A VENTURI BASED WET GAS METER WITH ON-LINE GAS MASS FRACTION ESTIMATION

Mr Paul Daniel, ISA Controls Limited
Dr Mark Tudge, ISA Controls Limited
Mr Jonathan Lund, BG Technology

1 INTRODUCTION

An increasing number of publications pertaining to wet gas flow measurement is testimony to the growing importance of the technology. The economic viability of developing new fields often depends on the ability to measure unprocessed well stream fluids with sufficient accuracy to allow for the possibility of commingling fluids from a number of fields/wells prior to separation.

The ubiquitous Venturi meter can achieve this and is one of the few technologies that is currently being used successfully in wet gas applications [1]. Recent publications have indicated that a venturi used in conjunction with semi-empirical correction algorithms can provide uncertainties better than 2% [2] and even as low 1% [3]. Unfortunately, the correction algorithms invariably require a knowledge of the gas mass fraction (GMF), which is not easily obtained. A tracer-venturi combination can be used [4], but tracer dilution techniques do not provide an on-line indication of the GMF and require repeat tests whenever a change in the liquid rate is perceived. Successful on-line estimation of the GMF would produce a stand-alone wet gas meter that could ultimately be capable of accuracy's of 1-2%. Measurement of the GMF has already been achieved through the use of multiple DP measurements [5]. This paper details the progression of this work and highlights the development undertaken to arrive at the Dualstream II - a wet gas flow meter that is capable of measuring the gas flow rate in a wet gas stream to within 2.5% without prior knowledge of the liquid rate. Results obtained from the wet gas test loop at the National Engineering Laboratory are presented.

Fig. 1 - The Dualstream II Wet Gas Flow Meter

The initial work on GMF estimation was carried out by BG Technology for BG International and is the subject of a patent application. The work detailed in this paper has culminated in an improved meter design by ISA Controls that is the subject of a joint patent application.

2 THEORETICAL BACKGROUND

The generic term 'wet gas' is frequently used but rarely defined. Even when defined, definitions tend to vary quite considerably [8]. The term wet gas is usually applied to multiphase flow where the volume of flowing gas is high with respect to the total volume. Typically, when the gas constitutes somewhere between 95-100% of the total volume - i.e. Gas Volume Fractions (GVFs) of 95-100% it is generally considered to be wet gas. Wet gas flow measurement is therefore merely a subset of multiphase metering.

It has been demonstrated to date by various sources [6, 7] that venturis used with correction algorithms can provide an accurate measurement of the gas flow rate in a wet gas stream. The correction algorithms proposed by Murdock [9], Chisholm [10] and De Leeuw [2] are probably the most widely known and are defined,

Murdock $$Q_g = \frac{Q_{gi}}{1 + M \frac{1-x}{x} \frac{Cd_g}{Cd_l} e_g \sqrt{\frac{r_g}{r_l}}} \approx \frac{Q_{gi}}{1 + MX} \qquad (1)$$

Chisolm $$Q_g = \frac{Q_{gi}}{\sqrt{1 + CX + X^2}} \qquad C = \left(\frac{r_l}{r_g}\right)^{\frac{1}{4}} + \left(\frac{r_g}{r_l}\right)^{\frac{1}{4}} \qquad (2)$$

De Leeuw $$Q_g = \frac{Q_{gi}}{\sqrt{1 + \tilde{C}X + X^2}} \qquad \tilde{C} = \left(\frac{r_l}{r_g}\right)^{n} + \left(\frac{r_g}{r_l}\right)^{n} \qquad (3)$$

where

$$n = 0.606\left(1 - e^{-0.746 Fr_g}\right) \qquad Fr_g \geq 1.5$$

$$n = 0.45 \qquad 0.5 \leq Fr_g \leq 1.5$$

$$Fr_g = \frac{Vs_g}{\sqrt{gD}} \sqrt{\frac{r_g}{r_l - r_g}}$$

$$X = \frac{1-x}{x} \sqrt{\frac{r_g}{r_l}} \qquad (4)$$

Murdock's correlation is perhaps the most applied, whilst De Leeuw's was developed based on tests conducted on petroleum fluids and has been specifically derived to accommodate the observed change in the venturi over-read characteristic with varying pressure and gas velocity. All three techniques have one common feature - in order to apply the correction a knowledge of the liquid flow rate or gas mass fraction (GMF) is required. To date this has typically been achieved through the use of tracer dilution techniques. However, if two different devices were to exhibit significantly different Murdock constants then two simultaneous equations exist that can be solved to yield the gas mass fraction [5],

$$Q_g = \frac{Q1_{gi}}{1 + c_1 + M_1 \frac{(1-x)}{x} \sqrt{\frac{r_g}{r_l}}} = \frac{Q2_{gi}}{1 + c_2 + M_2 \frac{(1-x)}{x} \sqrt{\frac{r_g}{r_l}}},$$

$$x = \frac{\sqrt{\frac{r_g}{r_l}} \left(\frac{Q2_{gi}}{Q1_{gi}} M_1 - M_2\right)}{\left(1 + c_2 - M_2 \sqrt{\frac{r_g}{r_l}}\right) - \frac{Q2_{gi}}{Q1_{gi}} \left(1 + c_1 - M_1 \sqrt{\frac{r_g}{r_l}}\right)}. \qquad (5)$$

This method of calculating the GMF will subsequently be referred to as the Dual DP technique and forms the basis of the Dualstream II wet gas flow meter detailed herein.

