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MEASUREMENT OF GAS AND LIQUIDS

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Review of Mass Measurement

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1. Introduction

The ability to measure quantities of gas and liquids accurately is very important to the industry. In the case of process measurements, accuracy is the basis for good production optimisation. Its perhaps not obvious that absolute accuracy is necessary in custody transfer measurements, since the errors would tend to average out during the long run. The problem is however that nobody argues when he gets more than he is paying for, so there will be a systematic error in favour of the bayer.

In the case of hydrocarbons the interesting property is normally weight (mass) or energycontent.

This lecture is restricted to mass determination by static or dynamic methods. Of course the time is too short to cover all available methods. Emphasis is put on the necessity to determine the density accurately, because one can see many mass determination systems where tremendous effort is put into deteurmining the volume, where as the density measurement is not very accurate.

2. Density

As already stated in the introduction, determination of any measurable quantity is a combination of measuring it with a suitable measuring equipment and the calibration of this measuring equipment itself. The calibration is a comparison with higher accuracy equipment preferably traceable to international standard units i.e. meter, kg a.s.o.

In the case of density there is no standard unit. Density is defined as mass per unit volume and the only way to determine true density is by measuring mass and volume of a sample of the gas or liquid in question.

Since we are interested in the density only as a means of determining the mass, there is an absolute need for measuring the density at the same conditions as the volume.

In practice this is not always possible and one has to compromise by measuring at other than normal operating conditions and establish the density by calculation.

2.1 Areometer

The use of an areometer is shown in fig. 1. The method is suitable for liquids under atmospheric conditions. The principle is that the mass of the displaced liquid is the same as the total mass of the areometer. The areometer mass is known and the scale is really an inverse volume scale. The volume of the areometer has to be temperature compensated.

2.2 Displacement density meter

Fig. 2 shows a density meter working with a fully immersed body. The buoyancy (weight of displaced fluid) of this body is measured by an automatic measuring system. This meter can be used on line both for liquids and gases. Its mainly used on atmospheric gas. On high pressure gas

application the mass of the immersed body tend to be to large compared with the buoyancy.

2.3 Gravimetric

Fig. 3 shows a density meter where a length of pipe is weighed. The fluid, liquid or high pressure gas, flows through the pipe at normal operating conditions. After temperature and pressure compensation the pipe volume is known and the density can be calculated at operating conditions.

2.4 Vibrating tube/cylinder

Fig. 4 shows an example of the most widely used principle for on line measurement of high pressure gas density. The measuring element consists of a cylinder vibrating at its resonant frequency in vacuum. If the cylinder is surrounded by gas, the gas will also vibrate and the total vibrating mass is changed. This cause the vibration frequency to change and the frequency can therefore be used as a measure of gas density.

Exactly the same principle applies to the vibrating tube used for liquids, shown in fig. 5.

2.5 Calibration

All the densitometers mentioned above have to be calibrated against gases or liquids of know densities. Most of the densitometers are also influenced by other properties than the density alone, often in a way that is not very well predictable. This means that the densitometers should be calibrated under the same conditions as normal operating conditons.

In the case of hydrocarbons this is often almost impossible. Hydrocarbons consists of a nearly infinite number of

components in different combinations, which is practically impossible to simulate in a calibration laboratory.

The normal procedure is to calibrate with some well known "standard" gas like nitrogen or pure methane.

The PT ρ relations for nitrogen and pure methane are well established so it is easy to calibrate a densitometer against one of these gases at different pressures and temperatures. The temperature can be held at the normal operating temperature and the pressure effect on the densitometer is normally small.

With other hydrocarbons however, the only way of accurately determining the density is to go back to the basis of mass and volume. Of course, it is impractical to do this for all combinations of hydrocarbon mixtures. The practical solution is to make a set of experiments and interpolate mathematically for other compositions.

So far the world database for these relations is not extensive enough to give very accurate prediction of the density of a given mixture. Different organisations are using equations giving different results by as much as 1 or 2% for a given composition.

For a given installation where the accuracy is important, for inst. in the North Sea it would be worthwhile calibrating the densitometers with the actual process gas in the laboratory using the basic method of mass and volume. For high pressure gas this can be done with an accuracy of a few tenths of a percent by weighing a "bomb" filled with gas. Fig. 6.

Up till now the normal procedure has been to use either the nitrogen calibration curve directly, the methane curve directly or a calibration curve based on calculated compensation for gas properties. The use of one or the other method is really based on belief or disbelief in the validity of the compensation.

In this type of compensation the characterizing property of the gas is taken to be speed of sound in the gas at operating conditions. The reason is that changing the speed of sound changes the coupling between the cylinder and the gas.

Fig. 7 shows a typical curve for this type of compensation. The shape of the curve is totally dependent on the design of the densitometer. That means that every new design has to go through an extensive calibration program to establish the curve.

2.6 Pressure and temperature compensation

Where the composition of the gas mixture is known to be nearly constant, pressure and temperature compensation is often used instead of densitometers. The validity of the results depends on the accuracy of the base density of the mixture and the accuracy of the Z-factor, the gas compressibility. If the base density is calculated rather than measured the results will also depend on the analyser accuracy.

As said earlier the world data base for the calculation of density and Z-factor is not very well established. Fig. 8 shows typical differences between different sources of ethylene data.

3. Volume determination

The volume can be determined by static or dynamic methods. In theory the static method is the easiest and also the most accurate. In practice the dynamic method is the most accurate, when the necessary calibration are done correctly.

Fig. 9 shows a tank filled with liquid. The volume of the liquid is determined by the tank dimensions and the level. The dimensions of the tank is influenced by the temperature of the tank wall, nearly the same as the temperature of the liquid along the wall, and also by the static pressure of the liquid. In theory, therefore, one must know the pressure and temperature at any point on the tank wall, and also any sinking of the bottom due to liquid pressure. Again in practice one have to go for a compromise and just make a few temperature measurements in the liquid.

The pressure influence is normally calculated when the tank volume is determined and the calibration tables are worked out based on the pressure exerted by the liquid normally stored in the tank and based on a reference temperature. For atmospheric tanks the pressure correction is normally too small to be accounted for if the density of the liquid changes slightly.

On the other hand the temperature correction is very important. The tank itself changes dimensions and the density of the liquid changes with temperature. The mass is the volume x density, both measured at the same conditions. Normally the tank volume table is referred to a standard temperature (0° C, 15° C, 20° C), and the density of a sample of the liquid is also referred to a standard temperature. Since the tank and liquid have different coefficients of expansion, both volume and density have to be calculated at operating conditions.

The level of the liquid is normally measured by a tape, manually or automatically. The reference point is in practice the roof of the tank or the top of a standpipe fixed near the bottom of the tank. The position of this reference point is influenced by both the liquid temperature and the vapour phase temperature, which could be quite different especially on cooled tanks. The length of the tape itself is influenced by the vapour temperature.

Fig. 10 shows a typical temperature profile along the vertical center axis of a spherical tank filled with liquified gas. It is obvious that a large number of temperature measurements are necessary to determine this profile under conditions of varying level:

With the temperature profile established, quite extensive mathematics is necessary to establish the volume of the sphere, the corrected level measurement and the average densities of the liquid and gas phase (horizontal temperature gradients are not taken into account).

Fig. 11 shows a method where the level and density measurement are combined. The differential pressure between top and bottom of the tank represents the mass per unit area and the only other parameter required is the tank area. For a true cylindrical tank only the average temperature is required to establish the average area.

For spherical tanks both temperature profile and level are required to calculate average volume and density based on the differential pressure method.

3.1 Ships tanks

Additional problems with ships tanks are caused by the peculiar shapes necessary to contain the tanks efficiently in the ships hull. It is also necessary to compensate for trim and list variations, the ships vertical axis deviation from vertical position due to uneven loading.

4. Calibration of tanks

4.1 Strapping

Calibration of tanks is normally done by measuring the dimensions of the tanks with a tape and calculate the volume at a reference pressure and temperature. This method

is used both on spherical and cylindrical tanks and even on ships tanks of different shapes.

4.2 Volume comparison

Small tanks are calibrated by direct comparison with other tanks of known volume. By using small calibration tanks and measuring the level after each filling, the volume table can be established as a function of level.

4.3 Photogrammetric

Large tanks and in particular caverns can be calibrated by photogrammetric methods. The method is basically the same as used when making land maps from air photos. The position of a large number of points on the wall are determined by stereo photo method and the volume is calculated by interpolation. This method is practicable even on rough blasted rock surfaces.

