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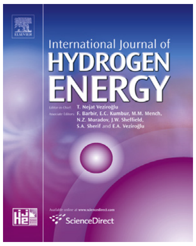

Simulation and performance analysis of the perforated plate flowmeter for liquid hydrogen

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ARTICLE INFO

Article history:
Received 3 April 2016
Received in revised form
1 September 2016
Accepted 7 September 2016
Available online xxx

Keywords:
Liquid hydrogen
Perforated plate
Flowmeter

ABSTRACT

The flow rate measurement of the liquid hydrogen (LH_2) is of significance for the effective and safe operation of the systems dealing with massive liquid hydrogen, e.g., hydrogen stations and hydrogen fuelled space rockets. A perforated plate flowmeter is one of the effective devices for measuring flow rate accurately. In order to explore the optimal structure of a perforated plate flowmeter, the perforated plates with different perforating form, thickness, equivalent diameter ratio and hole diameter are numerically investigated with the help of ANSYS Fluent, mainly focusing on discharge coefficient C and pressure loss coefficient ζ, when applied to liquid hydrogen. The realizable k-ε model is adopted to describe the turbulence. Schnerr-Sauer cavitation model is employed for the case of cavitation to investigate the cavitation effect on the performance of the perforated plate. The simulation results reveal that the perforated plate with a larger center hole diameter is more suitable for measuring liquid hydrogen than that with the equal-aperture holes, especially for the case of the perforating form matching the turbulent velocity distribution in the circular tube. The equivalent diameter ratio is the dominant factor influencing the liquid hydrogen cavitation, and the reasonable increases of plate thickness and equivalent diameter ratio help to improve the performance of perforated plates applied to liquid hydrogen.

Introduction

Hydrogen is an energy-efficient, low-polluting and renewable fuel, which is considered to be one of the most promising alternatives for fossil fuels [1,2]. Moreover, it's also widely used in aerospace industry applications [3]. Liquid hydrogen (LH_2) is an efficient and economically effective solution for hydrogen transportation and storage [2], especially the rising demand of cryogenic fluids along with the rapid development of space technology proposes higher requirement in the measuring technique for cryogenic fluids [3]. Compared with the standard orifice flowmeter, a perforated plate flowmeter with multiple holes distributed on a plate inherits its advantages, such as the simplicity in design and the absence of moving parts, and it also occupies the merits of better flow balance,

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http://dx.doi.org/10.1016/j.ijhydene.2016.09.072
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less turbulence, weaker dead flow effect and lower energy loss, leading to the promising application potential in the field of flow measurement [4,5], especially for cryogenic fluids. The studies on the characteristics of perforated plates have attracted much attention in the past decades. Two performance parameters, i.e., the discharge coefficient and the pressure loss coefficient, denoting the ratio of actual flow rate to theoretical flow rate and the permanent pressure loss, respectively [6], are mainly concerned when the perforated plate is used as a flowmeter.

The perforated plate acts as the throttling device of a perforated plate flowmeter. Many geometric parameters, such as the total opening area, hole diameter, numbers and hole distribution, will affect its performance. Many researches about the effect of geometric parameters on the discharge coefficient and the pressure loss coefficient have been done. As early as to 1957, Kolodzie and Van Winkle [7] experimentally studied the discharge coefficient of perforated plate with equal-aperture holes using air, and correlated the discharge coefficient with the geometric parameters, such as hole diameter, hole pitch and plate thickness. Smith and Van Winkle [8] expanded the Reynolds number range of the correlation established by Kolodzie and Van Winkle from 400 to 20000. The effects of plate thickness, porosity ratio and hole distribution on the discharge coefficient were assessed experimentally with water by Huang et al. [9]. The results indicated that the discharge coefficient rose with the increasing plate thickness before approaching a limit. Erdal [10] performed a numerical study on the parameters such as overall porosity, graded porosity and wetted perimeter, which may affect the dissipation characteristics of the perforate plate. It seemed that the graded porosity was responsible for quickly obtaining a velocity profile close to being fully developed. Zhao et al. [11] experimentally investigated the influences of the total hole number, equivalent diameter ratio and orifice distribution density on the dissipation characteristics of several perforated plates with water, and found that the equivalent diameter ratio was a dominant factor. Moreover, an empirical formula for estimating the pressure loss was provided. Similar investigations were reported by Malavasi et al. [12,13] and Maynes et al. [14], where the dependence of the pressure loss coefficient on the Reynolds number and geometric parameters was studied. The effects of thickness to diameter ratio, wall roughness and plate inclination angle on pressure loss of perforated plates were numerically studied by Guo et al. [15] with dry air, and the results showed that the pressure loss coefficient might rise when the inclination angle was increased above 30°.

