Flow Features of an Unstable Tangential Vortex Intake

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Abstract. Tangential vortex intakes are compact hydraulic structures commonly used in water supply, drainage and sewerage systems to convey water from high to low elevations efficiently. For certain design of tangential vortex intakes, flow instability can occur in the approach channel and the vortex dropshaft, resulting in undesirable hydraulic jump and shock waves. Due to the complex three-dimensional (3D) flow in the tangential vortex intake, current theoretical models are not sufficiently complete to interpret the flow process reliably. This paper presents an experimental and 3D Computational Fluid Dynamics (CFD) modeling study of an unstable tangential vortex intake flow. The CFD predictions are in good agreement with detailed point velocity and air core size measurements. Despite of the hydraulic jump at the tapering channel, the swirling flow at the vortex drop shaft is similar to that of a stable vortex intake with Rankine vortex behaviour.

Keywords: Tangential vortex intake · Swirling flow
Computational fluid dynamics · Volume-of-Fluid · Laser doppler anemometry
Stormwater management

1 Introduction

Vortex intakes are commonly used in water supply, drainage and sewerage systems. A tangential vortex intake consists of an approach channel with horizontal bottom and rectangular cross section, and a steep tapering channel connected to a dropshaft. The inflow enters tangentially into the dropshaft via the tapering channel, and the flow swirls down the dropshaft. The strong centrifugal effect in the swirling flow results in an air core which allows any entrained air to escape. However, under certain design of the vortex intake, flow instability can occur in the approach channel and the vortex dropshaft, resulting in undesirable hydraulic jump and shock waves (Yu and Lee 2009). The complex three-dimensional (3D) vortex flow in the intake has hitherto not been clearly understood. Current theoretical models (e.g. Jain 1984; Yu and Lee 2009) are not sufficiently complete to interpret the flow process reliably. To better understand the flow processes of an unstable vortex intake design, detailed velocity measurement and 3D computational modelling is required.

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Detailed flow field and air core measurement for a stable vortex intake has been attempted, using point Laser Doppler Anemometry (LDA) (Qiao et al. 2013). With the development of computational modeling techniques and advancement in computation power, attempts have been made to tackle the air-water flow in vortex intake problems using 3D Computational Fluid Dynamics (CFD) models with the Volume-of-Fluid (VOF) method. Plant and Crawford (2016) has reported the use of a commercial CFD code on the design of a tangential vortex intake. Chan et al. (2018) also studied the flow field of a stable vortex intake using the VOF method and revealed important flow details. The model is successfully validated against velocity and air core size measurement. This paper presents an experimental study and 3D CFD modeling on an unstable tangential vortex intake.

2 Experiments and CFD

2.1 Physical Model

The flow characteristics of a tangential vortex intake is mainly determined by the design parameters of junction width e, approach channel width B, drop shaft diameter D, bottom slope of tapering section β and tapering angle of width of tapering section θ (Fig. 1a). The tapering channel has a steep 1:1 slope, in contrast with milder slope in the stable design reported previously (Qiao et al. 2013; Chan et al. 2018). Based on the one-dimensional theory of Yu and Lee (2009), the free drainage discharge (Q_f = 18.2 L/s) is estimated less than the critical discharge of the intake (Q_c = 20.2 L/s), suggestive of unstable flow behavior. The air core size is measured by a specially designed eight-leg ruler (Yu and Lee 2009) for flow rates Q = 1–20 L/s. Detailed point velocity measurement is made using two-component LDA at the junction and at different azimuth angles of vortex dropshaft, with a specially designed measurement panel mounted at the external wall of the dropshaft for typical flows (Qiao et al. 2013).

2.2 CFD Model

The VOF model (Hirt and Nichols 1981) predicts two immiscible fluids (water and air) by solving a single set of momentum equations and tracking the volume fraction of each of the fluids throughout the computational domain. The tracking of the interface between the phases is accomplished by the solution of a continuity equation for the volume fraction of one of the phases. The resulting velocity field is shared among the two phases through the phase-averaged density and viscosity. The standard k-ε model is used for turbulence closure of air-water mixture flow. The governing equations are solved numerically using the "interFoam" solver in OpenFOAM 4.0 for two incompressible, immiscible fluids based on the interface capturing approach (OpenFOAM 2016).

