Effect of Gas Content on Tip Vortex Cavitation

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Abstract

Occurrence of tip vortex cavitation (TVC) is a common problem in axial hydraulic machines. The behavior of this type of cavitation is so sensitive to variations in the flow parameters and the gas content level of water. Regarding this, we have investigated TVC generated by an elliptical hydrofoil with NACA-16020 cross-section in the high-speed cavitation tunnel of EPFL. We measured the cavitation incipience and desinence thresholds for different flow conditions as well as various gas content levels of between 50 and 100 % oxygen saturation at 18 °C. We observed that the disappearance threshold of TVC increases with the gas content level, which is an indication of the fact that once the cavitation develops in the tip vortex, the dissolved gas in the surrounding supersaturated liquid diffuses into the cavity. Moreover, we found that the extent to which the desinence is delayed depends on the incidence angle and the upstream flow velocity; the parameters that determine the characteristics of the boundary layer on the hydrofoil. According to the flow visualization results, we argue that this gaseous cavitation is enhanced when a laminar separation bubble is formed on the suction side of the hydrofoil.

Keywords: *tip vortex cavitation, gas content, inception and desinence hysteresis, outgassing*

Introduction

The rotational motion of the fluid around the axis of tip vortices may result in very low static pressures in the core of these vortices, which makes them extremely vulnerable to the inception of cavitation. Occurrence of tip vortex cavitation (TVC) in axial turbines, pumps and marine propellers can lead to a severe erosion of the impeller blades and the stationary parts of the machine, with a significant increase in maintenance costs. In most of the cases, TVC is the first type of cavitation that appears in the machine [1, 2, 3, 4] and results in extensive noise emissions and structural vibrations [5]. McCormick [6] investigated the role of the boundary layer on TVC and stated that the size of the viscous core of a tip vortex scales with the boundary layer thickness on the pressure side of hydrofoils. Different authors [7, 8, 9] later proposed the following correlation for the cavitation inception number: $\boldsymbol{\sigma_i = KC_L^2Re^m}$, where C_L and Re are the lift coefficient and Reynolds number, respectively, and K and m are empirical constants. Besides the flow parameters, it is known that the gas content of water also plays a major role in the cavitation inception. Arndt and Maines [10] introduced the terms *‘‘weak’’* and *‘‘strong’’* water depending on the size and distribution of nuclei in water. They showed that in weak water with enough large nuclei, cavitation incepts when the pressure in the core of the tip vortex reaches the vapor pressure, however, strong water with fewer and/or smaller nuclei could resist significant tensions. Despite the efforts dealing with the inception of TVC, little attention was paid to its desinence. Holl et al. [11] demonstrated that hub vortex cavitation disappears at higher pressures when the gas content of water is increased. Recently, Groß et al. [12] examined the effect of gas content on the nucleation rate from a single nucleus trapped in a small hole. They demonstrated that the nucleation site does not disappear and permanently produces tiny bubbles as long as the flow is supersaturated. They have found that the nucleation rate from the wall-bounded nucleus is proportional to the velocity and the supersaturation degree of the freestream. In the present study, we address the role of the dissolved gas content in TVC for a variety of flow conditions. With this aim, the behavior of TVC is experimentally investigated in a simplified case study to determine how different flow conditions and gas content levels affect the TVC inception and desinence. The experimental methods and the corresponding results are presented in the following.

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Experimental set-up

The experimental studies were performed in the EPFL high-speed cavitation tunnel, which has a $150 \times 150 \times 750$ mm test section and a maximum inlet velocity of 50 m/s. A stainless steel hydrofoil with a NACA 16-020 cross section and an elliptical planform was used for the investigations, because it generates a well-defined and undisturbed TVC. The span and the root chord length of the profile are 9 mm and 6 mm, respectively. To monitor the gas content level, we used a Presens O_2 Dipping Probe (DP-PSt7) fitted upstream to the test section. To modify the gas content, we adopted the following procedure: A decrease of the gas content is obtained by running the tunnel with a super cavitation at 15 m/s upstream velocity, while an increase of the gas content is achieved by producing a highly turbulent free surface flow in the test section and downstream. In both procedures, the oxygen concentration is monitored in real time. Since the solubility of air in water is dependent on the temperature, the latter was kept constant at 18 °C. The procedure for the TVC inception/desinence tests was the following: For a given freestream velocity and incidence angle, the static pressure was gradually decreased from an initial value, high enough to ensure a cavitation-free regime. The cavitation inception index (σ_i) was determined upon the observation of a tiny cavitating core attached to the foil. The pressure was further reduced to allow for a well-developed TVC, and then the pressure was increased until the cavitation disappeared, which determined the cavitation desinence number (σ_d).

