Studies on Bearingless Turbine-type Flowmeters

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This paper summarizes two papers, Bearingless Windmill-type Gas Flowmeter (1) and Bearingless Watermill-type Liquid Flowmeter (2), and windmill and watermill in these papers called simply turbine wheel.

The turbine wheel of the flowmeter is mounted on a float, and the float is on liquid so that the friction against the rotation of the turbine wheel due to friction of the float to liquid is reduced to be negligible at slow rotating speeds. To keep the axis of rotation of the turbine wheel assembly to the center, a magnetic attraction is introduced.

The flowmeter shows a satisfactorily linear relationship between rotating speed and flow rate over a wide range from 15 to 500 l/min for gas flowmeter and from 0.003 to 3.0 l/min for liquid flowmeter.

1. Introduction

Although the turbine wheel itself is commonly made of light material and the pivot bearing is carefully adjusted to minimize friction, turbine-type flowmeters generally fail to respond to very low flow rates. Rotameters are also regarded as inadequate for such a low flow rate measurement. Another gas flowmeter employing a drifting membrane of soap bubbles has been developed for extremely low flow rate measurements, but it can cover only a limited, considerably narrow range.

The new turbine-type flowmeters described here are bearingless. The rotating part, i.e., the turbine wheel assembly,

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is entirely floating on liquid in a cup and is installed in a vertical cylinder. The fluid flow in the cylinder causes rotation of the turbine wheel. In order to prevent a drift of the axis of rotation, magnetic attraction is used and a steel ball is attached at the bottom center of the float. The liquid is Newtonian, so the friction between float and liquid is expected to be negligible when the relative speed is near zero. At high speed rotation of the turbine wheel assembly, the liquid in the cup naturally gyrates, and consequently produces a centripetal force upon the float. It makes the rotation stable over a wide range of fluid flow rates. The speed of the turbine wheel is detected and determined by means of opto-electronic counting procedures obviously without any effect on the rotation.

2. Bearingless turbine-type gas flowmeter[1]

A schematic and perspective drawing of the gas flowmeter is shown in Fig.1 (a) and Fig.1 (b). A, is the turbine

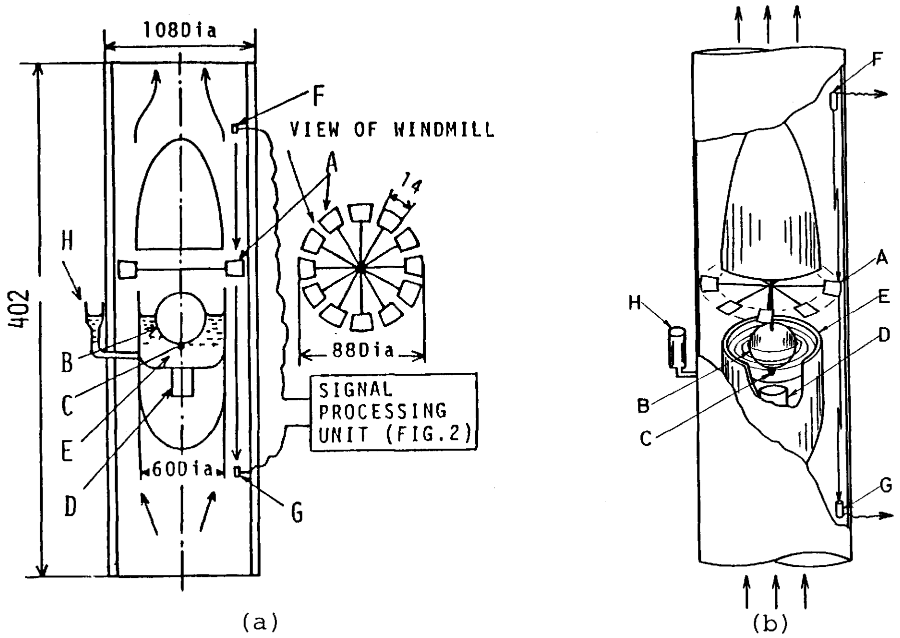


Fig.1 Schematic and perspective drawing of gas flowmeter

wheel equipped with twelve 45 degree blades of thin acryl plate and the hub is mounted on the top of spherical float B. A centering steel ball C, 0.8 mm in diameter, is held in place by a permanent magnet D which has been fixed at the bottom center of the cup E. The ball also acts as the ballast to adjust the center of gravity of the turbine wheel assembly. The liquid, water for instance, fills the cup to the determined level through the spout H with a transparent tube which can also be the liquid level gauge. The liquid level is not critical. F and G are a couple of opto-electronic devices, i.e., a light emitter and light beam receiver. The light beam is interrupted by each turbine blade as it passes, and is converted into an electric pulse train which is the signal output.

