A Computational Investigation of Flow Meters

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Abstract: Computational fluid dynamics (CFD) techniques provide investigations in conditions where the real experiment can't be fulfilled for some reasons, so these tools have found their applications in many spheres of science and technology; in particular they are widely used in flow metering. Some of CFD applications we would like to propose and discuss in this work in the context of turbine and ultrasonic meters. We discover non-drag type of turbine flow meters to check if created design with hydro-dynamic bearings should provide really floating rotor. For this purpose only numerical research can solve verification problem with minimal costs and simple realisation. Another computational investigation is dedicated to transit-time ultrasonic flow meters to optimize their design and get improved performance not only in normal conditions.

Keywords: Ultrasonic flow meter, Turbine flow meter, Meter Performance, CFD analysis, Error Curve

1. Introduction

Research work in flow metrology traditionally has deal with a lot of experiments. Currently due to the development of computational fluid dynamics (CFD) researchers have got a chance to substitute expensive full-scale experiments by numerical ones. Really, CFD is a well-proven technique that is used to visualize and optimize many measuring processes. It is good enough when experimental tests can't be done for some reasons.
Flow metering is one of primary fields, where CFD tools effectively help to solve such problems, as prediction of errors, investigation and modelling of different hydrodynamic effects inside measuring ducts, including visualization of velocity profiles, temperature fields, pressure contours, etc.
CFD numerical simulation is applied for solving Navier-Stokes equations and thus obtaining a velocity distribution law inside metering cell. Its advantages are obvious: low costs with comparatively high computational speed, and ability to predict results in real experiments.
Basically, overview of the numerical tools applications in flow metering gives us a following list of typically solved issues:

- flow meter reaction on flow disturbances such as contractions, expansions, bends, pumps, valves, etc.;
- revealing and correction of the shortcomings in the traditional design;
- investigation of different hydrodynamic phenomenon (vortices, swirls, etc.) in flow measuring ducts.

Today a lot of computational studies are devoted to investigations of ultrasonic and turbine flow meters. The optimal meter geometry has become the fundamental task for their designers. Developing this subject we would like to discuss our vision of CFD applications while investigating mentioned types of flow meters.

2. Analysis on Theory of Turbine Flow Meters

Turbine (Woltman) flow meters are frequently installed in water distribution networks. These meters are used for measuring the water quantity and flow rate in district metering areas. The

major source of error for these flow meters is in friction which takes place between the hub of the turbine and the bearing hub and between the turbine blade tips and the flow meter housing.
The error due to bearing friction can be minimised by application of hydro-dynamic bearings. For today we know some design principles to create these bearings[1]. But experimental verification of meters with hydrodynamically balancing rotor is pretty difficult task. The key information for its solving should be obtained through analyzing the static pressure field inside the meter. The most reasonable way to do it is based on numerical investigation of an axial type turbine flow meter with application of CFD code FLUENT.
The aim of the evaluation was to study the efficiency of the created meter geometry for reducing of bearing friction. So, we should obtain the curve of static pressure distribution along the measuring duct and analyze it for presence of ‘floating rotor’ effect.
The shape of the curve depends upon the viscosity of the liquid which varies with temperature, as well as on the flow rates on which the flow meter is used. Designing turbine flow meters researchers look for optimal tip clearance of the turbine, shape of the rotor blades and the hub/rotor ratio. All parameters somehow affect each other, so the main task consists in selection of correct sizes and their relations inside flow measurement section. It may take a lot of time if we will find rational size relations in usual experimental tests, so computational study in searching for optimal turbine meter design would be much appreciated.

3. Computational Study of the Turbine Flow Meters with Floating Rotor

DN 50 mm turbine meter's flow fields were simulated with CFD software FLUENT. We created design of turbine and conditioners (see figure 1) to provide a few numerical experiments.

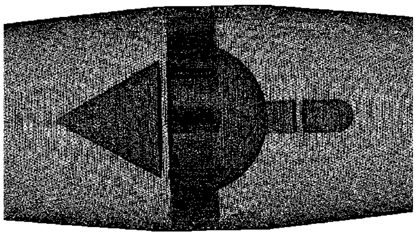

Fig. 1 Meshed model of floating rotor created in GAMBIT

A CFD simulation has been carried out to help in determination of pressure distribution inside flow measurement section to find out the best position of the rotor to achieve the hydraulic balance point.

