Proceedings of ASME 2014 International Mechanical Engineering Congress & Exposition
IMECE2014
November 14-20, 2014, Montreal, Canada

IMECE2014-40276

EXPERIMENTAL MEASUREMENTS AND FLOW VISUALIZATION OF WATER CAVITATION THROUGH A NOZZLE

Jeffrey Wilms, Graduate Student
Mechanical & Nuclear Engineering Department
Kansas State University
Manhattan, KS, USA

Terry Beck, Professor
Mechanical & Nuclear Engineering Department
Kansas State University
Manhattan, KS, USA

Christopher M. Sorensen, Professor
Department of Physics
Kansas State University
Manhattan, KS, USA

Mohammad H. Hosni, Professor
Mechanical & Nuclear Engineering Department
Kansas State University
Manhattan, KS, USA

Steven J. Eckels, Professor
Mechanical & Nuclear Engineering Department
Kansas State University
Manhattan, KS, USA

Don Tomasi, Project Manger
D&V Consulting, LLC
Stevensville, Michigan, USA

ABSTRACT

A typical refrigeration loop is composed of an evaporator, compressor, condenser, and an expansion valve. There are many possible refrigerants that can be used, but the physical properties of water make it ineffective in the traditional refrigeration loop. But if water could be used it would have many advantages as it is abundant, cheap, and is safe for the environment. As part of development of a new refrigeration loop using water, flow visualization and cavitation of water through nozzles are being investigated. Cavitation is generally defined as creating vapor from liquid, not through adding heat, but by decreasing the pressure. In a converging/ diverging nozzle as the cross sectional area is constricted the velocity of the flow will increase, decreasing the pressure. Therefore, by flowing water through the nozzle it will cavitate. Transforming liquid into gas requires a certain amount of energy, defined as the latent heat. When a liquid is turned to vapor by an increase in the temperature the latent heat is provided by the heat transfer to the system. As no energy is being added in the nozzle to cause the cavitation, the heat to create the vapor comes from the liquid, effectively causes a temperature drop.

This article presents results for the flow visualization of the water cavitating as it goes through the nozzle. Under different flow conditions and nozzle geometries the cavitation manifested itself in different formations. When gasses were entrained in the water they formed bubbles, creating a nucleation site and moving through the nozzle, called travelling bubble cavitation. In venturi nozzles the cavitation nucleated off of the wall, forming attached wall cavitation. When water flowed out of an orifice, a turbulent water jet was formed which caused vapor to form around it, causing shear cavitation. When the water was rotated prior to the throat of an orifice, the orifice jet expanded radially and formed swirl cavitation.

Keywords: Cavitation, Flow visualization, Vapor, Bubbles, Velocity.

INTRODUCTION

A traditional refrigeration cycle uses a compressor to increase the pressure and temperature of a fluid. The condenser primarily lowers the temperature, as heat is transferred to the environment. Then, the fluid goes through an expansion valve, lowering the pressure and therefore the temperature. Finally, the fluid goes through an evaporator, taking in heat from its surroundings. Figure 1 shows the refrigeration cycle used in the patent that led to this research, where the working fluid is tetraflouroethane (CH2FCF3), referred to as R-134. In this cycle the coefficient of performance is 2.4 [1].

The work presented herein is part of a larger research being conducted investigating the possibility of making an improved refrigeration cycle. Improving the cycle is defined in one of two ways: (1) increasing the coefficient of performance, and (2) utilizing water as a refrigerant. The advantage of increasing the coefficient is cheaper operating costs. The advantage of water is that it is cheap, abundant, and leaks from the system will not harm the environment.

* Jeffrey Wilms is employed by Grundfos Pumps Corp in Olathe Kansas, USA.

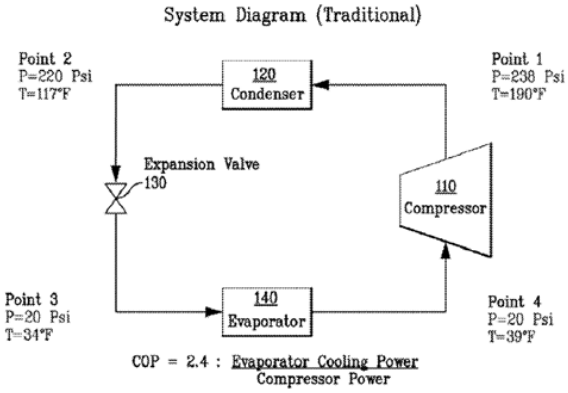

Figure 1 Traditional Refrigeration Cycle [1].

Instead of trying to improve the conventional vapor-compression cycle this project utilizes an alternate method of cooling. The concept from the patent is shown in Figure 2, and features a converging/ diverging nozzle. In the initial concept, the fluid is driven by a piston at the top of the nozzle, although later iterations have a pump driving the fluid through the nozzle [1]. From the fluid dynamics in a nozzle, as the flow is constricted the fluid velocity increases. Then, according to Bernoulli's principle, as the velocity increases, the pressure decreases. The fluid going into the nozzle is liquid, and when the pressure decreases to the vapor pressure some of the liquid turns to vapor. This process is called cavitation and it can cause a decrease in temperature in the fluid. The overall goal of this project is to use this temperature decrease to absorb heat from the surroundings, similar to the evaporator in a traditional refrigeration cycle. The research presented in this article focused on visualizing the flow of the cavitation through various nozzles. As a baseline for cavitation refrigeration development, the visualization of many different nozzles was investigated. Some of these nozzles were further analyzed by measuring the velocity and void fraction of the cavitation.

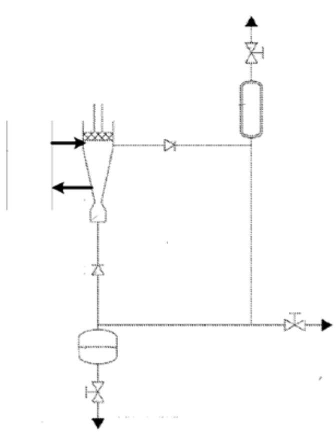

Figure 2 Refrigeration cycle utilizing a converging/ diverging nozzle [1].

