Evolution of Wet Gas Venturi Metering and Wet Gas Correction Algorithms

Alistair Collins Steve Clark
Solartron ISA (AMETEK Oil and Gas)

The Venturi meter is a straightforward pipeline device used for the metering of gas and liquids. This article presents a brief summary of the creation and characterisation of the modern Venturi meter, including the historic development of public domain algorithms to derive two phase (gas and liquid) flow rates from differential pressure measurements. The use of Venturi meters in multiphase oil and gas flow will also be briefly discussed.

1 History of the Venturi

The early history of the Venturi meter is intrinsically linked to the works of at least three scientists: Daniel Bernoulli (1700 - 1782), Giovanni Battista Venturi (1746 - 1822) and Clemens Herschel (1842 - 1930).

Bernoulli was the Dutch-Swiss mathematician who first applied his subject in earnest to Fluid Mechanics, with the publishing of Hydrodynamica in 1738. In this he formulated an early kinetic theory of gases, and arrived at what is now termed Bernoulli's Principle: that for inviscid flow (e.g. fluid with no viscosity) an increase in flow velocity occurs simultaneously with a decrease in pressure or a decrease in the fluid's potential energy.

Venturi, an Italian physicist, is credited with calling attention to the reduction in pressure of a fluid as it passes through a constriction in a pipe. He created this device by joining two truncated cones at their smallest size by a small throat section, drilling tappings in the pipe wall through which to measure the pressure from the upstream pipe to the centre of the throat section. By combining Bernoulli's principle with continuity laws, the difference in pressure (the differential pressure, Δp) could then be related to the change in velocity of the fluid (for incompressible flows and negligible height change):

$$p_1 - p_2 = \Delta p = \frac{\rho}{2}(v_2^2 - v_1^2) \tag{1}$$

However, it was not Venturi who recognised the practical applications of this relation, but instead it was Clemens Herschel, a Hydraulic Engineer with the Builders' Iron Foundary in America who patented the Venturi meter in 1895 (see [12] and figure 1). Although originally designed as a cost effective means of measuring water flow, the Venturi flow meter has been used in many industries, in particular as a means of measuring gas transmission through pipelines at high pressure.

2 Venturi as a flow meter

The flow rate of a fluid passing through a Venturi meter can be easily calculated from Bernoulli's principle and the conservation laws. From continuity (or mass conservation):

$$\rho_1 A_1 v_1 = \rho_2 A_2 v_2 \tag{2}$$

which initially assuming the density doesn't change through the device (i.e. $\rho_1 = \rho_2$) and combined with Bernoulli's principle from equation 1 gives:

$$\Delta p = \frac{\rho v_1}{2}\left(\left(\frac{A_1}{A_2}\right)^2 - 1\right) \tag{3}$$

Rearranging, and finding the mass flow rate where:

$$Q_m = v_1 A_1 \rho_1 \tag{4}$$

$$Q_m = \frac{A_1}{\sqrt{\left(\frac{A_1}{A_2}\right)^2 - 1}}\sqrt{2\rho\Delta p} \tag{5}$$

For a Venturi meter, where D is the pipe diameter at the meter's first tapping, and d is the orifice diameter at the tapping located at the throat section of the meter, the ratio of these diameters is known as the beta ratio, i.e.:

$$\beta = \frac{d}{D} \tag{6}$$

This allows for the mass flow equation to be further rearranged into its more familiar form:

$$Q_m = \frac{C}{\sqrt{1-\beta^4}}\varepsilon\frac{\pi d^2}{4}\sqrt{2\rho\Delta p} \tag{7}$$

where two coefficients have been included: the discharge coefficient, C, takes account of viscous effects; and the expansibility term, ε, compensates for the change in fluid density due to the increase