3 DEVELOPMENT HISTORY

3.1 Introduction

This section details the development of the wet gas meter, commencing with a short description of the initial work funded by BG International and carried out by BG Technology, through to the testing and development of the meter by ISA Controls at the National Engineering Laboratory.

3.2 BG Technology Trials

During 1997 BG Technology completed a programme of two-phase trials at their Low Thornley test facility. The main objective of the trials was the development of a low cost wet gas flow meter focusing particularly on the selection of a preferred meter design and orientation. Other key elements of the trials included an investigation in to the effects of system pressure and upstream disturbances on metering accuracy.

The wet gas meter for these trials consisted of a non-standard venturi (with elongated throat to facilitate the use of a nucleonic densitometer) downstream of a mixer plate. Two types of mixer plate were tested. The test matrix was devised to examine the performance of both meter configurations at the maximum test pressure of 25 barg and comprised of 39 tests, covering liquid flow rates of 500 to 5700kg/h and gas mass fractions of 0.3 to 1.0. At the test pressures, this corresponded to gas superficial velocities of 1 to 12m/s and gas void fractions of 0.95 to 1.0. The test matrix was used to test both meter designs in the vertical downward orientation and the preferred design in the horizontal orientation.

The tests concluded with the meter design shown below in Fig. 2 - a low cost wet gas meter that was capable of measuring gas flows to within ± 4 % FSD and liquid flows to within ± 6% FSD.

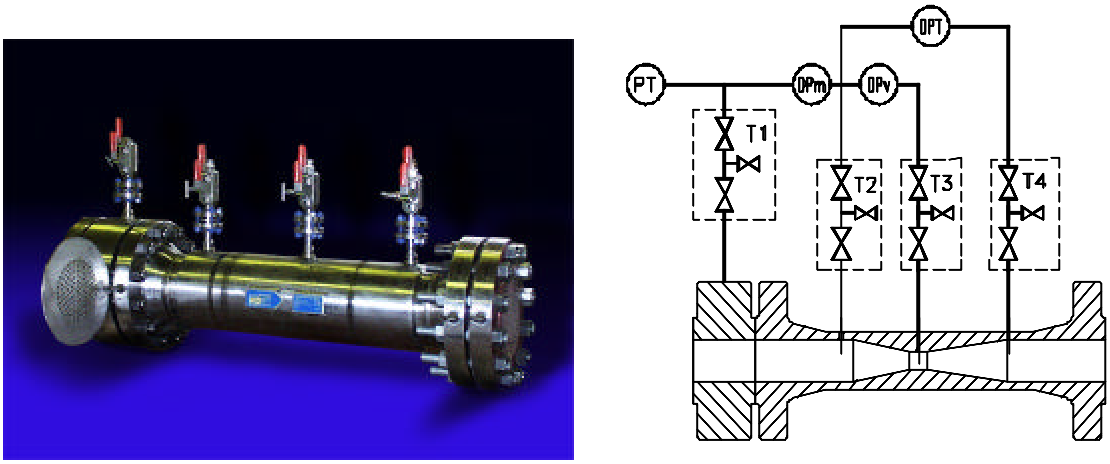

Fig. 2 - Wet Gas Meter Design Developed By BG Technology

Due to space constraints the reader is referred to [5] for a detailed analysis and presentation of the results. BG Technology have applied for a patent for the technology and granted ISA Controls Ltd the sole licence to manufacture and market the technology world-wide.

3.3 ISA Wet Gas Trials Conducted At The National Engineering Laboratory

3.3.1 Introduction

Prior to marketing the technology ISA manufactured a 6" unit for testing at the National Engineering Laboratory. The purpose of this test programme was twofold, firstly to repeat the BG results and secondly to check that the BG algorithms were transferable to standard venturis of varying size. Between December 1999 and June 2000 four test programmes were conducted. Each successive programme was planned on the basis of the findings of the previous one. This section details the evolution of the Dualstream II flow meter.

3.3.2 Test Programme 1 -December 1999

ISA manufactured a wet gas meter of the form shown in Fig. 2 consisting of a mixer plate and a classical venturi generally conforming to ISO5167. A spool piece with a nucleonic densitometer downstream of the BG meter was also included in these trials. The meter assembly installed in the NEL wet gas loop is shown in Fig. 3

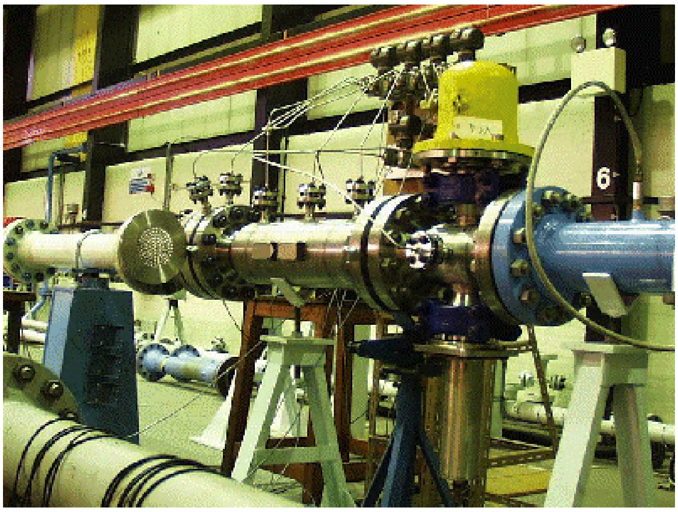

Fig. 3 - Initial Test Meter In The NEL Wet Gas Test Loop

The densitometer spool piece had originally been intended primarily as an aid to evaluating the response of the other DP signals. However, it was found that the densitometer restriction displayed a Murdock constant that differed sufficiently from that of the venturi to allow the GMF to be resolved (Fig. 4). The Dual DP technique using the signals from the densitometer spool piece and the venturi was shown to be capable of measuring the gas mass flow rate to well within 4% of reading. Liquid flow rates to within 10% of reading over a limited GVF range were also achieved (Fig. 5).

