Two-phase flow metering of heavy oil using a Coriolis mass flow meter: a case study

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Abstract
The use of Coriolis mass flow metering for two-phase (gas/liquid) flow is an emerging theme of both academic research and industrial application. The key issues are maintaining flow-tube operation, and modelling and correcting for the errors induced in the mass flow and density measurements. Experimentally-derived data is used to illustrate that these errors vary most notably with gas void fraction (GVF) and liquid flow rate, but other factors such as flow-tube geometry and orientation, and fluid properties such as viscosity are also influential. While undoubtedly a universal two-phase flow correction model is the ultimate research goal, there is currently no obvious candidate to explain the range of behaviours observed. This paper describes and demonstrates an empirical methodology that has proven effective in developing good correction models for a given choice of Coriolis flow-tube and flow mixture.

A growing proportion of the world's oil reserves may be described as "heavy", implying high density and high viscosity. Of the various metering challenges heavy oil poses, one of the most significant is its ready entrainment of gas, and the difficulties entailed in separating gas from the oil. Accurate two-phase measurement of heavy oil is therefore an especially desirable technical goal.

Trials were carried out at the National Engineering Laboratory (NEL), Scotland on a 75 mm flowmeter using a high viscosity oil. Flowrates from 1 kg/s to 10 kg/s were examined, with gas void fraction (GVF) up to 80 %. The resulting models were tested on-line in a commercial Coriolis mass flow meter and demonstrated good performance for both steady and slugging two-phase flows, with the corrected measurements typically within 1-5 % of the nominal mass flow and density.

Field trials in Venezuela have confirmed the performance of this two-phase solution.

While research continues into the development of a generic two-phase correction, this case study demonstrates that the current state of the art can provide, for economically important fluids, tailored models with good two-phase flow performance.

1. Introduction

Coriolis mass flow metering has been established as the most accurate of the commonly-used industrial flow measurement technology since its introduction in the mid 1980s [1]. Coriolis meters operate 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 50 Hz – 1 kHz 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, which is essentially proportional to the mass flow of the process fluid (this may approach 1 tonne/s for the largest sizes).

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 calculates the measurement data. A long-term research programme between the University of Oxford and Invensys Foxboro has been developing all-digital transmitter technology [2-4] with various improvements including fast response time [5, 6] and an ability to operate in two-phase flow [2-3, 7-9]. The transmitter architecture includes audio quality analog-to-digital convertors (ADCs) and digital-to-analog convertors (DACs), with typical performance characteristics of 24-bit samples delivered at 48k Hz.

This architecture is used in the so-called Oxford or research transmitter used for experimental and development purposes as well as its commercial variant, the CFT-50 product. The research transmitter has additional features, such as a comprehensive web interface, a local hard drive, additional software for automating experiments and dozens of additional analog and digital i/o channels, which are not available in the commercial device. However, given the common core architecture, the research transmitter can be used to develop new capabilities (e.g. a new two-phase flow model) that are readily transferred into the commercial meter.

Reizner [10] provides a good background to the problems associated with metering two-phase flow with Coriolis meters. In brief, it is technically difficult to maintain flow-tube oscillation during two-phase flow, 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.

For clarity, the term “two-phase flow” is here taken to mean any mixture of a gas and a liquid – for example air and water, or air and oil – and is not restricted to mixtures where the gas and liquid are of the same chemical composition.

In this paper, it is assumed that the transmitter is capable of maintaining flow-tube oscillation through continuous two-phase flow or batching to or from an empty flow-tube [3, 8, 9]. The focus is restricted to modelling and correcting for two-phase flow errors in the mass flow and density measurements, which are derived from the resonant frequency and phase difference properties of the flow-tube.

The development of theoretical models to explain the observed frequency and phase difference behaviour with two-phase flow is difficult. The so-called “bubble” model developed by Hemp and Sultan [11] considered the inertial losses generated by a single bubble surrounded by much denser fluid, when passing through a vibrating pipe. This model predicts monotonic, negative errors which are a function only of the gas void fraction (GVF), i.e. the proportion of gas by volume in the two-phase mixture. Specifically, the mass flow errors take the form [12]:

$$\frac{\dot{m}_{observed} - \dot{m}_{true}}{\dot{m}_{true}} = \frac{-2\alpha}{1-\alpha} \qquad (1)$$

Where $\dot{m}$ is the mass flow rate and α is the GVF on a scale of 0 … 1. The density error simply takes the form

$$\frac{\rho_{observed} - \rho_{true}}{\rho_{true}} = -3\alpha \qquad (2),$$

where ρ denotes density. Note that although in the above equations GVF is on a 0 …1 scale, it is more frequently considered on a percentage 0 …100 % scale, which will be used for the remainder of the paper.

For clarity, it is to be understood that the mass of the gas is assumed to be negligible, and hence the nominal mass flow of the two-phase mixture is equal to the mass flow of the liquid phase only. However, when assessing the density error, it is more useful to consider the meter's ability to measure the density of the two-phase mixture rather than of the pure liquid itself. Thus, with a liquid density of (say) 1000 kg/m^3 and a GVF of 10 %, assuming the gas has negligible mass, the nominal mixture density is 900 kg/m^3. In these conditions, a density error of say -5 % would mean that the meter was reporting a mixture density of only 855 kg/m^3.

As illustrated in the following section, although the bubble model is successful in predicting the general characteristics of two-phase flow errors (i.e. negative and increasing in magnitude with GVF), the pattern of errors observed experimentally are much more complex, at present poorly understood, and vary with a number of different parameters.

Several manufacturers are now acknowledging the technical possibilities of handling two-phase flow with Coriolis mass flow meters [13]. For example, Seeger gives experimentally derived mass flow errors [14], exploring such parameters as surface tension and viscosity. The current paper is intended to demonstrate that, even though the factors generating two-phase flow errors remain poorly understood, it is possible to provide on-line corrections leading to good two-phase performance. Specifically, customer-witnessed trials have taken place at a national flow laboratory in which satisfactory, corrected two-phase flow measurement has been achieved using a Coriolis mass flow meter with gas void fractions ranging from 0 % to 80 %, and that subsequent field trials have been adjudged to be successful.

2. Experimentally observed two-phase flow errors for air-water mixtures

The Oxford team has investigated two-phase flow errors using a variety of flow-tube designs and fluids. Their experience suggests that while for low viscosity fluids the negative errors predicted by the bubble model form a good first approximation of the experimentally observed errors, there are additional influencing factors which the model excludes. The underlying assumptions of the model – which include no interaction between bubbles, and no interaction between the bubbles and the flow-tube wall – are clearly not applicable in many circumstances, for example with slugging flow. One observation from experimental data is that, even at relatively low GVFs where the bubble model should be closest to reality, there is a high dependency of mass flow error on the mixture velocity. This is illustrated in Fig. 1, which show for a 75 mm flowmeter, the mass flow and density errors as they vary with both GVF and mass flow with water as the liquid component. These results were obtained at an industrial flow laboratory with instrumentation traceable to NIST, using equipment and procedures similar to those described later in the paper. At low GVF, say 5 %, the mass flow error can vary from -9 % down to -20 % as the flow rate ranges from 23 kg/s down to 3 kg/s.

Factors other than GVF and mass flow affecting the measurement errors include the following:

2.1. Flow-tube orientation.

Changing the orientation of the flow-tube (e.g. from horizontal to vertical positioning) results in different error curves. This suggests a role for buoyancy forces in the mass flow and density errors. For example, Fig. 2 shows mass flow and density error curves for the same 75 mm flowmeter as Fig. 1, in the same industrial flow laboratory, only in horizontal rather than vertical orientation. While the same basic trends of negative errors are observed for mass flow and density, there are also clear differences from Fig 1. There is a broader spread of errors for different flowrates in horizontal alignment, for both mass flow and density. For example, in Fig. 1, at 15 % GVF, the density errors vary by approximately 12 % and the mass flow errors vary by 21 %. Excluding the two lowest flow lines to consider only the flow range from 5 kg/s to 23 kg/s, the variation in mass flow error is only 5 %. By contrast, for horizontal orientation in Fig. 2, at 15 % GVF, the density errors vary by about 15 %, and the mass flow errors vary by 30 % for the reduced flow range from 5 kg/s to 20 kg/s.

A further observation is that in vertical orientation the mass flow and density errors are repeatable and follow smooth trends over a lower range of flow rates. Erratic behaviour is already visible for the lowest flow line (5 kg/s) in Fig. 2. This observation, which is also apparent for other flow-tubes and fluids, leads to the general recommendation that, where practical, vertical orientation with the fluid flowing up through the meter, is the preferred orientation.

2.2. Flow-tube geometry.

The complex geometry of a "bent" flow-tube might reasonably be assumed to influence the effects of two-phase flow. However, straight tube geometries are also found to exhibit similarly complex error curves. In each case, different flow-tube geometries produce somewhat different errors. Similar flow-tubes of different sizes (e.g. the same commercial offering with different diameter tubes) appear to produce similar, but not identical (scaled) error curves. Features such as whether the tube is split or continuous path are clearly significant. For example, Fig. 3 shows mass flow and density error data for a 100 mm meter, using a different bent flow-tube geometry from that of Figs 1 and 2. This data was collected at NEL on water, with a lower number of data points. Once again, the errors are negative, but there are significant differences. At high flows, both mass flow and density errors are close to zero for up to 10 % GVF, while for low flows the errors have higher magnitudes than in Fig 1 and 1. For mass flow, the variation in error at 15 % GVF is approximately 80 % across the flow rates shown.

2.3. Process fluid viscosity and other properties.

Viscosity is a significant contributory factor, as perhaps are other fluid properties and application conditions. An extended version of the bubble model which incorporates viscosity effects suggests that, as the viscosity tends to infinity, both mass flow and density errors tend to zero [12]. The actual error behaviour for a viscous oil, presented later in the paper, is therefore surprising. Another factor which might be expected to influence the behaviour of the two-phase mixture is the inlet pressure, or more particularly the ratio between the inlet pressure and the pressure drop across the flow-tube, which is likely to influence the increase of gas volume as it passes through the meter. Experimental experience suggests this is not a very significant factor (no data is reported here), but the inlet pressures are included in the reporting of experimental data later in the paper.