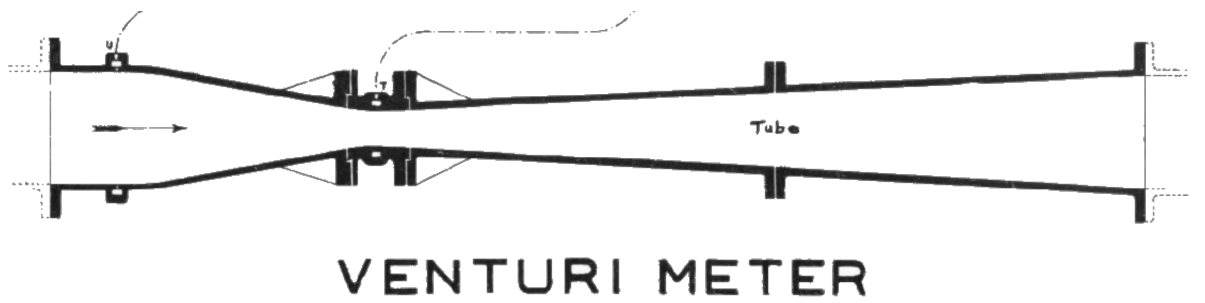

Figure 1: Diagram of Venturi Meter from Herschel's Booklet "The Venturi Meter"

in velocity between the pipe and throat diameters that was ignored in the equations above. For a Venturi, the expansibility term can be calculated under the assumption that the flow is isentropic (no energy is lost from the system) and at a constant height:

$$\varepsilon = \sqrt{\left(\frac{\kappa\tau^{2/\kappa}}{\kappa - 1}\right)\left(\frac{1-\beta^4}{1-\beta^4\tau^{2/\kappa}}\right)\left(\frac{1-\tau^{(\kappa-1)/\kappa}}{1-\tau}\right)} \tag{8}$$

The derivation of this equation, however, is beyond the scope of this current article.

Equation 7 is the primary equation provided in the ISO 5167 standard [13] (see also BS 1042 [5]), providing a relationship between the differential pressure across the Venturi and the mass flow rate, as the title of the standard implies. However, the volume flow rate Q_v is also simply found by dividing the mass flow rate by the fluid density, ρ:

$$Q_v = \frac{Q_m}{\rho} \tag{9}$$

It is also common across the industry to provide the volume flow rates at a "standard" set of pressure and temperature conditions (typically the equivalent of 1 atmosphere of pressure and at either 15 °C or 60 °F) from which the standard density, ρ_s of the fluid is found, such that:

$$Q_{vs} = \frac{Q_m}{\rho_s} \tag{10}$$

These flow rates are widely used throughout numerous industries where single phase fluids are transported through pipelines. Equation 7 can also be used for a number of different meter types: orifice plates, nozzles and Venturi meters are all included within the ISO 5167 standard, altering just the discharge coefficient and expansibility terms depending upon the chosen primary element.

However, where gases and liquids are combined in the flow this equation may no longer be accurate enough, and other factors may need to be taken into account. The use of the Venturi in these conditions will be considered in the next section, and the equations used to improve the flow measurements will be examined in section 4.

3 Venturi as a Wet Gas flow meter

A Wet Gas may be defined (for the purposes of this paper, at least) as a gas that contains a small amount of liquids, such that it has a Lockhart-Martinelli[19] parameter, $X < 0.3$. This parameter X indicates the "wetness" of a wet gas, and is the ratio of the pressure gradient for the liquid flow to pressure gradient of the gas under equilibrium flow conditions [21, Section 4.1]:

$$X = \frac{Fr_l}{Fr_g} = \frac{Q_{ml}}{Q_{mg}}\sqrt{\frac{\rho_g}{\rho_l}} = \frac{Q_{vl}}{Q_{vg}}\sqrt{\frac{\rho_l}{\rho_g}} \tag{11}$$

where the Froude numbers are the ratio of the kinetic energy to the gravitational potential energy of that particular phase:

$$Fr_g = \frac{v_{sg}}{\sqrt{gD}}\sqrt{\frac{\rho_g}{\rho_l - \rho_g}} \tag{12}$$

