

NUMERICAL MODELLING OF A TURBINE FLOW METER USED AS PART OF THE HYDROGEN COMPRESSOR SYSTEM

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This study analyses a turbine flow meter in the context of a hydrogen compressor system. Basic concepts of turbine flow meter, accuracy and linearity, as well as calibration are described. Physical experimental testing scheme is presented in the paper. The viscosity of the fluid is one of the major factors that affects the performance of turbine flow meters. Numerical modelling experiments for different fluids with different viscosities are performed. Performed numerical modelling experiments give a possibility to continue research into the hydrogen compression system.

Keywords: Calibration, CFD modelling, linearity, turbine flow meter, viscosity.

1. INTRODUCTION

The need for an accurate and cost-effective liquid flow rate metering method is increasing every day, especially when it is necessary to estimate the cost of a certain amount of liquid or gas transferred through a pipeline. Industrial technological processes require flow measurement for the needs of the process control. Certain flow rates are required for optimum performance of the equipment. Therefore, accurate flow

rate measurement is very important for industrial processes. There are two main ways to measure the flow: by volume and by weight. Liquids can be measured either in terms of weight or volume velocity, e.g., tonnes per hour, kilograms per minute, litres per hour, litres per minute, cubic meters per hour, etc.

In this study, a flow meter is considered as an integral part of the hydrogen com-

pression system. The system is patented and consists of hydrogen hydraulic compressors, where liquid and gaseous media are simultaneously supplied to the working chamber [1]. In this system, hydrogen is compressed by supplying a pressure fluid to a hydrogen cylinder. The use of a flow meter in this system provides the ability to control the level of hydrogen compression, enhancing the performance and reliability of the hydraulic hydrogen compression set.

A hydrogen compressor system is used to compress hydrogen gas to a higher pressure for storage or transportation. Hydrogen compressors are typically used in applications such as hydrogen fuelling stations, chemical processing plants, and hydrogen-powered vehicles. The compression process can involve one or more stages, using either positive displacement or dynamic compressors. The choice of compressor type and system configuration depends on various factors such as the required flow rate, inlet pressure, outlet pressure, and discharge

temperature. The hydrogen compressor system may also include components such as intercoolers, aftercoolers, filters, and pressure regulators to ensure safe and efficient operation.

There are three main types of speed flow or rate meters:

- Flow meters using a propeller or turbine mounted in the flow space, the rotation speed being the measure of the flow rate. The main flow meters in this category are as follows: Turbine, Propeller and Pelton wheel flow meters.
- Flow meters with the flow rate indication derived from the measurement of a pressure drop across a reduction in the flow area: Pressure Drop flow meters.
- Flow meters using more recent measuring concept such as: Ultrasonic; Electro-magnetic; Vortex shedding, Fluidic; and Swirl flow meter [2].

Different types of flow meters and their characteristics are presented in Table 1.

Table 1. Types of Flow Meters

Type of flowmeter	Flow range [l/min]	Accuracy	Maximum pressure [kg/m ²]	Temperature range
Turbine	–2700000	0.25 %	4535	–240 °C to +1380 °C
Magnetic	0.2–1900000	1 %	1644	–240 °C to +177 °C
Ultrasonic	0.2–75000	1 %	1360	–200 °C to +200 °C
Orifice - fixed	0–1900000	1 %	2721	–40 °C to +400 °C
Orifice - variable	150–1500	1 %	2721	–200 °C to +500 °C
Positive displacement	0.1–12000	0.25 %	653	–40 °C to +250 °C

The choice of the flow meter for a particular application will depend on the physical-chemical nature of the fluid, the pipe diameter and levels of pressure and temperature of the fluid, whose flow rate is to be measured. For our study purposes, a turbine flow meter was selected. As the main concern is the process pressure, the obvi-

ous choice among all the types of meters is the turbine flow meter, as it has the highest maximum pressure value. Applicable measurement standards and recommendations are stated by the International Organization of Legal Metrology [3] and the European Association of National Metrology Institutes [4].

