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Investigation Of The Behavior Of Ventilated Supercavities

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ABSTRACT

The topic of supercavitation is of considerable interest to drag reduction and/or speed augmentation in marine vehicles. Supercavitating vehicles need to be supplied with an artificial cavity through ventilation until they accelerate to conditions at which a natural supercavity can be sustained. A study has been carried out in the high-speed water tunnel at St. Anthony Falls Laboratory to investigate some aspects of the flow physics of such a supercavitating vehicle. During the present experimental work, the ventilated supercavity formed behind a sharp-edged disk was investigated utilizing several different configurations. Results regarding cavity shape, cavity closure and ventilation requirements versus cavitation number and Froude number are presented. Additionally, effects related to flow choking in a water tunnel test section are discussed. Results obtained are similar in character to previously reported results, but differ significantly in measured values. Cavity shape, particularly aft of the maximum cavity diameter, is found to be a strong function of the model support scheme chosen.

INTRODUCTION

Supercavitation is viewed as a significant drag reduction technology that can result in significantly higher speeds underwater. In order to fully capitalize on this technology ventilation is required for acceleration up to design speeds and for operation at less than optimal speed. Supercavitation occurs when a submerged, moving body is enveloped by a large, continuous cavity. It provides a means of significantly reducing the drag of an underwater body, thus enabling a dramatic increase in maximum speed. Small cavitation numbers, $\sigma_c = 2(p_o - p_c)/\rho U_o^2 < 0.1$, are required for supercavitation to occur. There are different ways of achieving this: (1) by increasing the free stream velocity, also referred to as natural supercavitation

(this requires $U_o > 45\text{m/s}$ at sea level, and increases with submersion depth, or p_o), (2) by decreasing the ambient pressure, p_o (only feasible in closed-circuit water tunnels), or (3) by increasing the cavity pressure, p_c , through ventilation of the cavity (artificial or ventilated supercavitation). Reichardt [1] first showed that it was possible to create and study supercavitation by artificially ventilating the flow around a body.

PREVIOUS RESULTS

Our study of ventilated flow was planned and implemented as an interactive experimental/numerical study. Initial studies were carried out using a test body with a sharp edged disk at the nose and special ventilation ports. It was also equipped with static pressure ports and miniature pressure transducers for measurement of unsteady pressure in the cavity. Careful consideration was given to cavitation choking in designing the size of the body. In this early work (Wosnik, [2]) we focused on some aspects of the flow physics of such a ventilated supercavitating vehicle. Cavity shape and re-entrant jet interaction were described qualitatively using digital strobe photography. Ventilation gas requirements to sustain an artificial cavity were studied at different velocities. It was found that the strut shape critically affects air demand through cavity-strut wake interaction. Velocity measurements were made in both the non-cavitating and the ventilated cavitating wake. A new grayscale technique was developed to measure the void fraction of gas to liquid in the wake. The technique was found to show promise as an inexpensive means to measure void fraction in two-phase flows [2].

Some of the detailed measurements Wosnik et al [2] are shown in Figure 1 where ventilation flow demand as a function of cavitation number is displayed. These data were collected for different disk sizes. The data are presented in the form of flow coefficient, C_q , versus cavitation number, σ_c . Note that the minimum cavitation number for the larger disk is higher than for the smaller disk. Also note that at the minimum cavitation number, further increase in the ventilation rate does not lower the cavitation number any further. As discussed in Schauer [3], this can be an effect of blockage. However, another consideration is the transition from one cavity closure mechanism (reentrant jet) to another (twin vortex). The problem is further complicated by the difficulty in measuring the cavitation number. Wosnik et al utilized the results of Brennen [4] to infer the cavitation number from measurements of the cavity shape. This procedure introduced a question of uncertainty in the results. In addition, the effects of the strut used to mount the test body also generated questions. This work provided a basis for further work, described herein.

