

Three-phase flow measurement using Coriolis mass flow metering

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Abstract

This paper describes a new three-phase flow metering technology, combining Coriolis mass flow and water cut readings and without applying any phase separation [1]. The system has undergone formal laboratory trials at NEL, UK and at VNIIR, Kazan, Russia; a number of field trials have taken place in Russia. Results from the NEL trial will be described in detail. Initial experiences from field trials will also be described. Together, these results demonstrate the potential for using Coriolis mass flow metering combined with water cut metering for three-phase (oil/water/gas) measurement.

Introduction

Coriolis mass flow metering has for several years shown promise as an additional measurement principle for multi-phase flow metering [2]. In this paper we describe a three-phase metering system combining Coriolis mass flow metering with a water cut measurement to provide separate measurements of oil, water and gas flow.

A Coriolis mass flow meter provides independent mass flow and density readings of a bulk fluid. Technology enhancements are required to enable it to maintain oscillation through gas/liquid mixtures and to provide accurate measurements. However, a third measurement is required to resolve gas, water and oil flow rates; several Water Cut meters have been tested and the one selected provides complementary robustness to gas/liquid effects.

While the long-term goal is to develop a Coriolis-based solution to cover the complete range of three-phase conditions, our current experience suggest the best performance is obtained by designing particular implementations for more limited process conditions – for example a Coriolis-based wet gas metering system works well [3]. The current system is designed for good measurement performance at up to 50% Gas Void Fraction (GVF), for any water cut, and with an 8:1 turndown on the liquid fraction flowrate. A series of trials have taken place at NEL's multi-phase flow facility in the UK with Coriolis meter sizes from ½" to 2"; results from formal trials on a 2" meter are presented. Further tests have taken place at VNIIR, in Kazan, and field trials are starting to take place, particularly in Russia.

Net Oil & Gas Skid Overview

Figure 1 shows the design of the Net Oil & Gas Skid. Flow is conditioned through the rising and falling of the pipework, with the Coriolis meter positioned on the downward and outward leg of the Skid. The Water Cut meter is positioned immediately below it. A multivariable transmitter is used to monitor pressure and temperature, while a Net Oil Computer performs the three-phase flow calculations, and provides a user interface and data archiving. Real-time data is available via a Modbus interface, with an update rate of 1 second.

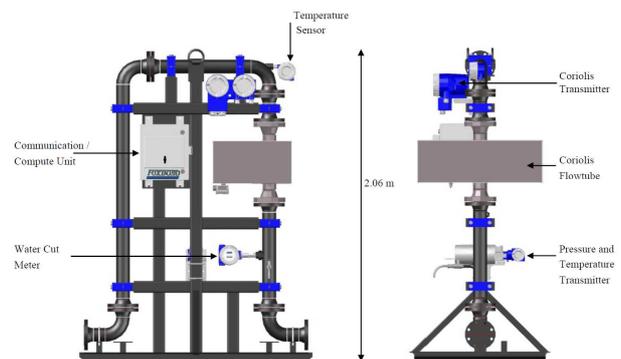


Figure 1: Design of Net Oil & Gas Skid.

Three-Phase Flow Models

The first requirement in providing multi-phase measurement based on Coriolis metering is to provide a flowtube drive control system which is able to maintain flowtube oscillation through the rapidly varying conditions (e.g. damping) induced by gas and liquid mixtures [3]. However, a further issue to address is the potentially large errors induced in the mass flow and density measurements from a Coriolis meter by the effects of a gas/liquid mixture. As described in [2], factors such as the geometry and orientation of the Coriolis flowtube influence the shape of the error functions. For a fixed flowtube geometry and orientation, the most significant dynamic parameters are the liquid flowrate and the GVF.

Previous work in [2] has described how these errors can be modelled so that corrections can be applied based solely on parameters observable within the Coriolis meter itself. When dealing with three-phase flow, an additional dimension is introduced. This can be described in terms of water cut, i.e. the percentage by volume of

