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ON THE DEVELOPMENT OF A TWO-PHASE FLOW METER FOR VERTICAL UPWARD FLOW IN TUBES

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Abstract – A new method for measuring the volumetric flow rate of each phase for two-phase, air and water, flowing upwardly in a vertical tube is developed. This noble device, a Two Turbine Flow Meter System (TTFMS), is composed of two turbine flow meters, a valve, two thermocouples, and two pressure transducers. For a given two-phase flow, the rate of rotation of the turbine flow meter is found to depend only upon the volumetric flow rates of gas and liquid at the point of measurement. A calibration model is developed for the turbine flow meter, which provides a simple, general, and accurate relationship between the output signal of a turbine flow meter and the actual two-phase flow rate. The volumetric flow rate of each of the two phases is determined by this model. TTFMS is a simple, durable, and inexpensive two-phase flow measuring device that does not require physical separation of a phase from the two-phase mixture.

Key words: *Two-phase Flow, Turbine Flow Meter, Two-phase Flow Meter, Volumetric Flow Rate*

INTRODUCTION

Systems involving two-phase flow are found widely in many chemical related industries, as well as in sewer treatment, air conditioning and refrigeration, chemical and biochemical reactors, oil and gas or partially liquefied gas transport, and cryogenics, just to name a few. In power generation facilities such as steam plants, two-phase flow is encountered in boilers, turbines, and condensers. Problems encountered in nuclear reactors include not only the optimal design of the system and control at steady states but also the system behavior at transient states, relating to accident conditions such as the loss of coolant accident (LOCA) as well as in the start-up and shut-down periods of the reactor. Moreover, with the fiasco of the Chernobyl reactor accident of the Soviet Union, studies in LOCA and thermal-fluid dynamics of two-phase flow, especially of steam-water flow, have become increasingly important research topics for process design and control.

A good understanding of two-phase flow behavior is of immense importance to the chemical and power generating industries because gas and liquid flow through pipe networks and equipments poses major difficulties in obtaining optimal process design, control, and safe operation. The multi-dimensional nature of two-phase flow is a function of flow conditions, fluids properties, and geometry of flow channels, and the existence of the gas-liquid interfaces in the fluid flow makes an accurate description of the flow behavior difficult and complex. The main complicating feature that distinguishes two-phase flow, such as a gas-liquid flow, from a single-phase gas or liquid flow is the existence of two phases. The coexistence of the two phases, with different velocities in a variety of flow configurations, makes it difficult to describe the flow behavior. For any given two-phase flow system, there is an infinite range of possibilities of deformable interfaces, whose shape and distribution are generally unknown but are of critical importance in determining the flow characteristics [Barnea et al., 1980, Taitel et al., 1980]. Many investigators have applied a rigorous mathematical approach to two-phase flow, however, none have been fully successful. When the mathematical models are compared with the actual experimental data, the results are inaccurate and often contradictory. Therefore, much of the research efforts for the last four decades have been in experimental work developing empirical correlations and models. Thus, most of the design and control problems are solved by using either the results of the experimental data from similar systems or the empirical correlation or computation models which are based on relevant measurements. Consequently, reliable and convenient devices to measure and characterize two-phase flow rates and other parameters are in great demand [Hetsroni, 1982].

Ideally, a flow rate measuring device should not require separation of a phase from the two-phase mixture nor should the device be hazardous to use. Many commercially available two-phase flow measuring devices, however, require some form of phase separation methods or employ radioactive sources. Furthermore, they need to be coupled with two or more different types of instruments to measure and determine two-phase flow; in fact, many are costly and inconvenient to use. A typical method to measure two-phase flow rates, for example, is to use a coupled system that composed of x-ray or gamma-ray source to measure the void fraction and at least an additional device to measure two-phase momentum or velocity to finally determine the mass or volumetric flow rates [Frank

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et al., 1977; Reimann et al., 1982].

