OpenFOAM vs FLOW-3D: a Comparative Study of Vertical Slot Fishway Modelling

Juan Francisco Fuentes-Pérez[1,2,✉], Ana L. Quaresma[3], Antonio Pinheiro[3], Francisco Javier Sanz-Ronda[1]

[1]Department of Hydraulics and Hydrology, University of Valladolid (UVa). Avenida de Madrid 44, Campus La Yutera, 34004, Palencia, Spain.

[2]Centro Tecnológico Agrario y Agroalimentario ITAGRA.CT. Avenida de Madrid 44, Campus La Yutera, 34004, Palencia, Spain.

[3]CERIS – Civil Engineering for Research and Innovation for Sustainability, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal.

✉Corresponding author: jfuentes@iaf.uva.es; jfuentes@itagra.com

Abstract

The objective of this study is to make a comparison between two 3D CFD platforms: OpenFOAM (free and open-source CFD software) and FLOW-3D (closed source commercial CFD software), focusing on vertical slot fishways, one of the most widespread solutions to facilitate the fish migration through transversal obstacles in rivers. Considering previous comparative studies, our initial hypothesis is that both OpenFOAMs' multiphase solver and FLOW-3D provide good comparable results. In this study, in contrast to previous comparative studies, turbulence was addressed using LES approach and the volume of fluid method was used to model the multiphase interface (air-water). Mesh independency was assessed through LES IQ index and the numerical models' accuracies were evaluated comparing representative hydraulic variables (velocity, its components, and turbulence kinetic energy) with ADV experimental data and discussing results in previous studies. Both platform codes reproduced the scenario under study, concurred with experimental data and offered a superior performance on flow structure velocity simulation than turbulent kinetic energy. Results validate the use of the free and open platform OpenFOAM as a viable alternative to commercial ones in the domain of fishway design and assessment. While OpenFOAM provides a reliable free alternative, FLOW-3D has a faster setup and makes the simulating experience apt for beginners.

Keywords: OpenFOAM, FLOW-3D, 3D hydrodynamic modelling, Fishways, LES

1. Introduction

The use of computational fluid dynamics (CFD) has become an essential tool for engineers and researchers working in the area of freshwater ecosystems (Bates et al., 2005) for a great variety of purposes, among others, to assess any intervention on them (*e.g.* Gisen et al., 2017; Machado Xavier et al., 2018), for risk assessment (*e.g.* Bohorquez and García-García, 2016; Zeng et al., 2020) or to study complex ecological interactions and physical processes (*e.g.* Gao et al., 2016; Juras et al., 2018).

When facing a CFD problem, one of the most important decisions for engineers and researchers is which software to use. On the one hand, it is possible to use commercial CFD software, black boxes that provide a user-friendly working environment, tested accuracy, and meshing and post-processing toolkits (such as FLOW-3D or ANSYS Fluent). On the other hand, there are free and open alternatives (such as OpenFOAM (Greenshields, 2015)), which are usually more complex to use due to the freedom that is given to the user and the need for third party codes or software for meshing, visualization, and post-processing.

This study aims to compare two three-dimensional (3D) CFD software: OpenFOAM vs FLOW-3D, focusing on vertical slot fishways (VSF). VSF are one of the most widespread mitigation measures to facilitate the passage of fish from one side to the other in transversal obstacles to the river (Fuentes-Pérez et al., 2017; Quaresma et al., 2018; Rajaratnam et al., 1986). Fishways, and in particular VSF, are a perfect test case to perform this comparison, due to: 1) the numerous hydraulic and biological research studies conducted on them (Puertas et al., 2004; Quaresma et al., 2018; Romão et al., 2017; among others), which makes possible the comparison of the results with external sources, and 2) their complex hydraulic performance, which allows exploring a non-uniform flow pattern in the pools.

Our initial hypothesis is that OpenFOAMs' multiphase solver (interFoam) is able to match commercial codes for the CFD simulation in VSF. Previous studies comparing OpenFOAM and FLOW-3D in water-air multiphase flows have reported good matching results between them, all using Reynolds-Averaged Navier-Stokes (RANS) turbulence modelling methods (Bayon et al., 2016; Duguay et al., 2017). However, despite the popularity of RANS methods (Barton et al., 2009; Cea et al., 2007; Marriner et al., 2014; among others), they neglect the rapid turbulent structures in the flow as well as small temporal scales (Fuentes-Pérez et al., 2018b).

Thus, in this comparative study, Large Eddy Simulation (LES) turbulence modelling techniques are used. In contrast to RANS, LES includes large-scale turbulent velocity fluctuations and provides time-resolved flow fields including turbulent structures. Thus, at a higher computational cost (LES usually requires thinner meshes than RANS), LES methods have the potential of providing the "missing piece" of information to understand the relation between fish behaviour and hydraulic conditions within a fishway (Fuentes-Pérez et al., 2018b; Silva et al., 2012).

To achieve our aim and test our hypothesis, a VSF (design #11 defined by Rajaratnam et al., 1992) was modelled under uniform flow conditions (Duguay et al., 2017; Fuentes-Pérez et al., 2018b), using the two listed CFD software: OpenFOAM and FLOW-3D. After a mesh independency analysis using the LES Index of resolution Quality (IQ) (Celik et al., 2005), the two models were evaluated comparing their output with acoustic Doppler velocimeter (ADV) experimental data to obtain model performance. Results seem to validate the free and open software OpenFOAM as a viable alternative to closed commercial alternatives in the domain of fishway design and assessment. However, both alternatives have pros and cons that potential users should address before selecting one or the other.