4.4 Master meter

Tank volume tables can also be established by filling or emptying the tank through a master meter. This method also requires accurate level and temperature measurements.

4.5 Level calibration

The reference of the tank level measurement is normally at the bottom end of the stand pipe. This reference position is measured when the tank itself is calibrated.

This reference is used only during manual dipping or calibration of the automatic level gange. The practical reference for the automatic level ganger is the top of the stand pipe where it is mounted. For accurate measurements this position should be temperaturecompensated.

5. Volume determination by meters

The most common meters for both liquid and gas are the turbines and the positive displacement meter.

The only meter that measures true volumetric is the positive displacement (pd-) meter. Fig. 13. This meter passes a certain volume of liquid or gas per revolution. The actual volume is affected by temperature and pressure of the meter itself. There are also corrections to be made due to leakages in or out of the defined volumes, but the basic principle is a true volumetric measurement.

A typical calibration curve is shown in fig. 14. The pd-meter is sensitive to particles passing through and it can easily get stuck, thereby blocking the line completely. Large diameter pd-meters are very heavy and expensive, especially high pressure versions.

All other meters measure flow velocity in one way or other. The turbine is already mentioned. For accurate measurements of large quantities of liquids it is almost exclusively used. It is a lot less mechanically complicated than the positive displacement meter and the repeatability is approximately the same, in the order of 0.01% for a good meter within its normal operating range.

This repeatability is referred to constant conditions in terms of flow velocity and liquid properties, especially the viscosity.

Under conditions of varying viscosity the calibration factor can vary with a few percent. These variations are theoretically predictable, and manufacturers normally supply "typical" curves showing the viscosity dependence. However, machining tolerances are so critical that two meters never give identical curves, and thus every meter needs calibration.

Fig. 15 shows "typical" curves supplied by a manufacturer and fig. 16 shows actual curves for one of the meters from the same manufacturer.

One of the biggest advantages of both positive displacement meters and turbine meters is the digital output. The number of pulses are a direct representation of the number of revolutions of the meter, and there is no need for a transducer that is inevitably introducing additional errors in the metering system.

The pulse output is also well suited for the digital electronics supplied to do the necessary calculations of mass flow.

6. Calibration of meters for liquids

6.1 Master meter

The easiest method of calibration is to run the meter against a master meter. As said before there are a few factors affecting the calibration making it necessary to consider the calibration conditions very carefully. Ideally the master meter should have been calibrated under exactly the same conditions as the meter to be calibrated. This is of course impracticable, especially if the master meter is going to be used under a lot of various conditions. Since the primary factor affecting the liquid meter, is the viscosity, the normal procedure is to calibrate the master meter with different liquids covering the range of viscosities.

6.2 Tank

Calibration against a calibrated tank is the most common method for small meters. The volume of the tank should be at least equal to the meter throughput in one minute to make sure that the errors caused by standing start/stop are small. With this method the meter can be calibrated under normal running conditions.

Larger meters can be calibrated off-line by the same method. The reason for off-line calibration is that it is not practical to move big calibration tanks around to the meter installation.

Fig. 17 shows a calibration laboratory at Norsk Hydro in Porsgrunn, intended for off-line calibration at a throughput of up to 1000 m³/h.

6.3 Mechanical displacement provers

Large meters are calibrated against moving piston/ball meter provers. A typical ball prover is shown in fig. 18. The volume between detectors 1 and 2 is determined to an accuracy of $\pm 0.5\%$ or better. The volume of the pipe should as a minimum represent 10.000 pulses from the meter under test, 1:200 of the hourly flow rate, and the velocity of the ball should not exceed 3 m/s.

These requirements lead to large size provers. Typical figures for a prover for 8" turbines are 20" diameter and a length of 30 m between the detectors.

By this method the meter is calibrated under normal operating conditions and where the accuracy is very important i.e. in the North Sea the provers are installed permanently so that the meters can be calibrated at arbitrary short intervals.

The pressure and temperature control of the system is just as important as when calibrating against a tank, only in this case it is much easier. With the prover lagged the total length of the calibrated volume have a constant temperature equal to the liquid temperature.

Typical repeatability of the ball prover is in the order of 0.01%. The calibration of the prover itself is done by the water draw method. The prover is filled with water

and when the ball is passing detector 1 the water is routed to a calibration tank until the ball is passing detector 2. The water in the tank is measured by volumetric or gravimetric methods.

The piston prover works by the same principle as the ball prover, but the use of a piston requires the proving pipe to be one straight length.

A very short piston prover is shown in fig. 19. This prover does not comply with the requirement that the volume is 1:200 of the hourly flow rate or that the number of pulses are minimum 10000. This is compensated by the fact that detection of the position of the piston is accurate enough to facilitate splitting of the pulses from the meter. Fig. 20 shows the principle. Over the calibration period both the total travel time and the travel time for a whole number of pulses is measured. Then the number of pulses corresponding to the calibrated volume, are calculated to an accuracy of a few decimals.

A typical size of this prover for an 8" turbine is 18" diameter and 2 m length of the cylinder.

Calibration of the prover is done by the same method as with a ball prover.

The most critical part of this prover is the sealing of the piston and the valve inside the piston.

7. Gas metering

7.1 Orifice plate

The most widely used meter for large gas quantities is the orifice plate/differential pressure transducer. The main reason for using the orifice plate is that there is no absolute need for calibration. Laboratory calibration shows that the meter factor can be calculated based solely

on measurement of mechanical dimensions and knowledge of the physical properties of the gas.

One of the problems is, however, that different standards give different results. Also even the latest ISO-standard (ISO 5167-80) issued in 1980, differs as much as 0.4% from some recent laboratory results. The standard itself gives a tolerance of $\pm 0.6 - 0.8\%$ under specified conditions. The requirements include very long straight lengths of pipe, up to 88 pipe diameters, and eccentricity of orifice installation less than 0.1 - 0.2% of the pipe diameter. The last requirement is almost impossible to fulfill in practice. Outside the limit an additional uncertainty of $\pm 0.3\%$ applies.

The quadratic relationship between flowrate and differential pressure gives a range of only 1:3 for each d/p-transducer, so that for larger ranges 2 or more transducers in parallel are required. On the other hand, since the massflow is proportional to the square root of the density, a 1% error in the density determination will give only 1/2% error in the massflow.

The calibration factor of an orifice plate is very sensitive to wear, deposits or deformation. It is also worth mentioning that most of the factors affecting the calibration, tend to give low readings.

It is necessary to inspect the orifice plate at frequent intervals. If the pressure cannot be taken off the line for this inspection, an orifice fitting similar to the one shown in fig. 21 is used. With this type of installations it is of course difficult to make sure the eccentricity specification is fulfilled.

7.2 Calibration

Even though one of the prime advantages of the orifice measurement is the ability to calculate the calibration factor, it is quite common to calibrate the orifice installed in its straight length of pipe. In this way one can avoid any errors due to inaccuracy of the standard, machining tolerances or mechanical installation.

Such calibration is dependent on very accurate knowledge of the properties of the calibration gas, especially if the comparison is referred to a volumetric measurement, since in the orifice calculation one needs the gas density.

The problem is reduced when calibrating against a sonic nozzle. Fig. 22. The mass flowing through the sonic nozzle, is mainly proportional to the square root of the gas density, as is the case with the orifice plate, and the square root of the inlet pressure.

The main advantages of the sonic nozzle is that there is no need for a differential pressure measurement and that it is by far less sensitive to mechanical wear than the orifice. Main disadvantages is the pressure loss of 10 - 20% of line pressure.

7.3 Gas turbine meters

A typical custody transfer gas turbine meter is shown in fig. 23. Typical calibration curves for atmospheric air and high pressure gas (in this case 8 bar natural gas), is shown in fig. 24. The repeatability is in the same order as for the liquid turbine, $\pm 0.01\%$. As can be seen from these curves the linear range is approximately 1:20 on high pressure gas.

The calibration shift from 8 bar to 60 bar is very small. Since we are in the same situation as with the liquid turbine, that the machining tolerances are very critical every single turbine has to be calibrated.

7.4 Calibration

Gas turbine meters are sensitive to gas density rather than viscosity. Therefore if the turbine cannot be calibrated under normal operating condition, the gas density should be as near normal as possible.

The only practical way of calibrating a large turbine meter is comparison with a master meter or a sonic nozzle.

