Vortex Fluid Flow for Generation of Hydrodynamic Cavitation Aimed at Enhancing Manufacturing Processes

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Abstract

The energy emanating from hydrodynamic cavitation can play a significant role in enhancing manufacturing processes that utilize fluid medium as a force transmitter, a lubricant, or as a carrier. The fluid flow characteristics in a vortex cavitation generator is studied to determine how bubbles could be transported to a target location prior to implosion. Preliminary CFD simulations and experimental results have shown that the cavitating fluid stream exhibits a swirl flow pattern causing the cavitating stream to remain at the core of the stream. This phenomenon opens avenues for developing mechanisms for controlling and transporting cavitating bubbles to target locations prior to implosion.

Keywords: Hydrodynamic cavitation, CFD, Water cavitation peening, Cavitation polishing

1. Introduction

Hydrodynamic cavitation (HC) is the formation, growth, and burst of gas bubbles in a rapidly flowing fluid. The implosion of gas bubbles releases concentrated energy in the form of pressure waves, high-speed micro jets, and thermal energy. Cavitation is a promising technology that has attracted many researchers and has been widely employed in numerous fields such as disinfection, cell disruption, sludge treatment, biodiesel synthesis, nano emulsion production, polymer processing, food processing, manufacturing etc., [1, 7].

A typical example of the application of HC in manufacturing is the cavitation peening process, which has attracted much attention due to their advantages over the conventional surface treatment processes, such as shot peening and laser peening [8, 9]. In the cavitation peening process, cavitation is formed as a fluid passes through a Venturi-type nozzle or an orifice. Upon impact with the workpiece, the imploded bubbles supply energy for the peening process resulting in local plastic deformation and work hardening of the workpiece material [10, 11]

Polishing is another manufacturing process, where hydrodynamic cavitation energy could be used effectively. Precision polishing of hard, brittle materials such as silicon, which is widely used for optical components, is challenging. Regardless of the particle size of abrasives, traditional contact grinding and polishing methods are bound to produce microcracks on the surface [12]. Zhao et al. [13] developed a polishing system with multiple venturi cavitation channels to form a rotary abrasive flow above the workpiece. Polishing for 8 hours yielded a surface roughness of 7.8 nm, as compared to 10.5 nm in a non-cavitation polished workpiece.

Most of the devices for generating hydrodynamic cavitation are based on fluid flow in venturi tubes, orifices and nozzles. In these devices bubbles will nucleate, grow and collapse. To harness this energy for application in manufacturing processes, a number of venturi tubes need to be integrated into a system. Such a design can be complex or unfeasible. An ideal scenario will be a cavitation generator that facilitates nucleation of bubbles which are then transported to a target location where bubble implosion can take place. Vortex based cavitation generators can mitigate some of the challenges brought by conventional venturi and orifice reactors. Jain et al., [14] evaluated the performance of orifice and vortex cavitation reactors for treatment of waterborne bacteria (Escherichia coli and Staphylococcus aureus). The vortex reactor was found to be more efficient. A very high removal rate (99%) was achieved in 1 hour at a pressure drop of 0.5bar, whereas the orifice reactor could only achieve this rate at a pressure drop of 10 bars.

The main goal of this study is to study delivery mechanisms of condensed cavitation energy at target locations and identify key variables for augmenting manufacturing processes. Since implosion takes place when the size of the bubbles is in the nano-micro scale, the condensed energy emanating from cavitation can effectively be utilized in nano-micro manufacturing processes such as nano/micro polishing, nano emulsification processes for production of nano-lubricants, surface treatment of microscale metallic components, etc. The specific objective of this study is to investigate vortex flows that can generate continuous and fully cavitating fluid streams thus increasing the yield on the energy to be harvested.

2. CFD Simulation of cavitation in vortex flow

Computational fluid dynamic (CFD) simulations were carried out to study vortex flows for a cavitation generator shown in Fig. 1. The generator has four integrated chambers where the fluid streams enter the device tangentially to the four chambers as shown by yellow arrows. The fluid leaves the chambers at exits A, B, C, and D.

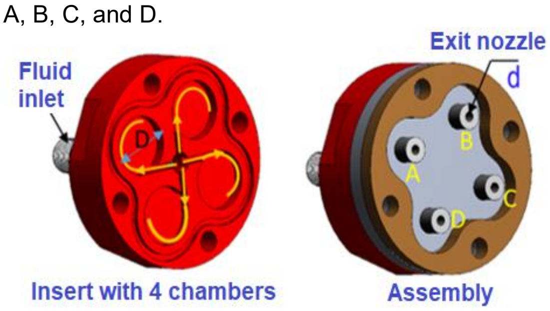


Fig. 1. Cavitation generator

The vortex flow in the chambers induces pressure differential with a low-pressure region at the core of the vortex, resulting in cavitation. Bubbles will form where the pressure of the liquid has fallen below that of the vapor.