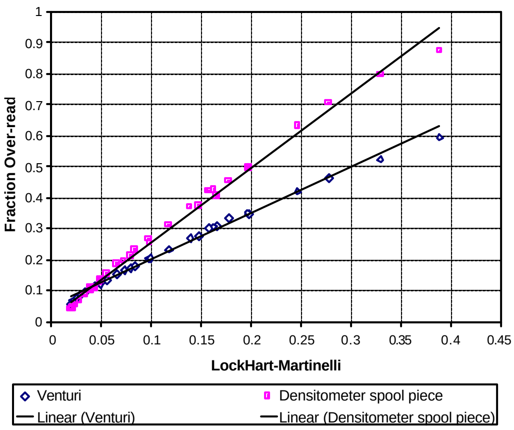

Fig. 4 - Murdock Plots For The Venturi And Densitometer Spool Piece

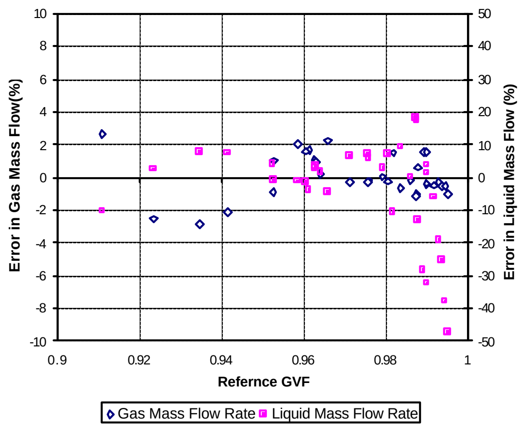

Fig. 5 - Plot Of Gas and Liquid Flow Errors - Venturi / Densitometer Spool Piece Combination

It was decided to carry out further work to try and obtain an understanding of the relationship between the geometry of a device and the Murdock constant. The ultimate aim was to maximise the demarcation between the second flow meter and the venturi, and thereby optimise GMF resolution.

3.3.3 Test Programme 2 - April 2000

Four different designs of DP flow meter were evaluated, brief details of which are outlined in **Table 1**. For reasons of economy it was necessary to test two meters at a time. DP device 3 was placed upstream of DP device 1, whilst DP device 2 was placed upstream of the DP device 4.

Table 1 - Meter Details For Test Programme 2

	Meter Details	
	(Effective) *b*	Restriction x-section (m^2)
DP device 1	0.716	0.01547
DP device 2	0.744	0.01007
DP device 3	0.772	0.01003
DP device 4	0.503	0.00425

A comprehensive test matrix encompassing a GVF range of 90-100% and a range of total volume flow rates of 200-800m^3/h was carried out at a test pressure of 40 bar for each meter pair.

The specific area of interest for these tests was the relationship between over-read and liquid content. The object was to find a meter with a Murdock constant differing significantly from that of the venturi and with as little scatter as possible.

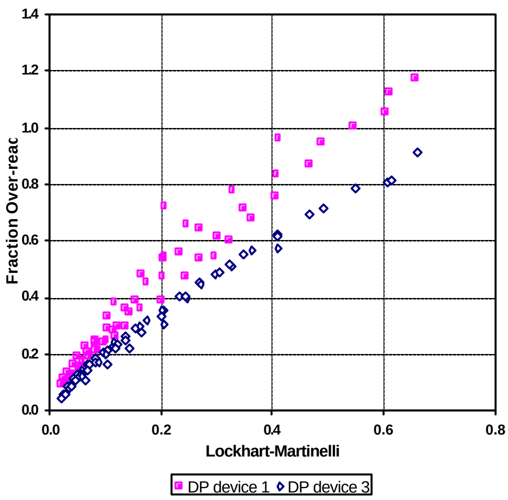

Fig. 6 - DP Device 1 and DP Device 3.

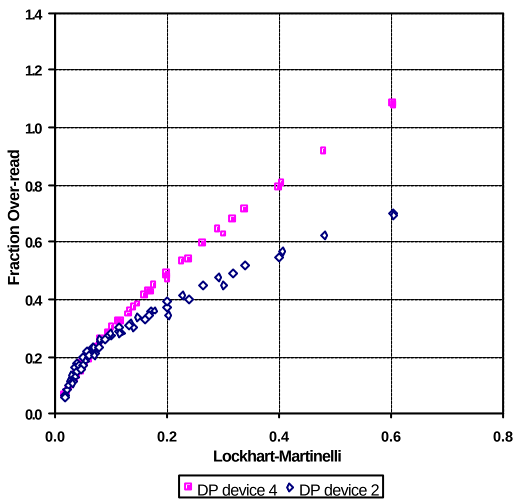

Fig. 7 - DP Device 2 and DP Device 4.

