# United States Patent [19]

**Liu et al.**

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[45] **Date of Patent: Jul. 9, 1991**

[54] **GAS/LIQUID FLOW MEASUREMENT USING CORIOLIS-BASED FLOW METERS**

[75] Inventors: **Ke-Tien Liu**, Cerritos; **Tanh V. Nguyen**, Fullerton, both of Calif.

[73] Assignee: **Chevron Research Company**, San Francisco, Calif.

[21] Appl. No.: **414,034**

[22] Filed: **Sep. 28, 1989**

**Related U.S. Application Data**

[63] Continuation-in-part of Ser. No. 307,156, Feb. 3, 1989, abandoned, which is a continuation of Ser. No. 112,350, Oct. 22, 1987, abandoned.

[51] **Int. Cl.**$^5$ .............................................. **G01F 1/74**

[52] **U.S. Cl.** ........................... **73/861.04**; 73/61.00 R; 73/61.10 R; 73/831.38

[58] **Field of Search** ............ 73/861.04, 861.38, 61 R, 73/61.1 R

[56] **References Cited**

U.S. PATENT DOCUMENTS

| | | | |
|---|---|---|---|
| 4,662,219 | 5/1987 | Nguyen | 73/861.04 |
| 4,689,989 | 9/1987 | Aslesen et al. | 73/861.04 |
| 4,773,257 | 9/1988 | Aslesen et al. | 73/61.1 R |
| 4,823,613 | 4/1989 | Cage et al. | 73/861.38 |
| 4,872,351 | 10/1989 | Ruesch | 73/861.04 |

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*Assistant Examiner*—Craig Miller
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[57] **ABSTRACT**

A method of determining mass flow rate and phase distribution of gas/liquid two-phase flows is disclosed. The method uses a Coriolis-based mass flow meter. Flow streams of known mass flow rate and phase distribution are directed through the meter and correlation factors are obtained using an apparent mass flow rate output and an apparent density output from the Coriolis meter. The true mass flow rate and phase distribution of unknown flow streams can then be determined.

