VERIFICATION OF OPENFOAM TO SIMULATE TANGENTIAL VORTEX INTAKE FOR CIVIL ENGINEERING APPLICATION

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Abstract

In urban drainage/sewerage design, it is common to encounter water flow with large drop in elevation, such as intercepting stream flow to deep drainage tunnel for urban flood protection in Hong Kong. Tangential vortex intake is an efficient way to convey flow with large drop due to its good energy dissipation and large air core in drop shaft to release entrained air. Physical modelling is the conventional way to design vortex intake but it is timely and expensive to build. Commercial CFD software, e.g. Flow 3D, is increasingly used by civil engineering industry in Hong Kong to design/review hydraulic performance of vortex intake and other complex hydraulic structures. However, there is no known study which has examined accuracy of CFD in modelling flow in such complex hydraulic structures in detail. This study aims at validating OpenFOAM using comprehensive measurements on tangential intake physical model by Qiao et al. (2013) on: (i) head-discharge (Q-H) relation; and (ii) flow structure at approach channel and drop shaft. The results show that OpenFOAM is capable of giving good prediction of Q-H relation, and resolving flow structure of the swirling flow in drop shaft. This demonstrates the potential of CFD software, particularly OpenFOAM which is free and open source, as a tool to advance design of complex hydraulic structures in civil engineering industry in a more efficient and cost effective way.

Keywords: *Tangential Vortex Intake, Drop Shaft, Vortex Flow, Swirling Flow, Air Core*

Introduction

Tangential vortex intakes are commonly used to convey flow with large drop in elevation in drainage system. A tangential intake is a compact hydraulic structure which is composed of: (i) a rectangular approach channel with horizontal bottom; (ii) steep taping channel; (iii) a narrow slot at the junction; and (iv) drop shaft. Yu and Lee (2009) proposed a stable design criterion for tangential intake based on 1D model assuming circular vortex flow in drop shaft and constant streamwise velocity in the junction. Yet these assumptions were not verified until the work of Qiao et al. (2013). They carried out detailed velocity measurements on the structure of a tangential intake vortex flow for the first time. The works of Qiao et al. form the basis of this study to verify capability of OpenFOAM to simulate tangential vortex intake for civil engineering application.

Experimental Study by Qiao et al. (2013)

Detailed velocity field measurement with Laser Doppler Anemometry was carried out Qiao et al. (2013) for the first time for a steady tangential vortex intake. The experimental setup for measuring vortex flow field with LDA is shown in **Figure 1** below.

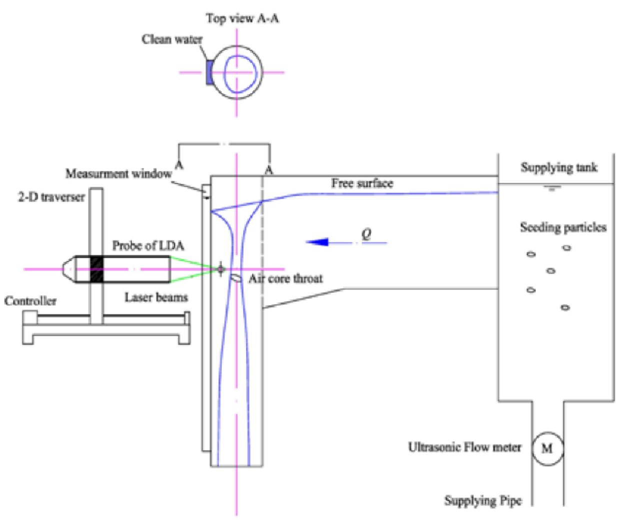


Figure 1: Experimental setup for measuring vortex flow field with LDA (Extracted from Qiao et al. (2013))

