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A comprehensive assessment of correlations for two-phase flow through Venturi tubes

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ABSTRACT

The objective of this study is to comprehensively evaluate established correlations for two-phase (gas-liquid) flow through Venturi tubes. Two-phase flow metering plays a critical role in the oil and gas industry and several commercial metering solutions incorporate a Venturi. However, despite its significance, there is no widely accepted standard for two-phase flow metering applications. In this paper, sixteen differential pressure correlations are critically assessed from literature and international standards, focusing on the Venturi tube. The discussions are supported by an independent dataset obtained from a two-phase flow test rig with an installed Venturi tube (following ISO 5167-4 2005) to assess correlations' performance within their own respective application range. The wide literature review and the obtained comparison results trended to inform that the homogeneous model performs better in most scenarios.

1. Introduction

Multiphase flow commonly occurs in petroleum systems (Kesana et al., 2018), with natural gas, water, condensates and condensed vapour being encountered in gas field developments. It is important to accurately track the flow rates of the co-produced fluids at each stage of production, where multiphase flow measurement (MPFM) plays a vital role. However, field MPFM always displays significantly higher uncertainty compared with that of single-phase flow measurements.

One of the most widely used flow measurement methods is to derive the flow rate from the pressure differential across pipe restrictions, so-named differential pressure devices, such as orifice plates, Venturi tubes, flow nozzles, cone meters and the like (Reader-Harris, 2015; Corneliussen et al., 2005; Oil and Gas Authority, 2015; American Petroleum Instit, 2013; Chen et al., 2016). The working principles of those differential pressure devices are similar, where the flow in a pipe is partially obstructed to build up a pressure differential between the upstream and the downstream of the device. It is estimated that over 40% of the currently installed industrial flow meters are differential pressure meters (NEL, 2013). Each of these devices has its own strengths and weaknesses, depending on the specific application. In this paper, correlations for two-phase flow through Venturi tubes are analysed to neaten their trends as reported in the literature. When a Venturi tube is inserted along a pipe, the pipe diameter will firstly narrow down along the flow direction to create a flow restriction and then widen back to the original diameter. Comparing to other differential pressure devices, the Venturi tube causes less influence on flow regimes and creates the lowest pressure loss (Abdul-Razzak and Shoukri JSC, 1995).

At present, the metrology of differential pressure devices for single-phase flows and for flows that can be approximated to single-phase are more established compared to that for multiphase flows. The recommended single-phase flow rate calculation and its associated uncertainty have been documented by the international standard ISO-5167 (non-pulsating flow) (ISO5167-1, 2003; ISO5167-2, 2003; ISO5167-3, 2003; ISO5167-4, 2003) and ISO-3313 (pulsating flow) (ISO 3313, 1998). The measurement of wet gas flow, which occurs when there is a very small amount of liquid in the flow, is also well established by the international standard ISO-11583 (11583:2012 I, 2012). In contrast, there is currently no internationally accepted procedure for the testing of multiphase flow meters. The recently launched ISO committee on MPFM is working to produce an ISO technical report that will direct the industry on how to meet the many flow metrology challenges associated with multiphase flows (OGUK, 2017). A reliable and standardised flow measurement practice for two- and multiphase flow conditions is highly desired by several industrial sectors. This potentially can be beneficial for the application of wet gas metering; as subject to the operation and production conditions, liquid content surges could take place in wet gas

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Nomenclature

Latin symbols

A_2	Sectional area of the Venturi throat, m^2
C_d	Discharge coefficient [-]
Fr	Densitometric Froude number [-]
K	Two-phase flow coefficient [-]
M	Mass flow rate, kg/s
m	Mass, kg
P	Pressure, Pa
ΔP	Differential pressure between the upstream and the Venturi throat, Pa
Q	Volumetric gas flowrates, m^3/s
Re	Reynolds number [-]
T	Temperature, °C
X	Lockhart-Martinelli parameter [-]
x	Quality factor [-]

Greek symbols

α	Gas fraction [-]
β	Ratio between the diameter of the Venturi throat and the diameter of the Pipe [-]
μ	Viscosity, cp
ρ	Density, kg/m^3

Subscripts

a	air
f	friction
g	gas
h	homogeneous
l	liquid
tp	two-phase flow
v	void fraction

production lines hence the wet gas flow will be really "wet"!

To date, almost all the differential pressure based two-phase flow metering correlations are semi-empirical formulae, which were derived from the basic single-phase flow approach and corresponding experimental data. Lockhart and Martinelli (1949) investigated the liquid holdup and the frictional pressure drop in two-phase flow correlations for horizontal pipes (Lockhart and Martinelli, 1949); this represents one of the earliest studies of its kind. The authors proposed the so-called "Lockhart and Martinelli parameter" which is regarded as key for all differential pressure devices. Subsequently, several investigators researched the relationship between pressure differential and flow rate under two-phase conditions, including Murdock (1962), Bizon (1965), James (1965), Chisholm (1967, 1977), Collin and Gasesa (1971), Smith and Leang (1975), Lin (1982) and Zhang et al. (1992). However, all these correlations were developed using orifice-based experimental datasets and therefore their applicability to Venturi tubes requires further validation.

Based on the authors' knowledge, before the late 1990s, there were only a few existing correlations in the literature that were tailored to Venturi tubes (Steven, 2002). Later, as the use of Venturi tubes became more widespread, its correlations were experimentally and analytically investigated by De Leeuw (1997), Moura and Marvillet (1997), Steven (2002), Xu et al. (2003), Zhang et al. (2005), ISO/TR 11583 (2012) (11583:2012 I, 2012) and He and Bai (2014). The performance of these correlations was tested by Steven (2002), Huang et al. (2005), Fang et al. (2007) (Lide et al., 2007), Oliveira et al. (2009), Meng et al. (2010) and Gupta et al. (2016) through various Venturi experimental setups. Although so far Venturi tubes have been primarily used for wet gas metering, more research and developments are focusing to MPFM.

The objective of this study is to comprehensively evaluate established correlations for two-phase flow through Venturi tubes to evaluate their performance against their claimed range of applicability. In Section 3, sixteen differential pressure correlations from literature and international standards are critically reviewed. Among them, eleven correlations were selected to assess their performance in Section 5 based on independent data obtained from a two-phase flow test rig with an installed ISO 5167-4 2005 Venturi tube at Cranfield University. The other five correlations, which were specifically built for wet gas flow metering are not evaluated in Section 5 as the current experimental setup is only suitable for MPFM. The results showed that the Homogeneous model performs better under the tested flow conditions.

2. Theoretical basis

2.1. Single-phase flow under steady-state conditions

Based on Bernoulli's equation, assuming the fluid is flowing through a pipe restriction under steady-state conditions, a relationship can be established between the mass flow rate and the differential pressure across the restriction. In addition, it is common practice to add a discharge coefficient (C_d) which characterises the flow and pressure loss behaviour of the Venturi tube in a fluid system. Therefore:

$$M = C \cdot A_2 \sqrt{\frac{2\rho \cdot \Delta P}{(1-\beta^4)}} \tag{1}$$

where M is the mass flow rate, kg/s; C_d is the discharge coefficient; ρ is the fluid density, kg/m^3; ΔP is the differential pressure, Pa; β is the ratio between the diameter of the Venturi throat and the diameter of the pipe.

Note that the compressibility of the fluid is not considered in this equation.