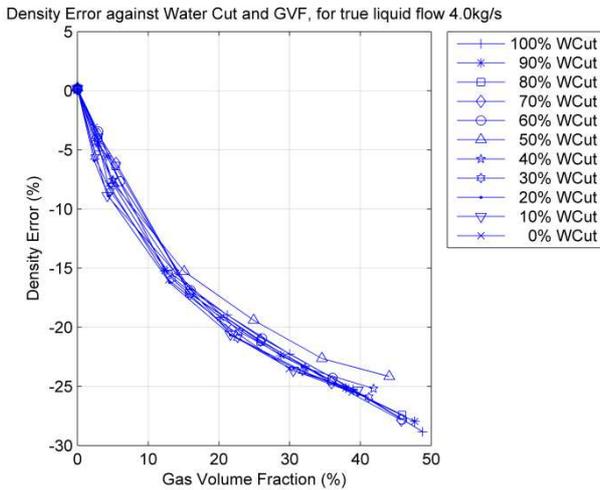


Figure 2: Density Errors at 4kg/s flow rate, with varying GVF and water cut

water as a proportion of the total liquid. Variable water cut introduces two difficulties. Firstly, the Coriolis meter mass flow and density errors are liable to change with water cut; secondly, a third measurement (in addition to the mass flow and density measurements from the Coriolis meter) is required to resolve the individual flows rates of oil, water and gas.

In the system described, the additional measurement is provided by a Water Cut meter; with the type selected demonstrating good robustness and repeatability with liquid/gas mixtures. Variations in the density and mass flow errors due to water cut have been modelled based on data collected at NEL. For example, figures 2 and 3 show the density and mass flow errors for the 2" Coriolis meter (positioned within the Net Oil & Gas Skid), with water cut varying from 0 to 100% in steps of 10%, where the true mass flow rate is maintained constant at 4kg/s, and where the GVF is increased up to 50%.

For both density and mass flow, the error curves are broadly similar as the water cut varies, but there are sufficient differences that the water cut measurement is

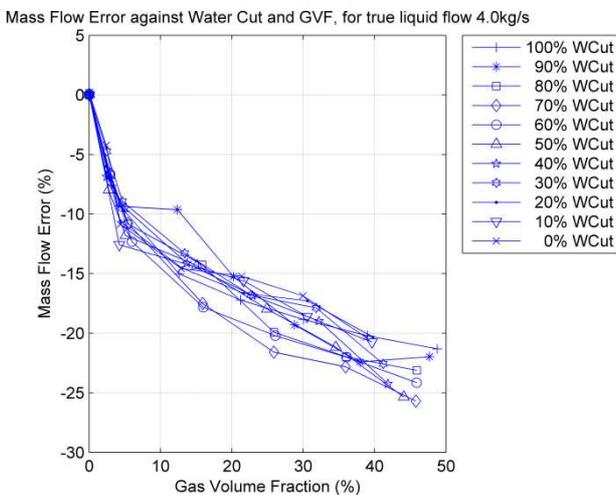


Figure 3. Mass Flow Errors at 4kg/s flow rate, with varying GVF and water cut

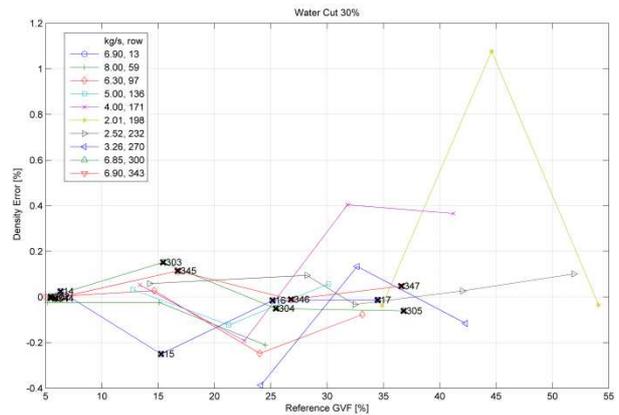


Figure 4: Residual Density Errors at 30% water cut, with varying GVF and liquid mass flow rate. Unlabelled points are used in the original model of density errors; labelled points (xNN) are tests where the model is applied, but which were not used to build the model.

included as one of the parameters in the modelling of mass flow and density errors for three-phase metering. Figure 4 shows typical results for the corrected density measurement; here the results for 10% water cut and for a range of flowrates are shown. The lines represent data points used in the model, while points indicated by an x and an index number show independent tests not incorporated into the model data. The residual density errors are mostly within 0.5%, which provides acceptable levels of accuracy when propagated into the calculations of oil, water and gas flow.