$$Fr_g = \frac{v_{sl}}{\sqrt{gD}}\sqrt{\frac{\rho_l}{\rho_l - \rho_g}} \tag{13}$$

and the superficial phase velocity (either gas or liquid) is found by calculating the velocity that phase would have if it passed through the pipe alone; for example, the gas superficial velocity would be:

$$v_{sg} = \frac{Q_{vg}}{A} = \frac{Q_{mg}}{\rho_g A} \tag{14}$$

A Venturi meter has long been considered a suitable wet gas meter, as the robust physical characteristics of the meter, including no moving parts or vibration issues and being less susceptible to wear than other differential pressure devices, as well as a low permanent pressure loss across the device are all of benefit when compared to other possible metering options. Venturi meters are also unlikely to be altered significantly by typical flow conditions of wet gas, which may include occasional "slugs" of liquid. These may be the result of accumulations of liquid in low points in the pipeline that, on fully blocking the pipe, receive significant acceleration by the gas and can cause damaging impacts to less-robust hardware incorporated in the pipeline. Likewise, erosion by sand (or similar) passing through the pipe, or a build up of scale at critical points within the meter, can each have a detrimental effect on equipment in the flow; however, papers such as [4] have shown that the Venturi is robust with regard to erosion, especially when compared to alternatives such as the cone meter. It is also unlikely to be "an excellent trap for debris and liquid", an accusation which Jamieson [17] levels at orifice plate meters.

Where a Venturi meter is designed specifically for wet gas flow conditions, two aspects of the ISO 5167 standard should be ignored, as they could otherwise compromise reliable flow conditions. Any liquid that builds up in the tappings for the pressure and differential pressure measurements would provide an additional "head" of pressure that would alter the transmitter values. Therefore, the use of annular chambers, piezometer rings or "triple-T" arrangements (as detailed in ISO 5167-4:2003 5.4.1) are discouraged, and single tappings at the 12 o'clock position for horizontal installations (or if multiple tappings are required they should be placed symmetrically at the top of the pipe) ensures that any liquid that enters the impulse tubing quickly and freely drains away. Likewise, any conditions which raises the possibility of hydrate (a structure of water molecules surrounding gas that looks like ice, also known as clathrates) formation within the pipeline or in the impulse lines is to be avoided. Therefore, the use of flow conditioners upstream of a Venturi (as per ISO 5167-4:2003 6.3) is not recommended for wet gas flow, as hydrates may result in partial or total blockage of the flow (see also [27, Section 4]). Hydrates are typically more likely to occur in colder sections and in smaller bore pipe such as those found in flow conditioners as well as in impulse lines, thus the use of insulation, heat tracing or diaphragm seals (see figure 3) may also be employed to prevent the loss of function that occurs when the normal fluid flow is hindered in this way.

ISO 5167-4 also provides a table of minimum straight lengths of pipe between the meter and other pipe fittings that should be employed upstream and downstream of a "standard" Venturi meter to employ the uncertainty values given within this document, with smaller lengths having an additional uncertainty term applied. Wet gas meter manufacturers may or may not employ this methodology, particularly where the discharge coefficient uncertainty of the specific meter is found by calibration at a suitable facility.

4 Wet Gas Corrections

The use of Equation 7 in wet gas conditions will typically give an error due to the presence of liquid, giving the appearance of too much gas (an "over-read") passing through the meter. The over-read of gas is given by the ratio of the indicated gas mass flow rate divided by the actual gas mass flow rate, which when combined with equation 7:

$$OR = \frac{Q_{mgi}}{Q_{mg}} \simeq \sqrt{\frac{\Delta p}{\Delta p_g}} \tag{15}$$

where Δp is the measured differential pressure across the Venturi, and Δp_g is the differential pressure if it was only the gas flowing.

