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Choked cavitation in micro-orifices: An experimental study

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ABSTRACT

Choked cavitation was experimentally investigated with three circular micro-orifices with diameters of 150 μm and 300 μm and thicknesses of 1.04 mm, 1.06 mm and 1.93 mm. Water was used as the test fluid, and experiments were carried out with upstream pressures in the range of 5.1–13.5 MPa. The cavitation number at the inception and cessation of choked cavitation was found to increase with increasing the micro-orifice diameter and thickness. This suggests that micro-orifices could be characterized by very small choked cavitation numbers and therefore might be less susceptible to choking than their macro-scale counterparts. The cavitation number at the inception and cessation of choked cavitation was independent of the upstream pressure, downstream pressure, average flow velocity and orifice Reynolds number. At choking, the ratio of the upstream pressure to the downstream pressure is constant for a given micro-orifice, while during choked flow the mass flow rate through the micro-orifice is proportional to the square root of the upstream pressure.

1. Introduction

The progress achieved over the last decades in microfabrication techniques has promoted the flourishing of microfluidics, which has become an active research area in modern fluid mechanics. Microfluidic systems such as micro evaporators, micro condensers, micro heat sinks, micro pumps and micro valves are critical in several industrial applications [1–8], while lab-on-chip micro devices are revolutionizing clinical pathology [9] and molecular biology [10]. Micro-orifices, in particular, are encountered in microfluidics systems such as micro cooling systems, micro evaporators, micro pumps, micro valves, and micro injectors. Moreover, micro-orifices have also been employed in corrosion studies to mimic the manifold to tube transition of heat exchangers and steam generators, notably for nuclear power applications [11]. Furthermore, micro-orifices are employed as expansion devices in vapor compression refrigeration systems for automotive and residential air conditioning [12–19]. In these latter applications, in particular, micro-orifices with diameter in the range of 400–1500 μm and thickness to diameter ratio up to 30–35 are implemented between the condenser and the evaporator to reduce the system pressure at the evaporator inlet and to control the flow of refrigerant through the system. A sound understanding of fluid mechanics phenomena at small scale, on the order of 1–1000 μm, is clearly required for the design and reliable operation of microfluidic systems. While fluid mechanics phenomena at conventional scale are typically controlled by inertia and other volumetric effects, in microscale systems surface effects become more important, and consequently fluids in microsystems can behave differently from macroscopic systems. Design methods specific for microscale systems are typically required in practical applications, as macroscale design tools frequently do not extrapolate to small scale.

Cavitation is broadly defined as the formation of gas or vapor cavities in a liquid triggered by a reduction in local pressure. With liquid flow in tubes and channels, in particular, cavitation occurs where the static pressure is lower than the local vapor pressure of the liquid, and is typically observed when the liquid flow undergoes strong accelerations that cause rapid changes in the static pressure. Dissolved gases and gas microbubbles in the flowing liquid provide nucleation points for cavitation inception. When subjected to higher static pressure, the voids generated in the liquid during cavitation can implode. High pressure shock waves propa-

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Nomenclature

d	orifice diameter (m)	t	orifice thickness (m)
D	tube diameter (m)	V	orifice average flow velocity (m s^{-1})
K	orifice dimensionless pressure drop (–)	ΔP	pressure drop across the orifice (Pa)
P_{down}	static pressure downstream of the orifice (Pa)	μ	liquid viscosity (kg m^{-1} s^{-1})
P_{up}	static pressure upstream of the orifice (Pa)	ρ	liquid density (kg m^{-3})
P_v	liquid vapor pressure (Pa)	σ	orifice cavitation number (–)
Re	orifice Reynolds number (–)		

gate from the implosion centers, inducing cyclic stresses on the exposed solid surfaces that can result in structural vibration, noise and surface wear.

Any fluid system is potentially vulnerable to cavitation, and microfluidic systems are no exception. If controlled, however, cavitation can be exploited to enhance fluid mixing and transport rates. This is particularly attractive in microscale applications, where liquid flows are most of the times laminar and transport processes are controlled by molecular diffusion, a relatively slow process. Schneider et al. [20], for example, reported a significant heat transfer enhancement with liquid flows through microchannels in the presence of cavitation induced by a micro-orifice placed at the microchannel inlet, notably with minimal pressure drop penalty with respect to a non cavitating liquid flow. Cavitation in micro-orifices can also be exploited to enhance the performance of multi microchannel evaporators [21]. In these systems, micro-orifices are manufactured at the inlet of the channels to promote an even flow distribution among the channels and avoid backflow and instabilities. Controlled cavitation at the inlet micro-orifices can be exploited to seed the flow with vapor bubbles to avoid the comparatively low efficiency liquid preheating phase that precedes the onset of nucleate boiling. Moreover, seeding the flow with vapor bubbles also eliminates the onset of nucleate boiling hysteresis and the resulting system oscillation typically observed at start-up with high wettability solid–liquid combinations, such as refrigerants flowing in metallic microtubes.