2. THEORETICAL BACKGROUND

The first turbine flow meter was invented in 1790 by Reinhard Woltman. The turbine flow meter is reliable for use with both liquids and gases. A turbine flow meter is constructed with a rotor and blades that use the mechanical energy of the fluid to rotate the rotor in the flow stream. The turbine flow meter design is presented in Fig. 1. Blades on the rotor are angled to transform the energy of the flow stream into rotational energy. The rotor shaft spins on bearings: when the fluid moves faster, the rotor spins proportionally faster. A turbine flow meter rotor with a pick-up sensor is presented in Fig. 2. Rotor movement is often detected magnetically when movement of the rotor

generates pulsation. When the fluid moves faster, more pulses are generated. Turbine flow meter sensors detecting the pulse are typically located externally to the flowing stream to avoid material of construction constraints that would result if wetted sensors were used. The RPM of the turbine wheel is directly proportional to the mean flow velocity within the tube diameter and corresponds to the wide range of the volume flow. A flow transmitter processes the pulse signal to determine the flow of the fluid. The flow transmitter and sensing systems are available to sense the flow in both forward and reverse flow directions.

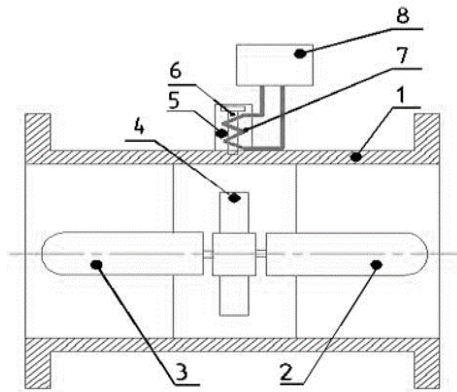


Fig. 1. Turbine flow meter design: 1 – body; 2 – upstream flow conditioner; 3 – downstream flow conditioner; 4 – rotor; 5 – magnetic induction sensor; 6 – core; 7 – coil.

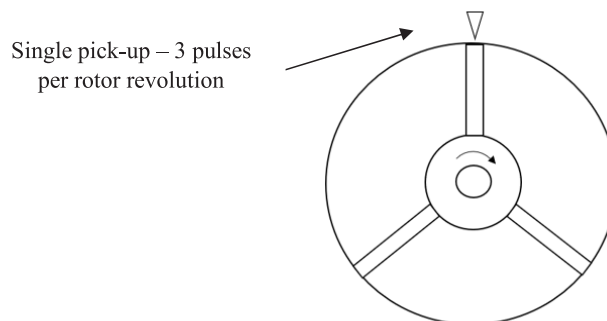


Fig. 2. Turbine flow meter rotor with a pick-up sensor.

The K-factor is used to describe the performance of meters to output of which is the form of electrical pulses (1):

$$K = \frac{n}{V_t}, \quad (1)$$

where n is a number of pulses per unit time. V_t is the volume passed in that time.

Advantages of turbine flow meters are the following:

- Wide flow range, including low flow rates.
- Good accuracy. For liquids it is usually $\pm 0.25\% \sim \pm 0.5\%$, for gas turbine flow it is mostly $\pm 1.5\%$. Turbine flow meters are relatively high accuracy flow meters compared to other types of meters.
- Simple and durable construction.
- Easy installation and maintenance.
- Flexible connection to flow instruments for flow control.
- Wide range of operational temperature and pressure.
- Low pressure drops in the turbine.
- Convenient signal output.

Disadvantages of turbine flow meters are the following:

- Constant back pressure is required to prevent cavitation.
- Accuracy is adversely affected by liquid bubbles.
- Can only be used for measuring clean liquids and gases (a filtering screen may

be required upstream the flow to prevent the damage caused by particles and inclusions).

- Not applicable for measuring corrosive liquids.
- A turbulent flow (constant fluid velocity throughout the complete pipe diameter) is required for measurement accuracy.
- Affected by changes in fluid viscosity.
- A straight pipe upstream and downstream the turbine meter is required to allow for dissipation of vortex paths in the flow.
- May not work accurately with high viscosity fluids if the flow pattern is laminar.
- The performance of a small size meter (2 inch or less) is critically affected by physical properties, and it is difficult to improve the flow meter capacity for a small size sensor.
- A turbine flow meter cannot retain its original calibration for a very long time as it will gradually change owing to surface wear or presence of dirt, requiring periodic recalibration to maintain high accuracy.

When the fluid passes through the turbine flow sensor rotor, it begins to spin due to the applied force. Simultaneously, there are certain opposing forces acting on the rotor. The turbine flow meter performance equation in stable condition is the following:

$$T_d - T_b - T_h - T_m - T_t - T_w = J \frac{d\omega}{dt} = 0, \quad (2)$$

where T_d is the rotor driving torque, T_b is journal bearing retarding torque, T_h is rotor hub retarding torque due to fluid drag, T_m is retarding torque due to mechanical friction in journal bearings and attractive force of magnetoelectricity detector, T_t is blade tip clearance drag torque, T_w both hub disk retarding torque due to fluid drag; T_r is a sum of drag torques; J is rotational inertia of the rotational system; ω is the turn speed of the rotor. The torques acting on the rotor of the turbine flow sensor are depicted in Fig. 3.

