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# CAVITATION NUCLEI POPULATION DYNAMICS IN A WATER TUNNEL

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## ABSTRACT

The free stream nuclei number distributions in the Low Turbulence Water Tunnel at Caltech were measured using a Phase Doppler Anemometer. The changes in nuclei number distributions with water tunnel running time, with initial air content, with tunnel velocity varying from $2\,m/sec$ to $9\,m/sec$ and with water tunnel static tunnel pressures ranging from $40\,kPa$ to $110\,kPa$ were examined. Quite complex changes in nuclei number distributions were observed in the nuclei size range of interest from the point of view of cavitation, namely the range from 5 to $200\mu m$. Order of magnitude changes were observed in the nuclei population.

## 1 Introduction

The bubble nuclei number distribution in a test facility can be very important in determining cavitation inception, limited cavitation and even fully developed cavitation (Keller and Weitendorf, 1976, Kuiper, 1978, Ooi,1985, Ceccio and Brennen, 1991). Many years ago Lindgren and Johnson (1966) showed that differences in cavitation in different facilities could be ascribed to differences in the nuclei content. But apart from Keller's (1972,1974) pioneering investigations we know little about why nuclei number distributions take the form that they do or about the changes that may occur during a cavitation experiment.

Very little has been done to investigate the question of the influence of nuclei size distribution on cavitation. The limited evidence available indicates that changes in the nuclei population can be an important factor in water tunnel cavitation experiments (Keller, 1972, 1974, Gates and Acosta, 1978 ) and that the population may vary by as much as an order of magnitude from facility to facility or within the same facility. Peterson (1972) measured cavitation nuclei distributions both by holography and by a light scattering method; his results showed about 1 order of magnitude changes in the nuclei number distribution. We are, however, unaware of any systematic investigation of the cause of these changes and of the factors that influence the nuclei number distributions. Recently, Kuhn de Chizelle and Brennen (1992) and Meyer (1992) attempted to synthesize the event rate on two axisymmetric bodies, using characteristic nuclei number distributions and they identified a significant discrepancy between the experimental and theoretical results, which further underscores the need to explore the free stream nuclei number distribution.

The main difficulty impeding study of cavitation nuclei population dynamics has been inadequate instrumentation for measuring the bubble nuclei (Billet, 1986). Though many techniques for the measurement of cavitation nuclei have been developed over the past 30 years (Ripken, 1959, 1962, Feldberg, 1971, Keller, 1972, Peterson, 1972, Morgan, 1972, Peterson et al, 1975, Gates, 1978 ), 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 processing holographic results is very time consuming and hologram resolution limits its application to particles with radius greater than about $10\mu m$.

Recently, a Phase Doppler Anemometer (PDA) made by Dantec has been used to measure velocities and size distributions of particles including cavitation nuclei (Saffman and Buchhave, 1984). In order to provide verification and calibration of this PDA system, simultaneous measurements of the free stream cavitation nuclei number distributions were made using a PDA and an on-line holographic system at different tunnel speeds, pressures and aeration levels. A typical comparison is shown in figure 1. As one can see in figure 1, substantial agreement between these two

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techniques was achieved. It should be noted that the holographic method was limited to nuclei radii larger than $10\mu m$ and the data only provide calibration of the PDA measurements for bubbles of radius larger than $10\mu m$. We believe that PDA measurements for smaller nuclei radius down to about $5\mu m$ are also valid. Note that the holographic data show some scatter. This is primarily because of the small numbers of nuclei counted in the larger size ranges.

