Tip-leakage cavitation in the clearance of a 2D hydrofoil with fillets: high-speed visualization and PIV/PTV measurements

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Abstract. Tip-clearance cavitation is one of the most aggressive forms of cavitation as it can cause surface erosion of hydraulic machinery elements and, as a result, their fatigue damage and disturb designed operating conditions. At present, the literature lacks for detailed experimental data on the inception and development of this type of cavitation at various flow conditions. In the paper, a tip-leakage cavitation occurring in the clearance between an end face of a 2D hydrofoil (a scaled-down model of guide vanes (GV) of a Francis turbine) and a transparent wall of the test section was studied. The experiments were carried out for different cavitating regimes on the cavitation number and two attack angles of 3º and 9º, with the gap size (tip clearance width) varied in the range from 0.4 to 0.8 mm. In order to determine the cavitation inception conditions and investigate the dynamics of the tip-leakage cavitation, a high-speed visualization was applied. A modified PIV/PTV technique with a diverging laser beam instead of a laser light sheet was used to measure the mean velocity distributions within the gap. It was shown that the cavitation pattern on the suction side of the GV model impacts the dynamics of the leakage flow in the gap but does not affect the sheet cavity formed close to the foil leading edge in the clearance as well as its size and dynamics. When the gap size is increased, the tip-leakage cavitation initiates at higher cavitation numbers or, in other words, conditions for the cavitation occurrence become more favorable.

1. Introduction
Tip-clearance cavitation occurs when a liquid leaks due to a high pressure gradient through narrow gaps between tip edges of rotor blades or end faces of guide vanes and stator housing when the clearance flow separates from the lateral surface of a hydrofoil. It is one of the most widespread forms of cavitation as it initiates at higher cavitation numbers, before any other type of cavitation appears [1]. General parameters of the tip-leakage flow that accompanies the tip-clearance cavitation are as follows: small gap thickness compared to its length and height, high pressure gradients and strong shear stresses. Thus, this type of cavitation has several recognizable features that make it difficult to study such flow both experimentally and numerically. According to the literature, the tip-clearance cavitation is commonly divided into three parts: gap cavitation itself occurring in the clearance, blade-end cavitation taking place at the leading edge due to stretching of the boundary layer vorticity when the gap size is small and the leakage vortex cavitation caused by interaction of the leakage flow with the primary flow and usually occurring when the gap size is relatively large [2]. In hydraulic
machinery, the presence of all these cavitation processes can cause erosion of surface material, decrease of equipment efficiency, increased noise and vibration level and pressure pulsations, which can eventually lead to the system failure.

In most research papers that can be found in the literature, the phenomena of the tip-leakage [3-5] and tip-vortex cavitation [6-9] are investigated numerically. The number of experimental studies is substantially lower [1, 10], which is linked with the technical difficulty of implementation of the specified flow geometry and application of measurement techniques under such conditions. Moreover, measurement results of velocity distributions in the clearance that are necessary to quantitatively compare numerical and experimental data and validate existing mathematical models are unavailable in literature nowadays. The research aims at experimental investigation of the tip-leakage flow, cavitation inception and development, assessment of the effect of the gap cavitation on velocity distributions in the clearance and evaluation of the influence of the gap size on all these processes. The study was carried out for the attack angle of 3° and 9° and various cavitation regimes on the cavitation number by means of a high-speed imaging and PIV/PTV technique adapted for velocity measurements in the clearance.

