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RESEARCH ARTICLE

Background nuclei measurements and implications for cavitation inception in hydrodynamic test facilities

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Abstract

Water susceptibility and background nuclei content in a water tunnel are investigated using a cavitation susceptibility meter. The measured cumulative histogram of nuclei concentration against critical pressure shows a power law dependence over a large range of concentrations and pressures. These results show that the water strength is not characterised by a single tension but is susceptible to 'all' tensions depending on the relevant timescale. This background nuclei population is invariant to tunnel conditions showing that it is stabilised against dissolution. Consideration of a practical cavitating flow about a sphere shows that although background nuclei may be activated, their numbers are so few compared with other sources that they are insignificant for this case.

1 Introduction

Inception of hydrodynamic cavitation in practical flows is invariably due to heterogeneous nucleation. These discrete sites of weakness, termed nuclei, are typically microbubbles either free in the liquid volume or volumes of gas trapped in or on adjacent surfaces. Depending on nuclei strength, water can sustain tensions well below the saturated vapour pressure before vaporisation occurs. Nuclei have been shown to control not only inception but also the dynamics of cavitation. Although nuclei may typically be microbubbles they may also be gas volumes associated with solid particles (Mørch 2007) or potentially biological entities (O'Hern 1987).

One method for measuring the nuclei concentration is by direct imaging. This may, however, be problematic for several reasons. First, often concentrations can be so low as to make optical measurement times impractically long. Second, nuclei can be so small, of the order of 0.1 μm, such that imaging with visible light wavelengths is beyond diffraction limits. Third, for the case of solid contaminants, imaging would only reveal the size of the particle itself, not the volume of the trapped gas, which is the governing parameter for cavitation inception.

To overcome these limitations, measurements may be taken with a cavitation susceptibility meter (CSM). These devices have been in use since the 1970s to directly measure the nuclei distribution in water. The operating principle involves passing sampled water through a venturi exposing it to reduced pressure, thus activating all nuclei with critical pressures greater than, or equal to, the throat pressure. Nuclei activations are counted by analysing the output signal from a high-frequency piezoceramic sensor, which measures the structural response of the venturi due to nuclei collapse. By varying the flow rate, and hence the throat pressure, a cumulative histogram of nuclei concentration as a function of critical pressure can be measured.

The quantification of the 'susceptibility' of a liquid to cavitation occurrence (i.e. its 'strength'), inherent in the name of the device described above, is a topic where a consensus has yet to be reached. Franc and Michel (2006) suggest that the susceptibility of a liquid is defined by the critical pressure associated with the activation of the largest nuclei present (based on a complete nuclei histogram obtained using a CSM in a time period of about 10 min). A number of authors, (e.g. Chahine and Shen 1986; Arndt 2012) have followed this approach and reported specific values of susceptibility for particular volumes of water. Alternatively, Gindroz and Billet (1994) suggest a practical definition of susceptibility as the tension when the microbubble population corresponds to 10^{-4} cm^{-3}. This second definition

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is somewhat arbitrary and may not be generally applicable. Both of these definitions have stemmed from nuclei measurements obtained using a CSM technique.

Susceptibility is of particular interest in test facilities where conditions can be controlled to a greater degree than in real flows. Nuclei populations are dependent on the dissolved gas content, levels of contaminants, artificial seeding of microbubbles and flow conditions about a model and around the test facility circuit. The cavitation tunnel at the Australian Maritime College (AMC) has the capability to continuously remove microbubbles generated either by cavitation or injected for the purposes of modelling nucleation. Microbubbles larger than about 100 µm are removed in a large settling chamber via coalescence and gravity separation and those remaining are dissolved in a resorber through extended residence at high pressure. The test fluid is demineralised water filtered to 1 µm. Despite these measures, there exists a background nuclei population of unknown nature, for which there may be limited control, that is not amenable to measurement via optical techniques. This population may, however, be characterised using a CSM which is the subject of the present work. A canonical flow about a sphere is also considered in this paper to demonstrate what role these nuclei may play regarding susceptibility, as well as the inception and dynamic behaviour of cavitation.

2 Susceptibility measurements

For this experiment, the tunnel water was degassed to 30% of saturation at atmospheric pressure, which is typical for cavitation testing to ensure all introduced microbubbles are dissolved in the resorber. The tunnel static pressure was controlled at 100 kPa and the water was not recirculated but maintained as a quiescent volume. Water was sampled from the resorber and passed through the CSM and returned to the tunnel via the settling chamber to avoid returned water being re-sampled within the duration of the measurement. The CSM developed at the AMC uses a centrebody type venturi based on a design by YLec Consultants (Grenoble, France) as reported by Pham et al. (1997).