3.1 Numerical results

Flow fields show us that meter's pressure change is influenced by front-end and tail-end conditioner shapes, radius of flow conditioner hub, the thickness of rotor blades.
To prove the effect of lowering the rotor bearing friction it was enough to plot static pressure distribution curves along metering cell at different flow rates.
As far as modelling was conducted at different flow rates so fixed boundary conditions were as following:

- for flow rate Q = 0,45 m^3/h - inlet velocity V= 0,06 m/s, rotational frequency n=1,88 rad/s ;
- for flow rate Q = 10 m^3/h - inlet velocity V= 1,42 m/s, rotational frequency n=50,24 rad/s ;
- for flow rate Q = 30 m^3/h - inlet velocity V = 4,246 m/s, rotational frequency n=151,98 rad/s

All plots (figures 2, 3, 4) demonstrate the same phenomenon, which consists in pressure lowering around the rotor and its increasing behind the rotor. In other words, zones with increased pressure located before and beyond the turbine do not allow it to move forward and back under flowing liquid. So the turbine will be kept in balance.

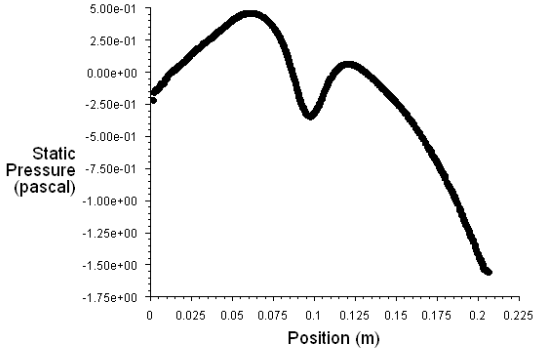

Fig. 2 Static pressure distribution curve along metering cell while Q=0,45 m^3/h

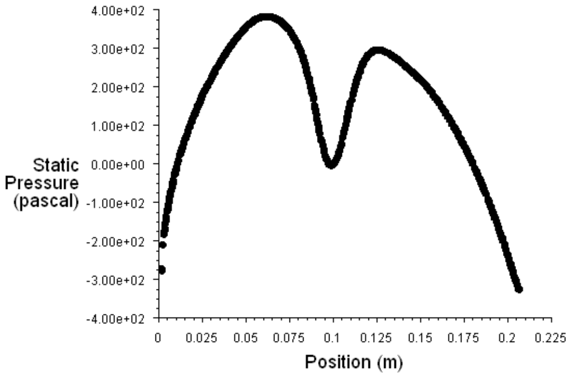

Fig. 3 Static pressure distribution curve along metering cell while Q=10 m^3/h

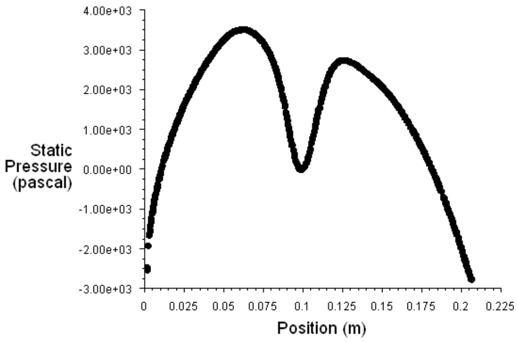

Fig. 4 Static pressure distribution curve along metering cell while Q=30,0 m^3/h

The results show that the simulation model is effective and can be used not only for selection of rational sizes of measuring duct. It is also good for examining created design on ability to provide a hydraulic balance mechanism for rotor in all points of measuring range and so to protect axial bearing from excessive deterioration.