The results of these tests are shown in Fig. 6 and Fig. 7. Of the four flow meters tested DP device 4 was the most promising. DP device 1 proved to be wholly unsuitable for wet gas measurement, a large scatter was seen on the Murdock correlation whilst the DP signal had a tendency to vary even under constant flow conditions. The other three meters all had a well defined Murdock correlation. DP device 4 demonstrated less scatter and a greater sensitivity to liquid content than the others.

It was decided to carry out further, more extensive, tests on DP device 4.

3.3.4 Test Programme 3 - May 2000

DP device 4 was placed upstream of a venturi. The purpose was to evaluate the compatibility of the two meters for use as a Dual DP wet gas meter.

Table 2 - Meter Details for Test Programme 3

	Meter Details	
	(Effective) *b*	Restriction x-section (m^2)
Venturi	0.634	0.00676
DP device 4	0.611	0.00628

The test matrix shown in Fig. 8 was conducted at test pressures of 40, 50 & 60 bar over the full range of flow rates which could be supported by the NEL loop.

A plot of the overread versus the Lockhart-Martinelli parameter is shown in Fig. 9.

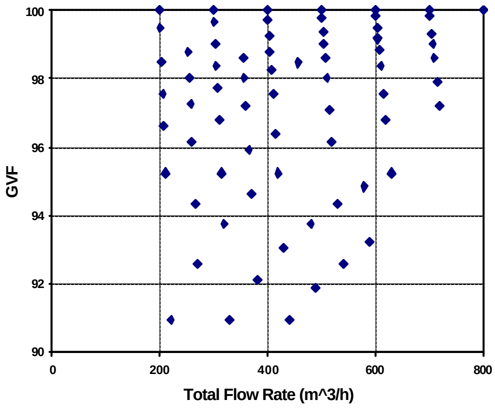

Fig. 8 - May 2000 - Test Matrix

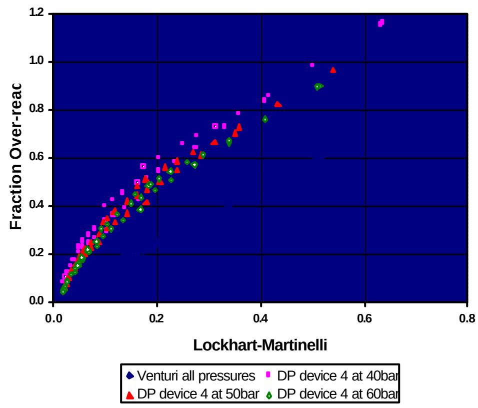

Fig. 9 - Device 4 and Venturi - LM verses Over-read at 40, 50 and 60bar

The Murdock correlation for the venturi meter was very well defined and was very repeatable over all three pressures. DP device 4 however, showed a lot of scatter at all three pressures and a distinct change in characteristic from one pressure to another. The scope of the scatter on the Murdock correlation for DP device 4 meant that it was impossible to resolve the GMF satisfactorily from the Dual DP equation.

These observations seemed to indicate that the performance of the venturi was enhanced by the fluid mixing provided by DP device 4, but that the absence of a fluid conditioner upstream of DP device 4 degraded its own performance.

In the light of these findings it was intended that DP device 4 should be used as a fluid mixer upstream of the venturi. The issue still to be resolved was the choice of meter to provide the second DP measurement. There was insufficient evidence to support the use of any of the meters tested so far in a commercial Dual DP meter, but it was believed that DP device 1, DP device 2 and DP device 3 could be eliminated, leaving DP device 4 and the original densitometer spool piece. It was therefore decided that a final programme of tests would be carried out in which DP device 4 would be retained as an upstream fluid conditioner. The purpose of these tests would be to compare the performance of the densitometer spool piece and a second DP device 4 as the downstream, second wet gas flow meter element.

3.3.5 Test Programme 4 (June 2000)

These tests were performed in two stages. For the first stage the configuration was DP device 4 → venturi → densitometer spool piece (DP4/V/DS) and for the second stage the configuration was DP device 4 → venturi → DP device 4 (DP4/V/DP4).

Table 3 - Meter Details For Test Programme 4.

	Meter Details	
	(Effective) b	Restriction x-section (m^2)
Venturi	0.634	0.00676
Densitometer spool piece	0.774	0.01007
DP device 4	0.611	0.00628

Tests were done at two pressures (40 bar and 60 bar). A comprehensive test matrix, similar to that shown in Fig. 8, was carried out at both pressures and for both meter configurations (DP4/V/DS plus DP4/V/DP4). The results are shown in Fig. 10 to Fig. 18.

The DP4/V/DP4 configuration was clearly superior to the DP4/V/DS configuration. There was excellent discrimination between the Murdock correlations of DP device 4 and that of the venturi, with very little scatter on either, see Fig. 11 & Fig. 15.

The curves were both quadratic rather than linear in nature and so two approaches were taken to solve for the GMF. The first was to use a piecewise linear function and split the Lockhart-Martinelli vs Fraction Over-read plots into two predominately linear regions and use Equation (5) to solve for the GMF. The second was to use a quadratic fit over the full data range. Fig. 12 and Fig. 13 show the relative error in the gas and liquid mass flow rates achieved using the first method, over the upper GVF range, at a test pressure of 40bar when using a linear fit. Fig. 16 and Fig. 17 show the same thing for 60 bar. An accuracy of better than 2.5% is demonstrated for the gas mass flow and an accuracy of generally better than 10% is achieved on liquid. Fig. 18 and Fig. 19 show the accuracy that was achieved when using a quadratic fit over the full data set for the solution of the dual DP.

