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THE RELATION BETWEEN THE NUCLEI POPULATION AND THE CAVITATION EVENT RATE FOR CAVITATION ON A SCHIEBE BODY

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Abstract

Simultaneous measurements were made of the cavitation event rates on a Schiebe body and the nuclei number distributions in the oncoming stream in the Low Turbulence Water Tunnel at Caltech. Cavitation inception occurred at an average cavitation number of 0.57. Cavitation event rates increased dramatically as the cavitation number was decreased. It was also found that both the magnitude and the shape of the nuclei distribution changed substantially with the operating condition. These changes had very strong effect on the event rate and therefore on cavitation inception number based on a fixed event rate. At the same cavitation number, the changes in the event rate due to different free stream nuclei populations can be as much as a decade. The changes in the shape of the nuclei distribution occurred mostly in the nuclei size range above 15 μm. The nuclei concentration tended to increase as cavitation number was decreased. And the cavitation event rate increased with the free stream nuclei concentration.

The measured nuclei density distributions are used in an analytical model which attempts to correlate the event rate with the nuclei population. The predicted event rates are compared with those observed experimentally.

1 Introduction

A detailed knowledge of the population and distribution of nuclei is vital to the understanding of the cavitation process. Schiebe (1972) found that cavitation on a body is largely dependent on the size and number of the micro bubbles. Since then there have been a number of efforts to measure the nuclei density distribution and to establish a relationship between nuclei spectrum and cavitation (Johnson, 1969, Acosta and Parkin, 1970, Kuiper, 1978, Gates and Billet, 1980 and Katz, 1981). However none of these efforts have established a quantitative relation between the free stream nuclei population and the cavitation event rate. This is largely due to the lack of adequate instrumentation for measuring the nuclei (Billet, 1986). Though many techniques have been developed over the past thirty years, few have been accepted as reliable and repeatable. An exception is the holographic method which involves reconstruction and analysis of a small, three dimensional volume of tunnel water. But the amount of time needed to process such holograms limits its application and does not permit detailed study of the dynamics of nuclei populations in a facility. In the present work, a Phase Doppler Anemometer (PDA) (Tanger and Weitendorf, 1992, Liu *et al.* 1993a, Sato *et al.* 1993) calibrated by the holographic method was used to measure the free stream nuclei.

Other efforts have been made to relate the event rate to the nuclei population. Meyer *et al.* (1992) did numerical calculations of cavitation on a Schiebe body in potential flow using Rayleigh-Plesset equation. By studying the growth and collapse of bubbles of different sizes under various conditions, they were able to calculate theoretical event rates. Ceccio and Brennen (1991) described an analytical model which is similar in concept to that employed by Meyer *el al.* (1992). Further refinements to this model have been introduced by Liu *et al.* (1993b). Important effects, such as the boundary layer flow rate effect, the bubble screening effect, the variation of bubble trajectory in the low pressure region and the observable bubble size effect have been included. The model qualitatively predicted changes in the cavitation event rate as a function of cavitation number, air content and headform size. However, both Meyer *et al.* (1992) and Liu *et al.* (1993b) used a characteristic nuclei distribution in their calculations because of inadequate information on the actual nuclei number distribution. In this paper, measured free stream nuclei distributions are used in the formula proposed by Liu *et al.* (1993b) to correlate the actual event rates and the simultaneously measured nuclei population.

2 Experiments

The experiments were conducted in the Low Turbulence Water Tunnel (LTWT) at Caltech. A full description of the facility is given by Gates (1977). The test section of LTWT has a $31cm \times 31cm$ cross-section and is $2.5m$ long. To minimize solid particles in the water, the tunnel water was filtered by using a $5\mu m$ screen for about 7 to 10 hours before each experiment.

A Schiebe headform of diameter 5.08 cm was made from lucite and was mounted in the center of the tunnel test section, as shown in figure 1. Three flush ring electrodes of silver epoxy covering the entire periphery were installed in the lucite headform and allowed the detection of cavitation events occurring on the headform (Ceccio and Brennen, 1991). A pattern of alternating voltages is applied to the electrodes, and the electric current from each is monitored. When a bubble passes over one of the electrodes, the impedance of the flow is altered causing a drop in current which can be detected. The time between events is also measured and event rate can therefore be calculated.

