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To cite this article: Jinghan Wang et al 2018 J. Phys.: Conf. Ser. 1065 092020

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A study on over-reading model for gas-liquid flow based on vertical Venturi

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Abstract. The accurate measurement of gas-liquid flow has great significance in industrial production, especially for natural gas. Venturi is a kind of differential pressure flowmeter which is widely used in gas-liquid flow measurement and the differential pressure would be higher in the gas-liquid flow than the gas alone due to the existence of the liquid. This phenomenon is termed as overreading(OR). In this paper, a modified model based on De Leeuw OR model has been proposed. Most studies of OR (including De Leeuw’s) were based on the horizontally mounted flowmeters, however this model was modified for the vertically mounted Venturi. The experiment was carried out with a low range of pressure (0.6-1.2 MPa) and relatively wider range of liquid content (compared to wet gas $X_{LM} < 0.3$, this experiment $X_{LM} = 0.04 – 1.14$). The relative error of OR predicted by the modified model was within 5% at the confidence level of 90%. According to the data analysis, this modified model could be a better choice for vertically mounted Venturi than the existing OR models.

1. Introduction
1.1. Research background
Gas-liquid flow exists widely in nature and various industrial fields, such as nuclear energy, petroleum, steam power and so on[1]. Due to the presence of liquid, the readings of differential pressure(DP) flowmeter for gas-liquid two phase flow are higher than the single phase gas flow, which is called overreading(OR)[2]. Many researchers have carried out a large number of studies about OR. Venturi is widely applied in the industry because of its minimum permanent pressure loss and less impact on flow pattern. When the gas flows through Venturi, its mass flow rate is related to the pressure loss through the throttle part, as shown in Eq.(1):

$$W_g = \frac{1}{\sqrt{1 - \beta^4}} C_d \varepsilon A_{th} \sqrt{2\rho_g \Delta P_g}$$

(1)

where $A_{th}, \beta, C_d, \varepsilon, \rho_g, \Delta P_g$ represent the venturi throat area, the ratio of throat diameter to pipe diameter, the discharge coefficient, the compressibility coefficient, the gas density, nd the pressure drop, respectively. When the gas-liquid flow goes through the DP flowmeter, the OR is defined as Eq.(2):

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\[
OR = \sqrt{\frac{\Delta P_g}{\Delta P_t}} = \frac{W_{tp}}{W_g}
\]

Where \(\Delta P_g\) represent the pressure drop of gas-liquid flow through the venturi, and \(W_{tp}\) is the over-reading mass flowrate calculated by replacing \(\Delta P_g\) to \(\Delta P_t\) in Eq.(1).

### 1.2. Review

The most widely used OR model was developed by Chisholm in 1967 for orifice plates[3]. The model assumed that the incompressible gas-liquid mixture flowed through the orifice with a constant void fraction. The influence of the interfacial forces was considered. The model had good predictions of OR when the pressure ranged from 1.0 MPa to 7 MPa and the quality \(x\) was less than 0.1. Chisholm's correlation was defined as Eq.(3):

\[
OR = \sqrt{1 + C_{ch}X_{LM} + X_{LM}^2}
\]

\(X_{LM}\) was a dimensionless parameter which was defined as \(X_{LM} = \frac{1-x}{x} \sqrt{\frac{\rho_l}{\rho_g}}\), \(x\) was quality of gas in the gas-liquid flow. Gas Froude number was another important dimensionless parameter and was expressed as \(Fr_g = \frac{U_{sg}}{\sqrt{gD}} \sqrt{\frac{\rho_g}{\rho_l - \rho_g}}\).

\(C_{ch}\) was an empirical coefficient. When \(X_{LM} < 1\), \(C_{ch}\) is only related to the gas-liquid density ratio. Which was shown in Eq.(4):

\[
C_{ch} = \left(\frac{\rho_l}{\rho_g}\right)^n + \left(\frac{\rho_g}{\rho_l}\right)^n
\]

Through a large number of experiments with steam and water mixtures, Chisholm concluded that \(n\) was a constant of 0.25 when \(X_{LM} < 1\).

In 1997, based on the Chisholm model, De Leeuw proposed a model which was suitable for the horizontally mounted Venturi [3]. The pressure ranged from 1.5 Mpa to 9.5 Mpa, and \(X_{LM}\) was from 0 to 0.34. De Leeuw modified the parameter \(n\) in Chisholm model under the wet gas conditions, as follows:

\[
n = 0.41, (0.5 \leq Fr_g < 1.5),\]

\[
n = 0.606(1 - e^{-0.746Fr_g}), (Fr_g \geq 1.5).
\]

Many researchers had verified that the De Leeuw model had good performance for horizontal Venturi OR predictions. In 2012, Xu verified that the De Leeuw model was suitable for the measurement in vertical Venturi under the condition of low-pressure and low-quality[4]. Xu modified the \(n\) in De Leeuw model and the satisfactory OR predictions were obtained under the experimental conditions.

