MULTIPHASE FLOW METERING: 4 YEARS ON

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1 Abstract

Since the authors' last review in 2001 [1], the use of Multiphase Flow Metering (MFM) within the oil and gas industry continues to grow apace, being more popular in some parts of the world than others. Since the early 1990's, when the first commercial meters started to appear, there have been more than 1,600 field applications of MFM for field allocation, production optimisation and mobile well testing. As the authors predicted, wet gas metering technology has improved to such an extent that its use has rapidly increased worldwide. A "who's who" of the MFM sector is provided, which highlights the mergers in the sector and gives an insight into the meters and measurement principles available today. Cost estimates, potential benefits and reliability in the field of the current MFM technologies are revisited and brought up to date. Several measurements technologies have resurfaced, such as passive acoustic energy patterns, infrared wavelengths, Nuclear Magnetic Resonance (NMR) and Electrical Capacitance Tomography (ECT), and they are becoming commercial. The concept of "virtual metering", integrated with "classical MFM", is now widely accepted. However, sometimes the principles of the MFM measurements themselves are forgotten, submerged in the sales and marketing hype.

2 Introduction

Over the past four years, MFM has come a long way from being generally recognised as an area of research, development and technology application, to representing a discipline *per se'* within the oil and gas industry. The benefits associated with MFM, as outlined in the authors' previous review [1], have been confirmed by the way MFM technology has succeeded in fitting with other technologies toward global field-wide solutions.

However, MFM has not yet achieved its full potential nor is everybody in the oil and gas industry aware of what MFM can and cannot do.

Nowadays, it is not surprising to hear of a multi-million dollar contract being signed by an Operator for a Manufacturer to supply fifty MFM's for a field development, but it is debatable whether there has been any revolutionary advancement in MFM solutions since 2001. What has undeniably improved is the confidence in the subsea versions of the MFM technology and in the hardware reliability, the stability of the sensors and the mean time to failure. Also improved is the collaboration between Operator and Manufacturer, forged by working together in the field over the past years.

However, have all the technical routes to MFM innovation been fully exploited? Are there still physical and economic constraints that prevent this technology from moving forward?

3 MFM Trends

Since 2001 there have been several published reviews on the number of MFM installations worldwide [2][3]. However, it remains difficult to establish the official figures, as it is necessary to distinguish between:

- MFM's installed and currently working;
- MFM's installed, but now discontinued;
- MFM's ordered, but not yet delivered;
- MFM's delivered, but not yet installed;
- MFM's used as portable well testing solutions.

This type of information is commercially sensitive due to the high competition in the market of commercial MFM's.

Following a market research by the authors in 2005, it appears that a total figure for MFM installations to date, as defined in the bulleted list above, is in excess of 1,600. Of these, 10% is represented by mobile well testing applications and a further 20% corresponds to wet gas metering. Western Europe, Asia-Pacific and the U.S. together represent 75% of the total number of MFM installations. Asia-Pacific has seen a sharp increase in MFM applications since 2001 and has now overtaken the North Sea, where most of the initial installations of MFM's began. However, the 1,600 figure does not account for all of the installations since the early 1990's as some Manufacturers have disappeared and some of the solutions have been discontinued. The past four years has seen mergers amongst manufacturers, but the entry of newcomers has kept the total number of commercial manufacturers at around twenty. In some ways, these mergers have helped in the disclosure of information to the public domain, but knowledge has also been lost. Some of the smaller manufacturers, who were around four years ago, have experienced mixed fortunes, becoming established "names" and setting trends with the larger providers, while others have not really "cracked" the market.

Table 1 presents a list of the current commercial MFM's, divided into "traditional" MFM's (Gas Volume Fraction, GVF<95-98%), high gas volume fraction MFM's (GVF>95-98%) and Downhole MFM's (DMFM's).

