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The effect of dissolved non-condensable gas on cavitation within a nozzle

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1 Introduction

Cavitation is a phenomenon where liquid changes phase to vapour when the static pressure drops below its saturated pressure. Contaminants in the liquid, wall roughness, and dissolved gas, can pose as nucleation sites enhancing cavitation behaviour. Cavitation bubbles collapse when the static pressure increases. However, when dissolved non-condensable gas is present, gas may diffuse into the cavitation bubbles, impeding collapse. The release of gas changes the effective bulk modulus and viscosity, which in turn affects performance and reliability of hydraulic systems (Freudigmann *et al.*, 2017). Optimisation and mitigation strategies for gas release in hydraulic systems can be developed by understanding cavitation behaviour in the presence of dissolved gas.

2 Methodology

The current study investigates cavitation across a transparent acrylic round nozzle with a diameter $D = 1.67$ mm and length $L = 3.8$ mm (figure 1b)). A bladder accumulator is connected upstream of the nozzle, where the working fluid is pressurised using Nitrogen gas (figure 1a)). The downstream end of the nozzle is connected to a storage tank which in turn is connected to a vacuum pump. Downstream pressure is controlled by a back-pressure regulator placed between the vacuum pump and the storage tank.

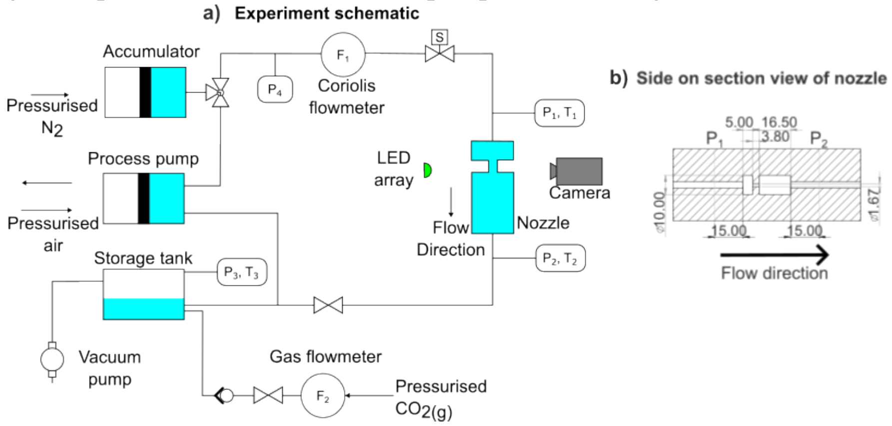

Figure 1. a) Flow loop, inclusive of equipment and sensors, connecting the nozzle to the accumulator and the storage tank. **b)** Section view of the nozzle geometry.

The mass flow rate ($\dot{m}$) through the nozzle is measured using a coriolis flowmeter placed upstream. Static pressure transducers (P_1, P_2) and temperature sensors are placed 15 mm upstream and downstream from the nozzle contractions. Measurements from these sensors are used to calculate the Reynolds number and cavitation number using equations 1 and 2 where μ, and $P_{sat.}$ denote the liquid viscosity and saturation vapour pressure, respectively.

$$Re = \frac{4\dot{m}}{\pi D \mu} \quad (1) \qquad K = \frac{P_1 - P_{sat.}}{P_1 - P_2} \quad (2)$$

The working fluid used for the experiment is water and the non-condensable gas used is carbon dioxide. The water is degassed for approximately a week prior to the experiments. For the experiments with dissolved gas, CO_2 is steadily introduced into the water in the storage tank through a gas line fitted with a sparging stone. A magnetic stirrer mixed the water whilst filling CO_2, thereby ensuring homogeneous dissolved gas concentration. CO_2 is introduced until the pressure of the storage tank (P_3) reached 40 psi. Using Henry's law, the concentration of non-condensable is given by:

$$H_s^{cp} = c/P_3 \tag{3}$$

where H_s^{cp} is the temperature dependant Henry's constant for CO_2 solubility in water, the concentration (c) of dissolved CO_2 is calculated to be 107.98 mol/m^3.

