VENTILATED CAVITY TEST OF A 3-INCH DIAMETER STREAMLINED NOSE

J. W. Holl, D. R. Stinebring and W. R. Hall

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The Pennsylvania State University
Institute for Science and Engineering
APPLIED RESEARCH LABORATORY
Post Office Box 30
State College, Pa. 16801

NAVY DEPARTMENT
NAVAL SEA SYSTEMS COMMAND

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A ventilated cavity test of a 3-inch diameter streamlined nose has been conducted in the 48-inch water tunnel. Tests were conducted at 10, 20, 30, and 40 fps for dimensionless cavity lengths (Lc/D) from approximately 1 to 4. The cavitating flow was documented by video tape and still photography. The purpose of the test was threefold namely (1) to approximate the ventilation flow rate coefficient (Cv) (2) to observe the stability of the pressure.
control system as gas was added to the flow, and (3) to observe the approximate boundary between the twin vortex regime and reentrant jet regime. The major results are (1) the ventilation flow rate coefficient is approximately 30% greater than that estimated for a quarter caliber ogive nose, (2) the pressure control system is stable and (3) the twin vortex regime is primarily confined to velocities of 10 fps and less for the gas flow rates employed in this investigation.
Subject: Ventilated Cavity Test of a 3-inch Diameter Streamlined Nose

References: See page 17

Abstract: A ventilated cavity test of a 3-inch diameter streamlined nose has been conducted in the 48-inch water tunnel. Tests were conducted at 10, 20, 30, and 40 fps for dimensionless cavity lengths ($L_c/D$) from approximately 1 to 4. The cavitating flow was documented by video tape and still photography. The purpose of the test was threefold namely (1) to approximate the ventilation flow rate coefficient ($C_q$) (2) to observe the stability of the pressure control system as gas was added to the flow, and (3) to observe the approximate boundary between the twin vortex regime and reentrant jet regime. The major results are (1) the ventilation flow rate coefficient is approximately 30% greater than that estimated for a quarter caliber ogive nose, (2) the pressure control system is stable and (3) the twin vortex regime is primarily confined to velocities of 10 fps and less for the gas flow rates employed in this investigation.
Acknowledgments: This investigation was conducted in the Fluids Engineering Department (FED) of the Applied Research Laboratory (ARL). The FED is located in the Garfield Thomas Water Tunnel Building of The Pennsylvania State University. The program was supported by the Naval Sea Systems Command, Code NSEA-0351 (T. E. Peirce)
TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>1</td>
</tr>
<tr>
<td>Acknowledgments</td>
<td>2</td>
</tr>
<tr>
<td>Table of Contents</td>
<td>3</td>
</tr>
<tr>
<td>List of Tables</td>
<td>4</td>
</tr>
<tr>
<td>List of Figures</td>
<td>5</td>
</tr>
<tr>
<td>List of Symbols</td>
<td>6</td>
</tr>
<tr>
<td>I. INTRODUCTION</td>
<td>8</td>
</tr>
<tr>
<td>II. DESCRIPTION OF THE TESTS</td>
<td>9</td>
</tr>
<tr>
<td>2.1 Objectives</td>
<td>9</td>
</tr>
<tr>
<td>2.2 Test Procedures</td>
<td>10</td>
</tr>
<tr>
<td>III. TEST RESULTS</td>
<td>11</td>
</tr>
<tr>
<td>3.1 Ventilation Flow Rate Coefficient</td>
<td>11</td>
</tr>
<tr>
<td>3.2 Stability of the Water Tunnel Pressure Control System</td>
<td>12</td>
</tr>
<tr>
<td>3.3 Flow Regimes - Reentrant Jet and Twin Vortex.</td>
<td>15</td>
</tr>
<tr>
<td>IV. RECOMMENDATIONS</td>
<td>16</td>
</tr>
<tr>
<td>V. REFERENCES</td>
<td>17</td>
</tr>
<tr>
<td>Tables</td>
<td>18</td>
</tr>
<tr>
<td>Figures</td>
<td>21</td>
</tr>
<tr>
<td>Table No.</td>
<td>Description</td>
</tr>
<tr>
<td>----------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>1</td>
<td>Tabulation of Basic Data for Ventilated Cavity Test of 3-inch Diameter Streamlined Nose (SN) ((P_a = 14.05) PSIA, Water Temperature = 68°F)</td>
</tr>
<tr>
<td>2</td>
<td>Calculated Values of (C_p) and (\dot{Q}) - Quarter Caliber Ogive (D = 3 inches)</td>
</tr>
<tr>
<td>3</td>
<td>Calculation of (\dot{Q}) for Streamlined Nose (SN)</td>
</tr>
<tr>
<td>Figure</td>
<td>Title</td>
</tr>
<tr>
<td>--------</td>
<td>----------------------------------------------------------------------</td>
</tr>
<tr>
<td>1A</td>
<td>Initial Model Configuration</td>
</tr>
<tr>
<td>1B</td>
<td>Final Model Configuration</td>
</tr>
<tr>
<td>2</td>
<td>Ventilation Air Flow System</td>
</tr>
<tr>
<td>3</td>
<td>Calculated Values of $\dot{Q}$ for a 3-inch Diameter Quarter Caliber Ogive in the Re-entrant Jet Regime</td>
</tr>
<tr>
<td>4</td>
<td>Comparison of $\sigma_V$ and $\sigma_C$ (Wade and Acosta 1966)</td>
</tr>
<tr>
<td>5</td>
<td>Reentrant Jet Regime on 3-inch Diameter Streamlined Nose (Run 25, $V_\infty = 30$fps, $P_\infty = 13.9$ psia)</td>
</tr>
<tr>
<td>6</td>
<td>Twin Vortex Regime on 3-inch Diameter Streamlined Nose (Run 23, $V_\infty = 10$ fps, $P_\infty = 13.9$ psia)</td>
</tr>
<tr>
<td>7</td>
<td>Proposed Model Design</td>
</tr>
</tbody>
</table>
List of Symbols