By replacing the parameters in Eq. (1) with the corresponding ones in two-phase flow conditions, differential pressure meters for two-phase flows can be characterised by the same type of relationship:

$$M_{tp} = \sqrt{2} \cdot \frac{C_{d(tp)} \cdot A_2}{\sqrt{(1-\beta^4)}} \cdot \sqrt{\rho_{tp} \cdot \Delta P_{tp}} \tag{2}$$

As can be seen in Eq. (2), the determination of the two-phase mass flow rate through a differential pressure device also depends on the discharge coefficient, fluid properties, pressure differential and the geometry of both the used meters and the pipe. Additionally, Eq. (2) is often expressed as:

$$M_{tp} = K \sqrt{\rho_{tp} \cdot \Delta P_{tp}} \tag{3}$$

where K is the two-phase flow coefficient.

In principle, Eq. (3) is applicable to all differential pressure flow meters.

2.2. Lockhart-Martinelli parameter

In two-phase flows, the gas phase has relatively high compressibility compared to the liquid phase and its density varies considerably with pressure. In contrast, the liquid phase can be considered as virtually incompressible. The Lockhart-Martinelli parameter (Lockhart and Martinelli, 1949) analytically defines the relationship between the

components' densities and their mass flow rates. The experimental data used for its development were collected from four types of isothermal two-phase, two-component flows (benzene, kerosene, water, and various oil) in horizontal pipes with diameters of 0.0586 and 1.017 inches, respectively (Lockhart and Martinelli, 1949).

The original Lockhart-Martinelli parameter is defined as:

$$X = \sqrt{\frac{(Re_g)^a}{(Re_l)^b}\cdot\frac{C_l}{C_g}\cdot\frac{\rho_g}{\rho_l}\cdot\left(\frac{M_l}{M_g}\right)^2} = \sqrt{\left(\frac{\Delta P_f}{\Delta L}\right)_l \Big/ \left(\frac{\Delta P_f}{\Delta L}\right)_g} \tag{4}$$

where Re_g and Re_l are the Reynolds numbers of the gas and the liquid, respectively; a and b are exponents of Reynolds modulus in the Blasius expression for the friction factor of the gas and the liquid phase, respectively; C_l and C_g are constants in Blasius equation for friction factors of liquid and gas, respectively; $\left(\frac{\Delta P_f}{\Delta L}\right)_l$ and $\left(\frac{\Delta P_f}{\Delta L}\right)_g$ are the frictional pressure losses per unit length, assuming that the liquid and the gas are flowing alone in the pipe.

As pointed out by several authors (Steven, 2002; Oliveira et al., 2009; FalconeGeoffrey Hewitt, 2009; Gioia Falcone, 2006), the definition of the Lockhart-Martinelli parameter is often inconsistent in the open literature. Two related parameters, often used in the public domain, are the "modified Lockhart-Martinelli parameter" and the "simplified Lockhart-Martinelli parameter", as discussed below.

During his work on stratified two-phase flow through orifice plates (Murdock, 1962), Murdock recommended a different version of the Lockhart-Martinelli parameter:

$$X = \sqrt{\frac{\Delta P_l}{\Delta P_g}} = \frac{M_l}{M_g}\cdot\frac{K_g}{K_l}\cdot\sqrt{\frac{\rho_g}{\rho_l}} \tag{5}$$

where ΔP_l and ΔP_g represent the pressure loss through the orifice when liquid and gas are flowing alone in the pipe, and K_l and K_g are the superficial flow coefficients of the liquid and the gas phase, respectively. This modified Lockhart-Martinelli parameter considered both accelerational and frictional losses through orifice plates, instead of just the frictional losses of the original formulation (Steven, 2002; Oliveira et al., 2009; FalconeGeoffrey Hewitt, 2009; Gioia Falcone, 2006).

Some researchers simplified the Murdock Lockhart-Martinelli parameter by assuming that the superficial flow coefficients of liquid and gas are equal, in which case the simplified Lockhart-Martinelli parameter can be expressed as:

$$X = \frac{M_l}{M_g}\sqrt{\frac{\rho_g}{\rho_l}} \tag{6}$$

Chisholm and Laird (1958) developed another form of the Lockhart-Martinelli parameter, which has been applied to several subsequent studies of two-phase flow through orifices, including the well-known Murdock's (Murdock, 1962) and Chisholm's correlations (ISO5167-2, 2003; Chisholm, 1977). The modified formulation can be expressed as:

$$X = \sqrt{\frac{\Delta P_l}{\Delta P_g}} = \frac{1-x}{x}\sqrt{\frac{\rho_g}{\rho_l}} \tag{7}$$

where x is the gas quality factor, $x = \frac{m_g}{m_g+m_l}$.

The modified Lockhart-Martinelli parameter is often used to define the wetness of gas production in the oil and gas industry: when $X \le 0.3$, the corresponding flows are identified as wet gas flows; when $X > 0.3$, the corresponding flows are defined as multiphase flows (Steven, 2006).

3. Overview of two-phase flow correlations through Venturi tube

3.1. General correlations of differential pressure flow meters

3.1.1. Homogeneous flow correlation (reported by (Steven, 2002; Zhang et al., 2005; Oliveira et al., 2009), (Huang et al., 2005; Meng et al., 2010; Gupta et al., 2016))

The Homogeneous correlation is one of the simplest approaches to calculating two-phase flow rates, assuming that the water and gas phases are well mixed and share the same velocity. Therefore, the slip ratio of liquid and gas phases, which is a function of $\frac{\rho_g}{\rho_l}$, is not considered here and the two-phase can be considered as one of the average properties. The two-phase flow density can be expressed via the gas quality factor (x):

$$\rho_{tp} = 1 \Big/ \left(\frac{x}{\rho_g} + \frac{1-x}{\rho_l}\right) \tag{8}$$

Based on Eq. (3), the total two-phase mass flow rate is defined as:

$$M_{tp} = K\sqrt{\Delta P_{tp}\rho_{tp}} = K\sqrt{\Delta P_{tp} \Big/ \left(\frac{x}{\rho_g} + \frac{1-x}{\rho_l}\right)} \tag{9}$$

3.1.2. Separated flow correlation (reported by (Huang et al., 2005; Meng et al., 2010; Gupta et al., 2016))

In the separated flow modelling approach, the density of the two-phase mixture is calculated by the general definition via the gas fraction (α), where two-phase flows are considered as separated flows:

$$\rho_{tp} = \alpha\rho_g + (1-\alpha)\rho_l \tag{10}$$

Accordingly, the total mass flow rate of the two-phase flow is (Huang et al., 2005):

$$M_{tp} = K\sqrt{\Delta P_{tp}\rho_{tp}} = K\sqrt{\Delta P_{tp}\cdot\left[\alpha\rho_g + (1-\alpha)\rho_l\right]} \tag{11}$$

In principle, the two correlations above can be applied to all types of differential pressure flow meters. However, the slip ratio is not considered by either of the approaches above.