Despite the practical relevance of cavitation in micro-orifice flow, the subject has not been extensively investigated to date and only a relatively low number of studies is available [22–30]. In particular, Ramamurthi and Nandakumar [23] investigated the behavior of water flow in circular orifices with diameters in the range of 300–2000 μm, Mishra and Peles [24] and Singh and Peles [27] performed similar experiments on rectangular micro-orifices with 20.6 μm and 56.8 μm hydraulic diameters using water and ethanol, while Tu et al. [26] tested two circular micro-orifices with diameters of 31.0 μm and 52.0 μm with refrigerant R134a. These investigations revealed similarities as well as differences between cavitation observed in micro-scale orifices and cavitation observed in their macro-scale counterparts, such as cavitation inception number values lower than those typical of macro-scale orifices and an effect of the micro-orifice geometry on cavitation. Notably, the available data are too scattered to advance a reliable theory on micro-orifice cavitation, and more experimental investigations are clearly needed. This study was therefore conducted to advance the knowledge on cavitation in micro-orifice flow by experimentally investigating chocked cavitation with water flow in circular micro-orifices with diameters of 150 μm and 300 μm and thicknesses of 1.04 mm, 1.06 mm and 1.93 mm.

2. Experiments

As schematically shown in Fig. 1 (top and middle), the test section used in the present study consisted of a 12.0 mm micro-orifice plate sandwiched between two 10.0 ± 0.1 mm ID and 12.0 ± 0.1 mm OD stainless steel circular tubes using a bored-through Swagelok port connector and two polymeric O-rings to seal the matching surfaces. The length of the straight tube upstream of the micro-orifice was 1.50 m, corresponding to a tube length to tube diameter ratio $L/D = 150$, which is sufficient to damp out inlet effects and provide fully developed flow conditions upstream of the micro-orifice. The length of the straight tube downstream of the micro-orifice was 0.50 m, corresponding to a tube length to tube diameter ratio $L/D = 50$. The test section was instrumented with five pressure gauges to measure the static pressure upstream and downstream of the micro-orifice: one pressure gauge was positioned one tube diameter upstream of the micro-orifice plate, while four pressure gauges were positioned downstream of the micro-orifice plate at distances of 0.1, 0.5, 1 and 15 tube diameters from the orifice plate. This allowed the measurement of the pressure drop across the micro-orifice and also of the static pressure profile immediately downstream of the orifice plate. It is worth highlighting that the pressure profiles measured downstream of the orifice plate are not presented here, and only the upstream pressure (measured one tube diameter upstream of the micro-orifice plate) and the downstream pressure (measured 15 tube diameters downstream of the micro-orifice plate) are considered in the analysis that follows. The pressure lines were built with stainless steel circular tubes (1.0/1.6 mm ID/OD), laid along the tube internal periphery in order to minimize the disturbance to the micro-orifice discharge. The pressure lines were precisely positioned and sealed at the end of the test section with Conax feedthrough connectors. The reduction in the tube flow area (2.6% upstream and 7.7% downstream of the micro-orifice plate) due to the insertion of the pressure lines was accounted for in the data processing. The combination of the Swagelok bored-through port connector, the polymeric O-rings and the Conax feedthrough connectors used to assemble the test section was proved in preliminary static tests to be leak proof up to a static pressure of 15 MPa.

As schematically shown in Fig. 1 (bottom), the test section was connected to a recirculating flow loop capable of delivering micro-filtered and ultra-high purity water (electrical conductivity of 0.055 μS/cm) at variable pressure (adjustable within 0.1–20.0 MPa) and low flow rate (up to 20 g/s). The recirculating flow loop comprises a recirculating autoclave, which enables accurate control of the water chemistry, with a flow cell line that is branched from the high pressure line. The flow rate and downstream pressure were controlled via a regulating needle valve fitted at the end of the line before the water was discharged to the drain. The recirculating flow loop comprises a feedtank where high purity water was stored and deoxygenated before being pumped into an autoclave vessel via a high pressure diaphragm pump, which was properly damped with a pulsation damper to assure pulsation free flow conditions. The test water was deoxygenated by purging the water with nitrogen at an absolute pressure between 180 and 280 kPa. The dissolved amount of oxygen measured with an oxygen sensor Orbisphere (510) was below 10 ppb. The mole fraction of the nitrogen gas dissolved in the test water