Fig. 23 shows in principle the stepwise procedure used to calibrate a master meter at 60 bar referred to an atmospheric bell prover. In this procedure it is essential to know the PTZ-relations for the calibration gas. Ideally the gas should be the same as the process gas under normal operating conditions.

Gas meters are also calibrated with water, but this should be regarded more as a function check than a real calibration.

7.5 Positive displacement meter

The Pd-meter is extensively used for small gas quantities especially at or near atmospheric pressure. This reflects the fact that the meter is very accurate, but that meters for large quantities and/or high pressure are very heavy and expensive.

Repeatability figures are in the same order as for the turbine meter.

8. Vortex meter

Over the last few years there have been quite a development of the Vortex meter, fig. 25. The meter consists of a straight pipe with a bluff body generating vortices in the liquid or gas. The frequency of the vortex shedding is proportional to flow velocity.

Because of the mechanical simplicity of the meter the calibration factor can be calculated, based on dimension measurements. In the same way as with the orifice plate the Reynolds number is the characterizing fluid property. Therefore the vortex meter can be calibrated with water even if it is going to be used for gas metering. Depending on fluid properties the turndown ratio could be from 1:5 to 1:100.

Rounding of the corners of the bluff body is less critical than rounding of the inlet of an orifice bore. The bluff body is also normally very robust.

Pressure loss is about the same or less than for an orifice.

There are a lot of different ways of detecting the vortices like mechanical deflection of the bluff body, pressure transducers, termistors and ultrasound. Irrespective of detector principle the pulses generated are not exactly regular. This causes a problem during calibration because a large number of pulses are required to average out the irregularities.

9. Ultrasonic flow meter

An ultrasonic flow meter is shown in fig. 25. An ultrasound pulse is transmitted through the fluid at an angle to the pipe centerline. The difference in time required to cross the pipe in both directions is a direct measure of the flow velocity. It represents the average flow velocity along the path of the ultrasound pulse. This means that the flow profile must be known for the average flow velocity over the whole pipe area to be calculated.

At the sophistication level of today's electronics, the limiting factors on the accuracy is mainly related to the mechanical part of the meter. The accuracy of installation of the pulse transmitters and receivers are very critical, especially on multipass meters. These meters are intended to calculate the flow profile based on measurements along 2, 3 or 4 ultrasound paths.

The best results are of course obtained when the meter have been calibrated. The long term stability is very good since there is virtually no possibilities for mechanical changes affecting the accuracy, except, corrosion or deposits.

The ultrasonic flow meter represents no pressure loss whereas most of the other meters could require 100 kW in a large metering station.