The piecewise linear fit provided greater accuracy than for the quadratic fit, but with the limitation that either an iterative solution would be required, or some knowledge of liquid content would be necessary to ascertain which part of the curve the meter was operating on.

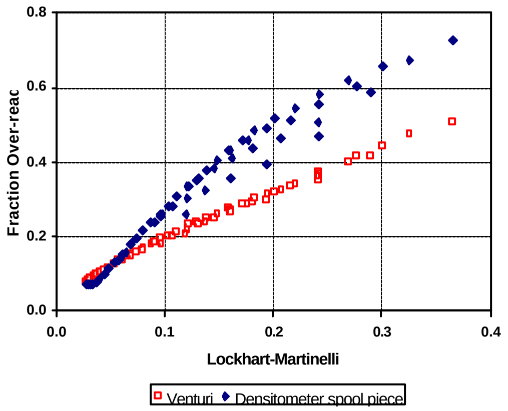

Fig. 10 - DP4/V/DS - 40 Bar

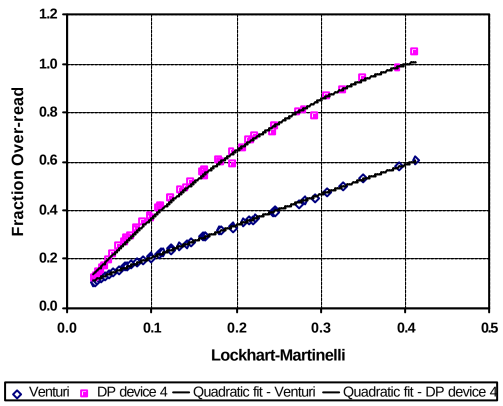

Fig. 11 - DP4/V/DP4 - 40 Bar

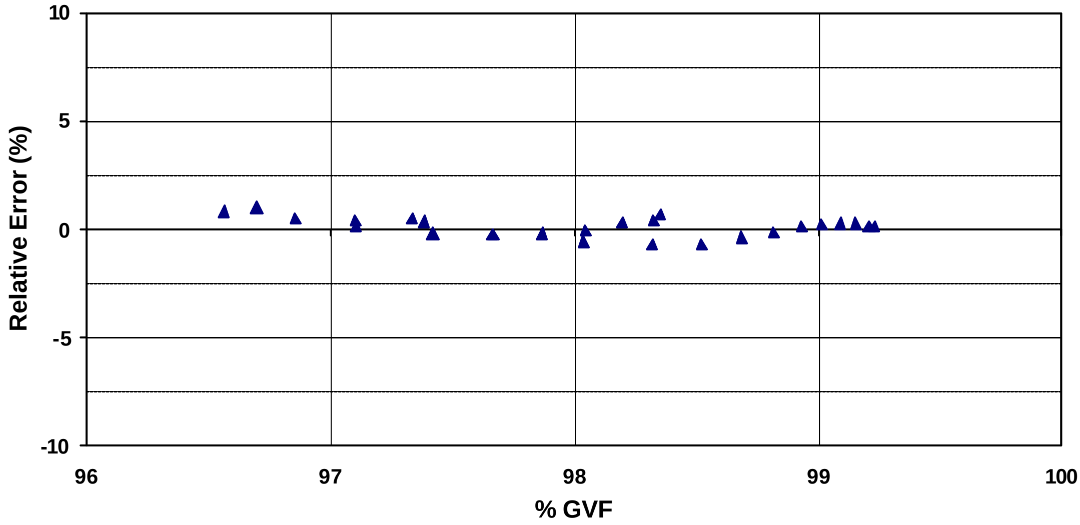

Fig. 12 - Error In Gas Mass Flow, Upper GVF Range, DP4/V/DP4 Configuration, 40 Bar

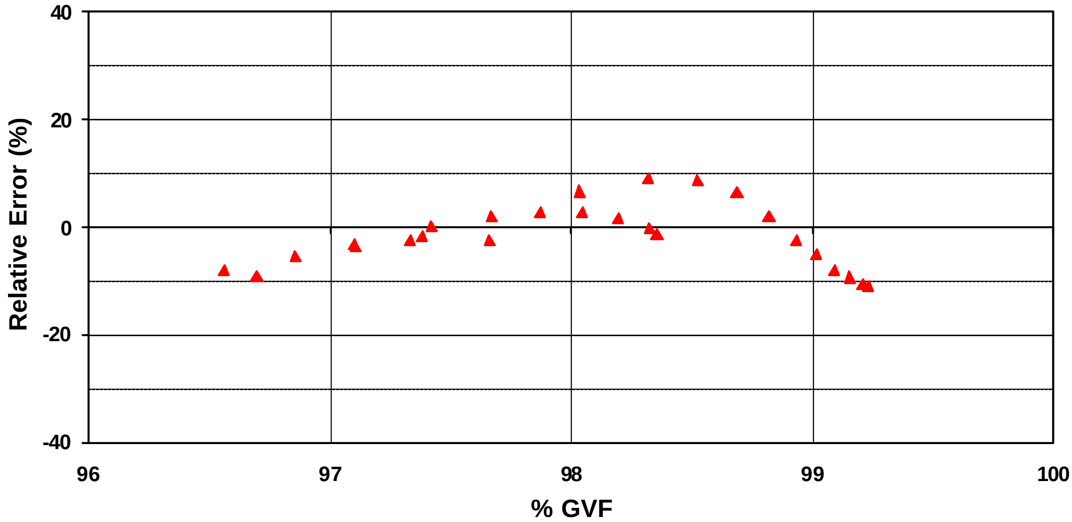

Fig. 13 - Error In Liquid Mass Flow, Upper GVF Range, DP4/V/DP4 Configuration, 40 Bar

