The effect of the clearance geometries on the cavitating vortices near the foil tip

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Abstract. The blade tip clearance is inevitable for an axial flow rotor. The clearance flow contains various vortices and the resulting vortex cavitation is a concern in hydraulic machineries. In the narrow gap, the vortex features are sensitive to the change of the clearance size, and then the geometry factors may influence the vortex cavitation characteristics. As a simplification of a blade, an isolated hydrofoil is convenient for adjusting the clearance geometries in different cases. The effects of the clearance shape, gap height and gap width on the cavitating vortices are discussed in present paper. As the limited space and the cavitation phenomenon make it difficult to measure the vortex flow features, the numerical simulation is widely used to investigate the cavitating vortices. An improved cavitation model, which is suitable for the vortex cavitation, is used in present work. Under the different geometrical conditions, the vortex structures, the pressure features and the cavitation characteristics are revealed from the simulation.

1. Introduction

The clearance between the rotatable blade tip and the fixed casing wall is inevitable for an axial flow hydraulic machinery. The clearance leakage will result in the flow losses, efficiency penalty and heat transfer [1-2]. Under the influence of the pressure difference between the pressure and suction side of the blade, there are two typical kinds of vortices near the tip gap. The one is the tip separation vortex (TSV) subjected to the boundary layer separation, and the other is the tip leakage vortex (TLV) due to the interaction between the leakage flow and the through-flow around the blade. A low-pressure center is formed in the vortex core because of the concentrated vorticity, leading to cavitation which always has a negative impact on the hydraulic machinery. Therefore, it is important to explore the vortex to get a better understanding of the cavitating flow.

Clearance geometries like the clearance shape, gap width and gap height can influence the vortex features. Laborde et al. [3] proposed to round the clearance edge on the blade pressure side to eliminate clearance cavitation inside the gap. Guo et al. [4] numerically compared the non-cavitating
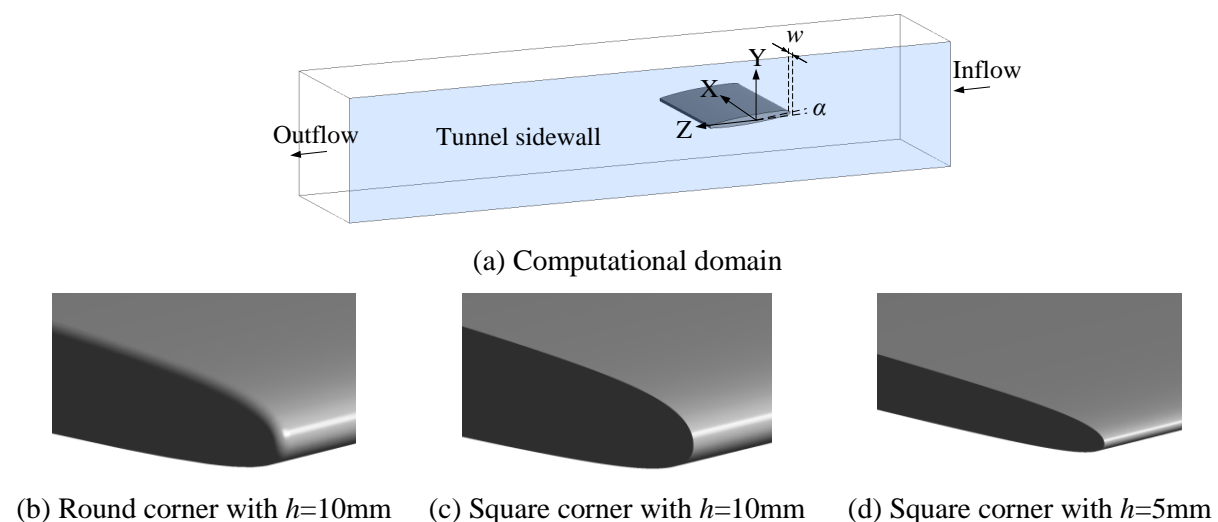
vortex flow from two hydrofoils with the round and sharp clearance edge respectively. It was found that the pressure in TLV would decrease without the TSV's interference. Due to the complexity of the rotating machinery, the hydrofoil is frequently studied as a benchmark case. For example, Dreyer et al. [5] used a simplified hydrofoil to investigate the effect of the gap width on the TLV features. In the test, the cavitating flow is used to visualize the trajectory of vortices, and the velocity field was measured in a cavitation-free regime. The gap height is related to the blade tip thickness, which is usually determined in the design process. In addition, a specially device of anti-cavitation lip [6] used in Kaplan turbines also changes the gap height locally. The main function of the anti-cavitation lip is to shift the TLV cavitation from the blade suction side, but the specific influence of the gap height on the vortices is not clear.