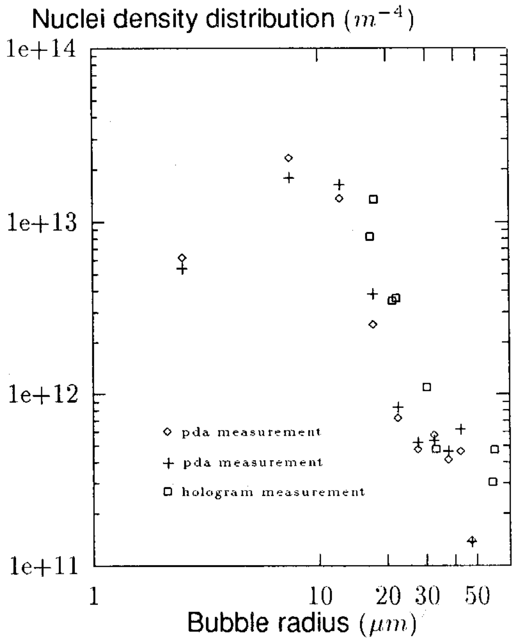

Figure 1: Comparison of PDA measured and holographically measured nuclei distribution functions at a tunnel velocity of $6.10\,m/sec$, pressure of $93.9kPa$ and corresponding cavitation number of $4.89$.

In this paper, free stream nuclei distributions in a water tunnel were measured using a PDA. Changes in nuclei populations with cavitation number, tunnel velocity, air content and tunnel running time are described.

## 2 Experiments

The experiments were conducted in the Low Turbulence Water Tunnel (LTWT) at Caltech. A full description of the facility was presented by Gates (1977). The test section has a $0.31m \times 0.31m$ cross-section and is $2.5m$ long. To eliminate solid particles in the water, the tunnel water was well filtered by using a $5\mu m$ screen for about 7 to 10 hours before each experiment. For all the experiments, the velocity was set, and the static pressure of the water tunnel was controlled by a vacuum system.

To control the air content in the water, a de-aeration system was used. The main component of this system is a closed cylindrical vessel measuring 2.54 meter in length and 0.91 meter in diameter. Tunnel water is pumped to the top of the vessel, then forced through a series of vacuum paths before it is returned to the water tunnel by another pump. The typical flow rate for the de-aeration system was about $2.0 \times 10^{-4}m^3/min$.

An air injection system was also used to change the tunnel nuclei distribution. The air injection draws water from downstream of test section and makes the water saturated by mixing the water with high pressure air. It is then injected into the water tunnel stagnation section by a series of very fine nozzles at a flow rate of about $2.5 \times 10^{-4}m^3/min$. Because of the relative low pressure surrounding the nozzle, it was believed that the air injection only generated very small bubbles.

The Phase Doppler Anemometer was used to simultaneously measure the fluid velocity, turbulent fluctuations, bubble diameter and nuclei concentration at the center of the water tunnel. The PDA utilizes a $200mW$ Argon-ion laser with $514.7\mu m$ wavelength. The transmitting optics were mounted horizontally and the receiving optics were mounted above the top window and focused on the center plane of the water tunnel. This focusing volume measured $0.204\,mm \times 0.203\,mm \times 2.348mm$. The receiving optics collected light scattered at an angle of $82°$ to the incident laser beams. During the experiments, it took about five to fifteen minutes to finish one PDA data acquisition. The number of validated samples for one experiment was from 1000 to 4000.

The experiments were performed under various tunnel velocities, $V$, varying from $2\,m/sec$ to $9\,m/sec$ and various tunnel pressures, $P$, varying from $40\,kPa$ to $110\,kPa$. The corresponding cavitation numbers, $\sigma$, varied from $1.71$ to $22.7$. The water temperature was $20°\,C$. At low speed, the free stream turbulence level was between 4% and 10%, at high speed it was around 2%.

## 3 Results and Discussion

A typical histogram of the nuclei or micro bubbles is shown in figure 2. Notice that a peak appears at the bubble radius of $8\,\mu m$. This is quite different from the results of Peterson, where the nuclei number distributions approach maximum values as bubble radius approaches zero. The velocities of the bubbles were very homogeneous. The root mean square of bub-