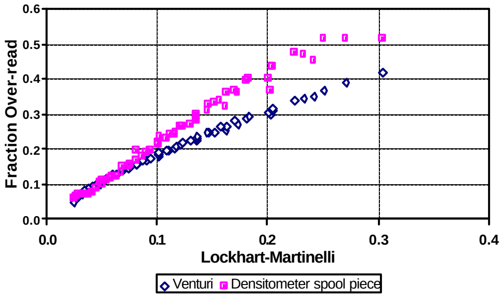

Fig. 14 - DP4/V/DS - 60 Bar

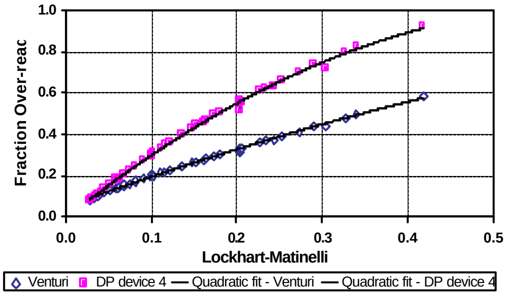

Fig. 15 - DP4/V/DP4 - 60 Bar

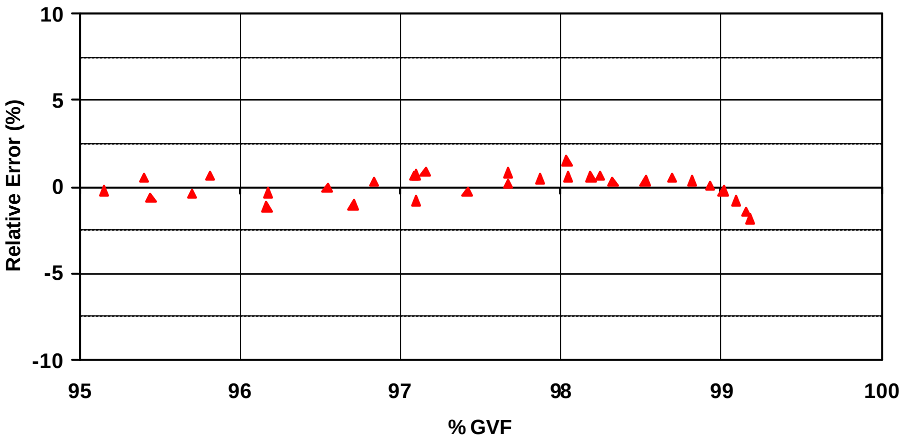

Fig. 16 - Error In Gas Mass Flow Over, Upper GVF Range, DP4/V/DP4 Configuration, 60 Bar

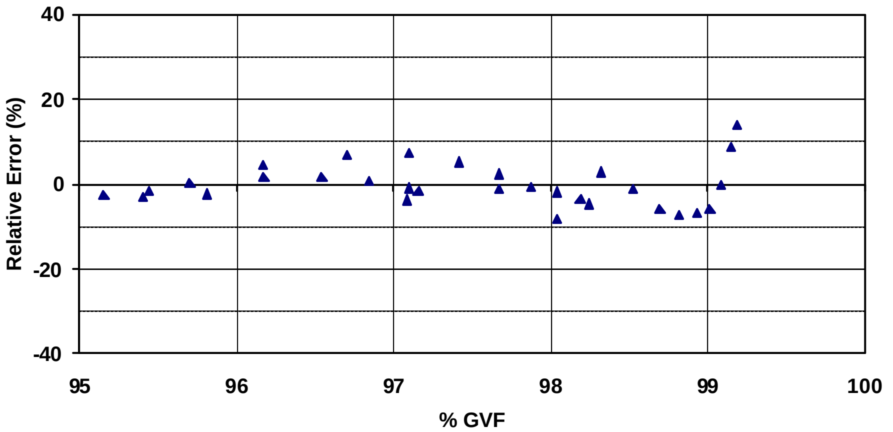

Fig. 17 - Error In Liquid Mass Flow Over, Upper GVF Range, DP4/V/DP4 Configuration, 60 Bar

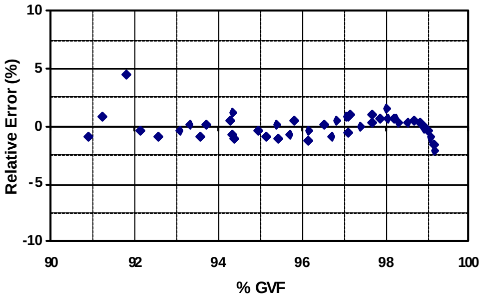

Fig. 18 - Gas Error - DP4/V/DP4 - 60 Bar

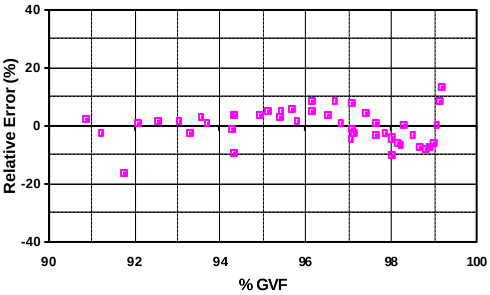

Fig. 19 - Liquid Error - DP4/V/DP4 - 60 Bar

4 FIELD TRIALS

A Dualstream II wet gas meter has been commissioned and is presently undergoing trials on the BG International operated Armada platform in the North sea (Fig. 21). The trial meter consists of a fluid conditioner, a wet gas venturi and a second DP device. The second DP device of the installed meter, Fig. 20, is of the same design as the densitometer spool piece detailed in the previous sections.