The numerical simulation has advantages on investigating the flow features deep into the cavitation regions with different cases. Based on a vortex cavitation model approved by Guo et al. [7], this paper will investigate the effects of the clearance geometries on the cavitating vortices near a foil tip.

2. Numerical setups

2.1 Computational cases
The case of a hydrofoil is from Dreyer et al.'s experiment [5], where a NACA0009 foil was in a water tunnel with a clearance (gap) between the foil tip and the tunnel sidewall. The foil chord is about 100mm and the outer contour size of the tunnel is 750mm×150mm×150mm. The typical clearance geometries in the reference test include the following elements: a round pressure side corner shape, a maximum gap height (h=10mm, the maximum foil thickness) and an adjustable gap width (w). According to the general type of the rotor blade, calculation cases with a square pressure side corner and a thinner thickness (h=5mm) are added in present work. Meanwhile, two kinds of gap widths with w=2mm and w=10mm are compared. The schematic diagram of the computational domain and the local view of the foil tip in different cases are shown in figure 1.

(a) Computational domain

 (b) Round corner with h=10mm   (c) Square corner with h=10mm   (d) Square corner with h=5mm

Figure 1. Computational domain and several kinds of foil tip

2.2 Mesh generation and boundary conditions
The mesh generation is finished in the ICEM software with the structured hexahedral grid. The detailed information about the grid division and the mesh validation have been shown in our previous work [4, 7]. Local grid adjustment is implemented near the foil tip for the different cases. The amount of grid cells is about 4 million and the averaged y+ is about 20 on the walls.

The boundary conditions include a velocity inlet and a pressure outlet, and the other physical walls are set as no-slip walls. Based on a specific cavitating condition in the test, the inflow velocity is V_{in}=10m/s and the inlet pressure is about p_{in}=1×10^{5}Pa. The incidence angle of the foil is α=10°, which is relative to the inflow direction along Z-axis.
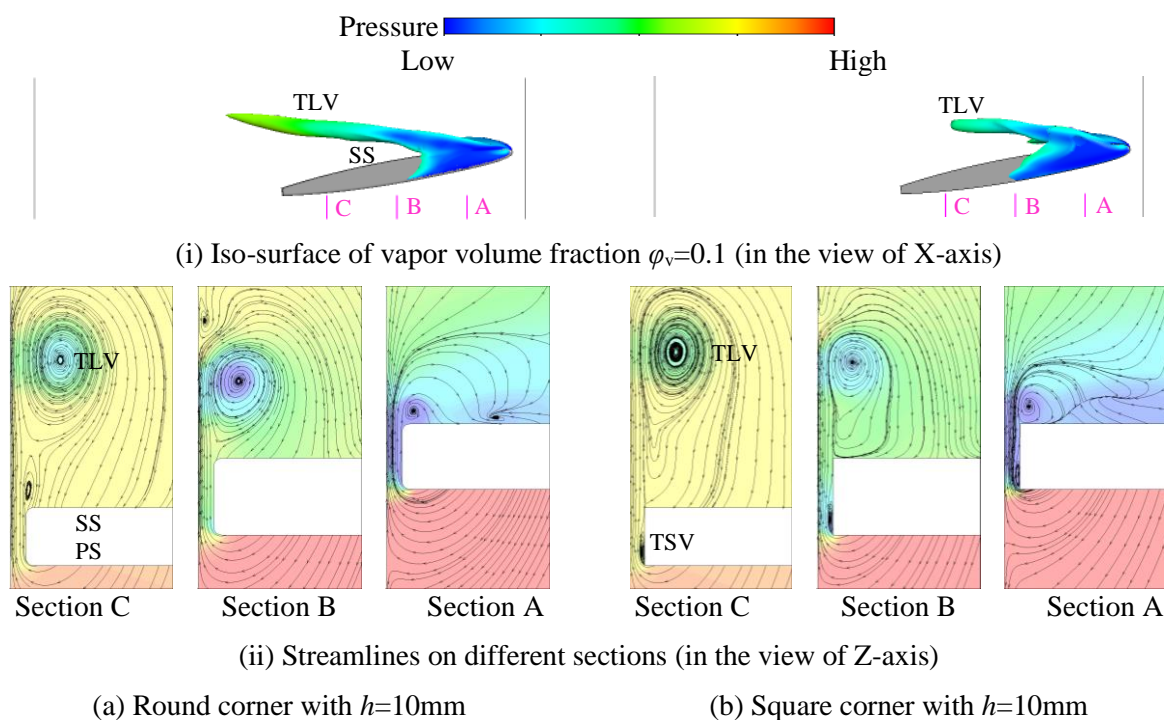
2.3 Numerical method
The steady RANS equations are solved in ANSYS CFX software, with the SST-CC turbulence model and the VIZGB cavitation model used. The simulation results of the cavitating TLV around the original foil in the experiment have been validated [7]. The high resolution scheme is used for the solver control and the convergence criteria is specified as the residual target of RMS=10^{-6} reached.