**7 Claims, 2 Drawing Sheets**

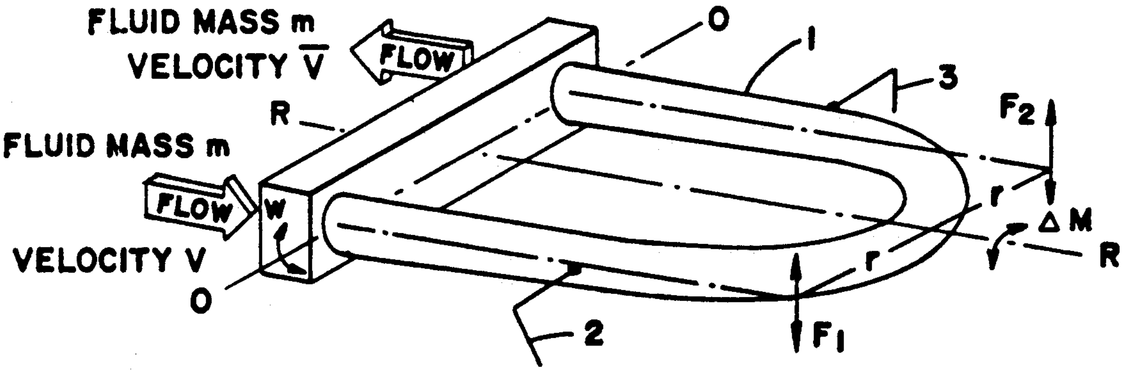

FIG_1

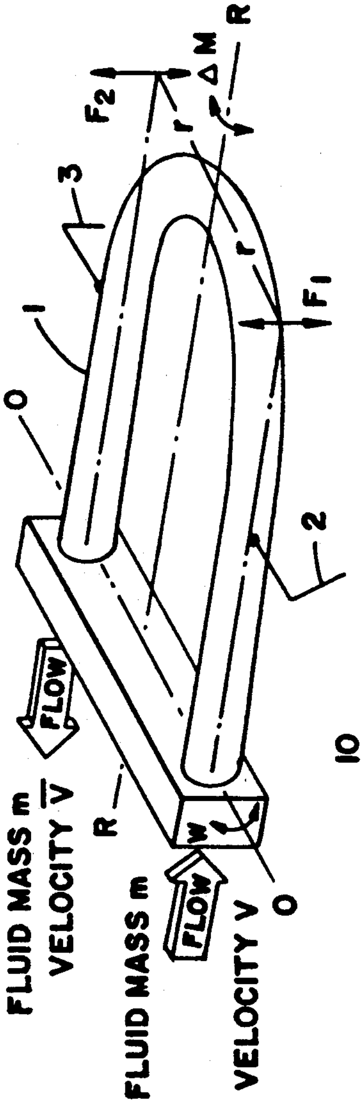
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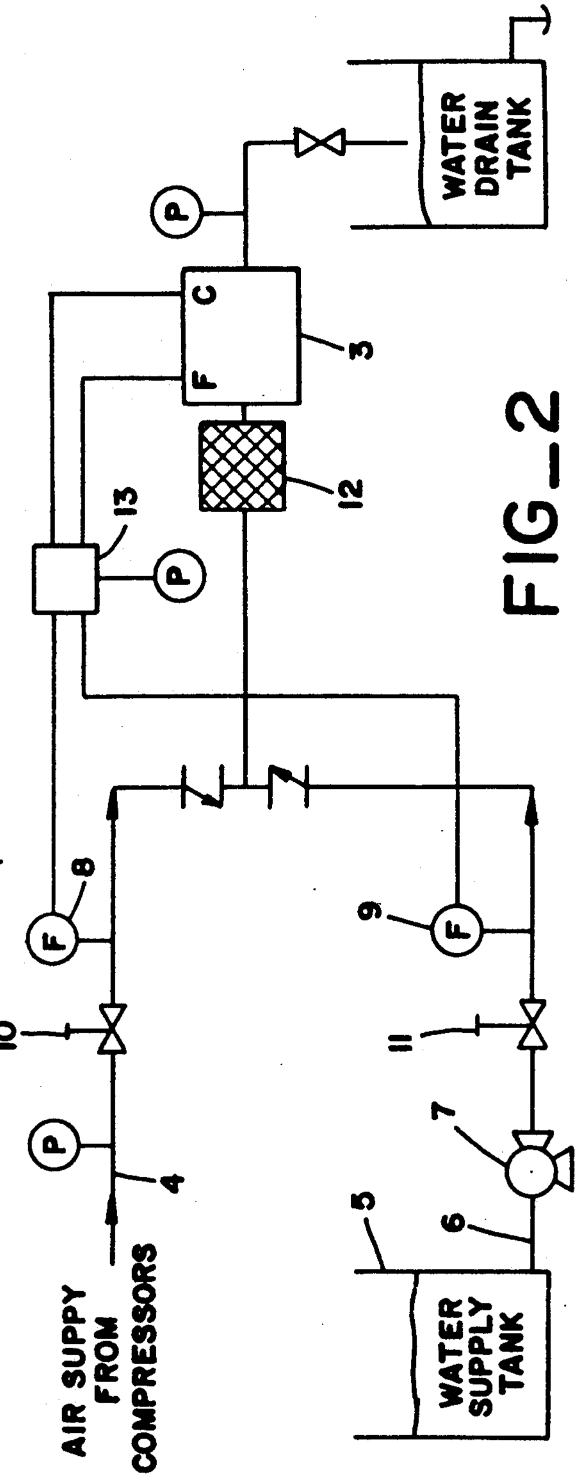
FIG_2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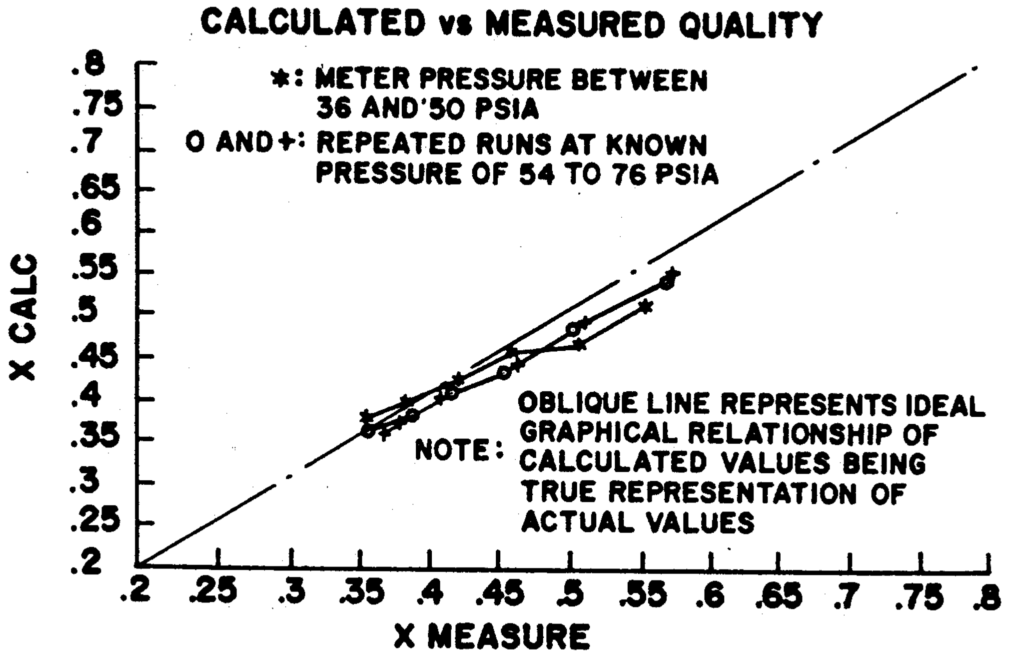
CALCULATED vs MEASURED QUALITY