Table 2, **Table 3**, **Table 4** and **Table 5** present possible ways to classify the current commercial MFM's based on their features. Those meters that are still under development have not been included (e.g. IFP, University of Manchester, Imperial College, Robert Gordon University/QuantX). Also omitted are those MFM solutions that need to be integrated with other techniques in order to provide the three flow rates (e.g. pressure pulse, virtual metering).

Although the authors have developed their own views on the MFM solutions available, the tables of MFM's only provide an immediate overview of the MFM market today and indicate what applications the contractors claim they may be used for.

MFM's	High GVF MFM's	DMFM's
Roxar-MPFM	Roxar-WGM	QuantX
Schlumberger/Framo-Vx	Schlumberger/Framo-Vx	Weatherford/CIDRA
Flowsys/FMC-TopFlow	Petrotech-Smartvent	Schlumberger
Jiskoot-MIXMETER		
TEA Sistemi-Lyra	TEA Sistemi-VEGA	
Agar-MPFM	Agar-MPFM 400 loop	
Red Eye-REMMS	Red Eye-REMMS (?)	
Abbon-Flow Master	Abbon-Flow Master	
Haimo-MPFM	Haimo-MPFM	
ESMER	ESMER (e.g. + V-cone)	
Kvaerner-DUET	Kvaerner-CCM	
Kvaerner-CCM		
Accuflow	Accuflow	
Daniel/Emerson-MEGRA	Solartron/Emerson-Dualstream II	
Hydralift-Wellcomp		

Table 1: current commercial MFM's, WGM's and DMFM's

Flow conditioning /Homogenisation	Leave-as-it-is	In-line separation	Isokinetic sampling
Roxar-WGM	Roxar-MPFM	Agar	TEA Sistemi-VEGA
Jiskoot-MIXMETER	Schlumberger/Framo-Vx	Wellcomp	
TEA Sistemi-Lyra	Flowsys/FMC-TopFlow	Accuflow	
Daniel/Emerson-Dualstream II	Daniel/Emerson-MEGRA (for GVF<25%)	Daniel/Emerson-MEGRA (for GVF>25%)	
ESMER (+ V-cone)	Abbon-Flow Master	Red Eye-REMMS	
	ESMER	Haimo-MPFM	
	Petrotech-Smartvent		
	Kvaerner-DUET	Kvaerner-CCM	

Table 2: current commercial MFM's with/without flow conditioning

Gamma source	No Gamma source
Roxar-MPFM	Roxar-WGM
Jiskoot-MIXMETER	Red Eye-REMMS
Daniel/Emerson-MEGRA	Daniel/Emerson-Dualstream II
Kvaerner-DUET	Kvaerner-CCM
Haimo-MPFM	Agar
Schlumberger/Framo-Vx	Wellcomp
TEA Sistemi-Lyra	TEA Sistemi-LYRA (for WC>30%)
	TEA Sistemi-VEGA
	Flowsys/FMC-TopFlow
	Petrotech-Smartvent
	Abbon-Flow Master
	ESMER
	Accuflow

Table 3: current commercial MFM's with/without gamma ray source

Intrusive	Non-intrusive[*]
Roxar-WGM	Roxar-MPFM
Jiskoot-MIXMETER	Schlumberger/Framo-Vx
TEA Sistemi-VEGA	TEA Sistemi-LYRA
Kvaerner-CCM	Kvaerner-DUET
Daniel/Emerson-Dualstream II	Daniel/Emerson-MEGRA
Haimo-MPFM (flow conditioning vessel)	Petrotech-Smartvent
Accuflow	Flowsys/FMC-TopFlow
Red Eye-REMMS	Abbon-Flow Master
Agar	ESMER
Wellcomp	

Table 4: current commercial MFM's intrusive/non-intrusive
(*) Venturi's are not regarded as intrusive devices

X-correlation	No X-correlation
Roxar-MPFM	Roxar-WGM
Kvaerner-DUET	Kvaerner-CCM
Haimo-MPFM (flow conditioning vessel)	TEA Sistemi-LYRA
Flowsys/FMC-TopFlow	Schlumberger/Framo-Vx
	Daniel/Emerson-MEGRA
	Petrotech-Smartvent
	Daniel/Emerson-Dualstream II
	Abbon-Flow Master
	ESMER
	Accuflow
	Red Eye-REMMS
	Agar
	Wellcomp
	TEA Sistemi-VEGA
	Jiskoot-MIXMETER

