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Experimental research on pressure drop of wet gas flow in Venturi

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ABSTRACT

In the research of wet gas, the pressure drop is an important parameter in the design of the pipelines and the selection of the wet gas flow meters. Although an algorithm is described in the ISO11583 technical report that used to predict pressure loss ratio (PLR), the exploration of this method still need to be studied under the different flow conditions. A new correlation of pressure drop is proposed based on the important influence factors. Dimensional analysis is adopted to find the significant dimensionless parameters to establish the correlation of PLR, such as Lockhart–Martinelli parameter and gas Froude number. The experiment of the Venturi tube has been carried out in the wet gas flow loop of Tianjin University. In the test, the static pressure of pipe ranged from 0.2 to 1.2 MPa and the superficial gas velocity ranged from 5 to 10 m/s. Results implied that the correlation of ISO11583 gave an unsatisfactory prediction of PLR. In order to improve the accuracy, the new correlation in this work was based on the dimensional analysis and experimental data. Finally, the average relative error of this correlation is about 3.85% and the root mean square error is about 2.5%.

1. Introduction

As a special branch of gas–liquid two phase flow, wet gas is ubiquitous in the industrial fields of power, chemical, nuclear energy, refrigeration, petroleum, metallurgy and so on. In the ISO 11583 technical report [1], wet gas is defined as a two-phase flow of gas and liquid in which the flowing fluid mixture consists of gas in the region of 95% volume fraction or more.

There are mainly two approaches for the prediction of pressure drop: empirical correlations [2–6] and phenomenological correlations [7–11]. Despite numerous theoretical and experimental investigations, there is no general model that can be used to predict two-phase pressure drops reliably. A reason for this is that two-phase flow includes all the complexities of single-phase like non-linearities, transition to turbulence and instabilities plus additional two-phase characteristics like motion and deformation of the interface, non-equilibrium effects and interactions between phases [12]. Nevertheless, the accurate prediction of pressure drop is important for the design of pipelines and the selection of the power cycling equipment, which is significant for operating the system safety, efficiency and economy. Besides these, the pressure drop is a major performance index in the design of Venturi tube. The research on the pressure drop of the Venturi tube under the condition of wet gas flowing is rarely reported. Reader-Harris [13] stated that the pressure drop increase obviously because of the liquid phase, and there was a relationship between the pressure drop and liquid cut. In the correlation of Reader-Harris, the gas liquid density ratio ranged from 0.02 to 0.09, namely the system pressure scope was about 1.6–7.8 MPa if the fluid media were air and water. However, if this correlation is used beyond this condition, the forecast accuracy cannot be guaranteed.

The pressure drop of wet gas flow through Venturi tube is sophisticated and influenced by a number of parameters. As a method for the analysis of complicated phenomenon, dimensional analysis is broadly employed in the research on wet gas. Dimensional analysis played an important role in the wet gas measurement model of Venturi tube [14] and V-cone [15]. Yuan et al. [16] utilized the differential pressure ratio, gas liquid density ratio, X_{LM} and Fr_g in the correlation of wet gas measurement. The relative errors of laboratory test were less than ±1% and the on-site test also gave a satisfactory results. Based on the above achievements, dimension analysis is adopted in this research to investigate the wet gas pressure drop in the Venturi tube.

This work applies the dimensional analysis to establish the correlation under the static pressure of 0.2–1.2 MPa. The inner diameter and beta ratio of the Venturi tube in this research is 50 mm and 0.4 respectively. Firstly, the dimensional analysis is used to find out the important parameters in the wet gas flow through

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Nomenclature

English symbols

A	cross-sectional area of pipeline (m^2)
c	discharge coefficient of Venturi (–)
C	defined in Table 2 (–)
d	diameter of throat (m)
D	diameter of pipeline (m)
DR	gas liquid density ratio (–)
Fr_g	gas Froude number (–)
GMF	gas mass fraction (%)
GVF	gas volume fraction (%)
g	acceleration of gravity (m/s^2)
H	defined in Eq. (7) (–)
LVF	liquid volume fraction (%)
m_g	gas mass flow rate (kg/s)
m_l	liquid mass flow rate (kg/s)
P	system pressure (Pa)
PLR	pressure loss ratio (–)
Re_{sg}	superficial gas Reynolds number (–)
RMSE	root-mean-square error (–)
U_{sg}	superficial gas flow velocity (m/s)
X_{LM}	Lockhart–Martinelli parameter (–)
Y	defined in Eq. (6) (–)
ΔP	differential pressure (Pa)
Δw	permanent pressure drop (Pa)

Greek symbols

β	beta ratio of Venturi (–)
ε	expansion factor (–)
ρ_g	gas density (kg/m^3)
ρ_l	liquid density (kg/m^3)
μ_g	kinetic viscosity of gas (Pa s)
μ_l	kinetic viscosity of liquid (Pa s)

the Venturi tube. And then, the correlation of PLR is fitted by the experimental data and the comparison between the new correlation and the ISO 11583 is presented. The final results indicate that the new correlation is a more accurate one.