The variables that were investigated are pressure distribution, mass transfer rates, and vapor volume fraction as a function of geometric and process variables. The geometric variables include chamber diameter (D), entry diameter (d_{ent}) exit diameter (d_{ext}) and chamber entry channel gap.

ANSY Fluent (2021) Software package was used in this study. The model had to account for two phases: (1) water liquid, (2) water vapor due to cavitation. A multiphase model was adopted for the two continuous phases, and cavitation was described by the Schnerr-Sauer model. The $k-\varepsilon$ turbulence model was used to capture features of the core flows. For brevity, only a few CFD simulation results are presented for the following conditions: Chamber diameter D=28mm, d_{entry}=10mm, d_{exit}=10mm, gap channel =0.5mm. An inlet pressure of 6,000kPa, outlet gage pressure of 95 kPa, and vaporization pressure of 3540 Pa were prescribed in the model. Fig 2. Shows pressure distribution in the fluid domain. A distinct pressure differential can be seen. At the core of the chambers the static pressure has dropped to the vapor pressure resulting in cavitation. To visualize the cavitation inception, vapor volume fraction distribution at the middle cross-section of the chambers is plotted in Fig. 3

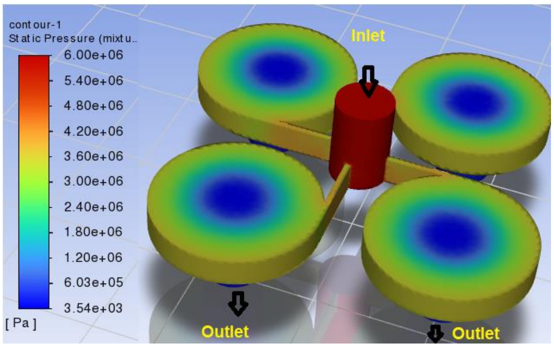


Fig. 2. Pressure differential in the fluid domain

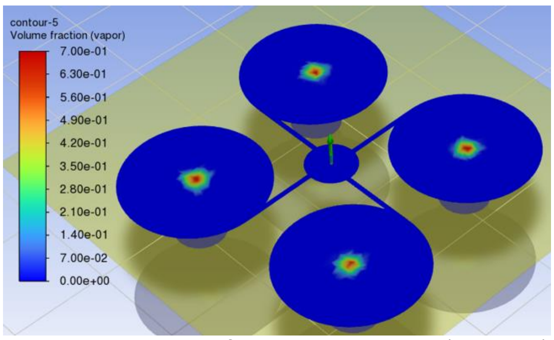


Fig. 3. Vapor Volume fraction middle section (cavitation)

To make use of this cavitation in a manufacturing environment, we desire that the majority of nucleated bubbles be transported to a target location prior to implosion. The transport is via the outlet nozzles labelled A, B, C and D in Fig. 1. Parametric study is thus carried out to determine bubble evolution and flow modes. One interesting observation from the CFD simulations is the continuation of the vortex/swirl flow pattern that is maintained as the fluid exits the chambers and enters into the outlet nozzles. Fig. 4 shows vortex pathlines from entry to exit. A swirl pattern of the mixture (water liquid and vapor bubbles) seen at the exit nozzles suggests that bubbles are held at the core and that the risk for eroding the surfaces of the nozzle due to bubble implosion is minimal. This phenomenon of holding the cavitating stream at the core provides avenues for controlling the transport of bubbles prior to implosion.

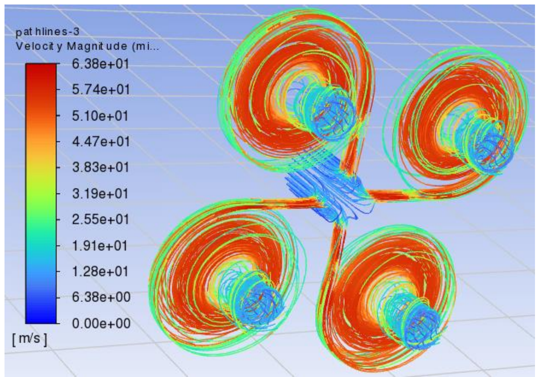


Fig 4. Vortex pathlines from entry to exit

The CFD simulation results also suggest that the geometric configuration of the exit nozzles may have less influence on the containment of the bubbles at the center. This implies that curved nozzles could be used to transport cavitating bubbles to desired locations.

