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To cite this article: C. Canale *et al* 2024 *J. Phys.: Conf. Ser.* **2685** 012015

A 3D numerical model for the performance analysis of a differential pressure flow meter in transient conditions for liquid fuels

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Abstract. In the present paper, the metrological performance of a single-hole, sharped edge, and the orifice flow meter is numerically investigated employing different liquid fuels. Numerical investigations have been performed for a three-dimensional transient flow. Turbulence has been modeled employing the Realizable K-ε turbulence model, based on the Unsteady Reynolds-averaged Navier-Stokes (URANS). The present work is conducted in the context of the European SAFEST 20IND13 project, aimed at investigating the performance of the orifice flow meter numerical model in a wide range of temperatures, density, viscosity, and different liquid fuels. The numerical model, validated according to the ISO standard 5167-2 is employed to analyze the metrological performance of a test rig available at project partners' laboratories and was aimed at reproducing the fuel consumption curve of a light and heavy transport vehicle.

1. Introduction

Greenhouse gas emissions produced in the transport sector, especially for road and maritime facilities, consistently contribute to climate change, therefore these emissions need to be reduced. Green hydrogen and renewable fuels are expected to play a crucial role in achieving net zero greenhouse gas emissions by 2050, particularly in the hard-to-abate and transport sectors. Nevertheless, the extensive use of green fuels opens new challenges from the metrological point of view. In the past few years, impressive improvements to engines and transition to new fuel types have been made. The metrological sector also needs improvements, for the reason that the new engine efficiency and impact of new fuels depend directly on the quality of measurements. Flow meters, nowadays are employed typically to measure fuel flows in the transport sector, but could show inadequate metrological performance when measuring green fuels. Besides, particular attention must be paid to the meter's ability to measure extremely variable flow rates, as green fuels are expected to be largely employed to measure consumption in the transport sector. Looking at the current metrological scenario, it can be seen that different types of flow meters are employed, depending on the specific application and the size. Among other meters, differential pressure-based measuring instruments are widely used all over the sectors, due to simplicity, reliability, and low maintenance costs. Such meters have been widely investigated in the scientific literature, especially the optimization of the geometrical parameters and the choice of the best orifice among the different choices.

Hutagalung et al. explored the impact of the orifice plate's release coefficient on the water system. Their study delved into the correlation among the Reynolds number, β ratio, and discharge coefficient. The authors deduced that the values of the discharge coefficient are influenced by both the β ratio and the Reynolds number. They further emphasized that all other factors contribute to the overall error in measuring the release coefficient Cd [1]. A comparison of the performance between a single-hole (SHO) and multi-hole (MHO) orifice plate flow meter was conducted by Bikić et al., showing the limits of the SHO approach due to high-pressure difference, slower pressure recovery and lower discharge coefficient. The numerical investigation shows the potentiality of the CFD approach applied to the metering sector and the possibility of avoiding energy losses and test rig optimization [2]. A comparison of the performance of the MHO was conducted by Tomaszewski et al. [3], showing the impact of the holes' position on the pressure and energy losses in the test rig.

Nevertheless, significant investigations are still required to analyze the dependence of metrological performance on new green fuels' composition and physical properties.

The present work fits into a European project 20IND13 SAFEST, which aims to develop a metrological infrastructure to perform advanced measurements in the transport sector, and aims to characterize the interaction between the fluid and the meter. A numerical model has been realized in the OpenFOAM environment, analyzing the performance of the orifice flow meter numerical model for different operating conditions and performing parametric analysis, thus avoiding expensive experimental campaigns.

The collaboration with the SAFEST research groups has made possible the CFD modeling of a four-hole orifice plate flowmeter, whose dimension has been given by the Technical Research Centre of Finland (VTT). This work is a preliminary study in metrological modeling and it allows us to understand the behavior of these meters in a numerical environment. The validation process has been realized taking into account the ISO Standard 5167 as a reference for the research, considering that an experimental validation will be performed in collaboration with the VTT research group to analyze the metrological performance of a test rig available at project partners' laboratories and to reproduce the fuel consumption curve of a light and heavy transport vehicle. Numerical investigations have been performed for a three-dimensional transient flow. Turbulence has been modeled employing the standard k-ε turbulence model, based on the Unsteady Reynolds-averaged Navier-Stokes (URANS).