4. Analysis on Theory of the Ultrasonic Flow Meters

A well-designed ultrasonic flow meter requires understanding the physics of sound propagation, signal processing and of course hydrodynamic phenomenon inside metering cell.
Literature survey[2-4] with respect to mentioned subject matter shows that many researches focus their attention on the effect of turbulent fluctuations on the trajectories of sound paths of transit

time ultrasonic flow meters and flow visualization near transducer housings. The results were discussed in terms of their consequences for the performance of certain ultrasonic meters. These studies indicate flow patterns and recirculation zones. The reason of such studies was in complex and unclear relationship between meter performance and the inlet flow profile. All researches had practically the same aim – the development of a high accuracy and low cost ultrasonic flow meters with minimal dependence on installation effects and variable flow conditions.

We investigated numerically as well as experimentally some ideas regarding reshaping of the duct to achieve optimum meter geometry in different temperature conditions for measured flow. Really, one more important tendency is impact of measured medium temperature on ultrasonic meter performance, because now these meters are often used to measure the flow rate of heat-conveying liquid in heat quantity measurements.

4.1 Computational study of the ultrasonic flow meters

Travel-time ultrasonic flow meters measure the difference between upstream and downstream pulse propagation times. This propagation can be diagonal or axial. Let's speak about flow meters with axial sound paths. Their basic geometry consists of two piezoceramic transducers mounted coaxially upstream and downstream within a circular duct. The transducers are separated from each other for certain distance.

Based on the practical structure of the flow meter we decided to analyze meter performance and to propose some ways for its improvement.

The flow measurements by ultrasonic meter include measurement of time delay at sound propagation along and against the flow with its following transformation to fluid velocity averaged for pipe cross-section. The procedure is to build up the mathematical model of the measuring process with real velocity profile. So the purpose of this research is in employing the CFD code FLUENT to obtain velocity distribution along sound propagation path and to see how it will change with reshaping of the meter's measuring duct.

The influence of various geometrical configurations on metrological performance of ultrasonic flow meters was simulated and results were verified by laboratory experiments on special test rig with accuracy of 0,03%.

In computational experiment the k-ε model was used to account for turbulence. Our studies were focused on the shape of transducer housings, contractions, and selection of correct relation between sizes of measuring duct. The diameter of the inlet for all models is 20 mm, and the inlet velocity was set according to flow measurement range 0.06–6m^3/h. The flow is assumed to be uniform. The grid for all models was generated in preprocessor GAMBIT.

4.2 Results

Calibration is generally done in the fully developed flow profile and typically to find the flow rate Q we use the following expressions[5,6]

$$Q = V_{av}S \tag{1}$$
$$V_{av} = V_l k \tag{2}$$

where

V_{av} : Fluid velocity averaged for pipe cross-section
S : Meter's cross-section area
V_l : Fluid velocity averaged for length of sound propagation path
k : Flow profile correction factor

For determination of correction factor k, it is basically applied the following set of formulas[5]:

$$k_{theor} = \frac{2n^2}{(1+2n)(1+n)} \tag{3}$$

where

$$n = 11.269 - 3.019 \lg \mathrm{Re} + 0.432 \lg^2 \mathrm{Re}\text{; Reynolds number } \mathrm{Re} = \frac{2V_l R}{n}$$

But this typical algorithm for determination of the k-factor is very questionable as far as it contains simplified information about velocity profile distribution.

Due to applying FLUENT or other CFD code we can find the real value of k-factor depending on different flow conditions inside and outside the measuring duct. So, to find k-factor with FLUENT application we used the following dependance

$$k_{\mathrm{fluent}} = \frac{\left(p R^2\right)^{-1} \int_0^R V_r \, 2p \, r dr}{R^{-1} \int_0^R V_r dr}$$

where

V_r : Velocity determined on the distance r from pipe axis

R : Pipe radius

Comparing results of traditionally found k_{theor}-factor used in measuring algorithm of ultrasonic meters and $k_{\exp}$ which is calculated due to FLUENT numerical experiment and then verified in full-scale experiments (figure 5) we can see especially big difference in the beginning of flow measurement range.