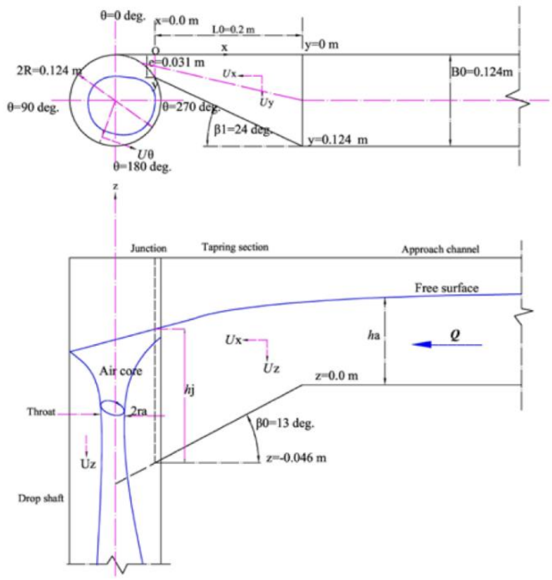


Figure 2: Main geometric parameters and measured vortex flow variables (Extracted from Qiao et al. (2013))

The geometry of tangential intake is shown in **Figure 2** and is determined by the following parameters: junction width (e), approach channel width (B0), drop shaft radius (R), bottom slope of tapering section (β0) and tapering angle of tapering section (β1).

The flow depth in the approach channel (ha) and the flow depth at the junction (hj) in the tapering channel were measured by point gauge. The local horizontal velocity Ux, the transverse velocity Uy perpendicular to the vertical boundary wall and the vertical velocity Uz are measured in a Cartesian coordinate system for Q = 2.0, 4.0, 6.0, 8.0 and 10.0L/s. The local vertical velocity Uz and the tangential velocity Uθ are also measured for the swirling flow velocity field in the drop shaft in a cylindrical polar coordinate system.

Model Setup & Description of Flow

Tangential intake in **Figure 2** was setup in OpenFOAM v4.1 using the standard solver, interFoam, for 2 incompressible, isothermal immiscible using volume of fluid phase-fraction based interface capturing approach. Parameters used are summarized in **Table 1** below. Overview of the model and water surface profile are shown in **Figures 3 and 4**.

Table 1: Parameters of the Model Setup

Parameters	Values
Meshing	blockMesh & snappyHexMesh
Number of Cells	1,485,577
Mesh Size	0.01m in approach channel, 0.0025m in drop shaft
Turbulence Model	kOmegaSST
Inlet patch	Flow rate boundary condition (variableHeightFlowRate)
Outlet & atmosphere patches	Atmospheric boundary condition (totalPressure)

For the range of flow simulated (Q=2L/s to 10L/s), flow regime in the approach channel is subcritical with smooth and flat water surface. The flow accelerates in the tapering and sloping section of approach channel, and it passes through critical depth at the junction before entering into the drop shaft horizontally. In the drop shaft, the flow attaches to the wall surface and the initial thickness of the flow is approximately equal to the width of junction. The swirling flow follows a helical path down the shaft and leaves the outlet patch at the bottom.

