Dynamics and acoustics of a cavitating Venturi flow using a homogeneous air-propylene glycol mixture

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Abstract. Dynamics and acoustics generated in a cavitating Venturi tube are followed up as a function of the input power of a centrifugal pump. The pump of 5 hp with a modified impeller to produce uniform bubbly flow, pumps 70 liters of propylene glycol in a closed loop (with a water cooling system), in which the Venturi is arranged. The goal was to obtain correlations among acoustical emission, dynamics of the shock waves and the light emission from cavitation bubbles. The instrumentation includes: two piezoelectric transducers, a digital camera, a high-speed video camera, and photomultipliers. As results, we show the cavitation patterns as function of the pump power, and a graphical template of the distribution of the Venturi conditions as a function of the cavitation parameter. Our observations show for the first time the sudden formation of bubble clouds in the straight portion of the pipe after the diverging section of the Venturi. We assume that this is due to pre-existing of nuclei-cloud structures which suddenly grow up by the tensile tails of propagating shock waves (producing a sudden drop in pressure).

1. Introduction

The behavior of cavitating Venturi nozzles has been investigated with great interest over the past 60 years because of the wide range of phenomena associated with their flow [1]. Accordingly, in [2] a theoretical development for bubbly flows together with experimental measurements emphasizing the role of the void fraction is found. In the same line of research, but including a theoretical-experimental treatment of shock emissions is found in [3]. Another theoretical analysis showed in [4], provides a robust set of expressions for the flow and shock waves generated in the nozzle. Another related topic is the design of commercial Venturi flow meters/controllers by ASME standards [5-6]. Nevertheless, these codes do not take into account the formation of complex flow patterns that may affect the proper operation and/or calibration of the device. Thus, a robust design requires studying the complexity of the phenomena associated with the flow including: two-phase bubbly flow, shock waves, luminescence, nucleation-expansion-compression of bubbles as single entities or cooperative-interacting clusters, formation of turbulent structures (gas-liquid-vapor), noise, and pulsating jets, among others as stated in [7-11]. Regarding numerical simulations, above complexities are addressed in [12]. Our observations show the complexity of the above mentioned local bubble phenomena.
Experiments also reveal the noise generated, and the light pulses emitted as well as how the flow stream is affected by turbulence, vorticity, and shock waves.

2. Experimental setup
A schematic of the test rig is shown in Fig.1; the connecting PVC pipes are 2.5 inches in diameter. The Venturi is manufactured in transparent PMMA with 33 cm long, 64 mm of inner diameter and 16.5 mm diameter in throat section. The pump has a modified impeller (with a reduction of 36% in the impeller output area), which acts as a generator of nuclei, increasing the bubbles formation; besides the circuit has a regulating valve, and an auxiliary tank. A compact variable frequency drive Yaskawa J1000, is used to change the output speed of the pump; a photomultiplier (PMT) Hamamatsu Photonics R5783-04 for luminescence detection; a dynamic force sensor PCB 200B05 and a piezoelectric transducer 5 MHz Olympus V310-SU are used for sensing the acoustics. All signals are acquired with a digital Lecroy LC584AM oscilloscope. High-speed video is obtained from a Phantom v9.1 camera in the interval of 25000-40000 fps.

3. Experimental procedure
The experimental run begins when the fluid is recycled in order to obtain a homogeneous air-liquid mixture (dissolved oxygen = 20) with the cooling device activated until the mixture reaches a uniform temperature of 15°C; the power output of the pump is maintained at 10% of full power. Later on, the mixture flow rate is changed by varying the rotation frequency of the pump, and consequently its total power percentage, %. Acoustic and luminescence measurements as well as high speed video are acquired for each flow rate stage. The Venturi is used also as a flow rate meter; in which a U-tube mercury manometer is installed. The test rig and its instrumentation are tested with tap water; these tests showed that the visible choked condition in the Venturi throat is reached at 35% of pump power.