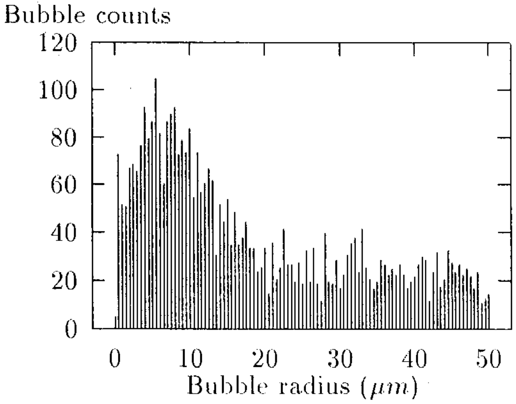

Figure 2: Histogram of cavitation nuclei at $V = 5.12\,m/sec$ and $P = 98\,kPa$.

ble velocities was $0.53\,m/sec$ and the skewness was -9.5 when the free stream velocity was $5.12\,m/sec$ and pressure was $98\,kPa$. Calculation of the correlation coefficient between the velocity and bubble radius shows values around 0.08, which means that the velocity of an individual bubble was quite independent of its size.

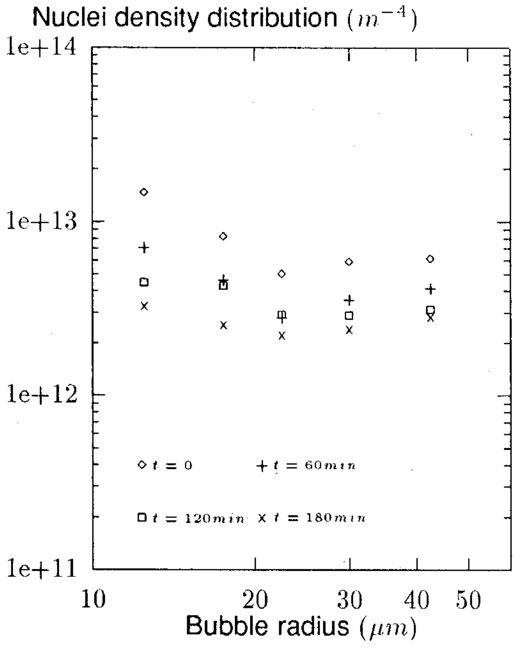

Figure 3: The effect of water tunnel running time on the free stream nuclei number distribution at $V = 3.16\,m/sec$, $P = 104\,kPa$, $\sigma = 22.7$.

The effects of water tunnel running time on the free stream nuclei distributions are shown in figures 3, 4, 5 and 6 and the changes in nuclei concentration as a function of tunnel running time are shown in figure 7. From these figures, It can be seen that the effects are quite different for large cavitation numbers ($\sigma \geq 8.28$), intermediate cavitation numbers ($7.63 \geq \sigma \geq 3.01$) and small cavitation numbers ($\sigma \leq 2.34$). Several experiments were performed at two large cavitation numbers : $\sigma = 22.7$ and $\sigma = 8.28$, where the velocity was $3.16\,m/sec$ and the tunnel static pressures were $104\,kPa$ and $40\,kPa$ respectively. Typical changes in nuclei number distributions at $\sigma = 22.7$ are shown in figure 3, where the water tunnel running time is denoted by $t$. As shown in the figure, the free stream cavitation nuclei distribution decreases about one decade during a three-hour running time. And from figure 7, it is very clear that the nuclei concentration is a decreasing function of time. At $\sigma = 22.7$, the nuclei concentration decreased from $406\,cc^{-1}$ at the beginning to $196\,cc^{-1}$ after 96 $min.$, and decreased further to $135\,cc^{-1}$ after 183 $min.$. And similar decrease in nuclei concentration happened at $\sigma = 8.28$. Also from figure 7, the rate of decline in nuclei concentration slows down as time proceeds. At both $\sigma = 22.7$ and $\sigma = 8.28$, the bubble nuclei concentrations approached the same equilibrium. Statistically, at $\sigma = 22.7$, the standard deviations of bubble