3. Preliminary experimental results

3.1. Experimental setup and test procedures

Fig. 5 shows the vortex cavitation experimental setup. It consists of a tank, pump, vortex/cavitation generator, light source, and a high speed camera. Water is suctioned from the tank by a plunger type pump and then supplied to the vortex /cavitation generator.

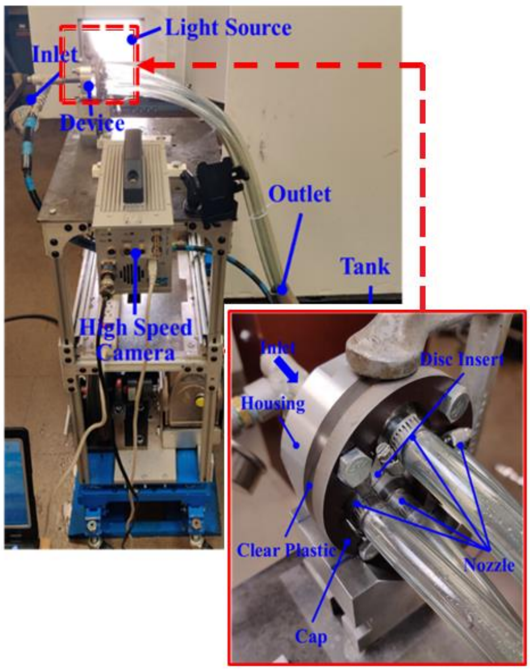
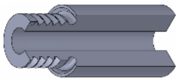
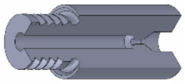


Fig. 5. Experimental setup; Vortex/cavitation generator

The pump operates at a speed of up to 1750 RPM and discharges the fluid at the maximum flow rate of 18 L/min. Two sets of test were carried out in order to characterize the flow behaviour of the cavitating fluid stream at the exit nozzles. As shown in Table 1, straight-hole and orifice type nozzles were used. For both cases the chamber inserts with four different channel width varying from 0.5mm to 3mm were used. These channels are the fluid gateways from the inlet to the chambers.

Table 1: Experimental matrix

Nozzle Type	Experiment #	Channel width
	H1	0.5 mm
	H2	1.0 mm
	H3	2.0 mm
Straight-hole	H4	3.0 mm
	O1	0.5 mm
	O2	1.0 mm
	O3	2.0 mm
Orifice type	O4	3.0 mm

3.1. Preliminary results and discussion

The behavior of the cavitating flow stream for straight-hole exit nozzles with channel width of 0.5mm can be observed in Fig. 6a & b. As was observed in the CFD simulations, the cavitation is concentrated at the core of the fluid stream. Looking at the close-up view (Fig6b) captured by the high speed camera, one can clearly see a swirl pattern flow behavior of the bubble cloud as it travels along the hose. It should be noted that liquid water surrounding the cavitating stream should exhibit the same swirl pattern, though not visible from the image. Fig. 6 also shows that, under the test conditions, the bubbles could travel over 250mm.

The experimental results have shown that the change in the channel width does not alter the swirl flow behavior. However, the bubble travel distance diminishes with increase in the channel width. Fig. 7 shows the cavitating flow stream for the straight-hole nozzle with channel width of 3mm. The bubble travel length has significantly decreased. The reason behind diminished bubble travel distance, is the fact that the channel width predetermines the inlet pressure since the water pump flow rate remains constant, at 18L/min.

Figures 8 and 9 show the cavitating fluid streams for the orifice type nozzles. No swirl patterns were observed from these figures. The change in the channel width from 0.5mm to 3mm did not affect the cavitation behavior as all the images looked similar. Furthermore, the inlet pressure remained the same irrespective of the change in the channel widths. This implies that the pressure was dictated by the size of the nozzle orifice. The influence of the vortex flow inside the chambers on cavitation could not be established.

As stated earlier, one of the goals of this study is to explore delivery mechanisms of cavitation energy at target locations. The swirl patterns observed at the exit nozzle presents the opportunity for developing effective cavitation-assisted manufacturing processes: The imposition of vortex/swirl flow ensures that the cavitating stream is concentrated at the core, thus erosion of nozzles is minimized. As observed from the experiments, bubbles remain at the core irrespective of some changes in the geometrical configurations of the exit nozzle. This is important, particularly, for transferring bubbles to intricate locations/difficult to reach locations.