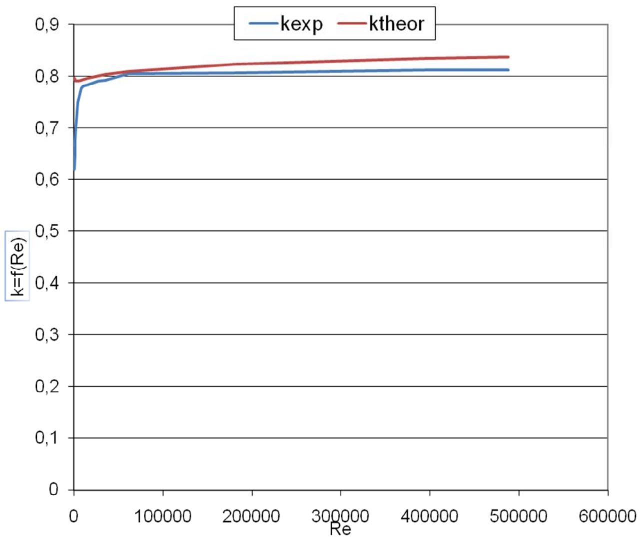

Fig. 5 Graphical dependencies for k-factors based on simplified (ktheor) and real (kexp) velocity profiles

This big difference was calculated as error according to formula

$$Error = \left(\frac{k_{\exp}}{k_{theor}} - 1\right) \cdot 100\%$$

So applying calibration curve based on theoretical values of *k*-factor founded in simplified way we would not achieve desirable accuracy of flow measurements even with improved design of ultrasonic meter.
The difference between theoretical and experimental *k*-factors varies up to 22% in the beginning of measurement range. So with plotting the last graph we can see really big importance of correctness for *k*-factor determination.
In the measurement range we can analyze the difference between error curves based on *k*-values determined in real experiments (exp1, exp2) and in computational experiment (CFD) (see figure 6). The last one was calculated as follows

$$Error = (\frac{V_l kS}{Q_{set}} - 1) \cdot 100\%$$

where

Q_{set}: Actual value of measured flow rate
The aim of experimental tests was to prove the results of numerical studies. So under numerical experiment (CFD) we defined velocity along sound propagation path, which then was substituted in the expression for flow rate calculation (see Eq. (1)-(3)). Knowing exactly the actual flow rate value we could calculate the error.

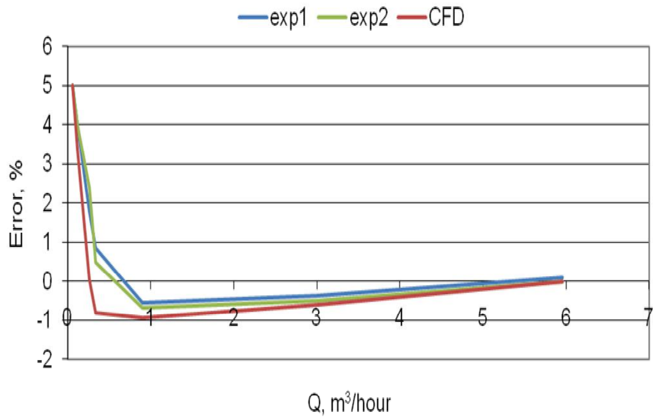

Fig. 6 The difference between error curves based on simulated and experimental k-factors

However as we see from figure 6, CFD techniques don’t always allow to achieve a complete coincidence between curves based on numerical and full-scale experimental approaches for obtaining *k*-factors. Especially it is obvious in transit regime, which should be avoided by different possible ways.
Generally speaking it is difficult to extrapolate theoretical dependencies or dependencies from one meter to other designs. So, application of typical dependence for *k*-factor leads to measurement errors. By the way it is clear that this approximation is only completely valid when the flow distortions are not severe. So, the larger the disturbance the more incorrect is the proposed approximation for *k*-factor theoretical dependence.

5. Temperature effect on ultrasonic meter performance

One more important problem consists in study of ultrasonic flow meter performance under measurement of heat-conveying liquids as far as it takes place in ultrasonic heat meters.
It has been established that ultrasonic flow meters are influenced by thermal conditions, since the fluid’s viscosity and density are functions of temperature. We conducted a lot of experiments to

see how measuring accuracy will be affected. The temperature affects not only velocity profile, but also acoustic propagation.
By using an experimentally determined velocity profile, a commercial CFD-code and a theoretical measurement model for the ultrasonic flow meter we have predicted the calibration factor curve for the meter at different temperature conditions.
Figure 7 shows how temperature will influence the error curve. In other words, we evaluate the shift of the calibration factor depending on different temperatures (50C, 60C, 80C, 100C) of measured flow. As we see especially for the beginning of measuring range this influence can't be dismissed.