Jean-Pierre Franc published a paper detailing cavitation titled "Physics and Control of Cavitation" in Design and Analysis of High Speed Pumps [2]. In this paper he focused on cavitation as it occurred on a hydrofoil. He experimented in depth about how the cavitation was formed, the different formations of cavitation, non-dimensionalized formulas of cavitation, an analysis of cavitation nuclei and its effect on the cavitation, the thermal effects in cavitation, and also the effects of the boundary layer and nuclei content on the cavitation patterns. Cavitation is described as the process of turning a liquid into a gas, not through increasing the temperature, but by decreasing the pressure. With moving flow, this decrease in pressure is facilitated by the Bernoulli equation. In incipient cavitation, it can be predicted that the Bernoulli's equation is still valid. However, in developed cavitation Bernoulli's equation starts to break down as the pressure stays close to the vapor pressure, even while the velocity is increased [2].

Figure 3 shows the four types of cavitation as described by Franc: travelling bubble, attached, vortex, and shear cavitation [2]. In the travelling bubble cavitation, weak points in the liquid, nuclei, grow from being almost invisible microscopic bubbles to being macroscopic bubbles when the pressure drops below the vapor pressure. Once the bubbles reach a region of sufficient pressure they explosively collapse. Attached cavitation is composed of cavities that are attached to the wall in a quasi-permanent manner. The attached cavitation shows variations in the flow pattern, with most of the fluctuations occurring near the end of the cavitation region. In vortex cavitation the pressure difference between the pressure side and the suction side results in a secondary flow going around the tip, which generates a vortex attached to the tip. The last form of cavitation, shear cavitation, gets its name from the shear layers of cavitation that form from an obstruction in the flow, or around submerged jets. The core of the submerged jet forms a core of low pressure where the cavitation will appear first. A non-dimensional cavitation number is defined by Franc [2]:

$$\sigma_v = \frac{p_{ref} - p_v}{\frac{1}{2}\rho V_{ref}^2} \quad (1)$$

In this equation Pref and Vref are the reference values for the pressure and velocity in the flow, with p_v being the vapor pressure and ρ being the density. The lower the cavitation number, the higher the probability of cavitation developing. However, due to a hysteresis effect, the cavitation will vanish at a critical cavitation number higher than the inception cavitation number. In theory all cavitation will behave the same at similar cavitation numbers, although there may be some second-order differences [2].

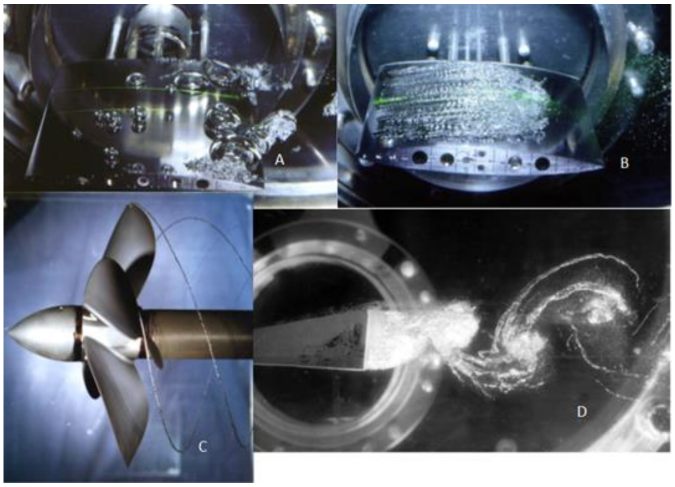

Figure 3 Four types of Cavitation; (A) Traveling bubble cavitation, (B) Attached wall cavitation, (C) Vortex cavitation, (D) Shear cavitation [2].

There were two main variables that affected cavitation over the hydrofoil, the nuclei content and the boundary layer flow. Figure 4, from Franc [2], shows how these variables can affect cavitation. In these images, deaerated water flowed over the hydrofoil, with a nuclei injection device adding engassed water where desired. In image A the separated laminar boundary layer is shown on a hydrofoil with a 0 degree attack angle. In the rear part of the hydrofoil an adverse pressure gradient forces a separation point. In image B the flow is run with a low nuclei count. This causes attached wall cavitation to form at the region where the flow separates from the wall. In image C the flow is run with a large nuclei count. The nuclei form travelling bubble cavitation, which then disrupts and prevents the attached wall cavitation. In image D nuclei are concentrated further into the page. This creates two forms of cavitation, attached wall cavitation out of the page, and travelling bubble cavitation into the page [2].

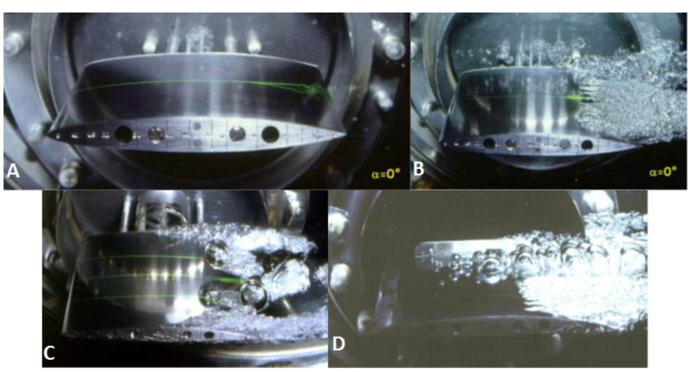

Figure 4 (A) Separated laminar boundary layer, (B) Attached wall cavitation, (C) Travelling bubble cavitation, (D) Travelling bubble and attached wall cavitation [2].

In a study by Sato, Hachino, and Saito [3], a glass venturi nozzle with a throat diameter of 10 mm and an exit diameter of 40 mm was used. A pump was used to flow water through the nozzle. In this study they found that there were three different forms of cavitation, as shown in Figure 5: traveling bubble cavitation, transition-type cavitation, and sheet cavitation. The traveling bubble cavitation was observed to have a spherical bubble characteristic that formed slightly downstream of the throat, and then at around 40 mm downstream of the throat the bubble collapsed [3]. The transition type cavitation was similar to the traveling bubble cavitation; however, as the bubble travelled downstream, cavitation remained upstream of the bubble. In the sheet cavitation the vapor nucleated around 10mm of the minimum throat area off of the wall. From the wall the vapor spread into the middle of the nozzle [3].

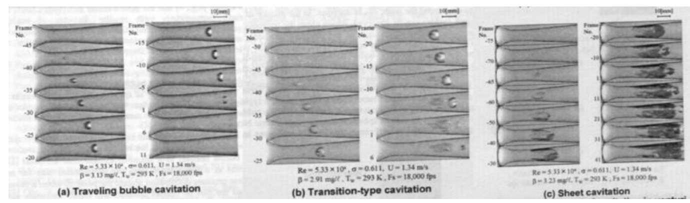

Figure 5 Three different types of observed cavitation [5].