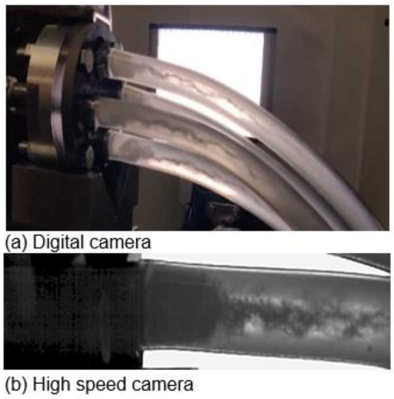


Fig. 6 Cavitation: 0.5 mm chamber entry gap channel (H1)

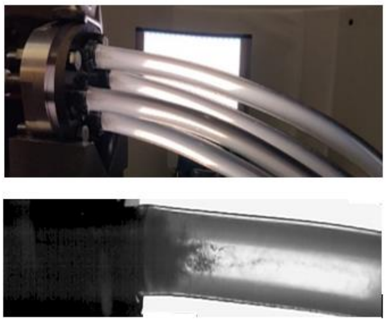


Fig. 7. Cavitation: 3mm chamber entry gap channel (H4)

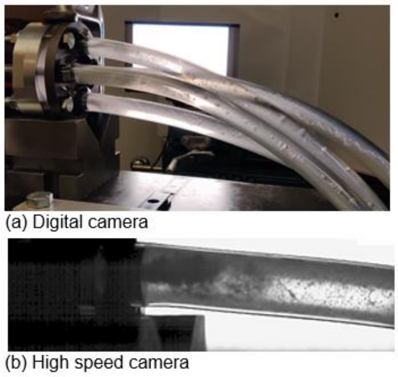


Fig. 8 Cavitation: 0.5 mm chamber entry gap channel (O1)

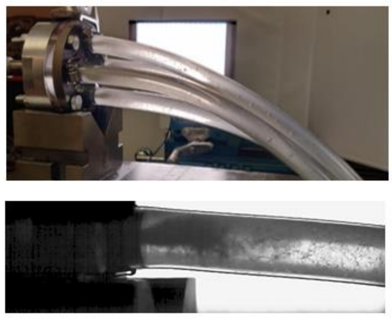


Fig. 9 Cavitation: 3 mm chamber entry gap channel (O4)

It should also be noted that the four chambers for the vortex generator were picked to represent multiple chambers. Numerous chambers could be integrated depending on the quantity of output nozzles needed. Furthermore, by varying the chamber sizes, the cavitation intensities can be altered from one nozzle to the other.

4. Conclusions and future work

Preliminary computational fluid dynamic simulations and cavitation experiments were carried out to study the development of cavitation in a vortex fluid stream. A cavitation generator with four cylindrical chambers was used. The vortex flow was achieved by pumping liquid water tangentially to the chambers. After creating the circular motion in the chambers, a cavitating stream of liquid was generated at the core of the chamber and exited through the exit nozzles. The conclusions drawn from this study are;

- A distinct pressure gradient on the four chambers was observed in CFD simulations. This is due to the imposition of the vortex flow. Since cavitation occurs in a fluid stream where the pressure has dropped below vapor pressure, pressure gradient is critical for the generation of cavitation.
- The CFD simulations also showed that the vortex flow inside the chamber results in a swirl flow pattern as the stream enters the exit nozzle. The swirl pattern was found to be maintained throughout the whole length of the nozzle.
- Experimental results for a few test conditions that were conducted exhibited similar flow patterns as those observed in the CFD simulations. From the experimental results we were able to clearly distinguish the cavitating stream from the non-cavitating liquid. The swirl flow caused the cavitating liquid to stay at the core of the stream. This phenomenon is of interest for exploring novel mechanisms for control and delivery of the cavitating stream to the desired location where bubble implosion should take place.

As the goal of this study is to devise mechanisms for continuous generation of cavitation and delivering to the desired locations where implosion of the bubble takes place, such that the cavitation energy can be employed to enhance manufacturing processes, several ongoing tasks need to be accomplished.

- Conduct further CFD simulations to understand the interrelationships of process and geometrical variables (vortex generator architecture) and how they influence cavitation intensity.
- Conduct CFD simulations to study swirl patterns with the goal of establishing optimal conditions for transporting the cavitation cloud to the workpiece.
- Design cavitation chamber inserts and nozzles for the vortex generator, conduct cavitation experiments, and demonstrate the viability of the process on a vortex-based cavitation-assisted peening process.

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