2.4. Transmitter effects.

As discussed in [8], even if flow-tube oscillation is maintained, unless the flow-tube frequency and phase are tracked very carefully and matched in the drive signal, the result may be forced rather than natural oscillation, introducing (in the authors' experience) random walk in the observed phase measurement, which is non-stationary and hence difficult to correct.

To summarize, the accumulated experimental experience using many flow-tubes and fluids suggests that the mass flow and density errors are generally smooth (with respect to flow rate and GVF) and negative. The exact forms of the curves are dependent on a number of complex factors, including orientation and flow-tube geometry, which are presently not readily amenable to analysis. At low flows the behaviour becomes more erratic, with this problem manifesting itself at higher flowrates in horizontal than in vertical orientation.

One means of assessing the "performance" of an uncorrected or corrected flow meter is to take a probabilistic approach. Fig. 4 shows the same data for mass flow and density errors from Fig. 1 (75 mm flow-tube, vertical orientation) as a series of probability distributions. Each line shows every experimental data point (irrespective of flow rate) with GVF less than the indicated value (+ for GVFs of up to 5 %, and so on). The data in each line are ordered by the magnitude of their mass flow or density error (i.e. unsigned), and each point is equally spaced along the y-axis to give a cumulative probability estimate. This arrangement thus provides an estimate of the probability that a certain level of measurement error will not be exceeded for a certain GVF range, irrespective of flowrate. For example, for GVFs of 5 % or less, the density error is less than 10 % in 95 % of cases. This representation of the data will be used in later sections to evaluate the performance of two-phase flow compensation algorithms.

3. Two-Phase Flow Correction Methodology

The definition of two-phase flow correction adopted in this paper 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. It is however reasonable to allow single-valued configuration parameters (such as the nominal single phase liquid density, perhaps with a temperature coefficient of expansion) to be provided by the user. An overview of an empirical methodology for developing a two-phase flow correction is provided in this section, while further details are given in the specific example later in the paper.

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 GVFs. Controlled variation in other conditions, such as inlet pressure and temperature, may be included in the experimental grid. Alternatively, uncontrolled variations of inlet pressure and/or temperature may be a consequence of limited rig control, or a desire to get results within a limited period of time. Such uncontrolled variations may be undesirable for the purposes of exploring the underlying physics of two-phase flow, but for the development of a robust heuristic model they are perhaps less objectionable. For example, the data shown in Fig. 1 constitute an experimental grid covering a flow range from 3 kg/s to 23 kg/s in steps of 1 kg/s, and for GVFs up to typically 20 % in steps of 0.5 %. In these trials, the inlet pressure varied from 0.24 bar (gauge) to 1.4 bar, while the temperature varied from 26.7C to 32.7C. Note that the combination of high flows and high GVFs can lead to an impractically large pressure drop across the flow-tube, and so for each flowline, there is likely to be a maximum practical GVF which decreases as the true flowrate increases. Thus in Fig. 1, at the highest flowrate of 23 kg/s, the maximum GVF is only 7 %, while at the lowest flowrate of 3 kg/s, the maximum GVF is 36 %. These flow-dependent limits on GVF are representative of industrial constraints: if a flowmeter encounters both high GVF and high flowrate simultaneously, it is likely that the meter has been undersized for the application.

Typically in such experiments, Coriolis meters are also used to meter the single phase liquid and gas streams before they are mixed and subjected to the test meter, so that the single phase component flow rates have uncertainties of 0.2 % for the liquid and 0.5 % for the gas stream. Section 3 describes the experimental setup used for the heavy oil trials presented in this paper, which is representative of the equipment used in other trials. At each experimental point, internal parameters are recorded and averaged over a pre-determined time period (typically 30-120s, selected to ensure a representative sample of the two-phase flow conditions) 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, as shown in Figs. 1-3 for different flowtubes or orientations. 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. Note that as pressure drop occurs across the flow-tube, the GVF is not constant, but increases through the meter. By convention, therefore, GVF is calculated based on the gauge pressure at the inlet to the flow-tube.

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 modelling applied, are described in [7]. As demonstrated in the following example, this approach has delivered effective error reduction.

In the case of the 75 mm flow-tube with water, whose mass flow and density errors are shown in Fig. 1, on-line correction models have been developed and applied. Fig. 5 shows the residual errors observed in separate trials at the same facility with the correction applied on-line, while Fig. 6 indicates the probability distribution of the resulting errors. The tests of the corrected data were all carried out within the experimental grid of the model data (mass flow between 5 kg/s and 20 kg/s, GVF < 25 %, inlet pressures between 0.3bar and 1.1bar, temperature between 27.8C and 32.3C), and hence the neural nets are interpolating rather than extrapolating. Additional techniques have been developed to deal with extrapolating beyond the known region. The resulting errors are fairly typical of two-phase correction achieved using this methodology, with the density proving particularly amenable to correction, while the corrected mass flow manifests higher error scatter. The probability distributions in Fig. 6 indicate that, for density, approximately 95 % of the experimental points for all GVFs have error magnitudes less than 0.4 % (for other flow-tubes and liquids a more typical value is 1 %). There is greater spread for the corrected mass flow reading. For GVFs less than 10 %, 95 % of the errors are less than 2 %, while for all GVFs the 95 % probability error is approximately 4 %.

4. Trial at the National Engineering Laboratory, UK

A growing proportion of the world's oil reserves may be described as "heavy". Of the various metering challenges heavy oil poses, one of the most significant is its ready entrainment of gas, and the difficulties entailed in separating gas from the oil. Accurate two-phase measurement of heavy oil is therefore an especially desirable technical goal.

Venezuelan oil is characterised by very high viscosity (up to 10,000 cSt). Longstanding field trials in upstream oil applications by Chevron in Venezuela using the commercial Coriolis meter 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. This over-compensation is predicted by theoretical considerations of the effects of high viscosity [10]. 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. Given an increasing industrial interest in heavy oils specifically and higher viscosity fluids more generally, 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 200-300 cSt over the temperature range 20 C-15 C, and is available on a temperature-controlled flow rig capable of supporting meter sizes up to 200 mm diameter, and delivering flow rates of up to 150 litres/s. While the available viscosity range does not extend to that of the heaviest oil, it was the highest available in a commercial flow lab with appropriate facilities for these trials. The purpose of the project was therefore 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 trials were carried out on a 75 mm flow-tube, aligned vertically with the flow passing up through the meter. As illustrated in section 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. 7. 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. Note that it would be considerably more difficult to ensure that both the flow rate and the inlet pressure are constant with varying GVF, and so only flowrate is controlled. 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 to provide good gas flow control over a range of 0.1 g/s to 100 g/s. It incorporates two Coriolis meters with flow-tube diameters 6 mm and 25 mm, three modulating valves and several shutoff valves. The gas subsystem is controlled by an additional research transmitter (not shown in Fig. 7) which accepts a gas mass flow rate set-point in the form of a frequency pulse input and adjusts the valve settings to deliver the required gas mass flow rate. The gas mass flow uncertainty is approximately 0.05 g + 0.5 % of reading.

With the streams of liquid and gas 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; there follows a further 10 pipe diameters before the test meter itself.

Research transmitter 1 controls the entire experimental system. In addition to acting as a conventional Coriolis transmitter for the single phase reference flow-tube, it reads data from other instrumentation (including the test meter, gas flow meter(s), temperature, pressure and differential pressure readings), and sends set points to the flow control values and the gas flow control skid. It includes software to run a fully automated series of experiments, so that it sets up the conditions for each point in an experimental grid, detects that stable conditions have been established, and then records all relevant data channels in a record file for the required duration (typically 30-120 s) before proceeding to the next point. It is further able to detect when, for a given liquid flow rate, the maximum achievable GVF has been reached, in which case the flow-line is terminated and the next is started. For example, at a particular flow rate and at (say) 25 % GVF, if the desired gas flow rate is, say, 80g/s, but the maximum achieved gas flow rate is only 78g/s (due to supply pressure limitations) , there is little point in attempting to generate 30 % or higher GVFs at this flowrate. This condition is detected, no higher GVFs are attempted, and the experimental system moves straight on to the next flow rate and 0 % GVF. This high degree of automation facilitates the collection of 200 data points during a typical working day.

The test flow-tube, which undergoes the two-phase experimental conditions, is controlled either by a second research transmitter, or in the final stages of testing, a commercial transmitter. When the research transmitter is used, it records the internal variables used to build two-phase models, as requested by the first research transmitter. When the commercial transmitter is used, its measurements outputs are recorded by the first research transmitter.

Data is recorded in one or more of the following forms:

- A tag file contains a complete specification of the configuration of the meter, software version, time stamp, and mean, minimum and maximum values of each of the variables recorded during the experiment. For convenience it is a simple text file, typically 13k bytes in length. This data format is usually sufficient for two-phase flow model building, where the average values of parameters are taken as representative of the experimental condition for the duration of the recording.

- A record file contains the values of each recorded variable, updated every half-cycle of the resonant frequency of the flow-tube (with a resonant frequency of typically 85 Hz, this gives 170 samples per second for each channel). Approximately 60 channels of data are recorded, including raw and corrected mass flow and density measurements, amplitude control data (sensor amplitudes, drive current and drive gain), and auxiliary measurements and settings for experimental control (e.g. absolute and differential pressures, gas and liquid flow rates and set points). One minute of data recorded in binary format is stored in 4Mbytes. This format is useful for observing detailed trends in the data, for example the tracking of slug flow, and allows data to be "re-played" off-line, for example in order to apply different two-phase correction algorithms, or to investigate suspicious average values recorded in the tag file.

- A sensor file contains the raw sensor data, recorded at 12k Hz. One minute of data recorded in binary format is stored in 10Mbytes. This format enables the most detailed analysis and replaying, and is particularly useful for monitoring the behaviour of the different modes of vibration of the flow-tube and recalculating the primary measurement data using alternative approaches.

5. Results

The data collection strategy was chosen to reflect the likely pattern of behaviour in the oilfield application. Generally flow rates are low, but low-frequency slugging behaviour (as described below) can occur leading to bursts of high flow. Accordingly, for model development, a range of steady-state flows from 1 kg/s up to 10 kg/s were examined, but model testing was carried out using either steady-state low flows (up to 4 kg/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 10 kg/s. The raw mass flow and density errors are shown in Fig. 8. This data was taken at a controlled temperature of 20.5C ± 0.5C, with a pure liquid viscosity of approximately 200 cSt, 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 Figs. 1-3. As both Fig. 1 and Fig. 8 are drawn from experimental data using the same 75 mm flow-tube design in vertical alignment, with similar temperature and pressure conditions, it is suggested that the primary source of difference between them is the properties of the liquids – water and Primol respectively. The most surprising feature of the density error curves is that the majority of the errors are positive. In the authors' experience, and as exemplified in Figs. 1-3, most flow-tube/liquid combinations have generated predominantly negative density errors, with perhaps some slightly positive errors for high flows and low GVFs. With the prediction of high viscosity leading to zero errors [10], it would have been reasonable to predict negative errors of lower magnitude than for water. It is the magnitude, as well as the sign of the density errors, that is surprising.