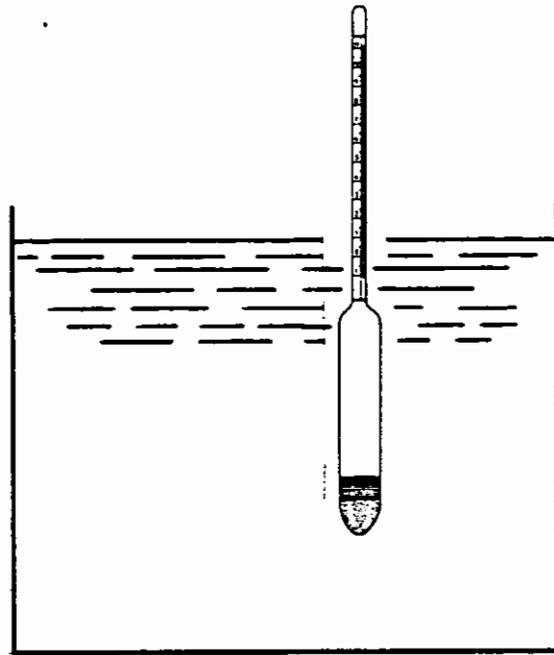


Fig. 1 Areometer

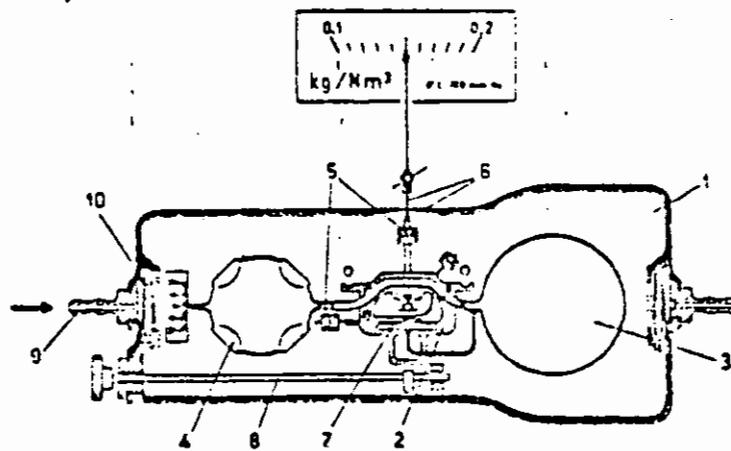


Fig. 2 Density meter for atmosphere gas

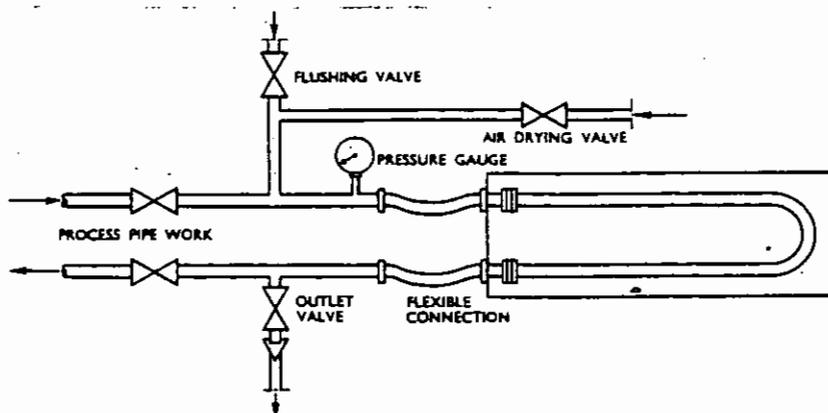


Fig 3 Gravitrol

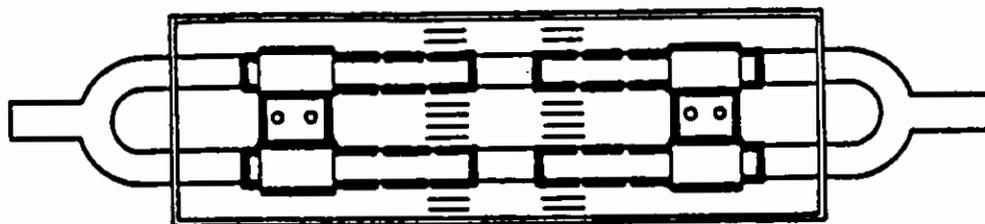


Fig.5 Vibrating tube densitometer

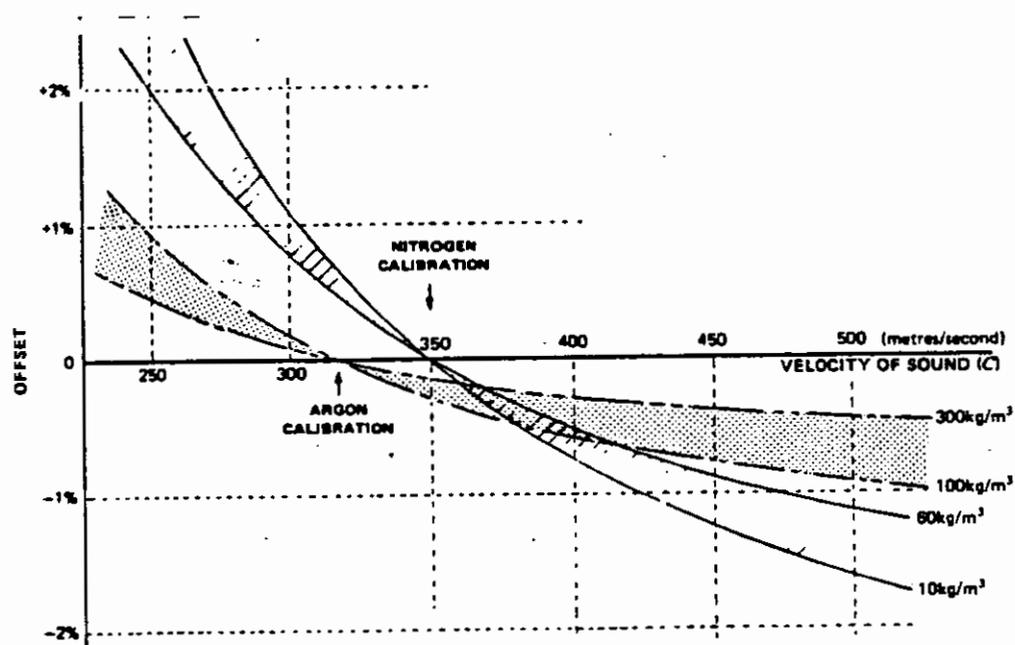


Fig. 7 Velocity of sound corrections

1 T °C	2 P bar abs	4 (ρ/ρ_n)ARG	5 (ρ/ρ_n)K-372	6 (ρ/ρ_n)K-372 (ρ/ρ_n)ARG
7.400	19.870	22.321	22.080	.98920
9.500	19.810	21.965	21.529	.98015
10.500	20.550	22.819	22.541	.98782
13.900	20.570	22.399	22.212	.99165
14.400	20.560	22.232	22.123	.99104
36.800	20.530	19.890	19.899	1.0005

