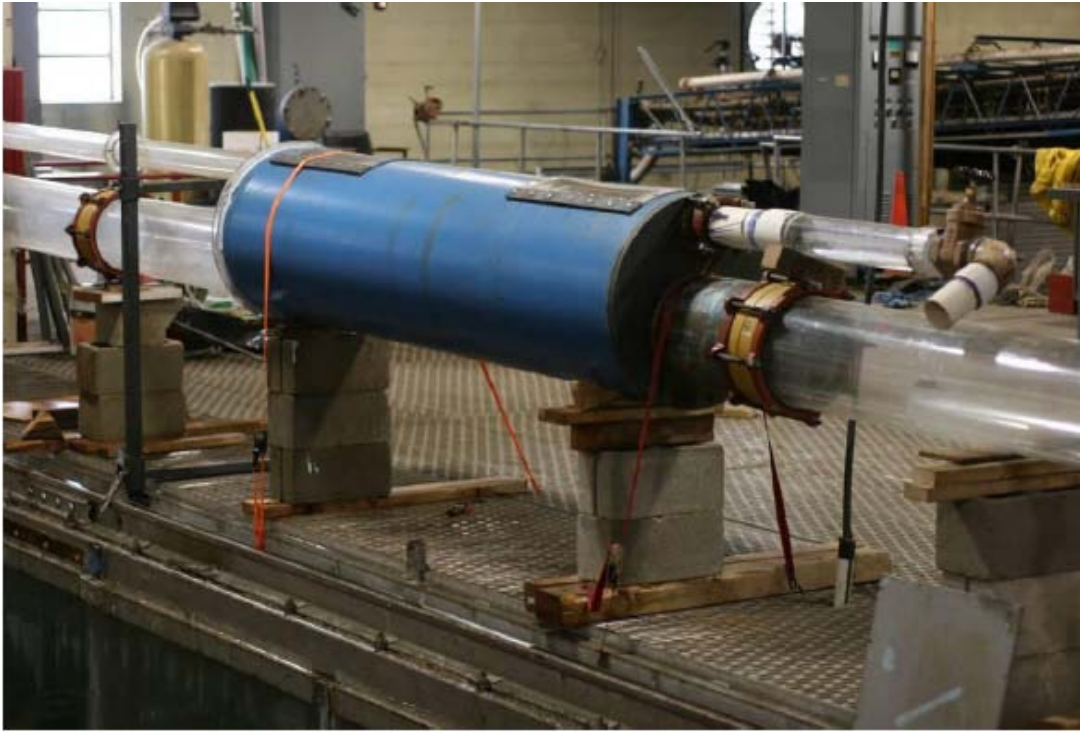Figure 17 12-inch pipe model and air capture chamber with vent

Figure 18 7-inch acrylic pipe model

Figure 19 3-inch acrylic pipe and air intake just downstream of flow nozzle

Figure 20 Air capture chamber and vent on the 3 inch acrylic pipe

Figure 21 Downstream control valve of 3-inch pipe and thermometer for size and

temperature scale tests

Figure 22 Rectangular Open Tank on the 3-inch acrylic pipe

Figure 23 Roughened flow nozzle for rough water surface tests in 3-inch pipe

Appendix B: GVF Spreadsheet and Repeatability Figures

Pipe Dia. =	3	inch		Water Temp =	55	deg F	Dia. of air inlet =		2.5	inch
Flow =	80	gpm		Viscosity =	1.32E-05		sp wt water =		62.4	enter equation
So =	0.042	4%		density =	1.94		Slope of pipe =		4.00	percent
Manning n =	0.008						Slope angle =		2.29	degrees
Flow nozzle:	0.25	25% of diameter								

