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Coriolis mass flow metering for three-phase flow: A case study

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ABSTRACT

Previous work has described the use of Coriolis mass flow metering for two-phase (gas/liquid) flow. As the Coriolis meter provides both mass flow and density measurements, it is possible to resolve the mass flows of the gas and liquid in a two-phase mixture if their respective densities are known. To apply Coriolis metering to a three-phase (oil/water/gas) mixture, an additional measurement is required. In the work described in this paper, a water cut meter is used to indicate what proportion of the liquid flow is water. This provides sufficient information to calculate the mass flows of the water, oil and gas components. This paper is believed to be the first to detail an implementation of three-phase flow metering using Coriolis technology where phase separation is not applied.

Trials have taken place at the UK National Flow Standards Laboratory three-phase facility, on a commercial three-phase meter based on the Coriolis meter/ water cut measurement principle. For the 50 mm metering system, the total liquid flow rate ranged from 2.4 kg/s up to 11 kg/s, the water cut ranged from 0% to 100%, and the gas volume fraction (GVF) from 0 to 50%. In a formally observed trial, 75 test points were taken at a temperature of approximately 40 °C and with a skid inlet pressure of approximately 350 kPa. Over 95% of the test results fell within the desired specification, defined as follows: the total (oil + water) liquid mass flow error should fall within ±2.5%, and the gas mass flow error within ±5.0%. The oil mass flow error limit is ±6.0% for water cuts less than 70%, while for water cuts between 70% and 95% the oil mass flow error limit is ±15.0%.

These results demonstrate the potential for using Coriolis mass flow metering combined with water cut metering for three-phase (oil/water/gas) measurement.

1. Introduction

Coriolis mass flow metering is a widely-used technique for industrial flow measurement. A Coriolis meter consists of an electronic transmitter and a mechanical flow tube. The meter operates by oscillating the flow tube (typically 1–300 mm in diameter), at the natural frequency of a selected mode of mechanical vibration. 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. For a given flow tube of fixed mass, the overall mass (flow tube plus process fluid) 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 further arranged so that Coriolis forces act to generate a phase difference between the two sinusoidal sensor signals, which is essentially proportional to the mass flow of the process fluid. The Coriolis transmitter, which monitors and maintains flow tube oscillation, extracts the sensor signals and derives the flow and density measurements.

The last decade has seen rapid developments in Coriolis mass flow metering with the introduction of digital technology to implement key aspects of transmitter functionality, particularly the generation of the drive signal [1–3]. Enhancements have included improving the dynamic response of the meter [4–6]. However, perhaps the most important recent development has been establishing the capability of Coriolis meters to measure two-phase flows. Previous Coriolis metering transmitters were unable to maintain flow tube oscillation in the highly damped conditions generated by the mixing of liquid and gas. However, using a digital drive, it has proved possible to continue operation through most gas/liquid mixtures, including the onset of liquid into an empty flow tube and the draining of a full flow tube back to the empty state. Unfortunately, maintaining oscillation is insufficient to ensure good measurement, as two-phase (gas/liquid) conditions induce potentially large errors into the mass flow and density measurements. However, it has proved possible to model these errors, based on parameters observable within the meter itself, and a number of two-phase flow Coriolis applications have been developed [7].

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Nomenclature

α_c	gas volume fraction based on corrected data (%)
ρ_g	gas density at local temperature and pressure (kg/m^3)
ρ_o	oil density at local temperature and pressure (kg/m^3)
ρ_w	water density at local temperature and pressure (kg/m^3)
ρ_l	liquid only (oil and water) mixture density at local temperature and pressure (kg/m^3)
ρ_{ma}	apparent mixture density from the Coriolis mass flow meter (kg/m^3)
ρ_{mc}	corrected mixture density from the Coriolis mass flow meter (kg/m^3)
dd	difference between the liquid-only mixture density ρ_l and the observed density ρ_{ma} (%)
$\dot{m}_g$	mass flow rate of gas (kg/s)
$\dot{m}_l$	mass flow rate of liquid (kg/s)
$\dot{m}_o$	mass flow rate of oil (kg/s)
$\dot{m}_w$	mass flow rate of water (kg/s)
$\dot{m}_{ma}$	apparent three-phase mixture mass flow rate from the Coriolis mass flow meter (kg/s)
$\dot{m}_{mc}$	corrected three-phase mixture mass flow rate from the Coriolis mass flow meter (kg/s)
P	absolute pressure at the inlet to the Coriolis mass flow meter (kPa)
T	process fluid temperature from the RTD sensor (K)
wc	water cut from the water cut meter, after any correction (%)