2. Material and methods

Measurements of the flow rate of liquids, gases, and vapors with orifice flowmeters have found wide use in industrial, scientific, and research measurements. A restriction fulfilling the function of a primary converter of the potential energy of the flow into kinetic energy by changing the cross-section of the pipe in which they are installed. The differential pressure flow meters are based on Bernoulli's working principle, which states that the pressure drop and subsequently the measured signal are functions of the square of flow speed under a specific hypothesis. The flow rate is linked directly to the pressure difference across the section and fluid characteristics, such as temperature, density, and viscosity. Due to high flexibility, great reliability of the measure, and low maintenance costs, the orifice plate flow meters have found great application in engineering and it has been chosen as the subject of the following numerical study.

2.1 The ISO Standard 5167 and geometrical characteristics

Modeling the orifice plate involves a systematic approach to ensure accurate flow measurement and establish uncertainty values. The ISO Standard 5167 part two is the metrological guideline for geometrical specifications and method of use, such as installation and operating conditions, of the orifice plates. As reported in the previous introduction, the measurement's working principle is based on installing a restriction into a pipeline, which causes a static pressure difference between the upstream and downstream sides of the plate. The mass flowrate, indicated as q_m, is reported in Equation (1):

$$q_m = \frac{C}{\sqrt{1-\beta^4}}\varepsilon\frac{\pi}{4}d^2\sqrt{2\Delta p\rho_1} \quad (1)$$

Where C represents the coefficient of discharge, dependant on the Reynolds number Re, and it is given by the Reader-Harris/Gallagher (1998) equation [4] and ε represents the expansibility factor and it is given by Reader-Harris equation [5] . The iterative process, given by the ISO standard 5167 part 1 and part 2, consents to the determination of the reference value of the mass flow rate (or the volumetric flow rate) in specified conditions, thus comparing the numerical simulation results to the ISO Standard reference.
As reported in the introduction, the studied geometry has been provided by the VTT institute and it is a multi-hole orifice plate flow meter, composed of four holes of 15.75 mm diameter, oriented at 45° from the horizontal axis. A representation of the analyzed case is reported in Figure 1, which reports the upstream and downstream faces of the meter:

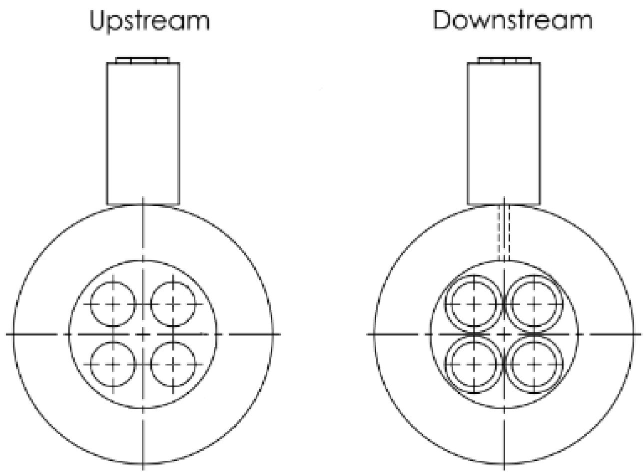


Figure 1 The orifice plate flowmeter chosen for the numerical campaign

As reported in ISO Standard 5167, the calculation of the β ratio is given by Equation 2.

$$\beta = \frac{d}{D} \tag{2}$$

Where the inner diameter d in the multi-hole case is calculated by doubling the distance from the center of the orifice, to the center of one of the four holes. The main geometrical characteristics of the flow meter are summarized in Table 1:

Table 1. Orifice plate dimensions and characteristics

Geometrical parameter	Dimensions [mm]
Pipe diameter	92.00
Orifice diameter	52.40
Four-holes diameter	15.75
45° edge length (downstream)	2.32
***β* ratio**	0.54