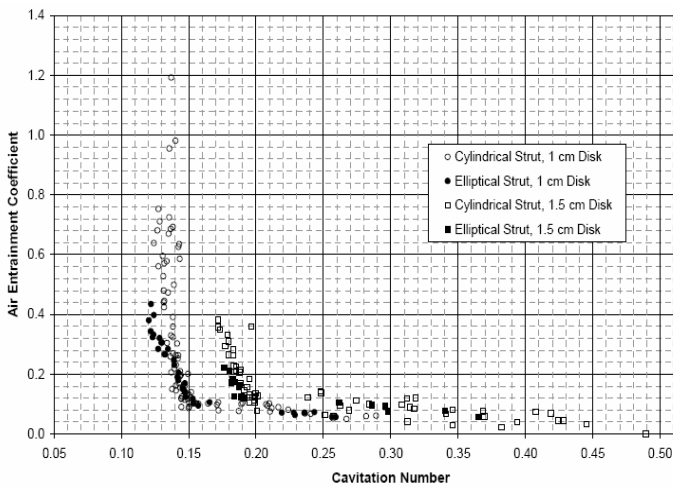


Figure 1. Air entrainment data for both disks and struts. Cavitation number computations were refined using data of Brennen [4]. From Wosnik et al [2]

EXPERIMENTAL SETUP

The experiments were carried out in the high-speed water tunnel at St. Anthony Falls Laboratory (SAFL). This water tunnel is a recirculating, closed-jet facility with absolute pressure regulation and is capable of velocities in excess of 20m/s. The test section measures 0.19m (W) x 0.19m (H) x 1m (L), and is fitted with observation windows on three sides. A special design of the tunnel allows for the removal of large quantities of air during ventilation experiments.

The tunnel has a minimum turbulence level of 0.4 % at 10 m/s. We have continued to upgrade this facility with new data acquisition hardware and software. Our new Time Resolved PIV (TRPIV) system provides excellent capability for obtaining wake data that will be very useful for validating and improving numerical codes for ventilation demand.

To meet the shortcomings of the previous experimental setup, we have considerably expanded our experimental

configurations for ventilation studies. This is illustrated in Figure 2 where both backward and forward facing configurations are shown. An advantage of the new models is the ability to directly measure cavity pressure.

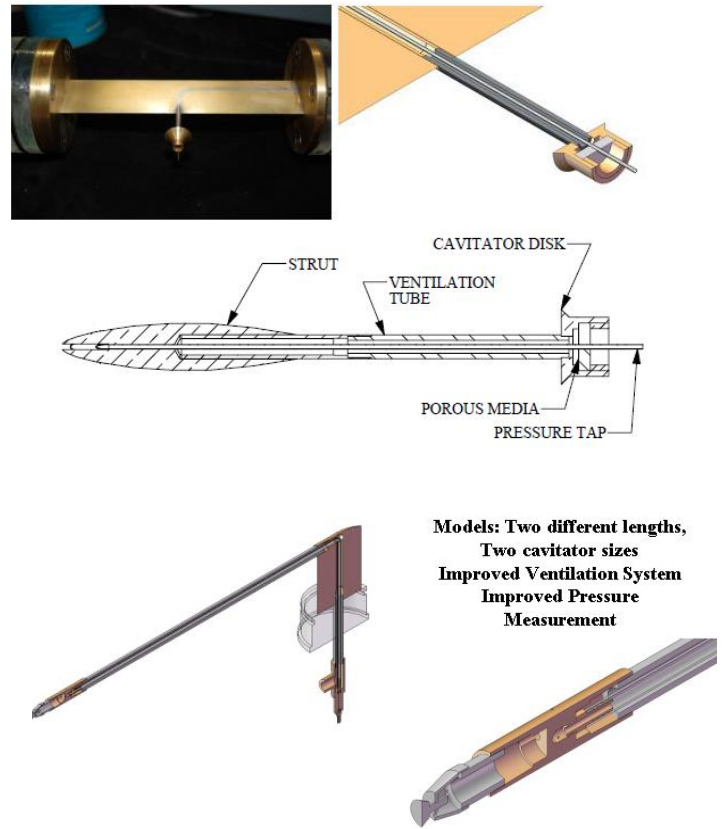


Figure 2. Backward facing model (top) and forward facing model (bottom)

RESULTS

Typical data obtained with the forward facing model over a range of Froude number are shown in Figure 3.