The mass flow errors also exhibit rather different behaviour than for water (e.g. Fig. 1). The mass flow errors in Fig. 8 are mostly negative, but are rather erratic, and in some cases show 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 tested in further real-time experiments, firstly on the research transmitter. Figs. 9 and 10 show the results of four trial lines using the on-line correction, in terms of residual errors against GVF up to 80 %, and the probability distribution of these errors. The temperature was controlled to 19 C ± 1.0 C, and the inlet gauge pressure varied between 0.9 – 3.0 bar. The greater range of density errors shown in Fig. 9 compared with Fig 5 can be attributed to several factors: the sparser data set, the wider GVF range, and the wider range of density errors in the raw data, and the more erratic mass flow error behaviour. From Figure 10 it can be seen that for GVFs less than 60 %, 95 % of density readings have errors less than 5 %, while with mass flow, 95 % of readings with GVFs of less than 60 % have errors less than 6 %.

In subsequent trials, further changes were introduced. Firstly, the neural net models were downloaded onto the commercial transmitter, CFT-50, which was used to drive the test flow-tube. In Fig. 7, the resulting configuration is achieved by switching from research transmitter 2 to the CFT-50. This is an important step in completing the two-phase flow model development cycle, but provides more limited data: the mass flow data from the CFT-50 is communicated via its pulse output, while density data is provided over a 4-20mA analog channel. Trials were carried out using this meter at 19C, and the results, which are not reported, were similar to those of Figs. 9 and 10.

A further modification to the test conditions was then introduced: the fluid temperature was reduced towards 15 C, thus raising its viscosity from approximately 200 cSt towards 300 cSt. This temperature change on the Primol was slow, and given the limited time available for the trials, flow lines were taken as the temperature dropped. Accordingly, the temperature varied during the experiment from 17.4 C down to 15.5 C (the corresponding viscosity of Primol is approximately 250 cSt to 290 cSt), while the inlet gauge pressure varied from 1.2 bar to 3.1 bar. The resulting errors are shown in Figs 11 and 12, and are broadly similar to those of Figs. 9 and 10. However the mass flow errors are all nearly positive, suggesting that some form of bias has been introduced by the temperature change and its associated increase in viscosity, as discussed below.

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. 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.

Fig. 13 gives an example of the resulting slugging behaviour for a mean flowrate of 3.25 kg/s and a 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 flow-tube. However, the resulting estimates can only be an approximate guide, as localised slugging will cause considerable variation in the actual flowrate and GVF. The CFT-50 tracks the slugs well. The mass flow error average 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.

6. Field Trials

The commercial meter incorporating the new two-phase correction model has been tested at a heavy oil field in Venezuela. 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 75 mm diameter flow-tube. However, the over-sized pipes result in slug flow behaviour at the flow stations, with much higher peak flow rates, as simulated at NEL (Fig. 13).

Prior to the introduction of the Coriolis meter, it was very difficult to measure the well production accurately, due to the high viscosity of the oil (approximately 10,000 cSt at a typical production temperature of 43^{o} C). The existing well testing equipment at the field consists of a vertical two-phase separator. 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 (note that, conveniently, the density of the oil is very close to that of water, so that the oil/water emulsion can for the purposes of Coriolis metering be considered as a single phase; mixed with the gas it can be treated as two-phase). The liquid flow rate with entrained gas is conventionally estimated by counting the number of times the test separator dump valve opens during the well test period, with the assumption that a constant and known volume of liquid is discharged each time the valve opens.

The well testing equipment is unsatisfactory in several respects. The uncertainty in the measurement of liquid volume is at best 10 %. The capital and maintenance costs are high, and so it is uneconomic to have a test system dedicated to each well. Instead, the output of several wells is brought to a single flow station where each stream may be monitored in turn, typically over a 24 hour period. The potential benefits offered by the Coriolis meter 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.

The trial Coriolis meter is currently installed at a flow station. This allows comparison of the mean flow rates recorded by the test separator and the Coriolis meter over several wells with different mean flow rates and flow profiles. Using the two-phase model developed at NEL, the Coriolis meter reports GVF levels varying between 10 % and 40 %, in a slug flow pattern similar to Fig. 13. A comparison of liquid flow rates for four wells as measured by the Coriolis meter and the existing test separator, over a 24 hour period in each case, is shown in Table 1. The two systems agree to within the uncertainty of the test separator equipment. Further evaluation of the Coriolis meters for testing heavy oil well production is continuing at this Venezuela field.

7. Discussion

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.

Examples of different mass flow and density error data have been provided, demonstrating that the general characteristics of the error surfaces against true mass flow and GVF under different conditions –flow-tube orientation and flow-tube geometry – are broadly similar for the same fluid, water. Nevertheless, a more detailed examination of the data shows important differences – for example in the spread of mass flow error at a particular GVF over a range of mass flow rates. Naturally, it is desirable to look for a physical model to predict behaviour without recourse to empirical data fitting. However, given the complexity of flow-tube geometries, and their clear influence on the resulting error surfaces (for example, the change in orientation from horizontal to vertical could be viewed as a very specific case of altering flowtube geometry), it is not clear how flowtube geometry might be characterised as a set of parameter values from which the errors surfaces could be calculated. Perhaps as scientific understanding increases, it will be possible to define standard error surfaces for mass flow and density for some specific flowtube geometry, and then to determine correlations for how these error surfaces are modified by fluid and application properties, such as viscosity and inlet pressure. It may also be possible to develop flowtube designs that are in some sense optimal for two-phase flow performance. However, at the current time, it is clear that the ability of parametric models to predict mass flow and density errors are much poorer than the repeatability of such errors when observed experimentally for a specific flowtube and fluid.

It is this repeatability, combined with the very great industrial requirement for low-cost, robust two-phase measurement, that renders a purely empirical approach to two-phase correction practical, if not especially desirable from a scientific point of view.

The methodology for developing empirical models has been set out, using the high viscosity oil as a case study. The density errors observed for the high viscosity oil illustrate once again the poor state of understanding of the underlying physics. Negative errors, of perhaps lower magnitude than for water, might reasonably have been predicted. Large positive errors were completely unexpected. That the purely empirical modelling technique was able to accommodate such data reinforces the view that this is an appropriate approach for the current level of understanding.

The obvious problem with an empirical approach is the validity of the resulting model beyond the immediate conditions in which it has been developed. This issue has been only partially addressed in this paper by the trials at lower temperature (and hence higher viscosity), and the field trials. In the case of the trials at lower temperature, the results in Fig. 11 suggest that up to a 50% increase in viscosity leads to a reduction in raw mass flow errors, and hence over-compensation by the correction model. This is in line with intuition, and suggests the possibility mentioned above of geometry-specific error curves which are adjusted according to fluid properties, such as viscosity. Systematic experimental work and data analysis could reveal the validity of this approach.

Irrespective of the modelling technique used, it is likely that there will be great variation between single-phase and two-phase measurement uncertainties for many years. For example, for single phase liquids, the mass flow and density errors may both be of the order of 0.2% or better, while with two-phase flow, uncertainties of up to 5% may be appropriate. There is furthermore great diversity in two-phase measurement, as illustrated in the contrast between Figs. 6 and 10. These figures also show that in general, lower corrected errors are observed at lower GVF levels. The concept of the self-validating sensor [15, 16], which generates an on-line estimate of its own uncertainty, including during “fault” conditions, was largely inspired by the Coriolis mass flow meter. The idea of reporting an increase in uncertainty in response to two-phase flow has been suggested repeatedly in the past (for example, in [9]). Probabilistic analysis such as Figs. 6 and 10 suggest a refinement in which the reported uncertainty is a function of the estimated GVF, reflecting the model’s varying ability to correct different degrees of two-phase flow.

Evidently, there is a great need for systematic trials, closely supported by basic physical modelling, to gain a deeper understanding of the error behaviour of Coriolis meters under two-phase flow. However, the methodology exists today for developing satisfactory empirical corrections for specific flowtubes and fluids, for circumstances where the economic benefits justify the development costs.

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

	Test Separator		Coriolis Meter		Difference
Well No.	**barrels per day**	**kg/s**	**barrels per day**	**kg/s**	**%**
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

