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Paper 6.2

Two-phase (Gas/Liquid) Flow Metering of Viscous Oil Using a Coriolis Mass Flow Meter: A Case Study

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1 INTRODUCTION

Coriolis mass flow metering has been established as the most accurate widely-used industrial flow measurement technology since its introduction in the mid 1980s. Coriolis meters operate (Fig. 1) by oscillating a flow-tube (typically 1-300 mm in diameter), at the natural frequency of a selected mode of vibration, the so-called drive mode. Two sensors monitor the flow-tube vibration as the process fluid passes through. The frequency of oscillation (in the range 50Hz - 1kHz depending on flow-tube geometry) is determined by the overall mass of the vibrating system, and hence for a given flow-tube, this varies with the density of the process fluid. Accurate determination of the frequency of vibration thus enables the process fluid density to be calculated. The geometry of the flow-tube is arranged so that Coriolis forces act to give a phase difference between the two sensor signals, roughly proportional to the mass flow of the process fluid (which in the largest meters may approach 1 tonne/s).

While the flow-tube is essentially a mechanical device with a few electrical transducers (sensors and drivers), the transmitter is an electronic and computational device which drives and monitors the flow-tube, and which generates the measurement data. A long-term research programme at the University of Oxford has been developing all-digital transmitter technology [3, 4, 5] with various improvements including a very fast response time [6] and an ability to operate in two-phase flow [1-5]. The transmitter architecture in Fig. 1 includes audio quality analog-to-digital converters (ADCs) and digital-to-analog convertors (DACs), with 24-bit samples delivered at 48kHz. Field Programmable Gate Arrays (FPGAs) are chips consisting of configurable logic blocks, capable of carrying out complex digital algorithms in real time and in parallel. FPGA tasks include interfacing to the ADCs and DACs, generating the drive waveform and pre-filtering of the measurement data. This architecture is used in Invensys Foxboro's commercial product, the CFT-50 Coriolis transmitter, which was used in the trials.

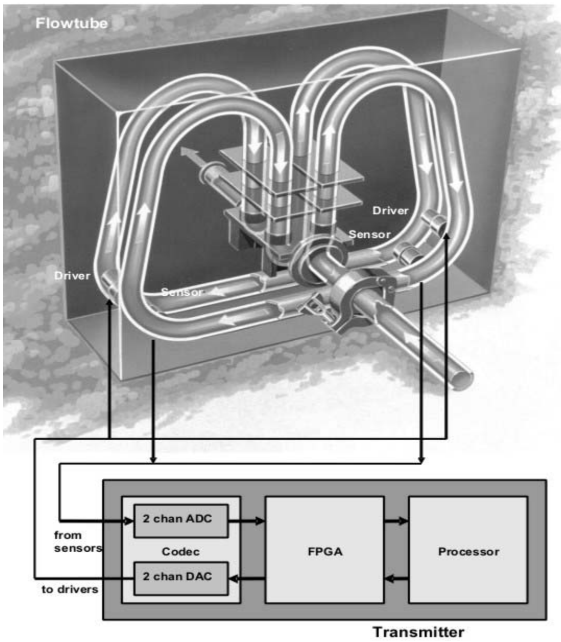

Fig. 1 - Coriolis meter architecture

Reizner [7] provides a good background to the problems associated with metering two-phase flow using Coriolis meters. In brief, it is difficult to maintain flow-tube oscillation in two-phase, as the condition induces very high and rapidly fluctuating damping (up to 3 orders of magnitude higher than for single phase conditions). When the transmitter is unable to maintain oscillation, the meter is described as "stalled", and no (valid) measurement can be provided. Even where stalling is averted, large measurement errors may be induced into the mass flow and density measurements.

Previous papers have described the use of a digital drive and an agile control system to maintain flow-tube oscillation through two-phase flow or batching to or from an empty flow-tube [2,8]. In this paper, it is assumed that the transmitter has this capability. The focus is restricted to correcting for two-phase flow errors in mass flow and density.

2 TWO-PHASE FLOW CORRECTION METHODOLOGY

The definition of two-phase flow correction used here is the application of compensation to the raw mass flow and density readings for the effects of two-phase flow, in order to generate improved (corrected) readings, where the correction is based solely on data available within the flowmeter. As discussed in [1,6] there have been a number of attempts to develop physical models techniques. An overview of an empirical methodology for developing a two-phase flow correction is provided in this section; the technique is the basis of a number of patents [3,4, 8-11].

The means of two-phase correction is some form of model which predicts, from configuration data and on-line internally-observed parameter values, the required corrections to the raw mass flow and density values. While a universal correction model based on physical principles would be ideal, the current state of knowledge is far from complete. However, there is an accumulating body of experience which indicates that, for a specific flow-tube geometry and process liquid, within a reasonable range of application conditions (e.g. flow, temperature, pressure), empirical on-line correction models can provide substantial improvements on the uncorrected measurements.

To develop a model, an experimental grid of test points is defined, covering a range of flowrates and gas void fractions (GVFs) – the proportion by volume of gas in the two-phase mixture. Controlled variation in other conditions, such as inlet pressure and temperature, may be included in the experimental grid. At each experimental point, internal parameters are recorded and averaged over a pre-determined time period (typically 30-120s) for use in model fitting. Given independent measurement of the true single phase flows of the liquid and gas phases, and assuming (or engineering) good mixing between the phases (i.e. no slip), it is possible to calculate the true mass flow and (mixture) density, and hence to calculate the corresponding errors in the raw measurements. Additional instrumentation is required to provide pressure and temperature information for the single phase gas and for the mixture, to enable PVT calculations of gas volume in the mixture and hence void fraction.