Formal Trials at NEL

A formal series of trials were carried out on a 2" Net Oil & Gas Skid in January 2012 at NEL's three-phase flow facility. The intention was to demonstrate compliance with the measurement performance requirements of the Russian Standard GOST 8.165 [5], which has the following key requirements:

- Total liquid flow accuracy requirement $\pm 2.5\%$
- Total gas flow accuracy requirement $\pm 5.0\%$
- Total oil flow accuracy requirement dependent upon water cut:
 - For water cuts less than 70%, oil accuracy requirement $\pm 6.0\%$
 - For water cuts between 70% and 95%, oil accuracy requirement $\pm 15.0\%$
 - For water cuts above 95%, no oil accuracy requirement is specified, but an indication of performance may be given.

It is understood that the requirement for gas accuracy is a relatively recent introduction, and it is noteworthy that the gas accuracy requirement is not specified on a sliding scale, while the oil accuracy does vary with water cut. This offers particular difficulties at low GVFs and for mass-based instrumentation.

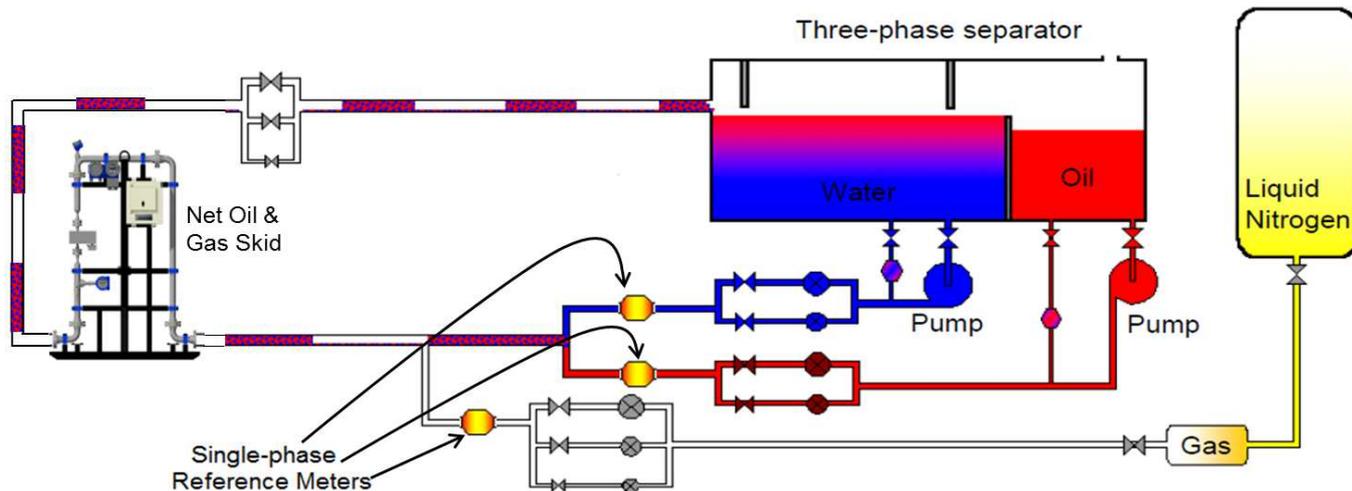


Figure 5: Experimental setup: Net Oil & Gas Skid in NEL three-phase test facility.

Figure 5 shows the Net Oil & Gas Skid positioned in the three-phase test facility at NEL. The separator system provides water and oil streams, while nitrogen is used as the test gas. Each phase is metered separately, before being combined and passed through the skid. For each test, steady conditions are established for the desired oil, water and gas flow rates, and then the reference single phase measurements are compared with the outputs of the Net Oil & Gas Skid over a 300 second test interval. The typical operating pressure was around 4 bar, while the operating temperature was around 40°C.

The test matrix is shown in Figures 6 and 7. A total of 75 tests were carried out. Figure 6 shows the GVF and mass flow rates used for each test. The mass flow rates range from 11 kg/s down to 2.3 kg/s. The maximum GVF decreases with increasing flow rate, reflecting a practical limitation on the pressure drop across the Skid of approximately 1.5 bar. Figure 7 shows the mass flow and water cut values used for the tests. Water cuts were tested in steps of 10% between 10% and 90%, with further tests at 2%, 5%, 95% and 98% water cuts. Tests on pure water or pure oil were not possible given the low levels of cross-contamination in the water and oil supplies from NEL's separator system. This cross-contamination was, however, monitored and included in the calculation of Net Oil & Gas Skid errors.