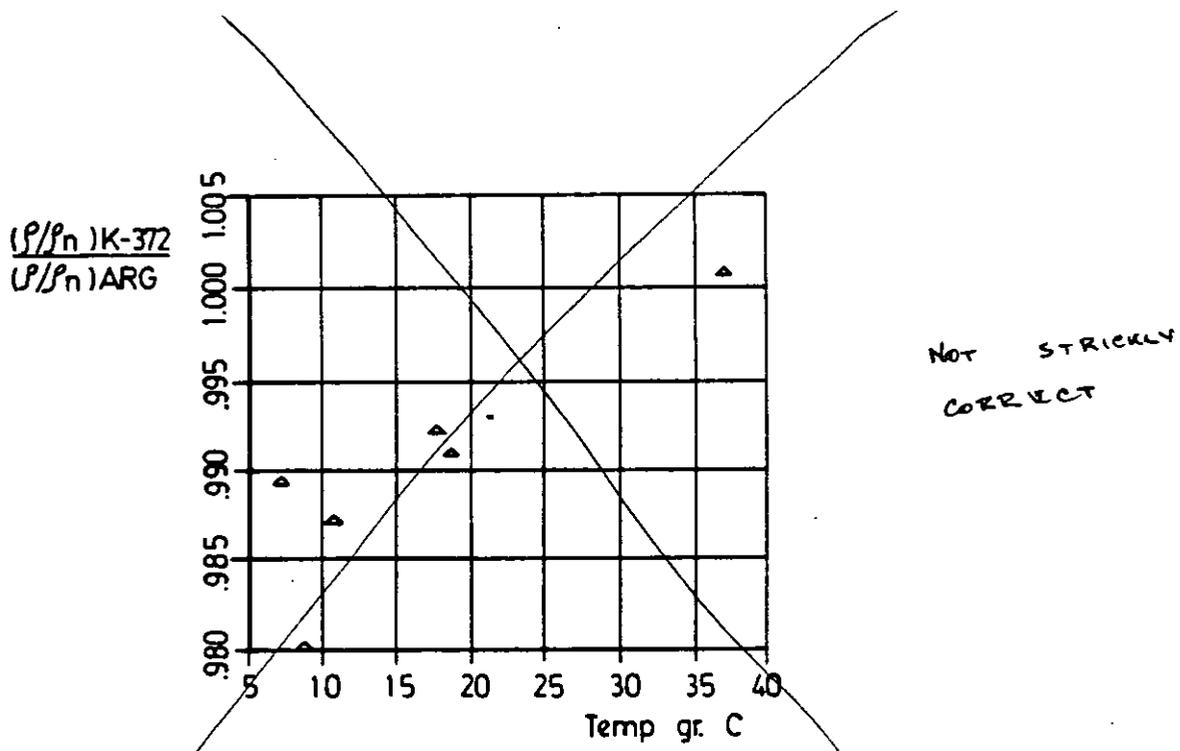


Fig. 8 Differences in ethylene data

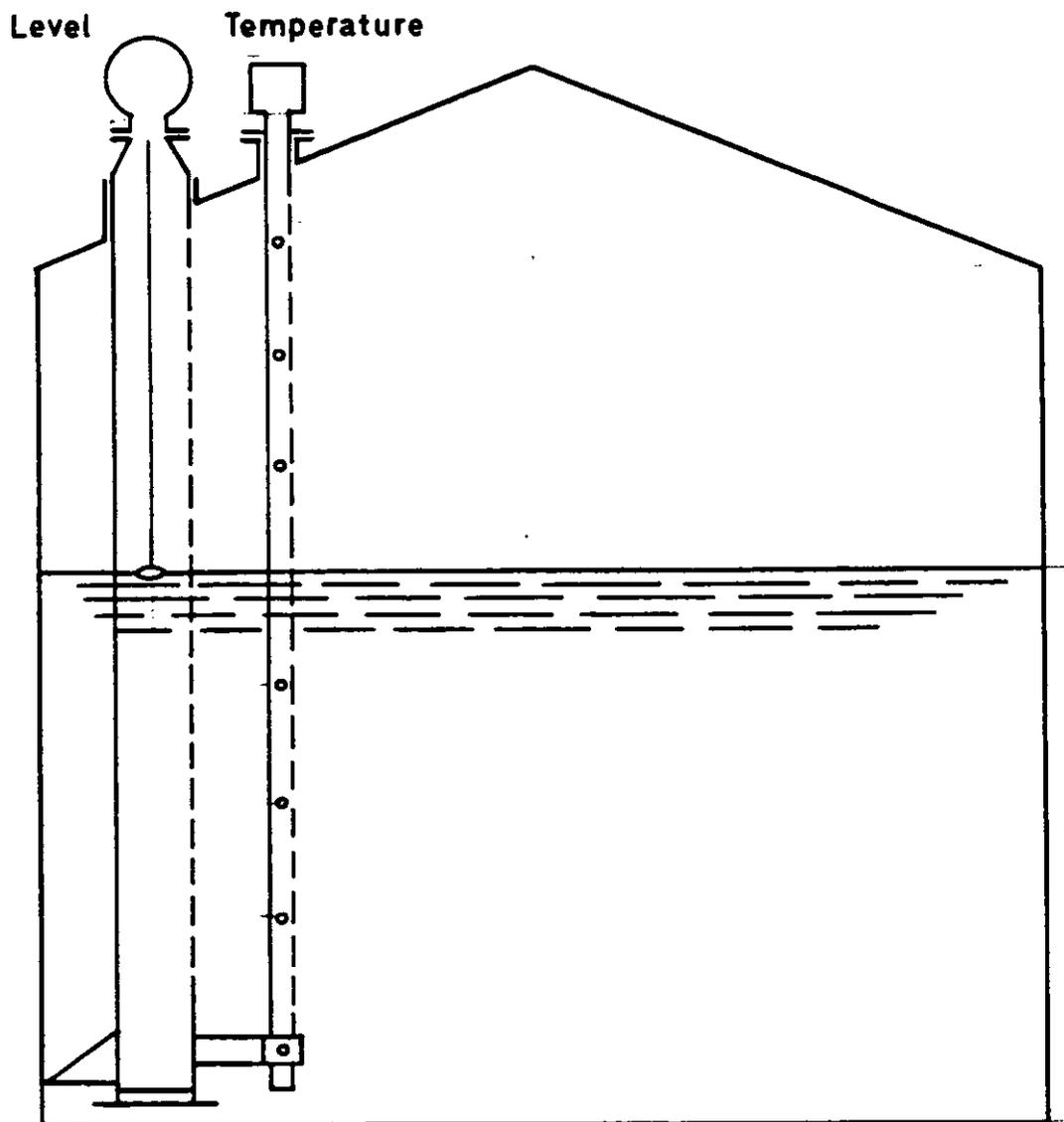


Fig.9 Atmospheric tank for liquids

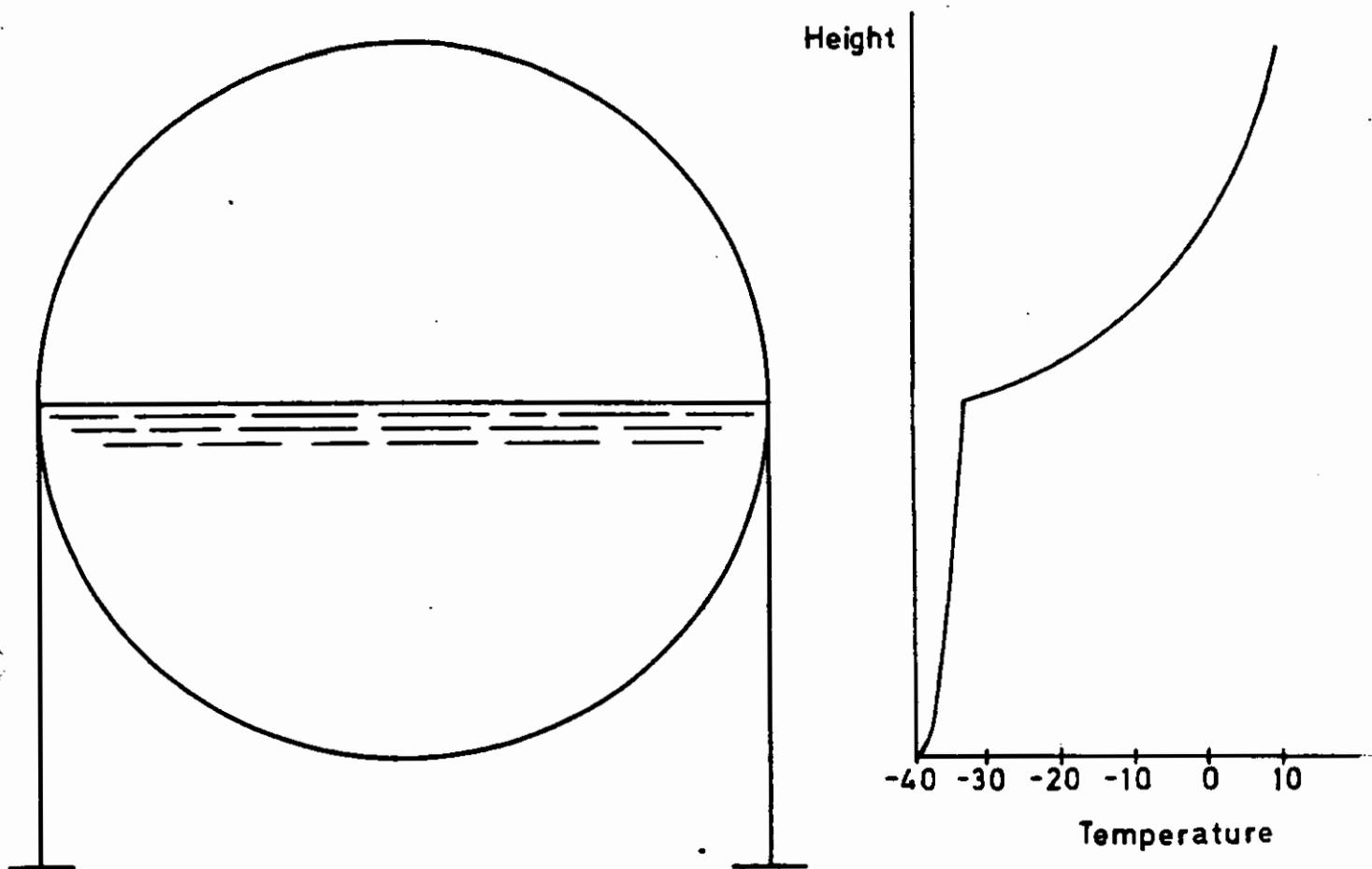


Fig.10 Temperature profile in cryogenic sphere tank

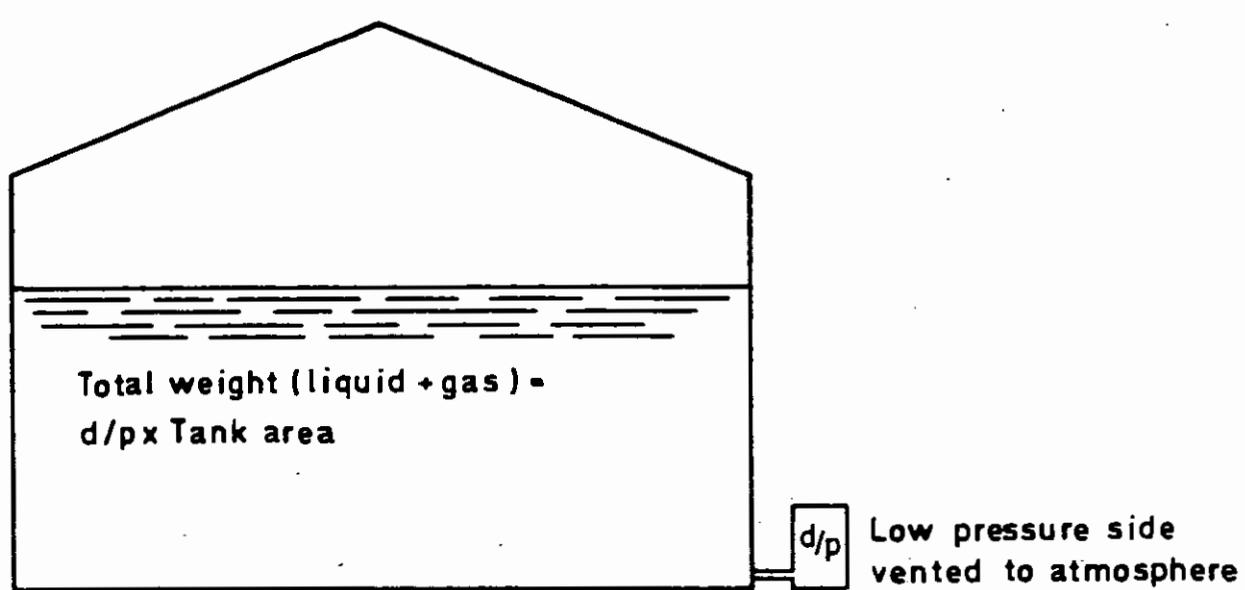
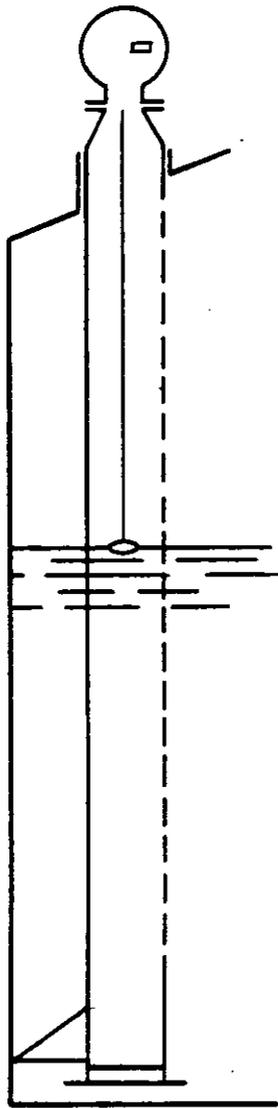
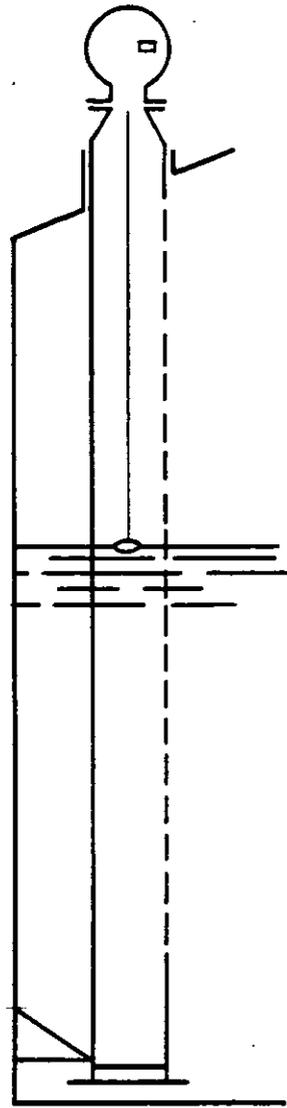