Research by Schneider, Kosar, Kuo, Mishra, Cole, Scaringe, and Peles [4] studied the heat transfer effects of water traveling through five microchannels. These microchannels had an orifice, a 20 µm channel flowing into a 200 µm channel. They created a CAD drawing of the observed flow patterns at adiabatic conditions, as shown in Figure 6. Out of the orifice, a liquid jet formed, with twin vapor bubbles surrounding it, and liquid surrounding the vapor bubbles. In the transition region "the flow became unstable, rapid shedding of vapor slugs were detected, and the void fraction was strongly time dependent" [4]. In the wavy annular flow the vapor formed into a solitary vapor bubble that eventually broke up into smaller channels before exiting the channels.

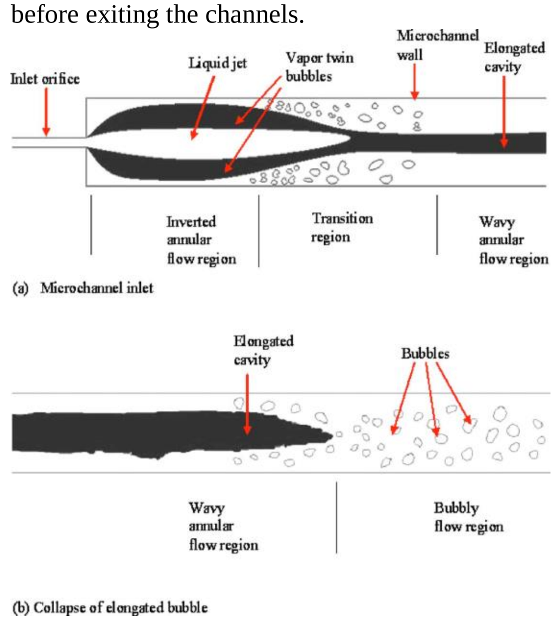

Figure 6 "CAD drawing of flow patterns" [4].

Predin and Bilus [4] numerically and experimentally analyzed the effect of water rotating as it flowed into a radial pump. As shown in Figure 7, the rotating flow created vapor, referred to as swirl cavitation. They varied the pump operating speed as well as the pressure in the inlet water tank. It was observed that neither the pump speed nor the tank pressure had any effect on the length of the cavitation; it was "a function of the pump impeller eye geometry" [4]. By decreasing the tank pressure, the diameter of the swirl cavitation decreased.

As shown in the literature, cavitation can appear in several different forms: attached wall, shear, swirl, and travelling bubble cavitation. Many nozzles of varying geometries were developed and then categorized by their form of cavitation.

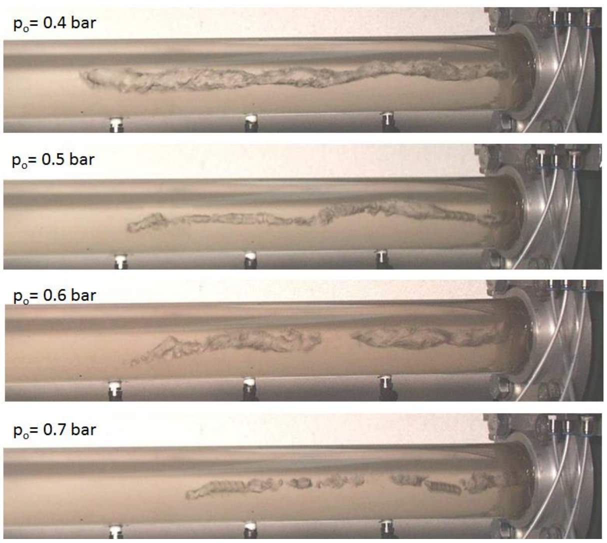

Figure 7 Swirl cavitation flowing into a radial pump [5].

NOMENCLATURE

[ρ] : Density
[Cp] : Specific Heat
[L] : Latent heat
[Pg] : Partial pressure of gas
[Pv] : Partial pressure of vapor

EXPERIMENTAL SETUP

Water Testing Rig

A diagram of the water testing rig is shown in Figure 8, with the images of the rig in Figure 9. A large water tank held the majority of the fluid in the water loop. The primary loop was the driving loop that pushed the fluid that was being studied through the nozzle. The fluid was driven by a centrifugal pump, model T51 made by MTH Pumps. The fluid then traveled through an electric heater. It was then filtered by a Shelco Micro Gaurdian filter. It then traveled through a reverse osmosis device. The mass flow, inlet pressure (P1), and inlet temperature (T1) were then measured. The fluid then flowed through the nozzle and then returned to the water tank. The secondary loop was utilized in order to regulate the temperature of the fluid. The fluid in the secondary loop was driven by another centrifugal pump. The heat exchanger cooled the fluid with tap water. The fluid was then sent through a heater and returned to the water tank.

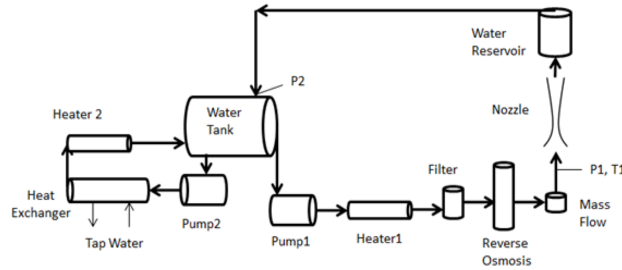

Figure 8 Water testing rig.

Figure 9 The water loop setup. On the left there is the water tank, filters, pumps, and heaters. On the right is the test section.

Nozzles

Square Inlet and Curved Inlet Nozzles: There were two plastic nozzles made specifically for use with high speed camera, shown in Figure 10. These nozzles incorporated a two degree expansion angle starting from the throat, one having a square inlet into the throat while the other had a curved inlet. These nozzles had a throat diameter of 2 mm, and an outlet diameter of 4.5 mm. In order to minimize refractive effects, four flat surfaces were added on the outer surface of the nozzle.

Figure 10 Square Inlet (left) and Curved Inlet (right) Nozzles.

Glass Nozzles: After the plastic nozzles were tested, the switch was made to use glass nozzles for testing. The main advantages of using glass were that they took much less time create, and they cost significantly less than the acrylic nozzles. The main disadvantage was that these glass nozzles were blown by hand, meaning that they could not be machined to specific dimensions. The first nozzle made is given in Figure 11, shown with a mixture of Rhodamine B dye and water. The throat of the glass nozzle was similar to the curved plastic nozzle, and had a rapid decrease of the diameter leading to the inlet of the throat, with a linear expansion past the throat.