EXPERIMENTAL SETUP

The schematic drawing of the upward flow loop with the Two-Turbine Flow Meter (TTFMS) test section is shown in Fig. 1. The water tank had a capacity of 0.38 cubic meter (100 gallons), and with an automatic make-up and draining system a constant water level was maintained. Water was pumped through the loop by a centrifugal pump (20 Hp), and the flow rate of water was adjusted by an air-controlled pneumatic valve. For the gas phase, air was supplied from a rotary air compressor (not shown) which had a maximum capacity of 170 cubic meters per hour (cmh) flow rate at 790 KPa. The air flow rate was adjusted by two air-controlled pneumatic valves.

The mixing unit and the screen section were designed and built in order to provide a well characterized, two-phase flow in the test section. Fig. 2 shows the details of the two-phase mixing unit and screen section. It was composed of mixing chamber and baffles. Each mixing chamber had a 83 % cut baffle with ten steel tubes (ten holes per tube) where the gas was purged and mixed, with the water. Out from the mixing unit, the fluid passed through the screen section which was made up of three levels of meshes; the first mesh had a 6.35 mm (1/4") spacing, the second and the third meshes had 2.54 mm (1/10") spacings. Here the fluids were further mixed and

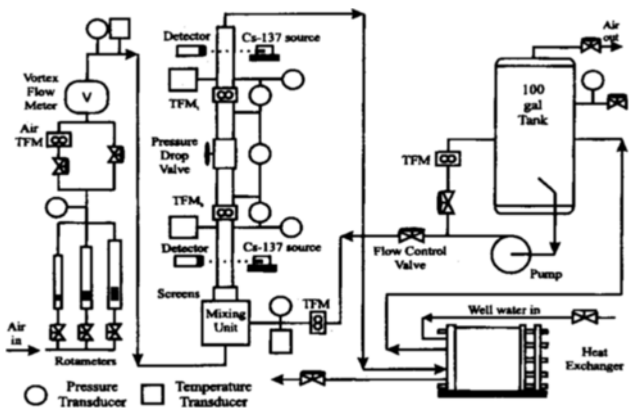

Fig. 1. Schematic diagram of flow loop.

the large bubbles were broken up and reduced in size before entering the test section. The two-phase fluid then passed through the test section in vertical upflow. From the test section, the fluid passed through the plate-and-frame type heat exchanger (81 plates, 13.66 m^2) where it was cooled to a desired temperature. From the heat exchanger, the cooled fluid went back to the water tank. The air was separated from the water in the water tank and exited through the vent.

The inlet water from the water tank to the mixing unit was measured by two turbine flow meters, 50.8 mm (2") and 25.4 mm (1"). The air from the compressor entered and passed through one of the three parallel rotameters and to a vortex flow meter and a gas turbine flow meter if the flow was in the range of the gas turbine flow meter. The gas turbine flow meter had a nominal 12.7 mm (1/2") which covered the range of gas flows 3.4 to 51 scmh. The nominal 25.4 mm vortex flow meter covered the range of gas flows 20 to 102 scmh. The three rotameters, nominally 12.7 mm, 12.7 mm with a larger float, and 25.4 mm, covered the range of gas flow 0 to 1.97, 0 to 8.3, and 0 to 40.1 scmh, respectively. The pressure at the rotameters was always close to 650 KPa (80 psig). Another 50.8 mm turbine flow meter was located at the inlet of the heat exchanger. Thus every gas and liquid flow measurement was checked by at least two instruments. Temperatures were measured throughout the loop by thermocouples of types J and K, and pressures were measured by absolute pressure transducers and differential pressure transducers.