$C_D$ Drag coefficient
$C_Q$ Ventilation flow rate coefficient (Eq. 1)
$D$ Maximum diameter of the body
$F$ Froude number (Eq. 7)
$g$ Gravitational acceleration
$L_B$ Body length
$L_C$ Cavity length
$n$ Number of measured values (Eq. 17)
$P_C$ Cavity pressure (Eq. 13)
$P_G$ Noncondensable gas pressure in the cavity
$P_{G-S}$ Gas pressure at saturation
$P_V$ Vapor pressure
$P_\infty$ Pressure at infinity
$\dot{Q}$ Volume flow rate of the ventilation air
$\bar{Q}$ Average value of $\dot{Q}$ (Eq. 17)
$\dot{Q}_i$ The $i^{th}$ value of $\dot{Q}$ (Eq. 17)
$\dot{Q}_D$ Diffused gas flow rate (Eq. 2)
$\dot{Q}_T$ Total gas flow rate (Eq. 2)
$R$ Reynolds number (Eq. 7)
$s$ Standard deviation (Eq. 17)
$S$ Relative standard deviation (Eq. 18)
$V_\infty$ Velocity at infinity
$\alpha$ Dissolved gas content (Eq. 6)
$\beta$ Henry's law constant (Eq. 6)
\( \nu \) Kinematic viscosity of the liquid
\( \rho \) Mass density of the liquid
\( \sigma_c \) Cavitation number based on cavity pressure (Eq. 10)
\( \sigma_v \) Cavitation number based on vapor pressure (Eq. 12)

Subscripts

QCO Quarter caliber ogive
SN Streamlined nose
I. INTRODUCTION

For several years the Applied Research Laboratory (ARL) has conducted a research program on the cavity running phase of the water entry phenomenon. This program is in support of water entry studies at the Naval Surface Weapons Center (NSWC). The ARL contributions to this program are concerned with the following two basic problems:

1. When will the entry cavity disappear or become small enough so that the control surfaces and propulsor can be actuated?