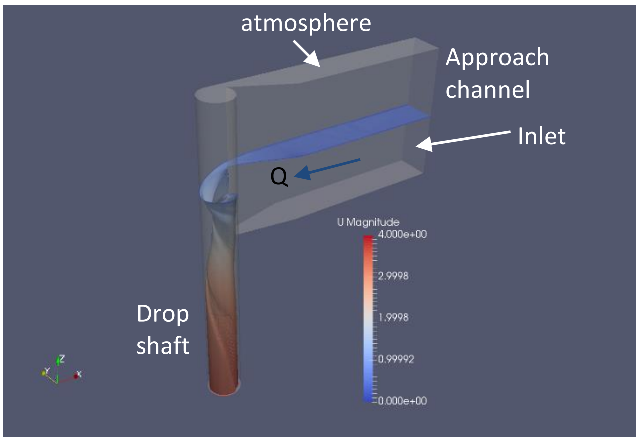


Figure 3: Isometric View of Water Surface Profile at Q=10L/s

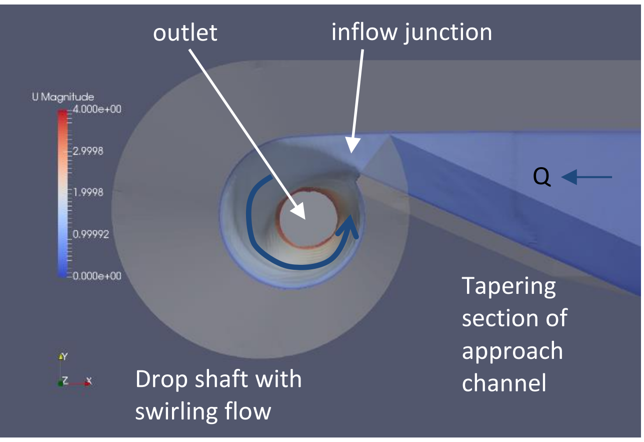


Figure 4: Top View of Swirling Flow in Drop Shaft at Q=10L/s

Depth Discharge (Q-H) Relation

Water depth (ha) at approach channel of vortex intake is important as it affects hydraulic profile of its upstream drainage system. Therefore, accurate prediction of Q-H relation is essential for proper design of vortex intake to avoid water overtopping at upstream. Based on the measurements by Qiao et al. (2013), discharge and depth at approach channel (blue dots) show a close to linear relation as shown in **Figure 5**. Results of OpenFOAM (orange dots) show the same linear trend and the water depths (ha) in approach channel are reasonably well predicted. At the largest discharge of 10L/s, the difference is less than 10%. Q-H relation of tangential intake can be estimated with reasonably good accuracy for practical use.

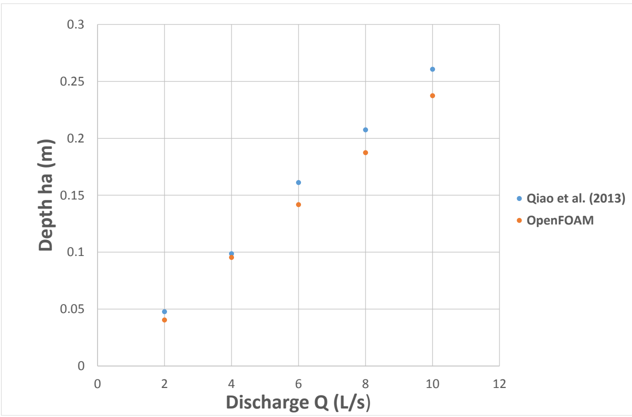


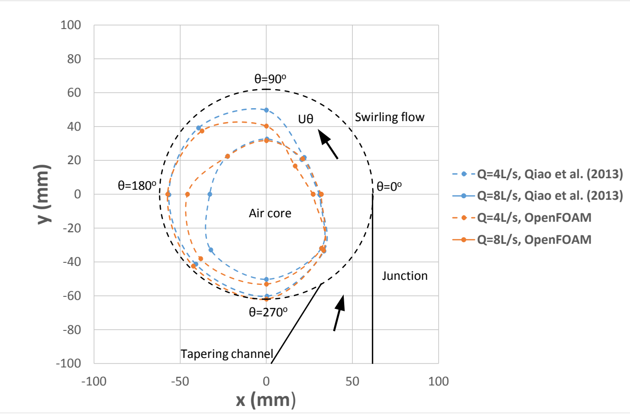
Figure 5: Comparison of depth-discharge relation

Minimum Air Core Area Ratio

The air core size decreases with discharge. Yu and Lee (2009) defined a key parameter λ as the ratio of air core area to the drop shaft cross-sectional area, $\lambda=b^2/a^2$ where a, b=radius of drop shaft and air core, respectively. The value of λ must be sufficiently large to allow free passage of air and ensure stable operation of the vortex intake. A typical criterion is λ ≥ 0.25 for the design discharge. Yu and Lee (2009) assume circular air core in order to derive an analytical equation to calculate air core area ratio from a given discharge Q.

In **Figure 6**, the air core shapes from physical measurement (blue lines) and numerical model (orange lines) are compared at z=-0.04m at Q=4L/s and 8L/s. It is clearly seen that the actual air core is of D-shape and is asymmetrical about the axis of the drop shaft. The thickness of the flow layer being almost minimum at swirling angle θ=270°. The shape of simulated air core agrees reasonably well with the measured one.

In **Figure 7**, the variation of air core area ratio (λ) down the drop shaft at different flow rates are compared. Results of OpenFOAM are consistent with the measurements in general. The physical measurements show that the throat, i.e. the critical section of vortex flow with minimum air core area ratio, is located at z=0m to -0.05m. Elevations of throat are depicted by OpenFOAM correctly under different flow rates. The minimum air core area ratio (λ) predicted by OpenFOAM is reasonably accurate, taking into account of the possible human measurement errors in using specially designed ruler in measuring air core size in drop shaft.