The total test section length was 2.39 m long. It consisted of seven sections; four transparent polycarbonate single tubing, two 50.8 mm Hoffer turbine flow meters, and a 50.8 mm manual gate valve section. The single tube inside diameter was 57 mm and its wall thickness was 3.175 mm. The distance between the turbine flow meters was 0.94 m. The schematics of the test section is shown in Fig. 3. For void fraction measurements, the Beer's law was used for two gamma densitometer that employed two collimated 50 mCi CS-137 sources; one at the exit (the mid-point of the last transparent section) and the other at the inlet (the mid-point of the first transparent section) of the test section. Also connected to the test section were five pressure transducers and three differential pressure transducers-details on the instrumentation can be found in Shim [1993].

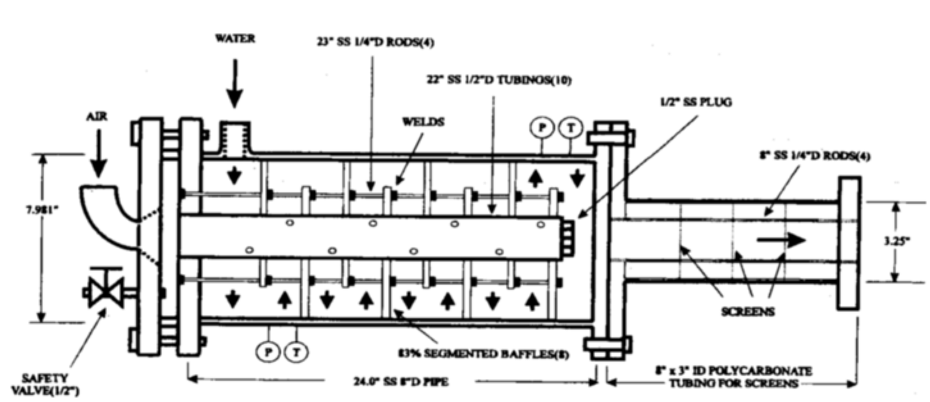

Fig. 2. Cross section of mixing unit and screen section.

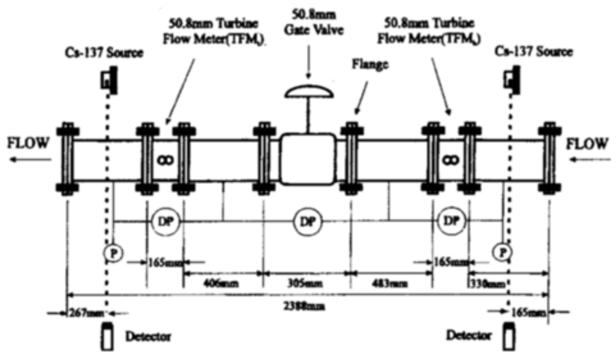

Fig. 3. Layout of two turbine flow system (TTFMS).

Experiments were carried out starting with a constant nominal water flow rate. The air flow was then slowly increased stepwise from 0 to a maximum flow rate of up to 47 scmh and stepwise decreased back to 0 scmh, where the fluid would be all liquid. Then the nominal liquid flow rate was incremented to a new nominal flow rate and the procedure was repeated. The maximum liquid flow rate attained was 22.71 cmh. At each step, when a desired flow condition was reached, 500 continuous data points per input channel were scanned and collected using an on-line data acquisition system. An IBM 386SX, PS/2 model 55, and OPTO 22 solid state relays were used for the data acquisition system. The time duration of data acquisition interval was 12.25 sec with a rate of 40.82 scans per second.

RESULTS

Experimental values of the void fraction vs. percent volume fraction of gas at the top (outlet) of the test section are shown in Fig. 4. The effect of increasing slip ratio (slip ratio is defined as the ratio of velocity of gas phase to that of liquid phase) with increasing gas velocity can be seen at the lowest water flow rate (2.27 cmh). This is primarily due to the buoyancy effect, where the gas phase tended to rise faster than the liquid and the slip ratio is greater than 1. At other liquid flow rates, the liquid phase and the gas phase flow relatively together at about equal velocity; that is the data points are on or near the 45° line in the Fig. (data on the 45° line has the slip ratio is 1, and below this line the data has the slip ratio greater than 1).

