594. Optimization of ultrasound beam transmission path within measurement channel of ultrasonic flowmeter

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Abstract. The numerical simulation of the water flow through the semicircular duct is presented. The results of the simulation show that by implementing such duct into ultrasonic time-of-flight flowmeters it is possible to get an almost flat and linear function of hydrodynamic correction. The optimal choice of the dimension of ultrasonic transducers and the optimal positioning of them allows us to achieve a hydrodynamic function with the slope ~ 4%. It is expected that flat hydrodynamic calibration function gives the possibility to expand the dynamic measurement range of ultrasonic flowmeters and to increase stability and repeatability of the measurement results.

Keywords: ultrasonic flowmeter, ultrasound wave propagation in duct, hydrodynamic correction, flow profile.

Introduction

A typical ultrasonic flowmeter working on time-of-flight measurement principle suffers from the non-linearity of the hydrodynamic correction function within a wide dynamic measurement range. Moreover, the temperature changes of the flowing liquid affect the changes of kinematic viscosity of the liquid and it requires additional correction of the hydrodynamic functions [1]. These factors limit the accuracy class and dynamic measurement ranges of the contemporary flowmeters. The known methods for solving this problem are:

- the implementation of additional functions of temperature measurement and the correction of temperature-dependent hydrodynamic errors of the flow and heat measurement devices [1],
- the arrangement of the multi-path scanning of the flow velocity profile by means of the ultrasonic time-of-flight measurement technique [2],
- the introduction of special measurement channels with a triangular, rectangular or hexagonal cross-section and the transmission of the ultrasonic pulse into the spiral acoustic path along the measurement channel [3-8].

In this work the authors present an innovative method of linearization of the hydrodynamic correction coefficient. The method is based on the formation of liquid velocity profile inside the measurement channel and the ultrasonic pulse transmission close to the region of velocity profile where normalized velocity is less dependent on the changes between the laminar and turbulent flow regimes. In the authors' earlier work [9,10] it was shown that the ultrasonic flowmeter with the triangular cross-section measurement channel has a turbulent and laminar flow velocity profile crossing curve which is flatter than in other ducts (round, rectangular or hexagonal). Moreover, it is possible to arrange a more optimal location of the ultrasound beam path which is closer to the crossing line of laminar and turbulent flow profiles and, as a result, it is expected to achieve a more linear and flatter hydrodynamic correction function.

The investigation of the hydrodynamic correction factor was performed by means of computer modeling of the ultrasound propagation through the measurement channel with the flowing fluid inside. The semicircular measurement channel of the ultrasonic flowmeter was used for the channel properties modeling, because the cross-section of this channel is similar to the cross-section of the triangular duct. The only difference is that the semicircular cross-section has a rounded apex of the triangle. Another reason for choosing the semicircular measurement channel is the possibility of simple implementation of such channel by inserting a dividing plate along the round measurement tube and dividing the channel into two semicircular ducts. The aim of this computer modeling study is to obtain optimal positioning of the ultrasound beam transmission path within measurement channel in order to get a more linear and flatter hydrodynamic correction function of the ultrasonic flowmeter.

Methods

Computer modeling of the fluid flow through the semicircular duct was performed, and the cross-sections of the fluid profile at different velocities were calculated. The semicircular measurement channel with the following dimensions of length L=90 mm and radius R=7 mm (or the diameter of semicircle D=14 mm) were chosen according to limited dimensions of the small-sized ultrasonic flowmeter with the relative diameter DN20 and the maximum flow rate 5 m3/h. The flow profiles were estimated within the velocity range 0.019 – 25 m/s. The transformation of the profile change from laminar regime (the mean velocity V_{mean} = 0.019 - 0.22 m/s) to the turbulent flow regime (V_{mean} = 1 - 5 m/s) is shown in Fig. 1.