Figure 11 Nozzle 1, with Rhodamine B dye.

Flow Visualization

In order to establish baseline knowledge of what was occurring in the nozzle, photos and video of the flow were needed. Standard video cameras film at thirty frames per second. At a minimum, the velocity in the nozzle was ten meters per second, and the observed area was ten millimeters along the nozzle. Thus the camera had to have the capability of filming at least 1000 frames per second. In addition to the need for a High Speed Camera, proper lenses, and a sufficiently intense light source were needed.

High Speed Camera: In order to provide the flexibility required for the project, a SA5 High Speed Camera was purchased from Photron. The camera had a maximum resolution of 1,024 by 1,024 pixels. The frame rate at the maximum resolution was at 7,000 frames per second. The camera could go up to 775,000 frames per second; however, the tradeoff was reducing the resolution down to 128 by 24 pixels.

Figure 12 shows the high speed camera while in use. The camera was connected to a computer through an Ethernet cable. The computer controlled the operation of the camera, using the Photron Fastcam Viewer (PFV) software provided by the manufacturer.

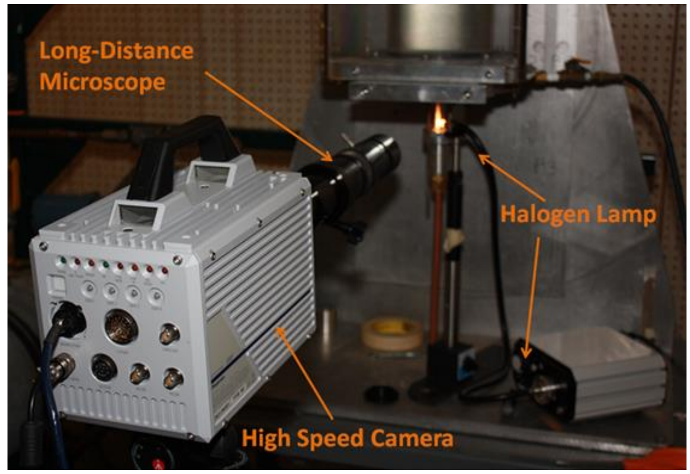

Figure 12 Experimental set up with the high speed camera.

Lens and Lighting: In order to develop close up images of the cavitation, a long-distance microscope was purchased. The long-distance microscope was an Infinity K-2 lens with a set of attachments referred to as the Close-Focus (CF) lenses.

The proper lighting is important in any photography situation. The high speed camera required more light intensity than a conventional video camera. With every increase in the frame rate of the camera more light is needed. In addition to the application of adequate light, the light must be delivered in a form specialized to the type of measurement being made. When the light is delivered directly into the nozzle many of the features could be washed out. For most experiments conducted here, the light was sent through a frosted pane of glass resulting in diffuse light illumination. However, when the cavitation filled up most of the region of interest, direct light is needed to fully penetrate and illuminate the fluid flow. The continuous white lighting source used was a halogen light source from Thor Labs. Shown in Figure 12, the halogen light source had a fiber optic cable to deliver the light to the back of the nozzle.

Flow Visualization Results

The objective of this section is to explore what cavitation will result from various nozzle geometries and various test conditions. Cavitation manifested in several different ways in the nozzle: attached wall cavitation, shear cavitation, swirl cavitation, and travelling bubble cavitation. The attached wall cavitation was typically found in venturi nozzles and featured a vapor column initiating off of the walls. Shear cavitation was found in nozzles with a rapid expansion, an orifice. When the fluid flowed out of the orifice it turned into a jet, referred to as an orifice jet, composed of liquid and vapor. The shear forces from the orifice jet caused vapor to form around it. Swirl cavitation was found in nozzles with a rapid expansion and an Internal Flow Modifier (IFM). The IFM rotated the flow prior to the inlet of the nozzle, and after the throat the orifice jet expanded radially, causing a large vapor region. Certain nozzle geometries caused the flow to start as attached cavitation, but then transition into shear cavitation. Travelling bubble cavitation was found when there were dissolved gases in the water. These gases separated from the water at low pressures. These gas bubbles formed nucleation sites which initiated cavitation. Most of the time these gas bubbles disrupted other forms of cavitation, but it was possible for these types of cavitation to be present at the same time. Travelling bubble cavitation can induce or disrupt attached wall cavitation. In some cases a bubble was capable of moving past the attached wall cavitation, displacing the fluid around it, but leaving its initiation unchanged.

Attached Wall Cavitation: Similar to the hydrofoil in Figure 4 B [2], attached wall cavitation occurred in venturi nozzles. A venturi nozzle is a nozzle that converges to a minimum area throat and then diverges without any sudden changes in the diameter. In the case of the nozzles used for this research, there was a reduction in area from nine millimeters to approximately 2 mm in the converging section. After the minimum area cross section, the throat, the cross sectional area increased at a very gradual rate, ranging between zero to five degree expansion. In these venturi nozzles the attached wall cavitation initiated a few millimeters downstream of the minimum area of the throat. This location was most likely caused by a separation region.

The Curved Inlet Acrylic Nozzle was the first nozzle that utilized the high speed camera. Shown in Figure 13, this nozzle had a gradual inlet, followed by a two degree, linear, expansion. Section A shows the initiation of the attached wall cavitation. The initiation of the nucleation occurred at approximately two millimeters downstream of the throat, most likely at the separation region. In this plastic nozzle there were typically three vapor columns of attached wall cavitation, roughly equidistant from each other. These vapor columns moved around the circumference of the nozzle, occasionally dissipating or splitting into two separate columns. In the first third of section B, the vapor streams split off from the wall and as this transition occurred the stream became turbulent. From that point where it became turbulent, more light was scattered, resulting in less light reaching the camera.

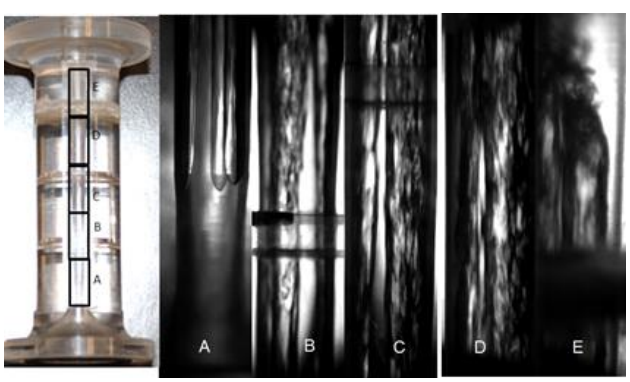

Figure 13 Curved Inlet Nozzle visualization.