Although a lot of work concerning the effect of geometric parameters on the performance of perforated plates has been done, it should be noted that the geometric parameters are not yet optimized systematically. Moreover, the perforated plates investigated are mainly the plates with equal-aperture holes. The case with a larger hole at the center which may perform better according to the velocity distribution in the pipe has seldom been studied. In addition, the studies are merely related to common fluids around ambient temperature, such as water and air. Little effort was made on the cases of cryogenic fluids, which are widely used in the fields of air separation industry, aerospace application, etc.

In this work, the effect of geometric parameters on the performance of perforated plates with liquid hydrogen (LH_2) will be numerically investigated with the help of ANSYS Fluent. Our emphasis will be devoted on the discharge coefficient and the pressure loss coefficient. It can be found that a perforated plate with a larger hole at the center do achieve better performance than that with equal-aperture holes, especially for the case of the perforating form matching the turbulent velocity distribution in the circular tube.

Working principle of perforated plate flowmeter

As a differential pressure flowmeter, the volumetric flow rate q_v can be obtained by measuring the throttle pressure difference Δp across the perforated plate based on Bernoulli principle [16], which can be given as:

$$q_v = \frac{C}{\sqrt{1-\beta^4}}\beta^2 A\sqrt{\frac{2\Delta p}{\rho}} \tag{1}$$

where C is the discharge coefficient, A is the pipe cross-sectional area, ρ is the fluid density, and $\beta = (A_h/A)^{1/2}$ is the equivalent diameter ratio (where A_h denotes the total opening area of perforated plate). In our simulation, the value of C is calculated according to Eq. (1) after the throttle pressure difference Δp was acquired with corner tappings [17].

The local resistance of perforated plate can lead to permanent pressure loss $\Delta\varpi$ in the process of fluid flow measurement, which can be characterized by the pressure loss coefficient ζ as follows [17]:

$$\zeta = \frac{\Delta\varpi}{\frac{1}{2}\rho u^2} \tag{2}$$

where u is the bulk mean fluid velocity in the pipe. In our simulation, $\Delta\varpi$ is the wall pressure difference between $1D$ (D is the inner diameter of pipe) upstream side and $6D$ downstream side of the perforated plate [17].

Numerical model and validation

Computational domain and the structure of perforated plate

The three-dimensional schematic layout of the computation domain and the perforated plate are shown in Fig. 1. According to Singh et al. [18,19], the disturbance caused by various openings of the gate valve and imposed swirl had no significant effect on the discharge coefficient of the cone flowmeter when the disturbance was over $5D$ upstream from the cone. In this study, the length $10D$ upstream and $15D$ downstream of the perforated plate are chosen to attain reliable prediction of the discharge coefficient and the pressure loss coefficient.

Table 1 lists the structural parameters of the perforated plates. The inner diameter of the pipe is $D = 25$ mm. All the perforated plates have the same hole number $N = 7$, among which one hole locates at the center with the diameter of d_0, and six holes with the diameter of d_1 uniformly locate on the circle of D_1. β is the equivalent diameter ratio, and t is the thickness of the perforated plate. In the simulation, the inlet

Please cite this article in press as: Jin T, et al., Simulation and performance analysis of the perforated plate flowmeter for liquid hydrogen, International Journal of Hydrogen Energy (2016), http://dx.doi.org/10.1016/j.ijhydene.2016.09.072