Results and discussion

Our observations on the inception and desinence of TVC reveal that under specific flow conditions there exists a relatively large gap between the two thresholds. Figure 1 illustrates this hysteresis for fully air-saturated water at upstream velocity of 10 m/s (Re=600,000) and 12° incidence angle. We have reported on the same figure the cavitation number and the corresponding values of the static pressure measured at the tip of the hydrofoil. One may easily observe that TVC incepts at $\sigma_i = 1.7$ and disappears at a much higher cavitation number, $\sigma_d = 4.0$, which is associated with a pressure of around 1.4 bar at the tip of the hydrofoil.

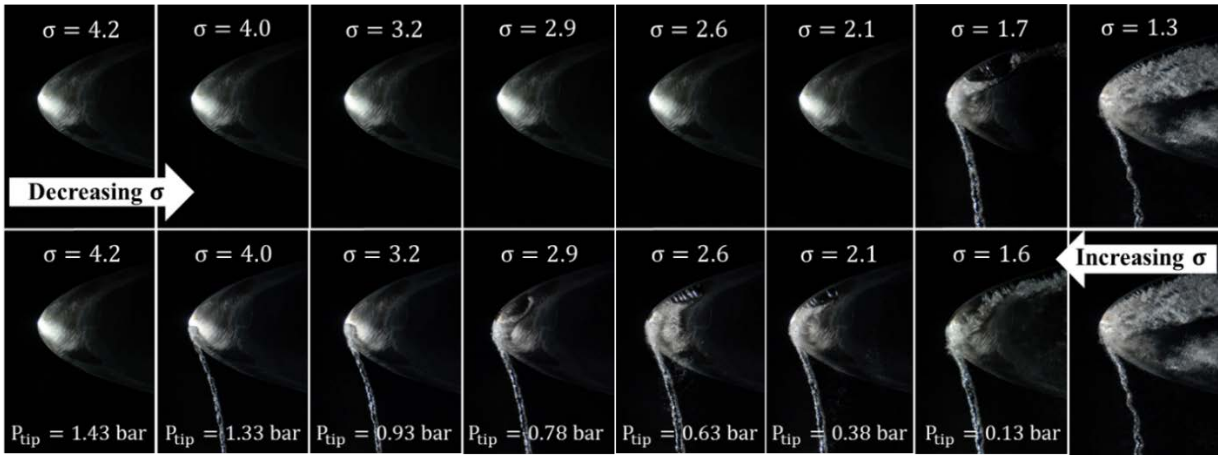

Figure 1: Hysteresis in TVC inception and desinence at $V_\infty = 10\ \mathrm{m/s}$, $\alpha = 12°$, and 100 % of O_2 saturation

Similar observations were conducted for two upstream velocities, different incidence angles and oxygen concentrations, the results of which are depicted in Figure 2. Almost for all the cases, the cavitation desinence number is significantly higher than that of the incipience. As expected, lower pressures are required for the initiation of the TVC at 50 % of oxygen saturation, because a lower gas content level is normally associated with lower amounts of active nuclei in water. We also observe that the TVC disappears at much higher pressures when water is fully saturated. In addition, the results of Figure 2 illustrate the role of the flow velocity and the angle of attack in the gap observed between the cavitation inception and desinence thresholds. The hysteresis clearly shrinks when the velocity is increased from 10 to 15 m/s. It is also found that the gap is the largest around 12° incidence angle and diminishes as we move toward 8° or 16°.

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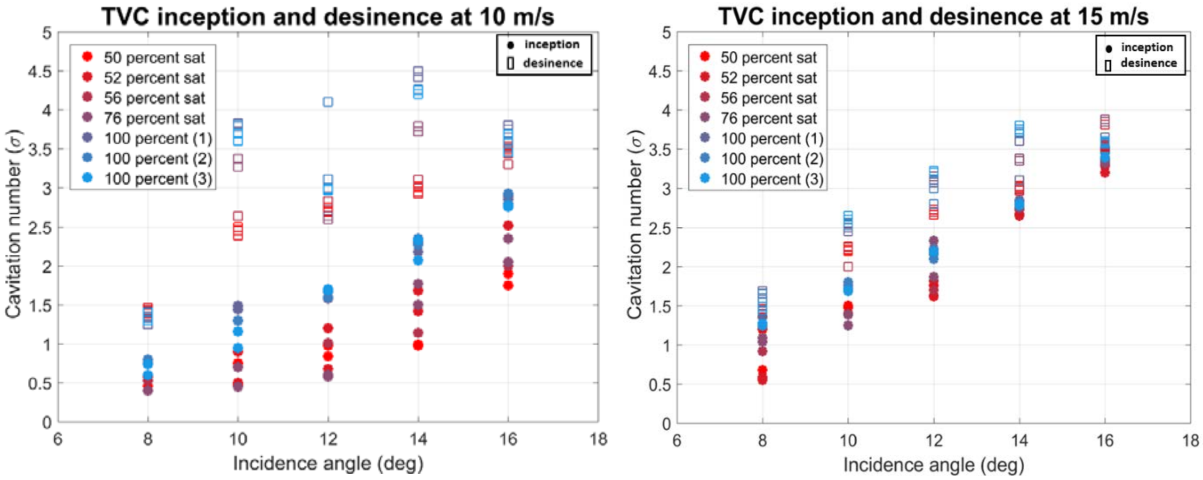