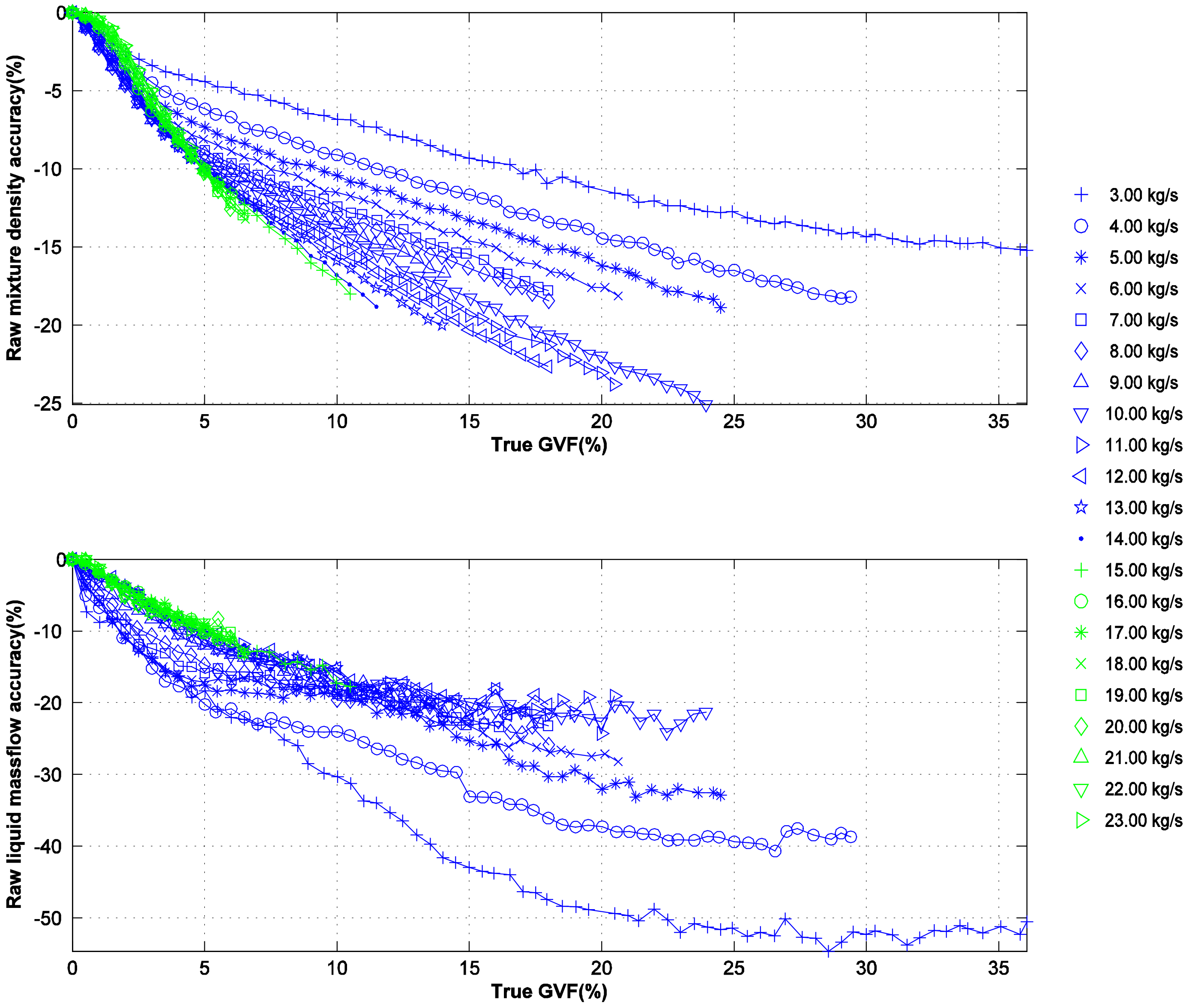


Fig. 1: Raw massflow and density errors for a 75 mm Coriolis meter in vertical alignment under two-phase flow; the liquid is water and the gas is air.

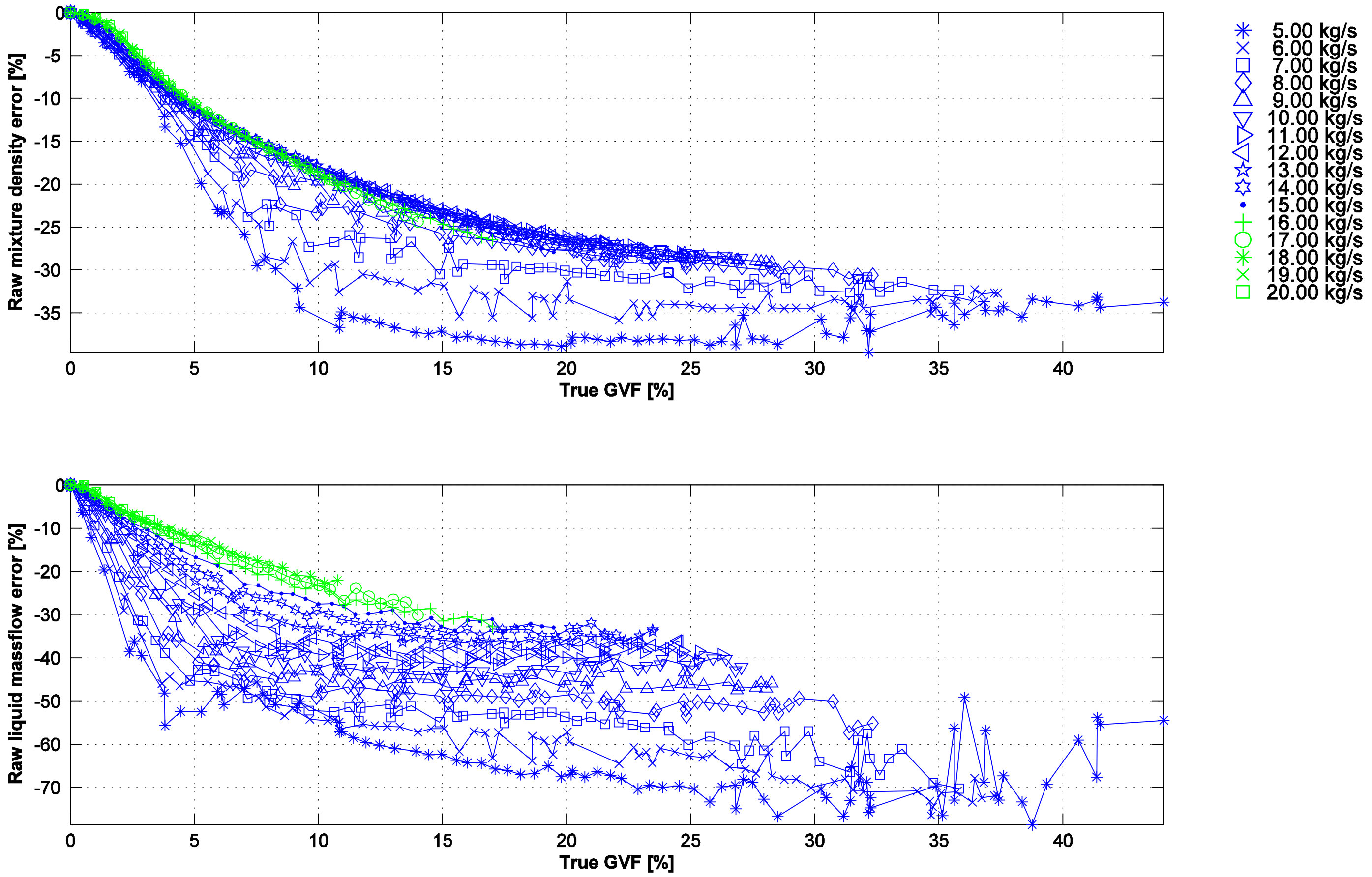


Fig. 2: Raw massflow and density errors for a 75 mm Coriolis meter in horizontal alignment under two-phase flow; the liquid is water and the gas is air.

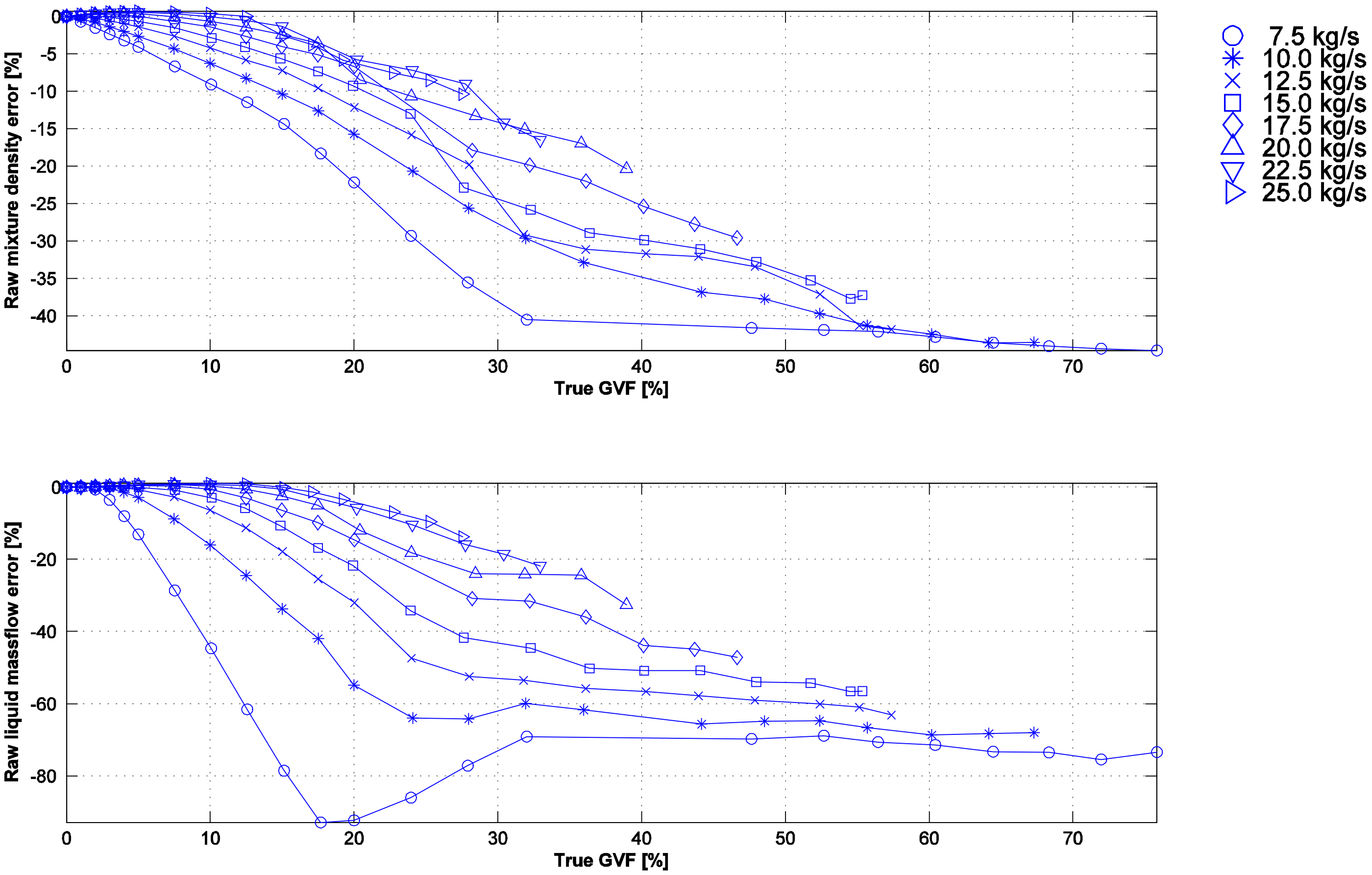
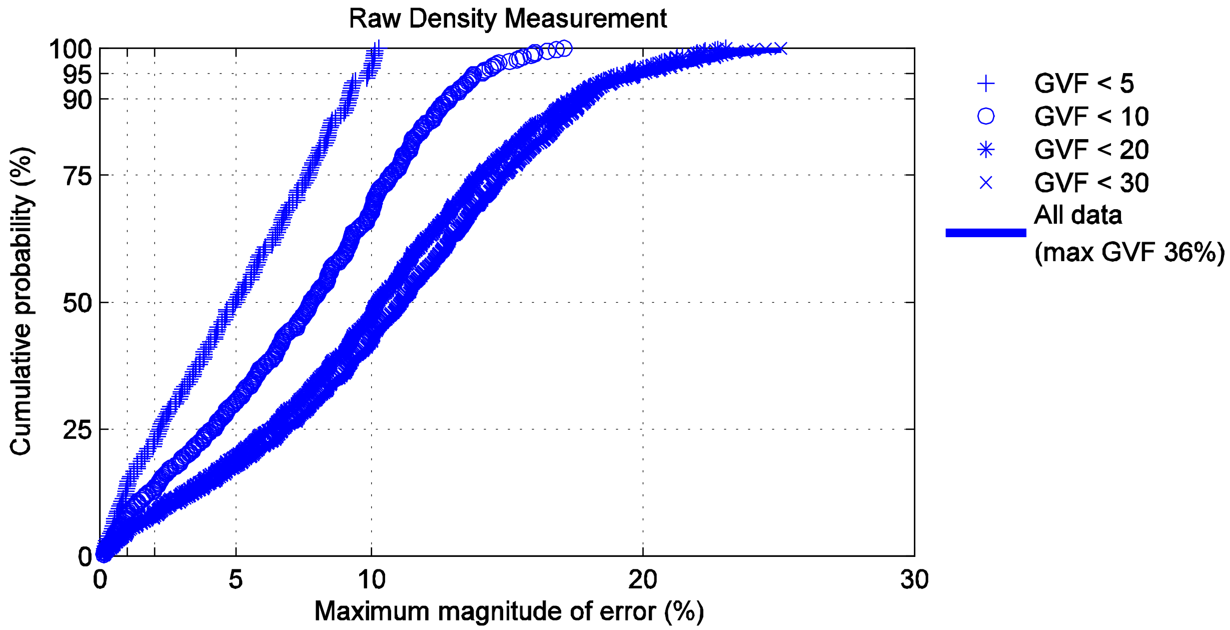