A number of different model-fitting techniques might be used to predict the mass flow and density errors based on the internally observed parameter values, but the Oxford experience has found the use of neural nets to be satisfactory. The resulting neural net models can be run on-line to apply corrections to the raw mass flow and density readings in the presence of two phase flow. Examples of the types of parameters, and the neural net models, are described in [1].

3 TRIAL AT THE NATIONAL ENGINEERING LABORATORY, UK

Venezuelan oil is characterised by very high viscosity (up to 10,000cSt). Longstanding field trials in upstream oil applications in Venezuela, using the Coriolis meter type under consideration, have demonstrated an ability to maintain operation during high levels of two phase flow. A typical application consists of a test separator, where occasional surges, high oil viscosity and/or insufficient residence time may result in gas carry-under in a liquid leg. Field experience suggested that the default two-phase corrections in the commercial meter did not deliver satisfactory mass flow and density performances, with a general tendency to over-read the mass flow rate during bursts of two-phase flow. It was proposed to develop a new model of the two-phase errors for high viscosity oil in order to provide improved performance in the Venezuelan oil fields and elsewhere.

The National Engineering Laboratory (NEL) is the National Flow Standard laboratory for the UK, based near Glasgow in Scotland. Given an increasing industrial interest in heavy oils and higher viscosity fluids, NEL has been developing a heavy oil capability; after a world-wide survey this facility was selected as the most suitable to carry out model development and trials. The transparent oil Primol has a viscosity of 200-300cSt over the temperature range

Fig 2 - Two-phase experiment at NEL

20C-15C, and is available on a temperature-controlled flow rig. The purpose of the trial was to develop a two-phase flow correction model suitable for implementation in a commercial Coriolis mass flow meter to provide good tracking of liquid mass flow and void fraction for this fluid.

All experiments were carried out on a 75mm flow-tube, aligned vertically with the flow passing up through the meter (Fig 2). Experience suggests that this is the preferred orientation, especially for low flows. With a horizontal alignment at low flow, phase separation is likely to occur; the resulting errors show poor repeatability and are difficult to correct. By contrast, the slug or even churn flow that occurs in vertical orientation with higher GVFs and low liquid velocities remains amenable to correction, as demonstrated in the results described below.

A schematic of the experimental equipment is shown in Fig. 3. The single phase Primol liquid is metered using a reference Coriolis meter (mass flow uncertainty 0.2%), with the flow rate controlled using a local modulating valve. This is necessary to maintain a constant liquid flowrate, as the introduction of increasing levels of injected gas creates additional back-pressure which would otherwise reduce the liquid flowrate. The single phase nitrogen gas (from a liquid nitrogen tank, to ensure zero moisture content, and hence a known, constant gas density) is controlled and metered using a gas flow control skid. This subsystem was built at Oxford to provide good gas flow control over a range of 0.1g/s to 100g/s. The gas flow uncertainty is approximately 0.05g + 0.5% of reading.

With both liquid and gas steams separately measured and controlled, they are combined via a gas injection nozzle placed in the liquid stream. This is placed approximately 10 pipe diameters before a right angle bend in the pipework taking the flow vertically upwards (which helps to ensure good mixing between the phases); there follows a further 10 pipe diameters before the test meter itself.

4 RESULTS

The data collection strategy was chosen to reflect the likely pattern of behaviour in the oilfield. Generally flow rates are low, but low-frequency slugging behaviour can occur, leading to