Table 5: with/without cross-correlation

The cost of MFM's today remains in the range of US$100,000-US$500,000 (varying with onshore/offshore, topsides/subsea, the dimension of the tool and the number of units ordered), even though there has been an estimated increase of 25-50% in production facilities CAPEX since 1999 [4]. This CAPEX rise has been "cancelled out" by the fact that MFM's have become up to 50% cheaper, mainly due to the increased competition in the market and the rise in units sold.

When comparing a traditional production layout (with test separator and test lines) with an installation with MFM, it still appears that the second option involves much lower CAPEX. The installed cost of a separator varies enormously with rates, pressures, temperatures, chemistry of the fluids to be treated, onshore/offshore, but is typically in the range US$1m-5m. It may also require several instruments, depending on its complexity.

The test lines may be omitted in some MFM installations. Carbon steel flow lines of 4-6" in diameter cost approximately US$1.3m-3.6m per Km installed.

OPEX costs associated with test separators can be around US$350,000 per year for offshore installations. In 1999, it was estimated [4] that the OPEX for a MFM was likely to be 25% of the cost of the meter itself for the first year, then US$10-40,000 per year (for both onshore and topsides applications). Today, with the increased reliability of the MFM hardware and more structured training of personnel, OPEX is spread more evenly over the operating life of a MFM.

4 The MFM Community

The oil and gas industry is a global business, yet the MFM expertise is not equally distributed worldwide. Not all Operators have in-house MFM specialists and, within the Service Companies, only a select handful of people can be defined as experts in MFM. As with all in-house specialists in any particular discipline, there is reluctance to share too much of their hard-won knowledge, which can lead to them being isolated from the rest of the company.

With MFM now being accepted as a standard solution for existing and new developments, competition among MFM suppliers has intensified. Despite the existence of a global MFM community, it remains very difficult to release and share confidential data. A small/medium Operator without direct MFM experience will find it almost impossible to obtain a fair and independent view of the advantages and disadvantages of each commercial MFM from discussions with the Manufacturers or other Operators. The old trick of going to see Manufacturer A to ask about the downfalls of the product sold by Manufacturer B (and *vice versa*) only works up to a certain point.

There has been a constant rise in the availability of MFM handbooks, guidelines, recommendations and technical publications, but so far, none of them has described in detail the pros and the cons of each commercially available MFM solution. Such guidelines are usually limited to lists of MFM solutions (full separation, partial separation, in-line, etc.), MFM definitions (what GVF is, how calibration is done, etc.), standards by the International Organization for Standardization (not always directly applicable to the specific case of MFM) and ways to report the performance of a meter. This only captures the performance of a MFM as a "black box", but does not teach how to keep track of all the possible uncertainties and inaccuracies that are inherent in each individual MFM technique. Also, there is the risk of continual reference to original equations or relationships, while their actual implementation in commercial solutions is often adapted to suit a specific approach. There are very few worked examples in the public domain that do not have a "commercial agenda" and are sufficiently accurate to enable a critical and informed selection of meters.

As a result, there is an emerging class of consultants who perform studies on behalf of Operators and Government bodies and mediate between them and the Manufacturers.

5 Example of "forgotten basics"

As previously stated, the hardware and sensors have improved tremendously, but it is important not to forget the principles of the measurements themselves. Let us consider the basic concept of the gamma ray measurement of two-phase flow.