2. How does the drag coefficient ($C_D$) vary with the cavity length-to-body length ratio ($L_c/L_B$)?

The tests described in this report are relevant to both problems but were primarily conducted to determine a solution of the second problem.
II. DESCRIPTION OF THE TESTS

2.1 Objectives

In pursuit of an answer to the $C_D$ versus $L_C/L_B$ question indicated in section I, ARL plans to conduct a ventilated drag study of a 3-inch diameter cylindrical body with a streamlined nose. Prior to this study it will be necessary to design a drag balance. In view of uncertainties associated with such a design and with conducting tests in the 48-inch water tunnel with large amounts of gas emission it was desirable to conduct a preliminary ventilated cavity flow test with the streamlined nose alone.

The objectives of the test program were threefold:

1. To approximate the ventilation flow rate coefficient ($C_{Dv}$) in order to estimate the ventilation flow rate ($\dot{Q}$) for various velocities and cavity lengths ($L_C$).

2. To observe the stability of the pressure control system as gas is added to the flow.

3. To observe the approximate boundary between the twin vortex regime and reentrant jet regime.
2.2 Test Procedures

An initial test was conducted utilizing a three-inch diameter streamlined nose positioned approximately four inches upstream of the vertical support pipe as shown in Figure 1A. This configuration caused significant disturbance to the cavity flow, with a cavity forming in the wake behind the vertical support pipe. To help alleviate the problem a fairing was constructed about the vertical support as shown in Figure 1B. In addition, shortening the horizontal support further reduced disturbances at the downstream portion of the cavity where most of the entrainment occurs.

The system designed for the introduction of the ventilation air is shown in Figure 2. There were two flowmeters connected in parallel that could be used either independently or together. A pressure gage was located just after the flowmeters for measurement of the ventilation air pressure.

A total of 30 runs were made in the 48-inch water tunnel at velocities from 10 to 40 fps and the basic data are tabulated in Table 1. The maximum ventilation air flowrate for the tests was 9.64 scfpm. The test procedure was as follows:

1. The tunnel velocity and static pressure were first set for the test conditions.
2. The ventilation air was then adjusted for the desired cavity length while a video tape system recorded the cavity behavior. Larger ventilation flow rates required both flowmeters 1 and 2 to be used in parallel. For smaller flowrates flowmeter number 2 was used alone.
3. The freestream velocity, static pressure, flowmeter readings, flowmeter pressure, and cavity length were recorded during the test.

Graduated rulers were taped to the windows on both sides of the test section. By sighting across the test section and aligning the two rulers the cavity length could be determined. The cavity length was also measured from the images recorded by the video tape system. Photographs of the cavity were taken with both a stroboscopic flash and continuous lighting during runs 20 through 30.

Several difficulties were encountered with the gas emission and flow rate measurement systems. Recommendations to improve this system are given in Section IV.

*scfpm= standard cubic feet per minute i.e. cfpm at 14.7 psia.
III. TEST RESULTS

3.1 Ventilation Flow Rate Coefficient

The primary concern in this section is to present the ventilation flow rate data for the streamlined nose and to compare it with similar data for other headforms.

It is convenient to express the ventilation flow rate (\( \dot{Q} \)) in dimensionless form; namely, the ventilation flow rate coefficient \( (C_\dot{Q}) \) given by

\[
C_\dot{Q} = \frac{\dot{Q}}{V_\infty D^2}
\]  

(1)

where \( V_\infty \) and \( D \) are the velocity at infinity and maximum body diameter, respectively. Flow rate data have been determined at ARL for a variety of headforms namely quarter-caliber ogives [1]-[3], zero caliber ogives [1]-[3] and conical nosed bodies [4].