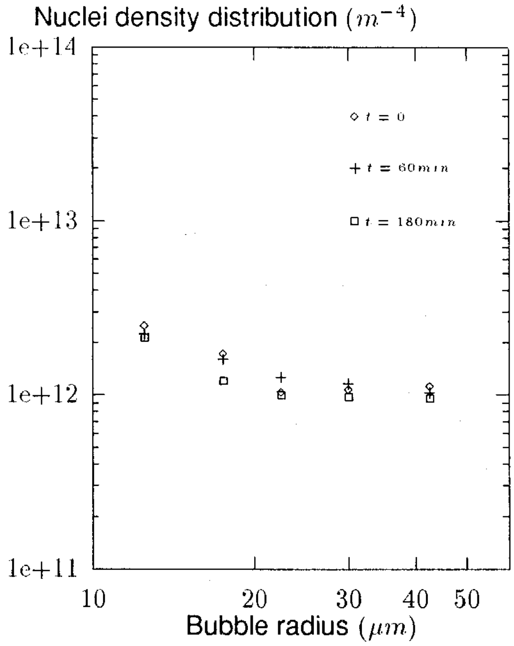

Figure 4: The effect of water tunnel running time on the free stream cavitation nuclei distribution at $V = 5.13\,m/sec, P = 98\,kPa, \sigma = 7.63$.

radii changed very little, namely from 1.26 at the beginning to 1.24 after $183\,min.$. But the mean of the bubble radii increased from $18.05\,\mu m$ to $20.38\,\mu m$. This means that the cavitation nuclei number distribution became flatter as time proceeded.

On the other hand, at intermediate cavitation numbers: $\sigma = 7.63$ and $\sigma = 3.01$, where the velocity is was $5.13\,m/sec$ and the pressures were $98\,kPa$ and $40\,kPa$ respectively, running time had little effect on the free stream cavitation nuclei distributions. As shown in figure 4, there was very little change in the cavitation nuclei number distribution during a 3 hour run at $\sigma = 7.63$. After a h3 our run at $\sigma = 3.01$, the nuclei number in the radius range from 10 to $25\mu m$ remained unchanged while the nuclei number in the radius range from 25 to $50\mu m$ increased slightly, as shown in figure 5. These two trends are also manifested in figure 7, where for both cases, the nuclei concentrations remained almost constant. Again both cases seem to yield the same asymptotic distributions for long running time.

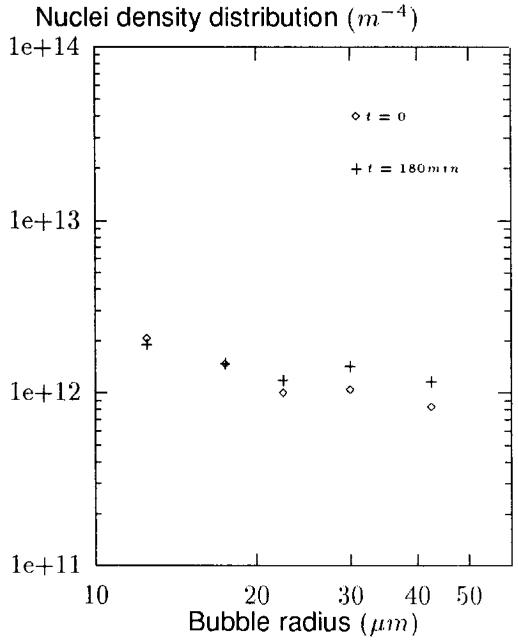

Figure 5: The effect of water tunnel running time on the free stream cavitation nuclei distribution at $V = 5.13\,m/sec, P = 40\,kPa, \sigma = 3.01$.

Finally experiments were also performed at two small cavitation numbers: $\sigma = 2.34$ and $\sigma = 1.17$, where the velocity was $8.00\,m/sec$ and the pressures were $77\,kPa$ and $40kPa$ respectively. Typical changes in nuclei number distributions at $\sigma = 2.34$ are shown in figure 6. The nuclei distributions increase as time proceeds at both of the small cavitation numbers. In figure 7, it can be seen that the increase in cavitation nuclei distribution was completed within 25 minutes, after which the cavitation nuclei distribution did not change. And at $\sigma = 1.17$, the nuclei concentration increases faster than at $\sigma = 2.34$, and the asymptotic distribution approached at $\sigma = 1.17$ is also a little higher than that of $\sigma = 2.34$.