*: METER PRESSURE BETWEEN 36 AND 50 PSIA
O AND +: REPEATED RUNS AT KNOWN PRESSURE OF 54 TO 76 PSIA
NOTE: OBLIQUE LINE REPRESENTS IDEAL GRAPHICAL RELATIONSHIP OF CALCULATED VALUES BEING TRUE REPRESENTATION OF ACTUAL VALUES
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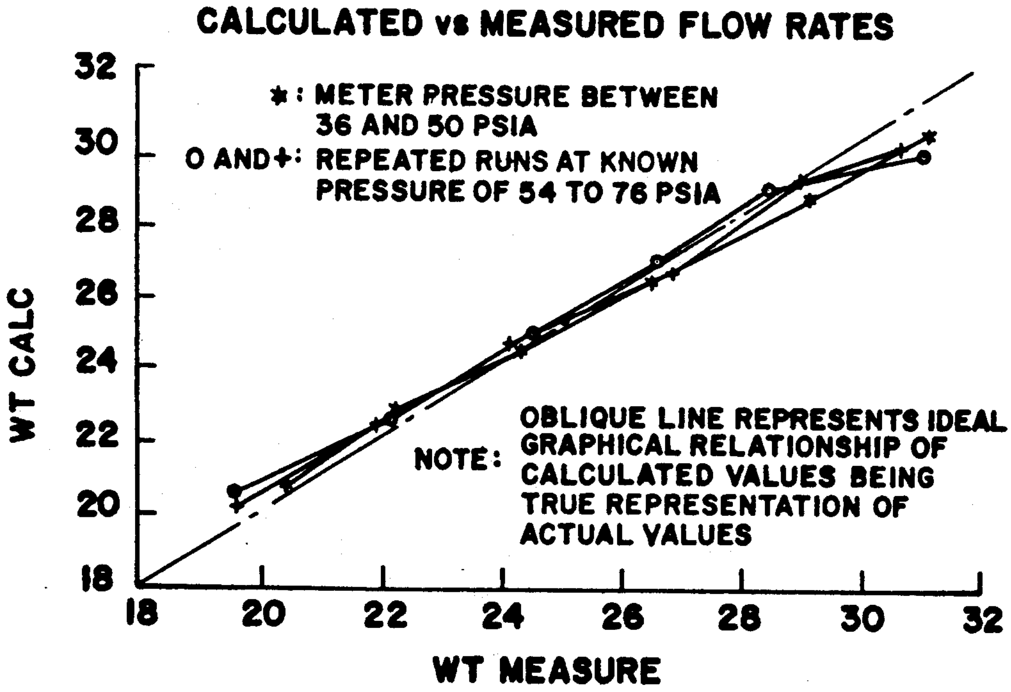
FIG_3