2. Methodology

2.1. Fishway facility, hydraulic scenario, and measurements

Lab experiments were conducted in an indoor 1:1 scale VSF at the Hydraulics and Environment Department of the National Laboratory for Civil Engineering (LNEC), in Lisbon, Portugal. The VSF is a glass-walled open channel 10.0 m long, 1.0 m wide, and 1.2 m high. The VSF type corresponds to design #11 defined by Rajaratnam et al. (1992). It consists of six pools divided by five cross-walls with a bottom slope (*S*) of 8.5%. The cross-walls are made of wood 0.022 m thick (*e*) with 0.125 m wide slots (*b*) measured between baffles. The fish passage performance of this design has been extensively investigated and validated in specialized references (Fuentes-Pérez et al., 2018a; Romão et al., 2018, 2017; among others). The facility also includes an upstream chamber (1.85 m long, 1.0 m wide, and 1.2 m high) and a downstream tank (4 m long, 3 m wide, and 4 m high) (Figure 1). The discharge (*Q*) is controlled by a pump frequency converter and measured by an electromagnetic flow meter. The water level in the downstream tank is regulated by a gate, which allows the boundary conditions to be modified to reach target scenarios.

A uniform scenario (that provides the same mean water depth in all pools and same water drop (*ΔH*) in each cross-wall, *ΔH* = 0.16 m) was selected to perform the test, with a discharge of 0.081 m^3/s and a mean water level (h_0) in the pools of 0.80 m.

The flow field of the VSF was measured using a Vectrino 3D ADV (Nortek AS) in the second pool from the downstream end of the VSF. In total 112 points were measured. The ADV sampling interval was 180 s at a rate of 25 Hz. This sampling time was chosen to ensure convergence of time-averaged values of velocity (*V*) and turbulent kinetic energy (*k*) (Romão et al., 2017). A parallel profile to the bottom (0.5·h_0) was selected to perform the measurements and subsequent analyses (Figure 1).

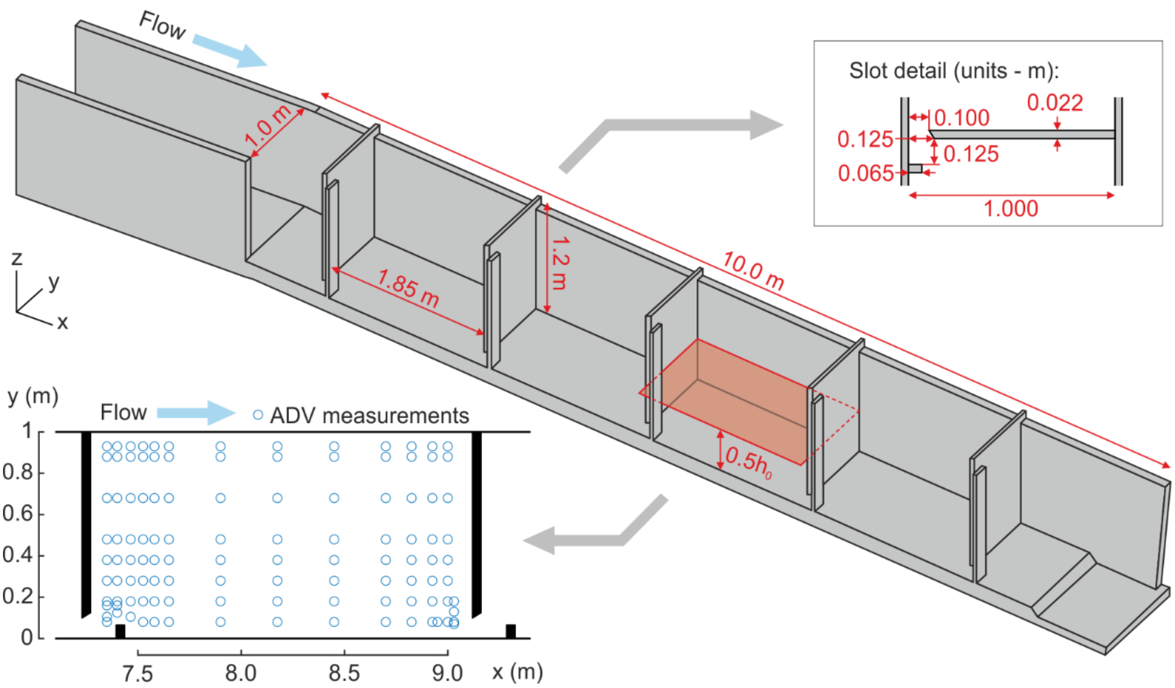

Figure 1. Schematic of the measured and simulated fishway, measurement grid for the ADV, and scenario and simulation details.

2.2. CFD methods

In this study, two 3D models are implemented, one using the open-source numerical code OpenFOAM (Greenshields, 2015) (release 20.06, www.openfoam.com) and another using the commercial software FLOW-3D (www.flow3d.com). The software selection was driven by the experience of the research groups involved (UVa: OpenFOAM and CERIS: Flow-3D) and due to the popularity of both software in the fishway modelling community (Duguay et al., 2017; Fuentes-Pérez et al., 2018b; Quaresma et al., 2018).

OpenFOAM is a C++ toolbox that uses a tensorial approach and Finite Volume Method (FVM) for the resolution of continuum mechanics problems, including CFD (Weller et al., 1998). The resolution of the transient flow of two fluids separated by a sharp interface can be achieved with the prebuilt Eulerian solver interFoam (Ubbink, 1997), which is an implementation of the classical Volume Of Fluid (VOF) method (Hirt and Nichols, 1981) and uses the PIMPLE algorithm for the pressure-velocity coupling, which combines PISO (Pressure Implicit with Splitting of Operator) and SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithms (Higuera et al., 2013). PIMPLE algorithm can be seen as a modification of SIMPLE algorithm that runs every time step (SimScale, 2021). A complete summary of flow equations, boundary conditions, and the simulation process applied to fishways can be found in Fuentes-Pérez et al. (2018).