3.2. Correlations originally developed for orifice plates with potential for application to Venturi tubes

3.2.1. Murdock's correlation (1962) (Murdock, 1962) and its modifications

Murdock (1962) suggested a practical correlation by testing several groups of fluids combinations, such as air-water, steam-water, natural gas-distillate, natural gas-salt water and natural gas-water with orifices of various dimensions, where the liquid weight fractions varied from 0.02 to 0.89. The proposed correlation can be given by:

$$M_{tp} = K\sqrt{\Delta P_{tp}\rho_{tp}} = K\sqrt{\Delta P_{tp}} \Big/ \left(\frac{x}{\sqrt{\rho_g}} + 1.26\frac{1-x}{\sqrt{\rho_l}}\right) \tag{12}$$

If the simplified Lockhart-Martinelli parameter (Eq. (7)) is imported into Eq. (12), then Murdock's correlation can be re-written as:

$$M_{tp} = K\sqrt{\Delta P_{tp}\rho_{tp}} = K\sqrt{\Delta P_{tp}\rho_g} \Big/ x(1+1.26X) \tag{13}$$

Following Murdock's effort, several authors derived further modified formulae:

- Bizon's Correlation (1965) (Bizon, 1965)

$$M_{tp} = K\sqrt{\Delta P_{tp}\rho_{tp}} = K\sqrt{\Delta P_{tp}} \Big/ \left(a\frac{x}{\sqrt{\rho_g}} + b\frac{1-x}{\sqrt{\rho_l}}\right) = K\sqrt{\Delta P_{tp}\rho_g} \Big/ x(a+bX) \tag{14}$$

where the values of a and b are determined experimentally.

- Collin *and Gasesa's Correlation (1971)* (Collins and Gacesa, 1971)

$$M_{tp} = K\sqrt{\Delta P_{tp}\rho_{tp}} = K\sqrt{\Delta P_{tp}} \Big/ \left(a\frac{x}{\sqrt{\rho_g}} + b\frac{1-x}{\sqrt{\rho_l}} + c\frac{\sqrt{x(1-x)}}{\sqrt[4]{\rho_l\rho_g}}\right) = K\sqrt{\Delta P_{tp}\rho_g} \Big/ x\left(a + bX + c\sqrt{X}\right) \quad (15)$$

where the values of a, b and c are determined experimentally.

- Lin's *Correlation (1982)* (Lin, 1982)

$$M_{tp} = K\sqrt{\Delta P_{tp}\rho_{tp}} = K\sqrt{\Delta P_{tp}} \Big/ \left(\frac{x}{\sqrt{\rho_g}} + \vartheta\frac{1-x}{\sqrt{\rho_l}}\right) = K\sqrt{\Delta P_{tp}\rho_g} \Big/ x(1+\vartheta X) \quad (16)$$

where ϑ is a function of $\frac{\rho_g}{\rho_l}$:

$$\vartheta = 1.48625 - 9.26541\left(\frac{\rho_g}{\rho_l}\right) + 44.6954\left(\frac{\rho_g}{\rho_l}\right)^2 - 60.6150\left(\frac{\rho_g}{\rho_l}\right)^3 - 5.12966\left(\frac{\rho_g}{\rho_l}\right)^4 - 26.5743\left(\frac{\rho_g}{\rho_l}\right)^5 \quad (17)$$

- Phillips Petroleum's Correlation (1998) (reported by (Steven, 2002; Lide et al., 2007))

$$M_{tp} = K\sqrt{\Delta P_{tp}\rho_{tp}} = K\sqrt{\Delta P_{tp}} \Big/ \left(\frac{x}{\sqrt{\rho_g}} + 1.5\frac{1-x}{\sqrt{\rho_l}}\right) = K\sqrt{\Delta P_{tp}\rho_g} \Big/ x(1+1.5X) \quad (18)$$

where the constant 1.26 in the original Murdock's correlation was replaced by 1.5.

3.2.2. James's correlation (1965) (James, 1965)

James (1965) carried out two-phase flow experiments using steam and water mixtures through orifices with different diameters, where the gas quality factor varied from 0.01 to 0.56. Based on the test results, a modified homogeneous correlation was proposed:

$$M_{tp} = K\sqrt{\Delta P_{tp}\rho_{tp}} = K\sqrt{\Delta P_{tp}} \Big/ \sqrt{\left(\frac{x^{1.5}}{\rho_g} + \frac{(1-x)^{1.5}}{\rho_l}\right)} \quad (19)$$

3.2.3. Chisholm's correlation (1967, 1977) (Chisholm, 1967, 1977)

Chisholm (1967, 1977) (Chisholm, 1967) (Chisholm, 1977) proposed a correlation for separated two-phase flow through orifices with the consideration of slip ratio:

$$\frac{\Delta P_{tp}}{\Delta P_l} = 1 + \frac{C}{X} + \frac{1}{X^2} \quad (20)$$

where C is an empirical number, $C = \frac{1}{S}\sqrt{\frac{\rho_l}{\rho_g}} + S\sqrt{\frac{\rho_g}{\rho_l}}$; ΔP_l is the pressure drop of liquid flowing alone; and if X < 1, $S = \left(\frac{\rho_l}{\rho_g}\right)^{1/4}$, while if X > 1, $S = \left[1 + x\left(\frac{\rho_l}{\rho_g} - 1\right)\right]^{1/2}$, where S is the interfacial shear force between phases.

Thus, Chisholm's correlation can be expressed as:

$$M_{tp} = K\sqrt{\Delta P_{tp}\rho_l} \Big/ \left[(1-x)\sqrt{1 + \frac{C}{X} + \frac{1}{X^2}}\right] \quad (21)$$

where, if X < 1, $C = \left(\frac{\rho_g}{\rho_l}\right)^{1/4} + \left(\frac{\rho_l}{\rho_g}\right)^{1/4}$ and if X > 1, $C = \left(\frac{\rho_g}{\rho_h}\right)^{1/2} + \left(\frac{\rho_h}{\rho_g}\right)^{1/2}$

In literature, the Chisholm's correlation is often written in a different form for wet gas measurements:

$$M_g = M_{g,\ Apparent} \Big/ \sqrt{1 + CX + X^2} \quad (22)$$

where X ≤ 0.3, $C = \left(\frac{\rho_g}{\rho_l}\right)^{1/4} + \left(\frac{\rho_l}{\rho_g}\right)^{1/4}$ and the term of $\sqrt{1 + \frac{C}{X} + \frac{1}{X^2}}$ is considered as a correction factor for wet gas conditions.

3.2.4. Smith and Leang's correlation (1975) (Smith et al., 1975)

Smith and Leang (1975) (Smith et al., 1975) proposed a two-phase flow correlation which they claimed could be applied to orifice plates, Venturi tubes and nozzles when the phases can be treated as separated. A parameter called "Blockage Factor (BF)" was brought into the equation to calculate the gas mass flow rate, quantitatively representing the partial blockage in the pipe due to the liquid phase, through the flow quality (x). This correlation, which was developed primarily for wet gas applications, can be expressed as:

$$M_g = K_g A_2 (BF)\sqrt{2\Delta P_{tp}\rho_g} = K_g A_2\left(0.637 + 0.4211x - \frac{0.00183}{x^2}\right)\sqrt{2\Delta P_{tp}\rho_g} \quad (23)$$

3.2.5. Zhang et al. Correlation (1992) (Zhang et al., 1992)

Unlike the above correlations, which can be applied to a relatively wide range of quality factor, Zhang et al. (1992) developed a correlation specifically for low-quality air-water flow through orifice plates, quality factor was controlled in the 0.007–1% range. Zhang et al.'s correlation is defined by:

Table 1
Relevant parameters of orifice-based experimental setups.