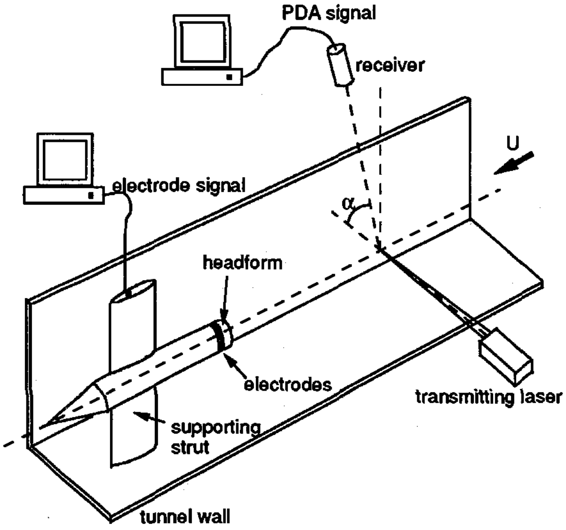

Figure 1: A sketch of the experiment setup. The upstream nuclei distribution is measured by a PDA and the cavitation event rate is measured by the surface electrodes.

A Phase Doppler Anemometer made by Dantec was used to simultaneously measure the fluid velocity, bubble size, nuclei number distribution and concentration, C, on the center line of the water tunnel, 16 cm upstream of the Schiebe body. The PDA uses a $200mW$ Argon-ion laser with $514.5nm$ wavelength. The transmitting optics were mounted horizontally to project through a side window; the receiving optics were mounted above the top window and focused on the center plane of the water tunnel. The receiving optics collected light scattered at an angle of 82° to the incident laser beams. The resulting focal volume measured $0.204\,mm \times 0.203\,mm \times 2.348\,mm$. The data acquisition time for one experiment was about 2 to 3 minutes and the number of samples or nuclei registered was between 500 and 2000. The experiments were performed at velocities, U, varying between $8.6\,m/s$ and $9.6m/s$ and various tunnel pressures, (p_∞), varying from $20.5\,kPa$ to $110\,kPa$, corresponding to cavitation numbers, $\sigma = (p_\infty - p_v)/\frac{1}{2}\rho U^2$ (p_v is the vapor pressure, ρ is the water density), of 0.45 to 2.66. The water temperature was $20^\circ\,C$.

3 Results and Discussion

First we present in figure 2 the variation in the cavitation event rate with cavitation number, for various nuclei concentration ranges. As shown in the figure, the cavitation event rates increased dramatically as the cavitation number decreased. Notice however, that the event rates can vary as much as a decade at the same cavitation number. At the same cavitation number, larger free stream nuclei concentrations correspond to larger cavitation event rates.

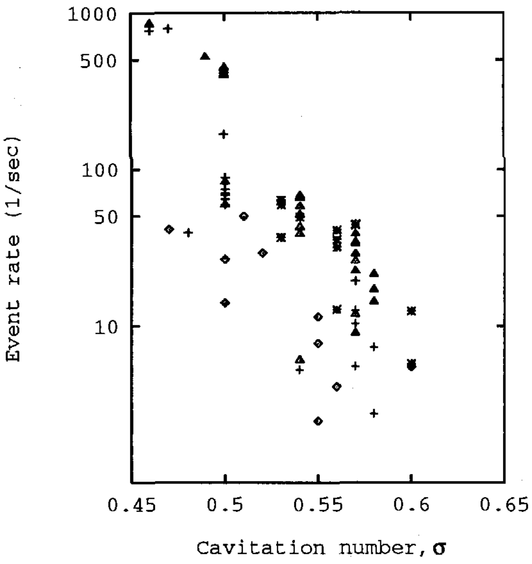

Figure 2: Variations of the cavitation event rate with cavitation number at $U = 9\,m/s$. The variations of event rates are distinguished for various ranges of free stream nuclei concentration, C, in (cm^{-3}): $C < 150$ (◇); $150 < C < 200$ (+); $200 < C < 250$ (△) and $250 < C$ (∗).

We conclude from figure 2, that the cavitation inception number based on a certain event rate, say 10 sec^{-1} increases with free stream nuclei concentration. At the typical criterion of 10 events per second, the cavitation inception number, σ_i, was 0.55 cavitation when the nuclei concentration was less than 150 cm^{-3}. On the other hand, cavitation inception occurred at $\sigma_i = 0.57$ when the concentration was between 200 cm^{-3} and 250 cm^{-3}, and when the nuclei concentration was above 250 cm^{-3}, $\sigma_i = 0.60$.