FLOW-3D software also makes use of FVM to solve the governing equations of fluid motion. One of the major features of FLOW-3D is the Fractional Area/Volume Obstacle Representation (FAVOR) method (Hirt and Sicilian, 1985). This method is used to represent obstacles through fractional areas and volumes in a fixed orthogonal grid. Flow Science (2016) presents additional details regarding the theoretical and numerical fundamentals of FLOW-3D, which has been used in recent years in multiple fishway research studies (Duguay et al., 2017; Kim et al., 2012; among others). A detailed summary of the CFD FLOW-3D model here presented can be found in Quaresma et al. (2018).

To solve the turbulence in both implemented models, LES turbulence modelling techniques have been used (Fuentes-Pérez et al., 2018b; Quaresma et al., 2018). So far, RANS turbulence modelling techniques have been the most extended alternatives for the 3D modelling of fishways (Barton et al., 2009; Bombač et al., 2014; Cea et al., 2007; Duguay et al., 2017; Khan, 2006; Marriner et al., 2016, 2014). However, in contrast to RANS, in LES the desired temporal resolution can be reached, that is to say, temporal velocity fluctuations can be explicitly resolved, which is crucial to understand and/or model time-dependent biological interactions on them. In addition, both LES and RANS have been shown to provide acceptable results when compared to laboratory average velocity measurements (Fuentes-Pérez et al., 2018b).

Aditional information on discretization, boundary conditions, and initial conditions can be found in Quaresma et al. (2018) and Fuentes-Pérez et al., 2018b.

2.3. Mesh and time sensitivity analysis

To achieve a time-independent solution, velocity, flow rate, and water levels within the fishway were monitored during the simulation process, by plotting the difference between consecutive time steps and ending the simulation when an asymptotic behaviour was reached (100 time steps were used for the analysis). In all developed models, the same behaviour was observed: the differences between the monitored variables in each time step were reduced progressively until an oscillatory behaviour was reached.

To verify the numerical model quality and mesh resolution, the LES IQ proposed by Celik et al. (2005) was used. According to Pope (2001), a good LES should have a LES IQ greater than 0.8, which means that 80% of the *k* is resolved. Celik et al. (2005) consider that a LES IQ of 0.75 to 0.85 may already be considered adequate for most engineering applications that typically occur at high Reynolds numbers. To perform this analysis and select an optimal resolution (*i.e.* the coarsest mesh able to solve the *k*) different mesh resolutions were compared (0.04 m, 0.02 m, and 0.01 m), finally selecting those with a LES IQ greater than 0.8. For both models, a 0.02 m grid size mesh provided an adequate LES IQ (0.81 for FLOW-3D and 0.94 for OpenFOAM).

However, it should be noted that this index is a verification index that only assesses mesh resolution quality (Quaresma et al., 2018). To assess model accuracy, a comparison with experimental data is still necessary.

Spatial discretization was achieved by dividing the study volume into orthogonal grids of target resolution (cubes) and applying refinements in each of the cross-walls (Fuentes-Pérez et al., 2018b; Quaresma et al., 2018).

2.4. Data treatment and validation

ADV data were post-processed for despiking and noise reduction (Quaresma et al., 2018, 2017). Spikes were removed using phase-space threshold despiking method (Goring and Nikora, 2002) and replaced by linear interpolation. Doppler noise reduction was then applied through the method of Hurther and Lemmin (2001).

Time-averaged velocity (V [m/s]) and turbulence kinetic energy per unit mass (k [m^2s^{-2} = J/kg]) were used for data comparison as both variables have been pointed as fundamental in the analysis of fishway performance (Fuentes-Pérez et al., 2018a; Quaresma et al., 2018; Silva et al., 2011). Eq. 1 and Eq. 2 show the formulation adopted for the calculus of these variables.

$$\bar{V} = \frac{\sum_{j=1}^{n} \sqrt{u_j^2 + v_j^2 + w_j^2}}{n} \quad (1)$$

$$k = \frac{1}{2}\left(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}\right) = \frac{1}{2}\left(\frac{1}{n}\sum_{j=1}^{n}\left(u_j - \bar{u}\right)^2 + \frac{1}{n}\sum_{j=1}^{n}\left(v_j - \bar{v}\right)^2 + \frac{1}{n}\sum_{j=1}^{n}\left(w_j - \bar{w}\right)^2\right) \quad (1)$$

where, u_j, v_j and w_j are the velocity components in a cell or a measured point during the time step j in m/s, n is the total number of time steps, and in Eq. 2 $\overline{u'^2}$, $\overline{v'^2}$ and $\overline{w'^2}$ are the variances of velocity components fluctuations and $\bar{u}$, $\bar{v}$ and $\bar{w}$ are the mean value of velocity components.

CFD data from FLOW-3D was visualised and exported into comparable text format with FLOW-3D user interface, while CFD data from OpenFOAM was visualised and exported to comparable text format with Paraview software (version 5.8.0). Final analysis, visualization and comparisons were performed in Matlab R2019a.

The comparative study of the models and the experimental data was carried out by plotting model results against experimental data and calculating the distance of the scattered points to a 1:1 line, using squared Pearson correlation (coefficient of determination, R^2) as an index. Likewise, contour analysis was performed to investigate differences between profiles. The triangulated natural neighbour interpolation method was used to plot the contours. To compare the performance between models, mean absolute errors (MAE) were computed for each data-point measured with the ADV with regards to 3D models; MAE distribution differences between models and ADV were tested using Mann-Whitney *u*-test for two samples. In addition, to detect differences between models MAE and squared Pearson correlations (MAE_{Models} and R^2_{Models}) were also computed between models.