The measured cumulative histogram of nuclei concentration with critical pressure is shown in Fig. 1, with uncertainties as discussed in Khoo et al. (2016). This measurement commenced with the lowest tension and greatest activation rate, and the CSM flow rate was progressively decreased to reduce tension, such that the lowest concentrations and longest measurements were made last. The flow rate was progressed when the first of two conditions were met, either the nuclei count exceeded 100 after recording for at least 30 s, or the time-out of 10^4 s. The long acquisition time was necessary because event rates become very low as the tension is reduced. At the tension of −5 kPa, only one event was recorded in over 2 h. This means that the uncertainty of the concentration at low tensions is higher than desired, but practical considerations prevent the acquisition of extremely long time series. The estimated time required to achieve 100 nuclei activations would be approximately 280 h. Tensions lower than −5 kPa were tested but no activations were recorded within the measurement duration.

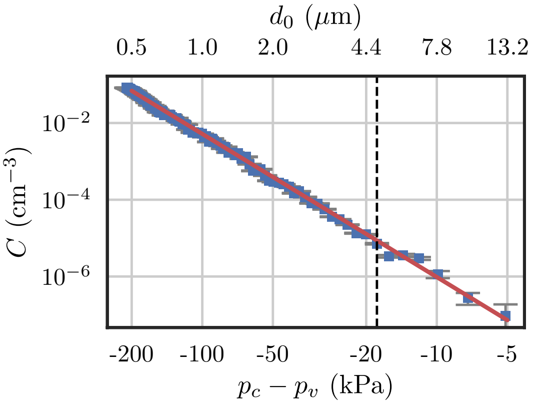

Fig. 1 Cumulative background nuclei distribution in the AMC cavitation tunnel. The trend line is a power fit and the dashed line corresponds to the minimum pressure on the surface of a sphere, as discussed in Sect. 3

The secondary horizontal axis shown in Fig. 1 represents the equivalent initial bubble diameter in the tunnel test section (d_0 at $p = p_0$), which can be calculated numerically as:

$$\frac{4}{27(p_\mathrm{v} - p_\mathrm{c})^2} = \left(\frac{d_0}{4S}\right)^3 (p_0 - p_\mathrm{v}) + \left(\frac{d_0}{4S}\right)^2, \tag{1}$$

where p_c is the critical pressure, p_v is the vapour pressure and S is the surface tension.

The data measured follow a power law, where the concentrations are in cm^{-3} and tensions are in kPa:

$$C = 1.8 \times 10^{-10} (p_\mathrm{v} - p_\mathrm{c})^{3.73}. \tag{2}$$

These results show that the water may not be characterised by a particular tension but rather is susceptible to ‘all’ tensions depending on the relevant timescale. This timescale will, in-turn, depend on relevant length and velocity scales. Equivalent bubble diameters in the test section are less than 13 µm, which is below typical sizes measured by various means in laboratory studies or in the ocean, making comparisons with other data difficult. As these sizes are at or below limits of optical measurement techniques it is also difficult to assess the nature of these nuclei. Due to the low concentrations involved it is also difficult to use microscopy techniques with high magnifications as the volumes required are impractically large. Additional tests have shown that the measured population is independent of the