2. Experimental setup and measurement techniques

The experiments were performed in the cavitation tunnel in Kutateladze Institute of Thermophysics SB RAS. Description of the test rig can be found in [11]. The test object was a scaled-down model of guide vanes (GV) of a Francis turbine, which is a symmetrical hydrofoil equipped with fillets to reproduce exactly the geometry of original guide vanes (Figure 1). The foil chord length $C$ equals to 100 mm, its maximum thickness of $h_{max}/C = 0.223$ is at $x/C = 0.44$. The GV leading edge is shaped with a rounding radius of 0.02$C$ and its trailing edge was blunt with the height of 0.013$C$. The detailed information about the foil profile is given in Table 1. The foil rotation axis with the diameter of 25 mm in the clearance $h_1$ between the GV end face and transparent wall of the test channel where the observations and measurements were conducted (see Figure 1-b) is located at the distance of 0.54$C$ from its leading edge. The fillets nearby the gap $h_1$ are rounded along the foil chord with the radii of 0.176$C$ and 0.143$C$ from the suction and pressure sides, respectively, and curved in the transversal direction with the radius of 0.113$C$ from both sides (Figure 1). In the experiment, $h_1$ was changed in the range between 0.4 mm and 0.8 mm. The attack angle $\alpha$ was set to be 3° and 9° and the cavitation number $\sigma = (p_{in} - p_V)/(\rho U_0^2/2)$, where $p_{in}$ is the static pressure at the inlet of the test channel, $p_V$ is the saturation vapor pressure of the distilled water (operating liquid), $\rho$ is the water density, $U_0$ is the mean flow velocity measured by PIV in the central longitudinal section close to the test channel inlet, was varied in the range from 1.66 to 0.74 for $\alpha = 3^\circ$ and from 3.58 to 1.66 for $\alpha = 9^\circ$ by changing the static pressure and/or $U_0$. The liquid temperature was stabilized at 30±0.1 °C.

Figure 1. (a) 3D model of the guide vane equipped with fillets and an axis of rotation at both sides and (b) schematic of its disposition in the test channel (top view).
In order to visualize the cavitation patterns in the clearance, a high-speed visualization was applied. For this, a high-speed Photron FASTCAM SA5 CMOS-camera (digit capacity 12 bits, resolution 1024x1024 pix., acquisition rate 7 kHz) with Nikon AF Nikkor 50 mm f/1.4D lens was used. To illuminate the region of cavitation occurrence uniformly, three halogen lamps with the total power of 2.5 kW were utilized as a continuous incoherent light source. In the experiment, the camera was inclined at the angle of 25° to horizon so it was able to register both cavitation structures on the GV suction side and gas-vapor cavities in the clearance. A PIV-system consisting of a CCD-camera ImperX GEV B2020 (pixel depth 14 bit, matrix resolution 2048x2048, acquisition rate 6 Hz) with a Nikon micro-Nikkor 60 mm f/2.8D lens and a low-pass optical filter (transmission edge at 570 nm), a Nd:YAG laser Quantel EVG00200 (emission wavelength 532 nm, pulse repetition rate 15 Hz, pulse duration 10 ns, pulse energy 200 mJ) and a synchronizing processor POLIS (8 TTL channels, repetition rate of pulse pairs 10 Hz, minimum pulse delay 100 ns) and operated through a PC using “ActualFlow” software was used to measure velocity distributions in the gap. The camera was installed perpendicular to the transparent test channel wall. The gap was illuminated by a laser beam expanded using an Edmund Optics 2-8X 532 nm beam expander to cover the whole GV end face. The laser beam was directed at the angle of nearly 25° to the camera optical axis in the horizontal plane. PMMA microparticles of 20-50 µm size dyed with Rhodamine B were applied as tracers to avoid overexposure and glares in images. The description of the image processing algorithms is given in [11].

| Table 1. Points of the generatrix of the GV model at different cross-sections x/C. y ± are the transversal coordinates of the points on the upper and lower foil sides with respect to its chord (zero line). The GV shape is a result of a cubic spline approximation of these values. |
|-----------------|-----------------|
| x/C  | y ±/C  |
| 0    | 0      |
| 0.1  | ±0.0658|
| 0.2  | ±0.0898|
| 0.3  | ±0.1045|
| 0.4  | ±0.1098|
| 0.5  | ±0.1087|
| 0.6  | ±0.0981|
| 0.7  | ±0.0792|
| 0.8  | ±0.0544|
| 0.9  | ±0.0312|
| 1    | ±0.0065|