The effect of the free stream nuclei concentration on cavitation event rate can also be seen in figure 3, where cavitation event rates are plotted against free stream nuclei concentration. At two typical cavitation numbers ($\sigma = 0.45$ and $\sigma = 0.57$) the cavitation event rate increased as the free stream nuclei concentration increased. At $\sigma = 0.45$ as the free stream nuclei concentration increased from 191 cm^{-3} to 266 cm^{-3} , the event rate increased from 589 sec^{-1} to 891 sec^{-1}. At $\sigma = 0.57$, as free stream nuclei concentration increased from 194 cm^{-3} to 257 cm^{-3}, the event rate increased from 10.3 sec^{-1} to 52.4 sec^{-1}. Notice that even at the same cavitation number and with same nuclei concentration, the event rate still varies considerably. This may due to differences in the distribution of nuclei size, which is also a very important factor in determining the event rate (See Liu *et al.*, 1993b). As demonstrated later, variations in

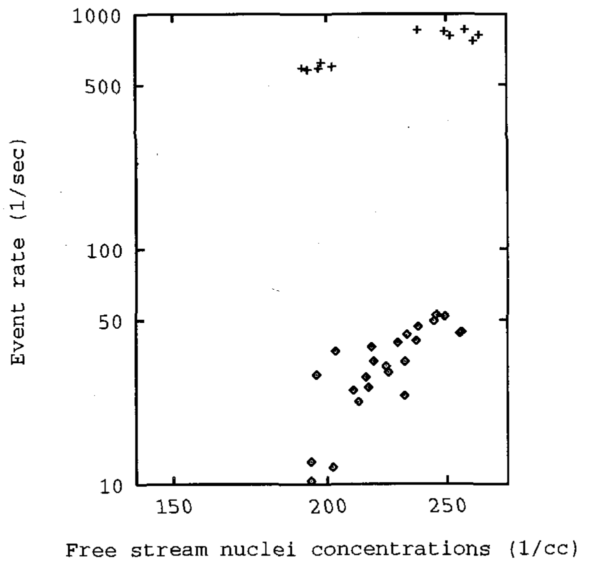

Figure 3: Changes in the cavitation event rate on the Schiebe body as a function of free stream nuclei concentration at $U = 9\,m/sec$ and two cavitation numbers, $\sigma = 0.57\,(\diamond)$ and $\sigma = 0.45\,(+)$.

the shape of the nuclei size distribution in the range above $15\mu m$ lead to different cavitation event rates.

In the present experiments simultaneous measurements were made of the free stream nuclei density distribution and the cavitation event rate. The changes in the free stream nuclei concentration as a function of cavitation number are shown in figure 4. Clearly, for a given cavitation number, the free stream nuclei concentration varied substantially. Since changes in the free stream nuclei concentration are caused by many factors such as cavitation number, initial air content, tunnel velocity and tunnel running time, etc. (Liu *et al.*, 1993a), the variation in the concentration at the same cavitation number is large. At the same cavitation number, the nuclei concentration can vary by more that 100 cm^{-3}. Despite these variations, a basic trend is evident, namely that the free stream nuclei concentration increases as cavitation number is decreased.

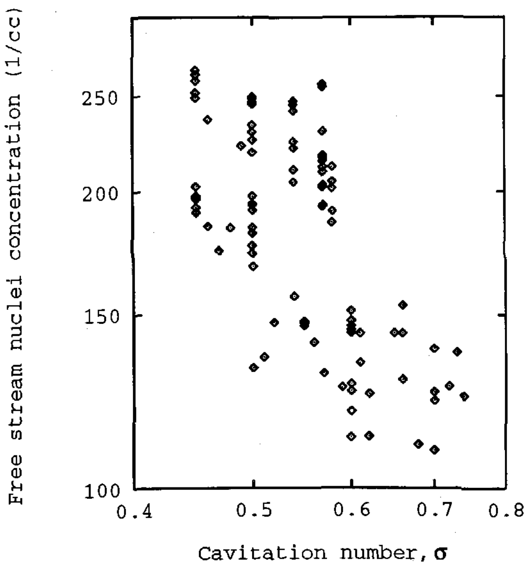

Figure 4: Free Stream nuclei concentration as a function of cavitation number at $U = 9\,m/s$.