| Run No.	Distance to hj	depth at jump	Froude @ dist	Approach Velocity	Flow Area	Flow	Velocity in pipe	Reynolds Number	Weber No.	Air inlet velocity	Air inlet Flow	Air vol. flow
	feet	inch		fps	sq-ft	cfs	fps	pipe dia		fpm	cfs	%
	0	0.75	15.53	18.6	0.010	0.178	3.63	352,674	91	10.0	0.01	3.8
	1	0.79	14.09	17.3	0.010	0.178	3.63	328,658	87		0.00	0.0
	2	0.83	12.85	16.2	0.011	0.178	3.63	307,677	84		0.00	0.0
	3	0.86	11.80	15.2	0.012	0.178	3.63	289,227	80		0.00	0.0
	4	0.90	10.88	14.4	0.012	0.178	3.63	272,912	78		0.00	0.0
	5	0.94	10.08	13.6	0.013	0.178	3.63	258,412	75		0.00	0.0
	6	0.97	9.38	12.9	0.014	0.178	3.63	245,471	72		0.00	0.0
	7	1.01	8.76	12.3	0.014	0.178	3.63	233,876	70		0.00	0.0
	8	1.04	8.21	11.8	0.015	0.178	3.63	223,455	68		0.00	0.0
	9	1.08	7.73	11.3	0.016	0.178	3.63	214,062	66		0.00	0.0
	10	1.11	7.30	10.8	0.016	0.178	3.63	205,574	65		0.00	0.0
	11	1.14	6.91	10.4	0.017	0.178	3.63	197,889	63		0.00	0.0
	12	1.17	6.57	10.0	0.018	0.178	3.63	190,917	62		0.00	0.0
	13	1.20	6.25	9.7	0.018	0.178	3.63	184,584	61		0.00	0.0
	14	1.23	5.98	9.4	0.019	0.178	3.63	178,823	59		0.00	0.0