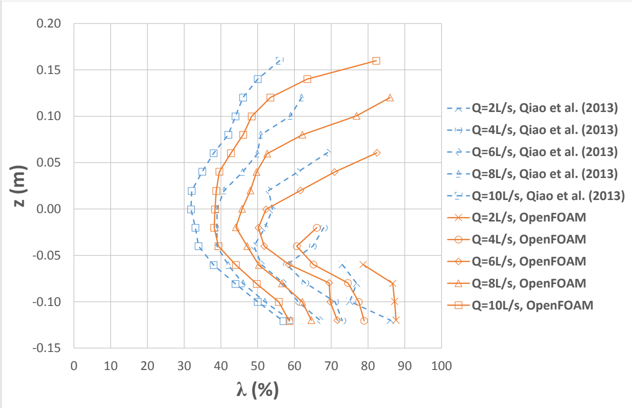


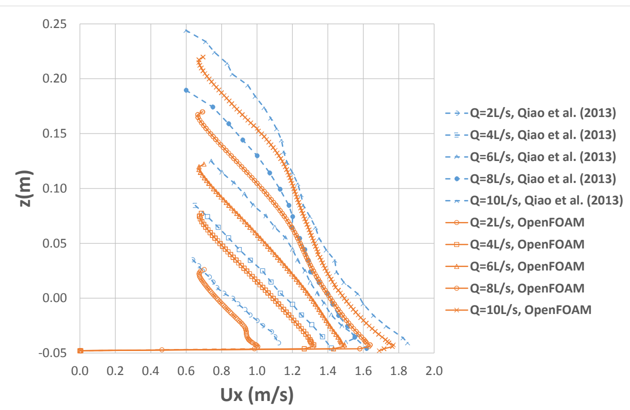
Figure 6: Comparison of air core shape at z=-0.04m

Figure 7: Comparison of air core area ratio

Velocity Distribution at Inflow Junction

Before the measurement by Qiao et al. (2013), the actual inflow pattern from the tapering channel into the drop shaft was unknown. Yu and Lee (2009) assumed a constant horizontal velocity Ux at the inflow junction in deriving an analytical equation to predict the free drainage discharge, i.e. the maximum discharge at which the vortex flow, after turning 360° in the drop shaft, doesn't disturb the parallel inflow jet at the junction. This is an important criterion to ensure formation of smooth and stable vortex flow.

In **Figure 8**, velocity distribution of Ux at inflow junction along depth of flow at different flow rates are compared. The physical measurements show that Ux varies linearly in the vertical direction for Q=2L/s to 6L/s. For larger discharge, Ux close to the bottom of inflow junction is affected by the swirling flow in the drop shaft after turning 360°, and the velocity profile of Ux starts to deviate from linear. Results of OpenFOAM give very good agreement with the measurements.



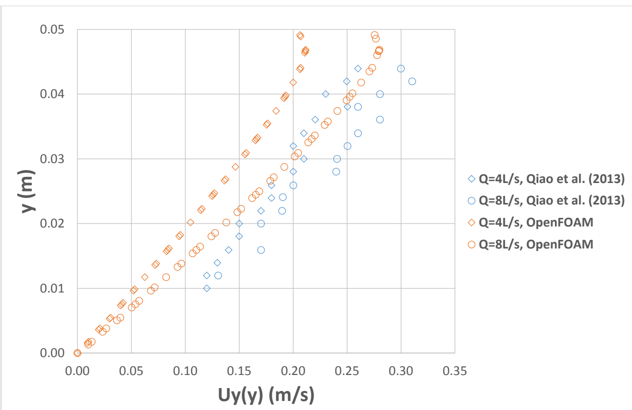


Figure 8: Comparison of velocity distribution $U_x(z)$ at the junction (y=0.009m, x=0.0m)

Figure 9: Comparison of velocity distribution $U_y(y)$ at the junction (x=0.045m, z=0.05m)

In **Figure 9**, there is small transverse velocity Uy at the junction due to tapering of the approach channel. All these detailed flow structures at the junction are very well predicted by the CFD model.

Velocity Distribution of Swirling Flow near to the Throat

Yu and Lee (2009) made another two assumptions in deriving an analytical equation for predicting minimum air core area ratio (λ) at the throat of swirling flow for tangential intake, they are: (i) horizontal tangential velocity Uθ of the swirling flow is inversely proportional to the radial position; and (ii) vertical velocity Uz is uniformly distributed in the radial direction.