Fig.11 Mass determination by tank bottom pressure measurement



Right



Wrong

Fig.12 Installation of level gauge

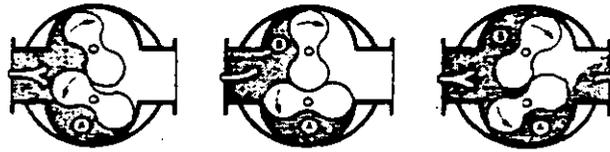
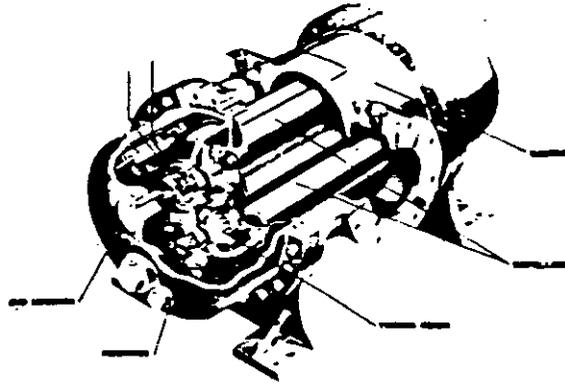


Fig. 13 Positive displacement meter

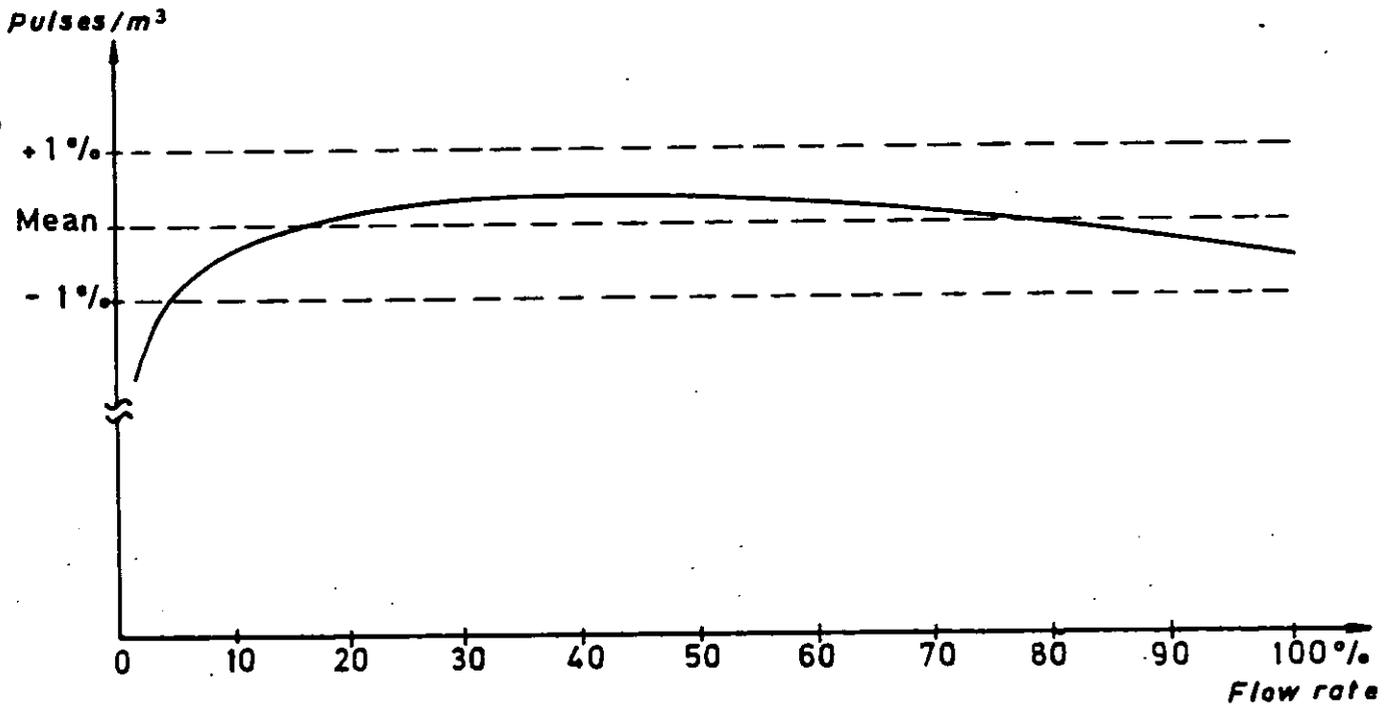
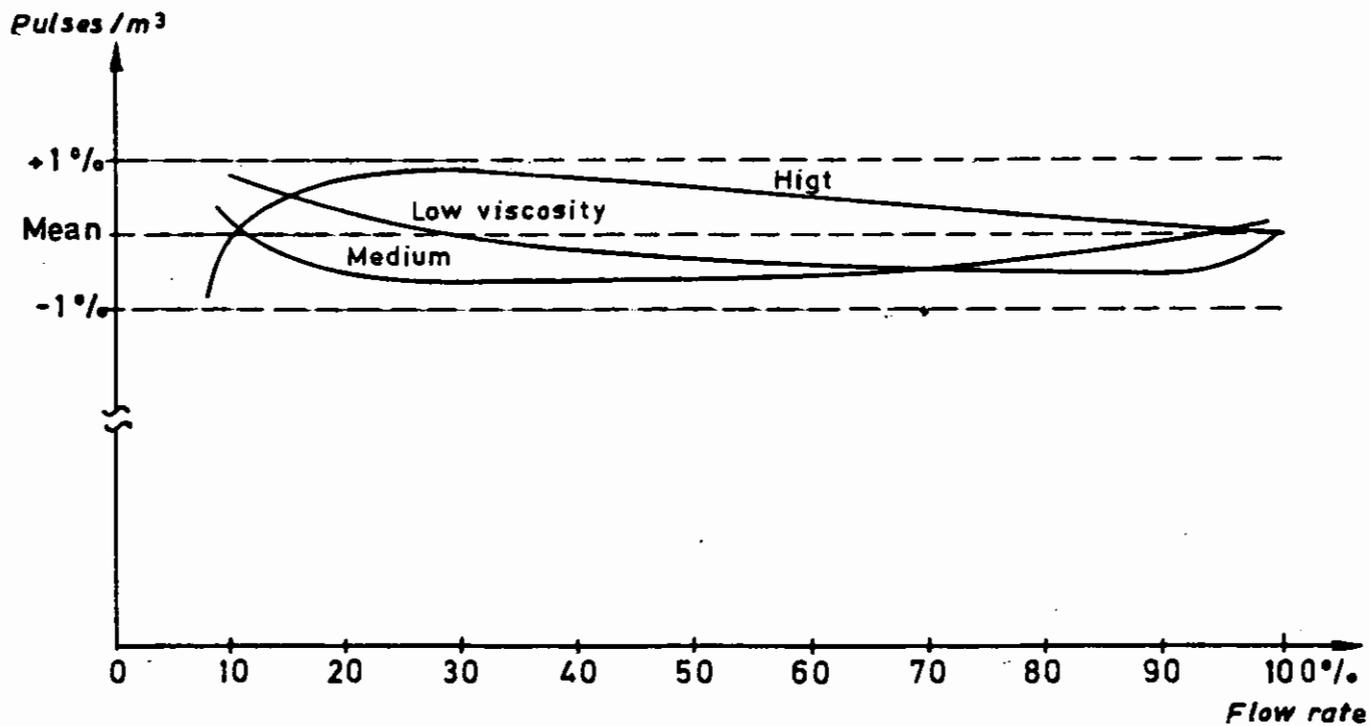
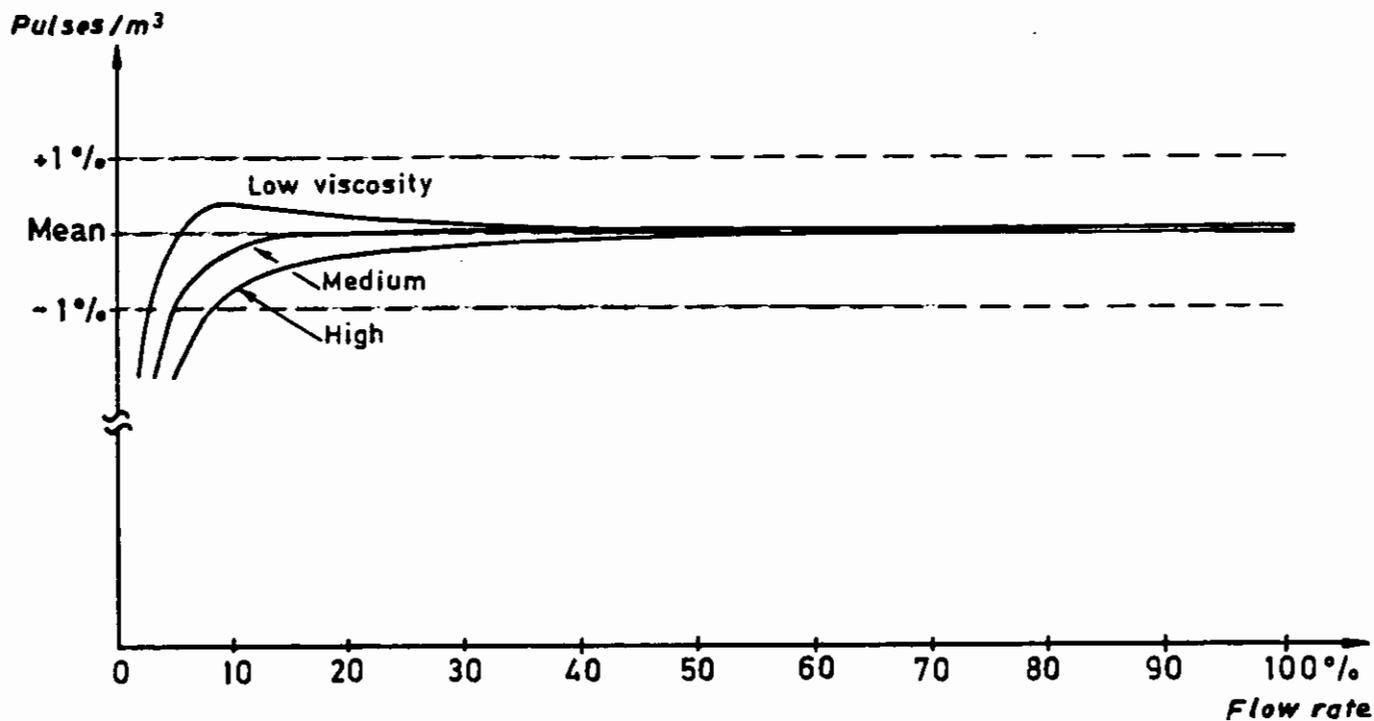