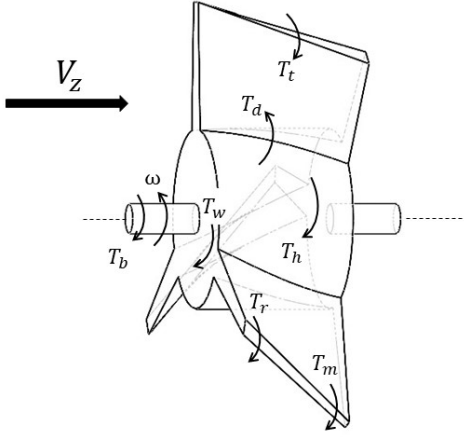


Fig. 3. Conceptual representation of the forces acting on the rotor (V_z is a direction of the axial velocity component).

The viscosity of the fluid is one of the major factors that affects the performance of turbine flow meters. For fluids with low viscosity (water: 1 mm²/s and below), the meter response is linearly dependent on the flow rate. However, for fluids with high viscosity (hydraulic fluid: 50 mm²/s to 100 mm²/s) the meter response is highly nonlinear [5]. The coefficient of viscosity, usually termed as viscosity, is a figure that indicates the amount of resistance a particular fluid offers to a shearing force under a laminar flow condition.

There are studies that analyse a viscosity effect on turbine flowmeter performance based on experiments and CFD simulation [5]–[8]. In research [5], results demonstrated that increasing viscosity led to a reduced meter factor and a rise in a linearity error. This is attributed to changes in wake flow and pressure distributions on the rotor blades, as detailed in CFD simulations. Similarly, the research outlined in [6] underscored viscosity influence on the

turbine flow sensor, particularly affecting the impeller inlet velocity profile and fluid leakage. Through strategies like modifying the sensor hub radius in relation to the housing inner radius and fine-tuning impeller length, the study achieved enhanced accuracy across diverse viscosity levels. This optimization brought down the discrepancy in the average meter factor between the extremes of viscosity from 22 % to a mere 2.2 %. Additionally, the newly introduced performance metric demonstrated a marked improvement from values exceeding 20 % to figures below 5 %. Further research indicates that the impeller blade shape of DN10 turbine flow sensor, defined by the structural parameter η (incorporating aspects like the blade axial length and the blade tip axial length), is a key determinant of fluid dynamics, wake flow patterns, velocity distribution, and, in turn, the sensor over-arching performance. To elevate a sensor efficacy, modifications in the rotor architecture, contour, and dimensions are pivotal. Specific studies [9]–[13] have focused on rotor optimization, pinpointing essential geometric facets of the rotor, such as blade count, blade tip radius, rotor hub radius, helical blade lead, blade thickness, blade bevel edge angle, and rotor hub length, as critical contributors to flow meter performance. Comparative evaluations between CFD simulations and empirical results, as cited in [14], [15], suggest a close correlation, endorsing the feasibility of predicting turbine flow meter efficiency via simulations.

The accuracy of turbine flow meter is expressed in terms of linearity and repeatability. The linearity is calculated as follows (3):

$$\delta_1 = \frac{K_{Max} - K}{K} \cdot 100\%, K = \frac{K_{Max} + K_{Min}}{2}, K_{Max} = \text{Max}\{K_i\}, K_{Min} = \text{Min}\{K_i\}. \quad (3)$$

Thus, K_{Max} and K_{Min} are crucial parameters when evaluating sensor performance indicators. Previous research [2] indicates that the highest meter factor K_{Max} emerges at peak flow rates, while the lowest meter factor K_{Min} is seen at the lowest flow rates, especially at elevated viscosities. Therefore, to enhance the sensor efficiency across a broad viscosity spectrum, the meter factor at low flow rates should be raised, or

the meter factor at high flow rates should be lowered.

Repeatability is the flow meter ability to give exactly the same output when measuring exactly the same flow rate. The output of some flow meters drifted with time, after a period of operation it would still give good repeatability but about in different point.

