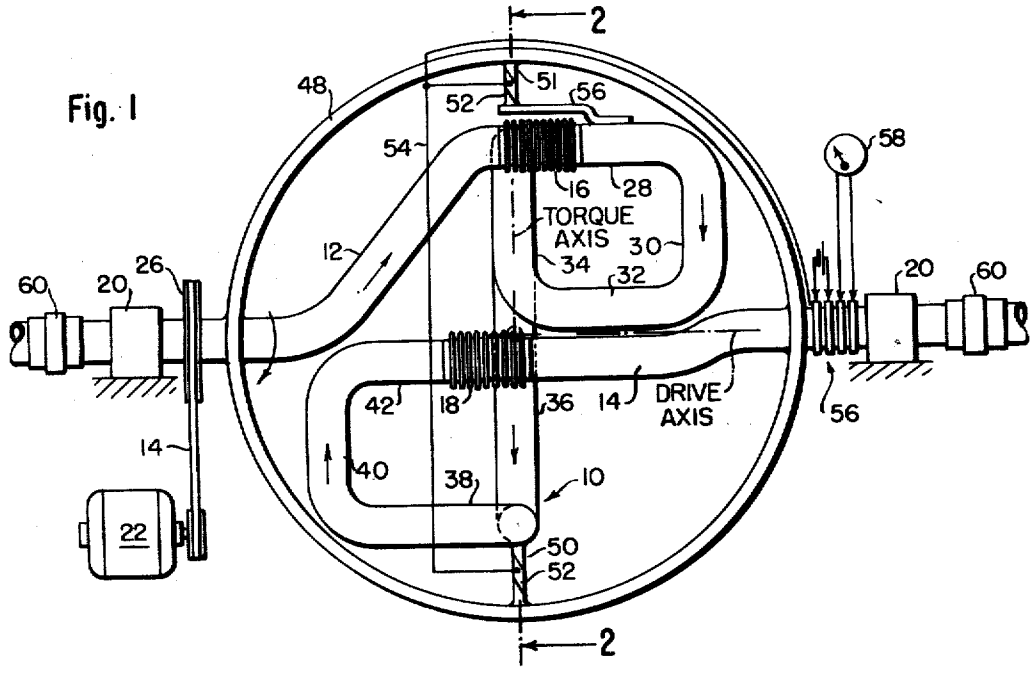
Nov. 19, 1957 M. D. ALTFILLISCH ET AL 2,813,423

GYROSCOPIC MASS FLOWMETER

Filed Sept. 7, 1954

Fig. 1



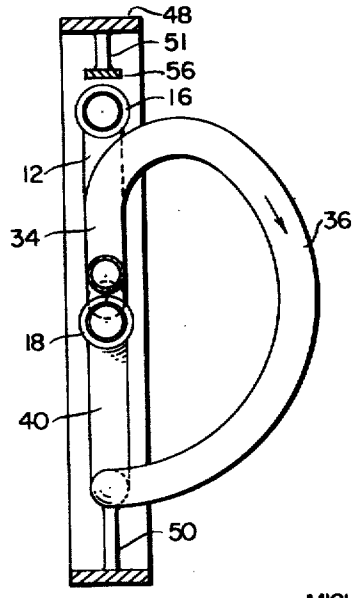




Fig. 2

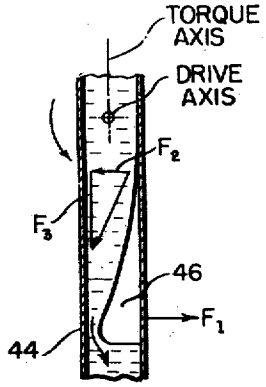



Fig. 3

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# GYROSCOPIC MASS FLOWMETER

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8 Claims. (Cl. 73—194)

This invention relates to flowmeters and more particularly to an improved mass flowmeter of the class described in the co-pending applications of George S. Cherniak et al., Ser. No. 380,414, filed September 16, 1953, now abandoned, and Michael D. Altfillisch et al., Ser. No. 454,487, filed September 7, 1954.