2. Dimensional analysis of wet gas pressure drop

In 1822, the concept of dimension was extended from geometry to physics by J.B.J. Fourier. Pi theorem, the core of dimensional analysis, has become the criterion of the model experiment and the numerical simulation which is widely applied nowadays [17].

The prototype is shown in Fig. 1. The inner diameter of this Venturi is 50 mm, and the beta ratio is 0.4. There are three static pressure tappings: the first one is placed around 0.5D upstream of the beginning of the convergent section. The second one is mounted around 0.5d downstream of the beginning of the throat. The third one is fixed around 6D downstream of the end of the divergent section.

According to the procedure of dimensional analysis, all of the parameters in the wet gas flow and their dimensions are listed in Table 1. The mass (M), length (L) and time (T) are the basic dimensions.

The length of the convergent, divergent and throat sections are determined with the given inner diameter for a standard Venturi tube. Therefore in the dimensional analysis, the geometric parameters about the structure of the Venturi tube are neglected.

The number of quantities is $n = 11$, and the number of basic dimensions is $m = 3$. Select three basic quantities $\rho_g(m/l^3)$, $m_g(m/t)$, $D(l)$. The number of dimensionless groups equals 8. It should be noted that variables $\Pi_1, \Pi_2, \ldots, \Pi_8$ are mutually independent. Any of the variables Π_i ($i = 1,2,\ldots,8$) can be replaced by combining them with other variables Π_j ($j \neq i$). Thus, to establish the over reading correlation, 10 dimensionless groups are combined appropriately to derive commonly used parameters in over reading correlations such as DR, Fr_g and X_{LM}. The dimensionless groups before and after the transformation are listed in Table 2.

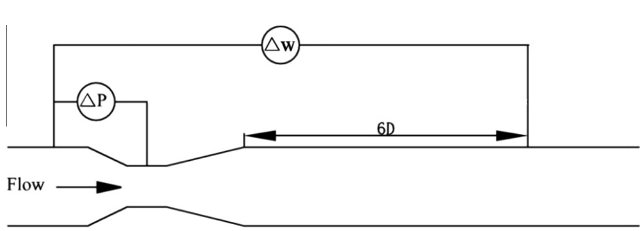

Fig. 1. Structure of the Venturi tube, D = 50 mm, β = 0.4.

Among the variables, the flow rate calculation formula of Venturi tube (Eq. (1)) is used in the derivation of Π_1.

$$m_g = \frac{c\varepsilon\pi D^2\beta^2}{4\sqrt{1-\beta^4}}\sqrt{2\rho_g\Delta p} \tag{1}$$

Thus, Eq. (2) is obtained by the Pi theorem.

$$\mathrm{PLR} = \frac{\Delta\omega}{\Delta p} = f\left(C, X_{LM}, \frac{\mu_l}{\mu_g}, Re_{sg}, \frac{\rho_l}{\rho_g}, Fr_g, \frac{P}{\rho_g U_{sg}^2}\right) \tag{2}$$

C depends on the discharge coefficient, expansion coefficient and beta ratio of the Venturi tube, thus C is approximately constant in this research for the given Venturi. Due to the constant viscosities of gas and liquid phase under the experiment conditions, the parameters such as $\frac{\mu_l}{\mu_g}$ and Re_{sg} are also ignored. In summary, the results of dimensional analysis are simplified to Eq. (3).

$$\mathrm{PLR} = \frac{\Delta\omega}{\Delta p} = f_1\left(X_{LM}, \frac{\rho_l}{\rho_g}, Fr_g, \frac{P}{\rho_g u_{sg}^2}\right) \tag{3}$$

The specific correlation of the PLR cannot be obtained only by using dimensional analysis. In the next section, the combination of the dimensional analysis and experimental data gives the correlation.

Table 1
Parameters and their signs, units and dimensions.

Parameter	Sign	Unit	Dimension
Differential pressure of Venturi tube	Δp	Pa	$ML^{-1}T^{-2}$
Permanent pressure loss	$\Delta\omega$	Pa	$ML^{-1}T^{-2}$
Mass flow rate of gas and liquid phase	m_g & m_l	kg/s	MT^{-1}
Density of gas and liquid phase	ρ_g & ρ_l	kg/m^3	ML^{-3}
Kinetic viscosity of gas and liquid phase	μ_g & μ_l	Pa s	$ML^{-1}T^{-1}$
Inner diameter of throat and pipe	d & D	m	L
Length of convergent and divergent section	L_1 & L_2	m	L
Acceleration of gravity	g	m/s^2	LT^{-2}
System pressure	P	Pa	$ML^{-1}T^{-2}$