3. High-speed visualization

3.1. Small gap size (0.4 mm)
At the lower attack angle of 3°, the cavitation first initiates over the GV fillets on the suction side in form of transient bubbles at σ = 0.97 (not shown). When the cavitation number is decreased to 0.92, the transient bubbles also appear in the central part of the hydrofoil and travel roughly from the GV leading edge to its midsection, where GV attains its maximum thickness (x/C ≈ 0.44). Downstream of the midsection, the bubbles collapse due to a local growth of the static pressure. At these regimes, no tip-leakage cavitation was registered. A further decrease of σ to 0.84 makes the cavity to grow and leads to its unsteadiness (not shown). The primary cavity in the central part of the GV model merges the lateral cavities on both GV fillets. In the gap, cavitation appears only in the aft part of the GV model right behind the rotation axis as a bubbly flow similar to that shown in Figure 2-a (σ = 0.74).
The regimes at $\sigma = 0.84$ and 0.74 do not differ essentially but cavitation in the second case is more intensive so below we consider only the latter regime. The size of cavitation area in the clearance is governed by the dynamics of the primary cavity and alternates in phase with its length pulsations as a result of variation of the local pressure field due to the unsteady flow behavior. In addition, the traveling bubbles are periodically entrained into the gap from the suction or pressure sides of the hydrofoil and then collapse or escape to the same or opposite side, depending on the phase of the primary cavity evolution (Figure 2-a).

At the higher incidence of $9^\circ$, cavitation occurs both on the GV suction side and in the clearance right behind the leading edge in form of a sheet cavity at $\sigma = 2.34$ (not shown). The sheet cavity in the gap has a streaky structure similar to the one in Figure 2-b. This is likely connected with a high level of turbulence in this flow region, which can be a reason for the bypass transition. At $\sigma = 2.15$, dimensions of both cavities increase but the cavitation patterns remain the same (not presented). When the cavitation number is decreased down to $\sigma = 1.65$, both cavities expand downstream and the flow regime modifies to an unsteady one – so-called cloud cavitation is observed over the foil suction side (Figure 2-b). Despite the primary cavity is unstable, the sheet cavity in the clearance appears to be stable, with the cavitation pattern unchanged (Figure 2-b). As for the inclination of $3^\circ$, the transient bubbles are also periodically entrained into the gap right behind the GV axis from its both sides. However, the number of the transient bubbles occurs to be noticeably lower as compared to the case of $\alpha = 3^\circ$.

**Figure 2.** Instantaneous images of tip-clearance cavitation along with partial cavities on the suction side of the GV section for $h_1 = 0.4$ mm when (a) $\alpha = 3^\circ$, $\sigma = 0.74$ and (b) $\alpha = 9^\circ$, $\sigma = 1.65$.

### 3.2. Large gap size ($0.8$ mm)

An increase of the gap width leads to noticeable changes in behavior of the tip-leakage flow. However, the primary cavity pattern and its dynamics change with a decrease of the cavitation number in the same way as it was for $h_1 = 0.4$ mm. At $\alpha = 3^\circ$, cavitation in the clearance initiates at $\sigma = 1.65$ right behind the foil leading edge as a sheet cavity similarly to the case presented in Figure 2-b but, for the smaller gap size, it is absent (see Figure 2-a). The sheet cavity in the gap has also a streaky structure and its dynamics remains stable even if the primary flow is unsteady (e.g. see the case of $\sigma = 0.74$ in Figure 3-a) as it was in the case shown in Figure 2-b. At the attack angle of $\alpha = 9^\circ$, the sheet cavity initiates in the gap at higher cavitation numbers (about $\sigma = 3.58$) in comparison with the case of $h_1 = 0.4$ mm for which the incipience cavitation number is $\sigma = 2.34$. The transition to cloud cavitation at $\sigma = 1.66$ does not modifies the tip-leakage cavity behavior like in the case of $h_1 = 0.4$ mm. In general, the larger the gap size is, the larger the cavitation area in the clearance occurs to be. For instance, it is twice larger for $h_1 = 0.8$ mm as compared to $h_1 = 0.4$ mm.