Several physical approaches to modeling the effects of two-phase flow have been reported in the literature, of which the most important are: the inertial/buoyancy effect [8,9], the compressibility effect [10,11] and the (asymmetric) damping effect [12,13]. While the development of such physical models is essential, they are unable at present to give good predictions of mass flow and density errors over practical industrial conditions. Nevertheless, the repeatability of such errors indicates that valuable measurements can be provided, and accordingly in this study a purely empirical approach is adopted. The error behavior is recorded, modeled, and predicted, based on internally observed parameters, without assuming any particular physical process underlies the effect.

As discussed in more detail below, further steps are required to attempt three-phase measurement, where the liquid component is further separated into measurements of (usually) oil and water. This is believed to be the first description of such a system developed by an academic group; however, given the substantial commercial interest in three-phase flow within the oil and gas industry, there have been a number of commercial developments, typically involving partial separation. For example, Agar Corporation has developed a commercial system using a similar combination of Coriolis and water cut meters [14].

A first approach to the empirical modeling of two-phase flow effects in a Coriolis meter [15] is to consider the mass of the gas to be negligible; this is a reasonable assumption for low pressure applications where only the mass flow of the liquid is of interest. Assuming a constant true liquid density, the two-phase flow can be characterized by the true liquid mass flow rate and the Gas Volume Fraction (GVF), defined as the percentage of gas by volume. A variety of parameters internal to the Coriolis meter may be used to correct the mass flow and density readings and to provide a corrected liquid mass flow and an estimate of the GVF. These include the observed mass flow rate and density, the 'density drop' i.e. the drop in density from a configured liquid-only density (as discussed below) and the drive gain.

A second approach to modeling two-phase flow is to consider both the liquid and gas mass flows [16]. This can prove necessary in high GVF and/or high pressure applications, where the mass of gas is not negligible, or where the flow rate of gas itself is of interest. Here additional information is needed. To perform PVT calculations for the gas, knowledge of the gas density is required (for example based on its composition), along with on-line readings of temperature and pressure. Composition and/or density information for gas and liquid (and how these vary with temperature and pressure) can be considered part of the system configuration, while on-line readings of temperature and pressure require additional instrumentation. Models of mass flow and density errors can be reworked to take the mass of gas into account, and the resulting calculation of liquid mass flow and GVF can be transformed to provide the mass flow of both the liquid and gas phases.

An obvious extension is to provide three-phase metering for the upstream oil and gas industry, where the three phases are water, oil and gas respectively. To a first approximation, this can be treated as a two phase (liquid/gas) problem, where the density of the liquid varies with the water cut. Here water cut is taken to represent the proportion by volume of the water in the total liquid. Thus if the water cut is 0%, the liquid is pure oil (irrespective of GVF) and if the water cut is 100%, the liquid is pure water (irrespective of GVF). In practice it is now possible to measure the water cut of a three-phase mixture with reasonable accuracy (for example the device used in this paper is specified as having $\pm$3% absolute error in water cut reading, for water cut less than 95% [17]) using a commercial water cut meter, and it is further possible to include water cut variation in the modeling of the mass flow and density errors; accordingly a three-phase metering system based on Coriolis mass flow metering has been developed. As previously, measurement of temperature and pressure are required for PVT calculations, while the configuration data must be extended to provide the densities of the pure water and pure oil, together with their variations with temperature and pressure.

A three-phase mixture can be specified in a number of ways; two will be used frequently throughout this paper. The first is to specify the mass flows of the oil, water and gas components; at the low operating pressures used in this work the oil and water flows are stated in kg/s, while the gas flow rate is stated in g/s. The alternative description is to specify the total liquid flow rate (usually in kg/s), water cut (between 0% and 100%) and GVF (from 0% up to 50% and beyond). Where it is assumed that the density of each phase is known along with temperature and pressure conditions, and that there is no slip between phases, it is straightforward to convert from one of these specifications to the other. Typically, the first description (mass flows of each phase) is used for specifying the accuracy of final results, while the latter description (liquid flow/water cut/GVF) is used for describing experimental conditions, particularly during model development.

In this paper we describe a three-phase metering system which combines Coriolis mass flow metering with a water cut measurement to provide separate measurements of oil, water and gas flow. While the long-term goal of our research is to develop a Coriolis-based solution to cover the complete range of