In Figure 14 the images show the initiation of the cavitation at mass flow rates of 40.3 and 50.1 grams per second. The horizontal bars are to show the distance from the bottom of the viewing area. As can be seen in the picture, there was very little deviation of the initiation site at different flow rates. It is also important to note that the initiation point was constantly moving laterally around the inside wall. In both cases the initiation was in the region 4- 4.5 mm for the majority of the time, with some time also spent in the 4.5-5mm region. Changing the mass flow rate did not affect the initiation of the cavitation, however it did affect the length of the cavitation region. Figure 15 shows the distance the cavitation travelled before shocking back to liquid. At very low mass flow rates there was no inception of cavitation. There was a range of mass flow rates where the cavitation may or may not initiate. This region is shown in the red boxes, and are from around 35 to 40 grams per second. From 40 grams per second and higher the cavitation was always present. This data showed a positive linear relationship between the mass flow and the length over which the cavitation formed.

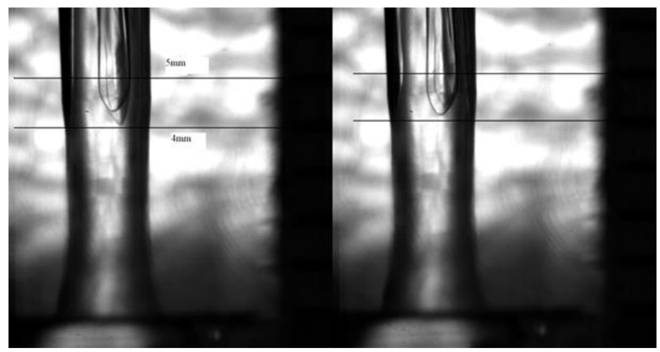

Figure 14 Initiation of cavitation, left image 40.3 gram/s, right image 50.1 gram/s.

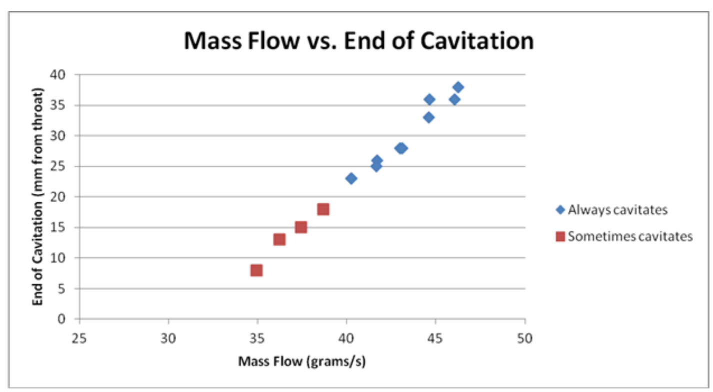

Figure 15 End of cavitation distances.

The Sudden Inlet Acrylic Nozzle is shown in Figure 10. The images of the flow are shown in Figure 16. As shown in section A, the cavitation initiated at throat. Unlike the curved inlet, instead of 3-4 vapor columns that moved around, attached wall cavitation formed around the perimeter. This cavitation switched from laminar to turbulent in section B. From that point on, the cavitation was similar to that in the other acrylic nozzle. The cavitation spread out and became more turbulent until starting to break apart in section E.

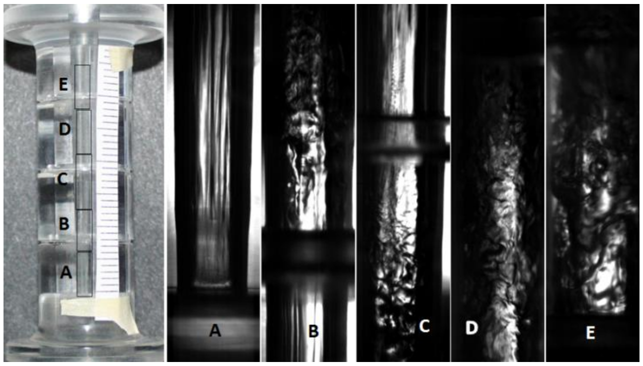

Figure 16 Square Inlet Nozzle visualization.

The first glass nozzles used for the current research had a design similar to that of the plastic Curved Inlet Nozzle. The design was changed to account for these nozzles being hand crafted by the scientific glassblower. Nozzle 1, in Figure 17, had a sudden decline in the diameter up to the throat and then an expansion of 2.18 degrees. In order to test the influence of the inlet, Nozzle 2 had a 2 degree inlet and outlet.

When Nozzle 1 was first tested, there was a small scratch on the surface near the throat. As shown in Figure 18, A and B, the scratch acted as a nucleation site. The cavitation still presented as attached wall cavitation, although the profile was altered. The nozzle was then heat treated, removing the nucleation site. After the cleaning, the attached wall cavitation nucleated similarly to that in the Curved Inlet Nozzle. However, unlike the Curved Inlet Nozzle, there was only one cavitation stream, with a few small streams occasionally splitting off. This main stream predominentily favored one side of the nozzle. This was due to a slight asymmetry in the nozzle. Similar to the Curved Inlet Nozzle, the changing of the flow rate did not affect the nuclation of the cavitation, just the distance the cavitation travelled from the throat.

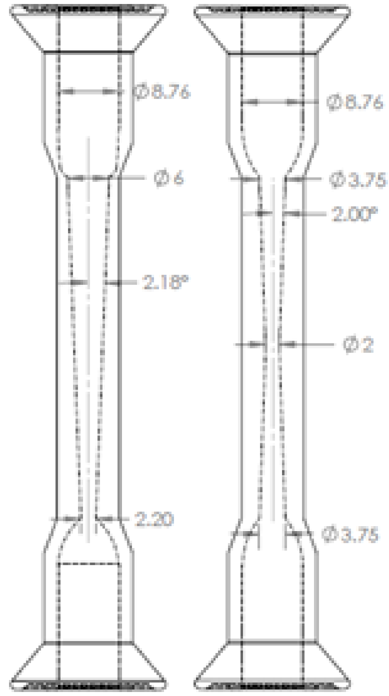

Figure 17 Design of Nozzle 1 and Nozzle 2.