Axial-flow type turbine flow meter (TFM) was used for this study. The rate of rotation of the rotor is proportional to the volumetric flow rate of a single fluid, which is liquid. The frequency output signal (commonly pulses), f, of the turbine flow meter is conveniently expressed in units of volumetric flow rate, cmh, and the turbine flow meter output expressed as the variable T is defined as the product Kf, where K is the flow coefficient of the instrument obtained in single-phase liquid flow. For the given two-phase flow in the vertical channel and at a fixed temperature, the rate of rotation of the turbine flow meter was, to a good approximation, found to depend only upon the volumetric flow rates of gas and liquid at the point of measurement.

$$T = f(Q_g, Q_l) \tag{1}$$

This rate of rotation was nearly a linear function of the volumetric flow rate of the gas phase, and when the gas flow rate was zero, the turbine flow meter output (T) should only read the liquid flow rate. Fig. 5 shows the outputs for the bottom and the top turbine flow meters vs. gas flow rates in standard cubic meters per hour (scmh) for each nominal water flow rate. For a fixed water flow rate, T is linearly related to the volumetric flow rate of gas:

$$T = k_1 + k_2 Q_g \tag{2}$$

where Q_g represents the volumetric flow rate of gas in scmh, and k_1 and k_2 are constants that depend only on the water flow rate. Fig. 6 shows the volumetric gas flow rate corrected for pressure and temperature at each of their corresponding location of the turbine flow meters. In other words, when the volumetric flow rates of gas or the data from Fig. 5 are corrected to actual cubic meters per hour (acmh) at the locations of each Turbine flow meter, the TFM output values, T, show approximately a linear relationship to the gas flow rate. Both at the top and the bottom TFM values collapse into a single line for a given liquid flow rate. Therefore,

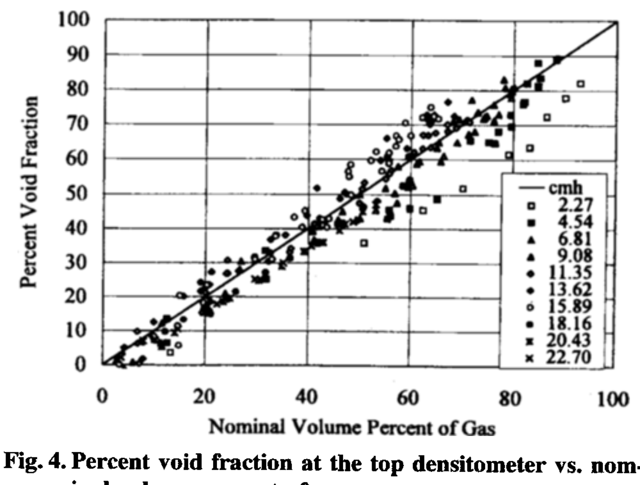

Fig. 4. Percent void fraction at the top densitometer vs. nominal volume percent of gas.

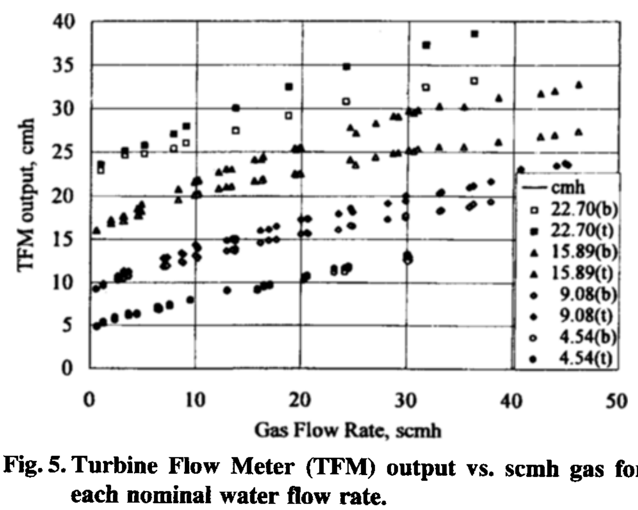

Fig. 5. Turbine Flow Meter (TFM) output vs. scmh gas for each nominal water flow rate.