Where a model of this over-read is provided for wet gas, it is typically renamed a Wet Gas Correction (WGC). A number of models have found more extensive acceptance into the Oil and Gas Community, and the major models are detailed in the sections below. These have typically been developed by combining theoretical knowledge of the physics of fluid flow with practical research from wet gas test flow loops, where metered amounts of gas, condensate and water are circulated through the meter at controlled pressure and temperature to form a best fit of the known data. Some of the historic research was primarily carried out on orifice plates, but as these models were sometimes applied to Venturi meters, they are still relevant to this discussion.

For more information, see the referenced papers from each section, as well as ASME MFC-19G-2008[3] Appendices G and H, which provides greater detail on each model and its derivation, including models not included in this paper.

4.1 Homogeneous Correction

The homogeneous model makes the assumption that the fluid passing through the Venturi can be assumed to be a pseudo-single phase with a density calculated based on the gas and liquid densities and their relative flow rates:

$$\rho_{Hom} = \frac{\rho_l \rho_g}{\rho_l x + \rho_g (1 - x)} \tag{16}$$

where x is the gas mass fraction or GMF:

$$x = GMF = \frac{Q_{mg}}{Q_{mg} + Q_{ml}} \tag{17}$$

This can be rearranged to give the Homogeneous model in terms of the Lockhart-Martinelli parameter, such that:

$$OR = WGC_{Hom} = \sqrt{1 + C_{Hom} X + X^2} \tag{18}$$

where:

$$C_{Hom} = \sqrt{\frac{\rho_g}{\rho_l}} + \sqrt{\frac{\rho_l}{\rho_g}} \tag{19}$$

As the model requires the gas mass flow rate as an input, it can be seen that this model and most of the following requires an iterative solution. However, using the uncorrected mass flow rate (equation 7) as the initial solution typically allows the correction model to quickly converge.

4.2 Murdock (1962) [20]

J.W. Murdock (the Associated Technical Director for Applied Physics at the Naval Boiler and Turbine Laboratory, Philadelphia, when he wrote [20]) published the first extensive wet gas meter model based on data from two-phase flow using steam-water, air-water, natural gas-water, natural gas-salt water and natural gas-distillate combinations through orifice plates. He was able to fit a simple straight line to the data, such that:

$$WGC_{Murdock} = 1 + MX \tag{20}$$

This equation used the least-squares fit to give $M = 1.26$ for the available dataset of 90 points to ±1.5% uncertainty at 2σ [15].

In later discussions by other authors (including [18]) the Murdock-style correction was considered for Venturi meters, although recognising the necessity of utilizing a different value for M. However, further testing [10] suggested that extra terms may be required in the correlation, where particularly at higher liquid rates the trend appears to no longer be linear in the Lockhart-Martinelli parameter, X.

4.3 Chisholm (1967-77) [6], [7], [8]

D. Chisholm worked for the National Engineering Laboratory in Glasgow, Scotland, which currently holds the Flow Measurement Standard for the UK National Measurement Office. His papers correlated the Lockhart-Martinelli parameter (see equation 11) with the wet gas flow through orifice plates, initially providing constant values of C_{Chis} varying from 2.66 to 4.76. However, he revised this[8] for wet gas flow (where $X < 0.3$, although the equation is quoted as being applicable for $X < 1$ in the paper) to:

$$\begin{aligned} WGC_{Chis} &= \sqrt{1 + C_{Chis}X + X^2} \\ &= \sqrt{1 + \left(\left(\frac{\rho_l}{\rho_g}\right)^{\frac{1}{4}} + \left(\frac{\rho_g}{\rho_l}\right)^{\frac{1}{4}}\right) X + X^2} \end{aligned} \tag{21}$$

This can be compared to the Homogeneous equations, noting that equation 19 can be rewritten as:

$$C_{Hom} = \left(\frac{\rho_g}{\rho_l}\right)^n + \left(\frac{\rho_l}{\rho_g}\right)^n \tag{22}$$

where $n_{Hom} = 0.5$ for the Homogeneous model, and $n_{Chis} = 0.25$ for the Chisholm Wet Gas Correction.