An unstructured boundary-fitted mesh with 76,320 hexahedral cells is developed according to the experimental design (Fig. 1b). Mesh refinement is made to close to the dropshaft wall to resolve the swirling flow, with minimum grid size of about 1 mm. The computational model has three open boundaries - the inflow, the bottom outflow of

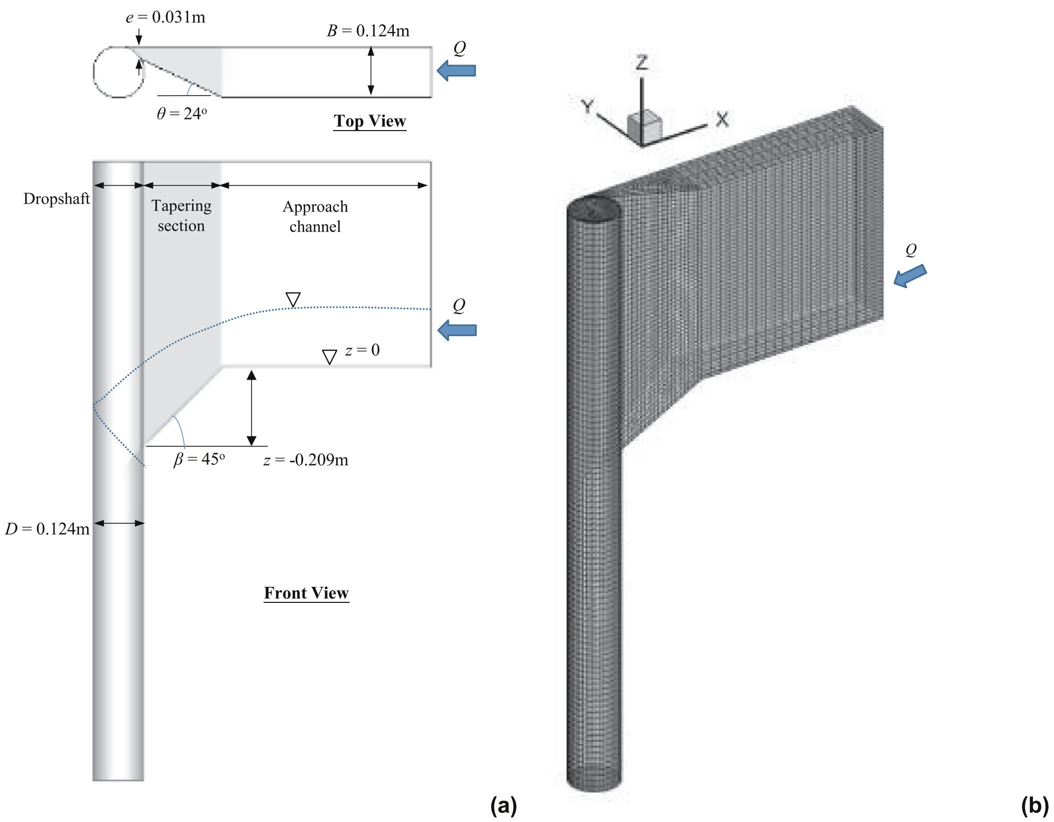

Fig. 1. (a) Geometry of the unstable tangential vortex intake and (b) the CFD model mesh.

the dropshaft and the top atmospheric boundary. The model is initiated from dry bed condition and the flow is developed from the inlet until quasi steady-state. A variable time step of ~0.1–1 ms is used to maintain computational stability. The computation time for one minute of flow on a single node 12-core 2.3 GHz high performance computing cluster is about 1 h.

3 Results and Discussion

3.1 Approach and Tapering Channel Flow

The predicted free surface profile at the approach and tapering channel is shown in Fig. 2 for Q = 4 and 8 L/s. For Q = 4 L/s (Fig. 2a), the flow remains supercritical in the entire tapering channel. For Q = 8 L/s (Fig. 2b), the flow transforms from critical flow at upper end of tapering channel to subcritical flow near the junction through an inclined hydraulic jump at the tapering channel. The flow accelerates towards the junction, due to the narrowing and sloping of the tapering channel. Predicted free surface compares well with the measurement. Near the junction, the horizontal velocity u is nearly constant in the vertical direction and about the same for both flow rates (Fig. 3a). The vertical velocity w varies linearly in the vertical direction, increasing from the surface to the bottom (Fig. 3b). The predicted flow velocity compares satisfactorily with point LDA flow measurement, despite the unstable flow due to the hydraulic jump.