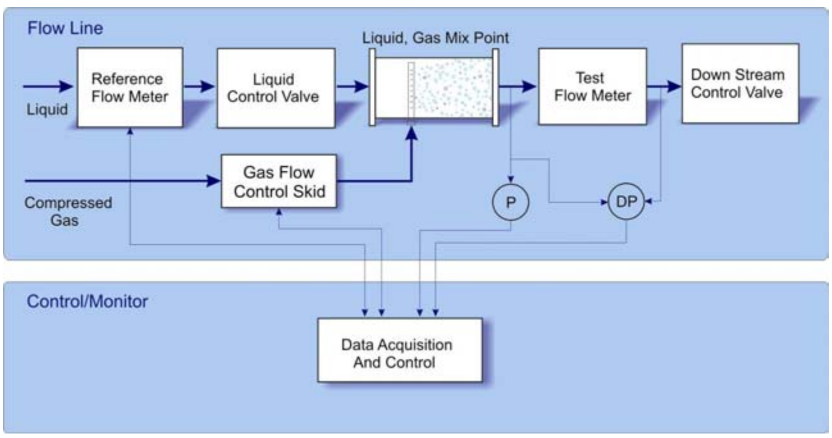

Fig 3 – Schematic of two-phase flow experiment at NEL

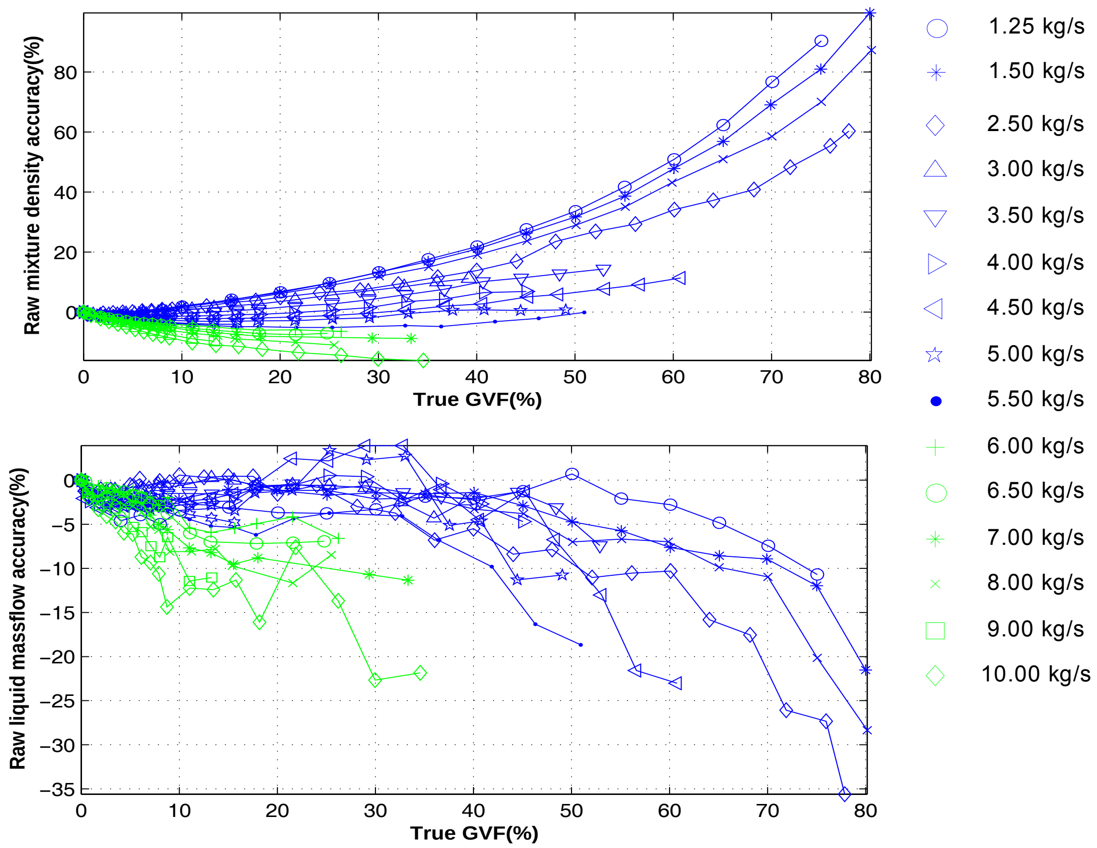

Fig 4 - Raw two-phase flow errors

bursts of high flow. Accordingly, for model development, a range of essentially static flows from 1kg/s up to 10kg/s were examined, but model testing was carried out using either steady low flows (up to 4kg/s) or deliberately engineered low-frequency slugging flow.

A first set of experiments was carried out to develop two-phase correction models for the Primol oil over the full range of flows to 10kg/s. The raw mass flow and density errors are shown in Fig. 4. This data was taken at a controlled temperature of 20.5C ± 0.5C, with a pure liquid viscosity of approximately 200cSt, and with gauge pressure at the flow-tube inlet varying between 1 and 3.5bar. The mass flow and density errors show a marked difference from those of less viscous oils and water. The most unusual feature of the density error curves is that the majority of the errors are positive. In the authors' experience, most previous flow-tube/liquid combinations have generated entirely negative density errors, with perhaps some slightly positive errors for high flows and low GVFs. Similarly, the mass flow errors exhibit quite different behaviour than for water, being mostly negative, but are rather erratic, and in some cases showing relatively little dependency on GVF (characterised by error curves lying more or less parallel with the x-axis). While this non-smooth behaviour makes modelling more difficult, this is compensated by the relatively small magnitudes of the mass flow errors.

Using this data set, neural net models were constructed to predict the mass flow and density errors. The resulting models were downloaded into the Coriolis transmitter and tested in further real-time experiments. Fig. 5 shows the results of four trial lines where the on-line correction was tested on steady two phase flow. The temperature was controlled to 19C ± 1.0C, and the inlet gauge pressure varied between 0.9 – 3.0 bar. For GVFs of less than 60%, 95% of density readings have errors of 5% or less, while with mass flow, 95% of readings with GVFs of less than 60% have errors less than 6%.

The creation and testing of steady-state two-phase flow conditions is useful for the development of correction models, but is not representative of actual conditions in the field.

