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Experimental optimization for dual support structures cone flow meters based on cone wake flow field characteristics

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ABSTRACT

Currently, poor safety and processing repeatability are two primary problems that restrict the development of cone flow meters. Cone flow meters with upstream and downstream support structures can improve the safety performance and the level of processing repeatability. For a dual support structures cone flow meter, known as a DSSC, the selection of the downstream support position can greatly affect the discharge coefficient and linearity error below a certain range ratio. Through computational fluid dynamics (CFD) simulation research, the conclusion can be drawn that there exists a large scale vortex ring in the wake field of the cone and that the distribution of the vortex is related to the parameters of the cone. Based on the characteristics of the cone vortex ring, optimizing experiments examining downstream pressure tapping and support structure positions have been designed. The downstream pressure tapping and support positions were obtained for DSSCs with DN100 and β values between 0.45 and 0.65. A set of DSSCs was manufactured according to the conclusions of the optimizing experiments, and performance tests were conducted. The DSSC prototypes had β values ranging from 0.45 to 0.65 and diameters of 50 mm, 100 mm, and 200 mm, respectively. Test results indicate that the discharge coefficient linearity error of DSSC flow meters is smaller than that of V-Cone flow meters. The discharge coefficient uncertainty of DSSCs with different inner tube diameters is 1.27%. The relative discharge coefficient uncertainty of prototypes because of machining consistency is 0.68%.

1. Introduction

As a type of differential pressure device, cone flow meters share common principles with other differential pressure flow meters. Cone flow meters have many advantages, such as lower permanent pressure loss [1], more resistance to dirt [2], better measurement performance [3] and shorter upstream and downstream straight length requirement [4].

Many scholars have researched multiple aspects of cone flow meters since the 1980s. Singh et al. [5] determined that the coefficients of the cone flow meters were affected by the geometrical factors of the cone but have nothing to do with inlet Reynolds number. Ifft et al. [6,7] found, through experimental research, that upstream blocking fittings have little effect on the discharge coefficient of cone flow meters.

Singh et al. [5,8] and Sapra et al. [9] studied the effect of upstream slide valve and elbow fittings on the cone wake flow field by using CFD methods. The cone flow meters have small linearity error and excellent repeatability over a large inlet Reynolds range, which means that the cone wake flow field follows certain laws.

Currently, the problems restricting the development of Cone DP flow meters include poor processing repeatability, low safety performance and lack of a theoretical basis for designing cone flow meters with different inner tube diameters and the same β value. As a support structure the cantilever beam is necessary to ensure the cone flow meter's safety, especially when the cone flow meter works under high flow rate, high pressure, or transient flow (slug flow or water hammer) conditions. The upstream and downstream support structures added to cone flow meters can not only improve the safety performance but also solve the problem of poor repeatability. Adding the dual support structures is helpful in easing Chinese petrochemical industry safety performance concerns over the cone flow meter. The definition of processing repeatability is the mechanical structure's repeatability over multiple cone flow meters manufactured by different manufacturers in accordance with unified regulations and technical standards.

Poor processing repeatability is the primary reason for the large coefficient uncertainty of cone flow meters [10]. The discharge coefficient uncertainty of cone flow meters manufactured in