The pulse train, whose frquency represents the rotating speed of the turbine wheel, is shaped and conveyed to the electronic pulse counter whenever the count number per unit time represents an accurate flow rate. At a very low flow rate where a slow rotation of the turbine wheel produces a very low output pulse frequency and consequently requires a longer time for acquisition of the coming impulses, this method is not suitable to measure the rotating speed. Ways of measuring such very low flow rates are described later in this paper.

This instrument was calibrated by using three rotameters connected in cascade as shown in Fig.2. These rotameters cover

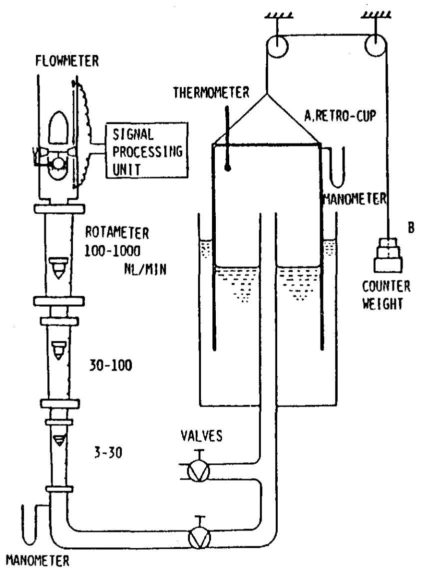


Fig.2 Calibration of the flowmeter

from 3 to 30, from 30 to 100 and from 100 to 1,000 l/min respectively. Retro-cup A supplies air to the flow line at regulated pressure when the counter weight B is removed. The flow rate can be determined from the submerging speed of the cup A. Fig.3 shows the relationship between the flow rate in m^3/s or l/min and the rotating speed ω of the turbine wheel in rad/s. Open circles plotted in Fig.3 were obtained at room temperature, while solid circles were obtained when the temperature of the liquid in the cup was raised 60°C in order to make the viscosity of the liquid approximately one half of that at room temperature. Both plot-

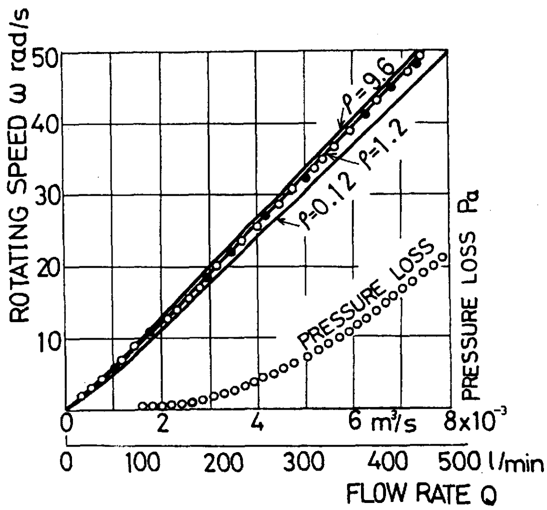


Fig.3 Relation among flow rate Q, rotating speed ω and pressure loss Pa

tings are close enough to fall on a single curve which shows good proportion to the flow rate. The curve at the bottom of Fig.3 shows the pressure loss due to the turbine wheel instrument inserted in the flow line, and is regarded as parabolic. The other solid lines in the same figure are described later in this paper.

The transient response of the flowmeter at an instantaneous change of the flow rate was examined by oscillograph. The time lag in decreasing flow rate is longer than in increasing transition. The response time in terms of 63% change to reach a steady speed is a few seconds. The main factors of such a time lag are deemed to be both the viscosity and the mass of liquid by which the liquid has to establish a new whirling state. From the experiments, the transient response is not affected even when the viscosity of the liquid is changed by a 60°C temperature rise.

