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Mass flowrate measurement using the swirl motion in circular conduits

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ABSTRACT

In this paper, a method of mass flow measurement was presented based on swirl motion motivated by specific shapes of swirlers. The measuring principle of the method has been proposed by theoretical analysis and has been verified by experiment and numerical simulation. The relationship between the average axial velocity ($\overline{v_z}$) and the static differential pressure between the pipe wall and pipe center of a cross section downstream of a swirler (ΔP) was especially emphasized. It shows that $\overline{v_z}$ is in direct proportion to $\sqrt{\Delta P}$ when certain fluid flows through a specific swirler. For a certain cross section downstream of a swirler, there exist two places with different radius and different corresponding tangential average velocities, whereas with the same values of tangential average acceleration. The RSM was used as the turbulence model in simulation. Compared with the experiments, the relative errors of the flow coefficient (α) are 1.25% and 4.74% for the cross sections of $2.7D$ and $11.8D$ downstream of the swirler, respectively, which are within the scope of acceptable. In addition, we conducted the numerical simulation work of the influences of swirler on α. The results show that the bigger the angle between each slice and pipe cross section and less numbers of slices will achieve less ΔP and bigger α. This method may provide an alternative way to mass flow measurement which is easier to be standardized than other nonstandard differential pressure flowmeters.

1. Introduction

The differential pressure flowmeter is deserved to be the first class of flowmeter due to its largest share in the area of flow measurement, long-term development, wide application range and increasing demand. At present, the commonly utilized differential pressure flowmeter can be divided into two categories: the standard type and nonstandard type. The standard type consist of orifice, nozzle, and venturi tube, while the nonstandard type include the slotted orifice plate, multi-plate, 1/4 orifice, the annular orifice, wedge, V-type inner cone, and averaging pitot tube, etc. Of all the differential pressure flowmeters, the standard orifice has the advantages of simple structure, mature application technology and standardization. Therefore, it is most widely used over other differential pressure flowmeters. However, the shortages of large permanent pressure loss, strict requirements of pipeline, and low accuracy caused by passivation of the edge also constrained its utilization. In addition, the measured fluid is required to be parallel to the pipe axis and not to be in rotational flow when fluid flows through the orifice. Compared with the orifice, the nozzle and venturi tube have more complicated structures and higher costs although the pressure loss is 30–50% lower under the same flowrate and aperture ratio. However, the requirement of long upstream pipe is the common characteristic of the three standard types of differential pressure flowmeters [1].

Either for the various kinds of orifice plates, nozzle, venturi tube, or for the wedge flowmeter, the averaging pitot tube and the cone flowmeter, the measuring principle is based on the axial pressure drop due to the reduction of the pipe cross section, which causing the vast majority of pressure loss. In contrast, Elbow flowmeter, one kind of the nonstandard differential pressure flowmeters, uses the lateral pressure difference between the outside and inside of the elbow to measure flowrate. It has the advantages of low cost, simple structure, easy installation and suitable for dirty fluids and is used in some special conditions such as the nuclear industrial systems, irregular pipe and the blast-furnace tuyere of the metallurgical industry. However, it is vulnerable to the interference of secondary flow and the flow coefficient is very sensitive to the parameters of structure. Therefore, the accuracy of elbow flowmeter is restricted and it is difficult to be standardized [2–4].

The swirler arranged in the pipe not only can enhance heat transfer, keep the particle in a suspended state to avoid precipitation [5], serve as a flow conditioner [6–8], it also can be used in various engineering applications such as heat exchanger, air conditioning, chemical reactors and refrigeration systems [9]. Inspired by the elbow flowmeter, we attempted to study the effect of swirl motion on the flow measurement. In this paper, we proposed a new method of mass flow measurement

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based on swirl motion motivated by specific shapes of swirlers. The cross section area of the pipe is little reduced when the thickness of swirlers arranged in the pipe was no more than 0.5 mm. Compared with most other differential pressure flowmeters, the new method may have the following advantages: (i) it causes less pressure drop as elbow flowmeters [2] and requires short straight pipe as the cone flowmeter [10,11].; (ii) it can not only measure the flowrate based on the radial pressure drop, but also promote the heat transfer effect because the stationary swirler has been proved to disturb the flow fluid and can strengthen the heat transfer efficiency [12,13]; (iii) the swirler, which can isolate multiphase flow into annular flow under certain velocity ranges, has favorable potential to multiphase measurement. In the previous study [14,15], we presented a phase-isolation method which can isolate phases to a respective space within a transmission pipe by applying various kinds of lateral forces to two-phase mixture (such as the swirler). After the phase-isolation being completed, two phases will flow concurrently and present the clear interface between them (similar to annular flow) which will greatly benefit for the separation of two-phase flow and for the measurement of two-phase flow parameters by a variety of methods. The swirler is one of the methods to achieve the precondition of phase-isolation, i.e., to rectify different patterns of multiphase flows to regular cocurrent flow which has a clear interface between each phase. The further research related to multiphase flow measurement by using the swirler is carried on in our ongoing research; (iv) owing to the swirler is the prominent factor on the measurement error, this method is easier to be standardized than other nonstandard differential pressure flowmeters.