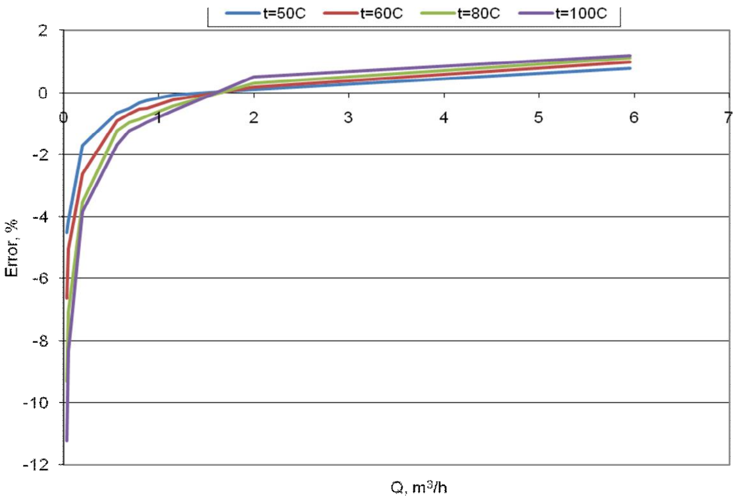

Fig. 7 Temperature effect on error curve of ultrasonic meter

The performance of flow meter is typically improved by measuring the temperature and choosing the right *k*-curve. But how many curves should contain meter's database. In this case more rationally would be providing the one curve for different Reynolds numbers.
So due to providing CFD investigations we conducted studies of calibration factors for ultrasonic meters under fluid flow temperature impact. We discovered real so called 'temperature error' in all measurement range and put necessary temperature correction in process of flow rate calculation.
This error was determined as following

$$Error = (\frac{k_t}{k_{t_0}} - 1) \cdot 100\%,$$

where

k_{t_0} : Calibration factor for normal conditions

k_t : Calibration factor for conditions with set temperature *t* for measured flow

6. Conclusion

The main task of CFD simulations in flow metering is to give effective tool for calculating the measurement uncertainty. Based on these techniques we discovered a possibility to improve performance of turbine and ultrasonic flow meters. During this study we've reached the following conclusions:

1. This work confirmed CFD usefulness as a design tool. Even reduced accuracy simulation proved useful because we could obtain calibration curves which coincide with real calibration curves practically in all measurement range except for transition zone, which desirably should be avoidable.
2. Designing turbine flow meters we could apply CFD to obtain pressure distribution in measuring duct and thereby to check the effect of hydrodynamic balance for rotating turbine. This effect significantly increases performance and longevity of turbine meters though its proving in real conditions is complex and expensive task.
3. Application of CFD techniques for design of ultrasonic meters (especially with coaxial transducers) really helps in searching for optimal duct form and for getting a suitable calibration curve. It was discovered that typically used theoretical dependence for calibration *k*-factor not always meet to real flow measurement conditions. So under computational investigation we can get necessary calibration curve which would be exactly suitable for examined meter configuration.
4. Estimation of the flow profile correction factor of a transit time ultrasonic flow meters is one of main tasks. Numerous experiments made by many researches confirm that not only the sensor housing shape but also the duct geometry impacts meter performance. We simulated different forms of sensor housings and provided computational investigation of different meter's designs to investigate how their performance will be affected.
5. It was known that temperature has an impact on ultrasonic flow measurement provoking so called temperature error, but the value of this error and its variation with flow velocity was questionable. Due to conducting CFD experiments we solved this problem and found how the error curves for certain temperatures would be deviated from the error curve obtained for normal conditions. Results have been used to find the temperature-induced correction for flow rate measurements in conditions different from normal.
6. With the continual improvement of grid generation 3D modelling of a flow field should soon be more practical for many flow metering problems.

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