Figure 2: TVC inception/desinence for different incidence angles and gas content levels, measured at 10 and 15 m/s

Of more interest in Figure 2 is what we observe on the desinence limits of the TVC. Considering that the cavitation is only a result of the vaporization of water, the TVC must disappear as soon as the pressure inside the vortex is higher than the saturation vapor pressure. Due to the high static pressures close to the vortex core depicted in Figure 1, it is very unlikely that the evaporation process sustains the cavity. In addition, the fact that the desinence threshold varies with the gas content (Figure 2) is a clear indication that TVC resists pressure levels higher than vapor pressure because of the diffusion of the dissolved gas in water across the interface of the vortex cavity. Indeed, the local decrease in the pressure due to the rotational motion of the fluid around the vortex axis changes the local saturation level of water. For instance in the case of the 100 % of saturation, as long as the pressure within the cavitating tip vortex is below the atmospheric pressure, the water flowing around the vortex core is supersaturated.

Besides the effect of gas content, Figure 2 also shows that the delay in the desinence of the TVC depends on the flow conditions and that the hysteresis is stronger between 10° and 12° and at the lower freestream velocity of 10 m/s. We argue that the upstream velocity and the incidence angle influence the cavitation desinence through the boundary layer state on the hydrofoil suction side. We have observed that the large hysteresis is always associated with the formation of a glassy cavity at the tip of the hydrofoil, as illustrated on Figure 3. According to high-speed visualizations (not presented here), this transparent cavity could be an indication of a laminar separation of the boundary layer. Nevertheless, it is not yet clear how such a laminar separation enhances the outgassing process and delays the cavitation desinence.

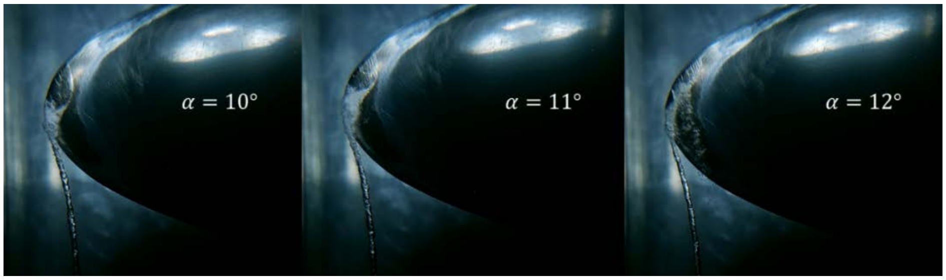

Figure 3: Evolution of the shape of the TVC with incidence angle at 10 m/s and σ = 3

The hysteresis in the TVC inception and desinence, evidenced here, poses a challenging problem for the design and the model tests of hydraulic machines. In fact, it is not clear which cavitation index (incipience/desinence) should be taken into account in the performance tests. Moreover, the actual scale-up rules always fail in predicting TVC occurrence in axial turbines. The work presented here is being pursued to address these challenges.

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Conclusion

We experimentally investigated the cavitation incipience and desinence within a tip vortex, developed by an elliptical hydrofoil, in a wide range of flow parameters and gas content levels. Our observations confirm the hysteresis between cavitation incipience and desinence thresholds. Besides the gas content, we have found that this phenomenon is also dependent on flow parameters, peaking at ~12° incidence angle and 10 m/s upstream velocity. We argue that once a TVC is developed, the excessive gas within the supersaturated water diffuses into the cavity and sustains cavitation at pressure levels as high as atmospheric pressure. The combination of the flow visualizations and inception/desinence measurements indicates that a laminar separation near the hydrofoil tip likely enhances this outgassing process. Further research is underway to distinguish between vapor cavitation and gaseous cavitation, compare their consequences and ultimately define relevant criteria for cavitation tests of hydraulic machines at reduced scale.

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