This turbine type flowmeter may be applicable to high pressure gases. In order to avoid experiments with dangerous high pressure gases and also to evaluate the characteristics of this flowmeter under various conditions, the relationship between the rotation of the turbine wheel and flow rate was studied analytically. In the analyses, the flow was assumed not to produce any radial flow, and the blades were assumed to be thoroughly smooth with a negligibly small thickness. The whole inlet gas flow was also assumed to be steady, uniform, homogeneous, purely axial and have a constant viscosity.

When the turbine wheel is regularly rotating at an angular velocity ω_0 (rad/s), the driving torque must be equal to the sum of both resisting torques: T_f due to the fluid drag on the blades, and T_b due to viscosity of the floating bearing as in Eq.(1)

$$T_f + T_b = \rho Q(v \tan\alpha - \omega_0 r)r \tag{1}$$

where Q is flow rate (m^3/s), ρ fluid density (kg/m^3), α twist angle of the turbine blade against the axis of flow, and v average gas velocity (m/s) respectively. r is the equivalent radius of the turbine wheel which is regarded to be the root mean square of inner and outer radii r_1 and r_0 of the blade: that is, $r = \sqrt{(r_1^2 + r_0^2)/2}$.

Moreover, T_f is divided into two parts: resisting torque T_{ff} due to the skin friction drag of blades and additional resisting torque T_{fs}

$$T_f = T_{ff} + T_{fs} \tag{2}$$

where T_{ff} is written as

$$T_{ff} = nrC_f\rho(v/\cos\alpha)^2 c\,l \sin\alpha \tag{3}$$

In Eq.(3), n is the number of blades of the turbine wheel, c the width of blades, l the length of blades and C_f is a function of Reynolds number.

T_{fs} in Eq.(2) is written as

$$T_{fs} = rD \tag{4}$$

where D is the sum of all incidental fluid drag derived from centrifugal movement of the flow, disturbance of fluid by blade spokes, and so on.

To deal with D, a dimensionless coefficient C_s called "incidental drag coefficient" may be introduced as in Eq.(5)

$$C_s = \frac{D}{\frac{1}{2}\rho(v/\cos\alpha)^2(2c\,l)} \tag{5}$$

where C_s is assumed to be a constant. From Eqs.(4) and (5), T_{fs} is written as in Eq.(6)

$$T_{fs} = rC_s\rho(v/\cos\alpha)^2 c\, l \qquad (6)$$

In a flow which has an appreciable low Reynolds number, the flow in the boundary layer at the surface of the blades may be regarded as sufficiently laminar. The flowmeter described here may behave in the laminar region since the Reynolds number is usually smaller than a few thousands. Hence, C_f is expressed as in Eq.(7)

$$C_f = B\sqrt{R_e} \qquad (7)$$

while the Reynolds number Re is expressed as

$$R_e = l\,\nu/v\cdot\cos\alpha$$

Substituting Eqs.(2), (3) and (6) into Eq.(1), we obtain Eq.(8)

$$\frac{\omega_0}{Q} = \frac{\tan\alpha}{F\cdot r} - \frac{T_b}{\rho Q^2 r^2} - C_f K - C_s K/n\,\sin\alpha \qquad (8)$$

where $K = nc\,l\sin\alpha/(rF^2\cos^2\alpha)$ and F is the mean cross sectional area of the effective annular flow passage at the turbine blades in m^2. In addition $v = Q/F$.

The resisting torque T_b due to the viscosity of the liquid obviously depends on the rotating speed of the turbine wheel. We considered about T_b as follows. In Fig.4 the liquid is filled up in semispherical cup of the radius R_2, and the spherical float of the radius R_1 is floating on the center of surface of liquid, with draft line at the center height of the float. When the turbine wheel is at an appreciable low rotating speed, the float produces both the velocity gradients of radial and tangential in the liquid, and results in the resisting torques on the surface of the float, while the tangential resisting torque may be negligibly small as compared to the radial one.