4. Results
Fig 1 shows the pump power (%) versus cavitation parameter $\sigma$ at different temperatures. The shock condition in the Venturi is attained at 35% of the pump power which corresponds at $\sigma = 0.5 \pm 0.2$, and the light emission is detected starting from $\sigma = 0.7$. The place where the shock wave and light flash occur, shifts as a function of flow rate; e.g. for $\sigma \approx 0.7$ it occurs in the exit zone of the throat and for $\sigma \approx 0.01$ it occurs in the transparent pipe line, see Fig 1. General observations of the flow dynamics as a function of pump power are summarized in Table 1. At 20%; incipient cavitation is visible, the Kelvin-Helmholtz instabilities generate swirls at the interphases along the horizontal line [11]. As we know, inside the swirls the pressure is less than in the outside giving place to evaporation, leading to the formation of a mixture cavitation layer. At 30 %; the implosion of bubbles takes place at 48 mm from the throat, where non periodical bubble filaments appear, the flow rate in the wall reaches 6.8 m/s and 14 m/s in the “middle”. At 35%; the implosion of the filaments occurs at 29 mm away from the throat, while the flow rate in the middle reaches 28 m/s. At this level, the emission of shock waves becomes observable. At 36%; a cloud stagnates and goes growing in an ordered fashion at 13.6 m/s until the diverging section of the Venturi is completely filled. This cloud is formed and destroyed periodically in the same place. At 38%; the cloud undergoes spallation and the clusters generated are dragged by the flow towards the straight section of the pipe. Some of these clusters become into nuclei-cluster structures that are practically imperceptible to the naked eye. Further increase in the pump power (41%) causes the cloud to be “reborn” in the straight section of the pipe. We think that this is partially due to pre-existence of nuclei-cluster structures which suddenly grow up by a sudden drop in pressure by the tensile tail of a shock wave. At this level the clouds in the diverging zone and at the straight section of the pipe emit shock waves into liquid phase at approximately 2450 m/s. The shock waves are reflected and returned up (identified with high density zones which are seen as darken regions in images) reducing the zone of remaining bubbles and clouds to some nuclei-cloud structures which are difficult to discern at a glance. At 42%; two clouds are clearly observed in the corresponding image, one filling the divergent zone of the Venturi and the
other emerging from accumulation of the nuclei-cluster structures after the propagation of a shock wave. From the analysis of the acoustical noise the wideband lies between (6 - 10) kHz; while the light pulse emission is approximately between (10 to 20) ns in width and is accompanied systematically by shock waves with a bandwidth of 2 MHz approximately.

5. Concluding remarks
Dynamics and acoustics of a cavitating Venturi using a homogeneous air-propylene glycol mixture have been experimentally studied. We show the cavitation patterns as function of the pump power, and a graphical template of the distribution of the Venturi conditions as a function of the cavitation parameter. Our observations show for the first time the sudden formation of bubble clouds in the straight portion of the pipe after the diverging section of the Venturi. We hypothesized that this is due to pre-existence of nuclei-cloud structures which suddenly grow up by a sudden drop in pressure by the tensile tails of shockwaves.
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Table 1. An example of the evolution of the cavitation in Venturi device using propylene glycol.

| %  | Representative frame | two-dimensional scheme | Description |
|----|----------------------|------------------------|-------------|
| 20 | ![Representative frame](image1.png) | ![two-dimensional scheme](image2.png) | A jet and turbulent zone (mixing zone inside the straight pipe) immersed in a homogeneous liquid. |
| 30 | ![Representative frame](image3.png) | ![two-dimensional scheme](image4.png) | Onset of streamer structures and turbulent zone. |
| 35 | ![Representative frame](image5.png) | ![two-dimensional scheme](image6.png) | Mixed cavitation in the axial layers and the onset of the emission of shock waves. |
| 36 | ![Representative frame](image7.png) | ![two-dimensional scheme](image8.png) | Phase change in the throat and the divergent zone of Venturi. |
| 38 | ![Representative frame](image9.png) | ![two-dimensional scheme](image10.png) | The stagnation cloud undergoes spallation and the clusters are dragged by the flow towards the straight section of the pipe. |
| 40 | ![Representative frame](image11.png) | ![two-dimensional scheme](image12.png) | New cloud formation and dissolution of the former. |
| 41 | ![Representative frame](image13.png) | ![two-dimensional scheme](image14.png) | The former cloud “reborn” in the straight section of the pipe by a sudden drop in pressure by the tensile tail of a shockwave. |
| 42 | ![Representative frame](image15.png) | ![two-dimensional scheme](image16.png) | Two clouds, one fills the divergent zone and the other emerges from the nuclei-cluster structures after propagation of a shock. |

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