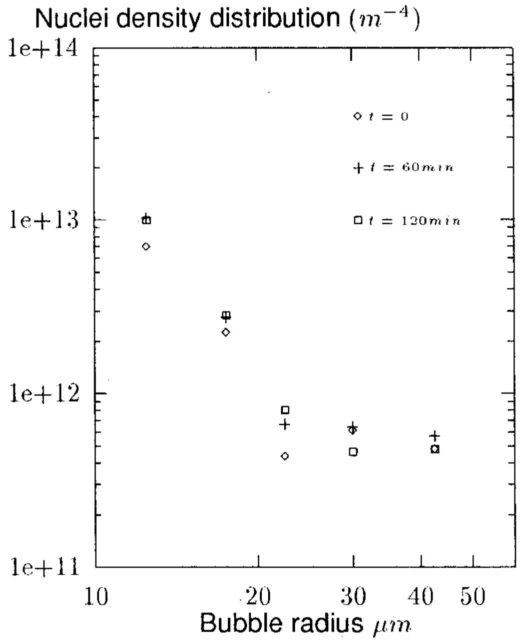

Figure 6: The effect of water tunnel running time on the free stream cavitation nuclei distribution at $V = 8.00\,m/sec, P = 77\,kPa, \sigma = 2.34$.

It may have been noted from figure 7 that the asymptotic nuclei concentrations for $\sigma = 3.01$ and $\sigma = 7.63$ are smaller than those of $\sigma = 8.28$ and $\sigma = 22.7$. The reason for this lies in the history prior to the measurements. The experiments with $\sigma = 3.01$ and $\sigma = 7.63$ were performed just after a four-hour run at $\sigma = 22.7$ during which substantial nuclei solution took place. And since at $\sigma = 3.01$ and $\sigma = 7.63$, the cavitation nuclei distributions remain almost unchanged, the nuclei concentration remained below the asymptotic concentration for $\sigma = 22.7$ and $\sigma = 8.28$ as a result of low initial free air content. It can also be seen in figure 7, that as the cavitation number decreases from 22.7 to 1.17 , the slopes of changes in nuclei concentrations as a function of time goes from negative to nearly zero, then to positive.

Since water tunnel flow fields are quite complicated,

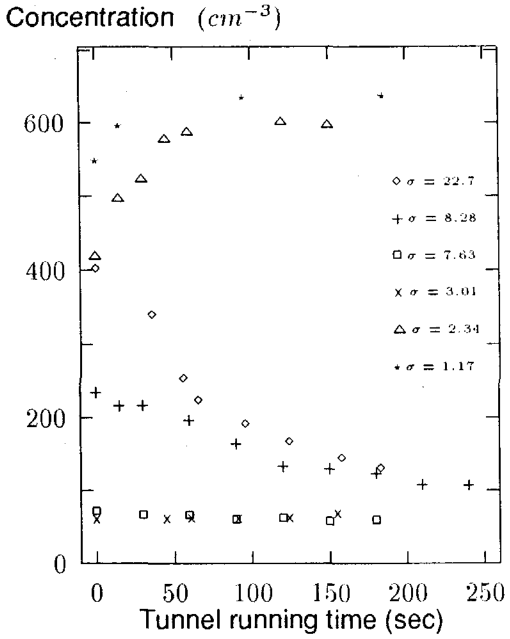

Figure 7: Bubble concentration as a function of water tunnel running time.