Chisholm notes, however, that the "Agreement is unsatisfactory with the values from... James [16] and Murdock [20]. This requires further study". (Note: the references are for this paper). Also, although this correlation is applicable to wet gas, it is based on orifice plates and therefore would need modification to be more readily utilized for Venturi meters.

4.4 de Leeuw (1997) [10]

Rick de Leeuw (working for Shell International Exploration and Production) provided a paper for the North Sea Flow Measurement Workshop that detailed a new correlation for Venturi meters in Wet Gas horizontal flow. This "differs fundamentally from the well known orifice plate correlations of Murdock and Chisholm in that the observed dependence on the gas Froude number is accounted for" [10, Summary].

de Leeuw acquired an experimental set of Venturi data from the SINTEF Multiphase Flow Laboratory, located near Trondheim in Norway. These tests used a 4" 0.4β Venturi meter, using Nitrogen as the gas and diesel oil as the liquid phase, covering a wide range of pressures, gas velocities up to 17 m/s and $0 \leq X \leq 0.3$. Data from a wet gas production field at Coevorden using a 4" Venturi meter is also utilized.

Given that the gas Froude number Fr_g is given by equation 12, the de Leeuw Wet Gas correction is generally expressed as:

$$\begin{aligned} WGC_{deLe} &= \sqrt{1 + C_{deLe}X + X^2} \\ &= \sqrt{1 + \left(\left(\frac{\rho_l}{\rho_g}\right)^n + \left(\frac{\rho_g}{\rho_l}\right)^n\right) X + X^2} \end{aligned} \tag{23}$$

where for $Fr_g \geq 1.5$:

$$n = 0.606\left(1 - \exp^{-0.746 Fr_g}\right)$$

and for $0.5 \leq Fr_g < 1.5$:

$$n = 0.41$$

where the correlated data is fitted to ±2% at 2σ uncertainty.

de Leeuw's data comes primarily from a single meter (a 4" Venturi with $\beta = 0.4$) tested mainly at a single facility (SINTEF Multiphase Flow Laboratory, located near Trondheim in Norway) on two phase flow using nitrogen gas and diesel oil as the hydrocarbon liquid, with additional data from previous tests on a 3" $\beta = 0.4$ Venturi at Coevorden taking gas flow from the test header and injecting water upstream of the test meter. The limitations of these test facilities mean that the minimum gas density of around $17kg/m^3$ should be noted, although the algorithm would be expected to continue to function at gas densities greater than the $100kg/m^3$ tested as the trend tends towards a theoretical limit where the gas and liquid densities are equal.

Although this correction uses data from the correct meter type when compared to the orifice plate correlations of Murdock and Chisholm, and is over a range of flows that are widely applicable to wet gas in industry, the use of only two meter sizes, one beta ratio and one fluid could be considered to restrict the applicability of this algorithm (although the author notes that "these effects are expected to be minimal." [10, Section 6 Conclusion]). Works by Steven [23] and Stewart [25] both appear to add some support to de Leeuw's algorithm, whilst also recognising the apparent weaknesses in certain areas. In particular, Stewart provides data to illustrate the effect of beta ratio.

4.5 Steven (2001-02) [23], [24]

Richard Steven completed his PhD in part sponsored by Solartron ISA (at that time known as ISA Controls). Subsequently he has worked for McCrometer (including working on a Wet Gas Correction for Cone Meters), and now works for CEESI Wet Gas Test loop in Colorado, USA, and DP Diagnostics LLC.