In recent years great effort has been applied to the development of mass flowmeters capable of dependably rendering highly accurate mass flow measurements. Most recently flowmeters employing gyroscopic principles have received particular attention, and many discoveries have been made to enhance their accuracy. More particularly it has been determined that separation of the fluid particles in heterogeneous mixtures in gyroscopic flowmeters produces inaccurate mass flow measurements unless some means is provided to restrict the separation to inactive portions of the spinning conduit. Furthermore, certain balance requirements have been found necessary to eliminate density sensitivity which otherwise introduces errors into the measurement of mass flow.

The invention disclosed in this application was made in an effort to overcome what has proved to be another major source of error in the measurement of mass flow.

It has been discovered that when a heterogeneous fluid or any fluid containing vapor is subjected to centrifugal force by rotation about an axis, the heavier particles of the fluid move under the influence of that force to a position remote from the axis of rotation while the lighter particles of fluid are displaced by the heavier particles and are moved inwardly toward the drive axis. This discovery as it effects flowmeters may best be illustrated by a more detailed description of this phenomenon in a conduit disposed radially with relation to its axis of rotation. If fluid composed of a mixture of air and water is introduced into the conduit, the particles of water will move to the radial extremity of the tube, while the air therein will, in reaction to the displacement by the water, move toward the axis. If the fluid mixture is considered to be flowing in a radially outward direction through the conduit under the influence of a pressure head, the particles of air will collect in the tube between the terminal portions thereof, and remain at that location under the influence of the opposing forces of the pressure head of the fluid and the centrifugal effect as described above. The air so affected collects in the form of a wedged-shaped bubble at one side of the conduit and partially interrupts the fluid flow therethrough. Obviously, the fluid is thereby directed against the opposite wall of the conduit and exerts a force at that location having a component perpendicular to the axis of said conduit.

If, however, the flow through the conduit is confined to a radially inward direction, it becomes apparent that the movement of the air will be in the same direction as that of the water. The centrifugal action of the water on the air and the pressure head of the fluid will act in the same direction, and accumulations of the lighter particles of fluid in the conduit will be eliminated.



The primary object of the invention, therefore, is to prevent the accumulation of air in the radial arms of the sensing loop of a gyroscopic flowmeter, without the aid of bleeds or other relief means connected thereto.

In the accomplishment of this and other objects we provide as one important feature of this invention a sensing conduit having the flow through the active arms thereof confined to a substantially radially inward direction about the drive axis.

These and other objects and features may be better understood and appreciated from the following detailed description of a preferred embodiment of our invention selected for purposes of illustration and shown in the accompanying drawing in which:

Fig. 1 is an inside elevation of a gyroscopic mass flowmeter constructed in accordance with this invention,

Fig. 2 is a view in a section of the flowmeter shown in Fig. 1, and

Fig. 3 is a fragmentary view of an active leg of a sensing coil illustrating the effect of radially outward flow therein.

Proceeding now to a detailed description of the embodiment of the invention illustrated in the drawings, and a demonstration of the advantages derived therefrom, the flowmeter is seen to comprise generally a sensing coil **10**, an inlet conduit **12** and an outlet conduit **14**. A pair of bellows **16** and **18** are observed to connect the conduits to the sensing coil and serve to direct through the sensing coil all of the fluid whose mass flow rate is to be measured. A pair of rigid support members **20** rotatably carry the inlet and outlet conduits and permit rotation of the sensing coil about the drive or precession axis indicated in Fig. 1. A motor **22** connected by means of a belt **24** to a pulley **26** mounted on the inlet conduit **12** rotates the sensing coil in the manner indicated above.

The sensing coil **10** will now be described in detail. An inspection of the drawing reveals that fluid entering the sensing coil from the inlet conduit through the bellows **16** passes into a horizontal arm **28** which is perpendicular to and whose axis intersects the torque axis. The arm **28** is observed to extend throughout its length substantially parallel to the drive axis. The fluid is then directed radially inwardly toward the drive axis by a radial leg **30** and is returned to the torque axis by a second arm **32** whose axis is parallel to the drive axis. The fluid flow through the coil is subsequently directed radially outward through a conduit **34** coaxially disposed on the torque axis.

A conduit **36** formed substantially in a semi-circle with its center on the drive axis and connected to the outer terminal end of the conduit **34** carries the fluid from the first portion of the coil to a similarly arranged portion having a first horizontal arm **38**, a radially inwardly conducting conduit **40** and a second horizontal conduit **42** which, through the connecting bellows **18** directs the fluid out of the sensing coil and into the outlet conduit **14**.

