Review of Some Methods of Flow Measurement

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IN the space allotted for this review (*1*), it will be possible to mention only a few of the more recent or more interesting developments in flow measurement, and these only briefly. The instruments or methods selected for mention include range extension for rotameters, critical-flow nozzle, viscous-resistance elements, acoustic flowmeter, electromagnetic induction flowmeter, and "mass" flowmeters of several types.

In speaking about "rate-of-flow" measurements, one must always distinguish between "volume flow" and "mass flow." Many of the conventional methods or devices for flow measurement unfortunately do not measure either one or the other but give indications that are some sort of hybrid functions requiring further measurements of the density (or velocity) in order to determine the flow, either on a volume basis or on a mass basis. The conventional flow orifices or nozzles illustrate this difficulty. For these, the pressure drop is proportional to the density of the flowing fluid and to the square of the velocity of the fluid. Thus, when used to measure the volume flow—in, say, gallons or cubic feet per minute—the quadratic expression has to be corrected for the density. Conversely, in determining the mass flow—in, say, pounds of mass per minute—one must again make a correction and determine separately either the density or the velocity in order to interpret the pressure drop across the orifice in terms of the mass flow. These factors should be kept in mind in considering the brief discussions that follow.

Range extension for rotameters. A rotameter consists of a tapered tube in which a "float" (ball, cylinder, disk, or other shape) is lifted, against gravity, by the flow to a level where the area of the annular orifice between tube and float will pass the flow with a pressure difference just sufficient to suspend the float. It is one of the most versatile devices for measurement of flow, widely used nowadays because it gives indications that vary directly with the flow rather than with the square of the flow, as does the conventional flow orifice. However, it too has the disadvantage that its indication is also affected by the density of the fluid. The ways in which the rotameter reading can be partially corrected for variation in density of the fluid and made reasonably free from variation with viscosity and other properties of the fluid have been explored in detail in recent years (*2*).

There are some tricks, which have not appeared elsewhere in the literature, whereby the versatility and usefulness of the rotameter may be enhanced for certain laboratory or plant applications. Since the weight of the float is constant, the pressure drop across the float is essentially constant, except for flows smaller or larger than the nominal range of the instrument. When the flow is too small to lift the float from its seat, the annular orifice around the float is of a constant size, and small flows will give a pressure drop across the rotameter that varies in the same way as the pressure drop across any fixed orifice. A water manometer, or other differential-pressure measuring gage, connected between top and bottom of the rotameter, as in Fig. 1, will therefore give an indication for the range of small flows before the float lifts. As the float rises, the pressure drop remains constant throughout the scale range of the rotameter. When this range is exceeded, the float is held against the stop at the top of the instrument and again forms a fixed orifice across which the excess flow will cause an increased pressure drop. So, by the simple addition of a water manometer, indications may be obtained of flows both below and above the scale range of the rotameter. There is, of course, some lack of accuracy to be expected if the rotameter float is not guided to exact seating at both ends of its travel. Figure 1 illustrates a typical curve of pressure difference as a function of flow.

Another application of this same characteristic of the rotameter, which is not as widely used as it might be, is the utilization of a small-range rotameter to monitor much larger flows whose incremental variations lie within that range. This is accomplished by installing the rotameter, as is shown in Fig. 2, in