In **Figure 10**, horizontal tangential velocity Uθ of swirling flow near throat of drop shaft is plotted against its radial distance (r) from centre of drop shaft at θ=45^o for Q=4L/s. From the measurement, there is clearly an inverse relationship between Uθ and r. Results of OpenFOAM can resolve this distribution of Uθ to a high degree, and the velocity drops rapidly to zero at drop shaft wall surface (r=62mm) due to no slip condition.

In **Figure 11**, vertical velocity Uz of swirling flow near throat of drop shaft is also plotted again its radial distance (r) at θ=45^o for Q=4L/s. From the measurement, the assumption of uniform distribution of Uz in the radial direction is obviously justifiable. Results of OpenFOAM not only show uniform vertical velocity Uz distribution in radial direction, but also correctly predicts increase in vertical velocities down the drop shaft. Results of OpenFOAM give good prediction of the distribution of Uθ and Uz, despite the flow in drop shaft is highly three-dimensional helical flow.

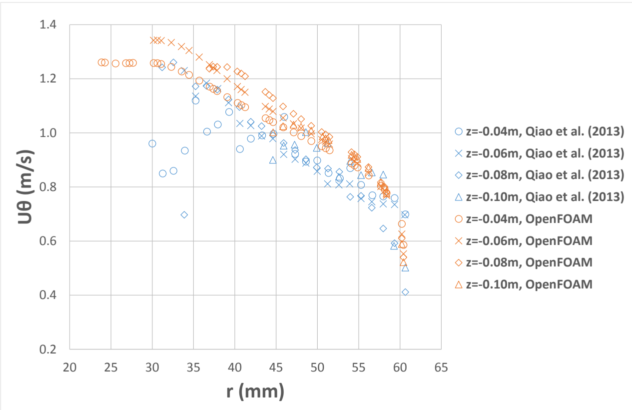


Figure 10: Comparison of tangential velocity (U_θ) of vortex flow at θ=45^o for Q=4L/s

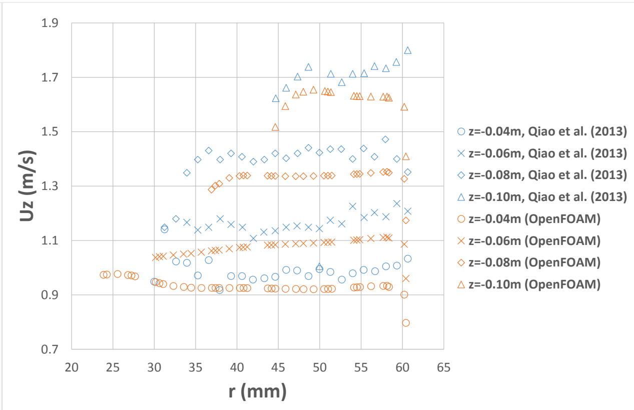


Figure 11: Comparison of vertical velocity (U_z) of vortex flow at θ=45^o for Q=4L/s

Conclusions

With the detailed measurements by Qiao et al. (2013) on physical model of tangential intake, comprehensive insight can be gained and the results provide solid basis to verify capability of OpenFOAM to simulate such complex flow. The results presented here have demonstrated the capability of OpenFOAM to predict two important parameters to civil engineers in designing tangential intake: (i) Q-H relation; and (ii) minimum air core area ratio.

More than that, OpenFOAM can also resolve complex flow structures of: (i) the accelerating inflow into the drop shaft at the junction, together with the effects of swirling flow in the drop shaft after turning 360^o at large discharge; and (ii) tangential and vertical velocity distribution along the radial direction of the swirling flow. It is of more interest to academics who develop theory for the hydraulics of tangential intake/complex hydraulic structures.

Findings in this study clearly illustrate the potential of this free and open source OpenFOAM to be used as: (i) an efficient and cost effective tool to supplement conventional physical model which is timely and expensive to build; (ii) a design tool for complex hydraulic structure for civil engineering application, as a cost effective alternative to the commonly used commercial software; and (iii) a research tool for academics to gain insight into complex flow problems to develop better hydraulic theory.

Acknowledgements

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