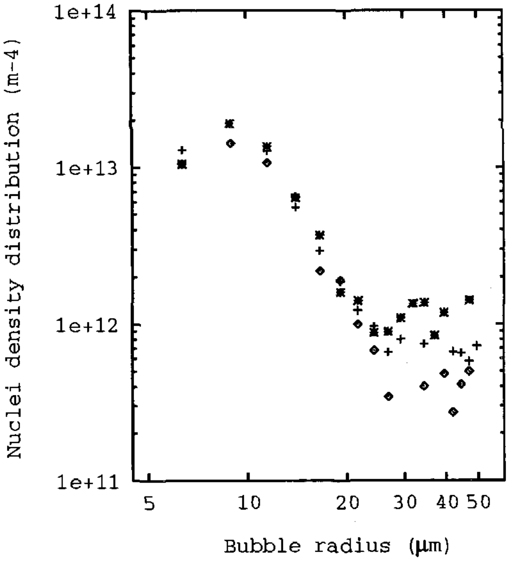

Figure 5: Free stream nuclei number distributions at different cavitation numbers, $\sigma = 0.57\,(\diamond)$; $\sigma = 0.50\,(+)$ and $\sigma = 0.45\,(*)$ and at velocity $U = 9.0\,m/s$

During the cavitation experiments, cavitation inception occurred at about $\sigma_i = 0.60$. It is noticeable in figure 4, that the free stream nuclei concentration exhibits a significant increase when cavitation number is decreased below 0.60. This implies that cavitation itself leads to an increase in the free stream nuclei concentration as often surmised. This is probably the explanation for the cavitation hysteresis effect observed by Holl and Treaster (1961).

Liu *et al.* (1993b) showed that the cavitation event rate depends not only on the free stream nuclei concentration, but also the shape of the nuclei distribution. Experimentally, it was observed that the magnitude and shape of the distributions varied with tunnel operating condition, with air content and with the previous history of operation. By comparing nuclei distributions at various cavitation conditions we may observe the effect of the nuclei distribution on the cavitation event rate (or vice versa). Free stream nuclei density distributions at different cavitation numbers are shown in figure 5 and nuclei distribution at the same

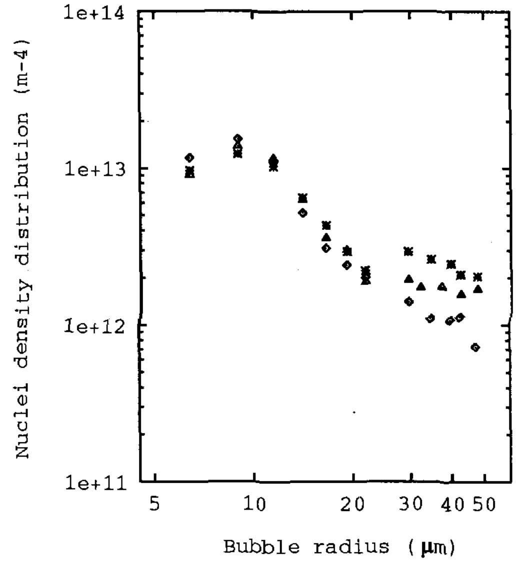

Figure 6: Free stream nuclei number distributions at different cavitation event rates $E = 3sec^{-1}(\diamond)$; $E = 14sec^{-1}(\triangle)$; $E = 34sec^{-1}(*)$; but at the same cavitation number, $\sigma = 0.57$ and velocity, $U = 9.0\ m/s$

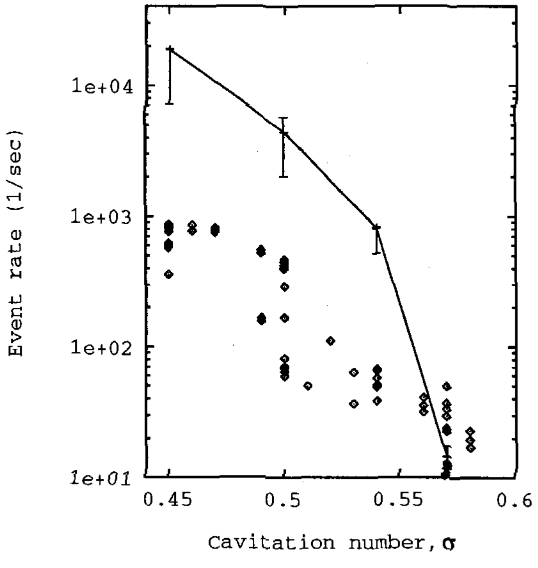

Figure 7: Calculated (⊢+⊣) and observed (◇) cavitation event rates as a function of cavitation number at a tunnel velocity of $U = 9.0\ m/s$.

cavitation number but at different cavitation event rates are shown in figure 6. Note that most of the changes in the shape of the free stream nuclei density occur for nuclei in the size range above $15\mu m$. There is little change in the number of nuclei smaller than $15\mu m$ when the cavitation number is changed. On the other hand, the changes in the number of nuclei larger than $15\mu m$ results in major alteration in the event rate.