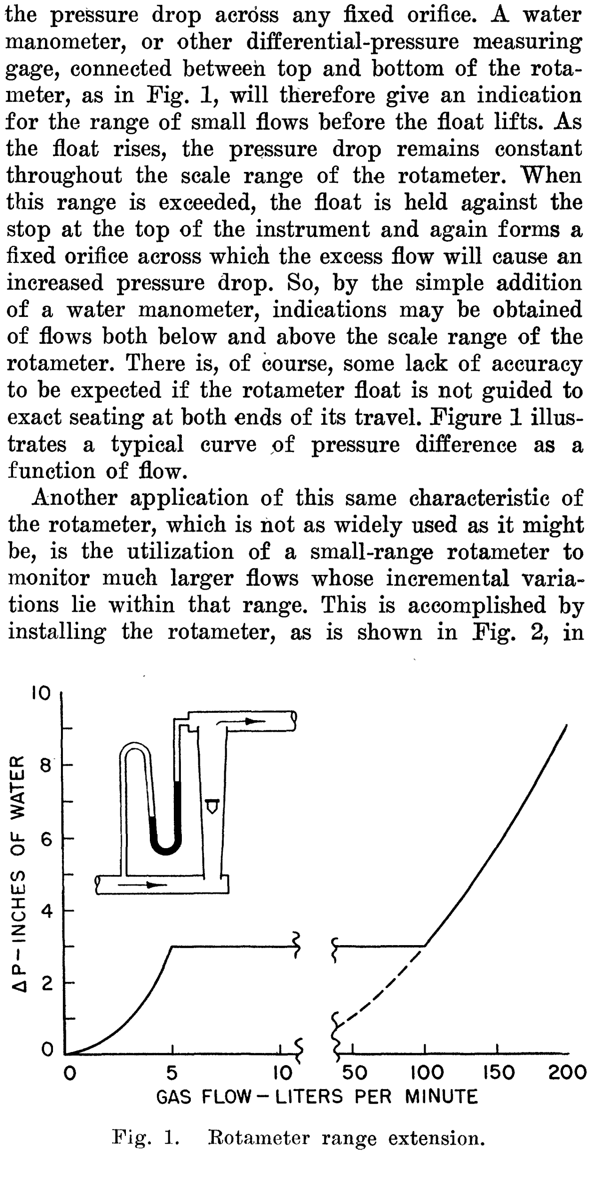


Fig. 1. Rotameter range extension.

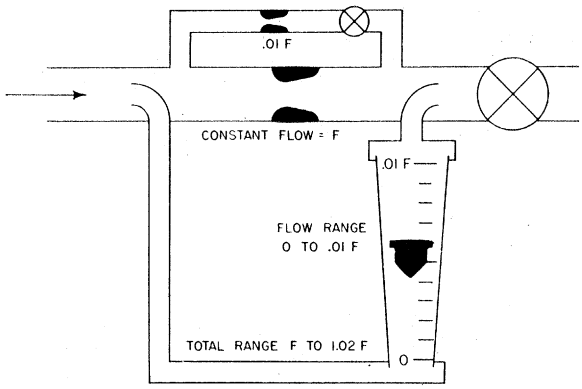


Fig. 2. High-precision flowmeter.

parallel with a flow orifice or nozzle of such size that the major part of the flow, say 90 or even 99 percent, goes through the orifice when the pressure drop across it rises to the value required to support the rotameter float. Under these conditions, any variation in flow will be shown almost entirely on the rotameter. The provision of an additional parallel branch, as shown, allows a selection of the flow range in which variation may be observed.

It should be pointed out that in many "bypass" installations of rotameters an entirely different theory is involved and entirely different results are obtained. A second orifice is installed in series with the bypass rotameter, so that the pressure drop across the rotameter is nearly negligible in comparison with the pressure drop across either the bypass orifice or the main orifice. Under these conditions, the rotameter indicates approximately a constant fraction of the total flow.

Critical-flow nozzle. A device that gives a flow of gas proportional to the absolute pressure is the so-called "sonic," or "critical-flow," nozzle, which is an ordinary nozzle with rounded approach (Fig. 3) operating under conditions such that the absolute pressure p_2 in the throat is less than about half the absolute pressure p_1 at the inlet. Under these conditions, the gas velocity at the throat of the nozzle is equal to the velocity of sound. Since the velocity of the discharge at the throat cannot exceed this value, the volume flow remains constant, regardless of variation in the downstream pressure, as long as the pressure ratio p_2/p_1 is less than the critical value of approximately one-half. (From the curves in Fig. 3, it is seen that this is only approximately true for the sharp-edged orifice.) The volume flow will vary with the temperature, which affects the velocity of sound. The mass flow will also depend on the entrance pressure and temperature, since they affect the density. (For pressure ratios nearer unity, the flow through the nozzle or orifice is given by the familiar equation relating it to the square root of the pressure difference.)

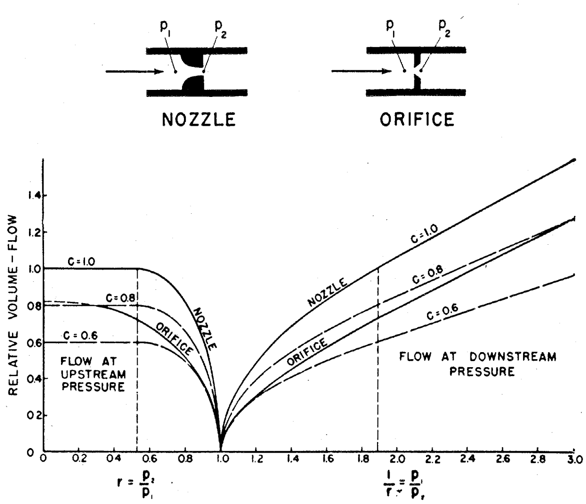


Fig. 3. Flow chart for nozzles and orifices.

