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High pressure steam–water two-phase flow measurements by flow division and separation method

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ABSTRACT

This paper proposes a method for high pressure steam–water two-phase flow measurements by flow division and separation. The flowrate of a steam–water mixture is metered by diverting a small fraction (about 2%) of total mass flow to a division loop, where the diverted mixture is separated into steam and water flows by means of a small separator and they are metered with single-phase flow meters respectively. The metered values are then converted to total flowrates according to the extraction ratios. The first equation of the extraction ratios was derived from the relation of resistance between the main loop and the division loop, and the second equation of the extraction ratios was developed from the distribution characteristics of the division loop. The extraction ratios were then determined by solving these two equations. Experiments were carried out in an once-through boiler for steam flooding. The inside diameter of pipe was 50 mm, and the experimental flowrate ranged from 2000 kg/h to 8000 kg/h, the steam mass quality varied from 60% to 81%, and pressure ranged from 7.6 MPa to 16 MPa. Experiments show that the flow division and separation method is a reliable technique. The flowrate measurement error is less than ±2.5%, and the steam quality measurement error is less than ±3.5%.

1. Introduction

The measurement of steam–water two-phase flowrate is very important in many technical and industry applications, such as nuclear reactor safety research, and operation of geothermal wells. Ever since the application of steam to commercial heavy oil recovery, the petroleum industry has been searching for a method to determine both steam quality and flowrate for monitoring, analyzing and optimizing the steam drive projects. Traditional method of steam water two-phase flowrate measurement employs a large separator system [1], which separates the two phase mixtures into single phases of steam and water firstly, and then meters them with conventional flow meter respectively, and remixes them after the measurements. Both the capital and operating costs of equipment are usually very high. During the last 40 years, various techniques have been tried to measure the steam–water two phase flowrate. Duo to their simplicity and reliability, differential pressure flow meters have been extensively studied for two phase flow [2–4]. However the response of a differential pressure flow meter to the two-phase flow depends on not only the flowrate but also on the steam quality. For instance, under a certain flowrate, the higher the steam quality, the larger the differential pressure passing through an orifice. Therefore, a single phase flow meter alone is not capable of measuring the flowrate and steam quality, and a combination with other measuring device is needed. Reiman et al. [5] compared and evaluated four different techniques for the measurement of steam–water mass flowrates: the true mass flow meter, the radio nuclide tracer technique, the combination of a free field drag disk-turbine meter-transducer and a gamma densitometer, and the combination of a Venturi nozzle and a full flow turbine meter. Dueymes [6] used five-hole probe and chemical tracer technique to measure wet steam flow in large diameter pipes. Chan and Bzovey [7] metered the steam–water mass flux using a combination of Pitot tubes and a gamma densitometer. Brown [8] measured the mass flowrate of steam and water in evaporator tubes on operating boilers by radiotracers. Lovelock [9] successfully used alcohol and benzoate as steam and water tracer to meter the steam and water flowrate in geothermal field. Amini and Owen [10] studied the characteristics of critical flow Venturi nozzles with saturated wet steam. Redus et al. [11,12] used the combination of a critical flow nozzles and an orifice plate to measure the steam water two phase flowrate and steam quality.

These combined methods mentioned above can work well within their corresponding metering ranges, however, the measurement error would increase rapidly and the instruments may even fail to work once beyond their narrow ranges of application.

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Nomenclature

A	tube cross sectional area
C_i	water conductivity at the input of boiler
C_o	water conductivity at the output of boiler
d	tube inner diameter
K_0	extraction ratio in the case of single phase flow
K_m	mass extraction ratio
K_s	steam extraction ratio
K_w	water extraction ratio
l	tube length
M	total mass flowrate
M_s	total steam mass flowrate
M_w	total water mass flowrate
M_{ss}	division steam mass flowrate
M_{sw}	division water mass flowrate
S_i	salts concentration of softened water at the input of the boiler
S_o	salts concentration of condensed water at the output of the boiler
ΔP	pressure loss.
ΔP_{ms}	pressure loss when steam phase flows in the main loop alone
ΔP_{mw}	pressure loss when water phase flows in the main loop alone
ΔP_{ss}	pressure loss when steam phase flows in the division loop alone
ΔP_{sw}	pressure loss when water phase flows in the division loop alone
X	steam mass quality