3. Results and discussion

3.1 Effects of the foil tip shape
Two kinds of foil tip shape with round and square corner are compared with the same gap height (h=10mm), corresponding to figure 1 (b) and (c). In the simulation results, the cavitation region can be illustrated by the vapor volume fraction (φ_v) and the vortex structure can be shown by the flow traces. Take the narrow gap condition (w=2mm) for example, figure 2 uses the iso-surface of φ_v=0.1 to show the cavitation region and the vortex structure is shown by the streamline on three cross sections. The contour in figure 2 indicates the pressure distribution.
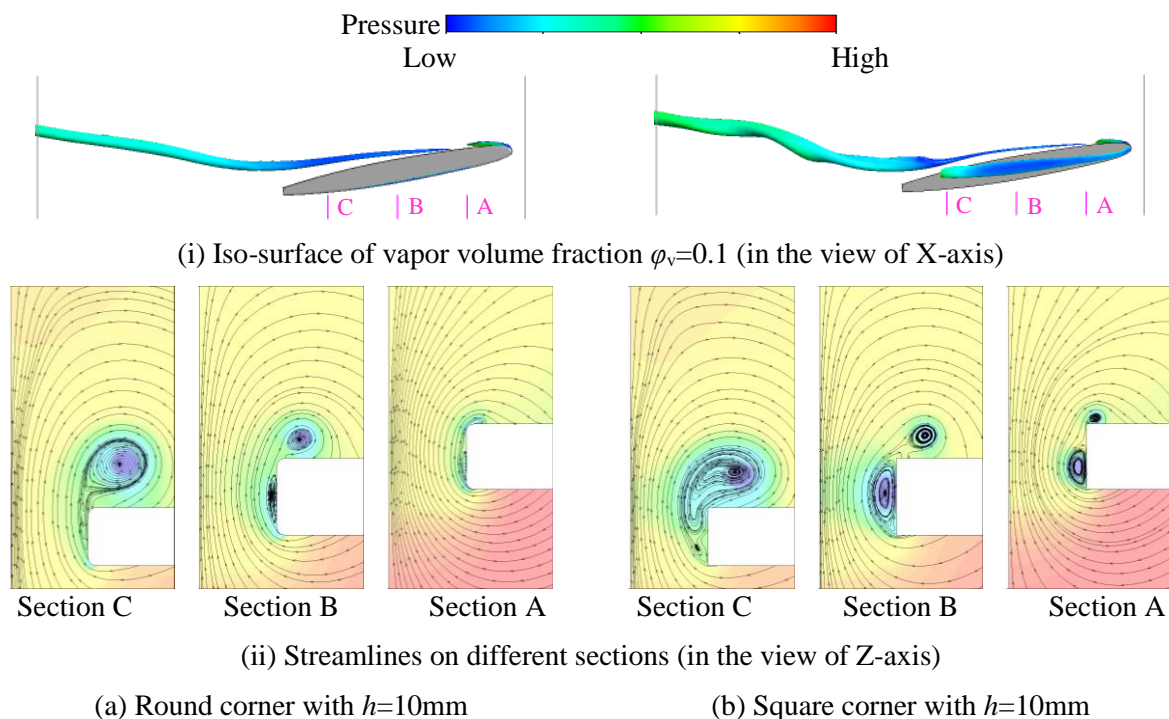

(i) Iso-surface of vapor volume fraction φ_v=0.1 (in the view of X-axis)