Flowmeters of the class illustrated are governed by the operative equation $T=2\pi R^2\Omega W$ where T is the gyroscopic couple produced about the torque axis, R is the radius of a circumscribed circle intersecting the outer radial extremes of the active legs **30** and **40**, $\Omega$ is the precessional velocity in radians/sec. about the drive axis and W is the mass flow rate in slugs/sec. It is obvious that the quantity $\Omega$ in the equation may either be maintained substantially constant by the use of a synchronous motor to rotate and induce precession of the coil or it may readily be determined by a tachometer or drag-cup or direct-current generator regardless of the means employed to rotate and induce precession of the coil. Therefore, by measuring the torque about the torque axis, the mass flow rate W may be determined.

Before proceeding to a description of the means pro-

vided to measure the gyroscopic couple produced about the torque axis, the necessity for restricting the flow in the active legs **30** and **40** to a radially inward direction will be graphically demonstrated. Fig. 3 has been presented for this purpose. If, for example, the active leg **30** of the sensing coil illustrated in Fig. 1 extended across the drive axis as does the conduit **44** of Fig. 3, and flow therethrough of a fluid containing vapor were confined to the direction indicated, the centrifugal force created by rotation of said conduit about the drive axis in hte direction of the arrow would cause a wedge-shaped bubble to collect against the side of the tube as suggested at **46**. As set forth in the introductory paragraphs, the vapor pocket or bubble collects at the location indicated under the influence of the pressure head of the flowing fluid and the displacement forces of the heavier particles of the fluid under the influence of the centrifugal force.

The exact position of the bubble is obviously determined by the balance of those forces. Because the bubble moves when changes occur in either of the forces, it becomes apparent that bleeder methods for disposing of the bubble are not satisfactory.

Continuing with an analysis of the fluid flow through the conduit illustrated in Fig. 3, the vector $F_1$ represents the force applied by the angularly moving pipe on the fluid. The fluid flow around the bubble **46** has also been illustrated in vector form, $F_2$ representing the momentum of the cross flow of fluid acting on the pipe while vector $F_3$ represents the radially outward fluid flow. It is apparent, therefore, that the presence of the bubble **46** reduces the total force applied to the moving fluid, resulting in the introduction of a negative error into the torque measurement made about the torque axis.

Referring now to Fig. 1, it will be appreciated that radially outward flow has been restricted to only those portion of the coil that are ineffective in the production of a torque about the torque axis. Those portions of the coil may be referred to as inactive legs. Specifically, radially outward flow in the leg **34** does not produce a torque about the torque axis for the flow therethrough is coaxial with said axis. Therefore, although a vapor pocket may form between the ends of the leg **34**, any force applied against the side of the conduit by the fluid therein will radiate from the torque axis. Obviously, the presence of an air or vapor pocket in the leg cannot affect the torque measured.

Flow through he semi-circular conduit **36** also fails to affect the total torque response about the torque axis, for the fluid passing through said conduit remains in the plane of the torque axis and a fixed distance from the drive axis. Obviously, therefore, the precession of the coil does not produce a tangential acceleration in the conduit **36** to affect that torque. The conduit **36**, in addition to providing fluid communication between the two segments of the sensing coil, performs a second very important function, namely, it provides centrifugal balance of the entire sensing coil about the torque axis. The necessity for such a balance has been graphically demonstrated in the above named co-pending application of Altfillisch et al. Suffice it to state that the couple about the torque axis produced by the centrifugal forces of the displaced and rotating major segments of the sensing coil is balanced by the centrifugal forces created by said rotation of the displaced semi-circular conduit **36**. Because no extraneous forces are exerted about the torque axis, the total torque is equal to the gyroscopic couple about that axis.

Proceeding now to a description of the means employed to measure the total torque, a gimbal **48** is observed to be mounted on the inlet and outlet conduits **12** and **14** respectively and rotates with the sensing coil. A pair of torque bars **50** and **51** rigidly secured at their outer ends to the gimbal have their inner ends fastened to the displaceable sensing coil **10**. Because the bars are positioned coaxially with the torque axis, a bracket



**56** is employed to secure the inner end of bar **51** to the sensing coil, for obviously the connection may not be made to bellows **16**.