3. Results

Regarding discharge ($Q_{openFOAM}$ = 0.081 m^3/s; $Q_{FLOW\ 3D}$ = 0.080 m^3/s) and mean water depth ($h_{0,\ OpenFOAM}$ = 0.80 m; $h_{0,\ FLOW\text{-}3D}$ = 0.81 m), both models showed the capacity of achieving the target scenario with marginal differences. Table 1 shows the final computation details for both simulations. The main difference are software related, FLOW-3D only considers active cells for simulation (cells that contain water) which reduces the number of needed computations for its time step. Likewise, OpenFOAM allows to stablish a dynamic time discretization in a single simulation, that is to say to use thicker time step until certain degree of equilibrium has been reached and after select a thinner one to report final results, reducing the final computational time.

Table 1. Computation details for both simulations.

Software	**Final cells**	**Processor**	**Time**
OpenFOAM	1786930	i7-4710 MQ CPU @ 2.50 GHz x 8 cores	7 h per 10 seconds of simulation time
FLOW-3D	1333545	i7-3770 CPU @ 3.40 GHz x 8 cores	15 h per 10 seconds simulation time

Figure 2a illustrates the modelled mean velocities against ADV measurements in each of the measuring locations (Figure 1). For both models, the agreement with measurements was high, R^2 of 0.87 and 0.82 for OpenFOAM and FLOW-3D respectively. Regarding *k* (Figure 2b), the modelled-measured distribution had lower accuracy, R^2 of 0.48 and 0.57 for OpenFOAM and FLOW-3D respectively. For both variables (*V* and *k*), the agreement was higher between modelled results (Figure 2c).

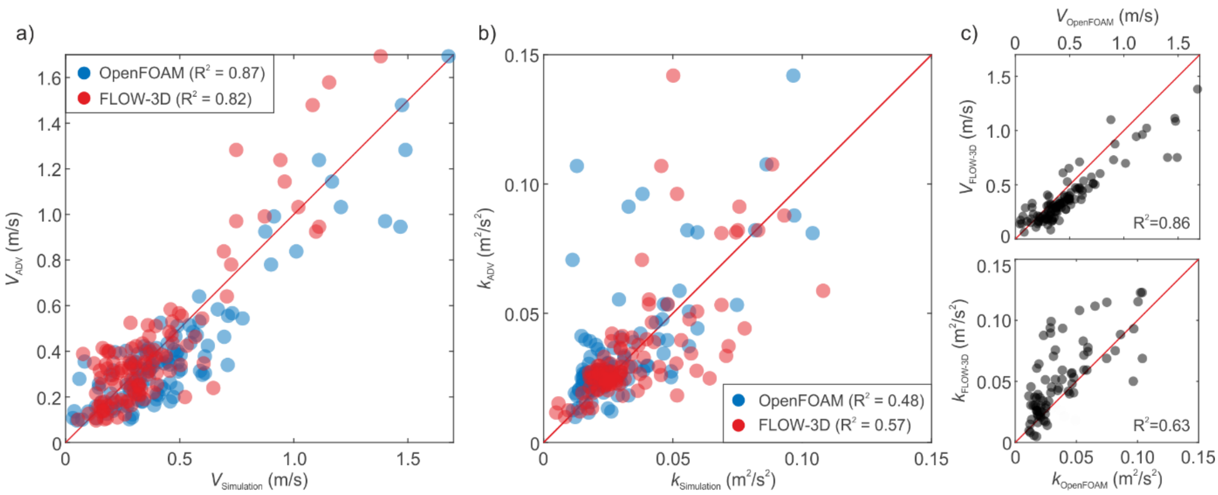

Figure 2. Scatter plot of ADV measurements against model results. a) V scatterplot. b) k scatterplot. c) CFD model comparison.

Figure 3 illustrates the spatial pattern of the flow and hydrodynamic variable distribution of the *V* and *k* measured with ADV and modelled with OpenFOAM and FLOW-3D. All showed similar flow patterns, with two main recirculation areas separated by a jet. The spatial distribution of variables was similar for all of them, while the magnitudes differed in accordance with Figure 2.

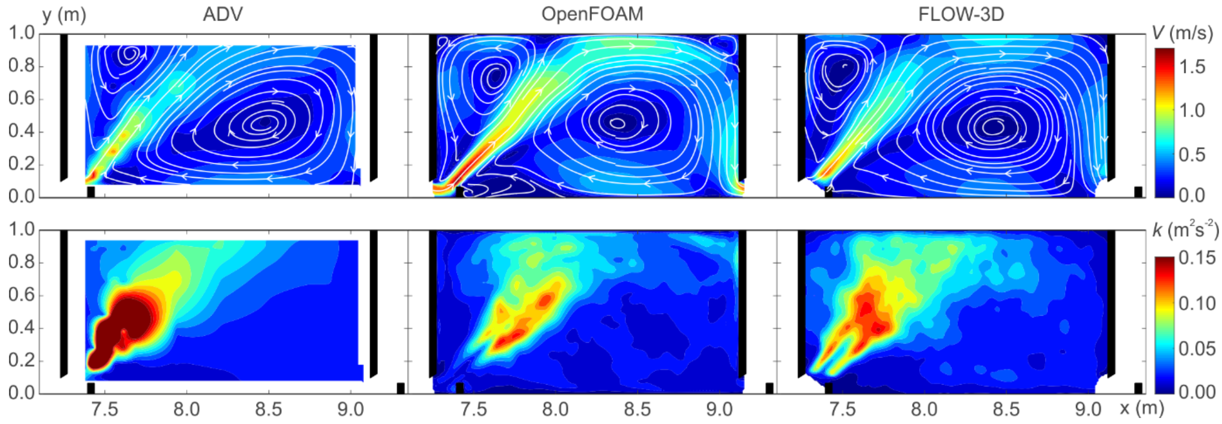

Figure 3. Contour plot of V and k for ADV measurements and the two CFD models under study.