For a given flow state the total flow of gas (\( \dot{Q}_T \)) entrained at the trailing edge of the cavity is given by

\[
\dot{Q}_T = \dot{Q} \pm \dot{Q}_D
\]  

(2)

where \( \dot{Q} \) and \( \dot{Q}_D \) are the ventilated gas flow rate and diffused gas flow rate, respectively. Thus in order to determine the total gas flow rate (\( \dot{Q}_T \)) it is necessary to know both \( \dot{Q} \) and \( \dot{Q}_D \). The flow rate \( \dot{Q} \) can be measured directly but \( \dot{Q}_D \) is difficult to determine although Billet and Weir [1] [2] have been reasonably successful in calculating its value by means of a diffusion theory developed by Brennen [3]. Hence in order to determine \( \dot{Q}_T \) in the most direct manner it is prudent to conduct the test so that

\[
\dot{Q}_D = 0
\]  

(3)

and hence

\[
\dot{Q}_T = \dot{Q}
\]  

(4)

In principle Equation (3) can be satisfied if the cavity pressure (\( P_C \)) is constant along the cavity and if it is set equal to the gas pressure at saturation (\( P_{G-S} \)) that is

\[
P_C = P_{G-S}
\]  

(5)

* Number in brackets refer to documents in list of references.
where \( P_{G-S} \) is given by Henry's Law

\[
P_{G-S} = a_5
\]  

(6)

in which \( a \) is the dissolved gas content and \( \beta \) is the Henry's Law constant. However, Equation (3) can only be approximately satisfied since the pressure does vary somewhat along the cavity. Nevertheless, Billet and Weir [1] [2] have shown that the aforementioned test procedure works satisfactorily and has been employed to find \( C_Q \) for ogives [1] - [3] and cones [4].

The intent of the \( \hat{Q} \) tests for the streamlined nose was to obtain sufficient data in order to estimate the volume flow rate characteristics of the nose over a range of flow states for the drag studies to be conducted in the future. Thus, the aforementioned test procedure which was employed with the ogives and cones was not utilized with the streamlined nose since it is very time consuming and in any case \( \hat{Q} \) is significantly smaller than \( \hat{Q} \). Instead the \( \hat{Q} \) data for the streamlined nose were obtained by setting the tunnel pressure at a convenient level for each run and then estimating the cavity pressure by a procedure which will be described subsequently.

The \( C_Q \) data for the ogives and cones have been correlated with an equation of the form

\[
C_Q = C R^a F^b (L_c/D)^c
\]  

(7)

where

\[
R = \text{Reynolds number} = \frac{V \rho \rho}{\nu}
\]

\[
F = \text{Froude number} = \frac{V}{\sqrt{g D}}
\]

a, b, c, D are constants for a given configuration.

Of the three models previously tested at ARL the quarter caliber ogive (QCO) can be expected to be the best approximation of the streamlined nose and will thus be employed as a basis for comparison. The correlation for the QCO [3] is

\[
C_{Q-QCO} \cdot 0.32 x 10^{-4} \ R^{0.46} \ F^{0.26} \ (L_c/D)^{0.74}
\]  

(8)

and the relation between \( \sigma_c \) and \( L_c/D \) for the QCO [6] is given by

\[
\sigma_c = 0.460 \ (L_c/D)^{-0.66}
\]

(9)

in which \( \sigma_c \) is the cavitation number based on cavity pressure \( (P_c) \) given by

\[
\sigma_c = \frac{p_c - p_c}{\gamma_0 V^2}
\]  

(10)
The values of $C_\infty$ and $\dot{Q}$ for the OCO calculated by means of Equation (8) for a 3-inch diameter nose for velocities from 10fps to 60fps and for values of $L_c/D$ from 1 to 12 are tabulated in Table 2. The $\dot{Q}$ data of Table 2 are plotted in Figure 3. All values of $\dot{Q}$ correspond to the cavity pressure ($P_c$).