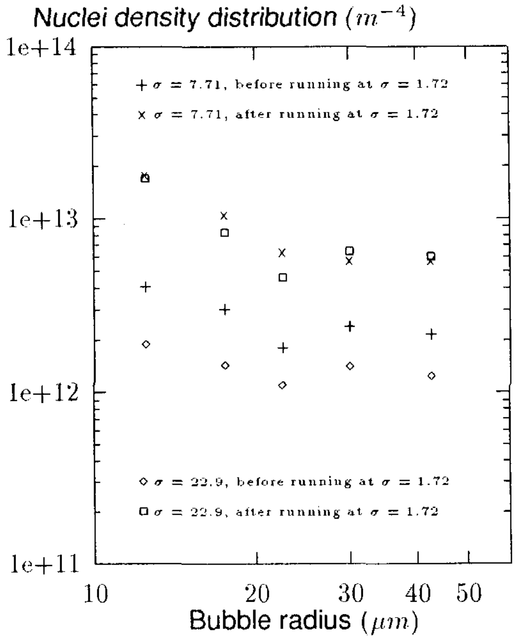

Figure 8: Changes in the free stream cavitation nuclei distribution before and after running the water tunnel at $V = 8.86 m/sec, P = 71kPa, \sigma = 1.72$ for 10 minutes.

we cannot claim that the present trends would necessarily occur in other facilities. But some of the trends would seem to have generality. At large cavitation numbers ($\sigma > 7.63$), when there is no cavitation in the water tunnel, free air bubbles dissolve into the water slowly. But at low cavitation numbers ($\sigma < 3.01$), when there is cavitation in the water tunnel (on the propeller blades, behind the honeycomb or screen), free air bubbles are generated. This raises a question as to whether the cavitation on a model in the working section would, in itself, control the nuclei population in the water tunnel. How long would it take for the model/tunnel generated distribution to reach equilibrium and would that equilibrium differ greatly from operating point to operating point. These questions need further attention.

To verify that running the water tunnel at low cavitation numbers increases the nuclei concentration, the water tunnel was first run at a large cavitation number. Then it was run at a very low cavitation number. After a short time, it was again run at the original condition. Then the nuclei number distributions are compared for the same velocity and cavitation number. Experiments were performed in which the water tunnel was first run at $\sigma = 22.9$ $(V = 3.19\, m/sec,\ P = 106\, kPa)$ and $\sigma = 7.71$ $(V = 5.10\, m/sec,\ P = 98\, kPa)$ respectively for fifteen minutes. After this the water tunnel was run at $\sigma = 1.72$ $(V = 8.86\, m/sec,\ P = 71kPa)$ for ten minutes. Then, in the final phase the water tunnel was again run at initial conditions. The corresponding changes in the nuclei distribution are shown in figure 8. In all cases the nuclei number distributions increased substantially after the low pressure period. Large changes occurred in the nuclei concentrations. The nuclei concentrations were $71\, cc^{-1}$ for $\sigma = 22.9$ and $126\, cc^{-1}$ for $\sigma = 7.71$ originally. After running the water tunnel at $\sigma = 1.72$ for 10 minutes, the nuclei concentration jumped to $472\, cc^{-1}$ for $\sigma = 22.9$ and $460\, cc^{-1}$ for $\sigma = 7.71$. And when the water tunnel was running at $\sigma = 1.72$, the nuclei concentration was $510\, cc^{-1}$.

The de-aerator described above was used to lower the initial air content in the water. As shown in figure 9, de-aeration did change the nuclei distribution, but the decrease in nuclei number distribution was not large. The nuclei concentration decreased from $248\, cc^{-1}$ at the beginning to $178\, cc^{-1}$ after two hours de-aeration, and further decreased to $151\, cc^{-1}$ after another six hours de-aeration. It is also noted that when the air content decreases, the effectiveness of de-aeration goes down. During the first two hours of de-aeration the nuclei concentration decreased by 28%, but the nuclei concentration decreased by only 15% in next six