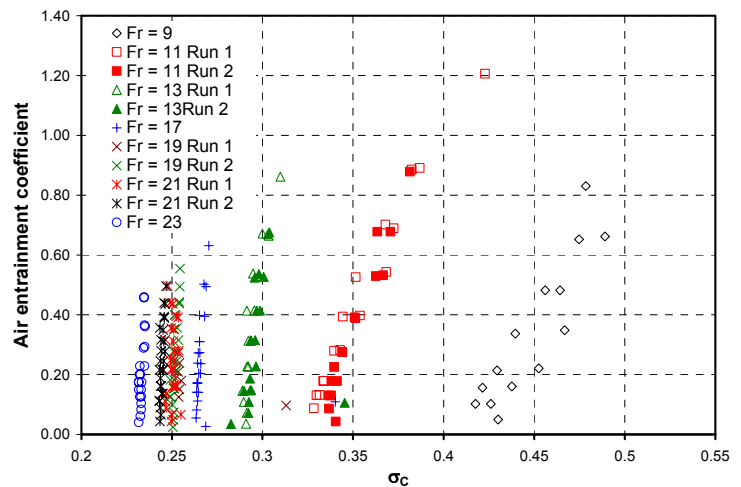


Figure 3. Flow demand at various Froude numbers, 20 mm cavitator.

The results were unexpected in the sense that stable data could only be obtained at the minimum cavitation number. The reason was that reliable pressure measurements could only be obtained after a clear cavity was developed. Several features of these data are of interest. The minimum cavitation number that can be obtained is strongly a function of Froude number as shown. It was also noted that at lower values of Froude number an increase in cavitation number occurs with increasing flow rate. In addition, as the flow demand increases at relatively constant cavitation number, the appearance of the cavity changes as shown in Figure 4.

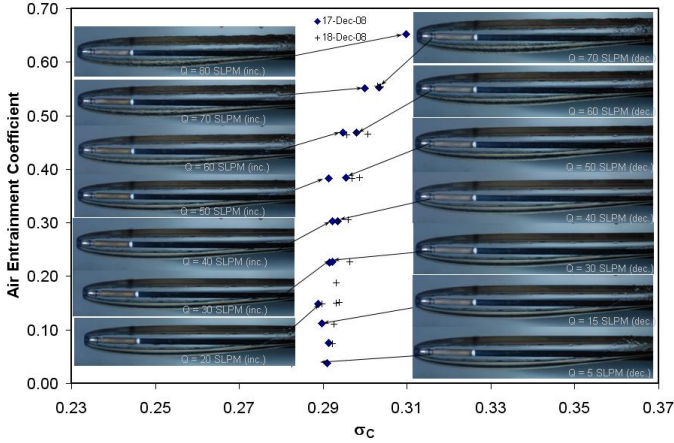


Figure 4. Cavity development at $Fr = 13$. With increasing flow the cavity wall becomes rougher.

The fact that flow demand data could not be obtained at higher cavitation numbers was traced to the fact that reliable measurement of cavity pressure can only be made with a clear cavity. This is indicated in Figure 5. Note that a clear cavity occurs only when the minimum cavitation number is reached. At higher values of cavitation number the cavity has a frothy appearance and pressure measurements were unreliable. In the region, resort was made to inferring the cavitation number from measurements of the cavity shape as was done by Wosnik et al [2]. The two methods agree very well at the minimum cavitation number, providing more confidence in the older data of Wosnik et al.

Additional consideration was given to the blockage

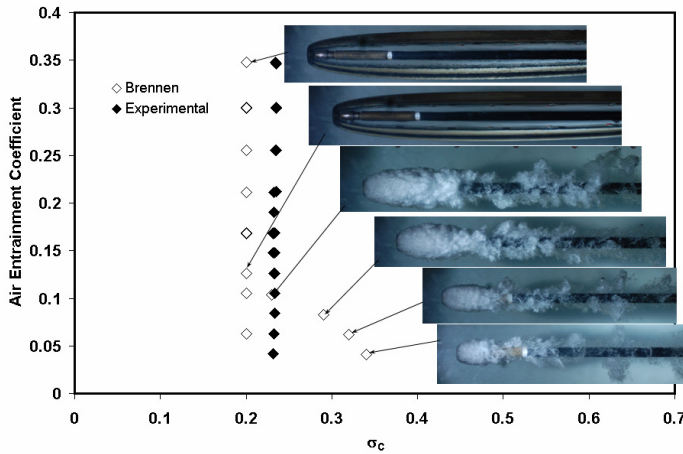


Figure 5. Comparison of cavitation measurement via cavity pressure and measurement of cavity shape. Note that the two methods agree well at the minimum cavitation number. $Fr = 23$, $d = 20\text{mm}$