In order to compare the measured streamlined nose data with that of the OCO it is necessary to correct the measured values of $\dot{Q}$ at one-atmosphere to cavity pressure. It is thus necessary to estimate $P_c$ for the streamlined nose since it was not measured. Analysis of data for a nose which is quite similar to that of the test nose indicates that

$$\sigma_v = 0.456 \left( \frac{L_c}{D} \right)^{0.292} \tag{11}$$

where $\sigma_v$ is the cavitation number based on vapor pressure given by

$$\sigma_v = \frac{P_\infty - P_v}{\frac{1}{2} \rho V_\infty^2} \tag{12}$$

Since the cavity pressure is given by

$$P_c = P_G + P_V \tag{13}$$

where $P_G$ and $P_V$ are the noncondensable gas pressure and vapor pressure, respectively it follows that

$$\sigma_c < \sigma_v \tag{14}$$

We thus need an estimate of the relationship between $\sigma_c$ and $\sigma_v$. To obtain this estimate we employ some plano-convex hydrofoil data of Wade and Acosta [7] plotted in Figure 4. It is seen that these data are approximated by the relation

$$\sigma_c = 0.8333 \sigma_v \tag{15}$$

The measured values of $\dot{Q}$ at 14.7 psia for the streamlined nose were corrected to cavity pressure by employing Equations (10), (11) and (15) and the calculations are tabulated in Table 3. The runs of major interest are those corresponding to the reentrant jet regime. Excluding twin vortex regime data (Run #5) and Runs #1 and #10 because of strut interference and averaging the remaining runs indicates that

$$\bar{\dot{Q}}_{SN} = 1.3 \bar{\dot{Q}}_{QCO} \tag{16}$$

The standard deviation ($s$) is defined as
See for example page 198-199 of Reference [8] for the definition of \( s \). The relative standard deviation in percent (\( S \)) is defined as

\[
S = \frac{s}{\bar{Q}} \times 100 \quad .
\]  

(18)

\( S \) was calculated and found to be 46.5\%, which indicates a rather broad variation in the data about the mean. This is perhaps not surprising considering that the effects of \( Q_0 \) were ignored, that \( \sigma_c \) was estimated and that \( L_C/D \) is basically an inaccurate measurement.

Applying Equation (16) to Equation (8) yields the estimate

\[
C_{Q\cdot SN} = 0.42 \times 10^{-4} R^{0.45} F^{0.26} \left( L_C/D \right)^{0.74} \quad .
\]  

(19)

Equation (19) together with the data in Table 3 provide sufficient information for estimating \( Q \) for the streamlined nose.

3.2 Stability of the Water Tunnel Pressure Control System

The emission of gas into the water can influence the control of the pressure level. It is of course necessary to be able to control the pressure during a ventilated cavity test and it was therefore important to observe the stability of the water tunnel pressure control system during the gas emission tests. In general, it can be stated that the pressure control system was very stable over the entire range of test conditions displayed by the test data in Table 1. No instabilities were observed over the time spans investigated, one of which was over two minutes at 9.4 scfpm. For all cases, the time spans were significantly greater than that necessary to obtain force measurements.
3.3 Flow Regimes – Reentrant Jet and Twin Vortex

The trailing edge region of a cavity flow produced by vaporous cavitation is characterized by the so-called reentrant jet. However, ventilated cavity flows are characterized by two flow regimes; namely, the reentrant jet and twin vortex [9]. The twin vortex regime can occur for a ventilated cavity flow if the gravitational force vector is not parallel to the direction of motion.

Both flow regimes were observed during the ventilated cavity flow test with the streamlined nose and photographs of typical examples of the reentrant jet and twin vortex flow regimes are shown in Figures 5 and 6. In general, for the gas flow rates employed in this test program, the twin vortex regime occurred at velocities of 10 fps and less.
IV RECOMMENDATIONS

It is suggested that the final model design be statically tested before installation in the 48-inch water tunnel. In this way, the entire system including the flowmeter assembly and all interconnecting plumbing could be checked out for the flow rates required during water tunnel testing.