By disregarding the tangential velocity component, we obtain equation (9) for radial velocity gradient du/dR,

$$-\frac{du}{dR} = \left(\omega + R\frac{d\omega}{dR}\right)\sin\theta \qquad (9)$$

where ω (s^{-1}) is rotating angular velocity of the float, and u (m/s) is circumpherential velocity of the followingly rotating liquid at radius R.

Assuming the coefficient of viscosity of the liquid as μ (Pa.s), the viscosity force f ($N\cdot m^{-2}$) is expressed by Eq.(10)

$$f = -\mu\frac{du}{dR} = -\mu R\frac{d\omega}{dR}\sin\theta \qquad (10)$$

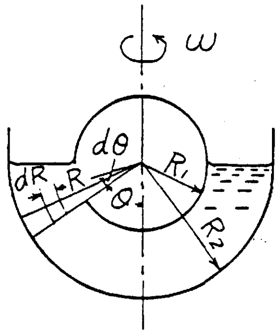


Fig.4 Analysis of fluid force on floating sphere

The torque ΔT which is considered at a thin annular layer $2\pi R \cdot R \cdot d\theta$ is expressed as

$$\Delta T = f \cdot 2\pi R\sin\theta \cdot R d\theta \cdot R\sin\theta = -2\pi\mu R^4 \frac{d\omega}{dR}\sin^3\theta d\theta \qquad (11)$$

By putting $R^4 \cdot d\omega/dR$ = const. since ΔT is a constant with the small range $d\theta$, and by applying the boundary conditions $\omega = 0$ at $R = R_2$, $\omega = \omega_0$ at $R = R_1$, equation (12) is obtained.

$$\frac{d\omega}{dR} = -3R^{-4} \cdot R_2^3 \cdot R_1^3 \omega_0 / (R_2^3 - R_1^3) \qquad (12)$$

From Eq. (11) and (12), we obtain,

$$T_b = \int_0^{\pi/2} \Delta T = 4\pi\mu R_1^3 R_2^3 \omega_0 / (R_2^3 - R_1^3) \qquad (13)$$

In Eq.(13), T_b shows a linear relationship to the rotating speed, but this relation is lost at higher rotating speed at which Reynolds number is higher than 60. This is because of a centrefugal force which gives rise to an incidental upward flow. This flow goes up along the surface of the float from the bottom centrito the draft line at which the float has the maximum relative speed against the liquid. This upward flow gives a resistance to the rotation by producing an additional velocity gradient in the liquid. For higher speed of rotation which induce the incidental upward flow, the value of T_b is experimentally determined.

In turbulent gyratory flow due to a high rotating speed of the turbine wheel, an experimental result for T_b has been obtained as in Eq.(14) on a cylindrical float.

$$T_b = 0.253 \cdot \rho_n \cdot \ell \cdot R_1^{\frac{7}{2}} \cdot \nu_n^{\frac{1}{4}} \cdot \omega_0^{\frac{7}{4}} \qquad (14)$$

$$(2.3\times10^3 < Re < 5.7\times10^5)$$

where ρ_n is density of liquid, l depth of cylindrical float, R_1 radius of float, and ν_n kinetic viscosity of liquid respectively.

The resisting torque T_b on the cylindrical float in laminar region is theoretically given by Eq.(15)

$$T_b = 4\pi\mu\ell R_1^2 \cdot R_2^2 \omega_0 / (R_2^2 - R_1^2) \tag{15}$$

Since the raised bottom construction of the cylindrical float traps an amount of air, the bottom panel is contact with liquid, so the skin friction at the bottom panel has been neglected in Eq.(15). In Eq.(15) the draft depth l is equivalent to the radius R_1.