Strain gauges **52** are fixed on the bars **50** and **51** and through appropriate circuitry diagrammatically represented by conductor **54** and slip-ring assembly **56** produce a signal at the meter **58** proportional to the gyroscopic coupled exerted about the torque axis. Because the measuring means per se forms no part of this invention, it will not be illustrated and described in detail. A simple circuit capable of performing the function intended is fully described on page 18 in Electrical Resistance Strain Gauges by Bobie and Isaac, English University Press Ltd., London. Moreover, the strain gauges may be replaced by a dynamo transformer of the type disclosed in the patent to Mueller, No. 2,488,734, issued November 22, 1949, with equal success.

Proceeding now to a description of the flowmeter's operation, a pair of fluid couplings **60** are provided to connect the meter into a line carrying fluid whose mass flow is to be measured. Upon excitation of the motor **22**, the sensing coil will rotate about the drive axis in the direction indicated. It is to be understood, however, that the motor may be replaced by any means which will rotate the coil about the drive axis, and the direction and speed of rotation is wholly arbitrary, for as has been suggested above, the speed of rotation may be readily determined and appropriate compensations made.

Continuing with the description of the flowmeter's operation, the flow of fluid through the sensing coil and the angular movement thereof will cause the sensing coil to displace about the torque axis under the influence of the gyroscopic couple. The bellows **16** and **18** permit the displacement of the coil about that axis without exerting appreciable resistance thereto. If the motor rotates the coil at a constant speed, the torque exerted on the torque bars **50** and **51**, and indicated at the meter **58** will be directly proportional to the mass flow rate of the fluid through the coil. If, on the other hand, the motor does not rotate the coil at a constant speed, the measured torque indicated at the meter will be a function of both the mass flow rate and the angular velocity $\Omega$ of the coil. By dividing the measured torque which is proportional to the product of W and $\Omega$ by $\Omega$, obviously the mass flow rate may readily be determined. The patent to Moore, No. 2,472,609, issued June 7, 1949, discloses a circuit for performing the division required when a variable angular velocity $\Omega$ is introduced and further discloses the necessary means for integrating the mass flow rate measurement with respect to time for obtaining total flow readings.

Having thus described in detail the flowmeter and its operation, numerous modifications and variations will readily occur to one skilled in the art to which this invention pertains.

For example, although the legs **30** and **40** have been illustrated as being radially disposed with respect to the drive axis to prevent variations of the effective radius R of the rotating mass when heterogeneous fluids are passed through the meter, they may respectively be formed as smooth curves connecting the arms **28** and **32**, and the arms **38** and **42**, without loss of accuracy if homogeneous fluids are to be measured. Although the flow through the active legs **30** and **40** would no longer be radial, nevertheless, the flow would remain in the direction of the drive axis, and, therefore, the pressure head and centrifugal effect on vapor carried by the homogeneous fluids would be in the same direction, thereby moving it along the fluid path. Therefore, it is not intended that the scope of this invention be limited to the specifically illustrated and described embodiment thereof, for obviously the invention encompasses a much larger field. Basically this invention teaches that in all flowmeters employing gyroscopic or Coriolis principles, the fluid flow in the sensing loop must be confined to a direction to-

ward the axis of rotation in all parts of the coil effective in producing a gyroscopic couple, i. e. in all portions of the coil except in those portions defining a path having a constant radius from the drive axis, perpendicular to the torque axis, or coaxially disposed on the torque axis. This requirement must be satisfied to obtain substantially 100% accurate mass flow measurements.

Aside from the advantages of accuracy achieved by flowmeters have the illustrated configuration, other very important advantages are derived, namely, the cost of construction of the sensing coil is substantially less than other configurations now known, and maximum utilization of space is obtained.

What we claim as new and desire to secure by Letters Patent of the United States is:

1. In a flowmeter, a sensing member comprising a conduit supported by gimbal means, said conduit being characterized by a plurality of legs, a substantial portion of said conduit being formed into at least a loop and located in the plane of said gimbal means, means for supporting said conduit for rotation about a first axis lying in the plane of said gimbal means, drive means for rotating said conduit about said first axis, means forming an inlet passage and means forming an outlet passage for directing through said conduit the fluid to be measured, and means disposed between said gimbal means and said loop for detecting precessional torque tending to rotate said conduit about a second axis lying in the plane of said gimbal means, said second axis being perpendicular to said first axis, and the configuration of said legs of said loop being such that substantially all flow of fluid in a direction parallel to said second axis and displaced therefrom is directed toward said first axis.