Authors	Tested Fluids	Installed device	Operating pressure, bar	Orifice Beta Ratio	Quality, %
Murdock (1962)	Steam-water	Orifice plate	39.61–40.31	0.5	78–95
James (1965)	Steam-water	Orifice plate	7.72–16.82	0.707	6.2–66.9
Bizon (1965)	Steam-water	Orifice plate	82.74	0.45 and 0.7	5–50
Collin and Gasesa (1971)	Steam-water	Orifice plate	67.57	0.62–0.753	5–95
Lin (1982)	Vapour-liquid (R-113)	Orifice plate	–	0.25–0.75	0–100
Zhang et al. (1992)	Air-water	Orifice plate	2.31–2.79	0.499 and 0.422	0.007–1

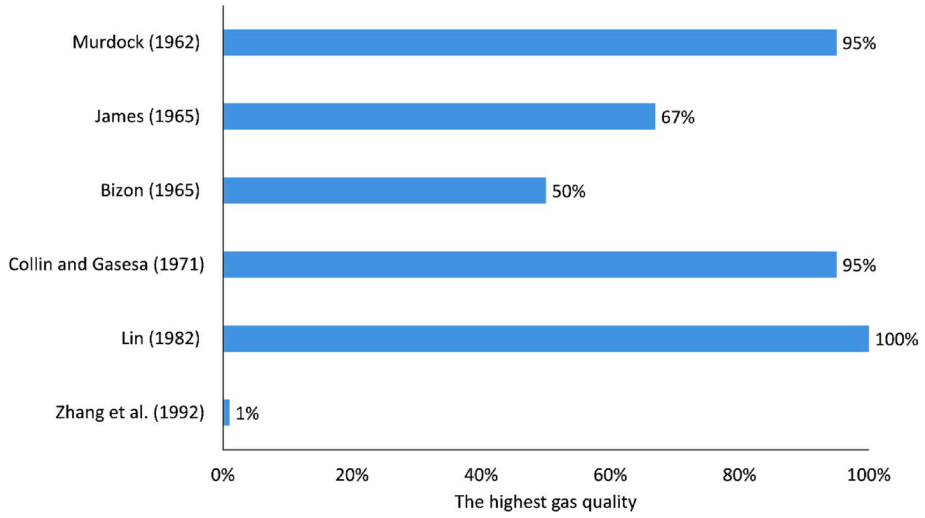


Fig. 1. The highest gas quality available in the orifice-based experimental setups.

$$M_{tp} = \left(K\sqrt{\Delta P_{tp}\rho_l}\right) \Big/ \left(\sqrt{x^{1.25+0.25x^{1/3}}\left(\frac{\rho_l}{\rho_g}-1\right)+1}\right) \tag{24}$$

3.2.6. Summary of correlations originally developed for orifice plates with potential for application to Venturi tubes

The experimental parameters of the orifice-based two-phase flow correlations reviewed above are summarised in Table 1. The data of Chisholm's and Smith & Leang's correlations were not included as there is insufficient information on the experimental setups in the original papers. As can be seen, a mixture of steam and water was often selected as the test fluid, as they are among the most convenient and safest fluids to use in a laboratory environment. Most authors attempted to produce a general two-phase correlation that can cover a relatively wide range of gas quality with the exception of Zhang et al. (1992), who focused on low-quality application. As shown in Fig. 1, the highest gas quality in Zhang's experimental setups is much lower compared to the other authors.

3.3. Correlations developed for Venturi tube

3.3.1. De Leeuw's correlation (1997) (DL, 1997)

The first dedicated Venturi's correlation was proposed by Leeuw in 1997. It is only applicable to wet gas measurements, where the Lockhart-Martinelli parameter must not be greater than 0.3. The author introduced the gas densitometric Froude number (Fr) to further clarify the measuring errors caused by the presence of the liquid phase. The basic formulation of De Leeuw's correlation is similar to Chisholm's correlation:

$$M_g = M_{g,\ Apparent} \Big/ \sqrt{1+\left[\left(\frac{\rho_l}{\rho_g}\right)^n+\left(\frac{\rho_g}{\rho_l}\right)^n\right]X+X^2} \tag{25}$$

where $n = 0.606(1-e^{-0.746Fr})$, if $\mathrm{Fr} \geq 1.5$; $n = 0.41$, if $0.5 \leq \mathrm{Fr} < 1.5$.

3.3.2. Steven's correlation (2002) (Steven, 2002)

Steven (2002) (Steven, 2002) developed a new correlation for wet gas Venturi measurements by employing independent test data from a wet gas flow loop, where a six-inch horizontal Venturi with a beta ratio of 0.55 was installed. Steven's correlation is defined by:

$$M_g = M_{g,\ Apparent} \Big/ \left(\frac{1+AX+BFr}{1+CX+DFr}\right) \tag{26}$$

where $A = 2454.51(\rho_g/\rho_l)^2 - 389.568(\rho_g/\rho_l) + 18.146$; $B = 61.695(\rho_g/\rho_l)^2 - 8.349(\rho_g/\rho_l) + 0.223$; $C = 1722.917(\rho_g/\rho_l)^2 - 272.92(\rho_g/\rho_l) + 11.752$; $D = 57.387(\rho_g/\rho_l)^2 - 7.679(\rho_g/\rho_l) + 0.195$.

3.3.3. Zhang et al. Correlation (2005) (Zhang et al., 2005)

Zhang et al. (2005) (Zhang et al., 2005) proposed a correlation that is specifically designed for oil and gas two-phase flow in low-quality conditions ($x \leq 1.98\%$) with the consideration of the ratio of oil and air densities, using Venturi and void fraction sensors. Through the control of void fraction (15–83%), this correlation has been applied to different flow regimes, including bubble flow, slug flow, wavy flow and annular flow. This is one of only a few correlations that explicitly account for the influence of flow patterns. The mixture mass flow rate and quality can be determined by:

$$M_{tp} = \left(C_d \cdot A_2 \cdot \sqrt{\frac{2\rho_l \Delta P_{tp}}{(1-\beta^4)}}\right) \cdot K_l \tag{27}$$

$$K_l = \left[c\left(\left(\frac{\alpha}{1-\alpha}\right)^n\left(\frac{\rho_l}{\rho_g}\right)^m+1\right)\right]^{-1/2} \tag{28}$$

$$x = c'\left(\frac{\alpha}{1-\alpha}\right)\left(\frac{\rho_g}{\rho_l}\right)^H \tag{29}$$

where c, n, m, c' and H are constants that are determined by the flow regimes and the experimental conditions. Under bubble and slug flow, $c = 0.5$, $n = 0.95$, $m = 0.02$, $c' = 0.51$ and $H = 0.65$; under wavy flow, $c = 1.3$, $n = 1.15$, $m = 0.08$, $c' = 1.25$ and $H = 0.7$; under annular flow, $c = 1.2$, $n = 0.95$, $m = 0.05$, $c' = 1.21$ and $H = 0.95$.

