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An experimental investigation of artificial supercavitation generated by air injection behind disk-shaped cavitators

Byoung-Kwon Ahn [a,*], So-Won Jeong [a], Ji-Hye Kim [a], Siyao Shao [b], Jiarong Hong [b], Roger E.A. Arndt [b]

[a] *Dept. of Naval Architecture and Ocean Engineering, Chungnam National University, Republic of Korea*
[b] *St. Anthony Falls Laboratory, University of Minnesota, MN, USA*

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Abstract

In this paper, we investigated physical characteristics of an artificial supercavity generated behind an axisymmetric cavitator. Experiments for the same model were carried out at two different cavitation tunnels of the Chungnam National University and the University of Minnesota, and the results were compared and verified with each other. We measured pressures inside the cavity and observed the cavity formation by using a high-speed camera. Cavitation parameters were evaluated in considering blockage effects of the tunnel, and gravitational effects on supercavity dimensions were examined. Cavity dimensions corresponding to the unbounded cavitation number were compared. In addition, we investigated how artificial supercavitation develops according to the combination of injection positions and direction.

Keywords: Cavitation tunnel; Cavitator; Supercavitation; Artificial supercavitation; Blockage effect; Gravitational effect

1. Introduction

The concept of supercavitation was originally proposed about six decades ago to avoid partial cavities, which result in many harmful consequences such as erosion and noise on marine propellers and turbomachinery. In the inevitable occurrence of cavitation, the creation of supercavity is favorable because of its steadiness and calmness. Focusing on natural supercavitation, many experiments were conducted and various empirical models for analysis of supercavities were proposed. Waid (1957) first measured profiles of two-dimensional symmetric supercavities generated from a flat plate and various shaped wedges. Self and Ripken (1955) showed typical features of axisymmetric supercavities obtained in a vertical water tunnel for spheres and disks. During this period, experiments were conducted in a free jet flow facility, where there are no blockage effects, and thus very low values of the cavitation number could be attained. Klose and Acosta (1965) measured cavity shapes on 45° cones and also obtained drag coefficients for circular disks in the closed test section of the water tunnel. However, wall interference was not taken into account and accordingly the data were biased towards smaller measured forces and longer cavity lengths as compared to an unbounded flow at the same cavitation number. A thorough review and summary of the findings of this era is presented in Knapp et al. (1979).

In recent years, supercavitation has again attracted interest and attention for practical advantages in drag reduction of underwater vehicles. As a submerged object travels at very high speeds and a vaporous cavity grows to cover the entire body, it is called as a natural supercavity. A supercavity can also be formed by injecting gas into the low pressure regions on the front part of a body, also termed as a ventilated or an artificial supercavity. Both types of supercavities appear to be

* Corresponding author.
E-mail address: bkahn@cnu.ac.kr (B.-K. Ahn).
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Nomenclature

C_q	Air entrainment coefficient
d_c	Diameter of the cavitator
d_t	Distance between two vortices
D	Equivalent diameter of the tunnel test section
D_s	Maximum diameter of the supercavity
D/d_c	Blockage ratio
F_n	Froude number
g	Gravitational constant
P_c	Pressure inside the cavity
P_v	Vapor pressure of liquid
P_∞	Freestream ambient pressure
$\dot{Q}$	Volumetric air flow rate
U_∞	Freestream velocity
Γ	Circulation
ρ	Fluid density
σ_c	Artificial cavitation number
σ_{min}	Minimum cavitation number
σ_n	Natural cavitation number
σ_∞	Unbounded cavitation number

alike at the same cavitation number conditions. However, the biggest difference between the two is the effect of gravity. Artificial supercavitation can be generated at relatively lower speeds than the natural case for given conditions, thereby making Froude number effects significant. Semenenko (2001) provided some basic aspects and a mathematical model of the unsteady axisymmetric supercavity. Recently, Kim and Ahn (2015) developed a viscous potential method to predict three dimensional axisymmetric supercavitation and compared the results with experiments. Many experiments have been conducted at Saint Anthony Falls Laboratory (SAFL) of the University of Minnesota. The SAFL cavitation tunnel has a special feature of discharging injected gas, which makes it very effective for carrying out ventilation experiments. Using this facility, Kawakami and Arndt (2011) investigated artificial supercavitation behind disk shaped cavitators and showed supercavity shape, closure and ventilation requirements corresponding to Froude numbers. Karn et al. (2015, 2016) also presented closure modes of ventilated supercavitation in steady and unsteady flows.

One of the main focus of the present study is to find and confirm main features of the artificial supercavity through experiments conducted at two different cavitation tunnels. The CNU CT has a similar capability to remove injected gas as the SAFL CT; it has a gas collector upstream of the inlet to the test section, allowing for removal of large amounts of air during the experiment. In consideration of blockage effects of the tunnel, same scale models were considered. The results of both facilities were in good agreement. One of key factors in experiments was to measure the pressure inside the cavity for estimation of the artificial cavitation number. Using absolute pressure sensors, we directly measured pressures inside the cavity and also observed the cavity formation in detail by using a high-speed camera. Based on the pressure measurements and high-speed images, hysteresis effects were carefully examined and also gravitational effects on supercavity dimensions were investigated. In addition, the effect of air injection direction and location was explored on the formation of a supercavity.

2. Experimental apparatus

2.1. Cavitation tunnel and blockage effects

Cavitation is governed by the parameter defined in Eq. (1), referred to as the cavitation number. A vaporous cavity is naturally formed on the body by increasing the flow speed, or by decreasing the pressure inside the cavitation tunnel. As the cavitation number is gradually decreased, a partial cavity grows longer and transitions into a supercavity.

$$\sigma_n = \frac{P_\infty - P_v}{1/2\,\rho U_\infty^2} \tag{1}$$

Based on the same principle, a supercavity can also be attained by injecting gas into the low pressure regions and making cavities to envelope the body. Artificially created supercavities mainly depend on the amount of injected air and the pressure inside the cavity. Especially, the influence of gravity causes the cavity to deform and its tail to go up. The phenomenon of artificial supercavitation (also known as ventilated supercavitation) is characterized by the artificial cavitation number and other parameters such as air entrainment coefficient and Froude number, which are defined in Eqs. (2)−(4). The key parameter of artificial supercavitation is pressure inside the cavity, which is determined by injected gas rate.

$$\sigma_c = \frac{P_\infty - P_c}{1/2\,\rho U_\infty^2} \tag{2}$$

$$C_q = \frac{\dot{Q}}{U_\infty d_c^2} \tag{3}$$

$$F_n = \frac{U_\infty}{\sqrt{g d_c}} \tag{4}$$

Contrary to the case of unbounded flow, when the supercavity is generated in a flow confined by the walls in tunnel experiments, blockage effects should be considered. From the mass conservation and the Bernoulli equation for steady and incompressible flow, the critical value of the cavitation number can be expressed as:

$$\sqrt{\sigma_{\min} + 1} = \frac{1}{1 - (D_s/D)^2} \tag{5}$$

Through numerical analysis, Tulin (1961) and Brennen (1969) showed the relations between the minimum cavitation and the blockage ratio. As the diameter of the supercavity

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