The present paper is structured as follows: the hydrodynamics and the operating principle of the measuring method are outlined in Section 2. The experimental study used to verify the hypothesis and uncertainty analysis are presented in Section 3. In Section 4 and Section 5, the numerical simulation work is prepared and the validations to the theoretical analysis and experimental study are particularly analyzed. Moreover, the effect of swirler on the flow measurement is studied in detail. Section 6 wraps up the whole paper with a number of conclusions.

2. Operating principle

As shown in Fig. 1, a swirler is located in the pipe and two pressure-tapping tubes are arranged at the downstream of it. The tubes are used to measure the static pressures between the pipe wall and pipe center. The velocity distribution changes dramatically between the upstream and the downstream of the swirler. At the upstream of the swirler, the flow line is straight which is parallel to the pipe wall and the velocity distribution of the longitudinal section is in a parabola form. However, at the downstream of the swirler, the flow line changes into a spiral form which is symmetric with the pipe central axis [16].

The swirler exerts a forced centrifugal force on the fluid and the flow direction changes when the fluid flows through the swirler, producing differential pressure between the pipe wall and pipe center of a certain cross section. The differential pressure can be measured by a differential pressure transmitter which connects two pressure-tapping tubes arranged at pipe center and the pipe wall, respectively. The magnitude of the centrifugal force is influenced not only by the Reynold numbers (*Re*), but by the style of the swirler and the distance away from the swirler.

An element, which is represented by a tangential velocity v_τ and a curved path of radius r, was taken from a certain cross section downstream of the swirler. The element has a linear dimension dr on the cross section and an area of dA normal to the cross section. The mass of this fluid element is $\rho dAdr$, and the normal component of acceleration is v_τ^2/r. Thus the centripetal force acting on the element toward the center of curvature is $\rho dAdrv_\tau^2/r$. Since the radius increases from r to $r + dr$, the pressure will change from p to $p + dp$. Therefore, the resultant force in the direction of the center of the curvature is $dpdA$. Equating these two forces and dividing by dA [17], we can get:

$$dp = \rho\frac{v_\tau^2}{r}dr, \tag{1}$$

where ρ is the fluid density and r is the distance away from the pipe center to the element; v_τ represents the tangential velocity of the element.

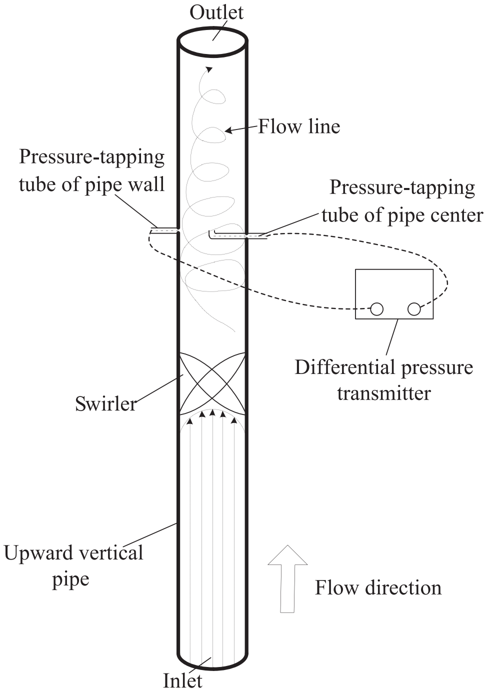

Fig. 1. The schematic diagram of the measuring principle based on swirl motion.

According to the characteristics of the tangential velocity along the radial of the rotating fluid, the flow area of a certain cross section can be divided into the forced vortex area (also called the solid body rotation area) and the free vortex area (also called the potential vortex area), as shown in Fig. 2. According to [18], there should exist a cylindrical surface (whose radius is r_0) with the biggest tangential velocity. The circle area ($r \le r_0$) is called the forced vortex area while the annulus area ($r>r_0$) is called the free vortex area. According to the mean value theorem of integrals, there is always existing at least one radius r^*, at which position the tangential velocity can represent the mean tangential velocity of the cross section.

Separating the variables and integrating between 0 and R of Eq. (1):

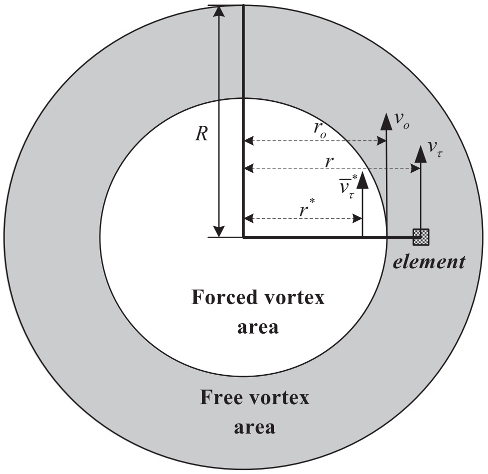

Fig. 2. The schematic diagram of a certain element with a tangential velocity v_τ and a curved path of radius r.