Greek symbols

λ	Darcy friction factor
ρ	fluid density
ξ	local loss factor
θ	correct factor

Subscripts

m	main loop
s	division loop; steam phase
w	water phase

One of the major reasons that cause the larger measuring error and the failure of measurement is that a two-phase flow is always in violent fluctuation. Fluctuation is an inherent feature of two-phase flow that makes the instruments become unsteady and unreliable. Nevertheless some people consider it as useful information that could be used to determine the steam quality or flowrate of steam water two-phase flow. Wang and Tong [13] measured a steam–water mixture flowrate and steam quality by the orifice plate differential pressure noise.

Compared with other flow meters Coriolis mass flow meters have the ability to directly measure the mass flowrate and the density of process fluid, independent of fluid property. Therefore it has been expected that this type of flow meter could deal with two-phase flow. Surely experiments had already proved that Coriolis flow meter could measure the oil in water or water in oil two-phase flow [14] and bulk material two-phase flows [15] in a high precision. On the other hand experiments also shown that a larger measurement error or even complete failure would occur in the condition of gas–liquid two-phase flow [16,17]. However Liu et al. [18] and Henry et al. [19,20] found that the errors induced by gas–liquid two-phase flows were highly repeatable and could be corrected. They had successfully used the neural network to correct the errors in digital Coriolis mass flow meters in the measurements of air–water and gas–heavy oil two-phase flow respectively, in which the residual errors had been as low as 2–5% with the gas void fraction up to 80%. Based on these results, it is assumed that Coriolis mass flow meters could also measure the steam–water two-phase flows in the bubbly and slug flow regimes.

The Extracting and Separating Method (ESM) [21] is a novel method of two-phase flow measurement, in which a small fraction (20%) of the total mass flow is extracted and separated, and the single phase flow meters are employed to meter the separated flows respectively. After metering, these flows are returned to the main stream, and the total flowrate of each phase is determined by the metered values of single phase flow meters and the extraction ratio. In order to ensure that the extracted stream (or the sample) can represent the total stream and the extraction ratio is stable under wider flow conditions, a special rotation drum is employed. However the rotation drum is very difficult to fabricate, and an extraction fraction of 20% is not small enough for a high pressure two phase flow meter.

The objective of present work is to develop a new reliable extraction method and the relevant devices for high pressure steam–water two-phase flow measurements. The extraction ratios are further reduced to as small as 0.007–0.05, and a more compacted measurement device is obtained. The equations for extraction ratios were developed and a series of experiments were conducted in an once-through boiler for steam flooding to verify the feasibility of the new method.

2. Flow division and separation method

As shown in Fig. 1, a flow division and separation system is installed in a horizontal steam–water two-phase flow line. As steam flows in the pipe, a small part of the flow (the division flow) will enter the division loop through six small division holes that are evenly spaced around the circumference of the main pipe, and joint in a collection ring surrounding the pipe wall, then runs into a small separator where it is separated into single phase steam and water and metered by a steam meter and a water meter respectively. After the metering, the steam and water recombine and passes through a throttle device and then returns to the main pipe through a port downstream of the main loop throttle device. The structure of division holes and collection ring can be seen in A–A sectional view of the Fig. 1. The inside diameter of the main pipe was 50 mm, and the thickness of the pipe wall was 3 mm. The inner diameter of the collection ring was 70 mm, and the diameter of the division hole was 3.5 mm. The small separator is a cyclone type with inner diameter of 42 mm and height of 1000 mm. It is vertically installed and the upper portion is the steam space, the middle and lower portion is the separation and water regions respectively. Two-phase mixture enters into the inner space from the middle of the separator at a tangential direction and separated by the strong centrifugal force and gravitational force. Some small water drops carried by the steam flow can be further removed by gravitational force during their rising in the steam space, since the maximum steam rising velocity in the steam space is less than 0.7 m/s, the steam drag force to the water drops is very small. According to steam boiler design code more than 99% of water can be separated by the separator, and less than 1% of water may finally be carried by the steam, which has little effect on the steam flow measure-