Table 2 shows the squared Pearson correlation coefficients (R^2) and mean absolute errors (MAE) for considered variables, between models and ADV measurements (R^2_{ADV} and MAE_{ADV}) and between models (MAE_{Models}). Mann-Whitney *u*-test shows that there is not enough evidence to reject the null hypothesis, i.e. there are non-significant differences in MAE_{ADV} for all variables (*p*-values > 0.05).

Table 2. Experimental scenario against modelled scenarios, R^2, MAE and Mann-Whitney u-test results.

Variable	Model	R^2_{ADV}	MAE_{ADV}	*p-value*	R^2_{Models}	MAE_{Models}
***V* (m/s)**	OpenFOAM	0.87	0.12	0.218	0.86	0.13
	FLOW-3D	0.82	0.11			
***k* (m^2/s^2)**	OpenFOAM	0.48	0.03	0.196	0.63	0.01
	FLOW-3D	0.57	0.03			
***u* (m/s)**	OpenFOAM	0.87	0.12	0.307	0.94	0.10
	FLOW-3D	0.85	0.10			
***v* (m/s)**	OpenFOAM	0.89	0.10	0.758	0.87	0.11
	FLOW-3D	0.78	0.12			
***w* (m/s)**	OpenFOAM	0.32	0.05	0.232	0.36	0.05
	FLOW-3D	0.65	0.04			

4. Discussion

The major drivers when choosing CFD software are cost and usage. In this sense, it is possible to find:

1) Licensed or paid alternatives, such as FLOW-3D, optimised to solve free-surface flow problems, with customer support and an intuitive Graphical User Interface

(GUI) that includes meshing, setup, simulation monitoring, visualization, and post-processing in a single software.

2) Free alternatives (no license cost), such as OpenFOAM, a C++ toolbox, without a GUI but with coded tools for meshing, setup, parallel running, monitoring, post-processing, and visualization although no customer support (but big community support and on-line resources).

For a new user, it will take minutes to set up a simulation with FLOW-3D but days or months (depending on the initial knowledge of coding and CFD) in OpenFOAM. However, OpenFOAM will provide the user freedom for experimenting with and dive through the code and problem formulation.

Both software alternatives have been used in the study of fishway hydraulics. FLOW-3D (*e.g.* Duguay et al., 2017; Kim et al., 2012; Quaresma et al., 2018) together with ANSYS FLUENT (*e.g.* Andersson et al., 2012; Marriner et al., 2016) have been the most common commercial alternatives for 3D modelling while the usage of OpenFOAM has been still marginal (Duguay et al., 2017; Fuentes-Pérez et al., 2018b), although it is the most common open alternative.

In published comparisons, both codes have demonstrated adequate performance under RANS turbulence modelling techniques (Bayon et al., 2016; Duguay et al., 2017). According to Fuentes-Pérez et al. (2018b) RANS turbulence modelling techniques provide similar results to LES technics when comparing averaged values of hydrodynamics variables at a lower computational cost. However, LES is superior when fish are involved in the analysis, as LES has a higher potential for correctly displaying instantaneous changes in turbulence, necessary to reach a better understanding between fish behaviour and hydraulic conditions inside a fishway. Considering the results of this study, we confirm similar performances for OpenFOAM and FLOW-3D using LES turbulence modelling techniques in VSF.

In both models, the estimation of V is more accurate than the estimation of k (Figure 2) when comparing to ADV data. This is in accordance with other performed studies, where models usually under predict TKE values (Duguay et al., 2017; Fuentes-Pérez et al., 2018b). The observed R^2 for V data validates both simulations. Despite OpenFOAM model predicts overall higher velocities in the jet region when comparing to ADV measurements, the observed pattern seems more accurate than the one predicted by FLOW-3D. In contrast, FLOW-3D models' predicted magnitudes are smaller than OpenFOAMs' ones and nearer to ADV measurements. This small difference can be related to the lower discharge and higher pool depth provided by FLOW-3D model when comparing with OpenFOAM model, with the latter closer to the target scenario conditions. The velocity vector components analysis for both models reveals that *u* (x direction) and *v* (y direction) are more correlated with ADV measurements than *w* component (z direction). This can be related to the lower magnitude of *w* in vertical slot fishways, where even some references have suggested the possibility of using 2D modelling techniques for their modelling (Cea et al., 2007). However, under natural scenarios (variable boundary conditions) or when trying to relate to fish preference patterns, it seems essential to consider their full 3D performance (Fuentes-Pérez et al., 2019b, 2018b).

Regarding model result comparison (OpenFOAM vs FLOW-3D) it can be seen that, although they are highly correlated between them (in some cases showing even higher correlation than with ADV (*k* or *u*)), as expected (due to their different internal coding) the magnitude of error (MAE_{Models}) is similar to those observed when comparing ADV data with the models.