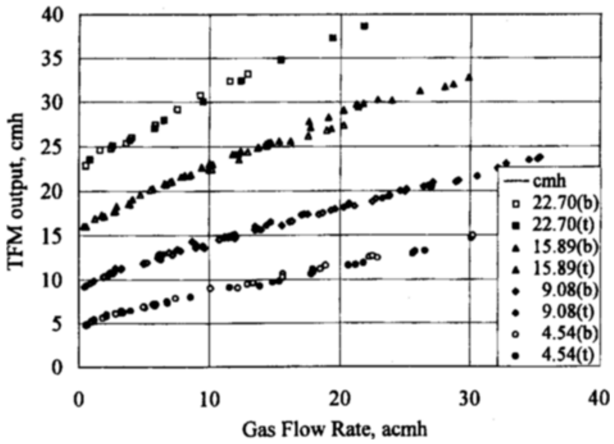

Fig. 6. Turbine Flow Meter (TFM) output vs. acmh gas for each nominal water flow rate.

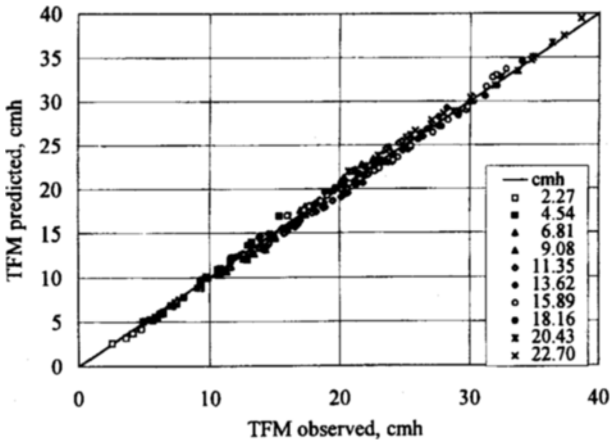

Fig. 7. Top Turbine Flow Meter (TFM_t) output predicted vs. observed values.

$$T = k_1 + k_2\, Q_{g,acmh} \tag{3}$$

where $Q_{g,\,acmh}$ represents the volumetric flow rate of gas in acmh. Assuming that k_2 is a linear function of liquid flow rate, Q_l, and the second term in the Eq. (3) represents the liquid-gas interactions,

$$k_2 = k_3 + k_4\, Q_l \tag{4}$$

where, k_3 and k_4 are constants. Thus,

$$T = k_1 + (k_3 + k_4\, Q_l)\, Q_{g,acmh} \tag{5}$$

However, k_1 in Eq. (5) should reduce to Q_l when the gas flow rate is zero,

$$k_1 = Q_l \tag{6}$$

From the equation of state,

$$Q_{g,acmh} = \frac{p_{stp}}{t_{stp}}\,\frac{t}{p}\,Q_g = 0.027747\,\frac{t}{p}\,Q_g \tag{7}$$

where, p_{stp} and t_{stp} are pressure and temperature at the standard condition (throughout the study, standard conditions are defined at 1 atm (101.3 KPa) and 21.1 °C (70 °F). Substituting Eqs. (6) and (7) into Eq. (5),

$$T = Q_l + 0.027747\,(k_3 + k_4\, Q_l)\,\frac{t}{p}\,Q_g \tag{8}$$

Eq. (8) is the general equation governing TTFMS for upflow. Eq. (8) is used for the top (t) TFM and the bottom (b) TFM, by correcting for pressures and temperatures at the corresponding locations of turbine flow meters. The equations are,