	15	1.26	5.72	9.1	0.020	0.178	3.63	173,576	58		0.00	0.0
	16	1.28	5.50	8.9	0.020	0.178	3.63	168,794	57		0.00	0.0
	17	1.31	5.29	8.7	0.021	0.178	3.63	164,433	56		0.00	0.0
	18	1.33	5.11	8.4	0.021	0.178	3.63	160,454	55		0.00	0.0
	19	1.36	4.94	8.3	0.022	0.178	3.63	156,821	55		0.00	0.0
	20	1.38	4.78	8.1	0.022	0.178	3.63	153,504	54		0.00	0.0
	21	1.40	4.65	7.9	0.023	0.178	3.63	150,475	53		0.00	0.0
	22	1.42	4.52	7.8	0.023	0.178	3.63	147,708	53		0.00	0.0
	23	1.44	4.41	7.6	0.023	0.178	3.63	145,181	52		0.00	0.0
	24	1.46	4.30	7.5	0.024	0.178	3.63	142,874	52		0.00	0.0
	25	1.48	4.21	7.4	0.024	0.178	3.63	140,767	51		0.00	0.0
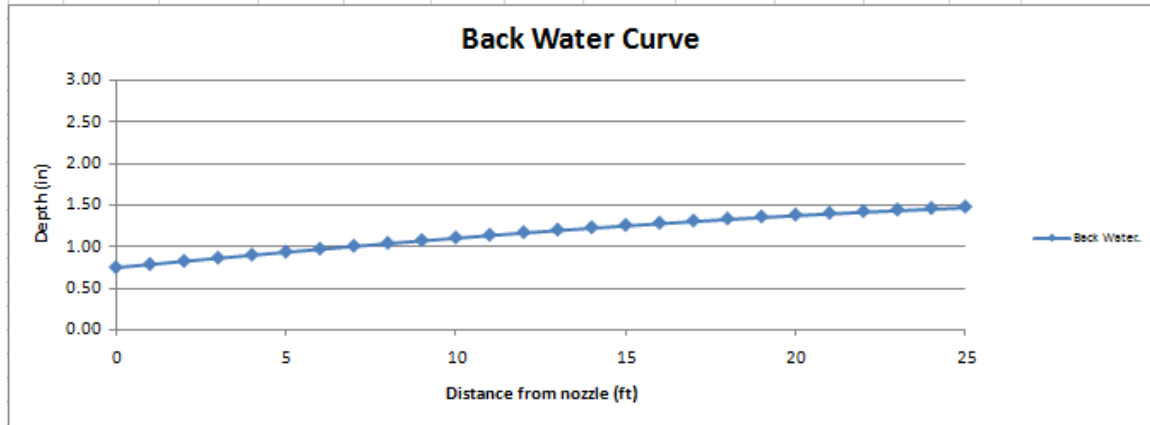
Figure 24 Example of spreadsheet used to calculated distance to jump, Fr, V, Q_{water} and Q_{air} using GVF water surface profiles (red text indicates values entered in spread sheet)
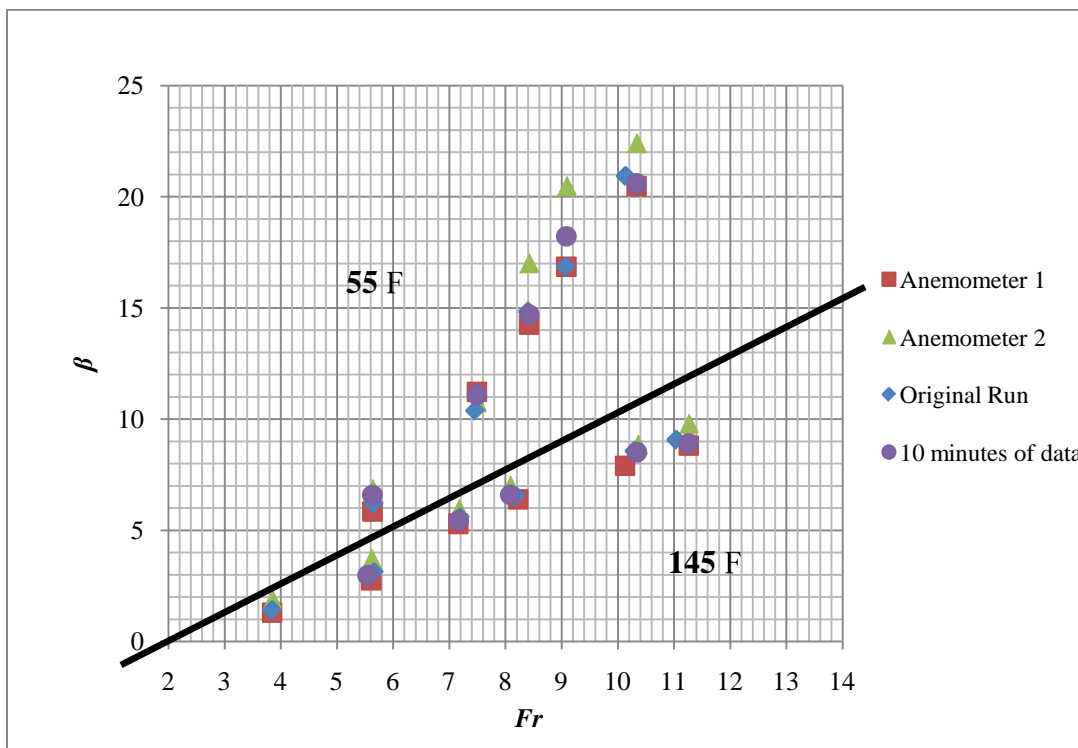
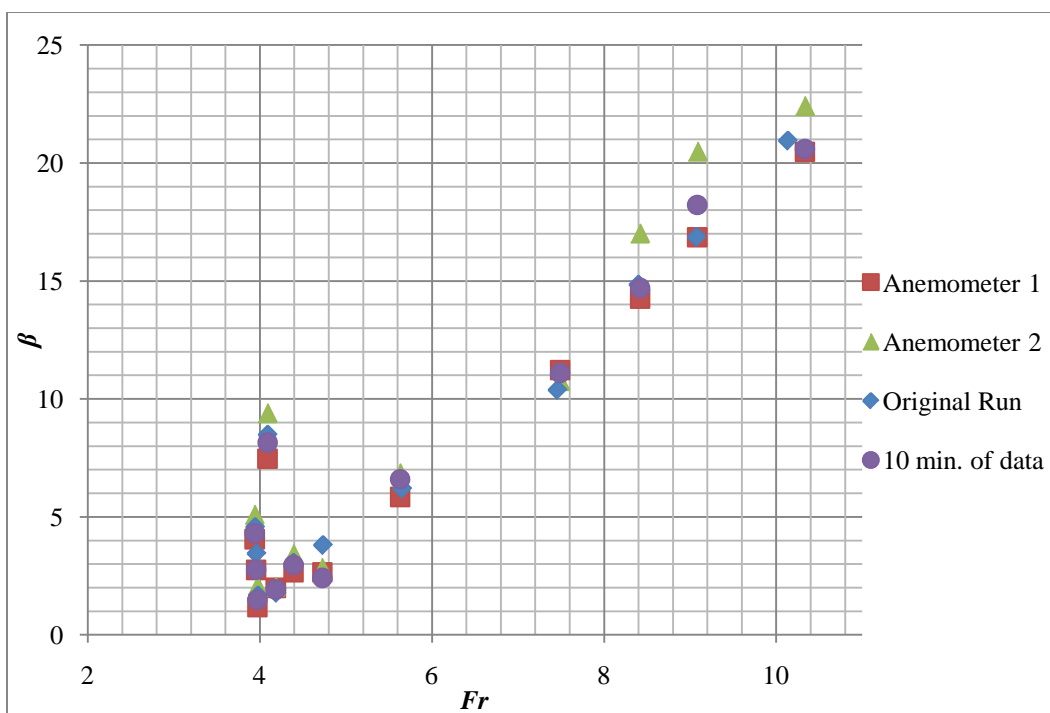Figure 25 Repeated runs for size and temperature tests to ensure repeatability of data

Figure 26 Repeated runs for location tests in open tank to ensure repeatability of data