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Nomenclature

C_d Discharge coefficient
C_{dimax} The maximum discharge coefficient in one calibration
C_{dimin} The minimum discharge coefficient in one calibration
C_{ij} Convection, $=\frac{\partial}{\partial x_k}\left(\rho u_k \overline{u_i' u_j'}\right)$
D Pipe diameter, mm
d Maximum cone diameter, mm
D_{ij}^T Turbulent diffusion, $= \overline{p(\delta_{kj})u_i'} + \delta_{ik}u_j'$
D_{ij}^L Molecular diffusion, $=\frac{\partial}{\partial x_k}\left[\mu\left(\frac{\partial}{\partial x_k}\overline{u_i' u_j'}\right)\right]$
E Internal energy losses, N m
E' $E/\rho g$
F_{ij} Production by system rotation $= -2\rho\Omega_k\left(\overline{u_j' u_m'}\epsilon_{ikm} + \overline{u_i' u_m'}\epsilon_{jkm}\right)$
G_{ij} Buoyancy production $= -2\rho\beta\left(\overline{u_j'\theta}g_i + \overline{u_i'\theta}g_j\right)$
g Local acceleration of gravity, 9.8 m/s^2
I Turbulence intensity $= 0.16(Re)^{-1/8}$
k Turbulence kinetic energy, N m
ks The roughness, mm
p_1 High pressure, Pa
p_2 High pressure, Pa
P_{ij} Stress production $= -2\rho\left(\overline{u_i' u_k'}\frac{\partial u_j}{\partial x_k} + \overline{u_j' u_k'}\frac{\partial u_i}{\partial x_k}\right)$
q_v Volume flow rate, m^2/s
$\rightharpoonup r$ Vector diameter between observation point and center of rotation
Re Reynolds number
S_{ij} The mean strain rate $= \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$
T The kinetic energy variation
$\bar{u}$ Mean velocity
u' Velocity perturbation
u_* Friction velocity
$\rightharpoonup v$ Velocity vector
v_1, v_2 Two particle velocity in the same streamline, m/s
Y Expansionability factor, for water
y The distance to the nearest wall
y_p Half height of the first layer of the near wall grid
z_1, z_2 Height of two particle in the same streamline, m
β Equivalent cone diameter ratio $= \frac{\sqrt{D^2-d^2}}{D}$
Δp Differential pressure $= p_1 - p_2$
δ_{ij} Kronecker delta
δ_l Linearity error of discharge coefficient $= \frac{C_{dimax}-C_{dimin}}{C_{dimax}+C_{dimin}} \times 100\%$
ϵ The dissipation rate
ϵ_{ij} Dissipation, $= -2\mu\overline{\frac{\partial u_i'}{\partial x_k}\frac{\partial u_j'}{\partial x_k}}$
λ Friction factor
μ Dynamic viscosity
ρ Density, kg/m^3
τ_w Wall shear stress
ϕ_{ij} Pressure strain, $= \overline{p(\frac{\partial u_i'}{\partial x_j} + \frac{\partial u_j'}{\partial x_i})}$
$\vec{\omega}$ Vorticity

accordance with unified regulations and technical standards, known as the discharge coefficient uncertainty, is the evaluation index for processing repeatability. A smaller discharge coefficient uncertainty corresponds to better processing repeatability. A structure with small discharge coefficient uncertainty can easily draft an international cone flow meter standard. In the cone flow meter international standard drafting and revision process, the dual support structure cone flow meter is a good choice.

Adding the supporting struts brings problems of how to determine the position of the downstream support and pressure taps with shorter tube length and higher measurement performance. Considerable experimental data are needed to select the locations and to design cone flow meters with different inner tube diameters.

Many documents indicated that the cone wake flow field determines the performance of the cone flow meter [4,5,10]. The efficiency issue in the cone flow meter can be solved if we can use CFD to simulate the cone wake flow field and guide the experimental design.

2. Introduction of cone flow meter

2.1. Structure of the cone flow meter

The V-Cone structure cone flow meter and cone flow meter with double support structure are shown in Fig. 1(a) and (b), respectively. On the precondition that the influence of the beam can be ignored, the V-Cone structure flow meter is axis-symmetric; however, the dual support structures cone flow meter is not axisymmetric because of the support structures.

As shown in Fig. 1, the upstream pressure p_1 is connected to the high pressure of the differential pressure transmitter and the downstream pressure p_2 is connected to the low pressure of the differential pressure transmitter. The differential pressure Δp can be read from the differential pressure transmitter in the experimental process.

For the V-Cone structure cone flow meter the downstream tapping port is located at the back of the cone element as shown in Fig. 1(a). The downstream tapping ports of dual support structures cone flow meter are shown in Fig. 1(b), and the three holes are uniformly distributed along the pressure guiding pipe. The downstream pressure p_2 is the average value of the pressure values in the three holes. The downstream pressure p_2 was transmitted to the low pressure port of the differential pressure transmitter by the pressure guiding pipe.

Similar to other formulas for differential pressure (DP) flow meters, the volume flow of the cone DP flow meter can be calculated by Formula (1) . For the uncompressible fluid with Y equal to 1, the discharge coefficient, C_d, can be calculated by Formula (2) transformed from Formula (1).

$$q_v = \frac{C_d}{\sqrt{1-\beta^4}} Y \frac{\pi D^2 \beta^2}{4}\sqrt{\frac{2\Delta p}{\rho}} \tag{1}$$

$$C_d = \frac{4q_v\sqrt{1-\beta^4}}{\pi D^2\beta^2\sqrt{2\Delta p/\rho}} \tag{2}$$

2.2. Relationship between cone flow meter's performance and velocity distribution of the cone wake flow field

Formula (1) is deduced using the Bernoulli equation as shown in Formula (3), which is effective for the same streamline flow particle.

$$\frac{v_1^2}{2g} + z_1 + \frac{p_1}{\rho g} = \frac{v_2^2}{2g} + z_2 + \frac{p_2}{\rho g} + E \tag{3}$$