2. In a flowmeter, a substantially rigid sensing conduit formed into at least a loop, means for directing through said conduit all of the fluid to be measured, mounting means for supporting said conduit for rotation about an axis of rotation in a reference plane, drive means for rotating said conduit about said axis of rotation, and flexible fluid couplings for connecting said conduit with said first named means for permitting a small angular displacement of said conduit with respect to said reference plane, said displacement taking place about a precession axis lying in said reference plane and perpendicular to said axis of rotation, portions, of said loop having an undeflected position in said reference plane, and all of said portions of said loop lying in said reference plane parallel to said precession axis and displaced therefrom being so constructed and arranged as to propagate fluid toward said axis of rotation.

3. In a gyroscopic flowmeter, a sensing conduit characterized by a plurality of fluid-carrying portions, some of said portions formed into at least a loop lying in a reference plane of said conduit, means for mounting said conduit for rotation about a first axis lying in said reference plane, drive means for rotating said conduit about said first axis, the effect of the flow of fluid in said conduit and of said rotation of said conduit being to induce a precessional torque tending to deflect said loop about a precession axis lying in said reference plane perpendicular to said first axis, and the configuration of all of said loop portions lying substantially in said reference plane and parallel to said precession axis but displaced therefrom being such as to direct fluid toward said first axis.

4. In a gyroscopic flowmeter, a sensing conduit having a plurality of portions arranged in series loops for carrying the fluid to be measured, means for supporting said conduit for rotation about an axis of rotation perpendicular to the axes of said loops, drive means for rotating said conduit about said axis of rotation the combined effect of said fluid flow and said conduit rotation being a tendency for said conduit to precess about an axis of precession perpendicular to said axis of rotation and to said axes of said loops, said loops of said conduit being so constructed and arranged that one portion thereof carries said fluid along said axis of precession while substantially all the remaining portions of said loops extending in the direction of said axis of precession carry said fluid toward said axis of rotation.

5. In a gyroscopic flowmeter, a sensing conduit according to claim 4 in which flexible couplings disposed substantially on said axis of precession are provided respectively to a fluid input line and a fluid output line, the effect of said flexible couplings being to permit some precession of said conduit about said axis of precession.

6. In a gyroscopic flowmeter, a sensing conduit according to claim 4 including gimbal means attached to said support means, and means resiliently connecting said gimbal means to said sensing conduit to permit rotation about said axis of rotation and limited precession about said axis of precession.

7. A flowmeter comprising a sensing conduit characterized by a plurality of fluid-carrying portions, at least some of said portions being formed into loops lying in a reference plane of said conduit, means for supporting said conduit for rotation about a first axis lying in said reference plane, drive means for rotating said conduit about said first axis the effect of the flow of fluid in said conduit and of said rotation of said conduit being to induce a precessional torque tending to deflect said conduit about a precession axis lying in said reference plane perpendicular to said first axis, and means for measuring the deflection of said conduit from said reference plane, the configuration of all of said loop portions lying substantially in said reference plane and parallel to said precession axis but displaced therefrom being such as to direct fluid toward said first axis.

8. A flowmeter comprising a length of conduit formed into at least two substantially coplanar serially connected loops, the axes of said loops being parallel one to another, means for supporting said conduit for rotation about an axis of rotation which is perpendicular to the axes of said loops, drive means for rotating said conduit about said axis of rotation, means for introducing fluid into said conduit, means for extracting fluid from said conduit, said fluid following a path through said loops between said introducing means and said extracting means, a first flexible coupling between one of said loops and said introducing means, a second flexible coupling between the other of said loops and said extracting means, a gimbal ring connected at first opposite peripheral points thereof to said support means substantially on said axis of rotation, torsion arms connected between second opposite peripheral points of said gimbal ring and said coplanar loops, all said peripheral points being equally spaced one from another about said gimbal ring, and said second opposite peripheral points defining a second axis, the configuration of said coplanar loops being such that substantially all flow of fluid in a direction parallel to and displaced from said second axis in the plane of said axis of rotation is directed toward said first axis, and means for measuring the displacement of said coplanar loops from said gimbal ring about said second axis caused by the gyroscopic couple resulting from the flow of said fluid through said conduit.

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