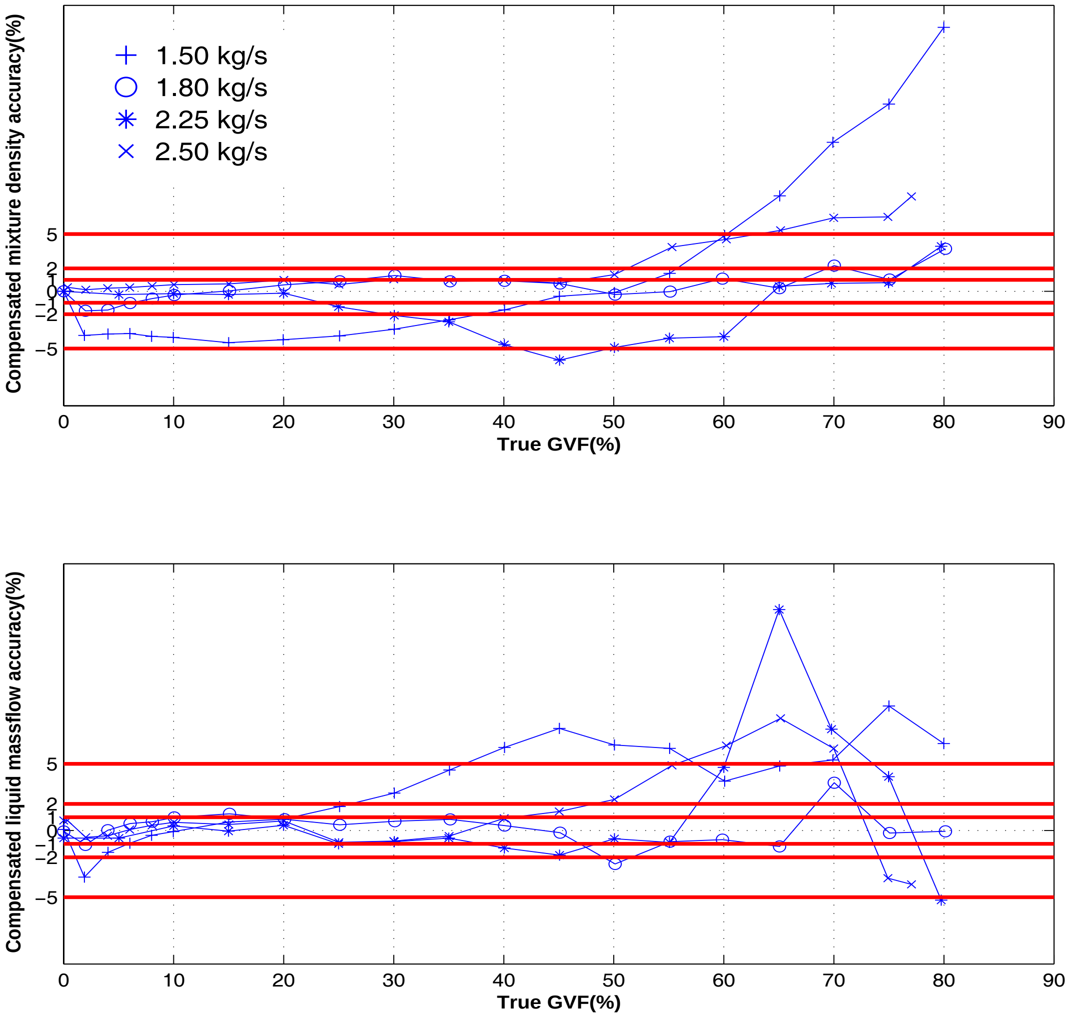

Fig 5 - Corrected steady two-phase results at NEL

Specifically, in the Venezuelan oil well applications slug flow is common. A further goal of the project was to evaluate the performance of the meter with slugging flow.

To create these conditions, it was necessary to disable the flow control in the loop. This was achieved by setting a steady low pump speed to establish a constant head of pressure on the single-phase liquid, but disabling control of the liquid flow control valve, and setting the gas flow rate to its maximum value. Under these conditions a natural resonance was established in the flow rig itself, with a typical period of 50 seconds, depending upon the pump speed.

Figs. 6 and 7 show two examples of the resulting slugging behaviour. Note that relatively small changes in the flow rate and mean GVF give quite different slug frequencies and amplitudes. In fig. 6, the mean flowrate is 3.25kg/s and the mean GVF of 43%. The “true” mass flow and GVF readings are based on the single phase flow readings and the instantaneous gauge pressure at the inlet of the flowtube. However, the resulting estimates can only be an approximate guide, as localised slugging will cause considerable variation in the actual flowrate and GVF. However, the pattern of behaviour shown is inherently plausible, with the highest surges of mass flow correcponding to the lowest GVF points.

The Coriolis meter tracks the slugs well. The mass flow average error over the experiment is 2.0%, while the mean GVF reading is only -0.2% in error. These relatively low errors are attributable in part to the fact that as the flowrate and GVF vary over the correction surface, there is a tendency for cross-compensation between positive and negative errors. Similarly, in fig. 7, the mean flow rate is 2.0kg/s and the mean GVF is 50%. Here the average mass flow error is 3.6% and the average density error is -3.5%.