The meter has been installed upstream of the production separator and results are presently being collated and analysed.

Fig. 21 - The Armada Platform

Fig. 20 - The Installed Trial Meter

5 SENSITIVITY ANALYSIS

The greatest potential benefits and capital savings brought about by accurate wet gas flow measurement are in subsea applications. The elimination of long subsea test lines and infrequent separator well tests provide obvious benefits. However, long term reliability and accuracy is of paramount importance in a subsea environment. Venturi technology has substantial benefits in this area, predominately because of the fundamental simplicity of the device. To demonstrate the accuracy that could be expected of the Dualstream II meter in a subsea wet gas application let us consider the following sensitivity / uncertainty analysis.

The Murdock correlation may be expressed,

$$Q_{gc} = \frac{Q_{gi}}{1 + M\frac{1-x}{x}\sqrt{\frac{\rho_g}{\rho_l}}},$$

By taking partial derivatives of the above equation the sensitivity of the corrected gas mass flow rate (Q_{gc}) to the accuracy of the Murdock constant (M), GMF (x) and indicated flow rate (Q_{gi}) can be derived,

$$A_{Q_{gc}} = \pm\sqrt{(X_M A_M)^2 + \left(X_{Q_{gi}} A_{Q_{gi}}\right)^2 + (X_x A_x)^2}\ .$$

where,

$$X_m = -\frac{M\frac{1-x}{x}\sqrt{\frac{r_g}{r_l}}}{1+M\frac{1-x}{x}\sqrt{\frac{r_g}{r_l}}},$$

$$X_x = \frac{M\sqrt{\frac{r_g}{r_l}}}{x\left(1+M\frac{1-x}{x}\sqrt{\frac{r_g}{r_l}}\right)},$$

$X_{Q_{gi}} = 1$ and

the accuracy of a variable Y is denoted,

$$\frac{dY}{Y} = A_Y .$$

The assumption that the uncertainties of the three parameters are independent of each other has been made. This is not strictly correct because the uncertainty on the gas mass fraction is also a function of the uncertainty on the Murdock coefficient as detailed below, but it does provide us with a practical working formula.

The expression for the GMF using the dual DP method is,

$$x = \frac{\sqrt{\frac{r_g}{r_l}}\left(\frac{Q2_{gi}}{Q1_{gi}}M_1 - M_2\right)}{\left(1+c_2-M_2\sqrt{\frac{r_g}{r_l}}\right)-\frac{Q2_{gi}}{Q1_{gi}}\left(1+c_1-M_1\sqrt{\frac{r_g}{r_l}}\right)}.$$

The sensitivity of the GMF calculation to the Murdock coefficients (M_1 and M_2) and the ratio of indicated flow rates ($Qr = Q2_{gi}/Q1_{gi}$) is given,

$$\frac{dx}{x} = X_{M1}\frac{dM_1}{M_1} + X_{M2}\frac{dM_2}{M_2} + X_{Qr}\frac{dQr}{Qr},$$

where,

$$X_{Qr} = \frac{Q_r(ad-bc)(cQ_r+d)}{(cQ_r+d)^2(aQ_r+b)}$$

$$X_{M1} = \frac{M_1(ad-bc)(cM_1+d)}{(cM_1+d)^2(aM_1+b)}$$

$$X_{M2} = \frac{M_2(ad-bc)(cM_2+d)}{(cM_2+d)^2(aM_2+b)}$$

The parameters a, b, c and d for each of the equations above are given in the table below.

Table 4 - Parameters For Sensitivity Coefficients

	a	*b*	*c*	*d*
X_{Qr}	rM_1	$-rM_2$	$\rho M_1 - c_1 - 1$	$1+c_2-rM_2$
X_{M1}	rQr	$-rM_2$	rQr	$1+c_2-rM_2-Qr-Qrc_1-rQrM_1$
X_{M2}	$-r$	$rQrM_1$	$-r$	$1+c_2-Qr-Qrc_1+rQrM_1$

r in this table is the square root of the ratio of the densities as it appears in the calculation for GMF.

The accuracy of the Gas Mass Fraction, x, can be ascertained by combining the three errors using the root-sum-square method,

$$A_x = \pm\sqrt{\left(X_{Qr}A_{Qr}\right)^2 + \left(X_{M_1}A_{M_1}\right)^2 + \left(X_{M_2}A_{M_2}\right)^2}\ .$$

The assumption that the uncertainties of the three parameters are independent of each other has been made.