Inasmuch as the absolute pressure of a gas can easily be measured with high accuracy, the critical-flow nozzle furnishes a means for accurate determination of flow. The disadvantage of the relatively low throat pressure p_2 required may be somewhat compensated by the use of nozzles with divergent exhaust cones, which increase the pressure at the cone exit. In the laboratory of the Office of Basic Instrumentation at the National Bureau of Standards, we have been able to obtain critical discharge with an over-all pressure ratio as high as 0.8. Although this interesting and useful property of the flow nozzle has been known for 75 yr, the device is not as widely used as its accuracy would appear to warrant. I have used critical-flow nozzles in a series of instruments for mechanical gaging, for measurement of temperature, and for gas analysis (*3*).

Viscous-resistance element. In addition to rotameters, there is another class of flowmeters that gets away from the quadratic pressure-flow characteristic of the orifice or nozzle. This is the class of so-called "linear resistance" flowmeters, in which the movement of the fluid is not turbulent, but laminar. Flow of this type occurs when a fluid moves slowly through a capillary tube or through closely packed granular or fibrous material. The standard equation for the pressure drop Δp associated with fluid flow in a long capillary tube is

$$\Delta p = KV\mu L/R^2 = Q_m \frac{8\mu L}{\pi R^4}$$

where K is a proportionality constant, V is the average velocity, μ is the coefficient of viscosity, L is the length of the tube, R is the radius of the tube, and Q_m is the volume flow-rate. For gas flow, Q_m is the volume flow-rate at the mean absolute pressure in the tube.

By using a bundle of capillary tubes, one may increase the capacity of the assembly to any practical value desired. Although the equation indicates that the over-all pressure drop is directly proportional to the flow-velocity, there is actually a small additive quadratic effect occasioned by pressure drops at inlet and outlet, so that the over-all relationship is not always exactly linear. Disks of sintered glass or metal show a characteristic almost like that of the capillary bundle, but, perhaps because of the wide varia-

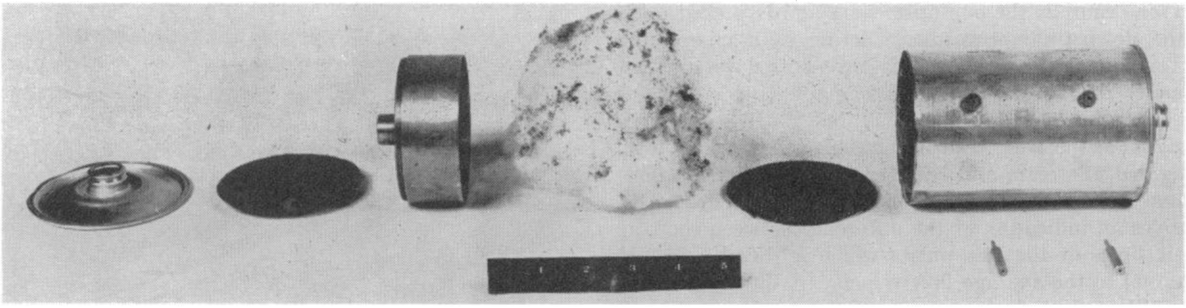
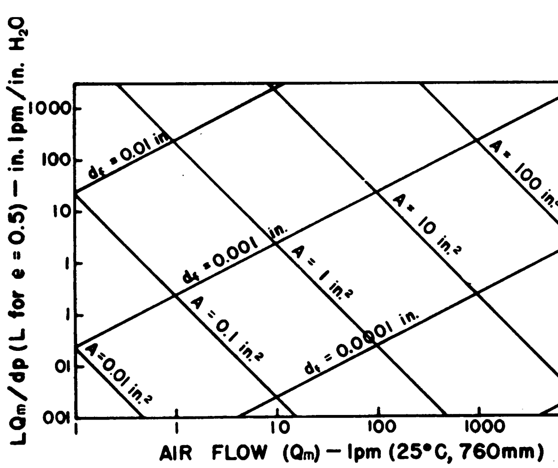


Fig. 4. Components of a simple linear flowmeter.



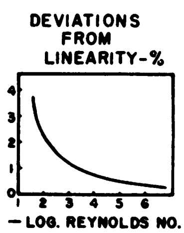


Fig. 5. Design chart for linear flowmeters for air.

tion in the size of their pores, they seldom show exact linearity.