Figures 1, **2** and **3** illustrate the absolute error in phase fraction measurement in a two-phase flow system of air-water, air-oil and water oil, respectively. The calculations

are based on a 4" diameter pipe section made of Perspex material, with single-energy gamma-ray beams passing through pipe walls of 12.7mm of thickness. The sources and energy levels used in this example are those commonly adopted in commercial MFM's, namely, Americium 241 (17.8 and 59.5 KeV), Barium 133 (31, 81 and 356 KeV) and Caesium 137 (33 and 661 KeV). Assuming that all sources can provide the same initial intensity, I_0 = 5,000 counts/s, it is possible to calculate the intensity (I) of a single-energy gamma-ray beam, transmitted through the Perspex conduit in which there are two static or flowing phases, as:

$$I = I_0 \exp\left(-\gamma_{wall}x_{wall} - \gamma_1 x_1 - \gamma_2 x_2\right)$$
Eq. 1

where:

γ_1 and γ_2 are the linear attenuation coefficients of phase 1 and phase 2, respectively;
x_1 and x_2 are the thicknesses of phase 1 and phase 2, respectively;
γ_{wall} is the linear attenuation coefficient of the conduit;
x_{wall} is the thickness of the conduit.

The absolute error in phase fractions is given by [5]:

$$\delta\varepsilon_{1,2} = \pm\frac{1}{(\gamma_1 - \gamma_2)D\sqrt{Ct}}$$
Eq. 2

where:

D is the internal diameter of the pipe;
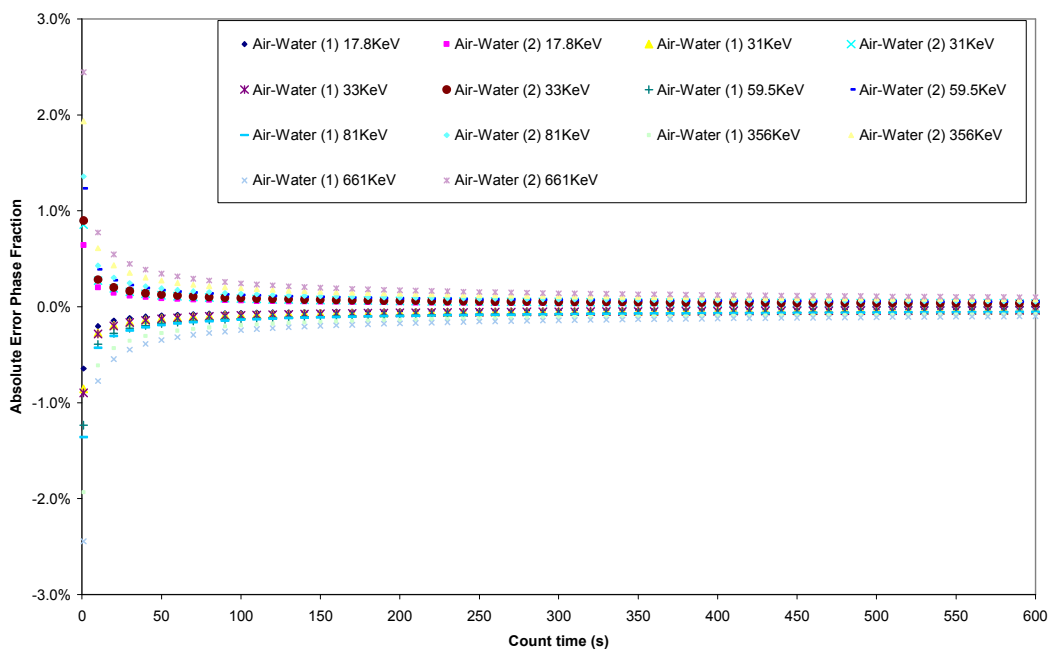C is the transmitted count rate;
t is the counting time.