One problem with the present model design is the possibility of choked flow at the ventilation holes. A model configuration which will remedy this problem is shown in Figure 7. The ventilation air is directed through a slot between an adjustable nose and the afterbody. The aft section of the nose is threaded where it joins the afterbody. The slot width can be varied by screwing the nose section in or out. Thus, the maximum ventilation flow rate through the slot can be varied quite easily.
V. REFERENCES


<table>
<thead>
<tr>
<th>Run Number</th>
<th>V&lt;sub&gt;∞&lt;/sub&gt; (FPS)</th>
<th>P&lt;sub&gt;∞&lt;/sub&gt; (PSIA)</th>
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16 - 30 Photographic Data Only

V<sub>∞</sub> = Velocity in test section at ∞

P<sub>∞</sub> = Pressure in test section at ∞

Q<sub>1</sub> = Volume flow rate as measured by meter #1

Q<sub>2</sub> = Volume flow rate as measured by meter #2

Q = Q<sub>1</sub> + Q<sub>2</sub>

P<sub>A</sub> = Local atmospheric pressure = 14.05 psia

P<sub>A-S</sub> = Standard atmospheric pressure = 14.7 psia

P<sub>F</sub> = Pressure at flow meter

L<sub>C</sub> = Cavity length measured from video tape

D = Maximum body diameter

RJ = Reentrant jet

TV = Twin vortex

*Strut interference
### Table 2: Calculated Values of $C_Q^*$ and $Q^*$ - Quarter Caliber Ogive (d = 3 inches)

$$C_Q = 0.32 \times 10^{-4} R^{0.46} F^{0.26} (L/D)^{0.74} ; \sigma = 0.460 (L/D)^{-0.66}$$

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*$Q^*$'s are in cubic feet per minute (CFPM) at cavity pressure.
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$\sigma_v = 0.456 (L_{C}/D) - 0.292$

$\sigma_c = 0.8331 \sigma_v$

$P_{A-S}$ = Standard atmospheric pressure = 14.7 psia

$P_C = \frac{\sigma_c \cdot c_0^2}{2}$ = cavity pressure

$\dot{Q}_{PC} = \dot{Q}_{P_{A-S}} \cdot \frac{P_{A-S}}{P_C}$

SN = streamlined nose

QCO = quarter caliber ogive

*These data were not included in the average value of $\dot{Q}_{SN}$

**Strut interference
Figure 1A Initial Model Configuration
Figure 13 Final Model Configuration
Figure 2 Ventilation Air Flow System

Pressure Gage
(0-100 psig)

To Model

N₂ Supply

Flowmeter 1
Fisher & Porter Co.
No. 85-27 10/27
20 standard cfpm
maximum at 14.7 psia

Pressure Regulators

Flowmeter 2
Fisher & Porter Co.
No. FP-1/2-27-6-10/27
3.35 standard cfpm maximum
at 14.7 psia

Supp'y maximum at 14.7 psia
Figure 3 Calculated Values of $\dot{Q}$ for a 3-inch Diameter Quarter Caliber Ogive in the Reentrant Jet Regime

$$C_Q = 0.32 \times 10^{-4} R^{0.46} F^{0.26} \left( \frac{L_c}{D} \right)^{0.74}$$

$$R \equiv \frac{V_\infty D}{\nu}, \quad F \equiv \frac{V_\infty}{\sqrt{gD}}$$

$\dot{Q}$'s correspond to cavity pressure
Figure 4: Comparison of $\sigma_v$ and $\sigma_c$ (Wade and Acosta 1966)
Figure 5  Reentrant Jet Regime on 3-inch Diameter Streamlined Nose
(Run 25, $V_\infty = 30$ fps, $P_\infty = 13.9$ psia)
Figure 7 Proposed Model Design

- Ventilation Air
- Nose
- Adjustable Gap
- Afterbody
- Ventilation Air
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