In the next steps of modelling, the evaluation of the mean velocity and the ultrasonically measured velocity within the duct was performed in order to get a hydrodynamic correction function for different cases of the positions and dimensions of the ultrasonic transducers (Fig.2). The ultrasonically measured velocity V_u is calculated from the formula:

$$V_u = \frac{(t_{up} - t_{dw})^* c^2}{2L}, \tag{1}$$

where c is the ultrasound velocity in the medium (for water c=1470 m/s, at T=16.7°C), T_{up} and T_{dw} are time-of-flight of ultrasound pulse propagation within the duct in the upstream and downstream direction, L is the distance between ultrasonic transducers in the measurement section (L=90 mm). While calculating ultrasonically measured velocity V_u, the spatial distribution of the insonated acoustic field within the zone between both transducers was evaluated (the zone where the integral velocity was calculated). The transducers with the central frequency f=2 MHz were used for the acoustic field calculation. The ultrasonically measured flow velocity with the mean velocity V_{mean} is related by the formula:

$$V_{mean} = k(Re,a)^* V_u, \tag{2}$$

The correction coefficient *k* is dependent on the Reynolds number and friction coefficient α, and for different flow regimes it has different expressions. For our cases of calculation, the relative correction coefficient K was calculated for each velocity value by:

$$K = \left(V_u - V_{mean}\right) / V_{mean}, \% \qquad (3)$$

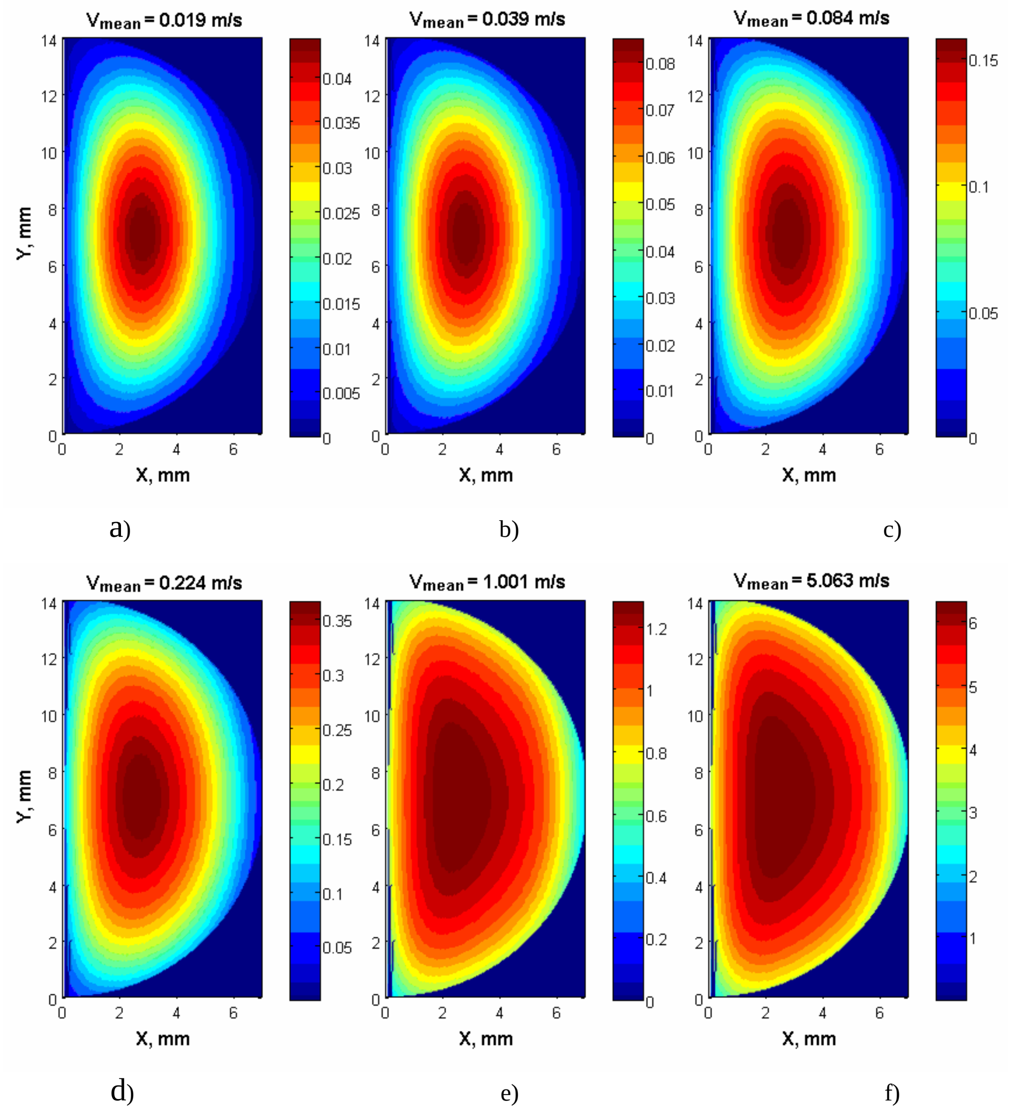
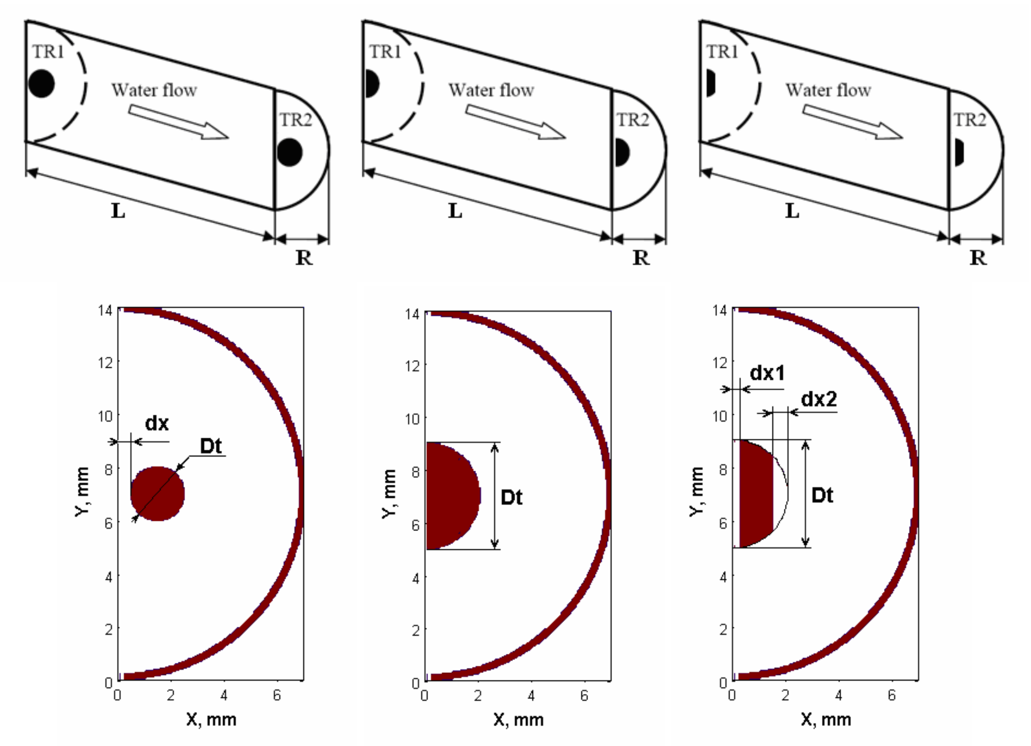