Repeatability (4) is calculated as follows:

$$\delta_2 = MAX \left[\frac{1}{K_i} \left[\frac{1}{n-1} \sum_{j=1}^n (K_{ij} - K_i)^2 \right]^{1/2} \cdot 100\% \right]. \quad (4)$$

3. METER STRUCTURE AND GEOMETRICAL PARAMETERS

For the numerical and physical experiment in a laboratory, water as working liquid was used. The object of investigation is a turbine flow meter KF500 used for the precise measurement of instantaneous flow rates and flow equities of low-viscosity fluids. It can be widely used in the fields of

industry, metallurgy, scientific research for measuring or control. Several output parameters and other options can be applied, the device is completed with instantaneous flow rate and totalizer. Technical features of KF500 are presented in Table 2.

Table 2. Turbine Flow Meter Technical Parameters

Parameter	Value
Measure range	0.01 to 800 m ³ /h
Accuracy	±1% in measure scale 1:10 & ±2% in measure scale 1:25
Temperature	20 to 100 °C (Medium) / -25 to 55 °C (Environment)
Body material	Stainless Steel
Wetted part material	Alloy Steel
Power supply	-24 V DC
Output signal	4–20mA and pulse output

Figure 4 illustrates the structure and key geometric dimensions of the turbine flow sensor. The sensor is equipped with both upstream and downstream flow conditioners. The conditioners, located on both ends of the sensor, ensure that the fluid flow is

uniform and conditioned before it interacts with the rotor. The rotor, being the central component, has blades that respond to the fluid flow, and its dimensions are critical to the sensor performance.

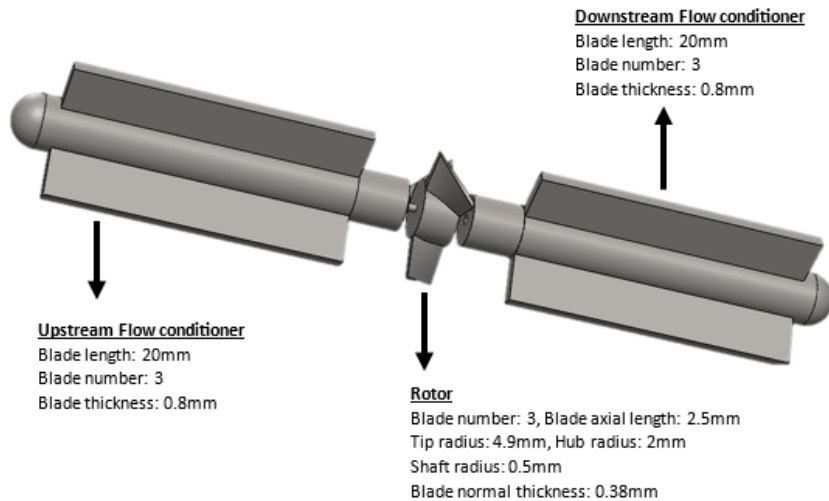


Fig. 4. The internal structure of a turbine flow meter.

4. NUMERICAL EXPERIMENT OF A TURBINE FLOW METER

The three-dimensional model of the DN10 rotor flow meter is constructed with the ANSYS Design Modeller function within the ANSYS Workbench platform. The dimensions were maintained with a high level of accuracy in accordance with the physical model. To ensure a more accurate representation of real-world conditions, straight pipes located upstream and downstream of the flow meter were extended by a length equivalent to 2.5 times their diameter in the simulation. The model was subsequently partitioned into three components, with the rotating region situated in the central portion and the surrounding portions positioned in the anterior and posterior sections, respectively.

The experiment involved the removal of the flow conditioner and blades using a Boolean command. This resulted in the division of the regions into three parts: a spinning region containing the turbine cavity, and a surrounding area containing the conditioner cavity. This approach has the potential to decrease the duration of the

simulation process. The tetrahedron mesh method is employed in the procedure to enhance the quality of the mesh. The computational domain was partitioned into three distinct regions: the upstream straight pipe and flow conditioner, the rotor region, and the downstream straight pipe and flow conditioner. Ensuring that the skewness of the model remains below 0.9 is done in order to improve the quality of the results.