In this study, experiments were carried out based on vertically mounted Venturi with the lower pressure range and the wider scope of \(X_{LM}\). The accuracy of OR predictions by De Leeuw model under this condition needed to be improved. Table 1 showed the difference of the experimental conditions between this study and De Leeuw's.

### 2. Test loop and experiments

This experiment was conducted in the TJU wet gas test loop, as shown in Fig.1. A vertically upwards mounted venturi was used, the diameter was 50mm and \(\beta\) equaled to 0.55. Shangrun WP260 diaphragm was adopted as the differential pressure transmitter with an accuracy of
Table 1. Difference of the experimental conditions.

| Designations | Installation method | Pressure (MPa) | $U_{sg}$ (m/s) | $Fr_g$ | $X_{LM}$ |
|--------------|---------------------|---------------|---------------|---------|----------|
| De Leeuw     | horizontal          | 1.5-9         | 4-14.5        | 0.5-4.8 | 0-0.3    |
| This study   | vertical            | 0.6-1.2       | 3-15          | 0.38-2.5| 0.04-1.14|

Figure 1. Structure diagram of TJU wet gas test loop.

Figure 2. The relative errors of OR predicted by De Leeuw model.

0.1. Yokogawa EJA530A was chosed as the pressure transmitter with an accuracy of 0.2. The experimental temperature was 25°C-28°C and pressure points were 0.6MPa, 0.8MPa and 1.2MPa. Using the method of control variables, at a fixed pressure point, superficial gas flowrate changed from 3m/s to 15m/s, and the liquid content started from 0 to a maximum of 10%.

Figure 3. Relationships between the parameter $n$ and $Fr_g$, $X_{LM}$.

3. Results analysis and the modified model
3.1. Results analysis based on De Leeuw model
Compared with experimental OR results, the relative errors of predicted OR by De Leeuw model was shown in Fig.2. The relative errors increased with the decreasing of $Fr_g$. The results were also influenced by $X_{LM}$. The maximum relative error was 28.8%. The parameter $n$ in De Leeuw model was calculated by this experimental data, as shown in Fig.3 (at 1.2 MPa ). For the horizontal gas-liquid flow in the Venturi, De Leeuw believed that $n$ was only related to $Fr_g$. As we can see in Fig. 3(a), when the gas-liquid mixture flowed upward, $n$ was not unique at a fixed $Fr_g$. The parameter $n$ had a significant correlation with $X_{LM}$(Fig.3(b)).
3.2. The modified model based on De Leeuw model

According to the analysis in Section 3.1, De Leeuw model had non-negligible errors in OR predictions of upward flow, but there were some rules to follow. When the \( Fr_g \) increased, the dispersion of the \( n \) decreased. In other words, the effect of the liquid on the parameter \( n \) gradually decreased with the increase of \( Fr_g \). When \( Fr_g \) was large enough, the influence of liquid on \( n \) gradually reduced. It can be regarded as a supplementary correction of the De Leeuw model in upward flow.

\( X_{LM} \) was introduced for optimization. Since the value of \( n \) changed logarithmically with \( X_{LM} \), a new OR model could be obtained by data fitting and it was shown in Eq.(6).

\[
n = \begin{cases} 
0.4509(1 - e^{-1.0501Fr_g}) + 0.1802(1 - e^{-3.6980X_{LM}}) & \text{when } 0.5 \leq Fr_g < 1.46, \\
0.5966(1 - e^{-1.6653Fr_g}) - 0.0967(1 - e^{-14.2826X_{LM}}) & \text{when } Fr_g \geq 1.46,
\end{cases}
\]

\( (6) \)

Fig. 4 illustrated the comparison between De Leeuw model, Xu LJ model and the modified model. The relative errors of the modified model were less than 5%, and the confidence probability was 90%. The relative error of the Xu LJ model had a confidence probability of 78% within 5%. Comparing with the OR predictions of De Leeuw model in Fig.2, the modified model performed better and gave the smallest relative error.

Figure 4. Comparison between experimental OR and the predicted OR by models

4. Conclusion

This paper discussed the OR model of gas-liquid mixture flowing through vertically mounted Venturi(with the pressure range of 0.6-1.2 MPa and \( X_{LM} = 0 - 1.14 \)). We analyzed the errors of OR predictions by De Leeuw model for vertically mounted Venturi. The affection of the liquid-gas density ratio, \( Fr_g \) and \( X_{LM} = 0 - 1.14 \) on the parameter \( n \) in De Leeuw model had been discussed. A new modified model was proposed and OR predictions had good agreement with the experiments. It is worth noting that this model was only for upward vertical gas-liquid flow, therefore, the extrapolation of this model remains to be further studied.

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