Fig. 1. The calculated cross-section of the flow profile in the measurement channel with the semicircular duct at different flow velocities: a) V_{mean}=0.019 m/s, V_{max}=0.044 m/s; b) V_{mean}=0.039 m/s, V_{max}=0.085 m/s; c) V_{mean}=0.084 m/s, V_{max}=0.157 m/s; d) V_{mean}=0.224 m/s, V_{max}=0.365 m/s; e) V_{mean}=1.001 m/s, V_{max}=1.279 m/s; f) V_{mean}=5.063 m/s, V_{max}=6.308 m/s. Laminar flow is for (a-d), turbulent flow is for (e-f). The vertical bars represent a velocity scale separately for each case of flow profile.



a) b) c)

Fig. 2. The calculation of the optimal hydrodynamic correction function performed for the cases: optimization of dx and Dt for the cylindrical ultrasonic transducer (a), optimization of Dt for the half-disc ultrasonic transducer (b), optimization of dx1 and dx2 half-disc ultrasonic transducer having optimal Dt=4 mm (c). The diameter of the semicircular measurement channel is 14 mm.

Results

The numerical calculation of hydrodynamic correction functions for a semicircular duct and the determination of the more linear and flatter function was performed for these three cases, as shown in Fig. 2.

The first case is the optimization of the positioning of the cylindrical ultrasonic transducer respectively to the measurement channel having a semicircular cross-section. The optimization was performed by changing the diameter of the ultrasonic transducer Dt and the distance dx between the vertical wall of the channel and the edge of the transducer (Fig. 2a). The results of the calculated hydrodynamic correction functions are shown in Fig. 3. – Fig. 5. A more optimal position of the transducer with Dt=2 mm was obtained when dx=4 mm (Fig. 3). For the transducer with Dt=3 mm, the optimal position was obtained when dx=3.5 mm (Fig. 4) and for transducer with Dt=4 mm, the optimal position was obtained when dx=3 mm (Fig. 5). The slope of the hydrodynamic correction functions for the cases of optimally placed transducer was obtained 3…5%. However, such positioning is sensitive, because the movement of transducers by 0.5 mm can affect the rising of the slope of the hydrodynamic correction functions up to 20% or more. In the cases when the transducers were placed not optimally, the high non-linearity of the hydrodynamic correction functions, exceeding the slope by more than 40% were obtained.

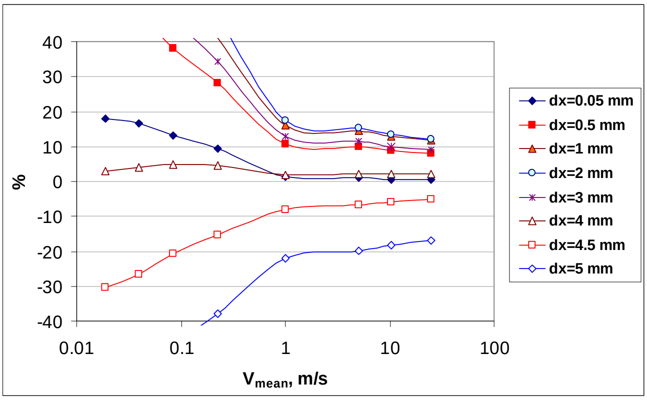


Fig. 3. The calculated hydrodynamic correction functions for different distances between the edge of the transducer and the vertical wall dx = 0.5 …5 mm. The diameter of ultrasonic transducer Dt=2 mm.

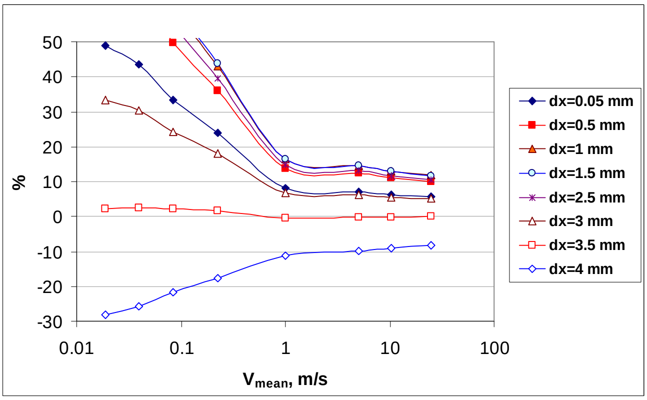


Fig. 4. The calculated hydrodynamic correction functions for different distances between the edge of the transducer and the vertical wall dx = 0.5 …4 mm. The diameter of ultrasonic transducer Dt=3 mm.

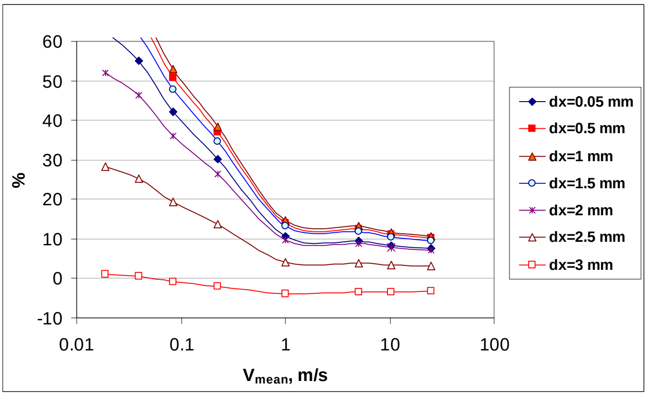


Fig. 5. The calculated hydrodynamic correction functions for different distances between the edge of the transducer and the vertical wall dx = 0.5 …3 mm. The diameter of ultrasonic transducer Dt=4 mm.