The simulation was conducted using the ANSYS Fluent software. The turbulence model was chosen for this study. The standard $k-\omega$ model was derived from the Wilcox $k-\omega$ model, with modifications made to account for low Reynolds number, compressibility, and shear flow propagation. In contrast to the traditional $k-\omega$ model, the SST $k-\omega$ model exhibits superior accuracy and algorithmic stability in the vicinity of the wall, as well as enhanced accuracy and credibility throughout a broader range of flow fields. The turbulence model chosen for this investigation was the SST $k-\omega$ model because of the low Reynolds num-

ber exhibited by the fluid flow in the pipeline. In the initial experiment, water was employed as the working fluid; however, for subsequent trials, a low-viscosity silicone oil was utilized. The cells that rotate and surround were allocated with their corresponding working fluid. The inlet boundary condition was specified as a velocity inlet, whereas the output boundary condition was specified as a pressure outlet. This study employed a passive method, specifically the 6DOF model and dynamic mesh, to simulate the internal flow field of the turbine flow sensor. This approach was chosen based on the operating principle of the turbine flow sensor. The simulation was initiated using a hybrid method, employing

a straightforward approach. The simulation was executed for a duration of 10 seconds. The resolution of the grid was vital for the simulation effectiveness.

The integrity of the grid cells profoundly influences the rate of convergence and the precision of the simulation. An example of grid resolutions is depicted in Fig. 5, aimed at ensuring the grid quality and minimizing the model grid count. The method used for meshing was Tetrahedrons with size of 0.4 mm for the whole body and 0.3mm for rotor walls. The number of nodes was 81115 and that of the elements was 368134. The maximum skewness was 0.88. Inflation was provided on the rotating region for better simulation.

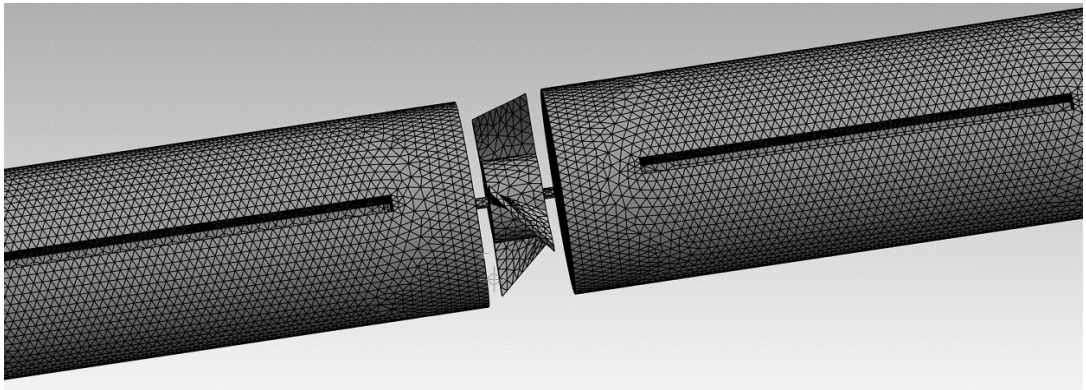


Fig. 5. An informative visualization of the grid structure used in the simulation model of a turbine flow sensor.

5. NUMERICAL SIMULATION RESULTS & DISCUSSION

During the testing process, water was the medium used. Specific flow rates were employed for this testing, including 0.2 m³/h, 0.3 m³/h, 0.48 m³/h, 0.84 m³/h, to evaluate the performance of the flow meter under these conditions. The variation of angular velocity with time for average fluid velocity of 0.54 m/s is shown in Fig. 6. Initially, ω ascends swiftly and then enters a

phase of periodic fluctuation upon attaining a particular value. It is inferred that the impeller achieves consistent rotational motion at this juncture. The fluctuation in ω is predominantly attributed to the angle at which the liquid strikes the blade. The mean velocity, ω , is determined by averaging the spinning speeds recorded at each time increment within a complete cycle.

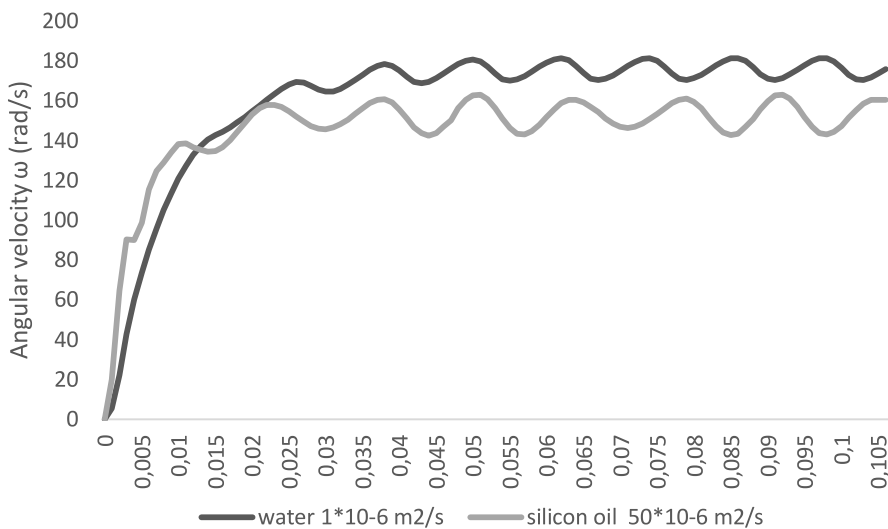


Fig. 6. The change in the angular velocity with time for average velocity of fluid equals to 0.54 m/s.