correction. Earlier work by Tulin [5] indicated that the minimum cavitation number was a function of the blockage ratio, d/D . His calculations are shown in Figure 6. It should be kept in mind that his calculations are based on an infinite Froude number. In reality the minimum cavitation number is based on both blockage ratio and Froude number. This is illustrated in Figure 7. Here the measured minimum cavitation number is normalized by the minimum value obtained from the information in Figure 6. Note that his ratio is both a function of blockage ratio and Froude number. Two sets of data are shown; for 1 and 2 cm disks. Both sets of data tend toward unity at infinite Froude number, as expected. In carrying out this analysis an equivalent tunnel diameter of 21.4 cm was used to compensate for the 19 cm square test section of the SAFL tunnel.

Our work to date with the backward facing model is more preliminary. Sample results are shown in Figure 8 for the same

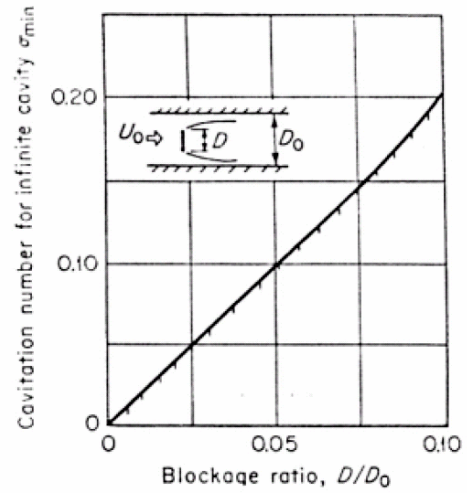


Figure 6. Blockage correction due to Tulin [5]

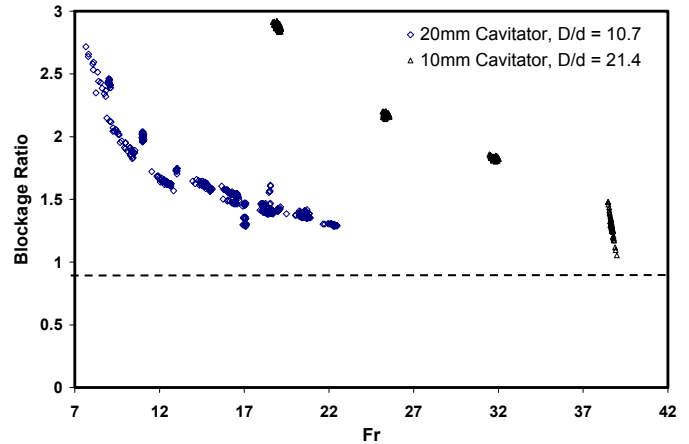


Figure 7. Ratio of minimum cavitation number to minimum cavitation number calculated by Tulin [5]. Data are for two different disk sizes of 1 and 2 cm.

conditions shown in Figure 5 for the forward facing model. Using the cavity shape method for determining cavitation number, the results agree very well with the forward facing data. However, the technique for measuring cavity pressure needs to be refined as is evident for data obtained using this method¹.

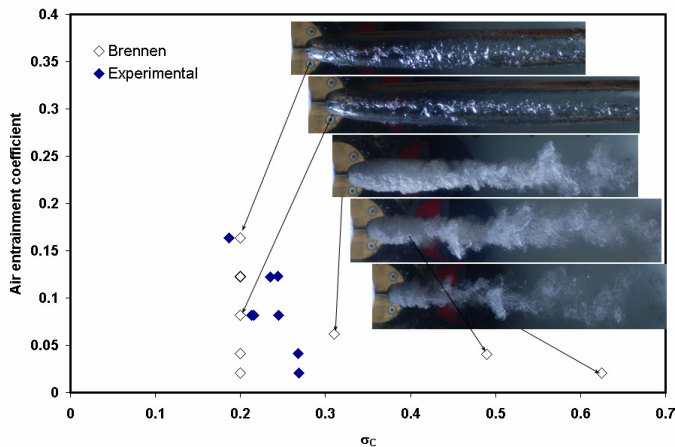


Figure 8 Comparison of cavitation measurement via cavity pressure and measurement of cavity shape for the backward facing model. Note that cavity shape method produces the same results as was obtained with the forward facing model, but the measurement of cavity pressure produces spurious results. $Fr = 23$, $d = 20\text{mm}$

Our new ventilation models permit detailed examination of cavity closure, an essential element in the physics of ventilation demand. This is illustrated in Figure 9.