The second case of the optimization was performed by changing the diameter of the half-disc ultrasonic transducers (Fig. 2b). The more optimal cases were obtained when the transducer diameter was Dt=4 mm. In these cases the slope of the hydrodynamic correction functions was ~7% (Fig. 6).

The third case of optimization was performed by shadowing the optimally chosen half-disc ultrasonic transducer having the optimal diameter Dt=4 mm. The shadowing of the transducer was performed from the left and right sides by changing the shadow dimensions dx1 and dx2 (Fig. 2c). The result of the optimization shows that by choosing the dimensions of the shadow dx1=0.3 mm and dx2=0.5 mm, the flattest function of hydrodynamic correction with the slope ~ 4 % was obtained (Fig .7).

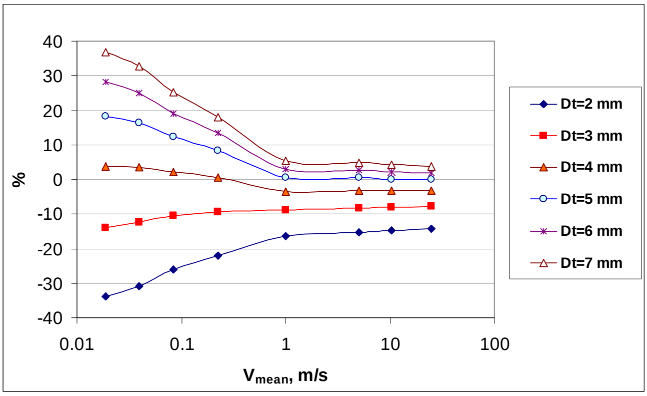


Fig. 6. The calculated hydrodynamic correction functions for different diameters of half-disc ultrasonic transducer (Dt = 2 …7 mm).

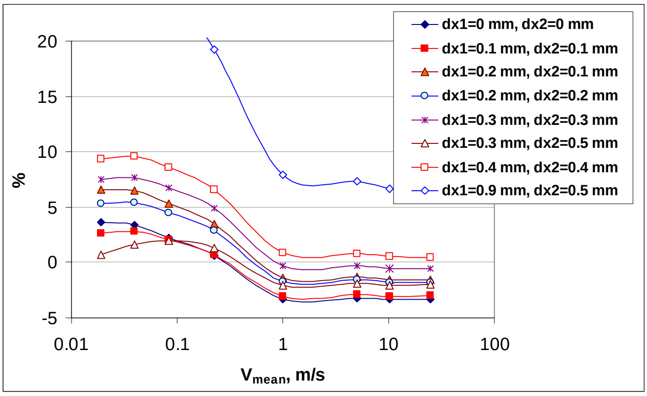


Fig. 7. The calculated hydrodynamic correction functions for shadowed edges of half-disc ultrasonic transducer having optimal diameter Dt = 4 mm (dx1 is shadow zone from left, dx2 is shadow zone from right).

Conclusions

The paper shows that by implementing the semicircular measurement channel for ultrasonic time-of-flight flowmeters it is possible to obtain an almost flat and linear function of hydrodynamic correction. The performed numerical simulation shows that by choosing the optimal position and dimension of ultrasonic transducers it is possible to get a small slope of the hydrodynamic correction function. The most promising situation was obtained for the case of using the shadowed half-disc ultrasonic transducers with dimensions Dt=4 mm, dx1 =0.3 mm and dx2 = 0.5 mm. For this case, the slope of hydrodynamic correction was obtained almost flat (~ 4 %). Such flattening of the hydrodynamic calibration function gives the possibility to expand the dynamic measurement range of ultrasonic flowmeters and to increase stability and repeatability of the measurement results.

Such improvement of technical parameters of the ultrasonic flowmeters can be achieved by using a cost-effective procedure of mechanical insertion and fixing of a thin stainless steel plate into the circular measurement channel of the existing flowmeters. The physical reason for these improvements is the usage of a cost-effective method which provides the possibility to transform the flow profile and to perform the ultrasonic scanning within the flow profile region which is less dependent on the changes between the laminar and turbulent flow regimes.

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