Figures 8 – 10 give a summary of the results obtained in these test trials. Figure 8 shows the total liquid errors against water cut. The liquid performance is similar across all water cuts, 97% of the points fall within the GOST spec of $\pm 2.5\%$, and all points fall within $\pm 4\%$. The gas mass flow rate was substantially within the GOST specification, as shown in Figure 9. Here 93% of the test points fall within the $\pm 5\%$ limit.

As discussed above, the GOST standard specifies a maximum oil error which varies with water cut. For water cuts below 70%, the permitted oil mass flow error is $\pm 6\%$; between 70% and 95% water cut, the oil mass flow error limit is $\pm 15\%$; and above 95% water cut no oil mass flow limit is specified. As shown in Figure 10, all test points match this performance requirement.

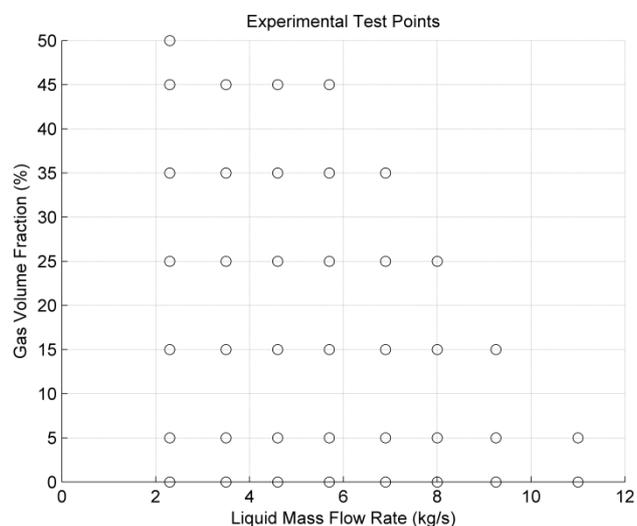


Figure 6: Experimental grid – mass flow rate vs. GVF

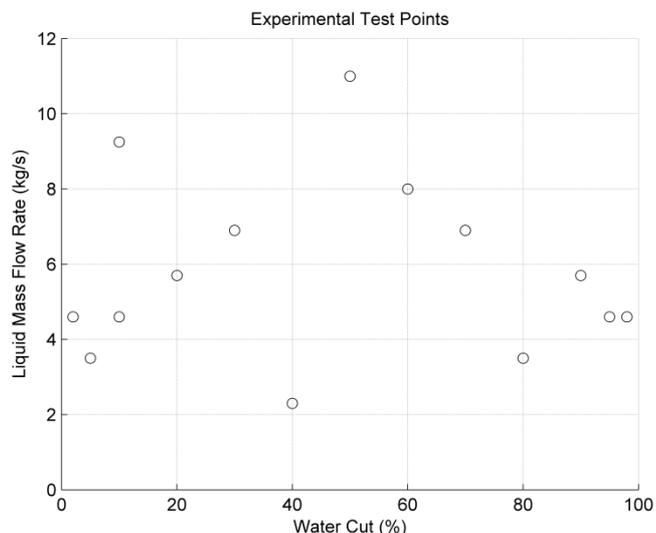


Figure 7: Experimental grid – liquid mass flow rate vs. water cut

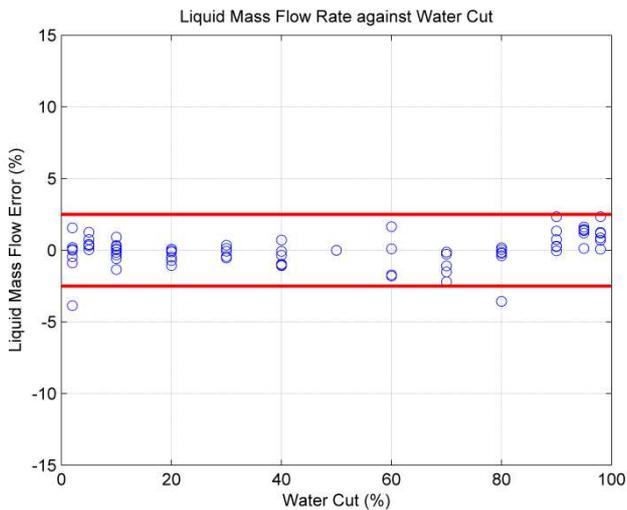


Figure 8: Total liquid mass flow rate errors against water cut. The target is $\pm 2.5\%$ (red lines).