CALCULATED vs MEASURED FLOW RATES
*: METER PRESSURE BETWEEN 36 AND 50 PSIA
O AND +: REPEATED RUNS AT KNOWN PRESSURE OF 54 TO 76 PSIA
NOTE: OBLIQUE LINE REPRESENTS IDEAL GRAPHICAL RELATIONSHIP OF CALCULATED VALUES BEING TRUE REPRESENTATION OF ACTUAL VALUES
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WT MEASURE

FIG_4

# GAS/LIQUID FLOW MEASUREMENT USING CORIOLIS-BASED FLOW METERS

## CROSS REFERENCE TO RELATED APPLICATIONS

This is a continuation-in-part of U.S. application Ser. No. 307,156, filed Feb. 3, 1989, which is a continuation of U.S. application Ser. No. 112,350, filed Oct. 22, 1987, now abandoned.

## BACKGROUND OF THE INVENTION

The present invention relates to the field of two-phase flow measurement. In particular, the present invention provides a method and apparatus for measuring the relative quantities of gas and liquid in a flowing fluid stream, especially for the measurement of wet steam.

One method of enhancing recovery of hydrocarbons in, for example, oil-bearing reservoirs, is to inject steam. In order to properly manage this enhanced recovery technique, it is necessary to know the "quality" and the mass flow rate of steam that is injected, wherein the "quality" is defined as the ratio of vapor to vapor plus liquid of the injected steam.

Many methods have been proposed for the measurement of steam quality in surface steam lines. For example, U.S. Pat. No. 4,662,219, to Nguyen, incorporated by reference herein for all purposes and assigned to the assignee of the present invention, discloses a method of using two orifice plates in series to determine steam quality. However, such methods actually provide only an indirect determination of steam quality because they are not directly measuring the mass and/or density of the liquid stream. They are in many cases only accurate over a limited range of conditions.

U.S. Pat. Nos. 4,689,979 and 4,773,257 to Aslesen et al., also assigned to the assignee of the present invention and incorporated herein by reference for all purposes, discloses a method of measuring the relative amounts of oil and water in a liquid stream. However, no method of determining steam quality is shown or suggested.

A "Q-Bar" device has also been described as being useful in the measurement of two phase streams. For example, the "Steamcheck Energy Monitor" sold by Baker Packers uses the "spike" resonant frequency of a resonating tube to determine steam quality. This device uses only a sample of the steam and has found to have only limited accuracy.

It is desirable, therefore, to devise an improved method of measuring wet steam.

## BRIEF SUMMARY OF THE INvENTION

A method of determining total mass flow rate and phase distribution of the individual component in a flowing gas/liquid stream is disclosed. The method comprises the steps of

flowing at least a first gas/liquid stream through a Coriolis-based flow meter, the first gas/liquid stream having a first known total mass flow rate and individual component phase distribution;

obtaining a first apparent total mass flow rate output and a first apparent density output from the Coriolis-based mass flow meter;

correlating the first known total mass flow rate and phase distribution with the apparent mass flow rate output and the apparent density output obtained from the Coriolis-based mass flow meter to determine a set of correlation equations;

flowing a second gas/liquid stream through the Coriolis-based mass flow meter;

obtaining a second apparent mass flow rate output and a second apparent density output from the Coriolis-based mass flow meter; and

calculating the total mass flow rate and phase distribution of the second gas/liquid stream based on the aforementioned correlation equations.