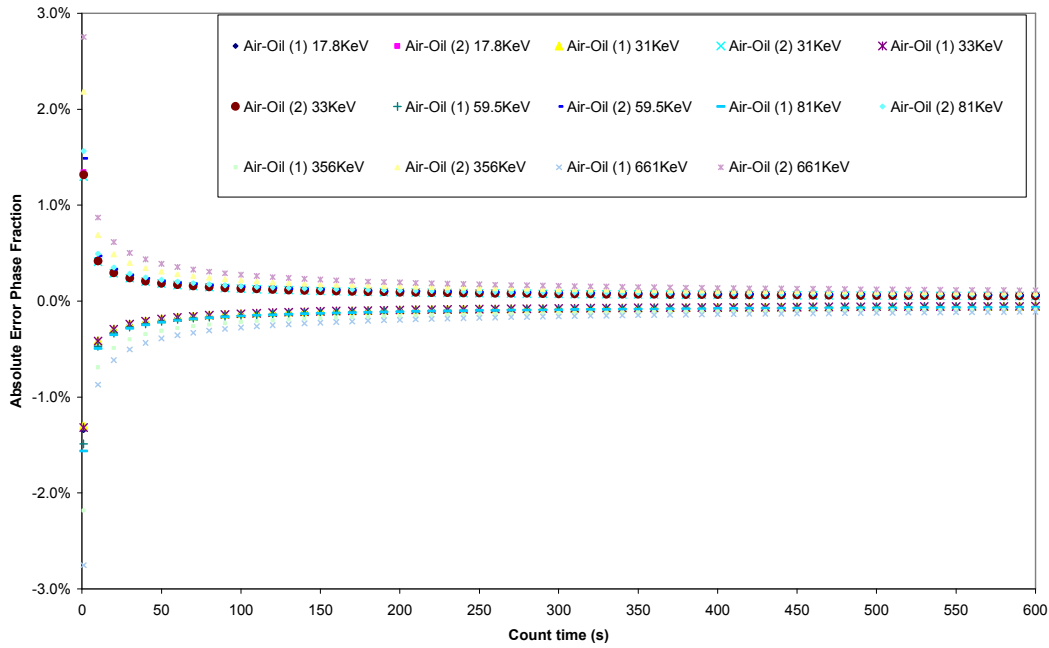**Figure1: Absolute error in phase fraction for an air-water system.**

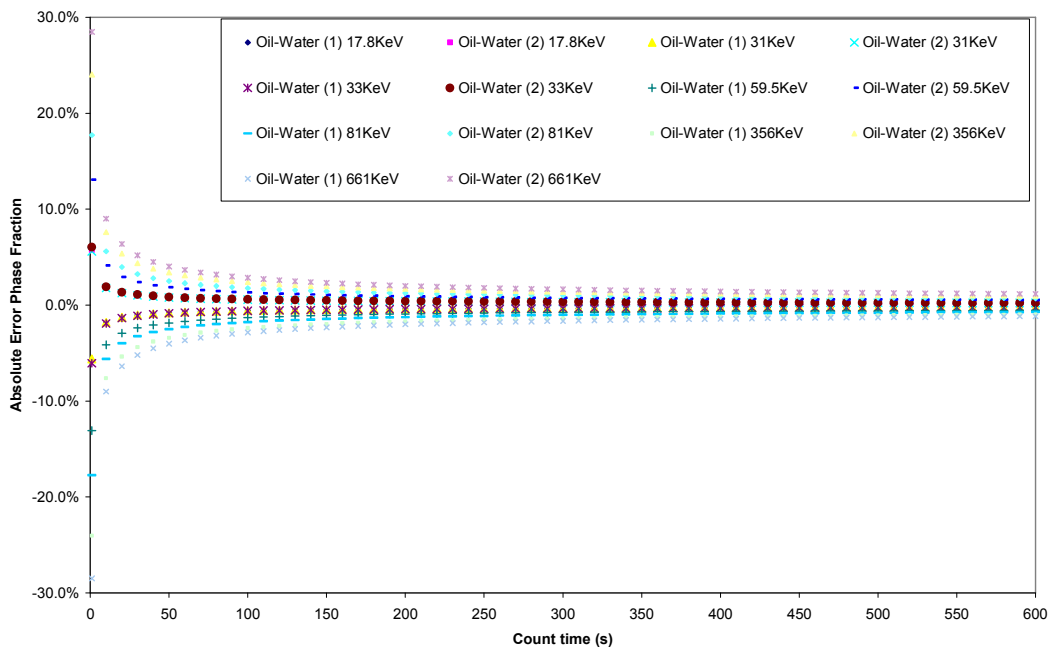**Figure 2: Absolute error in phase fraction for an air-oil system.**

Figure 3: Absolute error in phase fraction for an oil-water system.

