Investigation of oil-air two-phase mass flow rate measurement using
Venturi and void fraction sensor

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Abstract: Oil-air two-phase flow measurement was investigated with a Venturi and void fraction meters in this work. This paper proposes a new flow rate measurement correlation in which the effect of the velocity ratio between gas and liquid was considered. With the pressure drop across the Venturi and the void fraction that was measured by electrical capacitance tomography apparatus, both mixture flow rate and oil flow rate could be obtained by the correlation. Experiments included bubble-, slug-, wave and annular flow with the void fraction ranging from 15% to 83%, the oil flow rate ranging from 0.97 kg/s to 1.78 kg/s, the gas flow rate ranging up to 0.018 kg/s and quality ranging nearly up to 2.0%. The root-mean-square errors of mixture mass flow rate and that of oil mass flow rate were less than 5%. Furthermore, coefficients of the correlation were modified based on flow regimes, with the results showing reduced root-mean-square errors.

Key words: Oil-air two-phase flow rate, Venturi, Void fraction, Flow regime, Electrical capacitance tomography

INTRODUCTION

Accurate measurement of multiphase fluids flow rates in the petroleum industry is of great importance. The most reliable measurement technique for multiphase flow is separating the mixture and using conventional devices for measuring single-phase flow. However, in many cases the separation is not practical from both technical and economical points of view. An alternative solution is the multiphase flow metering system, usually consisting of a combination of devices for phase fraction measurement and velocity measurement.

The relationship between differential pressure, quality, void fraction and mixture flow rate must be known for measuring the flow rate by means of differential pressure devices. In the last decades, many investigations focused on air-water or steam-water two-phase flow measurement using orifices. Numerous orifice equations for gas-liquid mixtures have been developed and some typical equations were proposed by Murdock (1962), James (1965), Chisholm (1974), Lin (1982). Compared with other kinds of differential pressure devices, Venturi has little influence on flow regimes (Lin, 1987), the smallest pressure loss, and the shortest straight pipe upstream and downstream. Considering the great technical importance as well as pure scientific interest, two-phase flow through Venturi has been widely studied both experimentally and theoretically by Xu and Xu (2003), Steven (2002) and Moura and Marvillet (1997).

It is well known that measurement models based on experiments are closely dependent on experiment conditions such as pressure, temperature, medium, devices, etc. Due to lacking of valid oil-gas Venturi correlations, the oil industry has to choose between existing general air-water or steam-water two-phase flow orifice correlations so that measurement errors...
are inevitable. It is necessary to develop the measurement model of oil-gas two-phase flow using Venturi.

The mass flow rates measurement methods proposed by Murdock, James, Chisholm and Lin were based on quality measurement. However, measuring quality on-line is rather difficult at present so that measurement of mass flow based on quality is not practical in gas-liquid two-phase flow system. Alternative solutions have been researched. Air-water mass flow rates were measured with orifice and void fraction by Zhang et al. (1992), refrigerant R-134a liquid-vapor mass flow rates were measured with Venturi and void fraction meters by Moura and Marvillet (1997).

Void fraction could be measured by many methods such as quick-close valve, γ rays, X rays, microwave, etc. Electrical Capacitance Tomography (ECT) technology is prospectively useful because it is accurate, economical, non-intrusive, safe and fast. Electrical capacitance tomography technology is a kind of tomography process technology and provides a new way to solve the problems of void fraction measurement (Li, 2001). Different phase component of two-phase flow has different dielectric constant. The change of the value of the two-phase void fraction and its distribution will result in the variation of the measured capacitance. ECT sensor was applied successfully to measure the void fraction and identify the flow regime of gas-solid multi-phase flow by Huang and Ji (2002). The aim of this investigation is to combine the ECT sensor with a Venturi meter to measure the total combined oil-gas two-phase flow rate, and then to develop a new measurement model from which individual phase mass flow rates and the flow quality can be obtained simultaneously.

THEORETICAL MODELS

In single-phase flow that is in thermal equilibrium, the mass flow rate is related to the pressure drop across a differential pressure device by the following equation:

$$G = \frac{C \cdot A_o}{\sqrt{1 - \beta^2}} \cdot \rho \cdot \sqrt{2 \Delta P}$$  \hspace{1cm} (1)

where $G$ is the mass flow rate; $C$ is the Venturi discharge coefficient; $A_o$ is the area of the Venturi throat; $\beta$ is the throat-to-pipe diameter ratio; $Y$ is the compressibility coefficient of the fluid, the air-oil fluid is considered incompressible at low pressure and $Y$ is considered to be unity; $\Delta P$ is the pressure drop across the device (differential pressure between the upstream pressure and the throat pressure); and $\rho$ is the upstream density of the flowing fluid.

In two-phase flow, the two-phase mass flow rate and the two-phase pressure drop can be expressed in the form of Eq.(1) if an appropriate two-phase fluid density is used in place of the single-phase fluid density. The homogeneous flow model treats the two-phase flow as if it were a single-phase flow. Using the homogeneous equilibrium model, which assumes that the gas and the liquid have the same velocity and are in thermal equilibrium, the two-phase fluid density is given by:

$$\rho_h = \left(\frac{\chi \rho_o + (1 - \chi) \rho_L}{\rho_o + \rho_L}\right)^{-1}$$  \hspace{1cm} (2)

where $\chi$ is the quality of the two-phase flow, i.e. the ratio of the gas to total mass flow rate; $\rho_h$ is the homogeneous density and subscripts ‘L’ and ‘G’ are for liquid and gas, respectively. Therefore substituting this homogeneous density into Eq.(1) and replacing $\Delta P$ with the mixture fluid pressure drop $\Delta P_{TR}$, the two-phase mass flow rate is given by:

$$G = \frac{C A_o}{\sqrt{1 - \beta^2}} \cdot K_L \cdot \sqrt{2 \Delta P_{TR} \rho_L}$$  \hspace{1cm} (3)

For the homogeneous flow model, the theoretical equation for the liquid phase coefficient $K_L$ is as follows:

$$K_L = \frac{1}{\sqrt{1 + \left(\frac{\rho_L}{\rho_o} - 1\right) \chi^n}}$$  \hspace{1cm} (4)

where $n$ is coefficients and dependent on the test condition.

The relationship of mixture flow rates, liquid