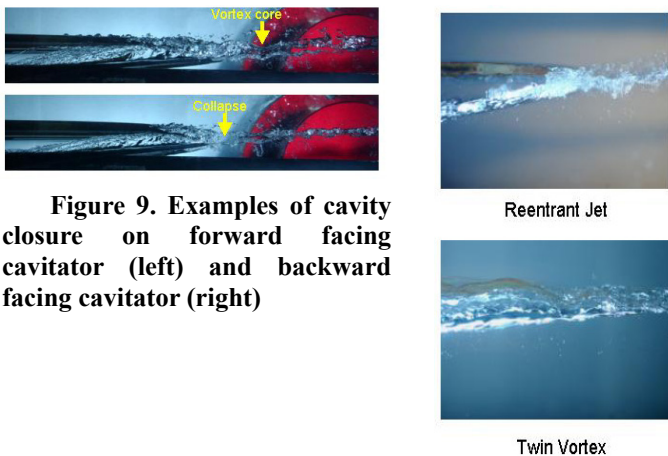


Figure 9. Examples of cavity closure on forward facing cavitator (left) and backward facing cavitator (right)

To date we have determined the dominant mode of closure to be the twin vortex mode. This is quite unexpected. In our experiments the reentrant jet mode was found to be unstable. Current theory suggests that a pulsating mode of reentrant jet closure should occur for values of $\beta = \sigma_v/\sigma_c > 2.7$. All our experiments were carried with this parameter well in excess of 2.7. We are planning experiments at lower values of β to determine if a stable form of the reentrant jet mode can be found.

DISCUSSION AND CONCLUSIONS

Results regarding cavity shape, cavity closure and ventilation requirements versus cavitation number and Froude number were determined for different configurations. Some unexpected results were found particularly relating to the stability of the reentrant jet mode. Additionally, effects related to flow choking in a water tunnel test section are also presented. These data provide new insight into the design of ventilation experiments. Preliminary data from the backward facing model agree well with data from the forward facing model when the cavity shape technique is used to determine cavitation number. When the measured cavity pressure is used, the agreement is not as good. Apparently the pressure measurement technique needs to be refined.

It is interesting to note that the new results are qualitatively in agreement with the previous results of Wosnik et al [2] that were obtained with an entirely different configuration.

A detailed understanding of the mechanism for ventilation demand is still not at hand. It is hoped that detailed exploration of the wake physics can be made with the backward facing model will provide new insight.

ACKNOWLEDGMENTS

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REFERENCES

- [1] Reichardt, H. The Laws of Cavitation Bubbles at Axially Symmetrical Bodies in a Flow. Ministry of Aircraft Production (Great Britain), Reports and Translations No. 766, 1946
- [2] Wosnik, M, Schauer, T, Arndt, REA "Experimental Study of a Ventilated Vehicle", Fifth International Symposium on Cavitation (CAV2003), Osaka, Japan.
- [3] Schauer, T "An experimental study of a ventilated supercavitating vehicle" Master of Science Thesis, University of Minnesota, 2003
- [4] Brennen, C. A numerical solution of axisymmetric cavity flows. *J. Fluid Mechanics*, **37**, pp. 671-688, 1969
- [5] Tulin, M.P. Supercavitating Flows. In Streeter, V. (ed.), *Handbook of Fluid Dynamics*, McGraw-Hill, New York, pp. 1224 to 12-46, 1961
- [6] Waid, R.L. Cavity Shapes for Circular Disks at Angles of Attack. Cal. Institute of Technology. Report No. E-73.4, 1957.

¹ It is important to mention that earlier studies used the cavity measurements of Waid [6]. These measurements were corrected by Brennen [4]. If this detail is ignored unrealistically low values of cavitation number are obtained.