Using the experimentally measured free stream nuclei distributions, cavitation event rates were calculated using the *model proposed by Liu et al. (1993b). Comparisons of the* calculated and observed event rates as a function of cavitation number are shown in figure 7. The variation in the event rate with the cavitation number is qualitatively similar to the experimental results, and the predicted cavitation event rates are quantitatively in agreement with the experimental results at the larger cavitation numbers. However, the predicted event rates increase more rapidly than the observed rates as cavitation number is decreased. Consequently, at low cavitation numbers, the predicted event rates can be as much as one order of magnitude bigger than those observed. The reason for this discrepancy at lower cavitation numbers is unknown but it may be caused by an interaction between the bubbles and the suppression of some potential events due to the fact that the nucleus is close to an already expanding bubble.

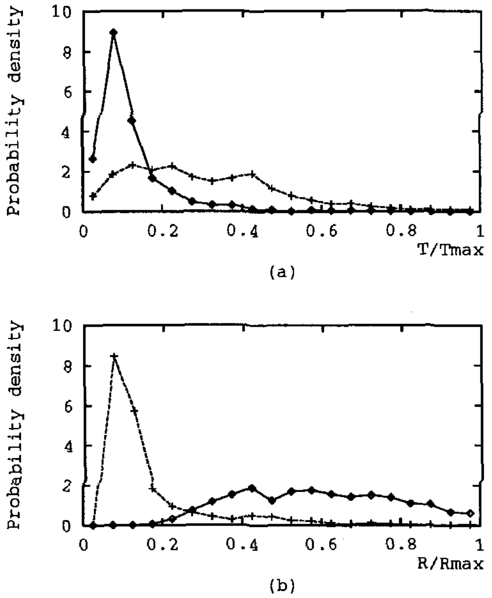

Figure 8: Probability density distributions of (a) the time, T, between two events normalized by the maximum time period between two events, T_{max} and of (b) the bubble radius, R, normalized by the maximum bubble radius, R_{max} at two different cavitation numbers: $\sigma = 0.45$ ($\diamond$) and $\sigma = 0.56$ (+) and at a velocity of $U = 9m/sec$.

The probability density distributions of the time between events and of the bubble radius at two different cavitation numbers are shown in Figure 8. It is clear that at the larger cavitation number ($\sigma = 0.56$) the time between events is more homogeneously distributed and the probability density of bubble radius has a peak in the small size range. Liu et. al. (1993b) showed that a bubble size is proportional to the inverse of the off-body distance of the original nucleus. This implies that at a larger cavitation number, all the nuclei have a good chance to cavitate. On the other hand, at a lower cavitation number ($\sigma = 0.45$), there are very few smaller bubbles and the time between events has a peak at a small value, which means that a nucleus with potential to cavitate but moving along a streamline which is outside a certain off-body distance does not have a chance to grow because of the increasing interaction with larger bubbles. Therefore, to quantitatively predict cavitation at lower cavitation numbers, the interaction between bubbles should be considered.

4 Conclusions

The following conclusions can be drawn from present work.

The cavitation event rate is mainly determined by the cavitation number, increasing dramatically as cavitation number is decreased. However the free stream nuclei population also has a significant effect on the event rate, which increases with nuclei concentration. The shape of the nuclei number distribution is also important. The result is that the cavitation event rate may vary as much as an order in magnitude at the same cavitation number due to the changes in free stream nuclei population. The cavitation inception number based on a certain event rate reflects these variations.

In the past, attempts to correlate the cavitation event rate and the nuclei population (Ceccio and Brennen, 1991, Meyer *et al.*, 1992 and Liu *et al.*, 1993b) have assumed, for lack of better knowledge, that the nuclei number distribution in a given facility has the same magnitude and shape, regardless of the extent of cavitation development on the headform. The present study has demonstrated that substantial changes in free stream nuclei populations may occur during cavitation experiments. As the cavitation number decreases, free stream nuclei concentration tends to increase and, as cavitation on the headform surface develops, the increase in the nuclei concentration becomes greater. The result is significant change in the free stream nuclei distribution, particularly in the size range above $15\mu m$. This causes substantial change in the event rate. At the same cavitation number, the resulting variation in the event rate can be as much as one order in magnitude. It follows that for more accurate evaluation of cavitation, changes in the nuclei population should be carefully monitored and included in any analytical model which attempts to correlate the cavitation event rate with the free stream nuclei population.

The analytical model provides good qualitative prediction of the event rate with cavitation number and free stream nuclei population. At the larger cavitation numbers, the calculated event rates are also in quantitative agreement with the experimental results. However, at the lower cavitation numbers, the predicted event rates are much larger than experimental results. This may due to the interactions between potential events at the lower cavitation numbers.

Acknowledgements

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