Steven's PhD (entitled "Wet Gas Metering") included extra data taken using a 6" 0.55β Venturi at the National Engineering Laboratory (NEL) Wet Gas Test Loop in Glasgow. This data was then analysed using multiple Wet Gas Corrections (including Homogeneous, Murdock, Chisholm, de Leeuw and others) and his own new correlation:

$$WGC_{Steven} = \frac{1 + A_{Steven}X + B_{Steven}Fr_g}{1 + C_{Steven}X + D_{Steven}Fr_g} \quad (24)$$

where for the data in Steven's PhD [23] (with the pressure P is in units of bar gauge):

$$\begin{aligned}
A_{Steven} &= 4.777285e^{-3}P^2 - 0.5242366P + 17.11304\\
B_{Steven} &= 1.233263e^{-4}P^2 - 0.0113753P + 0.203878\\
C_{Steven} &= 3.354571e^{-3}P^2 - 0.3673168P + 11.02978\\
D_{Steven} &= 1.149112e^{-4}P^2 - 0.0104724P + 0.177765
\end{aligned}$$

This was also published in [24] with polynomials in $\frac{\rho_g}{\rho_l}$ rather than pressure:

$$\begin{aligned}
A_{Steven} &= 2454.51\left(\frac{\rho_g}{\rho_l}\right)^2 - 389.568\left(\frac{\rho_g}{\rho_l}\right) + 18.146\\
B_{Steven} &= 61.695\left(\frac{\rho_g}{\rho_l}\right)^2 - 8.349\left(\frac{\rho_g}{\rho_l}\right) + 0.223\\
C_{Steven} &= 1722.917\left(\frac{\rho_g}{\rho_l}\right)^2 - 272.92\left(\frac{\rho_g}{\rho_l}\right) + 11.752\\
D_{Steven} &= 57.387\left(\frac{\rho_g}{\rho_l}\right)^2 - 7.679\left(\frac{\rho_g}{\rho_l}\right) + 0.195
\end{aligned}$$

Steven limits the applicability of this correlation to that of the data:

$$\begin{aligned}
20 \leq\ & P(bar) \leq 60\\
400 \leq\ & Qvg(am^3/h) \leq 1000
\end{aligned}$$

He states that the performance "was to predict the gas mass flow to less than ±3%". It should also be recognised that this testing was solely on a two-phase Wet Gas test loop (using nitrogen gas and kerosene as the liquid phase).

4.6 Reader-Harris and Graham (2008-09) [14], [22]

Most recently, Michael Reader-Harris and Emmelyn Graham, both of the National Engineering Laboratory (NEL), have published a further Wet Gas Correction incorporating additional data from the NEL two-phase wet gas test loop.

This "NEL" model continues the developments of Chisholm and de Leeuw, whilst incorporating data over both the full standard range of beta ratio for Venturi meters ($0.4 \leq \beta \leq 0.75$), and different liquid types (including hydrocarbons and both cool and very hot water). This is included as the H parameter, which is equal to 1 for hydrocarbon liquid, 1.35 for water at ambient and 0.79 for liquid water in a wet-steam flow, and is stated to be "a function of the surface tension of the liquid":

$$\begin{aligned}
WGC_{NEL} &= \sqrt{1 + C_{NEL}X + X^2}\\
&= \sqrt{1 + \left(\left(\frac{\rho_l}{\rho_g}\right)^n + \left(\frac{\rho_g}{\rho_l}\right)^n\right)X + X^2}
\end{aligned} \quad (25)$$

where

$$n = \max(0.583 - 0.18\beta^2 - 0.578\exp^{-0.8Fr_{gas}/H}, \\ 0.392 - 0.18\beta^2)$$

To account for a change in slope where the Lockhart-Martinelli parameter is small, an altered discharge coefficient is employed in equation 7:

$$C_{NEL} = 1{-}0.0463\exp^{-0.05Fr_{g,th}}\min\left(1, \sqrt{\frac{X}{0.016}}\right) \tag{26}$$

where:

$$Fr_{g,th} = \frac{Fr_g}{\beta^{2.5}}$$

The limits of this equation are stated to be:

$$\begin{aligned} 0.4 \leq\ & \beta \leq 0.75 \\ 0 <\ & X \leq 0.3 \\ 3 <\ & Fr_{g,th} \\ 0.02 <\ & \rho_g/\rho_l \\ & D \geq 50mm \end{aligned}$$

for an uncertainty of 3% for $X \leq 0.15$ and 2.5% for $0.15 < X \leq 0.3$.