The plots above illustrate that the accuracy of the measurement is a function of the counting time. They also show that the measurement errors for air-oil and air-water systems are quantitatively similar, while that for oil-water systems is several times larger due to the small difference between the water and oil density.

Gamma ray measurements are usually associated with a Venturi in order to measure the total (or mixture) momentum from which the phase flow rates are calculated. The

classical equation used to calculate the total flow rate, assuming homogeneous flow, is given by:

$$Q_t = C_q A \sqrt{2 \cdot \left(\frac{\Delta p}{\rho} - g \cdot \cos \theta \cdot L \right)}$$
Eq. 3

where:

C_q is the flow coefficient;
ρ is the bulk or mixture density;
A is the cross sectional area of the Venturi throat;
L is the distance between pressure taps;
ΔP is the measured pressure difference;
θ is the deviation angle from the vertical.

The above parameters can be divided into those that can be measured in the field and those that can be established in the factory. The design of the meter establishes the cross sectional area of the Venturi throat, the distance between the pressure tappings and the full scale of pressure transducer, while the flow coefficient can be determined in the factory by calibration. The remaining parameters are measured in the field. Of course, uncertainties in parameter determination can play an important role.
Figure 4 shows the relative error in mixture density from error propagation. The assumed uncertainty in gas density is 5% while that in liquid density is 1%. The gas fraction and the water cut are affected by an uncertainty of 3%. A strong influence of gas fraction is highlighted.
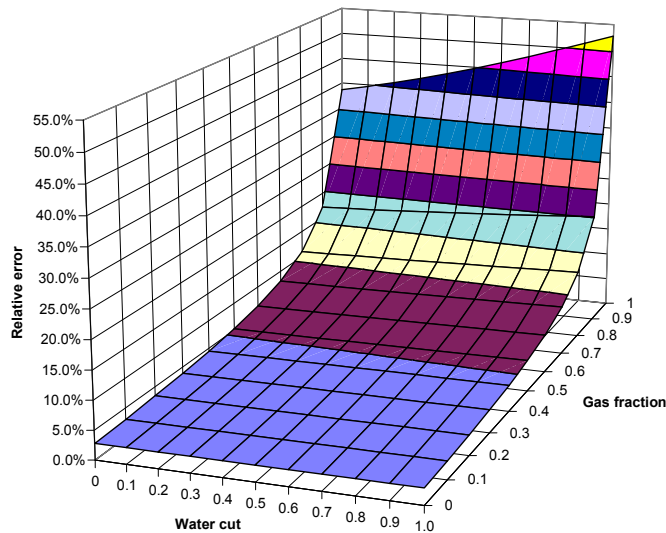

Figure 4: Relative error in mixture density for a gas-oil-water system.

The uncertainties for remaining parameters needed in the design of a 3" DN Venturi, with a cross sectional ratio of 0.5, are reported in **Table 6**.

Parameter	Uncertainty
Distance between pressure tappings	10^{-4} m
Cross sectional area	$1.2\ 10^{-5}$ m^2
Pressure difference	0.1 % of reading