The primary goal of simulation was to study the turbine response to fluids of varying viscosities. The turbine angular velocity was evaluated as it interacted with these fluids. In the simulation, it was noted that with an increase in viscosity, the torque also increased, which was consistent with the principles of hydrodynamics. This increase in torque due to higher viscosity directly affected the angular velocity of the turbine. Specifically, for a given input power, a higher torque would mean a reduced angular velocity. Therefore, as the viscosity of the fluid increases, the turbine angular velocity tends to decrease, unless additional power is supplied to counteract the increased drag and maintain the same rotational speed. Viscosity defines a fluid ability to resist deformation. In the context of the simulation, fluids with higher viscosity show greater internal resistance, complicating the movement of fluid layers over one another. When the fluid passes through the turbine blades, this increased resistance results in heightened aerodynamic drag on the blades, leading to an increased torque on the turbine. This drag is a key factor in

the observed changes in angular velocity.

Using water as our reference measurement, it is evident that as viscosity increases, the torque exerted on the turbine surface also increases. Consequently, the angular velocity of the turbine is affected. Based on our prior observations, variations in viscosity lead to differing rotational speeds of the turbine, thereby influencing the K-Factor of the turbine.

Figure 7 represents the relationship between flow rate and meter factor for two different fluids: water and silicon oil.

The shape of the curve depends on the viscosity of the liquid which varies with temperature and from liquid to liquid, as well as on the flow range over which the flow meter is used. The turbine can be designed that is less sensitive to one of those two factors. This can be done by varying the tip clearance of the impeller, by correct design of the rotor blades or by altering the hub/rotation. The effect of increasing the tip clearance is twofold, it frees the rotor from the high drag area at the tips, and also places the rotor in the region of higher velocity.

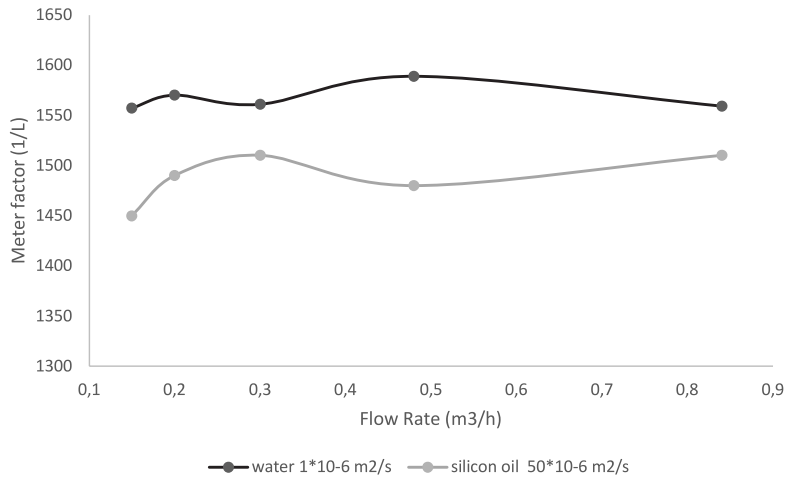


Fig. 7. Comparison of meter factor vs. flow rate for water and silicon oil.

The meter factor K varies across different viscosity levels, Fig. 8 showcases the relationship between K factor and the kinematic viscosity of the fluid for average

velocity of fluid being equal to 0.54 m/s. It is evident from the graph that as the viscosity rises, the meter factor K consistently drops throughout the entire range of viscosities.