Fig. 14 Calibration curve for Pd - meter



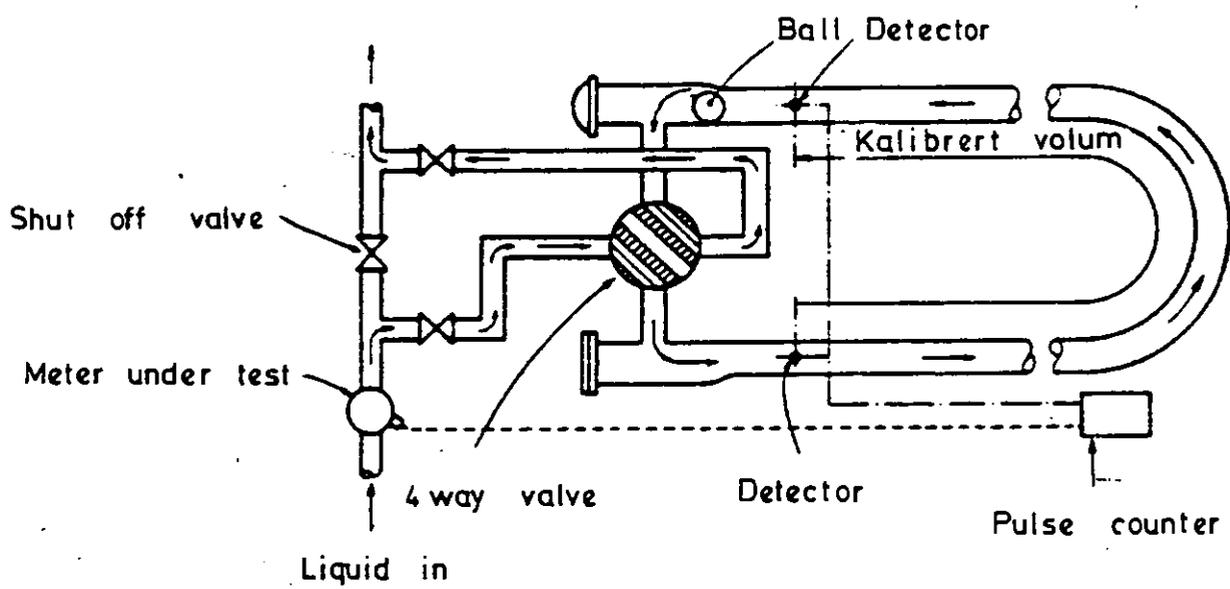


Fig. 18 Mechanical displacement prover

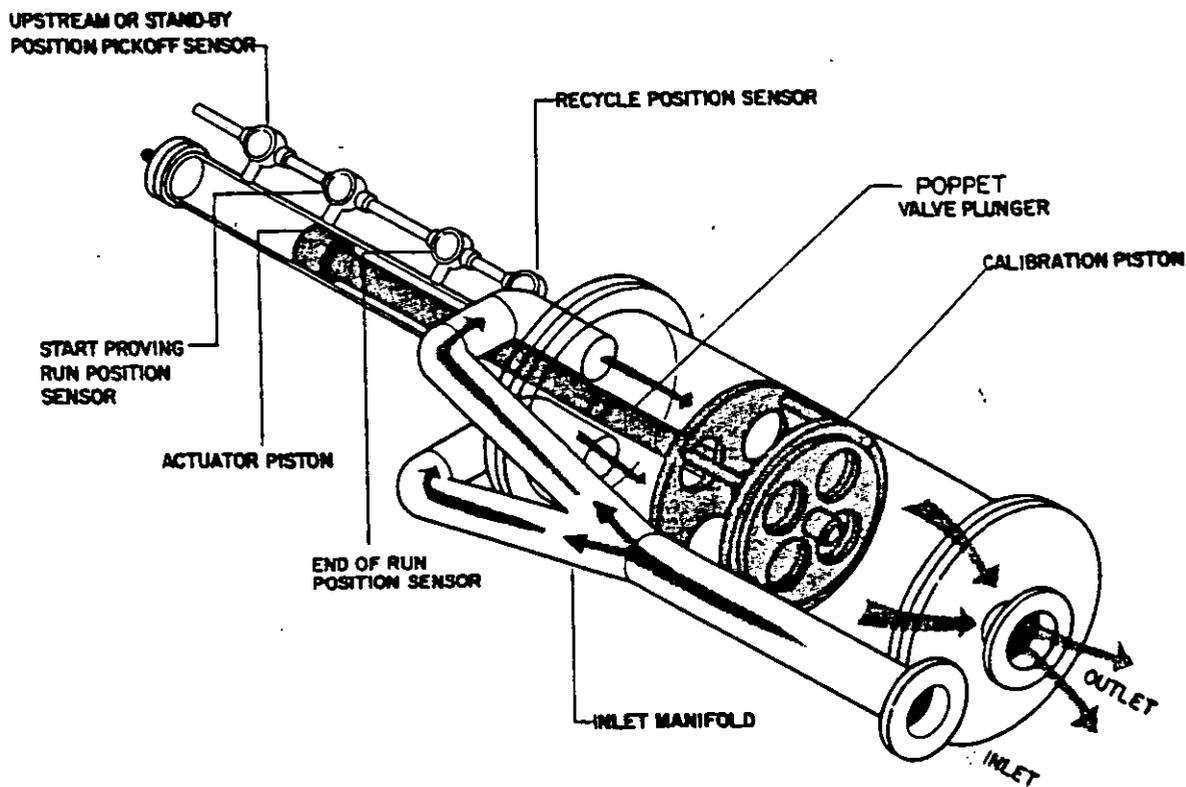
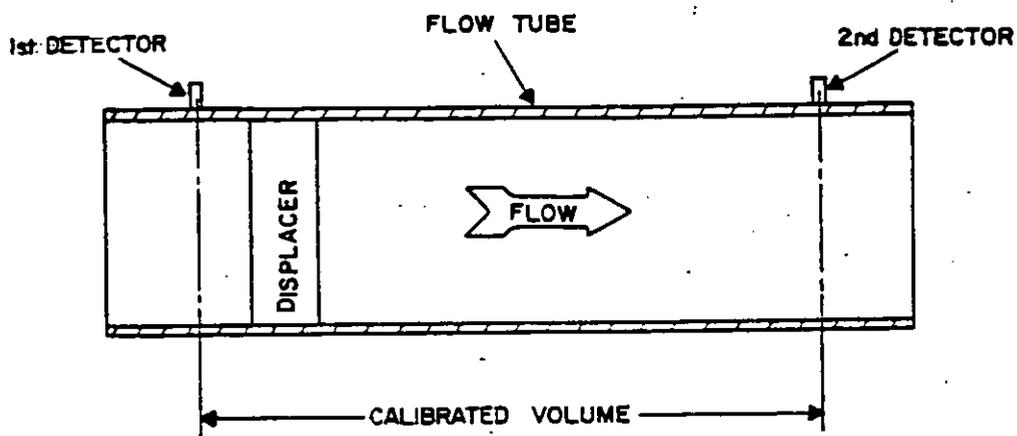