Table 6: Design uncertainties of Venturi's

It is possible to estimate the error propagation from **Eq.3** and so highlight the influence of the measured parameters, pressure difference and mixture density. **Figure 5** shows the error in mixture flow rate vs. the mixture density and the pressure difference. The two parameters exert a considerable influence on the error, especially when they are relatively small in value. Errors can vary between 3.5% and 75%.
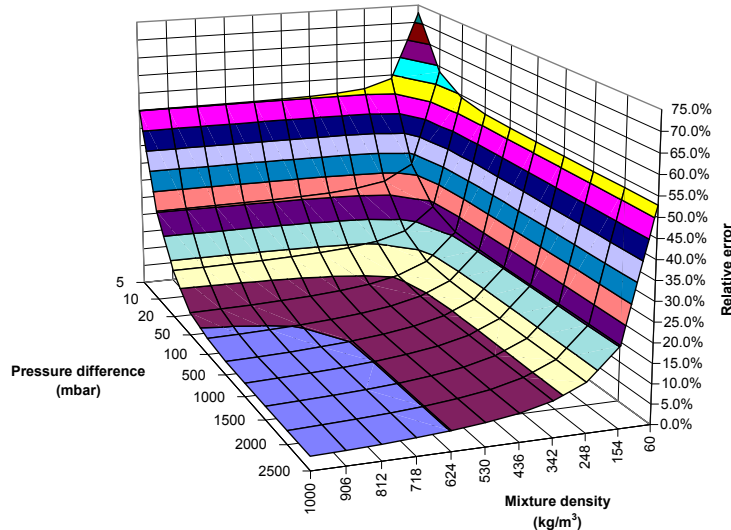

Figure 5: Relative error in mixture momentum for a gas-oil-water system.

The direct consequence of the above is the definition of an envelope of operation (rangeability), where the error is less than a fixed value, as shown in **Figure 6**.
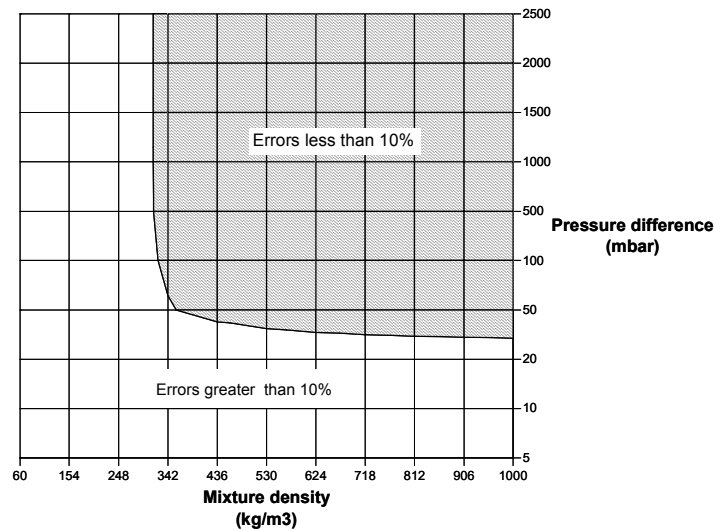

Figure 6: Envelope of operation for a mixture momentum for a gas-oil-water system.

Last but not least, the discharge coefficient is a model calibration parameter that is mainly dependent on the fluid properties. Oil viscosity can be much higher than that of water, whereas the density difference between the two phases is relatively small, so the Reynolds number of the flowing mixture will decrease as the oil fraction increases. For Reynolds numbers lower than 100,000, the discharge coefficient assumes a variable value, but this becomes constant at higher Reynolds numbers. Thus, the higher the oil viscosity, the more important it is to provide an accurate description of