Figure 4 shows the components of a very simple type of linear flowmeter developed several years ago at the National Bureau of Standards. It consists of glass-wool fibers packed into a metal canister, with pressure taps inserted in the canister in such a way that the glass wool at each end of the canister serves as a filter, and the pressure drop is measured across the intermediate part of the glass-wool pack. Figure 5 indicates the wide range of design parameters available in such meters for air, giving flows from a fraction of a liter per minute to hundreds of cubic feet per minute. There is some rather difficult theory involved in trying to predict the pressure drop resulting from flow through packed fibers (*4*), but the chart gives an empirical value $LQ_m/\Delta p$ which indicates what the pressure drop Δp will be for any combinations of length L, cross-sectional area A, fiber diameter d_f, and flow Q_m. The $e=0.5$ in Fig. 5 means that the fibers are packed half as tightly as they can conveniently be packed under standard conditions. When the fluid is compressible, one must specify whether the measurement is in terms of the flow that goes in or the flow that comes out. Since the pressure is different upstream and downstream, the volume flow-rate is greater on the downstream than on the upstream side. Only for the volume flow-rate as measured at average pressure is the calibration exactly a straight line (*5*).

Although the pressure drop across such flowmeters is a viscosity phenomenon and might be expected to be independent of gas density, there is nonetheless some slight correction to be made where gases are measured at very low pressures. Although this correction is negligible for most applications, the slope of the calibration curve may change by as much as 5 percent for air at an absolute pressure of 3 lb/in.^{2}, the volume flow being this much greater than at pressures near atmospheric.

Acoustic flowmeter. It has long been known that sound travels faster downwind than upwind, and various devices have been proposed or made for measuring flow by measuring the difference in the velocity of sound in the two directions (*6*). Further development of this idea at the National Bureau of Standards has resulted in the acoustic flowmeter illustrated schematically in Fig. 6 (*7*). A very short high-frequency sound pulse is generated by one of the transducers

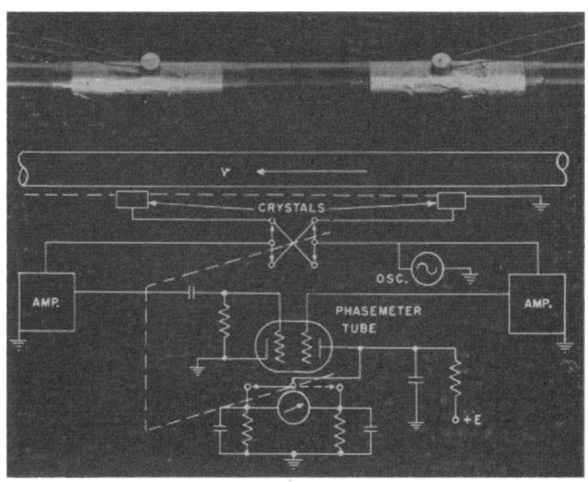


Fig. 6. Acoustic flowmeter.

(for example, the one upstream) and is picked up by the downstream transducer acting as a microphone. The signal thus received is transmitted to a phasemeter through a synchronous rectifier, which also reverses the circuit connections and generates a sound signal at the other transducer. This pulse is then propagated upstream and received by the first transducer, now acting as a microphone. The phasemeter circuit gives an indication of the difference between the transit times of the two pulses which is directly proportional to the average flow-velocity of the fluid.

When high-frequency sound waves are used, the sound path appears to be one of multiple reflections, so that the velocity indicated is very accurately the average velocity across the flow channel. The accuracy is about 1 percent or better down to velocities of 1 cm/sec. Although this device has at present 23 vacuum tubes in the electronic circuitry, it nevertheless has attractive possibilities for many industrial applications because nothing needs to be inserted in the flow channel, and measurements may be made from the outside of the conduit. At present it has been developed only for use on plastic tubes. However, it probably could be applied to metal pipes, particularly if spacings between the electrodes exceeding the present 5 or 6 in. can be provided.

Electromagnetic induction flowmeter. Any object, solid or fluid, conductor or nonconductor, that moves in a magnetic field has a voltage generated in it, in a direction perpendicular to the magnetic field and to the direction of motion. This effect was put to practical use in the electric generator some 30 or 40 yr after its discovery in 1830, but not until about 1930 was it applied to measurement of the flow-velocity of liquids, by Williams (*8*) in England and Kolin (*9*) in the United States. The first application of this principle was in measuring the flow in blood vessels that were partially excised from the body so that magnetic poles could be applied to them and electrodes could be fastened to them at right angles to the magnetic field. In recent years, the device has been developed for other laboratory and industrial applications (*10*), and installations have been made on pipe sizes as large as 20 in. in diameter. Figure 7 is a cutaway view illustrating the relative positions of electrodes, magnetic field, and flow tube.