$$T_t = Q_l + 0.027747\,(k_3 + k_4\, Q_l)\,\frac{t_t}{p_t}\,Q_g \tag{9}$$

and

$$T_b = Q_l + 0.027747\,(k_3 + k_4\, Q_l)\,\frac{t_b}{p_b}\,Q_g \tag{10}$$

Dividing Eq. (9) by p_b and t_t, and Eq. (10) by p_t and t_b, then the resulting equations are,

$$\frac{T_t}{p_b t_t} = \frac{Q_l}{p_b t_t} + 0.027747\,(k_3 + k_4\, Q_l)\,\frac{Q_g}{p_t p_b} \tag{11}$$

and

$$\frac{T_b}{p_t t_b} = \frac{Q_l}{p_t t_b} + 0.027747\,(k_3 + k_4\, Q_l)\,\frac{Q_g}{p_t p_b} \tag{12}$$

Then, by subtracting Eq. (12) from Eq. (11) and rearranging, the volumetric flow rate of liquid phase, Q_l, is solved.

$$Q_l = \frac{T_t p_t t_b - T_b p_b t_t}{p_t t_b - p_b t_t} \tag{13}$$

For the volumetric flow rate of gas phase, Eq. (10) is subtracted from Eq. (9) and solve for Q_g.

$$Q_g = \frac{(T_t - T_b)\,p_b p_t}{0.027747\,(k_3 + k_4 Q_l)\,(p_b t_t - p_t t_b)} \tag{14}$$

The constants in Eq. (5) are curve fitted with the following results,

$$T = 1.050941\, Q_l + 0.034519\, Q_l\, Q_{g,\,acmh} + 0.248743\, Q_{g,\,acmh} \tag{15}$$

Fig. (7) shows the model prediction of turbine flow meters vs. experimental values of turbine flow meters, and they are in a good agreement with each other. The constants in Eq. (15) are,

$$k_1 = 1.050941\, Q_l \tag{16}$$

$$k_3 = 0.248743 \tag{17}$$

$$k_4 = 0.034519 \tag{18}$$

Note, k_1 value is not exactly equal to Q_l as it was assumed in Eq. (6), and this correction factor should be included in Eq. (13). Including the factor,

$$Q_l = \frac{1}{1.050941}\left(\frac{T_t p_t t_b - T_b p_b t_t}{p_t t_b - p_b t_t}\right) \tag{19}$$

Therefore, by having a TTFMS system one can calculate both Q_l and Q_g, volumetric flow rate of each phase of liquid and gas simultaneously, assuming pressures and temperatures are available at each location of the turbine flow meter.

CONCLUSIONS

This study was an experimental work involving two-phase, air and water, upward flow in a vertical tube for the development of a new device to measure the volumetric flow rate of each liquid and gas phase. This device, Two-Turbine Flow Meter System (TTFMS), determines flow rates of both the liquid and the gas phase simultaneously using the two-phase calibration model. The model relates the turbine flow meter output, T, to the volumetric flow rate of the gas, Q_g, and the volumetric flow rate of the liquid, Q_l by the nonlinear equation: $T = aQ_l + bQ_lQ_g + cQ_g$ where the parameters a, b, c are determined by two-phase calibration. The three parameters in the calibration function depend primarily on the characteristics of the turbine flow meter and flow direction but are insensitive to the nature and properties of the gas phase. This permits considerable flexibility in the calibration process particularly in the choice of the calibration gas and, to a more limited extent, in the choice of the calibration liquid. Furthermore, TTFMS does not require void fraction nor volume fraction measurements in determining the flow rates.

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NOMENCLATURE

Q : volumetric flow rate [m^3/hr]
p : pressure [KPa]
t : temperature [$^{\circ}$C]
T : turbine flow meter values [m^3/hr]
f : frequency [pulse]
K : coefficient for single-phase liquid flow [cmh/pulse]
a, c : coefficients of Q_l and Q_g in TFM model [none]
b : coefficient of Q_gQ_l [hr/m^3]

Subscripts

g : gas
l : liquid
b : bottom of test section
t : top of test section

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