When it comes to the observed flow patterns (Figure 3) both models are in agreement with the ADV measurements, as well as, specialized references (Rajaratnam et al., 1986; Wu et al., 1999). In addition, an interesting finding, which needs to be further investigated, are the secondary small recirculation areas predicted by OpenFOAM model in the corners of the pools. These areas showed a high probability of fish presence in previous spatial preference analysis of Iberian barbel (Fuentes-Pérez et al., 2018a), but they have not been previously measured or predicted. Under non-uniform scenarios, which correspond to those field scenarios that trigger different water depths and water drops between fishway pools (due to a modification of design boundary conditions (Fuentes-Pérez et al., 2019a)), these small areas may evolve and became essential to explain the spatial selection of fish inside the fishway pools (Fuentes-Pérez et al., 2018a). Non-uniform scenarios are the most frequent scenarios on fishways under field conditions due to the natural river hydrological variability and they have the potential of increasing (non-uniform drawdown profiles – M2) or decreasing (non-uniform backwater profiles – M1) the magnitude of the variables inside the fishway (Fuentes-Pérez et al., 2016, 2019a) and therefore, to modify the fish passage rate or time of the fishway.

Turbulence has a direct influence on fish behaviour and consequently in the usage of fishways. It influences swimming behaviour (Lacey et al., 2012), stability (Silva et al., 2012), or path and spatial selection (Fuentes-Pérez et al., 2018a; Goettel et al., 2015). Thus, its consideration is important for fishway assessments. In this comparative study, *k* has been chosen for assessment. According to the results, the spatial distribution of measured *k* correlates well and similarly with the simulations in OpenFOAM and FLOW-3D, a high *k* region in the jet region that is attenuated fast when it approaches the sidewall (Figure 3). However, magnitudes measured with ADV were much higher. Despite similar observations have been reported in studies such as Duguay et al. (2017) in pool-weir type fishways, studies such as Fuentes-Pérez et al. (2018b) reported a good agreement between ADV measurements and RANS and LES turbulence modelling techniques using OpenFOAM in VSF (design #3, Rajaratnam et al. (1986)). *k* is a sensitive parameter for measuring in the field, which may be influenced by vibrations produced in the ADV by the water flow (ADV-flow interaction) or water recirculation pump, as well as the resolution of the measuring grid.

In general, the results provided by both modelling techniques are in agreement, which seems to validate both software, OpenFOAM and FLOW-3D. However, both show deviations when comparing to ADV data, which must be further investigated. For now, it seems necessary to encompass CFD with real measurements to validate its results.

5. Summary and Conclusions

This study aims to compare simulations of VSF using LES turbulence modelling techniques by means of OpenFOAM and FLOW-3D software platforms. The results confirm our initial hypothesis “OpenFOAMs’ multiphase solver (interFoam) is able to match commercial codes”. Considering the couple of comparative studies already published using RANS techniques and the present study, it is possible to conclude that both, OpenFOAM and FLOW-3D are viable alternatives for 3D modelling of fishways.

While the user-friendly GUI of FLOW-3D makes the simulating experience easier and apt to beginners in the field of CFD, OpenFOAM offers the possibility of simulating with already existing coded solvers (such as interFoam) and turbulence modelling techniques (*e.g.* LES: Smagorinsky, or RANS: *k*-*ε*, among many others), but also to program new solver and turbulence modelling techniques.

The computational time between both software differs, however it is directly related to the strategies used to reach the equilibrium. On the one hand, in both software, the user can predefine as the initial condition results from a thicker mesh which would directly influence the timing for reaching the equilibrium. On the other hand, time discretization can be dynamic, using thick time steps at the beginning and using thin time steps to reach final results. Therefore, reported results should be considered indicative as different strategies could provide different computing times for each software without influencing the final results, moreover considering the improvements of CPUs in recent years.

One of the main drawbacks of OpenFOAM when comparing with commercial alternatives is the meshing utilities. Meshing is one of the most important steps when modelling, while in FLOW-3D it is a semi-automatic process (the user just needs to have the 3D model of the structure (*stl* file) and select the grid size of the model), OpenFOAM requires the use of third party software or pre-existing tools (*e.g. blockMesh* and *snappyHexMesh*) which require a steep-learning process. Fortunately, today there are innumerable online resources (OpenFOAM, 2020), published examples (Bayon et al., 2016; Duguay et al., 2017; Fuentes-Pérez et al., 2018b), and a big user community that will initiate and guide gradually beginners through this process.

This preliminary study has raised three main future research paths: 1) the comparison of different LES turbulence modelling techniques including the analysis of the temporal domain of the simulated flow structure (to find the best modelling technique for fishway simulation) 2) the comparison of modelling results increasing the ADV mesh resolution or by means of alternative measuring techniques such as Particle Image Velocimetry (to reduce possible interactions of the measuring instrument with the flow) and 3) the re-analysis of fish spatial preferences in fishways under non-uniform conditions (Fuentes-Pérez et al., 2018a) considering the advantages of the spatial resolution offered by 3D simulations in comparison with ADV measurements. Additionally, it would be of interest to increase this software comparison including other software alternatives, such as ANSYS-Fluent, which is also a common alternative in the fishway 3D modelling community, as well as, to test studied software in more challenging or complex scenarios such as natural-like or Denil fishways.

6. Acknowledgments

This project has received funding from the European Union's H2020 research and innovation program under grant agreement No. 727830, FIThydro. Juan Francisco Fuentes-Pérez´s contribution was partly financed by a Torres Quevedo grant PTQ2018-010162.

7. References

Andersson, A.G., Lindberg, D.-E., Lindmark, E.M., Leonardsson, K., Andreasson, P., Lundqvist, H., Lundström, T.S., 2012. A Study of the Location of the Entrance of a Fishway in a Regulated River with CFD and ADCP. Model. Simul. Eng. 2012.

Barton, A.F., Keller, R.J., Katopodis, C., 2009. Verification of a numerical model for the prediction of low slope vertical slot fishway hydraulics. Aust. J. Water Resour. 13, 53–60. doi:10.1080/13241583.2009.11465360

Bates, P.D., Lane, S.N., Ferguson, R.I., 2005. Computational fluid dynamics: applications in environmental hydraulics. John Wiley & Sons.

