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Experimental Data from Underwater Conical Nozzles Exhausting N_2 Gas

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THERE is particular interest in nozzle performance at great depths where the external water pressure could adversely affect nozzle performance. It has been generally assumed that the conventional ballistic equations, applicable to an air environment, can be used for nozzles exhausting under water. This assumption was first tested by Lawrence and Beauregard in 1965.[1] These authors obtained quantitative data from underwater conical nozzle experiments at 1 atm of ambient pressure. They showed that submergence altered the behavior of the exhausting gas jet. When the nozzle is operating under a flow separation condition, the separation plane oscillates back and forth along the nozzle's axis of rotation (see Fig. 1). The external jet tends to pulsate and vary in size. Jet asymmetry and initial peaks in the nozzle pressure are produced as a result of submergence.

This article presents data† obtained at simulated depths down to 700 ft. The data are presented in the form of two linear equations in order to make its use easier.

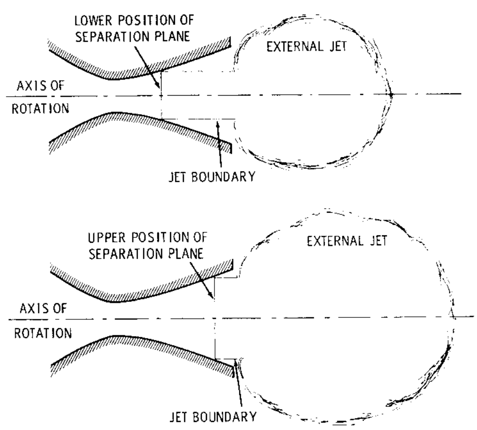

Fig. 1 Flow separation and external jet of gas exhausting from a conical nozzle submerged under water.

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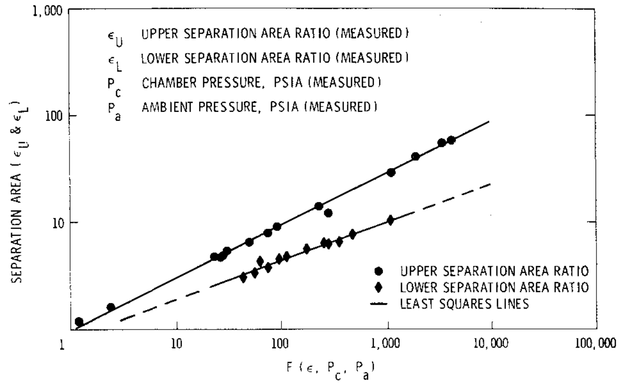

Fig. 2 Measured separation area ratio as a function of pressure for a conical nozzle exhausting nitrogen under water.

Depth simulation was carried out in the Naval Ordnance Laboratory (NOL) horizontal pressure vessel (HPV). A compressed gas facility was designed to permit operation of a compressed nitrogen gas rocket inside the 15,000 gal hydrostatic HPV.[1] Compressed nitrogen stored at 6000 psi permitted a maximum flow rate of 2.8 lb/sec using a 0.5-in. throat diameter nozzle. This corresponds to a steady-state rocket chamber pressure of 2500 psia and a chamber temperature of 50°F. A pebble bed storage heater was designed to maintain the required temperatures. The nozzle was made of Lucite so that the separation plane could be photographed. The throat diameters of the nozzles were 0.077 and 0.25 in. with a 15° half-angle. All nozzles were assembled to the same rocket chamber for firing.

Measurements were taken of the rocket chamber pressure and of the pressure in the HPV for each test. The HPV pressure remained essentially constant for the duration of each test. High-speed movies were taken of the separation plane. In almost every test, the separation plane oscillated back and forth along the nozzle axis. The lower and upper positions of the separation plane were obtained from the high-speed movie films. Thus, the data are presented in terms of the lower- and upper-separation area ratios, the chamber pressure and ambient pressure.

The data are represented by

$$\epsilon_U^{2.054} = 0.977\left[44.02\left(\frac{P_c^{0.588}}{P_a^{1.099}}\right)\epsilon_U - 362.4\left(\frac{P_c^{1.170}}{P_a^{2.179}}\right)\right] \tag{1}$$

and

$$\epsilon_L^{2.788} = 0.588\left[92.03\left(\frac{P_c^{0.425}}{P_a^{0.833}}\right)\epsilon_L - 211.0\left(\frac{P_c^{0.724}}{P_a^{1.338}}\right)\right] \tag{2}$$

where ϵ_U = upper-separation area ratio; ϵ_L = lower-separation area ratio; P_a = ambient pressure, psia; P_c = chamber pressure of rocket, psia. Equations (1) and (2) are equations that uniquely represent the experimental data (see Fig. 2). In Fig. 2, $F(\epsilon, P_c, P_a)$ represents Eq. (1) divided by 0.977 and Eq. (2) divided by 0.588. These equations do not necessarily state explicit relationships between the variables but provide an excellent means of interpolation and comparison of data. The following pressure (psia) limits should be observed when using these equations, $150 < P_c < 2400$ and $15 < P_a < 302$.

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