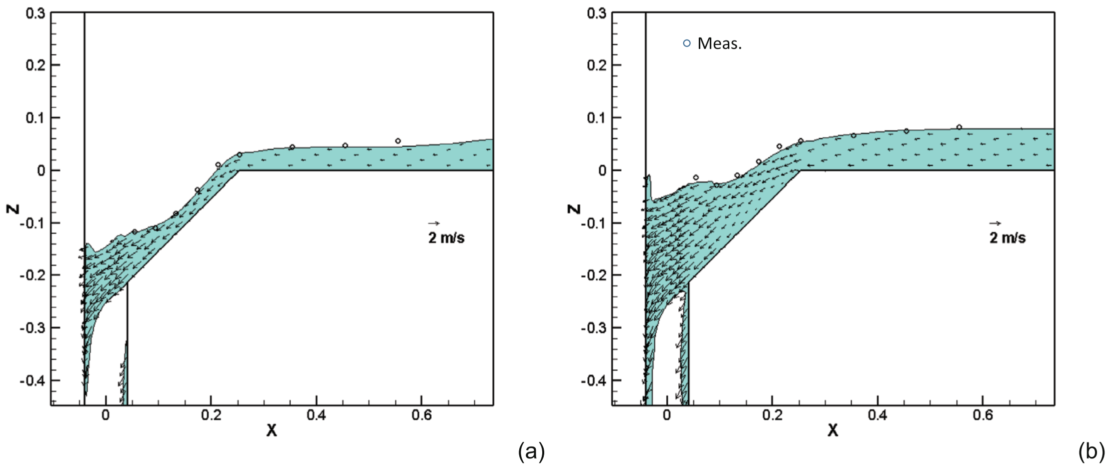

Fig. 2. Free surface profile and flow field at the approach and tapering channels for (a) Q = 4 L/s, (b) Q = 8 L/s. Open circles are measurement along the channel centreline.

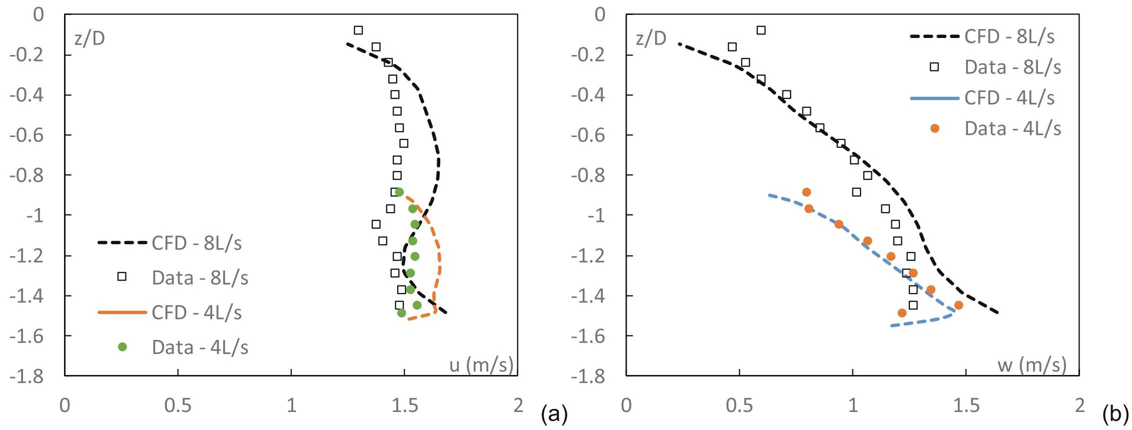

Fig. 3. Measured and predicted (a) horizontal velocity and (b) vertical velocity at the junction of dropshaft (Q = 4 and 8 L/s)

3.2 Air Core Area

Figure 4a shows the predicted minimum air core (z = −0.12 m) and the swirling flow field in the dropshaft for Q = 16 L/s. The inflow from the tapering channel enters the dropshaft as a slot jet. The air core is significantly asymmetrical about the axis of the drop shaft; the flow thickness is largest near the junction entry and decreases gradually to a minimum at 270° as it swirls around the circumference. The air core area ratio λ (air core size to dropshaft area) first decreases down the dropshaft (Fig. 4b), reaching a minimum at z = −0.1 to −0.2 m (bottom level of junction), and then increases again. The CFD prediction of air core size compares satisfactorily with laboratory measurement.

3.3 Swirling Flow at Dropshaft

The predicted and measured tangential and vertical velocities of the swirling flow agree reasonably well at the throat in the dropshaft (z = 0 m and −0.12 m, Fig. 5).