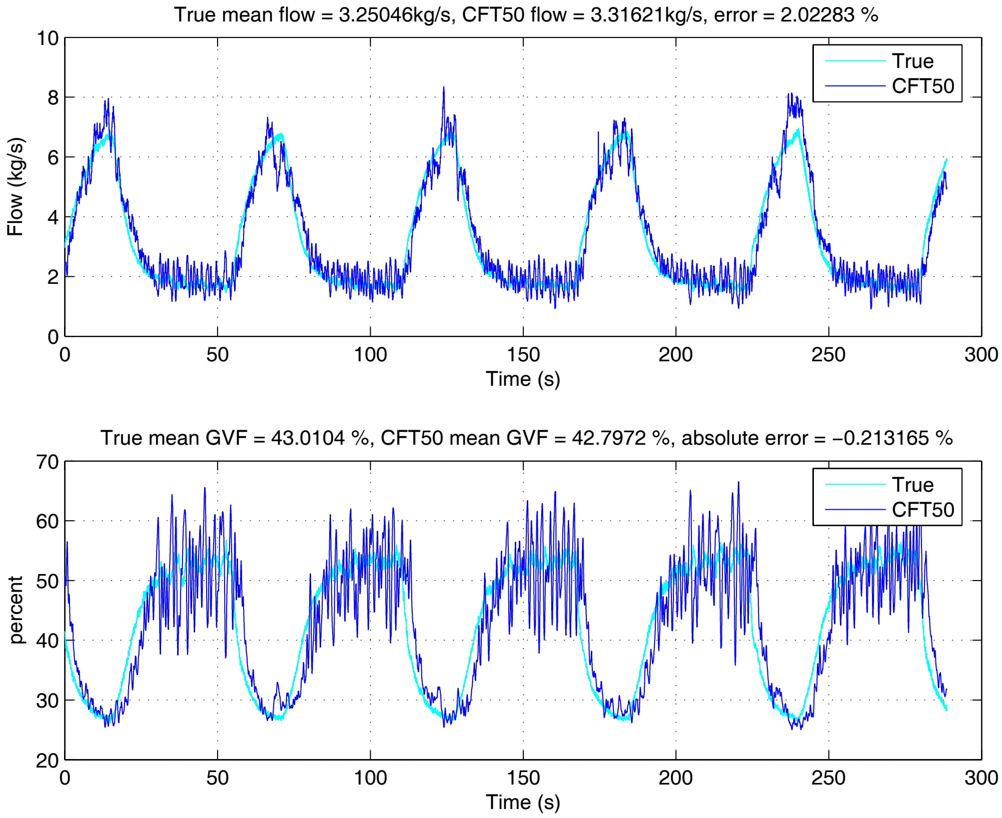

Fig 6 - Two-phase slug flow trials: 3.25kg/s 42% GVF

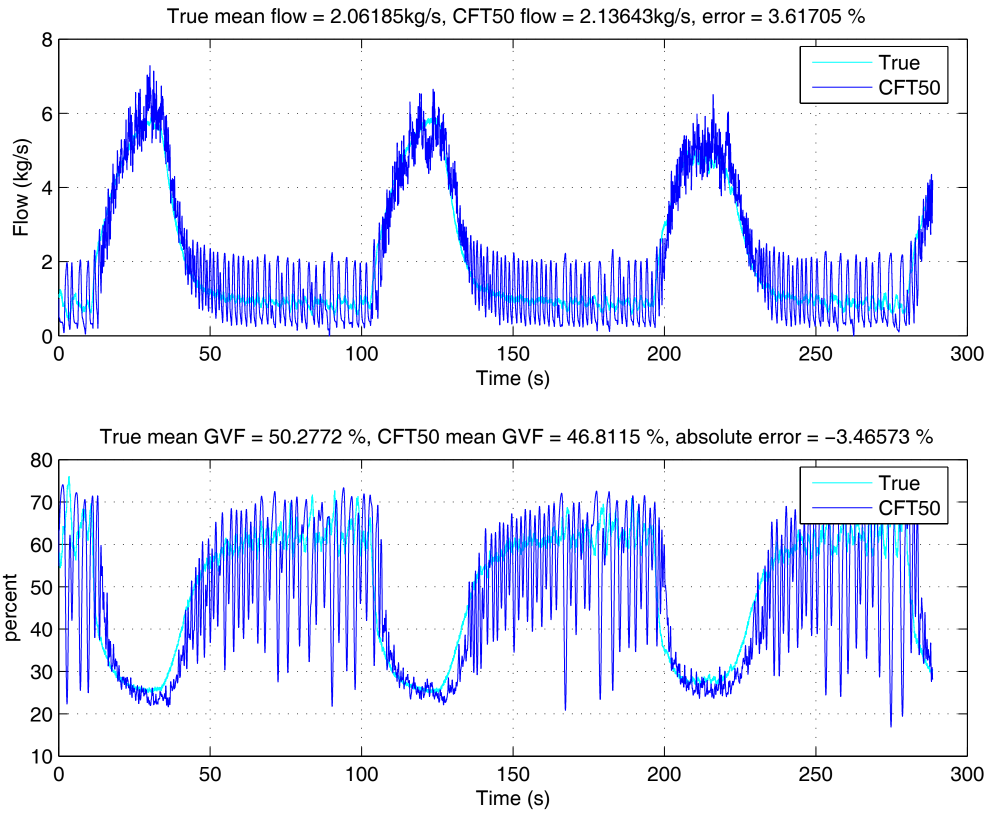

Fig 7 - Two-phase slug flow trials: 2.0kg/s, 50%GVF

5 FIELD TRIALS

The commercial meter incorporating the new two-phase correction model has been tested at a heavy oil field in Venezuela where the oil has an API gravity of between 11 and 13 (typically 10,000cSt at a production temperature of 43^{o} C). Mechanical pumping is used to extract the oils, including sucker rod pumps, electrical submersible pumps and progressive cavity pumps. The wells themselves are up to 2km distant from the flow stations where metering occurs. Consequently the pipelines are over-sized to keep pressure drop manageable despite the high viscosity of the oil. Typical average production rates for the well are 100-1200 barrels per day, or approximately 0.18 – 2.2l/s, which is low for the 75mm diameter flowtube. However, the over-sized pipes result in slug flow behaviour, with much higher peak flow rates, as simulated at NEL.

Currently the productivity of each well is measured only occasionally, by bringing the output of several wells together to a flow station, which includes a well test separator. The output of the well is passed through the separator over a period oftime, typically 24 hours. Pneumatic instrumentation is used to count how many times the separator is filled and then dumped. The separator arrangement is shown in Figure 8.

Electronic instrumentation has been installed on a test separator to increase the accuracy of the well test system. This is intended to provide a better flow reference when comparing the Coriolis meter in this application.

The free gas from the test separator is measured by an orifice meter. However, there is no suitable meter to measure the liquid outflow from the separator as an appreciable but undetermined amount of gas is still entrained in the heavy oil/water emulsion. The current system works by filling a fixed volume. Initially the inlet valve V-1 is opened and the dump valve V-2 is closed. When the calibrated level is reached the dump valve V-2 is opened and inlet valve V-1 is closed. Each action is tracked on a chart recorder.

The test separators require a lot of maintenance due to the need for regular recalibration of the pneumatic controllers and instruments. Hysteresis inherent in the pneumatic systems can introduce errors in the volumetric calculations of 10-20%. Additionally, back pressure may build in some stations due to the distance between the test separator and the tank. This can affect the volumetric calculation using the chart recorder, as the dump time is no longer negligible compared with the filling time. Test separators are normally deployed at flow stations as they require low pressure to dump crude oil. For installations requiring well test measurements close to the well, is not possible to use this arrangement, and other separation technologies are not suitable for the fluid conditions.