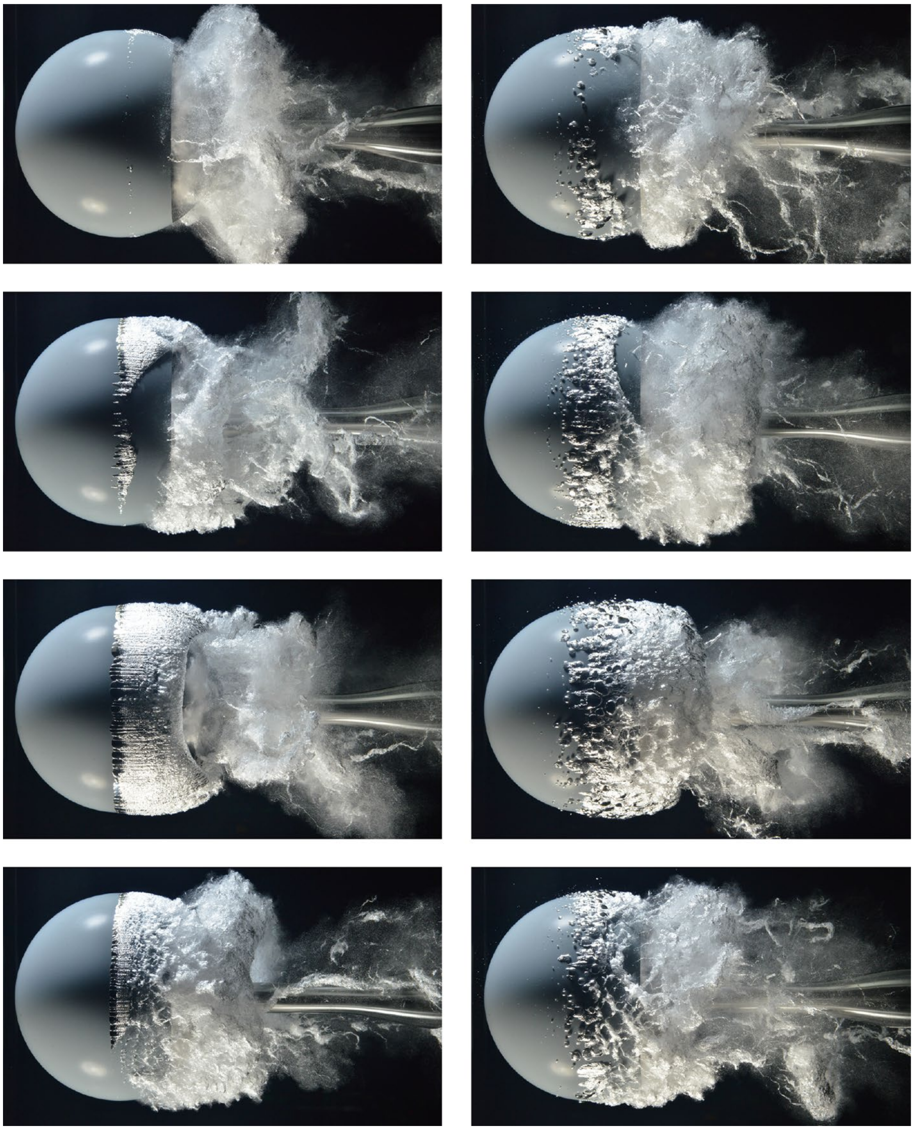

Fig. 2 Two sets of still images selected to depict shedding cycles of cavitation around a sphere for cases where the freestream was unseeded (left) and seeded with nuclei (right). The top row represents the nucleation of the cavity, the middle rows are the growth phase and the bottom row is the cavity collapse. The photographs were taken with a Nikon D800E digital camera with two synchronised stroboscopic light sources

direction of flow rate progression. Furthermore, the population is invariant for all tunnel operating conditions. This shows that unlike microbubbles, either created by cavitation or injected as nuclei, these background nuclei are stabilised against dissolution.

3 An example flow, cavitation about a sphere

To analyse implications of these results, the example of cavitating flow around a sphere is considered. This flow is examined for the cases with only background nuclei present and where the oncoming flow is artificially seeded with nuclei, as considered by de Graaf et al. (2016). The principal parameter characterising the flow is the cavitation number:

$$\sigma = \frac{p_0 - p_\text{v}}{\frac{1}{2}\rho U_\infty^2}. \tag{3}$$

For this example, the sphere diameter is 0.15 m, the freestream velocity is 10.6 m/s, the freestream pressure is 43.7 kPa, the dynamic pressure is 56 kPa and $\sigma = 0.75$. At this cavitation number, the flow undergoes energetic shedding with frequent large-scale cavity extinction and re-nucleation providing insight into nucleation physics. Two sets of four still images for the unseeded and seeded cases, selected to depict a cycle of cavity nucleation, growth and collapse, are shown in Fig. 2.

Single-phase pressure measurements by Achenbach (1972) have shown the minimum pressure coefficient, $C_{\text{p,min}} \approx -1.1$, at a Reynolds number of 1.5×10^6. Thus, for this experiment the minimum pressure in the flow field can be estimated as −18 kPa. This pressure is indicated by the dashed line in Fig. 1 indicating that only large nuclei ($> 5\,\mu$m), which have low concentration, will be activated. The number of activated nuclei can be conservatively estimated by considering potential flow about the sphere, the streamwise distance over which nuclei are activated and the local concentration of activated nuclei from Eq. 2. The total expected number of activated nuclei on the imaged half of the sphere can then be determined from integrating the local active population over all radii with pressure less than vapour pressure. Assuming nuclei are activated over $0.2D$ gives an estimated number of activated nuclei per image of about 6×10^{-4}, or some 1580 photographs to image a single activation.

The top two images of Fig. 2 for the unseeded case, depicting the typical nucleation phase of a shedding cycle, show large numbers of activated nuclei. Since the concentrations of background nuclei are low, this clearly demonstrates that these cannot be due to the background population. Therefore, these nuclei must be from the surface and/or provided by the previously shed cavity. For the seeded case, all images show a large number of activated nuclei continuously supplied from the freestream regardless of the stage of shedding. That is, while background nuclei may be activated, their numbers are so small in comparison with other nucleation mechanisms that they are insignificant.

4 Conclusions

Results of a detailed study into the susceptibility of water in the AMC cavitation tunnel are provided. The concentration of nuclei in the water is shown to follow a power law and is invariant of tunnel conditions and as such are stabilised against dissolution. Further, it is shown that the water is susceptible to all applied tensions, depending on the relevant timescale to activate weaker nuclei. This implies that the length and velocity scales of the flow in question are important in determining the required timescale for inception. Although ever present, the background population does not have any practical effect on the example flow about a sphere, as the number of activated nuclei are so few compared with other nucleation sources.

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