Advantages of the electromagnetic flowmeter are that it has no moving parts and offers no obstruction to the flow. However, the voltages generated are relatively small, and the high electric resistance of many liquids makes it necessary to use very high impedance amplifiers to measure the signal.

Coriolis-force mass flowmeter. A meter that utilizes Coriolis acceleration as a means of measuring mass-rate of flow has been described by Y. T. Li and S. Y. Lee (*11*) and is shown in Fig. 8. A constantly rotating shell is inserted in the pipe line, and the fluid moves in a spiral path from the axis out to the periphery, guided by a disk set with radial guide vanes. The fluid then returns to its axial flow through another set of rotating guide vanes, delivering to them practically all the angular momentum previously gained, and continues down the pipe. The circumferential Coriolis acceleration, multiplied by the mean moment of the fluid mass, provides a measurable torque between the two disks. The second rotating disk is integral with the rotating housing, but the first one is permitted a slight relative motion through a torque tube. The twist of the latter can conveniently be measured by strain gages. Since the torque that is sensed is proportional to the speed of rotation, the scale can be changed by changing this speed. The output signal is proportional to the mass flow of the material passing through the vanes, regardless of its pressure, viscosity, density, compressibility, or temperature, or the frictional torque requirement.

The Coriolis-force mass flowmeter will work with gases, liquids, foams, or slurries. It is adaptable for measurement of rapidly changing flow in either direc-

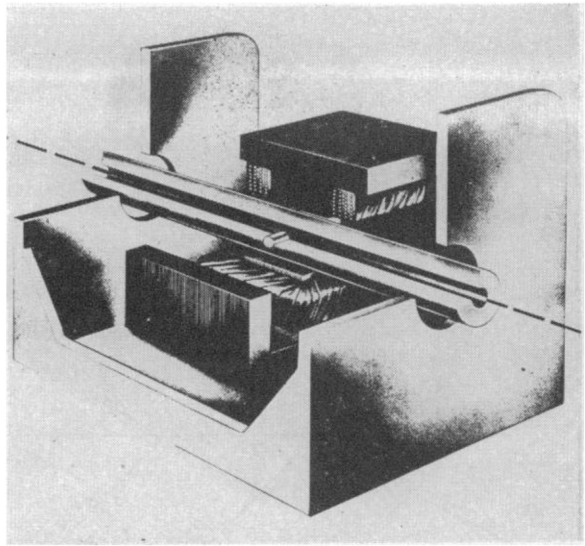


Fig. 7. Cutaway view of electromagnetic fluid flowmeter.

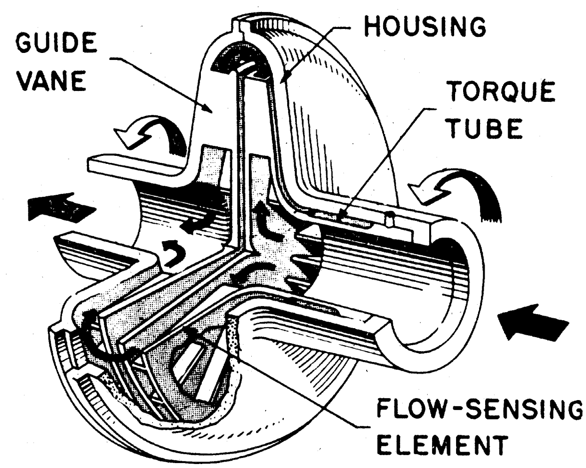


Fig. 8. Coriolis-force mass flowmeter. [Courtesy Control Engineering Corp., Norwood, Mass.]

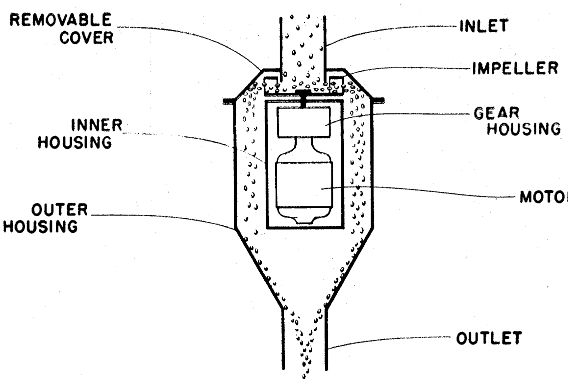


Fig. 9. Schematic drawing of the "massometer." [Courtesy Wallace & Tiernan, Belleville, N.J.]

tion, but it has the disadvantages of two large-diameter rotating seals and the need for a constant-speed drive. Accuracy is said to be within ± 0.3 percent and sensitivity within 0.1 percent (*12*).