2.2 Numerical model

The numerical tool developed in the present study is a three-dimensional, time-variant, and Eulerian numerical model, in which the continuity and momentum equations are solved to simulate a flow meter's performance. The present study aims to define the behavior of these particular flow meters under different operating conditions, far from the laboratory testing conditions. A non-conventional fuel has been chosen to realize this research, to estimate the performance of the flowmeter with new green fuels. The fluid properties and characteristics have been provided by the National Metrology Institute of the Federal Republic of Germany, the so-called Physikalisch-Technische Bundesanstalt (PTB), and they are summarized in Table 2:

Table 2. Fluid properties due to the temperature variation

Fluid properties			
Temperature	25	40	$[°C]$
Density	780.401	750.08	$[kg/m^3]$
Dynamic Viscosity	1.24	1.02	$[mPa \cdot s]$
Kinematic Viscosity	1.58741E-06	1.36132E-06	$[m^2/s]$

The governing equations used in this study are the continuity equation and momentum equation, which are respectively reported in equations 3 and 4:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho U) = 0 \quad (3)$$

$$\frac{\partial (\rho U)}{\partial t} + \nabla \cdot (\rho U \times U)) = \nabla \cdot \left(-\rho \delta + \mu(\nabla U + (\nabla U)^T)\right) + S_M \quad (4)$$

Where the capex T represents the transposition symbol of the matrix and the S_M represents the source term including the contributions due to body forces only.

As reported by Erdal and Andersson in [6], the authors showed a good agreement between the calculation of the $k - \varepsilon$ turbulence model and measurements. More recently, Shah et al. have proved the applicability of the standard k$-\varepsilon$ model and the better performance above the others, in the fully developed flow with the orifice plate. Hence, the standard $k - \varepsilon$ model has been chosen for the computations and the governing equations of the model are reported in equations 5 and 6:

$$\frac{\partial (\rho K)}{\partial t} + \nabla \cdot (\rho U k) = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_k}\right) \nabla k\right] + P_k - \rho \varepsilon \quad (5)$$

$$\frac{\partial (\rho e)}{\partial t} + \nabla \cdot (\rho U \varepsilon) = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right) \nabla \varepsilon\right] + \frac{\varepsilon}{k}\left(C_{\varepsilon_1} P_k - C_{\varepsilon_2} \rho \varepsilon\right) \quad (6)$$

Where C_{ε_1}, C_{ε_2} , σ_k and $\sigma_\varepsilon$are the standard $k - \varepsilon$ turbulence model constants and P_k represents the turbulence production caused by viscous and buoyancy force and it is defined as:

$$P_k = \mu_t \nabla U \cdot (\nabla U + \nabla U^T) - \frac{2}{3} \nabla \cdot U (3\mu_t \nabla \cdot U + \rho k) + P_{kb} \quad (7)$$

Furthermore, the turbulence viscosity is modeled as a function of turbulent kinetic energy, turbulent kinetic energy dissipation rate, and turbulent viscosity constant, in the form of:

$$\mu_t = C_\mu \rho \frac{k^2}{\varepsilon} \quad (8)$$

The PIMPLE (Pressure Implicit Method for Pressure-Linked Equations) algorithm and an adjustable time step have been chosen to conduct the CFD analysis. This involves that the time steps are controlled by the Courant number, which is given by Equation 9:

$$\mathrm{Co} = \frac{|\mathrm{U}| \Delta \theta}{\Delta x} \quad (9)$$

Where |u| is the magnitude of the flow velocity, $\Delta\theta$ is the time step and Δx is the characteristic mesh size. A maximum Courant number of 2 was chosen, while Arpino et al. showed in [7] an average deviation of 1% concerning a maximum Courant of 2 for incompressible and turbulent flow. An average of 10^{-7} was fixed for the numerical residuals in order to simulate the orifice performance and to get comparable characteristics of a flow meter measurement.