Fig. 3: Raw massflow and density errors for a 100 mm Coriolis meter, with a different geometry from that of the flow-tube in Figs 2 and 3, in horizontal alignment under two-phase flow; the liquid is water and the gas is air.



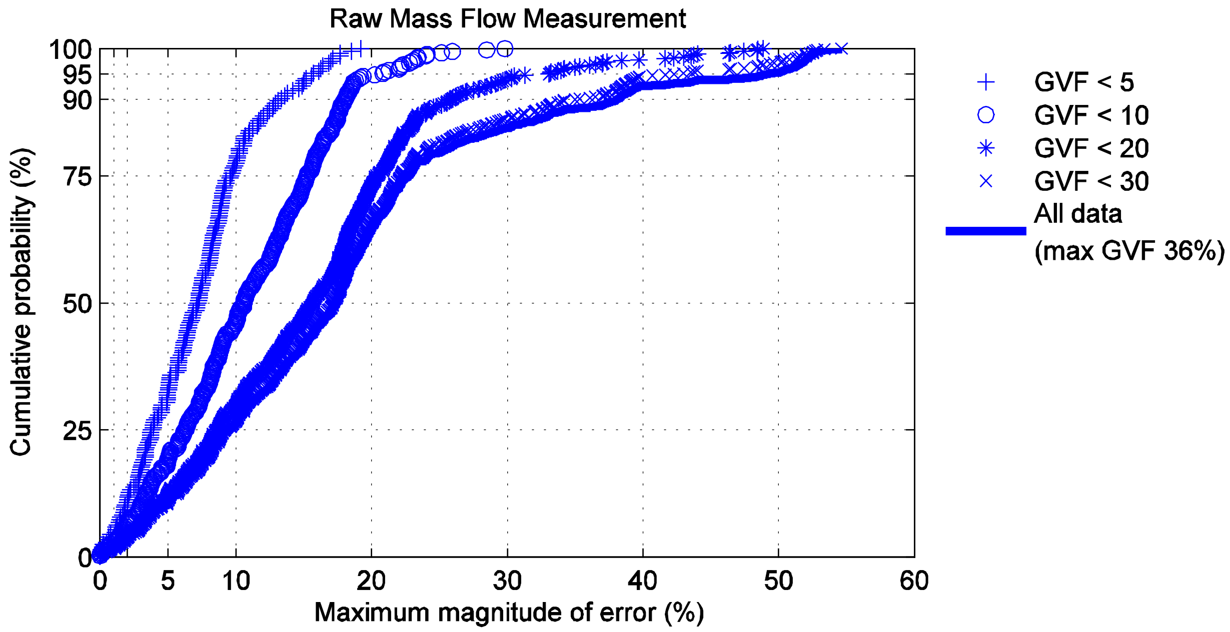


Fig. 4. Probability distribution of raw massflow and density errors for a 75 mm Coriolis meter in vertical orientation under two-phase flow. The liquid is water and the gas is air. Each line shows the probability distribution for all experimental points with GVF less than a certain value.

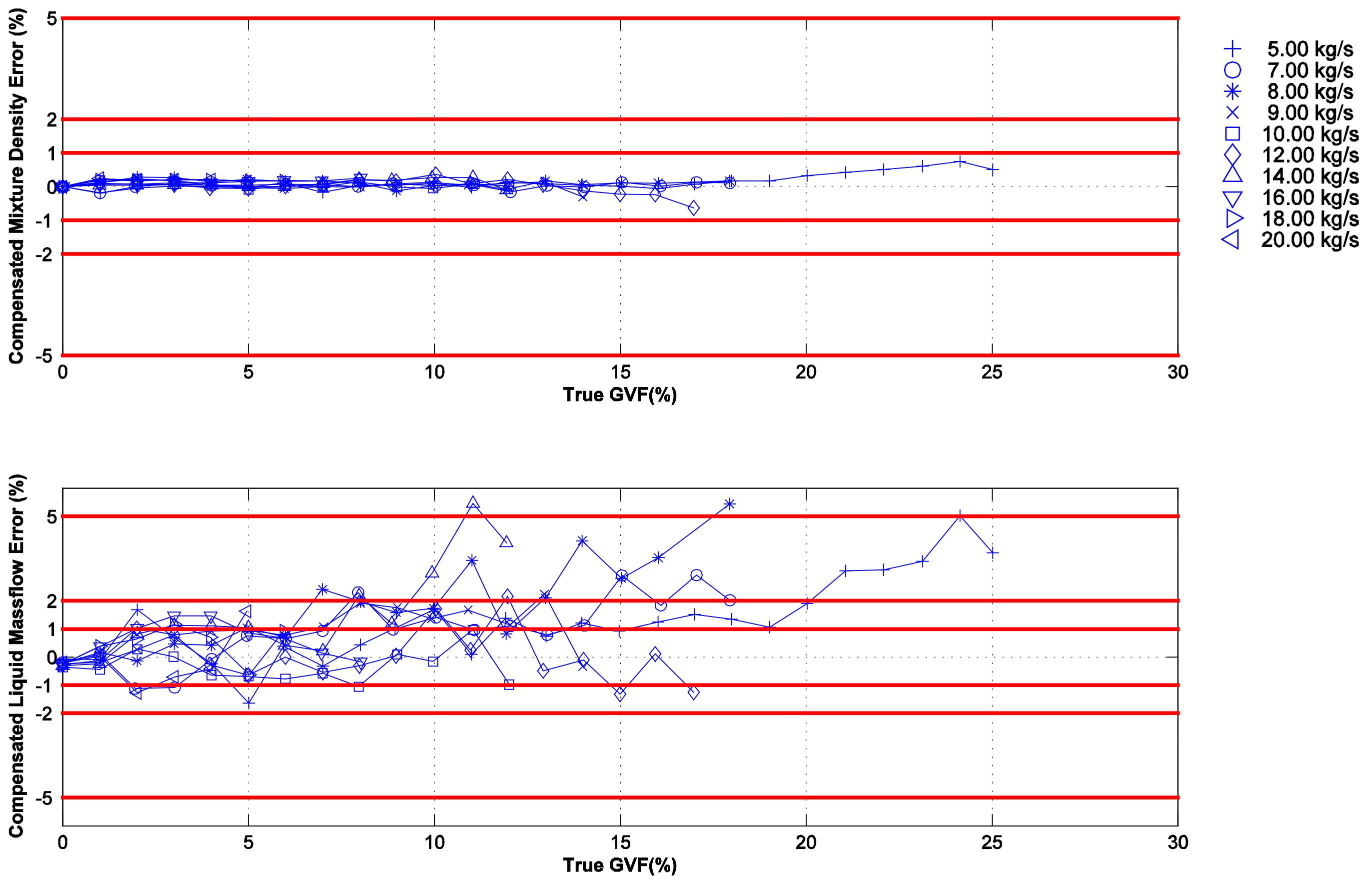


Fig. 5: Residual errors for massflow and density measurements with online compensation applied for a 75 mm Coriolis meter in vertical orientation under two-phase flow. The liquid is water and the gas is air.