Spin-torque mass flowmeter. A mass-flow device called the "massometer" (*13*) is particularly adapted for free-flowing granular material. It has a rotating impeller disk mounted on the upper end of a 1/20-hp, 1800-rev/min synchronous motor, the whole unit being enclosed in a dust-tight case (Fig. 9). The material falls on the central area of the impeller disk and moves outward as a result of centrifugal force, gaining the same tangential velocity as the edge of the impeller disk before it is slung off, to drop past the motor to an outlet below. The torque required of the motor, above that needed to overcome friction, is proportional to the mass flow. This torque reacts on the motor stator, turning it slightly about the rotation axis against the force exerted by an aneroid capsule (Fig. 10). The air pressure in this capsule is controlled through a nozzle and a flapper linked to the stator, via an air-relay valve supplied at 30 lb/in.^{2} The same pressure actuates the pen on a conventional pneumatic recorder. The accuracy is stated to be ± 1 percent between 10 and 100 percent of capacity, which may be 30 to 200 lb/min (*14*).

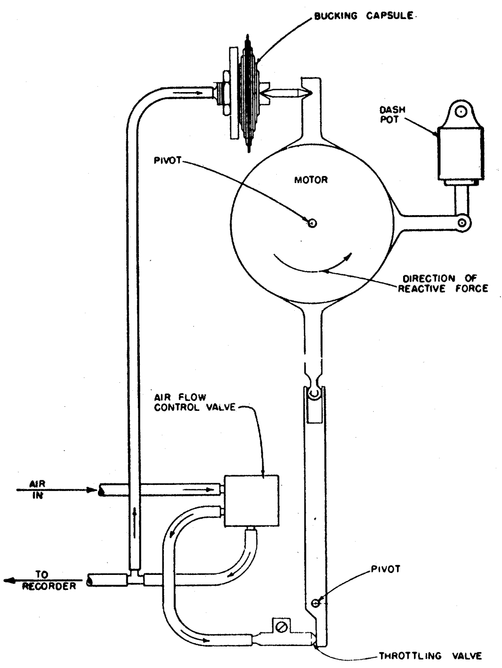


Fig. 10. Schematic of the force-balance system of the "massometer." [Courtesy Wallace & Tiernan, Belleville, N.J.]

Helical-flow cylinders. A mass flowmeter developed for measurement of aircraft fuels of various viscosities and densities was described by V. A. Orlando and F. B. Jennings (*15*). The sensing unit consists of two similar rotatable cylinders, called impeller and turbine, placed end-to-end in the pipe line (Fig. 11). The instrument housing closely fits their outer diameters. The central area of these cylinders is blanked off, but the peripheries are provided with a number of shrouded parallel passages. The upstream cylinder, rotated continuously at a constant speed, imparts to the fluid moving through it an angular momentum proportional to the moment of inertia of the fluid and, hence, to the mass-rate of fluid flow. The downstream cylinder is designed to remove this momentum, and the resulting torque turns it through an angle against the restraint of two calibrating springs. It was found desirable to shroud the two cylinders and to provide a decoupling disk between them to eliminate viscosity effects.

For measuring fuel flow to individual engines (*16*), a special generator furnishes three-phase, 400-cy/sec power to the impeller motor, submerged in the fuel and thus lubricated and cooled. A gear train drives the impeller at 63 rev/min. The external dimensions of the transmitter are approximately 3½ by 3½ by 10½ in. The pressure drop is only 0.81 lb/in.^{2} for a flow-rate of 12,000 lb/hr, and the speed of response is less than 2 sec across half scale. The motor incorporates a chronometric governor to maintain a constant speed of 2700 rev/min with an accuracy of 0.1 percent. The angular position of the turbine is transmitted to a remote indicator by a second-harmonic type selsyn system. The error-of-flow indication is given as about 0.2 percent of full scale in the range

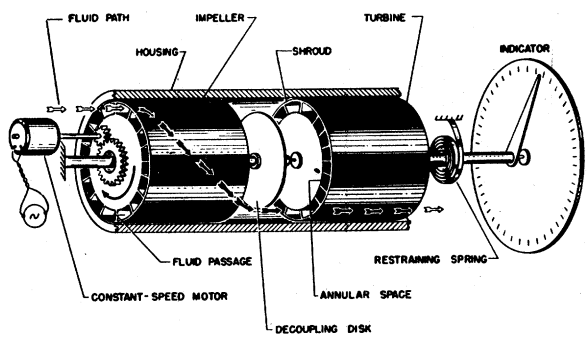


Fig. 11. Mass flowmeter using helical-flow cylinders. [Courtesy General Electric Co., West Lynn, Mass.]