Bayon, A., Valero, D., García-Bartual, R., López-Jiménez, P.A., 2016. Performance assessment of OpenFOAM and FLOW-3D in the numerical modeling of a low Reynolds number hydraulic jump. Environ. Model. Softw. 80, 322–335. doi:10.1016/j.envsoft.2016.02.018

Bohorquez, P., García-García, F., 2016. Understanding the long-term increase of flood risk in regulated rivers through combined use of CFD, paleo-hydrology and hydrological data.

Bombač, M., Novak, G., Rodič, P., Četina, M., 2014. Numerical and physical model study of a vertical slot fishway. J. Hydrol. Hydromechanics 62, 150–159. doi:10.2478/johh-2014-0013

Cea, L., Pena, L., Puertas, J., Vázquez-Cendón, M.E., Peña, E., 2007. Application of several depth-averaged turbulence models to simulate flow in vertical slot fishways. J. Hydraul. Eng. 133, 160–172. doi:10.1061/(ASCE)0733-9429(2007)133:2(160)

Celik, I.B., Cehreli, Z.N., Yavuz, I., 2005. Index of resolution quality for large eddy simulations.

Duguay, J.M., Lacey, R.W.J., Gaucher, J., 2017. A case study of a pool and weir fishway modeled with OpenFOAM and FLOW-3D. Ecol. Eng. 103, 31–42.

Flow Science, 2016. FLOW-3D Version 11.2 User Manual.

Fuentes-Pérez, J.F., Eckert, M., Tuhtan, J.A., Ferreira, M.T., Kruusmaa, M., Branco, P., 2018a. Spatial preferences of Iberian barbel in a vertical slot fishway under variable hydrodynamic scenarios. Ecol. Eng. 125, 131–142. doi:10.1016/j.ecoleng.2018.10.014

Fuentes-Pérez, J.F., García-Vega, A., Sanz-Ronda, F.J., Martínez de Azagra-Paredes, A., 2017. Villemonte's approach: validation of a general method for modeling uniform and non-uniform performance in stepped fishways. Knowl. Manag. Aquat. Ecosyst. 418, 23. doi:10.1051/kmae/2017013

Fuentes-Pérez, J.F., Sanz-Ronda, F.J., Martínez de Azagra-Paredes, A., García-Vega, A., 2016. Non-uniform hydraulic behavior of pool-weir fishways: A tool to optimize its design and performance. Ecol. Eng. 86, 5–12. doi:10.1016/j.ecoleng.2015.10.021

Fuentes-Pérez, J.F., Silva, A.T., Tuhtan, J.A., García-Vega, A., Carbonell-Baeza, R., Musall, M., Kruusmaa, M., 2018b. 3D modelling of non-uniform and turbulent flow in vertical slot fishways. Environ. Model. Softw. 99, 156–169. doi:10.1016/j.envsoft.2017.09.011

Fuentes-Pérez, J.F., Tuhtan, J.A., Branco, P., Eckert, M., Romão, F., Kruusmaa, M., Ferreira, M.T., 2019a. Hydraulics of vertical slot fishways: Non-uniform profiles. J. Hydraul. Eng. 145, 06018020. doi:10.1061/(ASCE)HY.1943-7900.0001565

Fuentes-Pérez, J.F., Tuhtan, J.A., Eckert, M., Romão, F., Ferreira, M.T., Kruusmaa, M., Branco, P., 2019b. Hydraulics of vertical-slot fishways: Nonuniform profiles. J. Hydraul. Eng. 145. doi:10.1061/(ASCE)HY.1943-7900.0001565

Gao, Z., Andersson, H.I., Dai, H., Jiang, F., Zhao, L., 2016. A new Eulerian–Lagrangian agent method to model fish paths in a vertical slot fishway. Ecol. Eng. 88, 217–225.

Gisen, D.C., Weichert, R.B., Nestler, J.M., 2017. Optimizing attraction flow for upstream fish passage at a hydropower dam employing 3D Detached-Eddy Simulation. Ecol. Eng. 100, 344–353.

Goettel, M.T., Atkinson, J.F., Bennett, S.J., 2015. Behavior of western blacknose dace in a turbulence modified flow field. Ecol. Eng. 74, 230–240. doi:10.1016/j.ecoleng.2014.10.012

Goring, D.G., Nikora, V.I., 2002. Despiking acoustic Doppler velocimeter data. J. Hydraul. Eng. 128, 117–126.

Greenshields, C.J., 2015. OpenFOAM: The open source CFD Toolbox. OpenFOAM Foundation Ltd.

Higuera, P., Lara, J.L., Losada, I.J., 2013. Realistic wave generation and active wave absorption for Navier–Stokes models: Application to OpenFOAM®. Coast. Eng. 71, 102–118. doi:10.1016/j.coastaleng.2012.07.002

Hirt, C.W., Nichols, B.D., 1981. Volume of fluid (VOF) method for the dynamics of free boundaries. J. Comput. Phys. 39, 201–225. doi:10.1016/0021-9991(81)90145-5

Hirt, C.W., Sicilian, J.M., 1985. A porosity technique for the definition of obstacles in rectangular cell meshes, in: International Conference on Numerical Ship Hydrodynamics, 4th.

Hurther, D., Lemmin, U., 2001. A correction method for turbulence measurements with a 3D acoustic Doppler velocity profiler. J. Atmos. Ocean. Technol. 18, 446–458.

Juras, M., Albertson, L.K., Cahoon, J., Johnson, E., 2018. Incorporating macroinvertebrate biological structures into gravel-bedded stream fluid dynamics using 3D CFD modelling. Ecol. Eng. 119, 19–28.