Section C   Section B   Section A   Section C   Section B   Section A

(ii) Streamlines on different sections (in the view of Z-axis)

(a) Round corner with h=10mm   (b) Square corner with h=10mm

Figure 2. Simulated cavitation region and vortical flow visualization for two tip shapes

(narrower gap with w=2mm)

Comparing the cavitation region between the two tip shapes in figure 2 (i), it shows that the cavitating TLV develops further downstream with a smooth appearance for the tip with round corner. For the square corner, there is local spirality for the TLV region and its streamwise length is shorter. These phenomena can be explained by figure 2 (ii), where the streamlines show the vortex structures near the foil tip. For the square corner, the flow separation near the foil pressure side (PS) inside the

gap results in a tip separation vortex (TSV) flow, this TSV makes the leakage flow through the gap become non-uniform and then affects the TLV's shape. In contrast, the round corner eliminates the TSV and the TLV has a more concentrated low-pressure center. Overall, the pressure at vortex center has some recovery and the cavitation vanishes gradually along the TLV trajectory, but the vortical flow will develop continuously to farther downstream.

Figure 3 shows the situation with a wider gap of w=10mm. Compared to the narrow gap in figure 2, the interference effect from TSV is more distinct for the square corner, with an obvious helical TLV shown in figure 3 (i). On the section A and B, the TSV area inside the gap is even bigger than the TLV region, shown in figure 3 (ii). On section C, the roll-up motion of the TSV from the gap to surrounding the TLV is clear. For the round corner, the TSV is not completely eliminated as shown by the streamlines, and its low-pressure center will cause cavitation when the ambient pressure is low enough. However, the small region of TSV has little influence on the TLV flow, which develops to far downstream keeping a smooth shape.

According to the analysis of the effects of the foil tip shape on the vortical flows, it shows that the round tip corner can weaken the clearance cavitation inside the gap, but it is hard to eliminate the TSV thoroughly in a wider gap, which means the clearance cavitation could happen when the ambient pressure is lower enough. Moreover, the existence of the TSV changes the uniformity of the clearance flow and makes the TLV twisted.
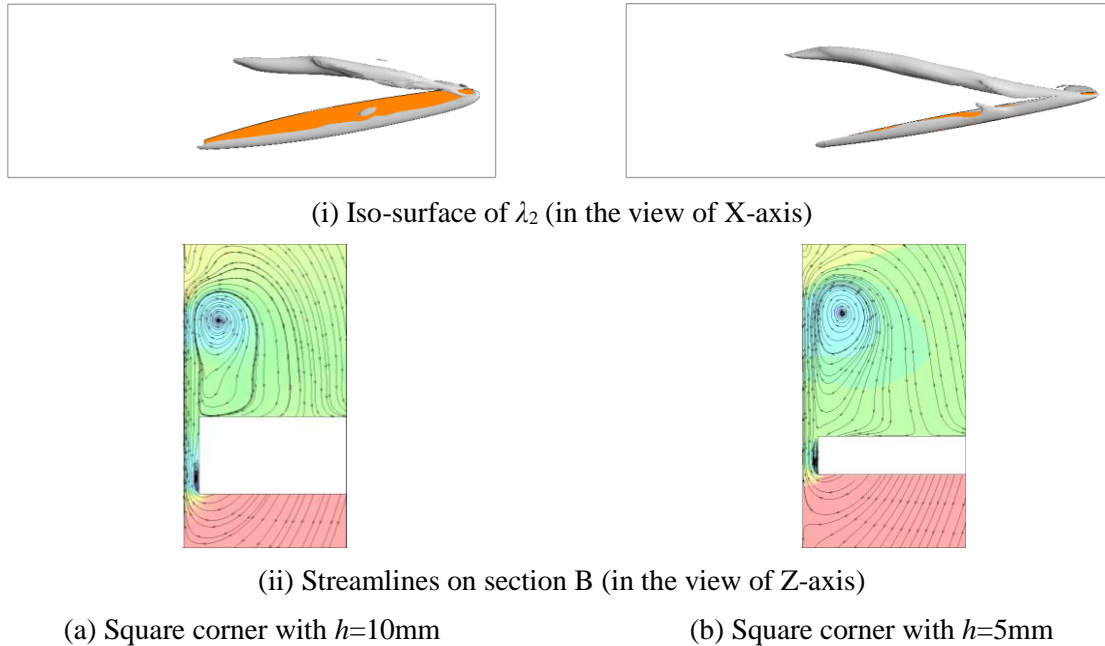