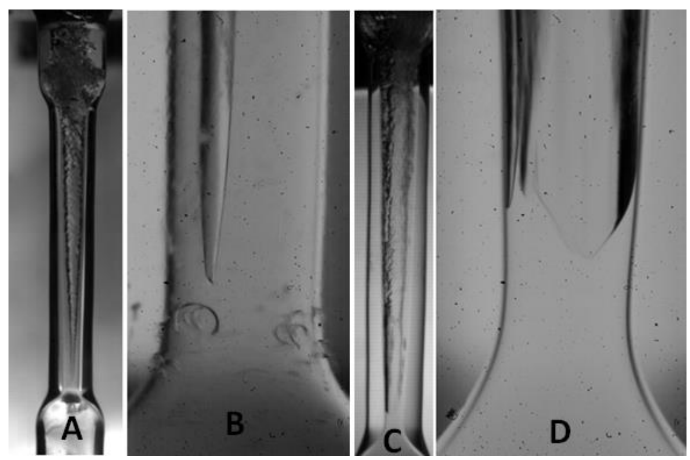

Figure 18 Nozzle 1 (A,B) With Scratch; (C,D) No Scratch.

As seen in Figure 19, the results for Nozzle 2 mirrored those found in Nozzle 1. There was a single column of vapor that formed a few millimeters from the throat. Again, due to a slight asymmetry in the nozzle, the cavitation favored one side. Therefore, the gradual inlet did not visibly change the cavitation.

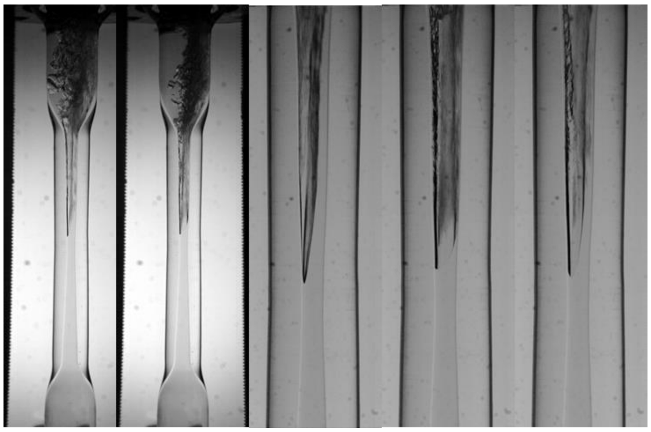

Figure 19 Nozzle 2 visualization.

Travelling Bubble Cavitation: In all of the other experiments, it was necessary to degas the water system. This involved running the water through the osmosis filter, while drawing a vacuum on the filter. This section shows the effect of not degassing the system with Nozzle 1. As described by Franc, entrained gases in water will cause travelling bubble cavitation.

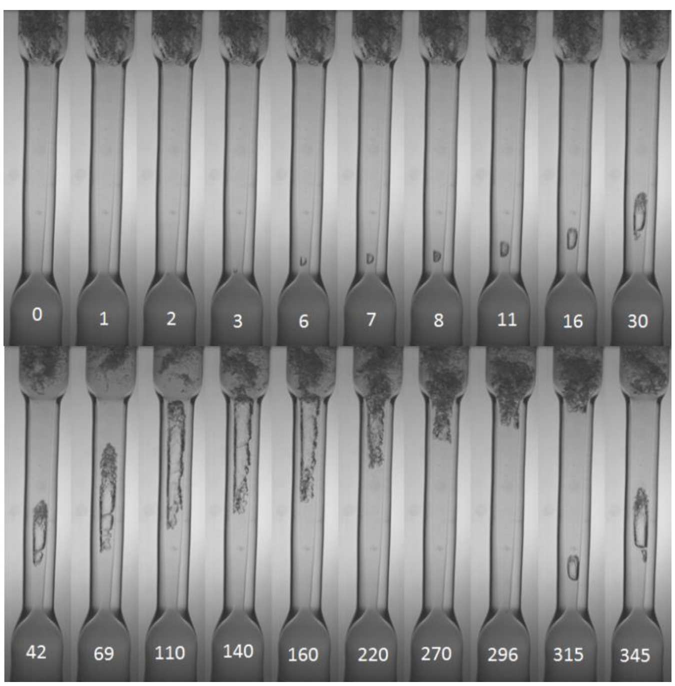

Figure 20 Nozzle 2 travelling bubble sequence with frame numbers.

The typical behavior of travelling bubble cavitation is shown in Figure 20. As the water traveled through the throat, the pressure decreases to the point where entrained gasses separate from the water. These gasses formed a bubble near the throat, and that bubble increased in size as it traveled down the throat. In most cases, these bubbles suppressed the cavitation, although occassionally attached wall cavitation still formed. An example of this is shown in Figure 21. In frames 156-191, the bubble induces the attached wall cavitation. Then, in frame 218, another bubble passes through the attached wall cavitation. Finally, another bubble travels through the nozzle and removes the other cavitation.

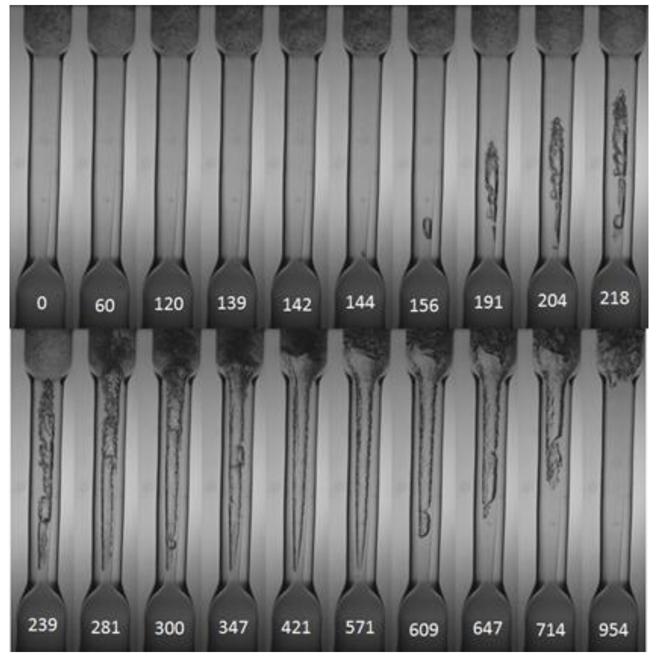

Figure 21 Nozzle 2 travelling bubble sequence and wall cavitation with frame numbers.