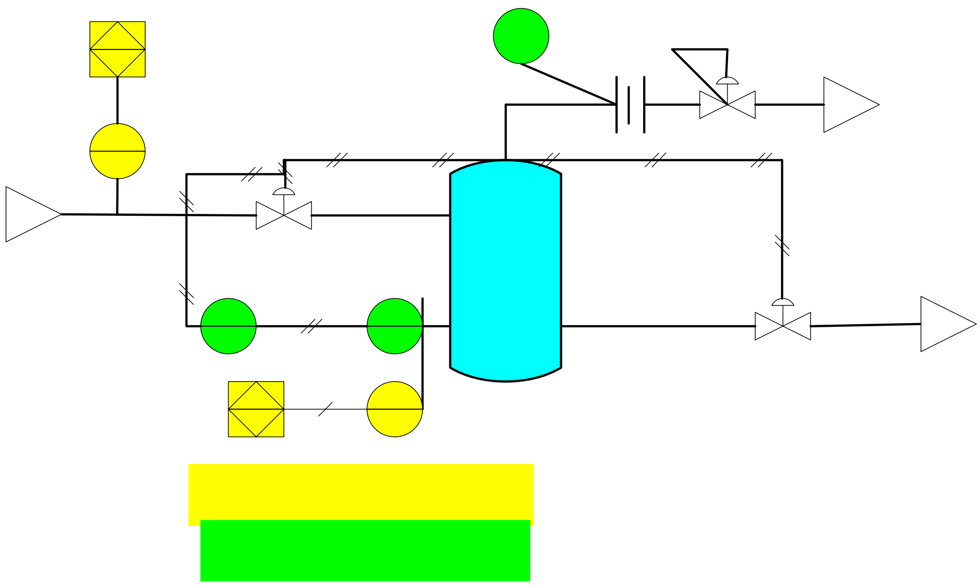

Fig 8: Schematic of well test separator

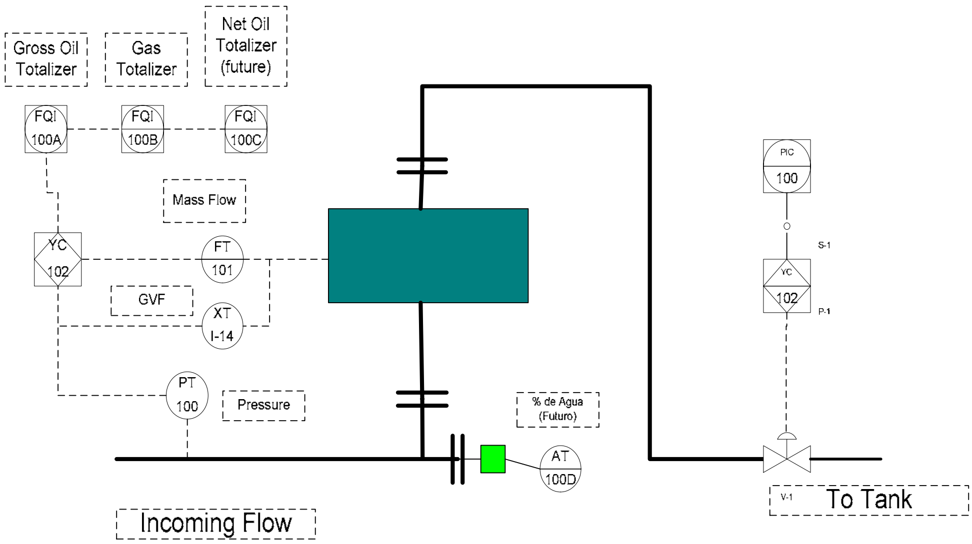

Fig 9 - Schematic of Coriolis meter in well test application

The potential benefits offered by the Coriolis meter as a replacement for the separator are low cost, low maintenance, and a compact form factor. The desired outcome is the ability to monitor each well, close to source and on a continuous basis, using a system that is economically and technically viable. Fig. 9 shows the arrangement used to test the Coriolis meter in the flow station.

The Coriolis meter measurements of mass flow, GVF, temperature and mixture density are recorded, while the pressure reading is used to calculate gas standard volume units and to control the pressure on the pipeline. The oil produced in the oilfield includes a significant water cut. Variations in water cut normally lead to changes in the gas-free liquid density, which is a further complication in the two-phase correction. Fortunately, however, the oil and water densities are very similar, and so the liquid can be treated as a single phase. Fig. 9 includes a water cut probe for future installation, however, in the tests described here there is no water cut measurement, and only the bulk liquid flow is calculated. Figs. 10 and 11 show the test separator and Coriolis meter installed in the flow station.

Fig 10: Coriolis meter installed at base of separator

After the trials at NEL in November 2005, the new two-phase flow correction was installed on-site in December 2005. Fig 12 shows the trend line for the GVF reading for one well during the course of 14th December 2005. The reading indicates a baseline GVF of approximately 8%, but as expected,

Fig 11 - Separator with Coriolis meter at base

slug flow is reported with peak GVFs in excess of 40%.

One difference with the NEL performance is that the mass flow measurement shows a higher level of noise at the trial site. This could be attributed to several factors, but above all the very low average flowrates. A consequence is that the instantaneous mass flow reading may show a negative value, as illustrated in Fig 13. Negative readings are considered unacceptable, and so higher damping has been applied (Fig 14) to remove the effect. This of course has an impact on the dynamic response of the mass flow measurement, but has no effect on the long term average mass flow reading generated by the meter.