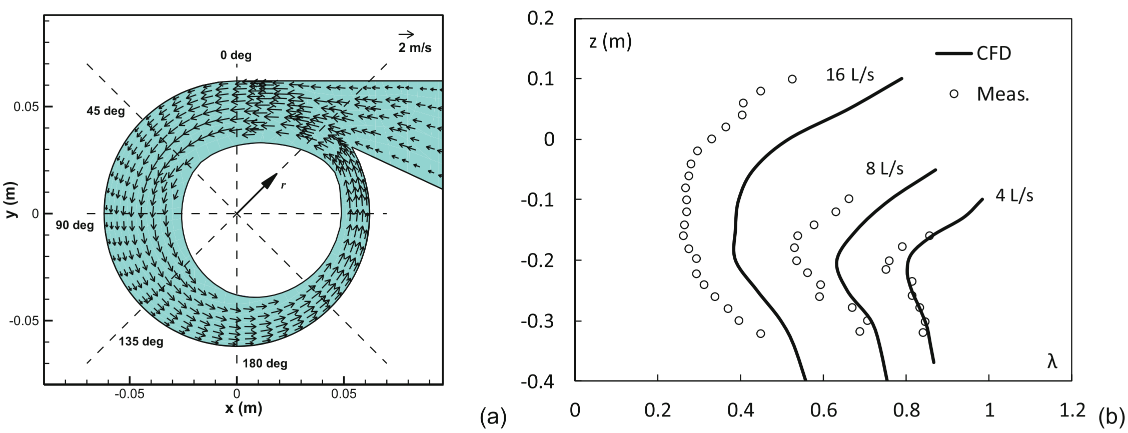

Fig. 4. (a) Predicted air core and swirling flow field for $z = -0.12$ m (throat), $Q = 16$ L/s. (b) Predicted and measured air core area ratio λ for three flow rates.

The tangential velocity u_θ first increases with radius near the air core, suggestive of solid body rotation (forced vortex) behaviour. It increases to a maximum at $r = 0.04$ m, then reduces again, suggesting free vortex behaviour. The vertical velocity remains constant for the thickness of the flow. Similar swirling flow feature at the dropshaft is also found in a stable vortex intake design (Chan et al. 2018).

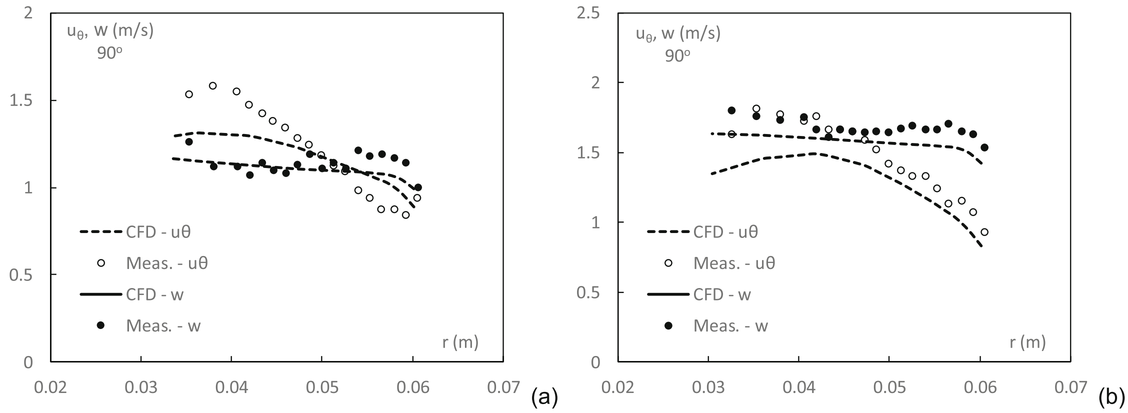

Fig. 5. (a) Predicted and measured tangential and vertical velocity at the dropshaft, azimuth angle of 90°, for $Q = 16$ L/s, (a) $z = 0$ m, (b) $z = -0.12$ m.

4 Conclusions

A numerical study of an unstable tangential vortex intake flow has been conducted using the open source 3D CFD code OpenFOAM and validated with experimental measurement. The CFD model predictions are validated against flow profile, air core and detailed point velocity measurements, offering comprehensive insights of tangential vortex intake flow and providing a basis for the hydraulic design of such vortex intake structures.

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