0 to 3000 lb/hr and about 1 percent in the range 3000 to 12,000 lb/hr. A six-engine installation weighs only 40.8 lb.

Fluid gyroscope mass flowmeter. A mass flowmeter operating on the gyroscopic principle is described in a patent issued to J. M. Pearson (*17*). In this device, the fluid is led through a pipe coil, which is either rotated or oscillated about an axis (precession axis) in the plane of the coil. The circulation of the fluid in the coil provides an angular momentum that is the product of the moment of inertia of the fluid and its angular velocity about an axis perpendicular to the plane of the coil. Owing to the precession (rotation or oscillation), there results a gyroscopic torque, about an axis perpendicular to the other two, that is a measure of the mass-rate of fluid flow.

Figure 12 shows a schematic oscillatory arrangement, under study by the Office of Basic Instrumentation, that is intended to eliminate the rotational seals and permit torque measurement by piezoelectric devices. The Pearson patent includes a mechanical gyroscope that is automatically maintained at such a rotational velocity as just to balance the torque exerted by the mass moving through the coil, this angular velocity being then a measure of the mass flow-rate. The commercial device (Fig. 13) is a rotating form, available in various sizes and materials (*18*). It is adaptable to applications requiring low-frequency response or the averaging of pulsating flows and is expected to give resolution in the handling of gases, liquids, and some fluidized solids.

Magnus-effect mass flowmeter. (i) *Pressure from transverse rotor.* A mass flowmeter, developed by W. J. D. Van Dijck of the Technical University of Delft, was engineered by the Royal Dutch Shell Laboratory and has been described by D. Brand and L. A. Ginsel (*19*). A constant-speed smooth-surfaced cylinder (Fig. 14) rotates about an axis transverse to the fluid flow, which is led around both sides of the rotor through gradually narrowing passages. The velocity of the fluid in one gap is increased, and that in the other is decreased in the same amount, because of the film adhering to the rotor. The difference of the pressures measured at the two gaps proves to be directly proportional to the product of the fluid density, the surface speed of the rotor, and the equivalent undisturbed stream velocity.

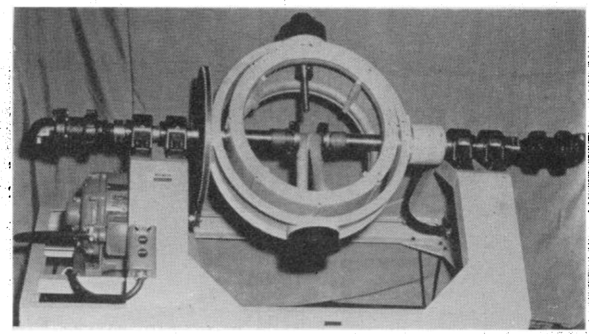


Fig. 13. Fluid gyroscope mass flowmeter. [Courtesy Control Engineering Corp., Norwood, Mass.]

Three prototypes of the Van Dijck mass flowmeter were built, the last for measuring a pulsating flow of 1000 metric tons of oil per day with a differential pressure of 72 in. of water. It was found that the velocity of the main flow should be kept well below critical, but that the output was substantially linear even with pulsating flows and liquids of widely different viscosities. The pressure drop across the meter is about one-fourth of the measuring-pressure differential. Attempts were made to use this meter for an air-liquid mixture, but the results were unsatisfactory.