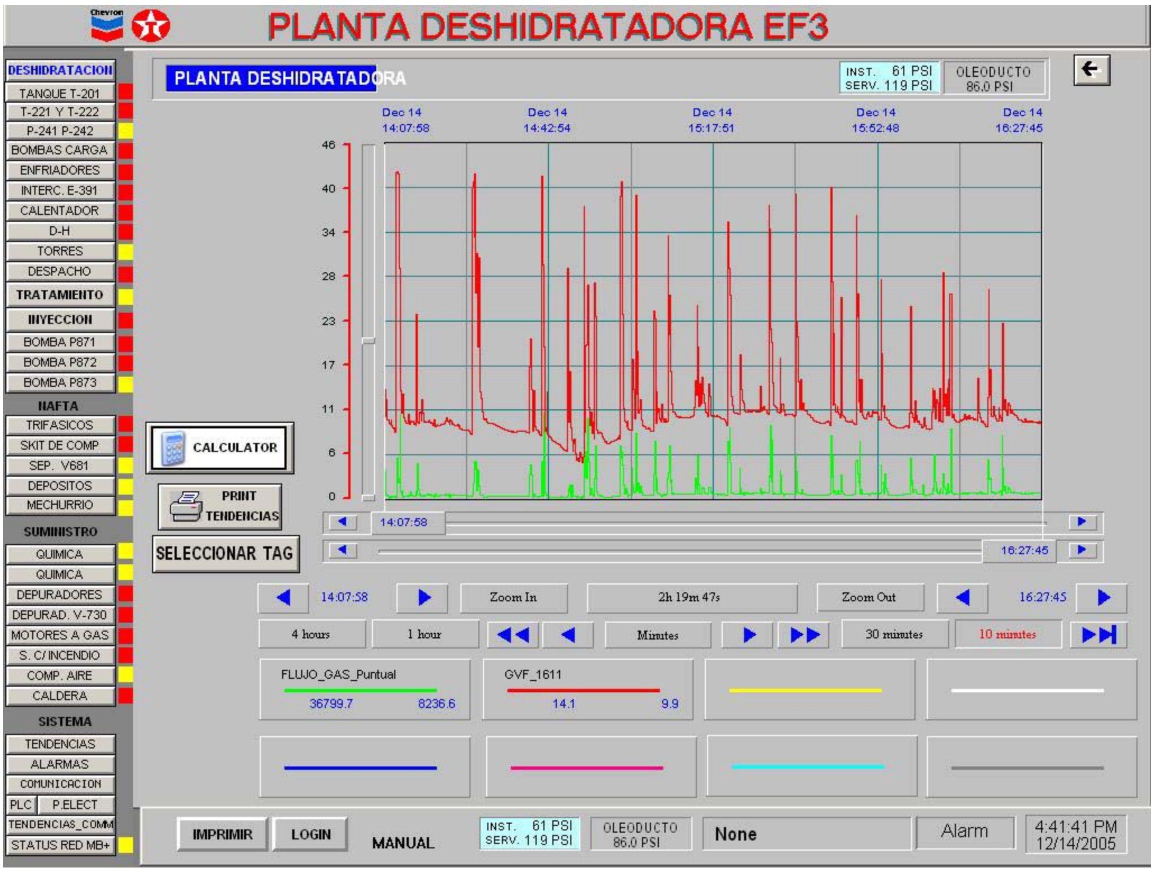

Fig 12 - GVF reading from Coriolis meter installed in flow station, showing slug flow