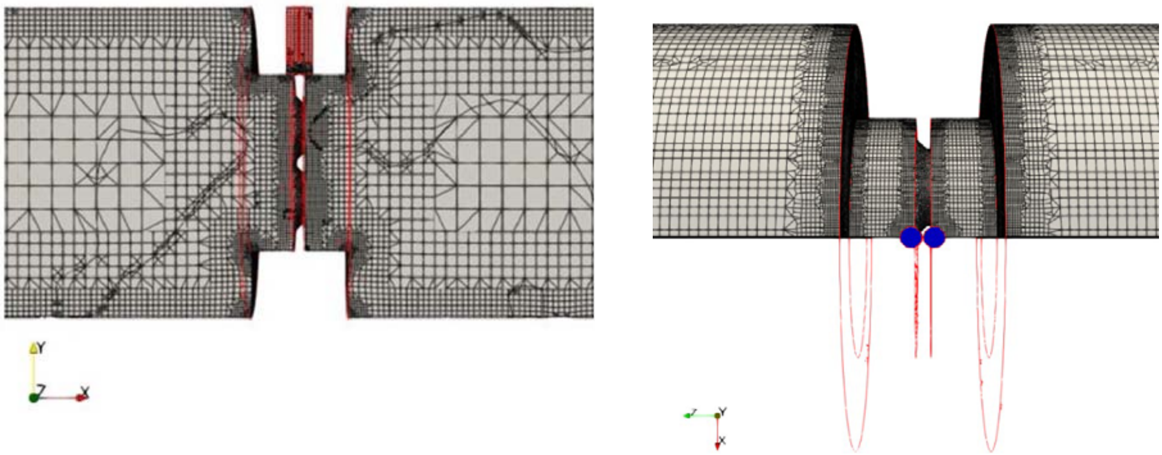
3. Results

In this section, the results obtained from the CFD analysis concerning the performance of the orifice plate flowmeter are illustrated and discussed in detail. The results are expressed in terms of:

- Mesh sensitivity analysis, comparing three different grid sizes;

- The CFD analysis is conducted by variating the temperature and consequently the fluid properties. The objective of the variation is to highlight the critical conditions in which the orifice plate flowmeter drastically decreases the performance;
- A validation of the results has been conducted through ISO Standard 5167, which gives a guideline to calculate the reference value comparable to CFD results.

3.1 Mesh sensitivity analysis
The mesh has been realized with a hybrid method, that is based on the geometry construction through MECA-Salome® and the mesh production with the OpenFOAM's tool "snappyHexMesh". This process consents to better control of the cells near the wall and in the zone of interest. Three different grids have been realized to get the proper sensitivity analysis, thus reaching a proper average error from the reference below the 3.2% or pressure and velocity field. A representation of the chosen grid is reported in Figure 2 (a) and Figure 2 (b), which respectively highlight the orifice and pressure taps (in blue) zone:



(a) (b)

Figure 2.(a) A x-y representation of the grid focusing on the holes. **(b)** A z-x representation focusing on the pressure taps.

The grid characteristics are reported in Table 3, described in terms of number of cells, max skewness, and non-orthogonality, which are the main parameters to get under control for a mesh:

Table 3. Max skewness and non-orthogonality for the three different grids used for the sensitivity analysis

	Number of cells	**Max Skewness**	**Non-Orthogonality**
Mesh 1	2 211 715	3.41	60.11
Mesh 2	3 984 202	3.12	60.06
Mesh 3	8 931 030	3.31	60.17

The sensitivity analysis is conducted by evaluating the velocity profiles one diameter upstream and a half diameter downstream of the orifice plate. The comparison between the velocity field is reported in Table 4 which highlights the good behavior of Mesh 2, composed of four million elements, against the reference grid of 8 million elements.

Table 4. The average error of the mesh from the reference grid.

	Upstream	**Downstream**
Avg. error (8M-4M)	1.87%	5.67%
Avg. error (8M-2M)	4.42%	82.38%

A representation of the average velocity reported in Figure 3. The primary device forces the fluid to pass into the four-hole section and an increasing velocity is clear downstream of the orifice. Consequently, the pressure drop is visible in Figure 3 following the principles described in the previous sections.