Knowing total mass flow rate and phase distribution of the gas/liquid stream, the individual amounts of gas and liquid phases can also be determined arithmetically, if desired.

The generalized form of the correlation equations can be expressed as:

$$W_{app}=f(W_t;\, y) \qquad (1)$$

and

$$D_{app}=g(W_t;\, y) \qquad (2)$$

where $W_{app}$ and $D_{app}$ are apparent mass flow rate output and apparent density output obtained from the Coriolis-based mass flow meter. $W_t$ and y denote the true total mass flow rate and true phase distribution parameter of the gas/liquid flow stream.

In the step of calculating, the use of the above simultaneous correlation equations provides a means to compute two unknown variables, $W_t$ and y, based on the two known outputs, $W_{app}$ and $D_{app}$ obtained from the Coriolis-based mass flow meter.

Note that the term "phase distribution parameter" or the symbol "y" as used herein can be uniquely characterized by a variety of engineering parameters; such as homogeneous mixture density ($\rho_m$), no-slip liquid holdup ($\lambda$) and homogeneous vapor mass fraction (X). The adjectives, "homogeneous" and "no-slip", as used herein refer to a physical state in which the gas-liquid flow stream is perfectly mixed and both phases are flowing at the same velocity in the flow line.

These three parameters are inter-related; knowing one of the parameters, the other parameters can be determined. In wet steam measurement application, the parameter "X" is commonly referred to as "steam quality".

## BRIEF SUMMARY OF THE DRAWINGS

FIG. **1** illustrates the Coriolis-based flow meter.

FIG. **2** illustrates the experimental equipment used to test the utility of the device.

FIG. **3** is a graph comparing actual quality with calculated quality using the invention described herein.

FIG. **4** is a graph comparing actual total mass flow rate with calculated total mass flow rate using the invention described herein.

## DETAILED DESCRIPTION OF THE INVENTION

In the discussion herein, two-phase steam is used by way of example, but it is clear that the method could be applied to other gas/liquid streams such as natural gas/-natural gas liquid streams. Referring to FIG. **1**, the Coriolis-type mass flow meter of the present invention measures a very small force generated by steam fluid as it moves through a U-shaped sensor tube (**1**). This force results from the acceleration or deceleration of the fluid particles as the tube vibrates perpendicular to the direction of flow. The force is analogous to the Coriolis force which causes air currents to circulate around the rotating earth, and to gyroscopic forces employed in navigation systems of ships and aircraft.

The forces induced by fluid flow on the sensor tube are the Coriolis or gyroscopic-type forces. FIG. 1 shows a tube with a fluid with mass (m) and velocity (V) moving through the tube which is rotating with angular velocity (ω) about axis 0—0.

The magnitude of the flow-induced Coriolis force is described by the following equation:

$$\bar{F}=2m\bar{\omega}X\bar{V} \tag{3}$$

where $\bar{F}$ is force and $\bar{F}$, $\bar{\omega}$ and $\bar{V}$ are directional quantities and X is the vector cross product operator.

The angular velocity (ω) of the sensor tube is not required to be constant, but can oscillate with a peak angular velocity ($\bar{\omega}_p$). The associated force is also oscillatory, with a peak value ($F_p$), proportional to the fluid mass (m) and velocity ($\bar{V}$).