(i) Iso-surface of vapor volume fraction φ_v=0.1 (in the view of X-axis)

| Section C | Section B | Section A | Section C | Section B | Section A |

(ii) Streamlines on different sections (in the view of Z-axis)

(a) Round corner with h=10mm   (b) Square corner with h=10mm

Figure 3. Simulated cavitation region and vortical flow visualization for two tip shapes
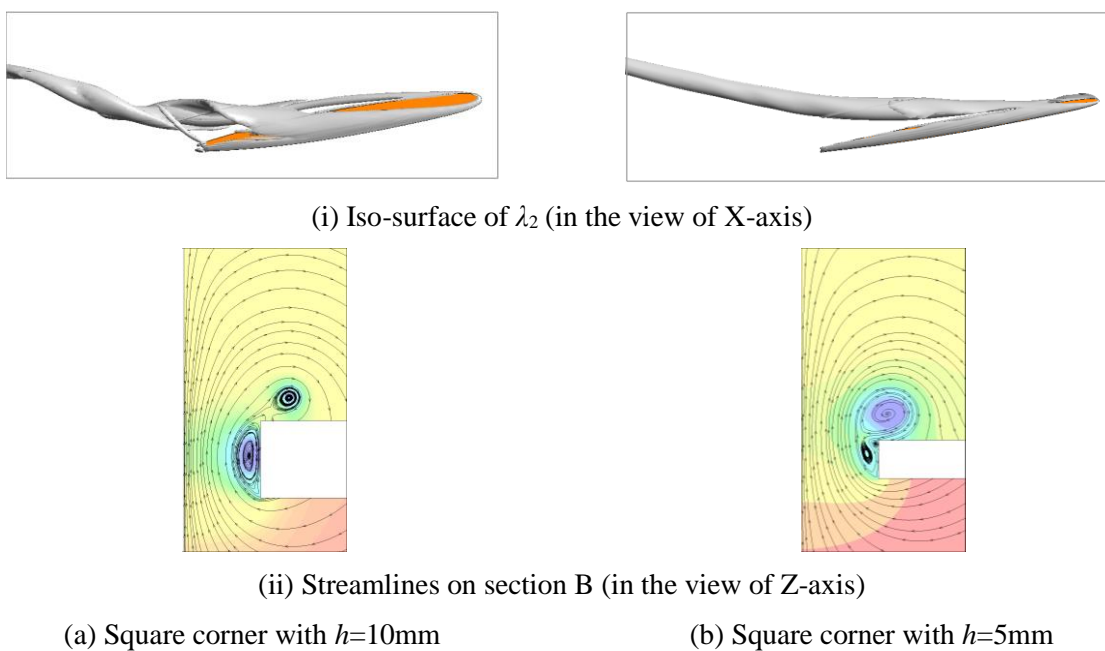
(wider gap with w=10mm)

3.2 Effects of the gap height

The gap height is related to the foil tip thickness directly. Referring to the design experience of an axial flow pump, the ratio of the blade tip thickness and the tip chord is usually between 2%~5%. This ratio for the original NACA0009 foil is about 10%, then a new thinner foil with the ratio of 5% is added to make a comparison. In view of the practical situation for an axial rotor, the square tip corner is considered in this part. Two foils with different gap height are shown in figure 1 (c) and (d).

Figure 4 uses a common vortex identification criterion of λ_2 [8] to show the vortex region near the narrow gap. The value of λ_2 for the iso-surface display is about $-2 \times 10^6 s^{-2}$. In figure 4 (i), it can be seen that the general shape and trajectory of the TLV are similar between the two foils with different gap height. The streamwise length of the TLV is a little longer for the thinner foil than for the thicker foil. In figure 4 (ii), the streamlines on section B reveals that the distribution and the region size for the vortex structures are similar between the two foils. As the distance between the TLV and TSV is relatively far, the interaction effect between the vortices is small.