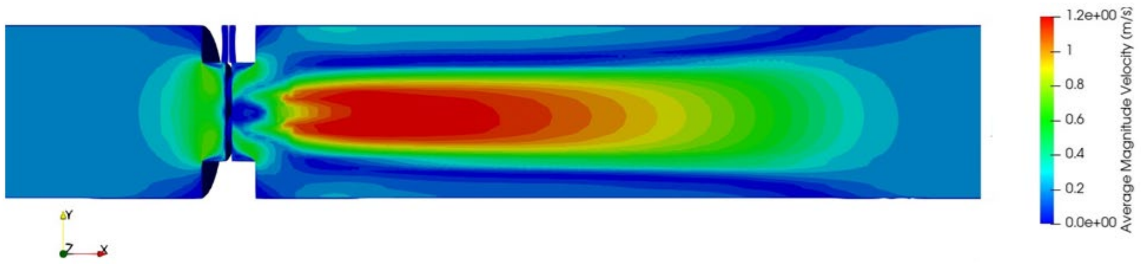
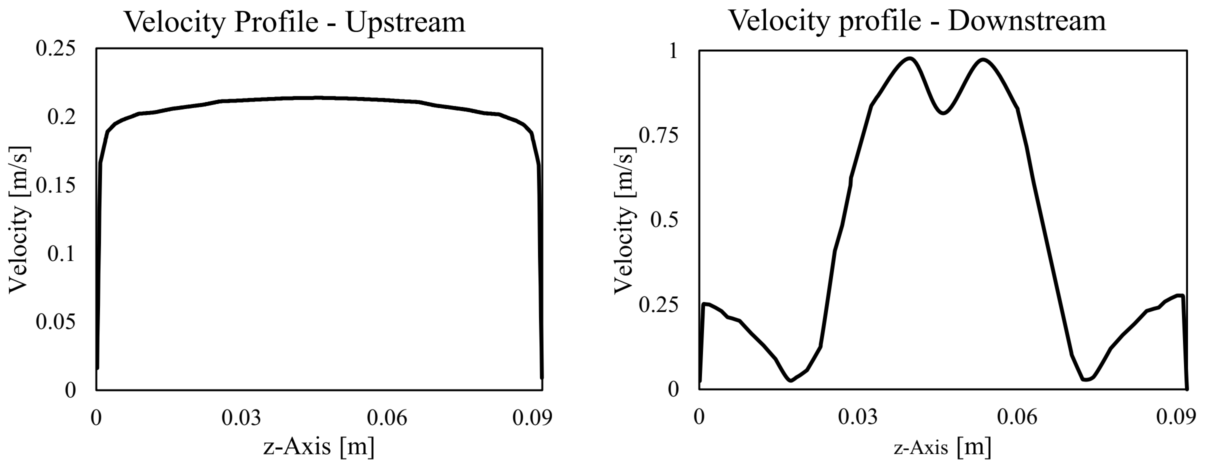


Figure 3. Average velocity field of the four million mesh in the orifice plate zone

A representation of the velocity profiles upstream and downstream of the orifice plate are reported in Figure 4a and Figure 4b, the profiles are extracted one diameter before (upstream) and an-half diameter after (downstream) the orifice plate.



(a) (b)

Figure 4 (a) velocity profile extracted one diameter before the orifice; **(b)** Velocity profile an-half diametr after the orifice

3.2 Fluid properties variation

Energy accounting is becoming more relevant in the energy transition process and energy-saving economy. According to 2022 IEA data [8], the transport sector weights 23% ca. on the CO_2 global emission of CO_2 and the transition process starts from the measurement chain and energy accounting. To become more aware of the problem of energy consumption, the measurement process is becoming increasingly relevant.