Forces exerted by the fluid on each leg ($F_1$ and $F_2$) are opposite in direction (180 degrees out of phase). As the tube vibrates about axis 0—0, the forces create an oscillating moment (ΔM) about axis R—R which is expressed by:

$$\Delta M=F_1r_1+F_2r_2 \tag{4}$$

Since $F_1=F_2$ and $r_1=r_2$, from equations 1 and 2:

$$\Delta M=2Fr=4mV\omega r \tag{5}$$

Now, m (unit mass/unit length) multiplied by V (unit length/unit time) yields ΔQ (unit mass/unit time), i.e., the mass flow rate. Equation 3 then becomes:

$$\Delta M=4\omega r\Delta Q \tag{6}$$

The total moment (M) about axis R—R due to all of the fluid particles is found by integrating Equation 4 around the sensor tube.

$$M=\int\Delta M=4\omega rQL \tag{7}$$

The moment M causes an angular deflection or twist of the sensor about axis R—R, which is at its maximum at the midpoint of vibrating tube travel. There is no twist at the upper and lower limits of travel since at these points ω is zero. The deflection of θ due to M is resisted by the spring stiffness ($K_s$) of the sensor tube. In general, for any torsional spring, the torque (T) is defined by:

$$T=K_s\theta \tag{8}$$

Since T=M, the mass flow rate (Q) can now be related to the deflection angle θ by combining Equations 5 and 6.

$$Q=\frac{K_s}{4\omega rL}\theta \tag{9}$$

The mass flow rate can be derived by measuring the deflection angle (θ) using the sensors 2 and 3 shown in FIG. 1. This measurement is accomplished by measuring the relative times that each sensor detects the midpoint crossing of the respective leg. The time difference at zero flow is nulled. As flow increases, causing an increase in θ, the time difference (Δt) between signals also increases. The velocity of the tube at the midpoint of travel ($V_t$), multiplied by Δt, is geometrically related to θ by:

$$\sin\theta=\frac{V_t}{2r}\Delta t \tag{10}$$

If θ is small, sin θ is nearly equal to θ. Also for small rotation angles, $V_t$ is the product of ω and the tube length (L), so:

$$\theta=\frac{L\omega\Delta t}{2r} \tag{11}$$

Combining equations 7 and 9 gives:

$$Q=\frac{K_sL\omega}{8r^2\omega L}\Delta t=\frac{K_s}{8r^2}\Delta t \tag{12}$$

The mass flow rate Q is therefore proportional only to the time interval and geometric constants. Note that Q is independent of ω, and therefore independent of the vibration frequency of the sensor tube.

The vibrating U-tube method of measurement also produces an output which is proportional to the density of the fluid in the meter. The output is a square wave at the natural frequency of the vibrating system. The natural frequency (f) of a spring system can be calculated directly from the mass (m) and a spring constant (k):

$$f=k\sqrt{\frac{1}{m}} \tag{13}$$

In the case of the flow tube, the vibrating system can be divided into the tube mass ($m_t$) and fluid mass ($m_f=\rho V$). The fluid mass is in turn proportional to the fluid density (p) since the tube volume is constant. Therefore, the density can be expressed directly in terms of the tube frequency (f) and constants $K_1$ and $K_2$:

$$\omega=2\pi f=\sqrt{\frac{K}{m_t+\rho V}} \tag{14}$$

$$4\pi^2f^2=\frac{K}{m_t+\rho V} \tag{15}$$

$$\rho=\frac{1}{V}\left(\frac{K}{f^24\pi^2}-m_t\right) \tag{16}$$

$$\text{let }\frac{K}{4\pi^2V}=K_1\text{ and }\frac{m_t}{V}=K_2$$

$$\text{giving }\rho=\frac{K_1}{f^2}-K_2 \tag{17}$$

Constants $K_1$ and $K_2$ can be determined by filling the sensor tube with two . fluids of known densities (at the same temperature) and noting the resulting frequencies.

When a Coriolis-based mass flow meter is used to measure a liquid mixture stream containing two or more different types of liquids, the two fundamental outputs provided from the mass flow meter still represent the true values of the mass flow rate and the density of the liquid mixture stream being measured. U.S. Pat. No. 4,689,979 and 4,773,257 to Aslesen, et al., have disclosed a method of using the above-mentioned flow meter to

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