### 4. PIV/PTV measurements

PIV/PTV measurements were performed only for $\alpha = 9^\circ$ and $h_1 = 0.8$ mm at the cavitation incipience ($\sigma = 2.37$) and cloud cavitation ($\sigma = 1.66$) regimes. The mean velocity distributions in the clearance are presented in Figure 4. The velocity distributions for both cases appear to be nonuniform and are influenced by the cavity. For example, the flow around the GV leading edge reaches the velocities up
to $1.5U_0$ (see Area I in Figure 4). As seen (cf. Figures 3-b and 4-b), the cavity size almost completely corresponds to Area I. The sheet cavity located in this region contracts the flow cross-section, which leads to its acceleration. In Area II (Figure 4), the flow moves upward and eventually escapes the gap to the GV suction side. This occurs because of the existing pressure gradient between the pressure and suction sides. Above the GV rotation axis, there exists a recirculation zone marked as Area III in Figure 4, where the flow rises from the fillet base to its top due to an additional contraction of the primary flow by each fillet. Behind the GV rotation axis ($x/C > 0.65$), the flow is directed downward from the suction side to the pressure one (see Area IV in Figure 4), which is the opposite case to the one in Area II as the pressure and suction sides switch their places downstream of the axis when the attack angle is nonzero. However, the flow velocity in this region is significantly lower than the bulk velocity and is only about $0.2U_0$ since the pressure gradient behind the axis is lower in comparison with the one in front of it. This result is in good agreement with the acquired visual data for the unsteady regime (see Figure 3), where the direction of the traveling bubble motion periodically changes, so the mean flow velocity is in general very low.

![Figure 3. Instantaneous images of tip-clearance cavitation along with partial cavities on the suction side of the GV section for $h_1 = 0.8$ mm when (a) $\alpha = 3^\circ$, $\sigma = 0.74$ and (b) $\alpha = 9^\circ$, $\sigma = 1.66$.](image)

5. Conclusions
The tip-leakage cavitation was successfully studied by means of a high-speed visualization and PIV/PTV approach. It was demonstrated that the cavity formation and evolution in the clearance is strongly dependent on the gap size for both attack angles. The larger the gap is, the more developed the cavity appears to be. The sheet cavity, in turn, influences the velocity distributions within the gap. At unsteady regimes, oscillations of the primary cavity over the foil suction side make the flow direction in the clearance to alternate periodically depending on the phase of the main cavity evolution, especially at small incidences. The GV fillets were shown to produce recirculation zone above the rotation axis where the flow rises from the fillet base to its top.

Acknowledgments
The research was funded by a grant from the Russian Foundation for Basic Research (Project No. 17-08-01199-A supervised by K. Pervunin) and a grant of the President of the Russian Federation for the state support of leading scientific schools (Project No. NSh-10179.2016.8 supervised by Prof. D. Markovich).

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![Figure 4](image-url)

**Figure 4.** Plane distributions of the mean velocity (absolute values) in the gap between the GV end face and test channel wall in case of $h_1 = 0.8$ mm at $\alpha = 9^\circ$ for (a) $\sigma = 2.37$ (tip-leakage cavitation inception) and (b) $\sigma = 1.66$ (cloud cavitation). Black arrows show the flow direction. The black circle depicts the GV rotation axis and the grey area indicates its shadow. The velocity fields are separated into several distinct zones corresponding to: I – tip-leakage cavitation, II – preaxial upward flow, III – recirculating flow above the rotation axis, IV – downward flow behind the rotation axis and V – flow in the foil aft part.