3.3.4. ISO/TR 11583 (2012) (11583:2012 I, 2012)

The international standard ISO/TR 11583 describes the measurement of wet gas flow (the gas volume fraction must be no less than 95%) with Venturi tubes and orifice plates. The proposed correlation for Venturi tubes is given by:

$$M_g = C_{wet}K_g A_2\sqrt{2\Delta P_{tp}\rho_g} \Big/ \sqrt{1+CX+X^2} \tag{30}$$

where $C_{wet} = 1 - 0.0463e^{-0.05Fr_{g,th}}\ min\left[1, \sqrt{\frac{X}{0.016}}\right]$; $Fr_{g,th} = \frac{Fr_g}{\beta^{2.5}}$; $C = \left(\frac{\rho_l}{\rho_g}\right)^n + \left(\frac{\rho_g}{\rho_l}\right)^n$; $n = max(0.583 - 0.18\beta^2 - 0.578e^{-0.8Fr_g/H},\ 0.392 - 0.18\beta^2)$; for hydrocarbon liquid, H = 1; for water, H = 1.35; for liquid

Table 2
Relevant parameters of Venturi-based experimental setups.

Authors	Tested Fluids	Fluids Types	Installed devices	Venturi direction	Beta Ratio	Pressure, bar	Flow rate
De Leeuw (1997)	Nitrogen-diesel oil	Wet gas [Gas Volume Fraction (GVF) = 90–100%]	Venturi	Horizontal	0.401	15–95	1.08–458.33 m^3/h (liquid); 50–1458.33 m^3/h (gas)
Steven (2002)	Nitrogen-kerosene substitute	Wet gas (GVF > 95%)	Venturi	Horizontal	0.55	20–60	3.04–65.11 m^3/h (liquid); 400–1000 m^3/h (gas)
Zhang et al. (2005)	Oil-air	Low quality fluids (x < 1.98%)	Venturi + void fraction sensor [Electrical Capacitance Tomography (ECT)]	Horizontal	0.55	2–4	4.5–6.3 m^3/h (liquid); 0–14 m^3/h (gas)

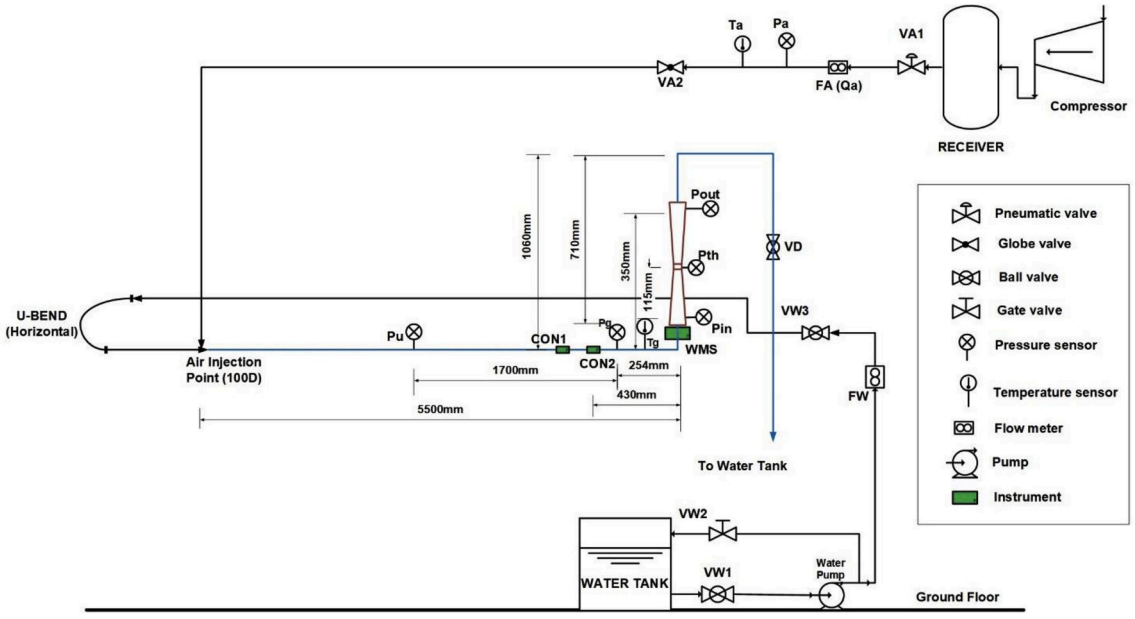


Fig. 2. Schematic diagram of the experimental facility.

water in wet-steam flow, H = 0.79.

3.3.5. He and Bai's correlation (2014) (He and Bai, 2014)

He and Bai (2014) introduced an alternative correlation for wet gas flow rate measurement based on the relationship between the two-phase flow coefficient, the density ratio (gas to liquid), the Lockhart-Martinelli parameter and the gas densitometric Froude number. The proposed correlation can be defined as:

$$M_g = \frac{K_g A_2 \sqrt{2\Delta P_{tp}\rho_g}}{1+\frac{X}{\sqrt{\rho_g/\rho_l}}}\left[\left(\frac{0.5681}{\sqrt{\rho_g/\rho_l}} - 0.1444Fr - 0.1494\right)X + 1\right] \quad (31)$$

The authors above paid great attention to developing Venturi tube correlations for wet gas measurements. In the five listed correlations, four of them are specifically considered for wet gas flow metering. The study by Zhang et al. (2005) is the only exception, as it covered very low-quality measurements. There seems to be a gap for a Venturi correlation that can measure two-phase flow in a general quality range. The relevant parameters of Venturi-based experimental setups are collected in Table 2. The data from ISO/TR 11583 and He & Bai's correlations are not included, as the details of the corresponding experimental setups were not mentioned in the original sources.

4. Correlation performance

In this paper, ad hoc tests were carried out to compare the performance of different correlations through the prediction of two-phase mass flowrates. The performance of eleven correlations out of the sixteen was verified based on an existing Venturi experimental setup at Cranfield University. Only the slug flow regime was tested in the experiments to exclude the influence of different flow patterns. It was noted that, under the current test flow conditions, the vertical upward intermittent flow regimes dominated the experiments. The results of the newly generated experimental data were then compared with six similar review studies available in the literature.

4.1. Experimental setup and procedure

The experimental setup consists of three major components, including a water supply system, an air supply system and a vertical flow test section (Venturi tube). A schematic diagram of the experimental facility is presented in Fig. 2. In the experiments, the water flow was supplied through 2-inch horizontal pipelines from an underground tank by a centrifugal pump. The air flow, which was provided by compressors, was injected at an injection point that is 100D away from the test section. The water flowrates were measured using an Autoflux Electromagnetic Flow Meter (0–4.524 m^3/h, ± 0.1% of the upper range) while the gas flowrates were recorded by a Quadrina Turbine Flow Meter (0–60 m^3/h, ± 0.1% of the upper range). The riser base is the location where the superficial gas and liquid velocities were referring to. The local pressure P_g and temperature T_g were measured and recorded. As the tests were conducted using air and water superficial velocities at the riser base hence only the local gas and water volumetric flow rates were required. The local volumetric liquid flow rates were directly taken from