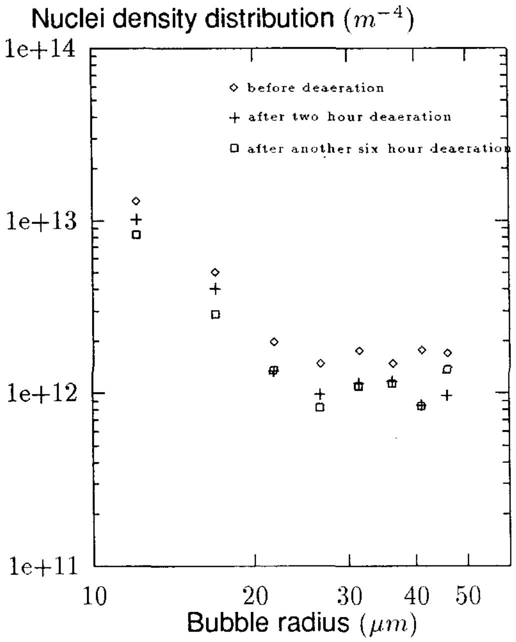

Figure 9: The effect of de-aeration on the free stream cavitation nuclei distribution at $V = 5.12\,m/sec, P = 97\,kPa, \sigma = 7.51$.

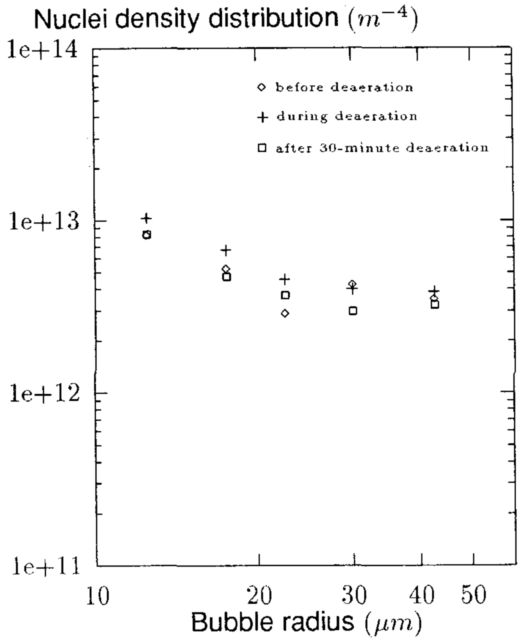

Figure 10: The effect of air injection on free stream cavitation nuclei distribution at $V = 3.16 m/sec, P = 109 kPa, \sigma = 23.66$

hours of de-aeration.

As shown in figure 10, during the course of air injection the cavitation nuclei distribution increased a little. But as soon as the air injection was stopped, the cavitation nuclei distribution returned to the original distribution. The nuclei concentration during air injection rose from $235\,cc^{-1}$ to $273\,cc^{-1}$ during air injection, and returned to $233\,cc^{-1}$ immediately after the air injection was stopped.

We conclude that the air injection used here is not an effective way to increase free stream cavitation nuclei distribution. The main reason is that the flow rate of the air injection used here was so small that it took a long time to make evident changes in the large volume of tunnel water.

## 4 Conclusions

We can draw the following conclusions from these *preliminary investigations of the population dynamics* of cavitation nuclei in the Low Turbulence Water Tunnel at Caltech:

1. The changes in cavitation nuclei distribution in a water tunnel are very complicated and may be influenced by the air content, water tunnel running time, velocity and pressure. The changes in the nuclei distributions can be as much as an order of magnitude.

2. Running water tunnel at different cavitation numbers for a long time has a large effects on the nuclei concentration. At low cavitation numbers, the concentrations increase within a couple of minutes; at intermediate cavitation numbers, the nuclei concentrations remain almost constant and at large cavitation numbers, the nuclei concentrations decrease over long times. There appears to be a specific asymptotic nuclei concentration for each specific operating condition.

3. De-aeration and running the water tunnel at very large cavitation number for a long time can decrease the nuclei concentration effectively. And running the water tunnel at a low cavitation number can increase the nuclei concentration substantially. But air injection with injecting saturated water into water tunnel is not an effective way to increase nuclei concentration.