Fig.5 shows theoretical resisting torque T_f and T_b at various rotating speeds. Values of T_b, measured experimentally on a

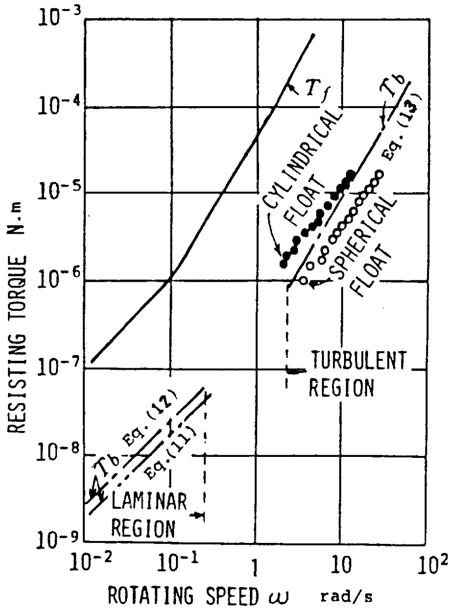


Fig.5 Relation between rotating speed and resisting torque

cylindrical float and also on a spherical float are plotted. The chain line in Fig.5 is theoretically depicted. The solid line in this figure shows T_f in Eq.(2). The torque T_f caused by the fluid drag on the surface of blades is obviously more than a factor of 100 greater than the bearing torque on the float. So the resisting torque of the liquid bearing T_b is almost negligible compared with T_f in the practical reagion.

Next, the numerical constant B in Eq.7 is considered as follows. The value B is well known to be 1.328 for a thin flat plate with zero pressure gradient, but the value is particularly given as 0.956 when the pressure gradient is a negative one. But we use the value B as 1.00 approximately.

The value C_s was determined by the experiment depicted in Fig.3. In Fig.3, a value $C_s = 1.19$ satisfies the relationship between Q and ω at a typical point, i.e., $Q = 7 \times 10^{-3}\ m^3/s$.

For gases with different densities, solid lines in Fig.3 shows the results calculated by using Eqs.(7) and (8) together with Fig.5, in all of which the values $B = 1.00$ and $C_s = 1.19$ are employed. These lines can be regarded as straight lines enough tc the plottings which show the results of experiments in normal atmospheric conditions as mentioned formerly. Solid lines in Fig.3 show a good linear relationship between the rotating speed and the flow rate. Only the curve for $\rho = 0.12$ shows a slight deviation from others and is somewhat distorted at low flow rates.

To conclude, this flowmeter is applicable in a wide range of flow rate measurements, especially when a capability to measure a low flow rate is desired.

The rotating speed of turbine wheel shows a distinct linear relationship to the flow rate from 15 to 500 l/min. The experimental results show good agreement with the analyses except that the turbine wheel still tends to hesitate to rotate at extremely low flow rates.

High pressure gas produces slightly higher rotating speeds than at normal atmospheric pressure, while reduced pressure gas produces a considerably low rotating speed. High pressure air of 0.94 Mpa causes 1.7 % higher rotating speed at the maximum handling flow rate, 500 l/min, of this instrument.

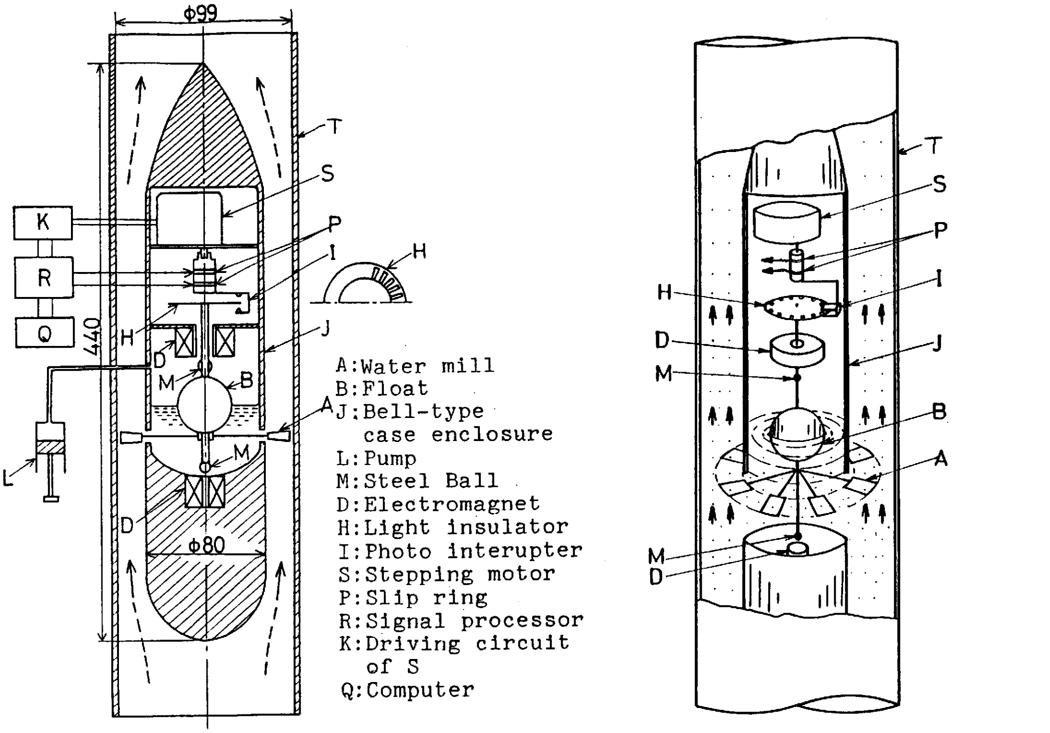
Plain water as the bearing liquid on which the turbine wheel assembly floats, may be commonly used over the probable room temperature range without any appreciable effect on rotating speed.