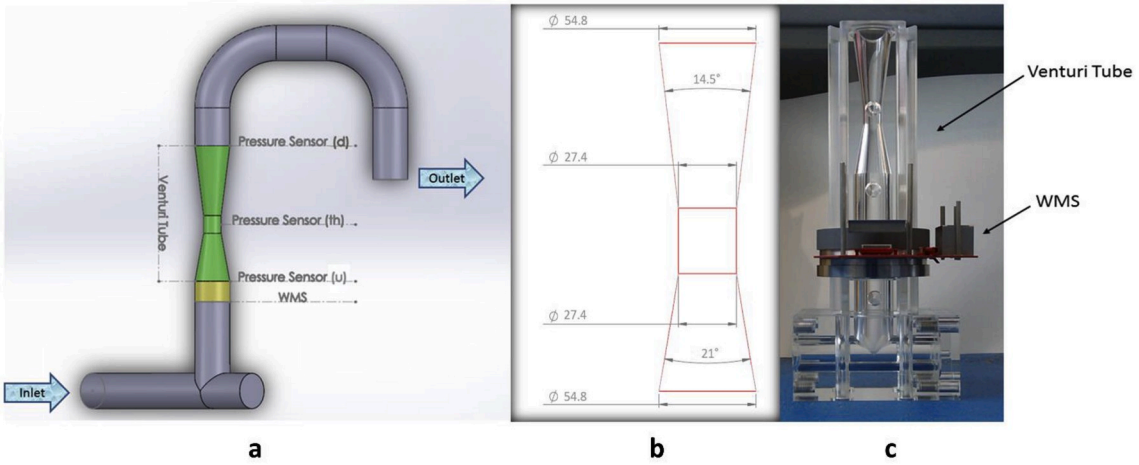


Fig. 3. Schematic diagram of the test section (a), geometric dimensions of the Venturi tube (b), and a photograph of the tested Venturi tube (c).

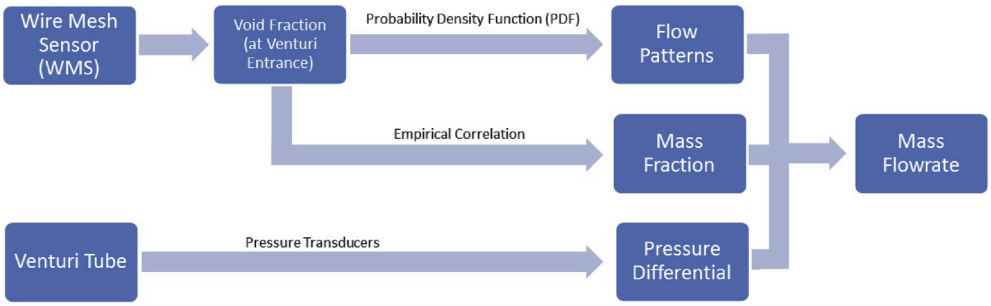


Fig. 4. Scheme of two-phase (air and water) flowrate measurements.

the water flow meter, while the local volumetric gas flowrates Q_g is calculated using the equation below:

$$Q_g = Q_a * \left(\frac{T_g}{T_a}\right) * \left(\frac{P_a}{P_g}\right) \tag{32}$$

where Q_a, T_a and P_a are volumetric gas flowrates, temperature and pressure at the gas metering point, respectively.

The experiments were performed under various superficial air and water velocity combinations to investigate the flow along the vertical test section. The tested superficial water velocities were in the range of 0.22 m/s to 1.18 m/s while the superficial air velocities varied from 1.03 m/s to 2.27 m/s. During the tests, the operating conditions were kept at a pressure of 1–3 bara under ambient temperature. The desired

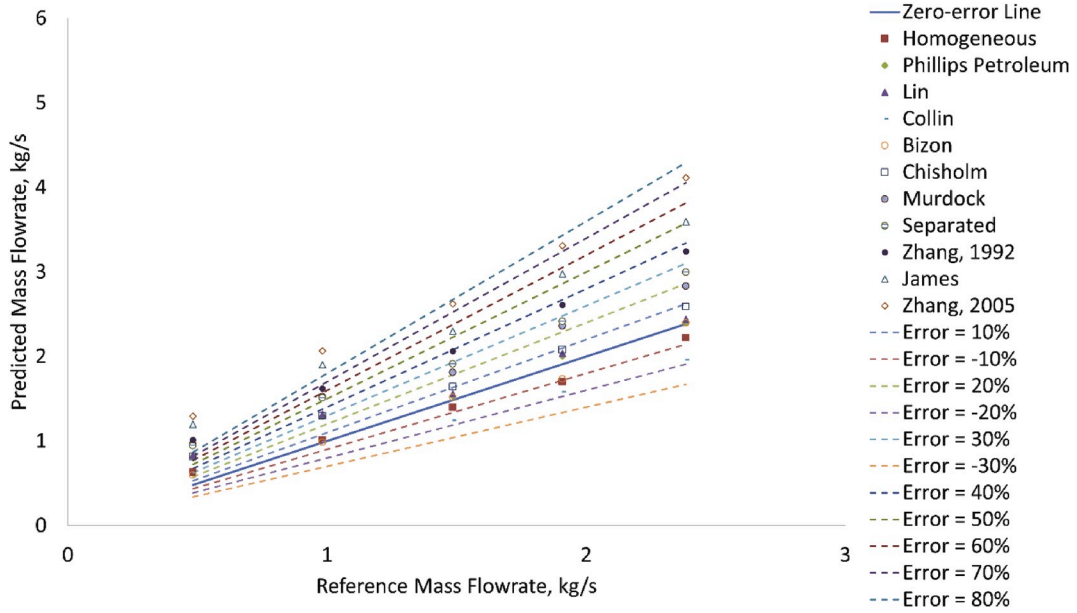


Fig. 5. Comparison between reference mass flowrates and those predicted by 11 existing correlations under slug flow pattern.

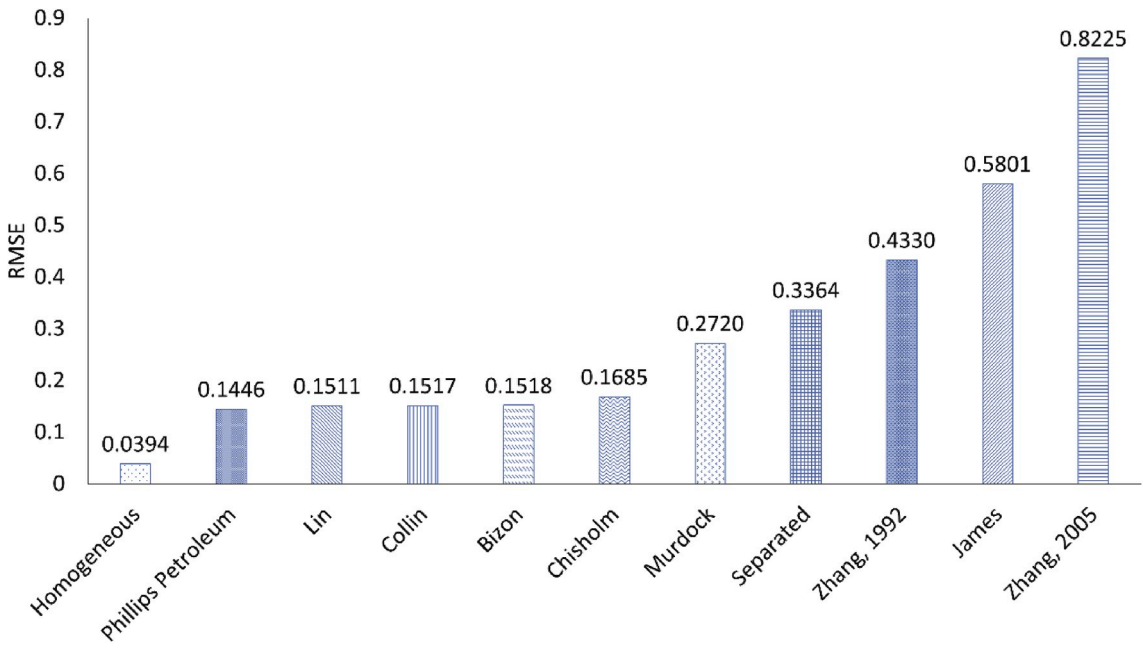


Fig. 6. RMSF of two-phase mass flowrate predictions of eleven existing correlations under slug flow conditions.

flow rates of both water and air were then circulated in the system via the corresponding control valves until a steady-state condition was reached. After that, the values of pressure at each observing point and the corresponding flowrates of each phase was recorded by the data acquisition system. The same experimental procedures were repeated for different flow rate combinations.