The uncertainty of the overall gas measurement can now be calculated by incorporation of the uncertainty of the individual indicated gas mass flow rates, $Q1_{gi}$ and $Q2_{gi}$ which can be estimated from,

$$A_{Q_{gi}} = \frac{dQ_{gi}}{Q_{gi}} = \sqrt{\left(X_{Cd}A_{Cd}\right)^2 + \left(X_D A_D\right)^2 + \left(X_d A_d\right)^2 + \left(X_{\Delta P}A_{\Delta P}\right)^2 + \left(X_{r_g}A_{r_g}\right)^2}$$

where,

$$X_{Cd} = 1, \qquad X_D = \frac{-2b^4}{1-b^4}, \qquad X_d = \frac{2}{1-b^4},$$

$$X_{\Delta P} = \frac{1}{2}, \qquad X_{r_g} = \frac{1}{2}.$$

The uncertainty in the density of the gas A_{rg} can be estimated from the uncertainty of the pressure measurement, A_p, and the temperature measurement, A_T,

$$A_{r_g} = \sqrt{\left(A_P\right)^2 + \left(A_T\right)^2}$$

Note that this uncertainty does not take account of many other influences which would effect the accuracy of the calculated density. Such things as the composition analysis and the choice of the equation of state would also impact the accuracy of the calculated density. The meter operates under the assumption of a time-invariant deterministic density formulation which in itself adds uncertainty.

The uncertainty associated with the expansibility has been neglected.

The ratio of the two indicated flow rates Qr, used in the gas mass fraction calculation has an uncertainty, A_{Qr}, that is the sum of the squares of the uncertainty of each of the measurements,

$$A_{Qr} = \sqrt{\left(A_{Q1_{gi}}\right)^2 + \left(A_{Q2_{gi}}\right)^2}$$

We now have sufficient information to estimate the uncertainty in the gas mass flow rate from the uncertainty in the key parameters.

Taking the uncertainty of the DP measurement based on the ISA SST 1500 transmitter specifications, and assuming an error of 1% on the Murdock coefficients yields the uncertainty characteristic shown in Fig. 22. This error includes a drift element for the DP transmitter that was assumed to be a random-walk rather than a systematic error causing a drift in one direction only. From inspection of Fig. 22 the maximum uncertainty in the gas mass flow rate over a 10:1 turndown in DP is less than 3% over a twelve year period.

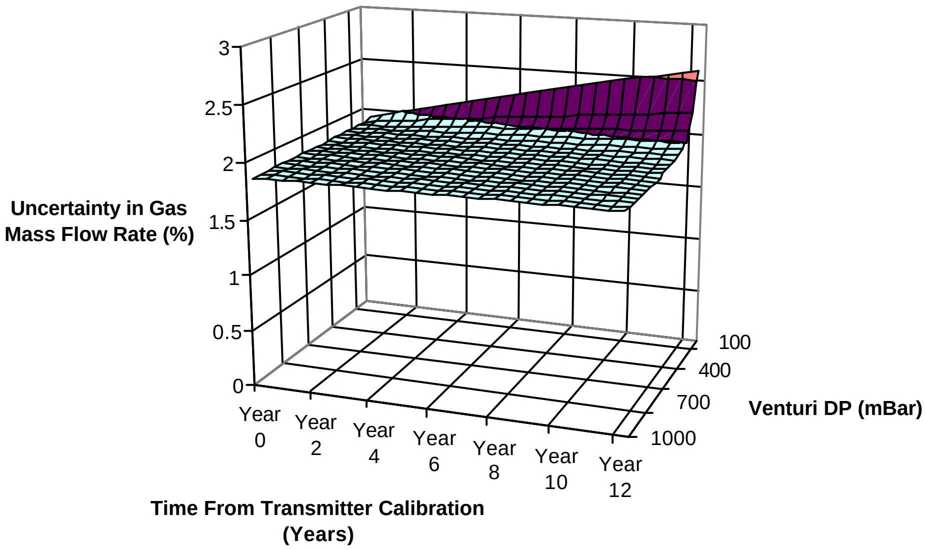

Fig. 22 - Uncertainty Analysis Of Dualstream II Wet gas Flow Meter.

6 CONCLUSIONS

The Dualstream II meter detailed in this paper has been shown to be capable of making allocation standard gas flow measurement in wet gas conditions. It is by no means a panacea for multiphase flow measurement and the authors believe it is unlikely that a single meter will be reliable, accurate and cost effective under all multiphase flow conditions and for all applications. Rather, the meter has been specifically developed for wet gas scenarios.

The Dualstream II meter calculates the GMF on-line and provides an accurate measurement of the gas mass flow rate and also a good indication of the liquid rate. It does not require the use of tracer dilution or other techniques to obtain the liquid rate, although, this does not preclude the use of tracers for meter verification and calibration checks. The device is a stand-alone wet gas flow meter that does not require manual intervention and is applicable for use subsea and in remote areas.

A major advantage of the Dualstream II approach to wet gas flow measurement is its simplicity. The parsimonious description used to characterise the venturi over-read in the presence of liquid, whilst still semi-empirical in nature, has numerous advantages over other more complicated metering methodologies where parameterisation is a significantly more arduous task. The meter is based on well proven and demonstrated principles and provides a very cost effective solution to wet gas measurement.

7 NOTATION

Q	Mass Flow rate
x	Gas Mass Fraction
X	Lockhart-Martinelli Parameter
D	Pipe Diameter
b	Beta Ratio
g	Acceleration Due To Gravity
Vs	Superficial Velocity
r	Density
M	Murdock Coefficient
c	Murdock Offset
C	Chisholm Constant
$\tilde{C}$	De Leeuw 'Constant'

subscripts

g	Gas
l	Liquid
gi	Indicated Gas
gc	Corrected Gas

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