Shear Cavitation: In nozzles that have a rapid expansion, an orifice, shear cavitation developed. When the fluid flowed out of the orifice it turned into a jet, referred to as an orifice jet, composed of a turbulent mixture of liquid and vapor. The shear forces from the orifice jet created a vapor cloud that formed around the jet. The three nozzles used for shear cavitation are shown in Figure 22.

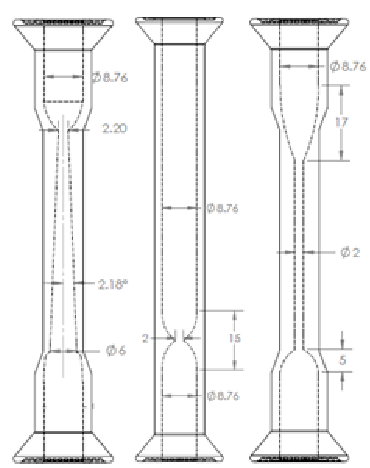

Figure 22 Inverse Nozzle 1, Nozzle 3, Nozzle 4.

Inverse Nozzle 1 was Nozzle 1 inserted into the testing setup in reverse. As shown in Figure 23, the flow in this nozzle was cyclical, although not entirely periodic. Using the first image as a reference, the flow initially showed a few bursts, composed of a highly turbulent combination of liquid and vapor. These bursts formed into a centralized, turbulent core, the orifice jet. Shear cavitation caused a vapor cloud to form around the orifice jet. The features on the outside of the vapor cloud in frame 210 showed no vertical movement, although they rotated around the core. The area outside of the vapor cloud was liquid with tiny bubbles suspended in it. These bubbles showed little movement overall. Eventually the vapor cloud started to contract. It contracted from the top on down to the bottom. Once the vapor core collapsed the bursting motion started the cycle over again. In the images shown in Figure 23 it took about 0.0415 seconds for a complete cycle. The time for each cycle was not entirely periodic, since each time the cycle started it took a seemingly random amount of time to complete. Changing the mass flow did not have any visible effect. Most likely this cyclical pattern was caused by the vapor cloud causing the velocity in the turbulent core to decrease. Once the velocity of the core decreased, the pressure rose above the vapor pressure, and the cloud would then collapse downward. At this point the turbulent core fluctuated, decreasing the cavitation into small fluctuations. Since cavitation constricts the flow, when that cavitation was removed the mass flow rate increased. This mass flow rate increase then caused the velocity to increase, starting the process over again.

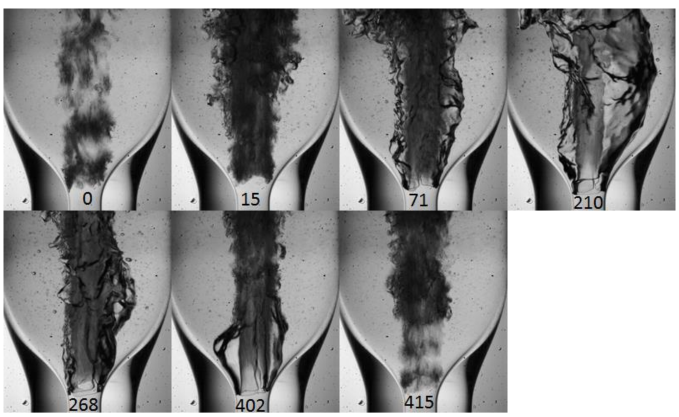

Figure 23 Inverse Nozzle 1 sequence with frame numbers

Figure 24 shows the shear cavitation from Nozzle 3. The cavitation was very similar to the Inverse Nozzle 1, except that some vapor was always present around the core. When a straight inlet was introduced, Nozzle 4 in Figure 25, the shear cavitation still had the turbulent jet, vapor cloud, and a liquid outer layer. However, the cavitation in this nozzle was no longer cyclical.

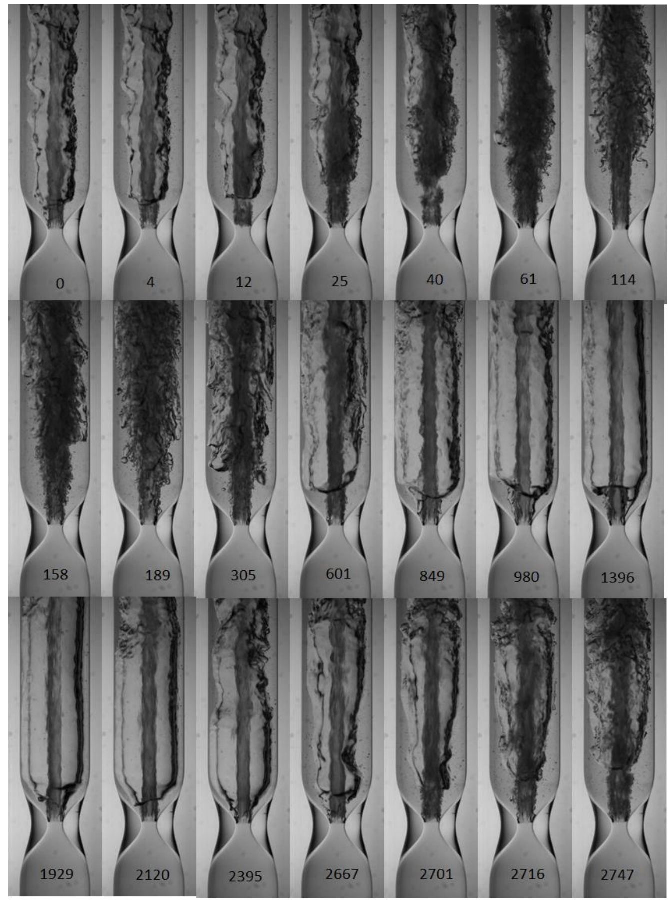

Figure 24 Nozzle 3 sequence with frame numbers.

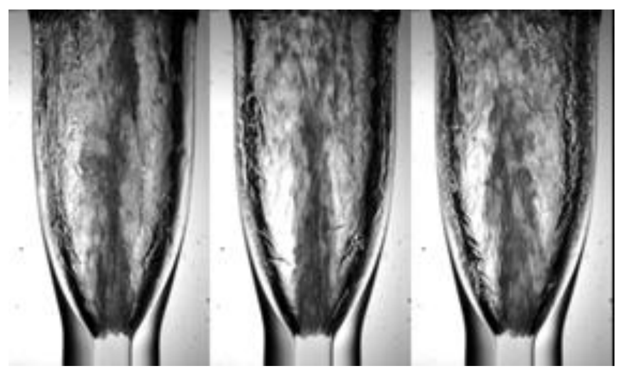
Figure 25 Nozzle 4, flow visualization.