This section aims to evaluate the performance under different operating conditions, for the reason that the laboratory conditions in which the meters are calibrated are different from the ordinary working conditions of the meters. Furthermore, the test liquid used to calibrate an orifice plate is typically water. Water is a common choice because it is readily available, and its properties are well-known and standardized. The green fuels may have different properties, such as viscosity and density, compared to traditional fuels. The accuracy of the flow meter measurement is dependent on the geometrical characteristics of the orifice, which are usually fixed, and on the fluid properties used in the application. The accuracy of the measurement, due to the employment of the innovative fuels, is attributable to:

- Variability in fluid properties: the viscosity and the density of green fuels are the main parameters that affect the measurements;
- Composition changes: some alternative fuels may have a variable composition and this is another uncertainty factor in the behavior of the fluid, compared to the traditional fuels used in the transportation sector;
- Calibration challenges: Orifice plates are typically calibrated for specific fluids under specific conditions. Calibrating for innovative fuels may pose challenges due to the lack of standardized calibration data for these fuels.

In the present study, a well-known biodiesel has been provided by the Physikalisch-Technische Bundesanstalt (PTB), including the viscosity and density characteristics due to the temperature variation and therefore the interaction between the orifice measure and the fluid properties have been tested. A non-conventional bio-diesel has been considered for the numerical simulations, whose characteristics are well-known and summarized in Table 2 in section 2.2.

Two different temperatures of 25 and 40 °C have been considered, to understand in which condition the meters are not able to maintain the accuracy and precision levels. The temperature variation induces a density and viscosity variation in the fluid properties and it affects directly the measurement performance. These two temperatures were chosen because they are the minimum and the maximum measured values for the non-conventional fluid used in the numerical campaign. The results of the two numerical simulations are compared to the ISO Standard reference in the same hypothesis:

Table 5. Comparison of the pressure drop and volumetric flow rate at 25°C and 40°C

		Δp $[Pa]$	q_m $[kg/s]$	**Avg. Error [%]**
$T = 25°C$	**ISO Standard 5167 reference**	6893.13	1.044	-
$T = 40°C$		7171.69	1.044	-
$T = 25°C$	**Numerical Model**	6430.23	1.008	3.42
$T = 40°C$		6338.21	0.981	5.99

As presented in Table 5 the numerical model is able to predict in standard conditions the behavior of the fluid, but increasing the temperature and lowering the density of the fluid, presents some difficulties in predicting the correct pressure drop.

3.3 Validation of results through ISO Standard 5167

The validation of the numerical CFD results has been conducted against the ISO Standard 5167 as a reference for the comparison. The comparison has been realized taking into account the pressure drop obtained by the numerical simulations, presented in Table 5, and the theoretical value calculated through the ISO Standard Equation 1 in section 2.1. The results provided in Table 5 show a good agreement of the numerical model for the temperature of 25°C, with an average error from the ISO Standard reference of 3.42%, while the error slightly up to 5.99% increase when the temperature is 40°C. Although the numerical model can predict the fluid behavior when the standard conditions are provided, the numerical model suffers more when the temperature increases the difference from the reference also increases due to the lower viscosity of the fluid.

4. Conclusion and future development

In this paper, we evaluated the performance of the numerical model of a four-hole orifice plate flow meter in different operating conditions. The 3D Computational Fluid Dynamics (CFD) numerical simulations were

validated against the ISO Standard 5167 reference. The geometry and dimensions of the orifice plate were provided by the Technical Research Centre of Finland (VTT) in the context of the European 20IND13 SAFEST project. The performance of the flowmeter was evaluated by calculating the volumetric flow rate from the pressure drop across the section observed in the numerical simulations.
The results of the CFD analysis demonstrated that the CFD model can predict with good agreement with the reference value the pressure drop across the section, with an average error of about 4%. Future developments of the study will be focused on the accuracy of the model and an in-field experimental evaluation of the orifice plate, to properly validate the results of the CFD simulations against the experimental data set.

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Acknowledgment
This project (EMPIR 20IND06 PROMETH2O) has received funding from the EMPIR programme co-financed by the Participating States and from the European Union’s Horizon 2020 research and innovation programme