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Design and optimization of a novel flowmeter for liquid hydrogen

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ABSTRACT

The wide spreading hydrogen energy requires accurate flow measurement. Constriction type flowmeters could be a favorable candidate for liquid hydrogen. However, their permanent pressure losses and installation length could significantly increase the manufacturing, installation, metering, maintenance, and replacement cost. The high permanent pressure losses may also cause cavitation. The present research introduces a novel constriction type flowmeter with an optimized flow profile. Numerical simulation, as well as multidimensional and multi-objective optimization, was utilized in order to minimize the flowmeter's loss coefficient and the required installation length. The applied optimization technique results in significant improvements of the flowmeter design and performance. The proposed flowmeter is shorter than the standard Venturi nozzle by 67.2% and its loss coefficient is lower by up to 10.6%. It measures the flow rate of liquid hydrogen with up to 25.5% higher discharge coefficient and 83.7% lower loss coefficient compared to a corresponding perforated plate flowmeter. Cavitation was not detected inside the proposed flowmeter up to a Reynolds number of 2.2×10^6. The present investigation shows that the proposed flowmeter is very promising for liquid hydrogen measurement.

Introduction

The clean and renewable energy from hydrogen is nowadays considered a promising alternative to the fossil fuels [1,2]. Accurate flow measurement is a prerequisite for the transport and storage of the hydrogen in its liquid or gaseous states [3,4]. Therefore, attempts have been made in order to investigate the performance of flowmeters handling hydrogen. Jin et al. [5] numerically simulated the flow of liquid hydrogen through different perforated plates. They reported that a perforated plate with a larger center hole diameter is more suitable for measuring the flow of liquid hydrogen than that with equal-aperture holes. Chen and Wu [6] investigated the inherent error of the ultrasonic flowmeter in the non-ideal hydrogen gas flow. They implemented the Computational Fluid Dynamics CFD in order to simulate the hydrogen flow downstream of a single right bend and an orifice plate at different Reynolds numbers. The numerical investigation of Chen and Wu [6] showed that the measurement accuracy decreases when the flowmeter position is closer to the disturbance sources. Morioka et al. [7] implemented critical nozzles installed in a multi-nozzle calibrator for the estimation of a high-pressure hydrogen gas flow. Yan et al. [8] utilized a vortex flowmeter to measure the real-time volumetric flow rate of hydrogen gas.

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Nomenclature

C_D	discharge coefficient (-)
D	pipe diameter (m)
d_{th}	throat diameter (m)
K	loss coefficient (-)
$\dot{m}$	mass flow rate (kg/s)
Δp	pressure difference (Pa)
Δp_o	total pressure difference (Pa)
p	static pressure (Pa)
p_v	saturated vapor pressure (Pa)
R	pipe radius (m)
Re	pipe Reynolds number (-)
r	flowmeter radius (m)
R^*	normalized radius (-)
T	temperature (K)
v	pipe velocity (m/s)
X^*	normalized length (-)
x	length (m)
Greek	
β	diameter ratio (-)
ε	expansion coefficient (-)
θ	included angle (°)
ρ	density (kg/m^3)
μ	viscosity (Pa s)
Subscript	
i	inlet
o	outlet
th	throat
v	valve

Constriction type flowmeters are favorable for severe flow conditions due to the absence of moving parts and the simplicity of design, manufacturing, installation, and replacement. Moreover, a wide variety of materials can be used in their manufacturing. This makes them applicable for erosive and corrosive fluids as well as other normal fluids. Constriction type flowmeters can also be used either for steady or unsteady flow conditions [e.g., 9, 10] as well as for dry and wet gases. Many authors [e.g., 11–17] have investigated the use of Venturi meters for the measurement of wet gases due to their popularity in petroleum, chemical and metallurgical industries. Authors [e.g., 18, 19] have also considered the use of orifice meters for the measurement of two-phase flow. Despite their numerous advantages, constriction type flowmeters produce considerable permanent pressure losses and they could be very sensitive to inlet flow distortions. The permanent pressure losses increase the energy consumption due to fluid metering and hence the pumping cost and the final product price. The high-pressure losses may also cause cavitation while measuring the flow rate of the liquid hydrogen. Extensive numerical investigations of the complex cavitating flow of liquid hydrogen were presented in Refs. [20–22]. Venturi meters and flow nozzles have significantly lower permanent pressure losses compared to the standard orifice meters. However, the space allocated for installing them could be very high for pipelines with large pipe diameter. This significantly increases their manufacturing, installation, repair, and replacement cost. Therefore, many attempts have been made to improve the design, performance, and accuracy of the different constriction type flowmeters. Shaaban [23] placed a ring downstream a standard orifice meter in order to reduce its permanent pressure losses by up to 33.5%. In another research work, Shaaban [24] improved the performance of a perforated plate meter by optimizing its hole geometry. Furuichi and Terao [25] examined the static pressure measurement error at the throat tap of a flow nozzle for a wide range of Reynolds numbers. They reported that the error of the differential pressure measurement is clearly influenced by the diameter of the tap and the viscosity of the working fluid. Weissenbrunner et al. [26] employed a standard Venturi nozzle for flow homogenization in a high-temperature water flow test facility. They reported that the uncertainties of the flow measurement were substantially reduced by placing an ultrasonic flowmeter or an electromagnetic flowmeter in the narrow part of a Venturi nozzle. Many authors [e.g., 27–30] have investigated the use of flow conditioners and swirl generators in order to reduce the required installation length and the sensitivity to incoming flow distortions of the standard orifice meters. However, these flow conditioners and swirl generators produce additional permanent pressure losses. Therefore, slotted and perforated plates were extensively investigated [e.g., 31–50] as a replacement of the standard orifice meters. This is because perforated plates are less sensitive to inlet flow distortions and may have lower pressure losses compared to the standard orifice meters [32,33,46]. They also have more stable discharge coefficient and smaller critical Reynolds number compared to the standard orifice meters [40,44]. Moreover, the effect of Reynolds number Re on the pressure losses of the perforated plates is not significant for some geometries [35]. However, Gan and Riffat [34] showed that the permanent pressure losses of a perforated plate with an area ratio of 0.5 in a square duct is higher than that of an orifice meter. The simulation results of Shaaban [24] also show higher permanent pressure losses of the perforated plate compared to the standard orifice meter. The experimental investigation of Ma et al. [41] demonstrated that the permanent pressure losses of the perforated plate and the standard orifice are close to each other. Due to the high permanent pressure losses of the perforated plates, Jin et al. [5] recommended the use of a large equivalent diameter ratio while measuring the flow of liquid hydrogen in order to avoid cavitation. This significantly affects the pressure difference across the perforated plate and hence the measurement accuracy.

The above discussion highlights the need to design a flowmeter that combines the advantages of the different flowmeters and reduces their disadvantages. While the small size perforated plates and standard orifice meters have high permanent pressure losses, the Venturi nozzles and the standard flow nozzles have significantly lower permanent pressure losses and higher installation length. Therefore, the present research work introduces a constriction type flowmeter that compromises the advantages of these different designs. The objective of the current research work is to minimize the required installation length and the permanent pressure losses due to fluid metering in industrial facilities. Flow measurement of liquid hydrogen using the proposed flowmeter is considered in the present work.

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