The outlet of the flow loop was connected to a hose under atmospheric pressure, where the air was discharged to the atmosphere and water sent back to the tank. The void fraction was controlled in the range of 0.15–0.49. As illustrated in Fig. 3 a, **b** and **c**, the Venturi tube has a throat diameter of 27.40 mm, a beta ratio of 0.50 and a total length of 267.86 mm, which was designed based on ISO 5167-4 2005. The convergent and divergent angles are 21° and 14.5°, respectively.

The current experimental procedure consists of three major steps (see Fig. 4). In the first step, flow patterns of two-phase flow were identified in real-time through the method of Probability Density Function (PDF) analysis. The void fraction data were collected through a 16 × 16 Wire Mesh Sensor (WMS) installed at the entrance of the Venturi tube, as presented in Fig. 3 a and **c**. The WMS has a measuring range of 0–100% gas volume fraction (GVF) with an accuracy of ±10%. In the second step, the gas mass quality was calculated from the corresponding correlations and measured void fractions. The empirical correlation between void fraction and mass quality is obtained by (Abdul-Razzak and Shoukri JSC, 1995; Huang et al., 2005):

$$\frac{1-\alpha}{\alpha} = 0.1531 X_v^{0.9833} \tag{33}$$

where X_v is a modified Lockhart-Martinelli parameter, which can be defined as (Abdul-Razzak and Shoukri JSC, 1995; Huang et al., 2005):

$$X_v = \left(\frac{1-x}{x}\right)^{0.9} \left(\frac{\rho_g}{\rho_l}\right)^{0.5} \left(\frac{\mu_l}{\mu_g}\right)^{0.1} \tag{34}$$

In the end, the mass flowrates were predicted by selected two-phase flow correlations of through calculated mass fraction and measured pressure differentials. Three pressure transducers were mounted along the Venturi tube: upstream (u), throat (th) and downstream (d) (see Fig. 3 a). The downstream and throat pressure transducers have a measuring range of 0–6 barg with an accuracy of ±0.15% while the upstream pressure transducer has a measuring range of 0–4 barg with an accuracy of ±0.5%.

4.2. Results and analyses

Eleven correlations were selected due to their suitable liquid/gas ratio combination compared to the experimental conditions at Cranfield University. Given the broad range of experimental conditions tested in previous studies, a direct point-by-point comparison with the present study was not possible. However, the set-up at Cranfield University represented a consistent platform to test all of the eleven correlations against the same experimental points. The predictions of two-phase mass flowrates by the Homogeneous, Separated, Murdock, Bizon, Collin, Lin, Phillips Petroleum, Jame, Chisholm, Zhang et al., 1992, and Zhang et al., 2005 are plotted in Fig. 5, compared with the reference mass flowrates. As can be seen, most of the correlations overestimated the measurements, with the exception of the Homogeneous, Bizon and Collin models.

The more direct root mean square error (RMSE) comparing method was also applied in this study. RMSE can be expressed as:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left[\frac{(M_{predicted})_i - (M_{actual})_i}{(M_{actual})_i}\right]^2} \tag{35}$$

where n is the number of tests.

The calculated results of the RMSE analysis are presented in Fig. 6, indicating that the Homogeneous model gives the best performance with an RMSF of 0.0394. The modified Murdock formulae (Phillips Petroleum, Lin, Collin, and Bizon) are the second-best, with RMSFs of ~0.15. These correlations, which were originally formulated for orifice plates, performed satisfactorily. The Chisholm correlation takes the third place, with an RMSF of 0.1685.

5. Comparisons with previous studies

The performance of various correlations for application to Venturi tubes has been investigated by several previous researchers. Steven (2002) assessed the performances of seven correlations listed in Section 3 for wet gas metering, including two wet gas Venturi-correlations and five general two-phase flow orifice-correlations. Huang et al. (2005) tested and compared five general orifice-correlations, using a Venturi

Table 3
Experimental setups in Venturi correlations performance tests.

Authors	Tested Fluids	Fluids Types	Void fraction, %	Installed devices	Flow direction	Beta Ratio	Pressure, bar	Flow rate	Tested Flow patterns	Tested Models	Correlations with the best performance
Steven (2002)	Nitrogen-kerosene substitute	Wet gas (GVF > 95%)	–	Venturi	Horizontal	0.55	20–60	3.04–65.11 m^3/h (liquid); 400–1000 m^3/h (gas)	Annular-dispersed	Homogeneous; Murdock; Chishlom; Smith & Leang; Lin; De Leeuw	De Leeuw (RMSE = 0.0211); Homogeneous (RMSE = 0.0237);
Huang et al. (2005)	Air-diesel oil	Relatively low quality fluids (x < 10%)	13–80	Venturi + void fraction sensor (ECT)	Horizontal	0.55	3.8–4	0–15 m^3/h (liquid); 0–30 m^3/h (gas)	bubble, slug, stratified and annular	Homogeneous; Separated; Murdock; Chishlom; Lin	Separated (RMSE = 0.1–0.3)[a]; Chishlom (RMSE = 0.15–0.5)[a];
Fang et al. (2007) (Lide et al., 2007)	Air-water	Wet gas	–	Venturi	Horizontal	0.4040, 0.55 & 0.7	1.5, 2 and 2.5	–	–	Homogeneous; Murdock; Chishlom; Smith & Leang; Lin; De Leeuw	Homogeneous (RMSE = 0.11021);
Oliveira et al. (2009)	Air-water	Relatively low quality fluids (x < 10%)	2–85	Venturi + void fraction sensor (ECT)	Horizontal & Vertical	0.5	2–3	≤4 m^3/h (liquid); ≤14 m^3/h (gas)	bubble, slug, churn and annular	Homogeneous; Chishlom; Zhang et al. (1992); Zhang et al. (2005)	Chishlom (RMSE = 0.079); Homogeneous (RMSE = 0.086);
Meng et al. (2010)	Air-water	Relatively low quality fluids (x < 10%)	3–93[a] (Estimated)	Venturi + void fraction sensor (ERT)	Horizontal	0.58 &0.68	3	0.1–16 m^3/h (liquid); 0.1–20 m^3/h (gas)	bubble, slug, stratified and annular	Homogeneous; Separated; James; Murdock; Bizon; Collin and Gasesa; Chishlom; Lin	Collin and Gasesa (RMSE = 0.0256–0.123);
Gupta et al. (2016)	Air-water	–	2–22	Venturi	Horizontal	–	~0.9	14.5–21.69 m^3/h (liquid); ≤0–3.47 m^3/h (gas)	–	Homogeneous; James; Murdock; Collin and Gasesa; Chishlom; Zhang et al. (2005)	Homogeneous (Error < 5%); Collin and Gasesa (Error < 5%); Zhang et al. (2005) (Error < 5%);
Current study	Air-water	Relatively low quality fluids (x < 10%)	15–49	Venturi + Wire Mesh Sensor (WMS)	Vertical	0.5	1–3	1.5–8.5 m^3/h (liquid); 7–16 m^3/h (gas)	slug	Homogeneous; Separated; Murdock; Bizon; Collin, Lin; Phillips Petroleum; Jame; Chisholm; Zhang et al. (1992); Zhang et al. (2005);	Homogeneous (RMSE = 0.0394);