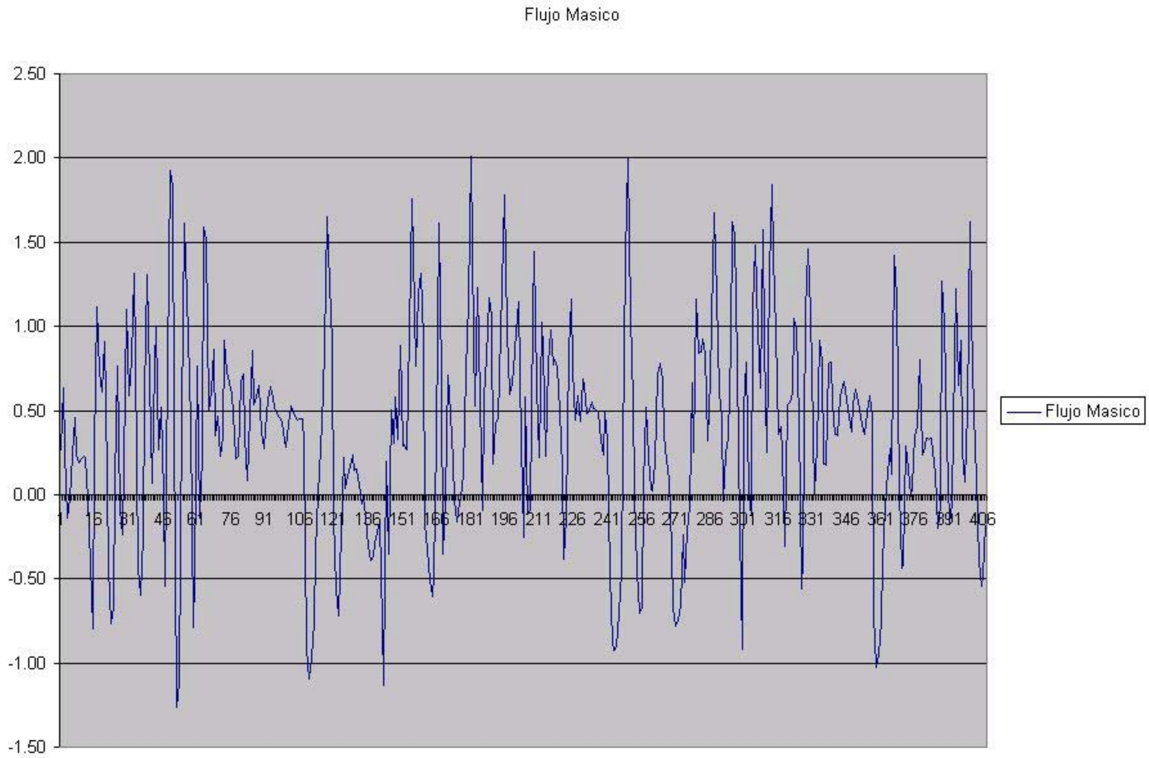

Figure 13 - Mass flow rate from Coriolis meter with 5 second damping (kg/s)

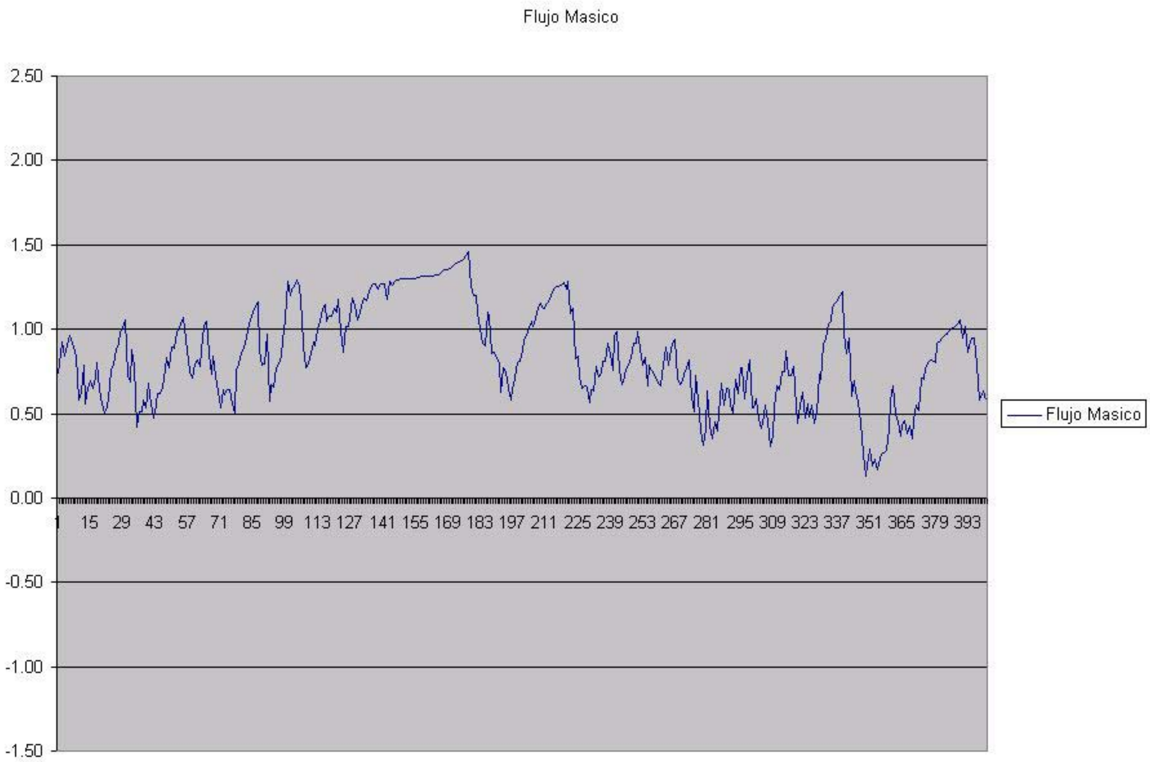

Figure 14: Mass flow rate from same well using 20 second damping (kg/s)

A comparison of liquid flow rates for four wells as measured by the Coriolis meter and the test separator, over a 24 hour period in each case, is shown in Table 1. Where two figures are shown for the Coriolis meter two 24 hour trials have taken place. While some of the differences shown are large compared with the errors reported in the laboratory trials at NEL, the uncertainty of the test separator measurement is large, and hence it is concluded that two systems agree to within the uncertainty of the test separator equipment.

Table 1 - Comparison of average liquid flow rates over 24 hour period in Venezuelan field trial

Well No.	Test Separator barrels per day	Test Separator kg/s	Coriolis Meter barrels per day	Coriolis Meter kg/s	Difference %
BN-100	178	0.328	174	0.320	-2.2
BN-101	217	0.399	198, 212	0.364, 0.390	-8.7, -2.3
BN-102	229	0.421	226	0.416	-1.3
BN-103	150	0.276	143, 158	0.263, 0.291	-4.7, +5.3

Further evaluation of the Coriolis meters for testing heavy oil well production is continuing at this Venezuela field.

6 SUMMARY AND CONCLUSION

This paper has described a methodology for developing a two-phase flow correction for gas/liquid mixtures, illustrated with a case study of high viscosity oil. The correction has been developed and tested in a laboratory for both steady and slugging two-phase flow. Field trials at a Venezuelan oilfield have demonstrated that the meter has the potential to replace conventional separators.

While more research is needed to get a deeper understanding of two-phase flow phenomena in Coriolis meters, and in particular to obtain more general models based on engineering principles, there can be little doubt that Coriolis metering can now offer two-phase capabilities for economically important applications.

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