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## References

Billet, M. L., 1986, "The importance and measurement of cavitation nuclei." *Proc., Advances In Aerodynamics, Fluid Mechanics and Hydraulics, ASCE.*

Ceccio, S. L., and Brennen, C. E., 1991, "Observations of the dynamics and acoustics of traveling bubble cavitation." *J. of Fluid Mechanics*, vol. 233, pp.633-660.

Kuhn de Chizelle, Y., and Brennen, C. E., 1992, "Cavitation nuclei concentrations and event rates." Ph.D. Thesis, California Institute of Technology, Pasadena, CA.

Feldberg, L. A., and Shlemenson K. T., 1971, "The holographic study of cavitation nuclei." *Proc., IUTAM Symp. Non-steady Flow of Water at High Speed*, pp.239-42, Leningrad, USSR.

Gates, E. M., 1977, "The influence of free stream turbulence, freestream nuclei populations and drag reducing polymer on cavitation inception on two axisymmetric bodies." Technical report, Rep. E182-2., Division of Engineering and Applied Sciences, California Institute of Technology, Pasadena, CA.

Gates, E. M., and Acosta, A. J., 1978, "Some effects of several free-stream factors on cavitation inception on axisymmetric bodies." *Proc., 12th Symp. Naval Hydrodyn., pp.86--108, Washington DC..*

Keller, A. P., 1972, "The influence of the cavitation nucleus spectrum on cavitation inception, investigated with a scattered light counting method." *ASME J. Basic Eng.*, pp.917-925.

Keller, A. P., 1974, "Investigations concerning scale effects of the inception of cavitation." *Proc., Conf. on Cavitation*, pp.917-925. Inst. Mech. Eng..

Keller, A. P., and Weitendorf, E. A., 1976, "Influence of undissolved air content on cavitation phenomena at the propeller blades and on induced hull pressure amplitudes." *Proc., IAHR Symp. Two Phase Flow and Cavitation in Power Generation System*, pp.65-76, Grenoble, France.

Kuiper, G., 1978, "Scale effects on propeller cavitation inception." *12th Symp. Naval Hydrodyn.*, pp.400-429, Washington DC..

Lindgren, H., and Johnson C. A., 1966, "Cavitation *inception on headforms: I. T. T. C. comparative experiments." Proc., 11th Intl. Towing Tank Conf..*

Meyer, R. S., 1992, "A relation between nuclei distribution and cavitation event rate via numerical solution." *Proc., ASME National Conference*, Los Angels, CA.

Morgan, W. B., 1972, "Air content and nuclei measurement." *Proc., 13th Int. Towing Tank Conf.*, vol. 1, pp.657-674, Berlin/Hamburg, Germany.

Ooi, K. K., 1985, "Scale effects on cavitation inception in submerged water jets: A new look." *J. of Fluid Mechanics*, vol. 151, pp.367-390.

Peterson, F. B., 1972, "Hydrodynamic cavitation and some considerations of the influence of free gas content." *Proc., 9th Symp. Naval Hydrodyn.,*, vol. 2, pp. 1131-1186, Paris, France.

Peterson, F. B., Danel, F., Keller, A., and Lecoffe, Y., 1975, "Determination of bubble and particulate spectra and number density in a water tunnel with three optical techniques." *Proc., 14th Int. Towing Tank Conf.*, vol. 2, pp. 27--52, Ottawa, Canada.

Ripken, J. R., and Killen, J. M., 1959, "A study of the influence of gas nuclei on scale effects and acoustic noise for incipient cavitation in a water tunnel." Technical Report Rep. 27-B.49, St. Anthony Falls Hydraul. Lab..

Ripken, J. R., and Killen, J. M., 1962, "Gas bubbles: their occurrence , measurement, and influence in cavitation testing." *Proceedings IAHR Symp.*, pp. 37-57, Sandai, Japan.

Saffman, M., and Buchhave, P., 1984, "Simultaneously measurement of size, concentration and velocity of spherical particles by a laser Doppler method." *Proc., 2nd Intl. Symp. on Applications of Laser Anemometry to Fluid Mechanics,* Lisbon.