[a] The value was extracted from a corresponding figure, marking it as "estimated".

meter and a void fraction sensor [Electrical Capacitance Tomography (ECT)]. Fang et al. (2007) (Lide et al., 2007) presented the re-tested results for the seven correlations that were originally proposed in Steven's work (Steven, 2002) under low pressure and low Lockhart and Martinelli parameter conditions. Oliveira et al. (2009) reported the comparisons of four correlations (one Venturi-correlation and three orifice-correlations) through a two-phase flow setup, using a Venturi meter and a void fraction sensor (ECT). Meng et al. (2010) selected eight orifice-correlations that were closest to their experimental operating conditions to test by a Venturi meter and a void fraction sensor [Electrical Resistance Tomography (ERT)]. Gupta et al. (2016) discussed the performances of six two-phase flow correlations in their investigation of flow measurements in a Pressurized Heavy Water Reactor (PHWR).

The experimental setups and tested models from the six previous studies described above and the current experiment that was introduced in Section 4 are summarised in Table 3. The goal of this data collection is to study the influence of various parameters in Venturi two-phase flow experiments, as well as find out the best performing model that fits most of the scenarios.

As presented in Table 3, the selected tested fluids are basically the combination of air-water or air-oil, where a polarisation of the gas proportion can be seen. The gas quality is either very high (e.g. GVF >95% in wet gas measurements), or very low (x < 10%). In addition, several previous authors ((Zhang et al., 2005), (Huang et al., 2005), (Oliveira et al., 2009), (Meng et al., 2010)) as well as the current study applied void fraction sensors (either ECT or ERT or WMS) to determine the gas quality and to identify flow regimes.

In the seven studies of Table 3, only the Oliveira et al. (2009) addressed flow direction as one of the variables in the tests, where both vertical and horizontal Venturi tubes were installed in the experimental setup. The authors claimed that the flow direction had no major impact on the results under their experimental operating conditions. However,

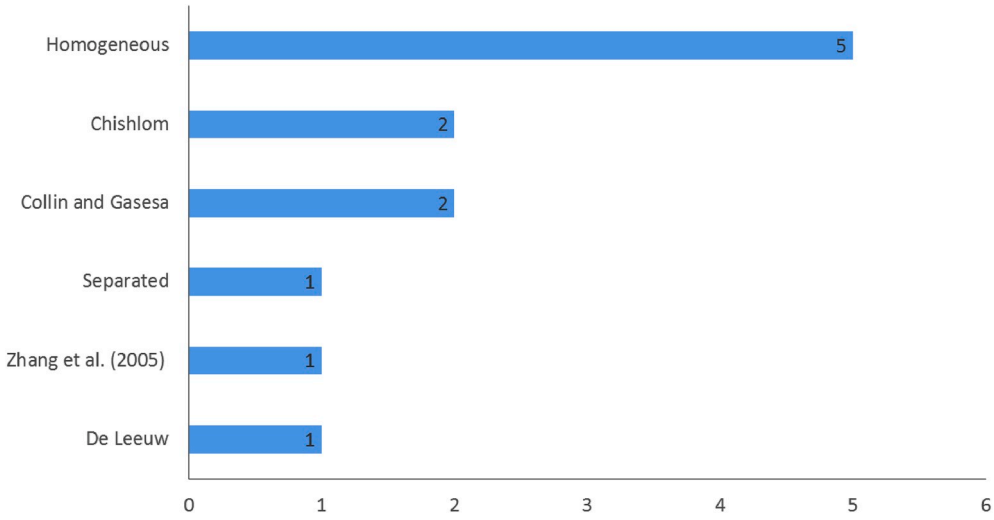


Fig. 7. The amount of times correlations scored as the best-performing in the present study (based on Table 3).

Steven (2002) stated that the vertical or horizontal flow direction can influence the flow measurement, as gravity plays a role in relation to changes in flow regime. Further investigations are required in this area, as a vertical installation of Venturi tubes is only seldom mentioned in public papers, in comparison with horizontal installations. In our experiments, as described in Section 4, the choice of a vertical set-up was made.

The influence of flow patterns has attracted growing attention in the area of two-phase flow measurement. As displayed in Table 3, Huang et al. (2005), Oliveira et al. (2009) and Meng et al. (2010) tested various two-phase flow correlations under different flow patterns: bubble, slug, stratified, churn and annular flow. Their experimental results confirmed that flow regimes have a direct impact and that the same correlation can perform differently under different flow patterns, and the latter is associated with different pressure losses through restrictions in a pipe. In our experiments, only one flow regime was selected to avoid the influence of multiple flow regimes.

The best-performing models for each test are presented in the last column of Table 3. Despite different tested fluids, liquid-gas ratio, Venturi geometry, operating pressure/temperature, flow patterns, and experimental setups, the homogeneous correlation, which is the simplest model among those considered, was scored as the best-performing (see Fig. 7).

6. Conclusions

This study has comprehensively evaluated well-established correlations for two-phase flow through Venturi tubes and assessed their performance against experimental data. Sixteen differential pressure correlations were critically reviewed with a focus on their applicability to Venturi tubes, including clarifications of the corresponding theoretical basis. Among them, the performance of eleven correlations out of the sixteen was verified based on a two-phase flow test rig with an installed ISO 5167-4 2005 Venturi tube. To compare the performance of the different correlations, ad hoc experiments were conducted through 2-inch horizontal pipelines, where a vertical Venturi tube was mounted along with a 16 × 16 WMS. Under current operating conditions, the vertical upward intermittent flow regimes dominated the experiments. Therefore, only the slug flow pattern was evaluated through the tests. The comparison showed that the Homogeneous model performed slightly better than other correlations, which had the lowest RMSF of 0.39. During the comparisons, most of the correlations overestimated the measured flow rates, except for the Homogeneous, Bizon and Collin models. A database was built by combining the current study and six previously published works, taking into consideration their claimed application ranges. A quantitative evaluation of these studies was carried out. Despite various Venturi geometry, pipe diameters, fluids properties, operating conditions, and tested flow patterns, the Homogeneous model, which has the simplest expression, was the one that performed best.

Recent evidence suggests that flow patterns have a great impact on the accuracy of two-phase flow measurement. In this study, only one flow regime was tested due to experimental limitations. More tests are required to cover other flow patterns commonly encountered in gas field developments.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Xiaolei Liu: Conceptualization, Methodology, Software, Investigation, Data curation, Formal analysis, Writing - original draft. **Liyun Lao:** Conceptualization, Methodology, Resources, Writing - review & editing, Supervision. **Gioia Falcone:** Validation, Writing - review & editing, Supervision.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jngse.2020.103323.

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A comprehensive assessment of correlations for two-phase flow through Venturi tubes

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