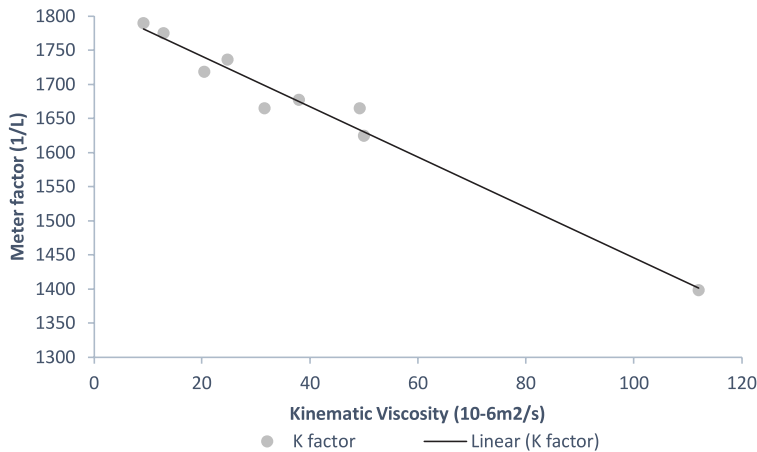


Fig. 8. Viscosity effect on K factor of turbine flow meter.

Viscosity greatly impacts the performance of turbine flow meters. High-viscosity fluids create more drag on turbine blades, requiring more torque for rotation. They also present a pronounced laminar flow profile, reducing effective flow velocity. Additionally, viscous fluids can increase start-up torque due to greater resistance to

initial movement, affect bearing friction, and alter the meter operational flow range. Thus, fluid viscosity is a crucial factor in the design and calibration of turbine flow meters for accurate measurements. Flow velocity distribution between the rotor blades is shown in Fig. 9.

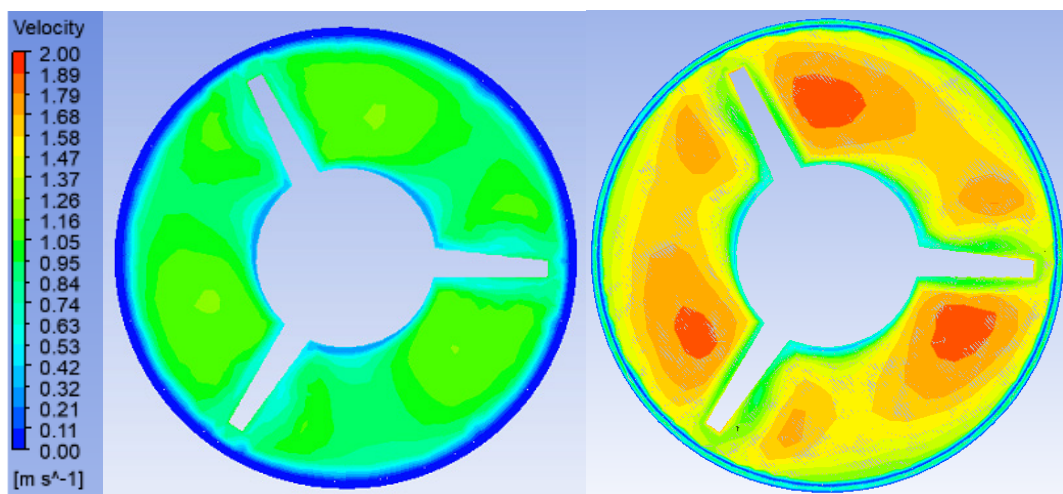


Fig. 9. Flow velocity distribution at the rotor inlet for water:
on the left – a flow rate of 0.2 m³/h;
on the right – a flow rate of 0.84 m³/h.

As accuracy of flow metering is important, turbine flow meters should be calibrated using exactly the same fluids which are to be measured. The calibration should also be carried out using the same upstream and downstream pipework as would be used in a particular installation. It means that calibration has to be carried out on site using a meter prover. To calibrate means to standardize (as a measuring instrument) by determining the deviation from a standard so as to determine the proper correction factors. There are two key elements to this definition: determining the deviation from a standard and ascertaining the proper correction factors. The calibration of the flow meters needs to be carried out on a regular basis. The procedure can be performed by using another calibrated meter as a reference or by applying a known flow rate. The accuracy can vary over the range of the instrument and with temperature and specific weight changes in the fluid, so all these factors have to be considered. Thus, the meter should be calibrated over temperature

as well as over the range, so that the appropriate corrections can be made to the readings. A turbine meter should be calibrated at the same kinematic viscosity at which it will be operated when in service.

The laboratory provers generally operate with a gravimetric calibration system. They can apply water/oil as the operational fluid. The gravimetric method is the weight method, where the flow of liquid through the meter being calibrated is diverted into a vessel that can be weighed either continuously or after a predetermined time.