However, there has also been responses as to the accuracy and applicability of this Wet Gas Correction, including [11].

4.7 Pressure Loss for Wet Gas Measurement

The effect of liquid on the Venturi meter is used to create the Wet Gas Corrections shown above. However, extra information may be derived from the use of an additional DP measurement from upstream to downstream of the Venturi. The influence of liquids reduces the amount of pressure recovered, as energy is taken from the gas to accelerate the liquid through the Venturi throat which is not fully recoverable, so by appropriately correlating this information a further algorithm can be found that removes the requirement for the Gas Mass Fraction (or similar) to be known.

de Leeuw [10], Steven [23] and the NEL Correlation [14] [22] all have investigated this effect, typically looking at the pressure loss ratio (PLR) - the differential pressure across the whole Venturi, p_t, to the differential pressure to the Venturi throat, Δp_v, (see also figure 2):

$$PLR = \frac{\Delta p_t}{\Delta p_v} \tag{27}$$

although this is often augmented by removing the PLR at dry gas conditions, such that correlations of the PLR to a measure of the amount of liquid (the Lockhart-Martinelli parameter, for instance) passes through the origin:

$$Y = PLR_{wet} - PLR_{dry} = \frac{\Delta p_t}{\Delta p_v} - \left.\frac{\Delta p_t}{\Delta p_v}\right|_{dry} \tag{28}$$

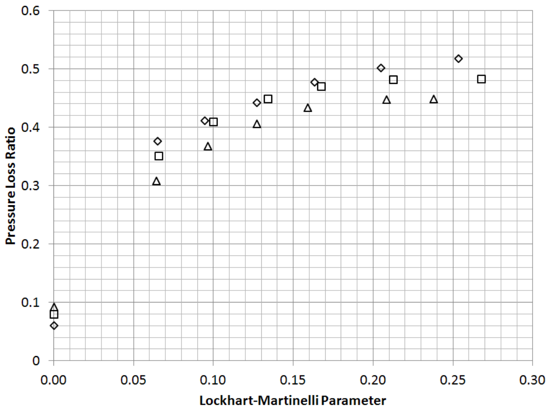

Figure 2: Typical Wet Gas Venturi Pressure Loss Ratio Data (from Solartron ISA Wet Gas Test Data)

de Leeuw [10] discusses that the PLR can be used to indicate whether there has been any change in the liquid content, and uses this as a trigger to run a new well test, using techniques such as tracer dilution to determine the new liquid flow rate. This method involves the injection of a chosen tracer chemical at a known rate, which when sampled and analysed far further down the pipe after the tracer is well mixed allows for the measurement of the targeted phase flow rate. Other techniques such as using a test separator may also be employed.

Steven and the NEL paper provide algorithms that can be used within their validated range of data (see the respective papers for more information). Both, however, show that this method is only applicable for lower liquid contents ($X < 0.1$) as the pressure loss ratio curves saturates, making the metering of greater amounts of liquid impractical (see also figure 2).

4.8 Manufacturer's Intellectual Property

The wet gas algorithms shown above have all been widely published, discussed and used throughout the Oil and Gas industry. However, it should be recognised that due to the large costs associated with acquiring Wet Gas test data, the dissemination of this information is not universal. Commonly the test data remains privileged to the meter manufacturer, utilized to further develop bespoke algorithms for their client. These proprietary algorithms may also claim better uncertainty than the public Wet Gas Corrections as they are specific to a particular meter (or meter type) with a reduction in the need for generalisations. Operators of Venturi meters may also have access to additional extensive wet gas data sets that are not in the public domain, both from wet gas testing and from flow meters in the field, which may be used to derive further correlations.