Pressure conditions are adjusted to study two different levels of cavitation intensity. The first is incipient cavitation where the upstream and downstream pressures of $P_1 = 78.1 \pm 2.1$ psi and $P_2 = 37.0 \pm 1.4$ psi resulted in a cavitation number $K = 1.89 \pm 0.06$. The second condition is the intermediate cavitation where the cavity length reached the end of the region of interest. The upstream and downstream pressures $P_1 = 76.6 \pm 1.5$ psi and $P_2 = 33.9 \pm 1.3$ psi, respectively, yielded a cavitation number $K = 1.79 \pm 0.05$. These two cases are repeated for the degassed and the dissolved gas conditions. The pressure conditions are adjusted such that a Reynolds number $Re_D = 3.9 \times 10^4$ (or similar) is maintained across all four experimented cases.

A light emitting diode (LED) array and a monochrome Photron SA-Z camera are placed either side of the nozzle. High speed images, captured at 100 kHz, are background-subtracted and normalised to identify vapour and gas locations within the nozzle.

3 Results & Conclusion

The time averaged intensity contour plots of the four cases (figure 2a)), revealed the increase in cavity length with the presence of dissolved gas. After binarizing the normalised image, the cavity length is measured by detecting the largest connected region. On average, with dissolved gas, the cavity is 0.25D longer at inception conditions and 0.35D longer at intermediate conditions (figure 2b)). The dissolved CO_2 acts as nucleation sites increasing the propensity for water to cavitate, thereby leading to longer cavities (Brennen, 2013).

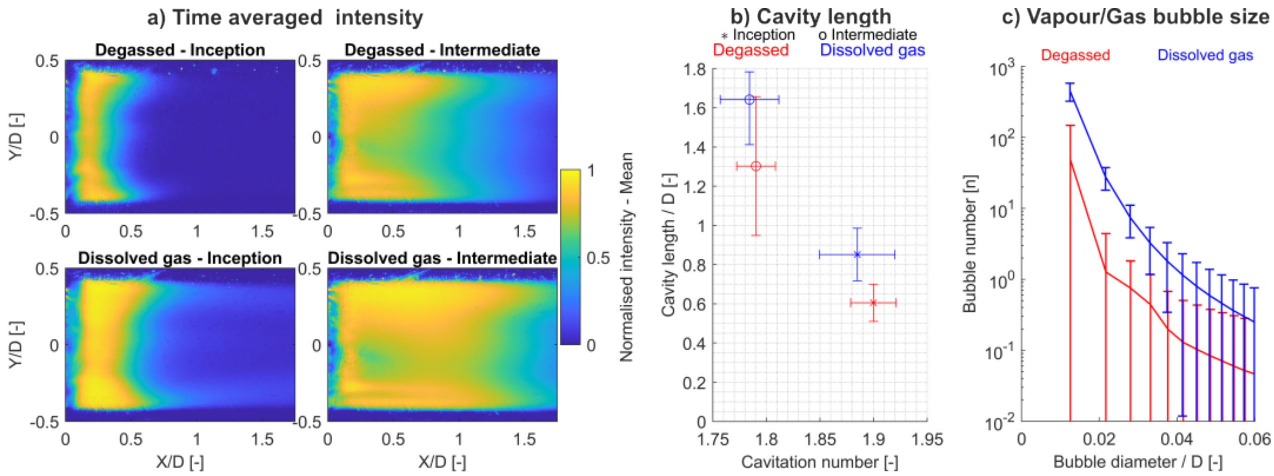

Figure 2. a) The time averaged mean of the normalised intensity distribution for all cases. **b)** The cavity length variation with the cavitation number. **c)** Histogram of the range of bubble diameters captured downstream of the cavity at inception pressure conditions. The error bars for both **b)** and **c)** represent the standard deviation.

At inception conditions with dissolved gas, elevated normalised light intensity levels are detected downstream of the cavity, signifying the presence of gas bubbles. The number of bubbles detected in the binarized images, were significantly higher in the dissolved gas case compared to the degassed case (figure 2c)). The dissolved gas diffuses into the voids created by cavitation, inducing gas release (Freudigmann *et al.*, 2017).

The current study reveals the increased extent of the gas phase, due to a lengthening cavity and gas release, when cavitation occurs in liquids with dissolved gases. The increase in gas within hydraulic systems has the potential to significantly affect the efficiency and reliability of such systems particularly in industrial processes that involve a liquid-gas interface.

References

Brennen, C., 2013, *Cavitation and Bubble Dynamics* Cambridge University Press.

Freudigmann, H., Dörr, A., Iben, U. and Pelz, P. 2017, Modeling of cavitation-induced air release phenomena in micro-orifice flows, *J. Fluid Eng. - T. ASME*