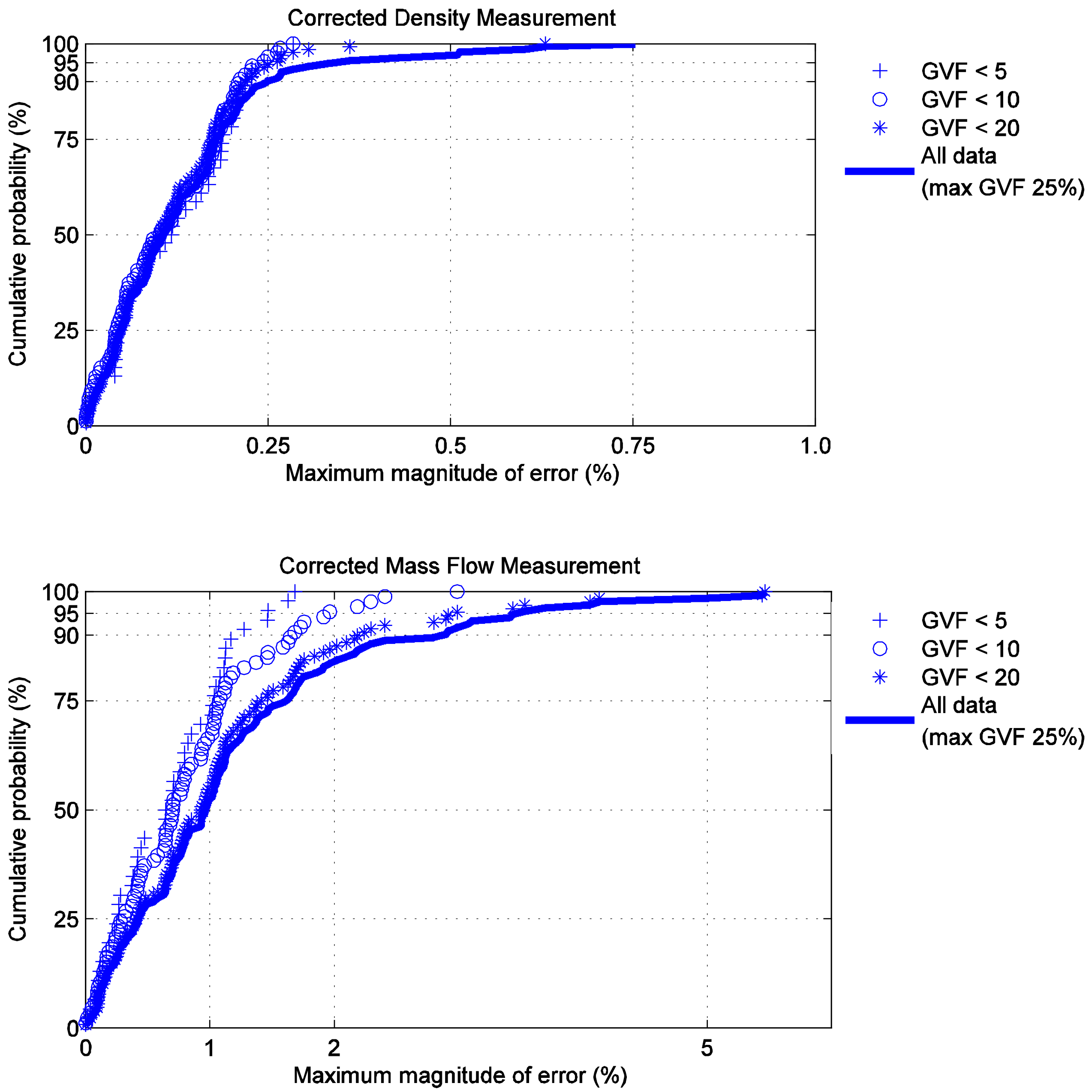


Fig. 6: Probability distribution of online compensated massflow and density errors for a 75 mm Coriolis meter in vertical orientation under two-phase flow. The liquid is water and the gas is air. Each line shows the probability distribution for all experimental points with GVF less than a certain value.

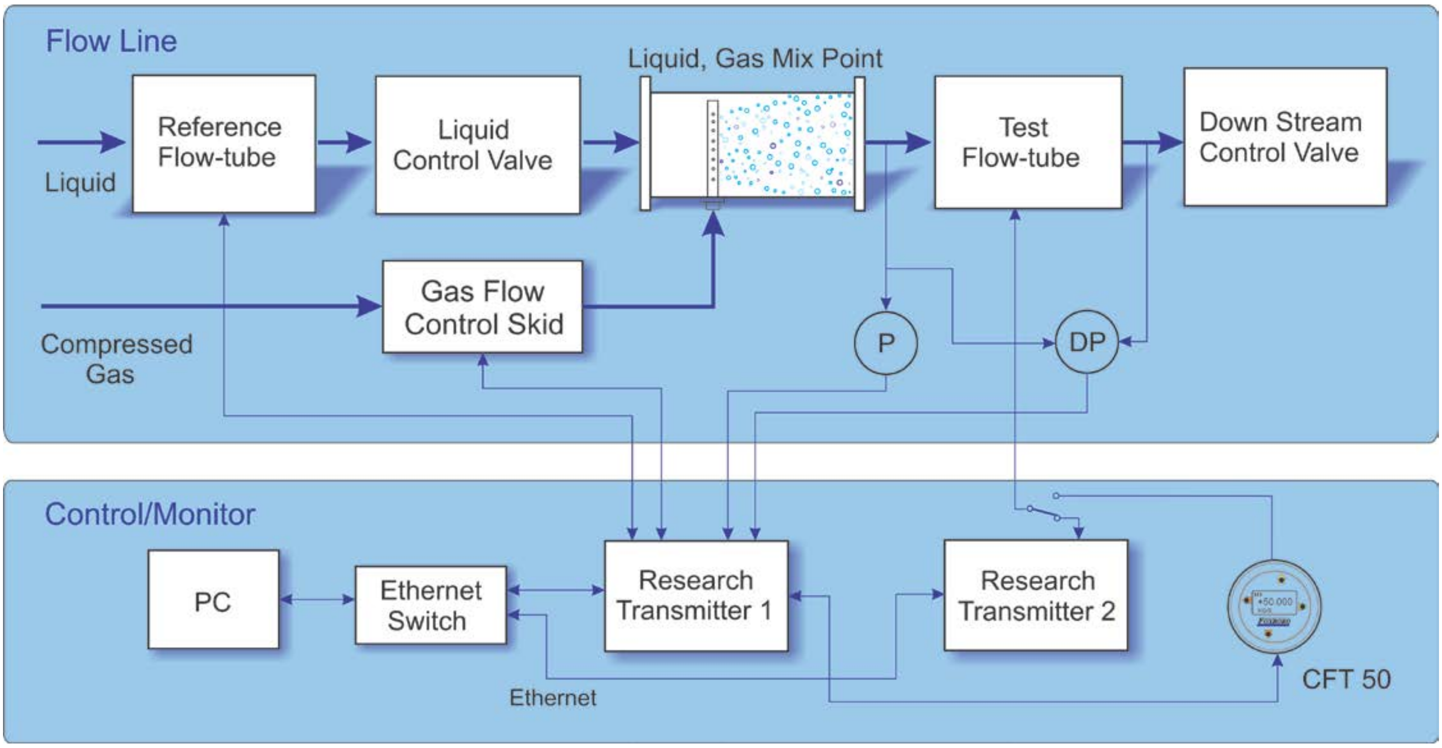


Fig. 7: schematic of two-phase experimental system, showing separate liquid and gas control, gas injection and the test meter, along with the control and monitoring system.

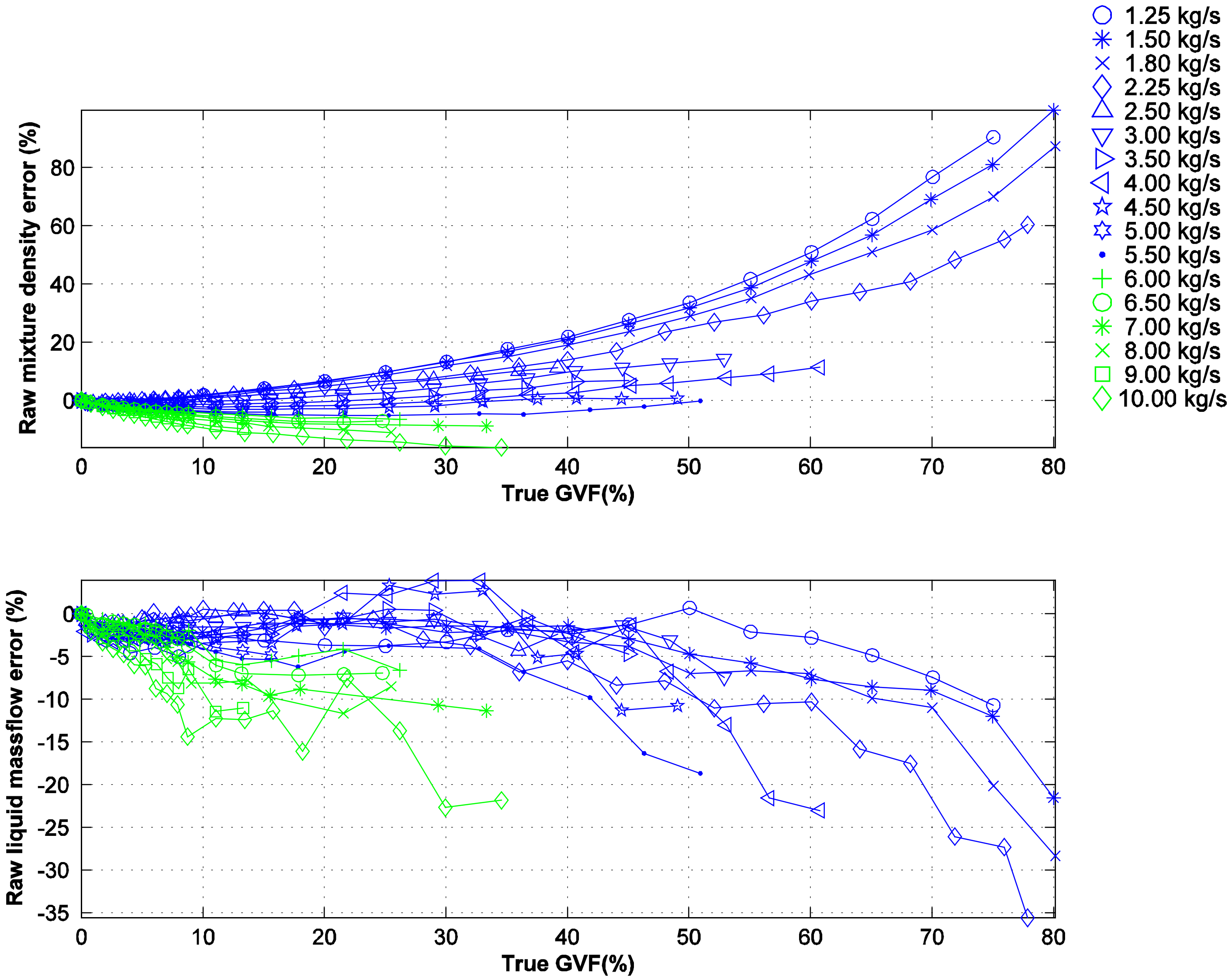


Fig. 8: Raw density and mass flow errors for a 75 mm Coriolis meter under two-phase flow; the liquid is Primol at 20C (viscosity 200 cSt) and the gas is nitrogen.