the discharge coefficient pattern vs. Reynolds number. Experimental data, which exhibit this dependency, are shown in **Figure 7** [15]. The oil viscosity, in this case, was only 10 mPa·s.
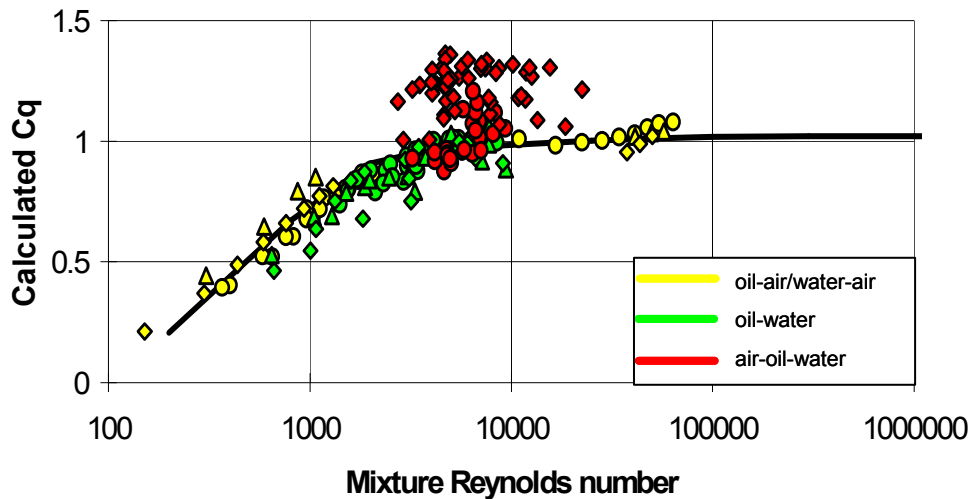

Figure 7: Discharge coefficient vs. Reynolds number.

6 Novel technologies, R&D trends

As mentioned previously, there have been no truly novel MFM technologies breaking through over the past four years. However, some of the novel technologies identified in 2001 have been the subject of rather intensive research that has now led to some significant results.

X-ray and gamma ray tomography [6], ECT [7][8] and microwave techniques [9] have already undergone noticeable improvements since the authors' previous review [1]. If combined with independent velocity measurements (e.g. cross-correlation, Venturi), they could provide the flow rates of each phase.

Water cut meters based on infrared spectroscopy are now commercially available. They aim at measuring the volumetric proportion of oil in a mixture of petroleum and water by passing through the stream a beam of infrared light that is absorbed by oil, but not water. Several infrared wavelengths can be measured to allow extending the range of applicability of this optical technology to low water cuts and to reduce the effects of the presence of gas.

Research has continued into NMR [10]. Surprisingly, Pulsed Neutron Activation (PNA) has not been the focus of any substantial studies, despite the fact that it could be the only way of directly measuring individual component velocities and fractions.

Cheaper "stand-alone" technologies such as pressure pulse [11][12] and acoustic noise interpretation [13] are now commercially available. Although there may cases

where these technologies are not suitable, they should be able to compete with other solutions on price.

The integrated monitoring and metering approach is nowadays referred to as "virtual metering" [14]. Commercial solutions are now available, although virtual metering should be treated as a supplement or back-up to MFM's rather than a replacement.

There is a developing trend in the industry to "mix and match" different MFM solutions from different provider to better exploit their inherent strengths. This has probably been triggered by the need to extend the operating envelope of previously existing MFM's and has led to some positive results.

Direct R&D efforts continue within academia, research organisations and Service Companies. While some oil companies still retain some level of in-house research, the majority of them have opted for contracted research projects, in which they share supervision.

7 Conclusions

The trends in MFM sales and installations, the establishment of wet gas metering as a special niche and the evolution of some novel technologies have been as predicted in 2001 [1]. Also, the interaction between Operators and Manufacturers has improved, but there remains a paucity of quality field data in the public domain. This is why more effort is needed to define much more specific MFM Regulations, with a special focus on the strengths and the downfalls of each MFM metering principle.

Though MFM technology has now been widely applied in hydrocarbon recovery systems, there are still unresolved questions regarding the accuracy and range of applicability of commercial meters. There is a tendency to forget some of the basic limitations, as exemplified here by the cases of gamma densitometry and Venturi meters. Even in the case of straight pipe flows, the structure and local behaviour of multiphase flows is still, in all but the simplest cases, poorly understood and certainly not predictable. Small wonder then that the developing flows through the complex geometries which occur in many metering systems are not captured by the simplified models use to interpret meter outputs. Perhaps the real surprise is that, even after discounting the sales hyperbole common in this field, the meters work even as well as they do! There is a long way to go in this field and the user should realise that MFM's are one piece of the optimised production system jigsaw.

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