Mixed Cavitation: Nozzle 5, shown in Figure 26, was designed to have an increasing expansion rate. When tested, a mixed cavitation was formed. In the beginning, the cavitation behaved like attached wall cavitation. The attached wall cavitation soon transitioned into shear cavitation, featuring the jet and vapor cloud. This shear cavitation was also cyclical.

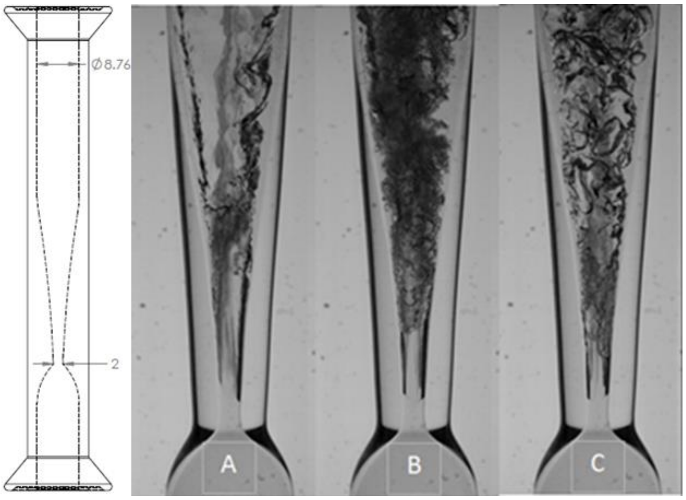

Figure 26 Nozzle 5 glow visualization.

Swirl Cavitation: This cavitation was developed with Nozzle 3, using an internal flow modifier to rotate the flow prior to entering the nozzle. The visualization is shown in Figure 27. Directly after the throat the results were the same as without the IFM; there was the orifice jet. However, this orifice jet quickly started to expand radially. On the edges of this rotating orifice jet there was a thin water layer surrounding vapor in the bulk of the jet. Outside of the rotating jet there was a void with no liquid, most likely vapor with litte to no velocity. This cavitation showed the largest amounts of void fraction.

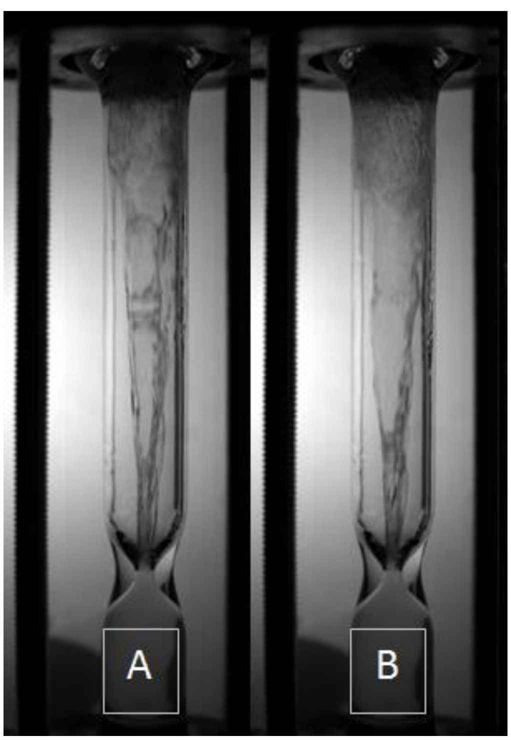

Figure 27 Nozzle 3 with IFM.

SUMMARY

The cavitation flows were categorized into five categories: attached, travelling bubble, shear, mixed, and swirl cavitation. Attached wall cavitation typically occurred in venturi nozzles. These nozzles all had a small expansion angle. Attached wall cavitation nucleated downstream of the minimum area throat, most likely where a separation region developed. This cavitation started attached to the wall and laminar. As it flowed downstream, it detached from the wall, became turbulent, and the void fraction grew.

How the cavitation formed in attached wall cavitation was dependent on one of two things: the presence of nuclei, or the separation region. The presence of nuclei was the dominant variable, whether the nuclei were in the water, travelling bubble cavitation, or on the surface, Nozzle 1. In the case of Nozzle 1, a scratch on the surface acted as a nucleation site, suppressing the usual attached wall cavitation. While there were exceptions, the travelling bubble cavitation suppressed the attached wall cavitation. When no nuclei where present, the separation region dictated where the cavitation formed.

In shear cavitation, an orifice jet, a turbulent mixture of liquid and vapor, formed from the water flowing through a rapid expansion. The shear forces from the orifice jet and the surrounding water caused vapor to form, called shear cavitation. The shear cavitation was affected by the inlet to the throat. In the nozzles with a converging inlet, the vapor cloud developed a cyclical pattern of forming and collapsing around the orifice jet. In the nozzles with a constant diameter inlet, the vapor cloud permanently developed around the orifice jet.

In the nozzle with an expanding expansion angle mixed cavitation developed. The mixed cavitation started off as attached wall cavitation and then transitioned into shear cavitation. The combination of a rotating flow and an orifice created shear created swirl cavitation; causing the orifice jet to expand radially.

REFERENCES

[1] S. Charamko, K. Debus and T. Gielda, "Cooling System Utilizing a Reciprocating Piston". United States Patent US 2012/0260673, 18 October 2012.

[2] J.-P. Franc, "Physics and Control of Cavitation," *Design and Analysis of High Speed Pumps,* pp. 2.1-2.36, 2006.

[3] K. Sato, K. Hachino and Y. Saito, "Inception and Dynamics of Traveling-Bubble-Type Cavitation in a Venturi," in *Proceedings of ASME FEDSM*, Honolulu, Hawaii, 2003.

[4] B. Schneider, A. Kosar, C.-J. Kuo, C. Mishra, G. S. Cole, R. P. Scaringe and Y. Peles, "Cavitation Enhanced Heat Transfer in Microchannels," *Jounal of Heat Transfer,* vol. 128, 2006.

[5] A. Predin and I. Bilus, "Cavitation Swirl in the Inlet Pipe of the Radial Pump," in *Proceedings of the 2nd IASME/ WSEAS International Conference on Water Resources, Hydraulics & Hydrology*, Portoroz, Slovenia, 2007.