Magnus-effect mass flowmeter. (ii) *Force on transverse rotor.* A mass flowmeter conceived by H. L. Mason, and now under study by the Office of Basic Instrumentation, utilizes the Magnus effect in conjunction with an elastic member. This has a constant-speed rotor (Fig. 15) with a vertical axis transverse to the fluid stream. The axis sustains a force that is the product of mass density, fluid velocity and the speed, cross-sectional area, and length of the rotor. No special shaping of the duct is required. In fact, such a meter could apparently be used to measure the local mass-velocity product in an infinite stream. The lateral force exerted might be measured either by a

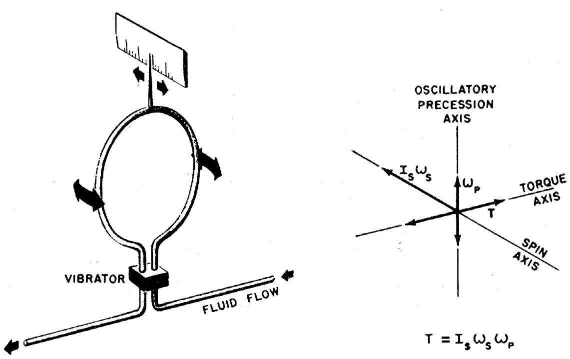


Fig. 12. Schematic drawing of the "vibro-gyro" mass flowmeter.

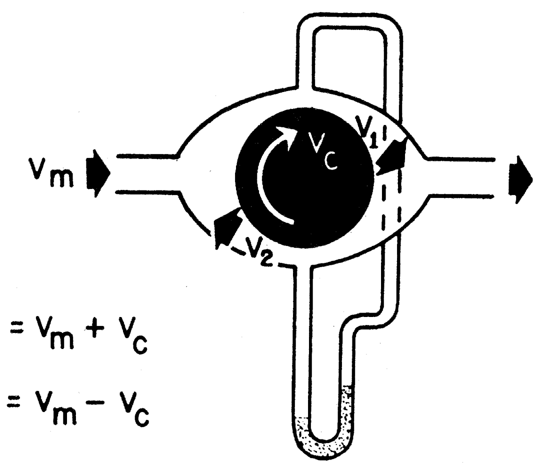


Fig. 14. Schematic drawing of end view of the Van Dijck mass flowmeter.

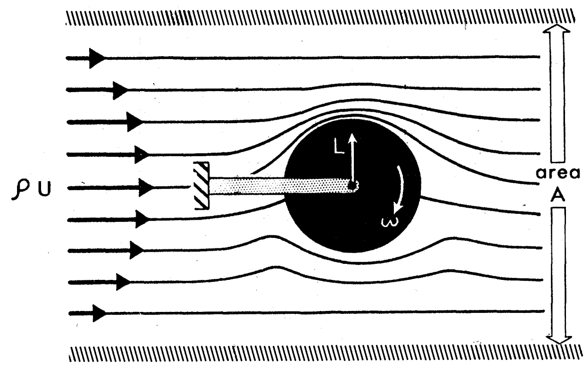


Fig. 15. Schematic drawing of mass flowmeter using Magnus effect.

pneumatic force-balance arrangement or by the calibrated deflection of a cantilever beam lying on the axis of fluid flow.

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Irradiation of Parts of Individual Cells II. Effects of an Ultraviolet Microbeam Focused on Parts of Chromosomes

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IN about half of the dividing cells of our cultures of newt heart (*1*), one or more chromosomes tarry near the centrosome(s) during part of metakinesis and metaphase. For periods ranging up to 30 min at 22°C, these "centrophilic" chromosomes lie with their kinetochores presented to the centrosome(s), but they regularly migrate, kinetochore foremost, to the metaphase plate before anaphase. With phase-contrast microscopy, the kinetochore is clearly distinguishable as a constricted region (Fig. 1*A*).

With a proton microbeam (*1*), preliminary experiments indicated that irradiation of a chromosome segment containing the kinetochore resulted in the chromosome drifting about the cell instead of migrating straightway, kinetochore foremost, from the vicinity of the centrosome to the metaphase plate. We have investigated this effect further by means of a newly developed *ultraviolet* microbeam (*2*).

As early as 1912, Tschachotin (*3, 4*) obtained a microbeam by using refracting lenses to reduce the image of an ultraviolet source to microscopic dimensions, but the difficulties associated with aiming have limited the usefulness of his devices (*5*), especially for irradiation of very small regions in preparations as complex as tissue cultures. By using a *reflecting* objective and the principle of incident illumination, we have constructed a simple apparatus in which the same lens is used simultaneously for observation and for ultraviolet microbeam bombardment (Fig. 2).

The aiming and viewing portion of the device is a microscope with a reflecting objective. The magnifying system is fixed, focusing being accomplished by adjusting the height of the stage. The image of the target is brought into focus in the plane of a set of aiming cross hairs in the ocular. An adjustable telescope, focused on these cross hairs, permits compensation for variations in eyesight and, thus, insures that a target under observation can always be brought into focus at exactly the same point below the objective.

For ultraviolet bombardment, a quartz lens focuses