The transient response in terms of the flow on time up to 63% instataneous increases of flow rate, ranges from 0.4s to 3.8s depending on the span of flow rate.

Pressure loss due to the flowmeter increases in proportion to the second power of the flow rate. At the maximum flow rate, the pressure loss amounts to approximately 20 Pa.

3. Bearingless turbine-type liquid flowmeter[2]

Fig.6 (a) and (b) show a schematic and perspective drawing of the liquid flowmeter of the same principle as the one previously mentioned. A is the turbine wheel equipped with eight 60 degree



(a) (b)

Fig.6 Schematic and perspective drawing of liquid flowmeter

blades of thin aluminum plate and the hub is mounted to the bottom of spherical float B. As liquid flows through the tube T upwards, liquid flows into a bell-type enclosure J, and air remains in the upper part. Then the liquid surface appears in it as in this figure. The spherical float B is on this surface. Appropriate vertical position of the turbine wheel assembly is obtained by adjusting the air quantity in the enclosure J, using a pump L. In order to prevent the drift of the float, two centering steel ball M, 2 mm in diameter are attached above and below the float. These are attracted by a couple of electric magnets D which have been fixed on the opposite sides of the balls. H and I are rotating speed counting sensors of the turbine wheel. I is a photo-interrupter which consists of a light emitter and a light receiver. The light beam passes through radial slits in the rotating circular plate H, and is converted into an electric pulse train which is the signal output.

The pulse train, whose frequency represents the rotating speed of the turbine wheel, is shaped and conveyed to the electronic pulse counter whenever the count number per unit time represent an accurate flow rate. At a very low flow rate, the slow rotation of the turbine wheel produces a very low output pulse frequency and consequently it requires more time for aquisition of the coming impulses. This method is not suitable for practical use as mentioned previously.

At such extremely low flow rate, rotating speed may be one revolution per hour or less. In such a case, we may contrive a non-contact measuring method which does not disturb the normal rotations. A photo-intrrupter and stepping motor are used for this measuring method.

Let us suppose that the light of the photo-interrupter is interrupted by the circular plate H with many radial slits. Since the plate H rotates with the water mill, a slit comes to the place where the light is able to pass through and then an electric pulse signal is produced by I. This signal passes through the slip-ring P, signal processing circuit R and stepping motor processing circuit K successively and then its signal is added to the stepping motor S with a reduction gear. The photo-interrupter I is fitting to the rotational shaft of the stepping motor, so I follows the rotation of the plate H and the light is intercepted by the slit again. This following speed may be 0.05° per one pulse, and thus the light will be once again interrupted. As the plate H is rotating, the slit comes to the place where the light is able to pass through. Such a phenomena will repeat, so that the stepping motor rotates with the plate H. The rotating speed of the turbine wheel therefore, can be estimated from the pulse signal of the stepping motor. This rotating speed ω is defined as

$$\omega = \theta / t_s \qquad (16)$$

where θ is angular displacement per one pulse, and t_s is the time interval between the coming pulses

As the rotating speed of the turbine wheel exceeds a certain limiting speed, $\omega = 0.188$ rad/s, rotation of I will stop automatically and after that the pulse signal caused by rotation of H may be counted by I which is stopped. In this case, rotating speed ω is defined as

$$\omega = 2\pi/nt \tag{17}$$

where n is the number of the slits of H and t is the time interval between pulses. The display of the flow rate has been obtained from a computer processing of the rotating speed ω.