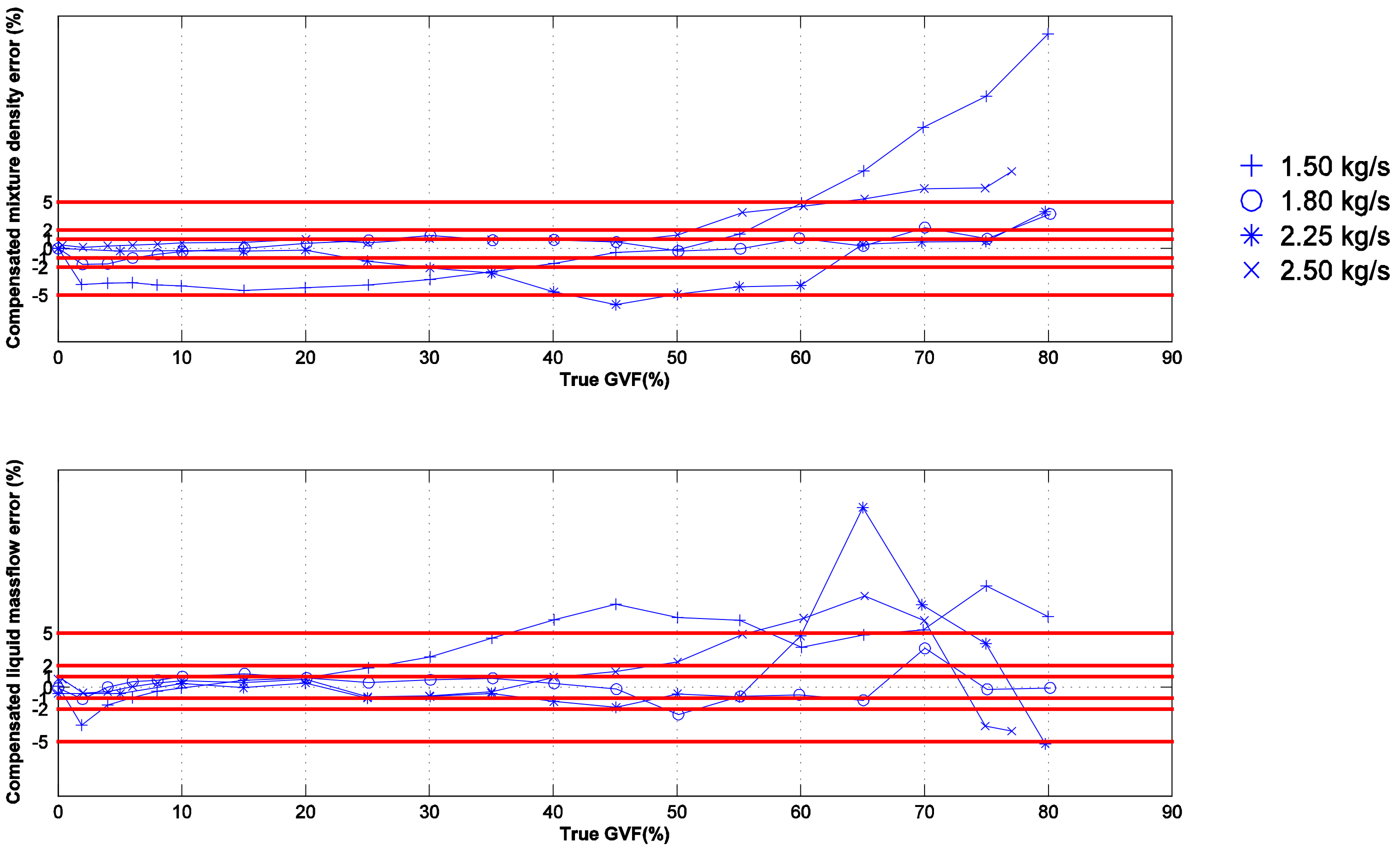


Fig. 9: On-line density and mass flow errors for a 75 mm Coriolis meter in vertical alignment under two-phase flow with correction applied, using the research transmitter; the liquid is Primol at 20C (viscosity 200 cSt) and the gas is nitrogen.

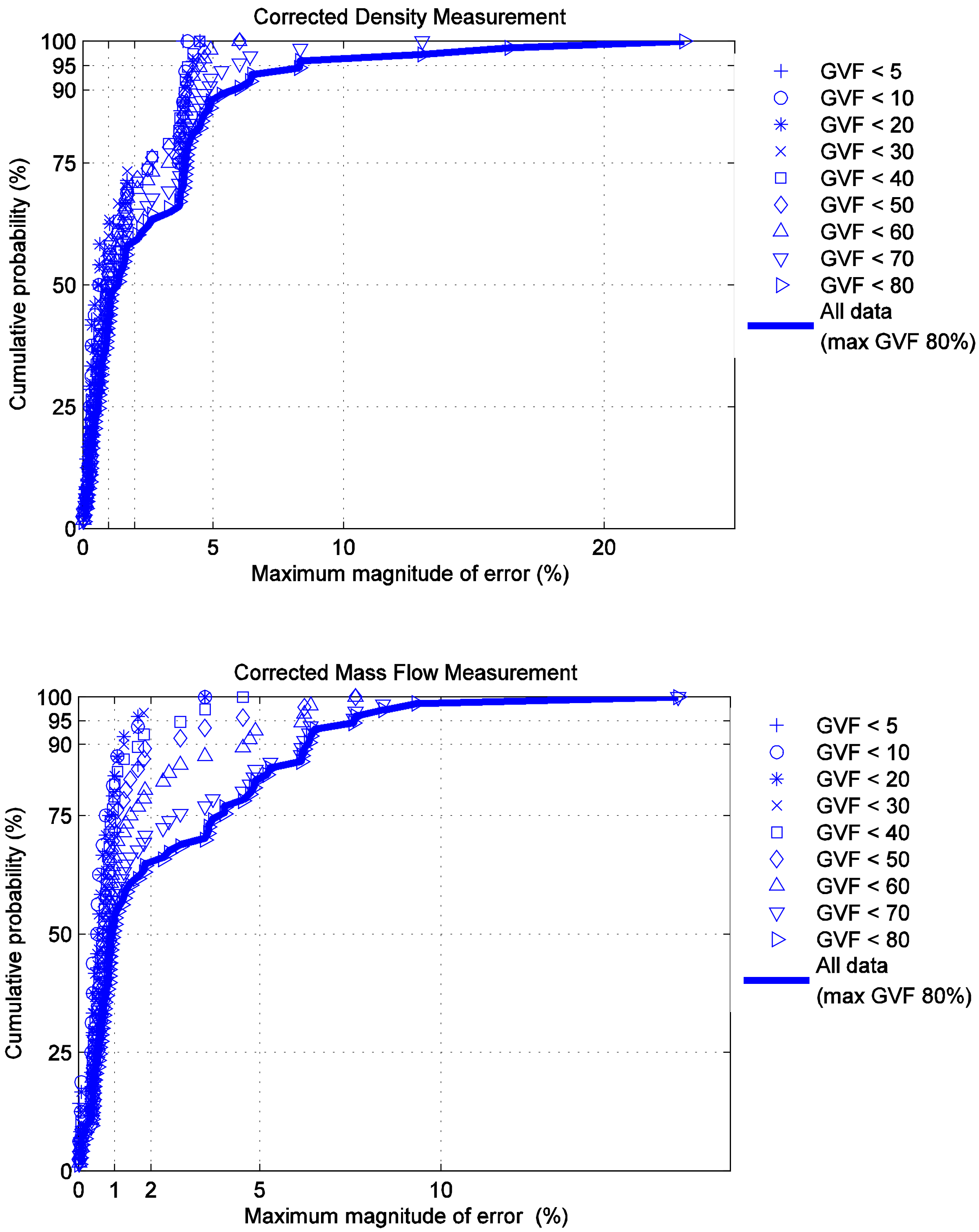


Fig. 10: Probability distribution of on-line density and mass flow errors for a 75 mm Coriolis meter in vertical alignment under two-phase flow with correction applied, using the research transmitter; the liquid is Primol at 20C (viscosity 200 cSt) and the gas is nitrogen.