Solartron ISA, as an example of a meter manufacturer, produce a range of Advanced meters under the Dualstream brand name, with proprietary algorithms developed from numerous Wet Gas tests at a range of loops (including NEL, CEESI, K-Lab, SINTEF and SwRI). Both the Dualstream 1 Advanced and the Dualstream 2 Advanced meters use a PLR-based method for lower liquid conditions, with the latter meter also including a second device for the metering of wet gas to $X \leq 0.3$. The Dualstream Elite incorporates microwave signal analysis based on a resonant cavity design to determine the water fraction, which is beyond the scope of this current article, whilst also making use of DP devices. (For more published articles on Dualstream meters, see [9], [26]).

5 Standardisation

Throughout the use of the Venturi as a flow meter, efforts have been made to standardise aspects of the design of the meter, and therefore to be able to develop algorithms that can be applied across all similar devices from any manufacturer. Many of the authors already mentioned, or named in the referenced documents, have contributed to the development of standard documents and guidelines such as BS 1042 [5], ISO 5167 [13], API RP85 [1], API RP86 [2] and ASME MFC-19G [3].

International Standardisation continues in Technical Committees such as ISO TC 30 “Measurement of Fluid Flow in Closed Conduits”, ISO TC 193 “Natural Gas” and ISO TC 28 “Petroleum products and Lubricants”, in which many of these same people (including the authors of this paper) participate.

6 Current Venturi and Multiphase Meters

Many modern Wet Gas Meters incorporate a Venturi meter as part of their overall package of sensors for their Wet Gas and/or Multiphase meters, often to provide information on the “total flow” rather than specific gas and liquid flow rates. This information is then used in conjunction with data from other sensors (such as gamma densitometers, sonar meters, infra-red sensors, microwave sections etc.) to create a correlation that gives the greatest accuracy across the known Wet Gas test loop data. This can lead to claims that these meters form more of a “black-box” in comparison to the models detailed above, as these calculations and the methodology for combining the various pieces of equipment remain proprietary knowledge of the manufacturer.

Figure 3: A Modern Subsea Wet Gas Venturi with Diaphragm Seals

Alternatives to using a Venturi meter do exist, with cones, sonar and partial separation, for instance, all find their uses in current Wet Gas and Multiphase meters. Determining which meter type is best for a particular application may depend upon the various client requirements of accuracy, robustness and cost, amongst other factors.

7 Summary

The Venturi meter has a long history of use across a number of industries, and its frequent use in modern multiphase flow meters serves to illustrate that this will certainly continue for some time to come.

The development of a number of major Wet Gas correction algorithms has been detailed in this paper, demonstrating over 60 years of continuous improvements, with recent Wet Gas Correction algorithms also indicating that there is still interest in better understanding this aspect of flow metering.

Whilst much data is in the public domain, flow meter manufacturers with bespoke algorithms based upon privately-held data also illustrate the relevance of further work in this area. Similarly, the use of Venturi devices as a key component of multiphase meters indicates the applicability of this device across a wider range of conditions than has been considered in the article.

Glossary of Main Terms

A	Area
C	Discharge Coefficient (see equation 7 and discussion)
d	Orifice Diameter
D	Pipe Diameter
Fr_g	Gas Froude Number (equation 12)
Fr_l	Liquid Froude Number (equation 13)
g	Acceleration due to gravity
Q_m	Mass Flow Rate
Q_v	Volume Flow Rate
OR	Mass Flow Rate Over-reading (equation 15)
p	Pressure
Δp	Differential Pressure
PLR	Pressure Loss Ratio (equation 27)
v	Velocity
WGC	Wet Gas Correction
x	Gas Mass Fraction, GMF
X	Lockhart-Martinelli Parameter (equation 11)
β	Beta ratio (equation 6)
ε	Gas Expansibility
ρ	Density
$_g$	(subscript) Gas
$_l$	(subscript) Liquid
$_s$	(subscript) At Standard Conditions

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