A calibration device for this flow meter is shown in Fig.7.

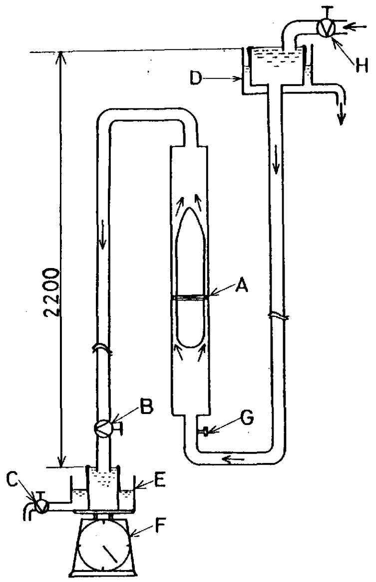


Fig.7 Calibration device

Fluid flow through the flowmeter is regulated by valve B, and the flow rate is estimated by using a spring balance F and a stop watch. In order to give a steady flow, over flow systems are adopted to the water supply tank D and to the flow rate measuring tank E. In this way, accurate flow measurement can be obtained.

The purpose of this flowmeter is to measure Newtonian fluid for example, kerosene, gasoline, alcohol, and water. We, however, used water as the fluid for experiment because it is safe and convenient. The flow characteristics of liquids other than water have been estimated by theoretical analyses. These analyses are treated in the same way as previously mentioned, but the parameter of air has been changed to water. By this analyses, we obtain the relationship between flow rate Q and rotating speed ω and also Q and ω/Q as in Fig.8. In this figure, the solid line,

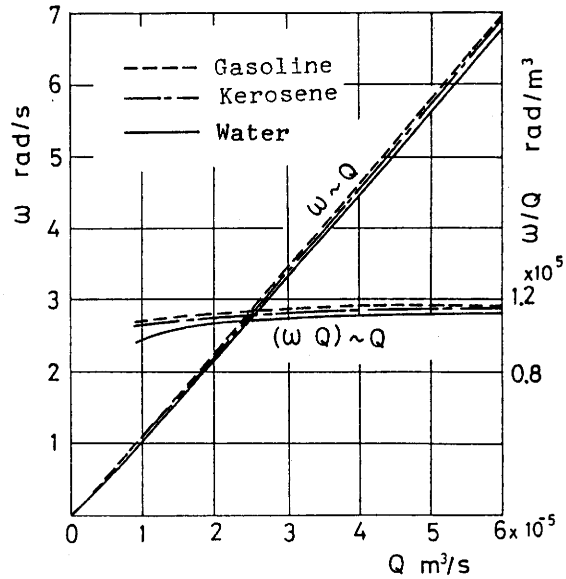


Fig.8 Relationship between Q and ω

chain line, and broken line show the characteristics of water, kerosene, and gasoline respectively. Sensitivity corresponding to gasoline or kerosene is 3 to 9% greater than that of water. The measuring range of this flowmeter is from 0.2 to 200 l/h.

For reference, there are turbine meters which are on the market, for low flow rate measurement, from 2 to 40 l/h, and there are also flowmeters called "Bearingless flowmeters" which are also on the market, able to measure flow rates from 0.78 to 52.8 l/h.

4. Conclusion

Bearingless turbine-type gas flowmeter and liquid flowmeter were investigated and these are applicable in wide range of flow rate measurement, especially with a significant capability of measuring low flow rate. For example, the gas flowmeter is able to measure from 15 to 500 l/min and liquid flowmeter from 0.003 to 3 l/min respectively. The rotating speed of the turbine wheel shows a distinct linear relationship to the flow rates.

References

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(2) M.Danno and others, Trans. of the JSME, 51, 472 (1985), 4188