Khan, L.A., 2006. A three-dimensional computational fluid dynamics (CFD) model analysis of free surface hydrodynamics and fish passage energetics in a vertical-slot fishway. North Am. J. Fish. Manag. 26, 255–267. doi:10.1577/M05-014.1

Kim, S., Yu, K., Yoon, B., Lim, Y., 2012. A numerical study on hydraulic characteristics in the ice Harbor-type fishway. KSCE J. Civ. Eng. 16, 265–272.

Lacey, R.W.J., Neary, V.S., Liao, J.C., Enders, E.C., Tritico, H.M., 2012. The IPOS framework: linking fish swimming performance in altered flows from laboratory experiments to rivers. River Res. Appl. 28, 429–443.

Machado Xavier, M.L., Janzen, J.G., Nepf, H., 2018. Numerical modeling study to compare the nutrient removal potential of different floating treatment island configurations in a stormwater pond. Ecol. Eng. 111, 78–84.

Marriner, B.A., Baki, A.B.M., Zhu, D.Z., Cooke, S.J., Katopodis, C., 2016. The hydraulics of a vertical slot fishway: A case study on the multi-species Vianney-Legendre fishway in Quebec, Canada. Ecol. Eng. 90, 190–202. doi:10.1016/j.ecoleng.2016.01.032

Marriner, B.A., Baki, A.B.M., Zhu, D.Z., Thiem, J.D., Cooke, S.J., Katopodis, C., 2014. Field and numerical assessment of turning pool hydraulics in a vertical slot fishway. Ecol. Eng. 63, 88–101. doi:10.1016/j.ecoleng.2013.12.010

OpenFOAM, 2020. OpenFOAM User Guide [WWW Document]. URL https://www.openfoam.com/documentation/guides/latest/doc/index.html

Pope, S.B., 2001. Turbulent flows. Meas. Sci. Technol. 12, 2020. doi:10.1088/0957-0233/12/11/705

Puertas, J., Pena, L., Teijeiro, T., 2004. Experimental approach to the hydraulics of vertical slot fishways. J. Hydraul. Eng. 130, 10–23. doi:10.1061/(ASCE)0733-9429(2004)130:1(10)

Quaresma, A.L., Ferreira, R.M.L., Pinheiro, A.N., 2017. Comparative analysis of particle image velocimetry and acoustic Doppler velocimetry in relation to a pool-type fishway flow. J. Hydraul. Res. 1–10.

Quaresma, A.L., Romão, F., Branco, P., Ferreira, M.T., Pinheiro, A.N., 2018. Multi slot versus single slot pool-type fishways: A modelling approach to compare hydrodynamics. Ecol. Eng. 122, 197–206. doi:10.1016/j.ecoleng.2018.08.006

Rajaratnam, N., Katopodis, C., Solanki, S., 1992. New designs for vertical slot fishways. Can. J. Civ. Eng. 19, 402–414. doi:10.1139/l92-049

Rajaratnam, N., Van der Vinne, G., Katopodis, C., 1986. Hydraulics of vertical slot fishways. J. Hydraul. Eng. 112, 909–927. doi:10.1061/(ASCE)0733-9429(1986)112:10(909)

Romão, F., Quaresma, A.L., Branco, P., Santos, J.M., Amaral, S.D., Ferreira, M.T., Katopodis, C., Pinheiro, A.N., 2017. Passage performance of two cyprinids with different ecological traits in a fishway with distinct vertical slot configurations. Ecol. Eng. 105, 180–188. doi:10.1016/j.ecoleng.2017.04.031

Romão, F., Santos, J.M., Katopodis, C., Pinheiro, A.N., Branco, P., 2018. How Does Season Affect Passage Performance and Fatigue of Potamodromous Cyprinids? An Experimental Approach in a Vertical Slot Fishway. Water 10, 395. doi:10.3390/w10040395

Silva, A.T., Katopodis, C., Santos, J.M., Ferreira, M.T., Pinheiro, A.N., 2012. Cyprinid swimming behaviour in response to turbulent flow. Ecol. Eng. 44, 314–328.

doi:10.1016/j.ecoleng.2012.04.015

Silva, A.T., Santos, J.M., Ferreira, M.T., Pinheiro, A.N., Katopodis, C., 2011. Effects of water velocity and turbulence on the behaviour of Iberian barbel (*Luciobarbus bocagei*, Steindachner 1864) in an experimental pool-type fishway. River Res. Appl. 27, 360–373. doi:10.1002/rra.1363

SimScale, 2021. Pimple algorithm [WWW Document]. URL https://www.simscale.com/forum/t/cfd-pimple-algorithm/81418 (accessed 8.24.21).

Ubbink, O., 1997. Numerical prediction of two fluid systems with sharp interfaces. University of London, London, UK.

Weller, H.G., Tabor, G., Jasak, H., Fureby, C., 1998. A tensorial approach to computational continuum mechanics using object-oriented techniques. Comput. Phys. 12, 620–631. doi:10.1063/1.168744

Wu, S., Rajaratnam, N., Katopodis, C., 1999. Structure of flow in vertical slot fishway. J. Hydraul. Eng. 125, 351–360. doi:10.1061/(ASCE)0733-9429(1999)125:4(351)

Zeng, J., Rakib, Z., Ansar, M., Hajimirzaie, S., 2020. Optimization and Risk Assessment in Design and Operation of Hydraulic Structures Using Three-Dimensional CFD Modeling, in: World Environmental and Water Resources Congress 2020: Hydraulics, Waterways, and Water Distribution Systems Analysis. American Society of Civil Engineers Reston, VA, pp. 170–182.