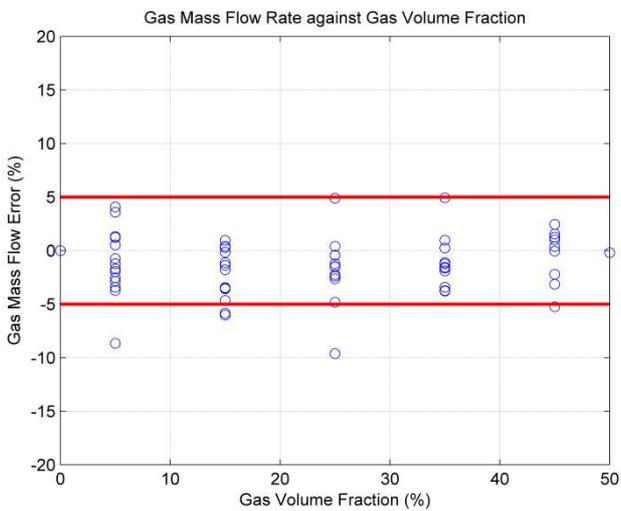


Figure 9: Gas mass flow error against gas void fraction. The target is $\pm 5\%$ (red lines).

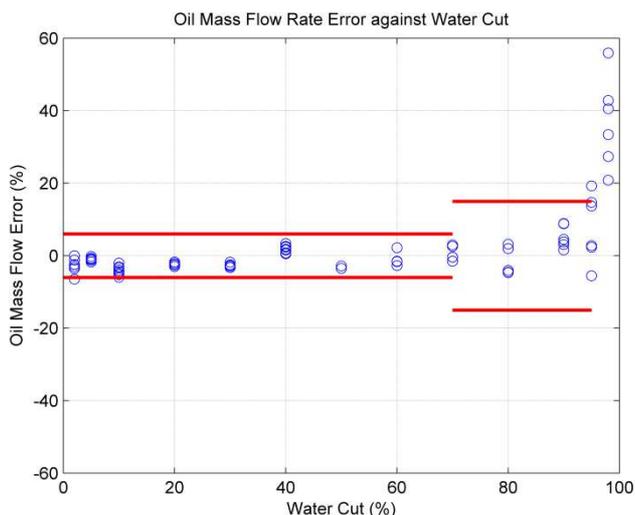


Figure 10: Oil mass flow error against water cut. The target performance (red lines) is $\pm 6.0\%$ for water cuts less than 70%, and $\pm 15.0\%$ for water cuts between 70% and 95%.

Further trials have taken place on a 1/2" Net Oil & Gas Skid in April 2012, and on a 3" skid at VNIIR, the Russian National Flow Laboratory in Kazan. Similar results were obtained in these two trials to those reported here for the 2" meter.

Field Trials and Dissolved Gas

The Net Oil & Gas Skid is being applied through a programme of field trials in Russia. Customers have requested that the Skid should be able to calculate the amount of dissolved gas present in the well stream. Accordingly, a dissolved gas model has been included in the system, which calculates dissolved gas based on pressure and temperature, and the flow rates of the oil and water and the free gas.

For example, figure 11 shows real-time data from a field trial, where the dissolved gas is measured alongside the oil, water and free gas flow rates.

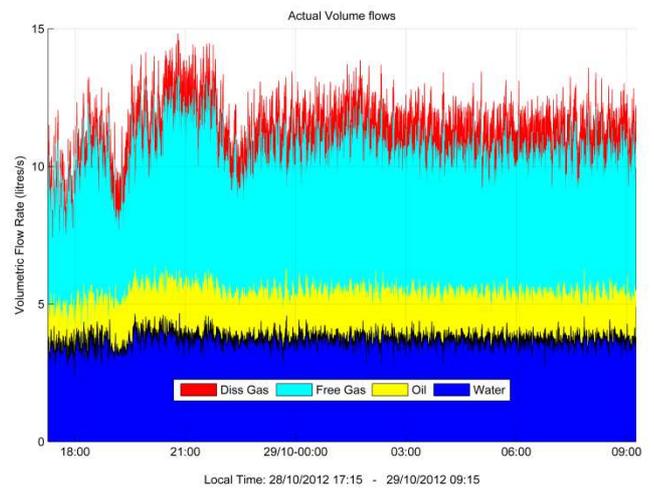


Figure 11: Skid data from a field trial, showing flow rate for water, oil, free gas and dissolved gas.

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