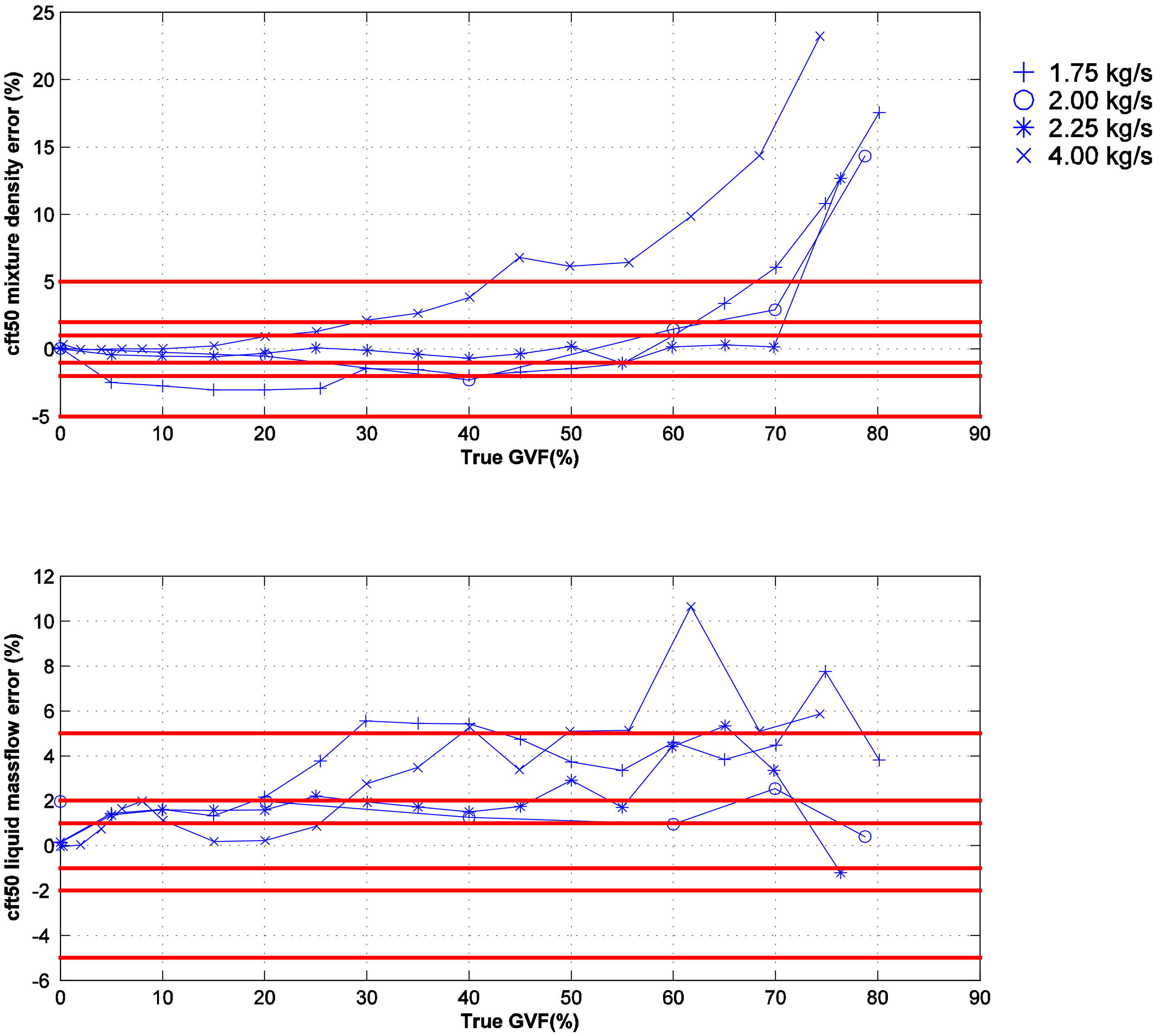


Fig. 11: On-line density and mass flow errors for a 75 mm Coriolis meter in vertical alignment under two-phase flow with correction applied, using the CFT-50 commercial transmitter; the liquid is Primol at 15C (viscosity 300 cSt) and the gas is nitrogen.

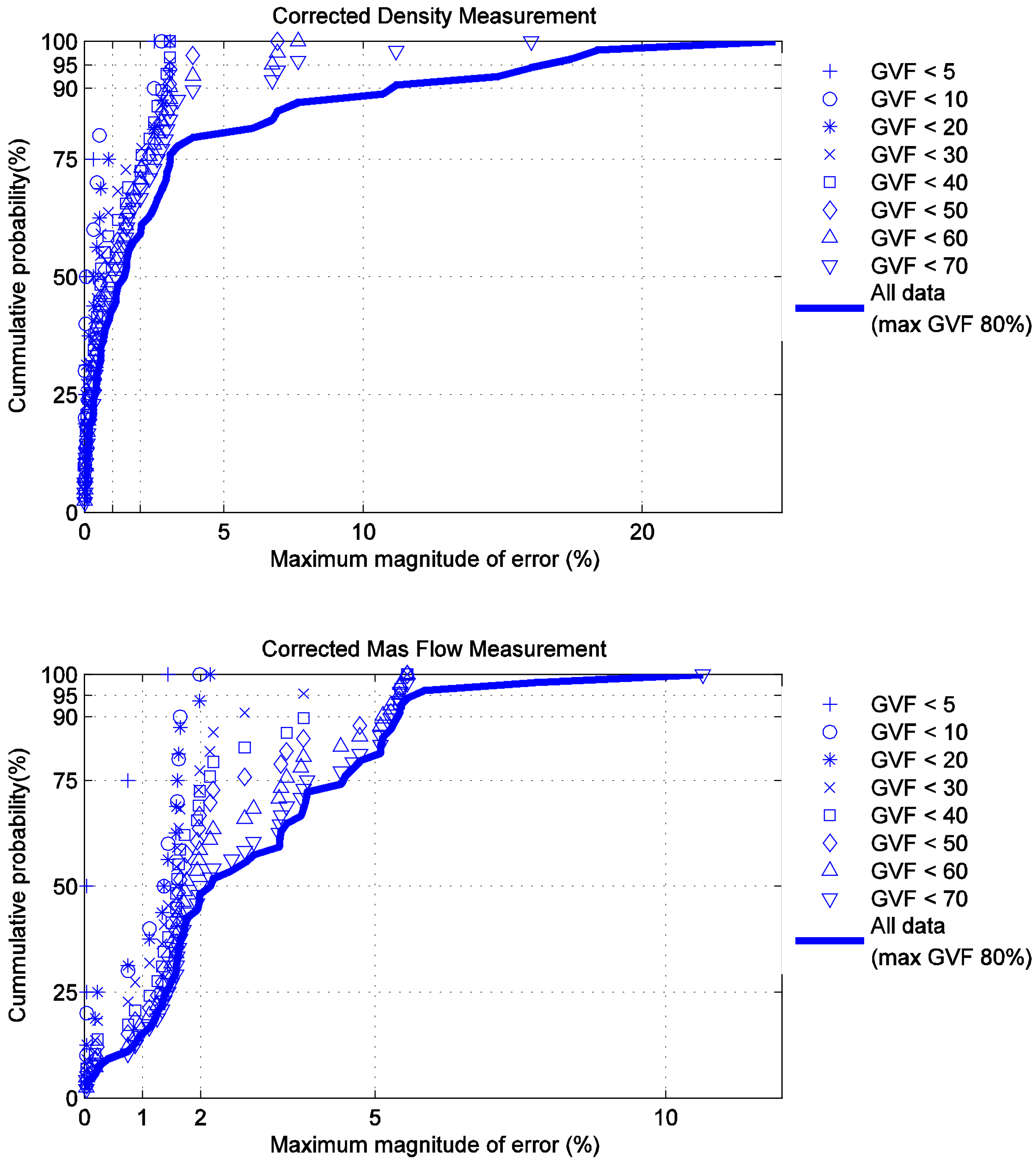


Fig. 12: Probability distribution of on-line density and mass flow errors for a 75 mm Coriolis meter in vertical alignment under two-phase flow with correction applied, using the CFT-50 commercial transmitter; the liquid is Primol at 15C (viscosity 300 cSt) and the gas is nitrogen.

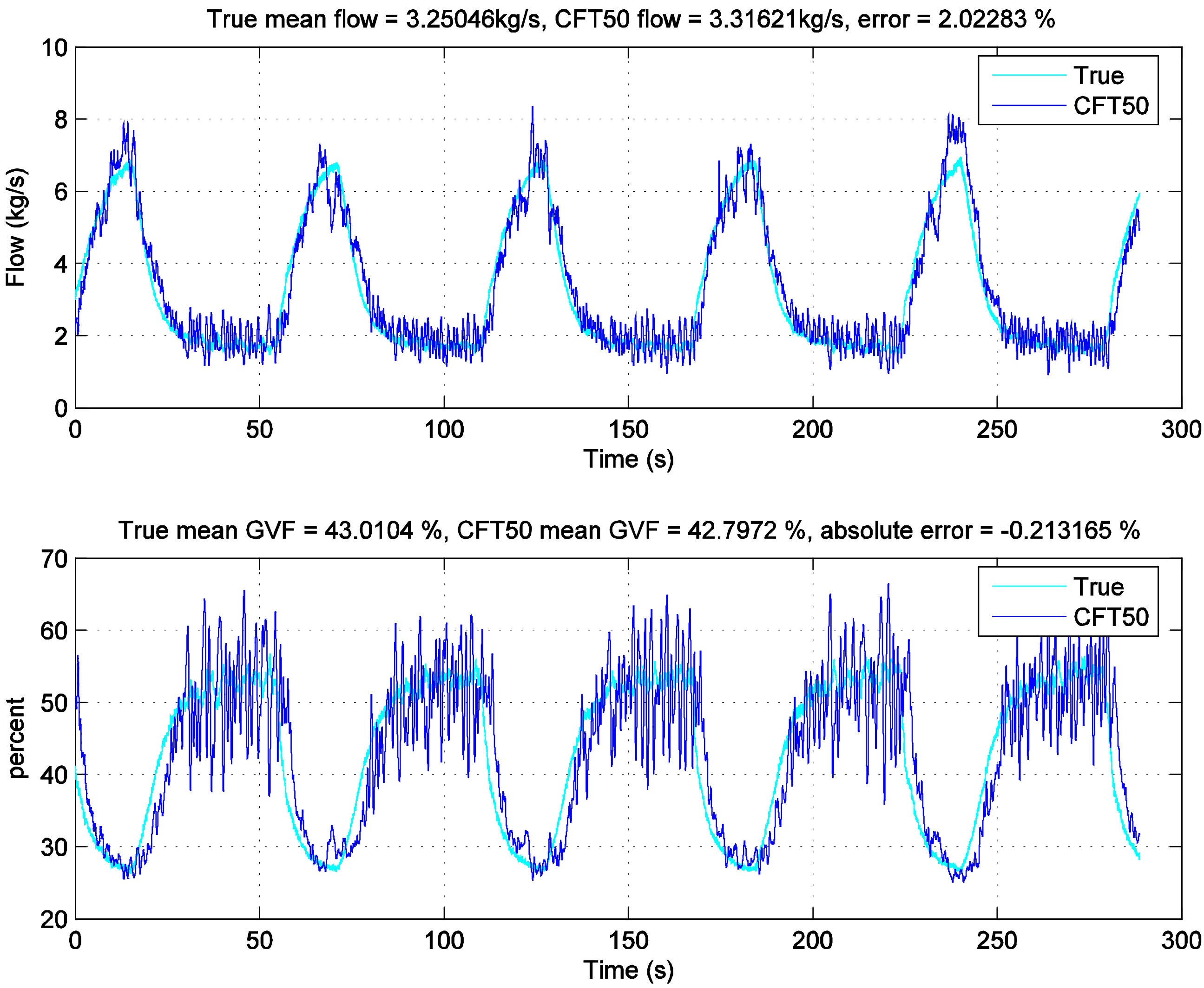


Fig. 13: On-line tracking of flow and gas void fraction. The true GVF reading is calculated from the instantaneous measurement of single phase liquid and gas, together with the pressure of the two-phase mixture at the inlet of the flow-tube.