The weight is usually measured with the help of load cells. The weight of the liquid is then compared with the registered reading of the flow meter being calibrated. Volumetric method is a technique, where a flow of liquid through the meter being calibrated is diverted into a tank of known volume. The time to displace the known volume is recorded to get the volumetric flow rate, e.g., gallons per minute. This flow rate can then be compared to the turbine flow meter readings.

6. EXPERIMENTAL EVALUATION

A controlled physical experiment was carried out in a laboratory setting to study the behaviour of a turbine flow meter when used with water at a working temperature

of 20 °C. For the study purposes, a physical experiment diagram was developed (Fig. 10), and the process algorithm was described (Table 3).

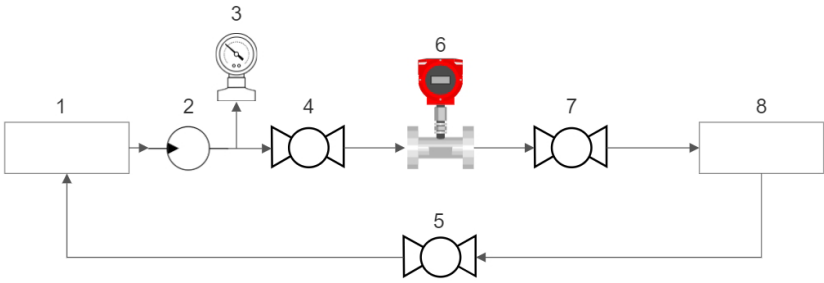


Fig. 10. The diagram of the experiment involving the pump: Closed inlet tank (1), pump (2), manometer (3), isolating ball valve (4), bypass ball valve (5), flow meter (6), flow regulation ball valve (7), outlet tank (8).

Table 3. The Experiment Process Algorithm

Number	Action
1	The liquid is poured into the inlet tank, the volume/mass of the liquid is recorded
2	Valves 5, 4, 7 are shut
3	Pump activation, waiting for the operational pressure on the manometer (3)
4	Opening of valves 4, 7
5	Liquid transfer from tank 1 to tank 8
6	Recording of the meter readings upon completion of the liquid transfer
7	Shutting of valves 4,7
8	Liquid volume/mass metering in tank 8
9	Recording and comparison of the meter readings and actual measurement figures, correction of the operation of the metering system
10	Opening of bypass valve 5, pump 2 activates the back flow
11	Transfer of the liquid into the inlet tank to check for steady state readings

Table 4 presents a side-by-side comparison of simulation and experimental results

focusing on the average meter factor and linearity error.

Table 4. Comparison of Experimental and Simulation Results

Simulation		Experiment		Error, %
Average meter factor	Linearity error, %	Average meter factor	Linearity error, %	
1573	0.01	1555.86	0.0089	1.09

The simulation predicted an average meter factor of 1573, while the experimental result was 1555.86, a minor deviation

of 1.09 %. Additionally, both methods exhibited incredibly low linearity errors, with the physical experiment being slightly

more consistent at 0.0089 % compared to 0.01% achieved in the simulation. Overall, the simulation closely mirrored the experi-

mental results, demonstrating its reliability and precision.

7. CONCLUSIONS

The study outlined in this document provides a comprehensive investigation into the performance characteristics of a DN10 rotor flow meter using ANSYS simulation tools and subsequent physical experimental validation. The meticulous construction of the three-dimensional model and the subsequent partitioning into distinct components allowed for the evaluation of the flow meter behaviour under various conditions, including alterations in fluid viscosity and flow rates. The use of the SST $k-\omega$ turbulence model and the dynamic mesh technique for simulating the internal flow field of the turbine flow sensor have been proven to be effective approaches, as evidenced by the close correlation between simulation and experimental results.

The investigation underscored the considerable influence of fluid viscosity on the performance of turbine flow meters. It was observed that as viscosity increased, there was a notable decrease in the turbine angu-

lar velocity due to the increased drag force.

In the comparison between water and silicone oil, it becomes apparent that the fluid kinematic viscosity plays a pivotal role in determining the meter factor (K), with a higher viscosity correlating to a decreased K-factor. This can have significant implications for industrial processes where precise flow measurements are essential for optimal operation.

Moreover, the experimental evaluation of the flow meter performance through a carefully designed laboratory setup provided tangible evidence that supported the accuracy of the numerical simulations. The slight discrepancies observed between the experimental data and the simulated results, in terms of the average meter factor and linearity error, fall within an acceptable range that validates the simulation model efficacy. The negligible error percentage of 1.09 % in the average meter factor is indicative of an exceptionally reliable simulation process.

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