(i) Iso-surface of λ_2 (in the view of X-axis)

(ii) Streamlines on section B (in the view of Z-axis)

(a) Square corner with h=10mm   (b) Square corner with h=5mm

Figure 4. Simulated vortex region and vortical flow visualization for two gap heights

(narrower gap with w=2mm)

(i) Iso-surface of λ_2 (in the view of X-axis)

(ii) Streamlines on section B (in the view of Z-axis)

(a) Square corner with h=10mm   (b) Square corner with h=5mm

Figure 5. Simulated vortex region and vortical flow visualization for two gap heights

(wider gap with *w*=10mm)

In a wider gap, figure 5 shows an obvious difference for the vortex shape between the two gap heights. The thinner foil eliminates the TSV to a great extent with a reduced vortex region inside the gap, and the pressure at the TSV center increases slightly. Meanwhile, the TLV has a smoother appearance but a lower pressure center in the thinner foil. From point of view of increasing the effective gap height, the installation of the anti-cavitation lip would weaken the TLV cavitation but the TSV cavitation is noteworthy. From point of view of simplifying the vortex field, the thinner foil is favourable but the effect of the thickness on the blade strength need consideration.

Overall, the trajectories of the TLV are similar between the two foils with different gap heights. Comparing the vortex region in figure 5 (a) and the cavitation region in figure 3 (b) for the thicker foil with *h*=10mm, it reveals that the minimum pressure region is concentrate in the TSV and TLV center and causes the cavitation, the other vortices like the trailing vortex has little effect on the cavitating flow field. Compared with the narrower gap situation in figure 4, the pressure in the flow field is higher as a whole for the wider gap.

In order to further investigate the effect of the gap width, figure 6 illustrates the variation of the leakage flow rate (Q_{gap}) with the gap width for two gap heights. It shows that the Q_{gap} is a little lower in the thinner foil than in the thicker foil. With the increasing of the gap width, the change of the gap flow rate presents a linear growth trend, and the difference between the two gap heights is not obvious.
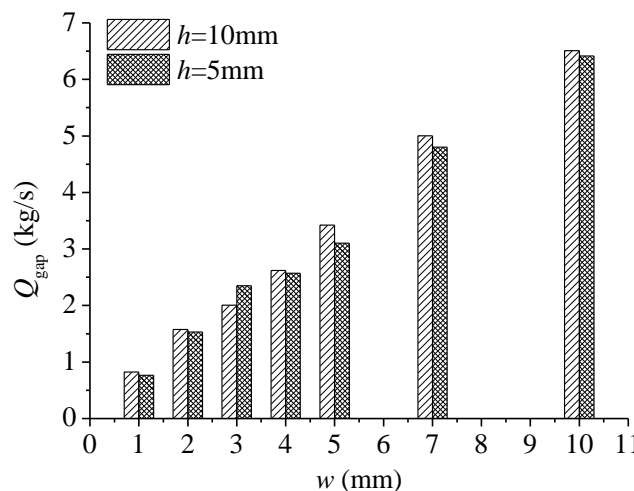
Figure 6. Variation of the gap leakage flow rate with gap widths for two gap heights

4. Conclusions
The cavitating vortices near the hydrofoil tip are simulated in present work. The effects of the clearance geometries on the vortex and cavitation features are investigated. Some observations made as results are as follows.

Two kinds of foil tip with the round and square tip corner respectively are compared. It validates that the round corner could weaken the tip separation vortex (TSV) inside the gap. For the square tip corner, the TSV will lead to the deformation of the tip leakage vortex (TLV) and the clearance cavitation inside the gap cannot be ignored especially in a wider gap.

Two gap heights corresponding to two foil thicknesses are compared. It shows that the smaller gap height can reduce the TSV area and simplifies the vortex flow field. Without the interference of the TSV, the TLV has a lower pressure center which is more likely to cause cavitation in the wider gap.

References
[1]   Booth T C, Dodge P R and Hepworth H K 1982 *J Eng Power Trans ASME* **104** 154–161
[2]   Rued K and Metzger D E 1989 *J Turbomach* **111** 293–300
[3]   Laborde R, Chantrel P and Mory M 1997 *J Fluids Eng Trans ASME* **119** 680–685
[4]   Guo Q, Zhou L and Wang Z 2016 *Renew. Energy* **99** 390–397
[5]   Dreyer M, Decaix J, Münch-Alligné C and Farhat M 2014 *Exp Fluids* **55** 1849
[6]   Motycak L, Skotak A and Kupcik R 2012 *IOP Conf. Ser. Earth Environ. Sci.* **15** 032060
[7]   Guo Q, Zhou L, Wang Z, Liu M and Cheng H 2018 *Ocean Eng.* **151** 71–81
[8]   Jeong J and Hussain F 1995 *J Fluid Mech* **285** 69–94