Fig. 19 INLINE BALLISTIC FLOW PROVER



SIMPLIFIED PROVER DIAGRAM

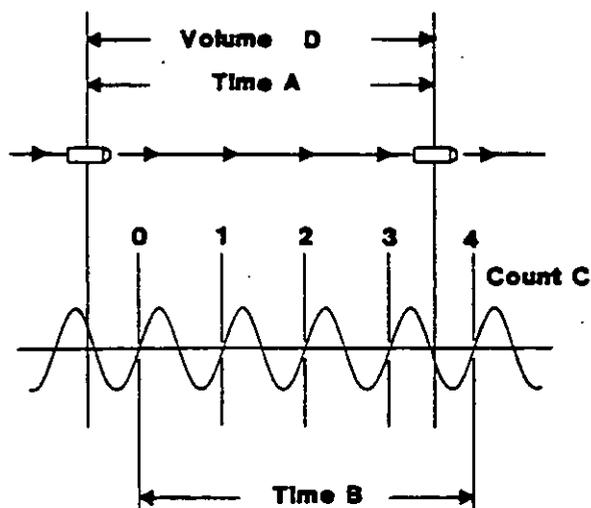


Fig. 20 Pulse splitting

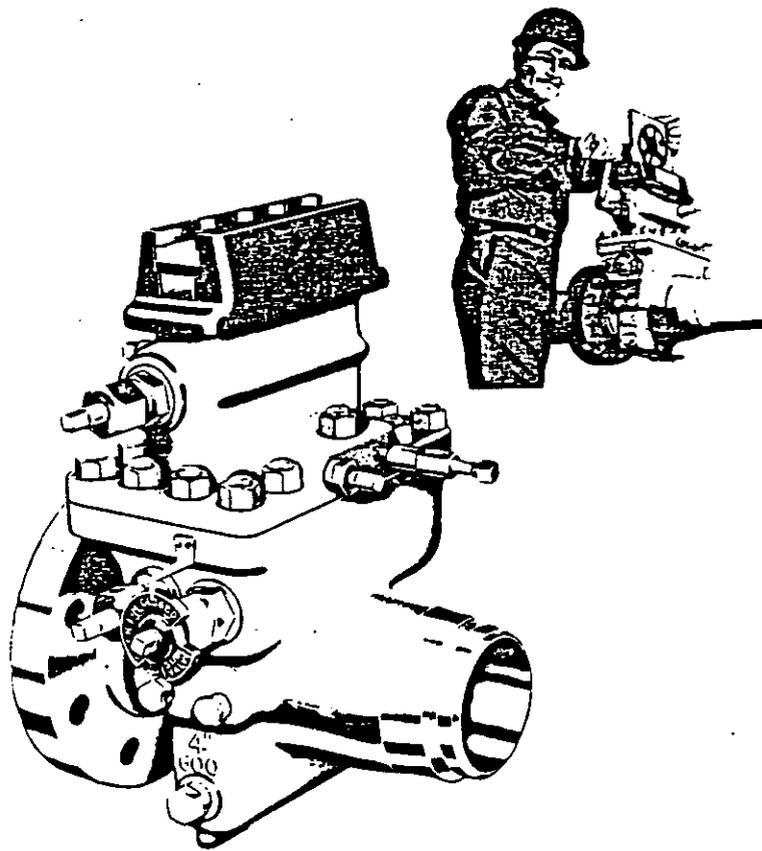
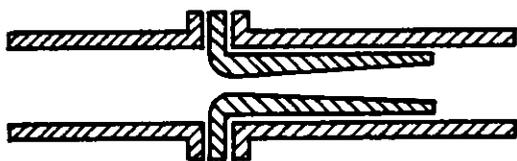


Fig. 21 Orifice inspection with line pressurized.



Sonic nozzle

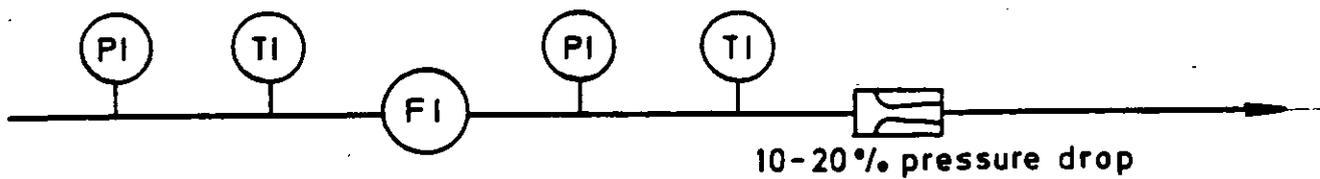


Fig. 22 Calibration against sonic nozzle

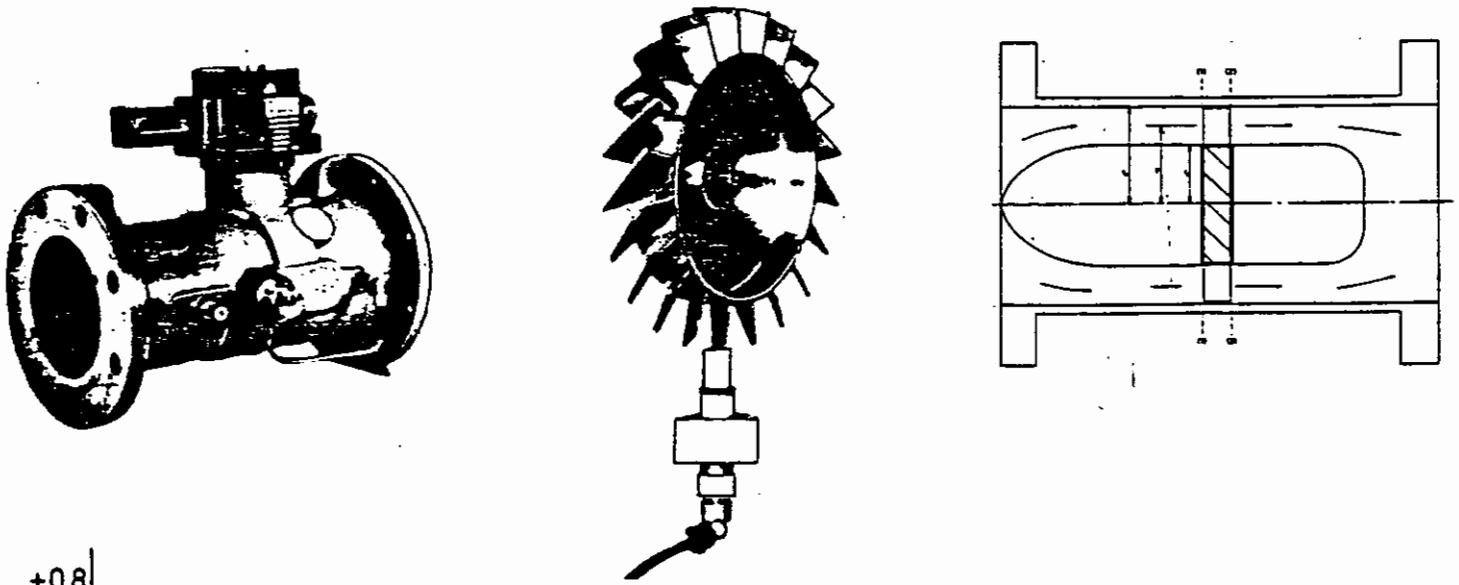


Fig.23 Gas turbine meter.

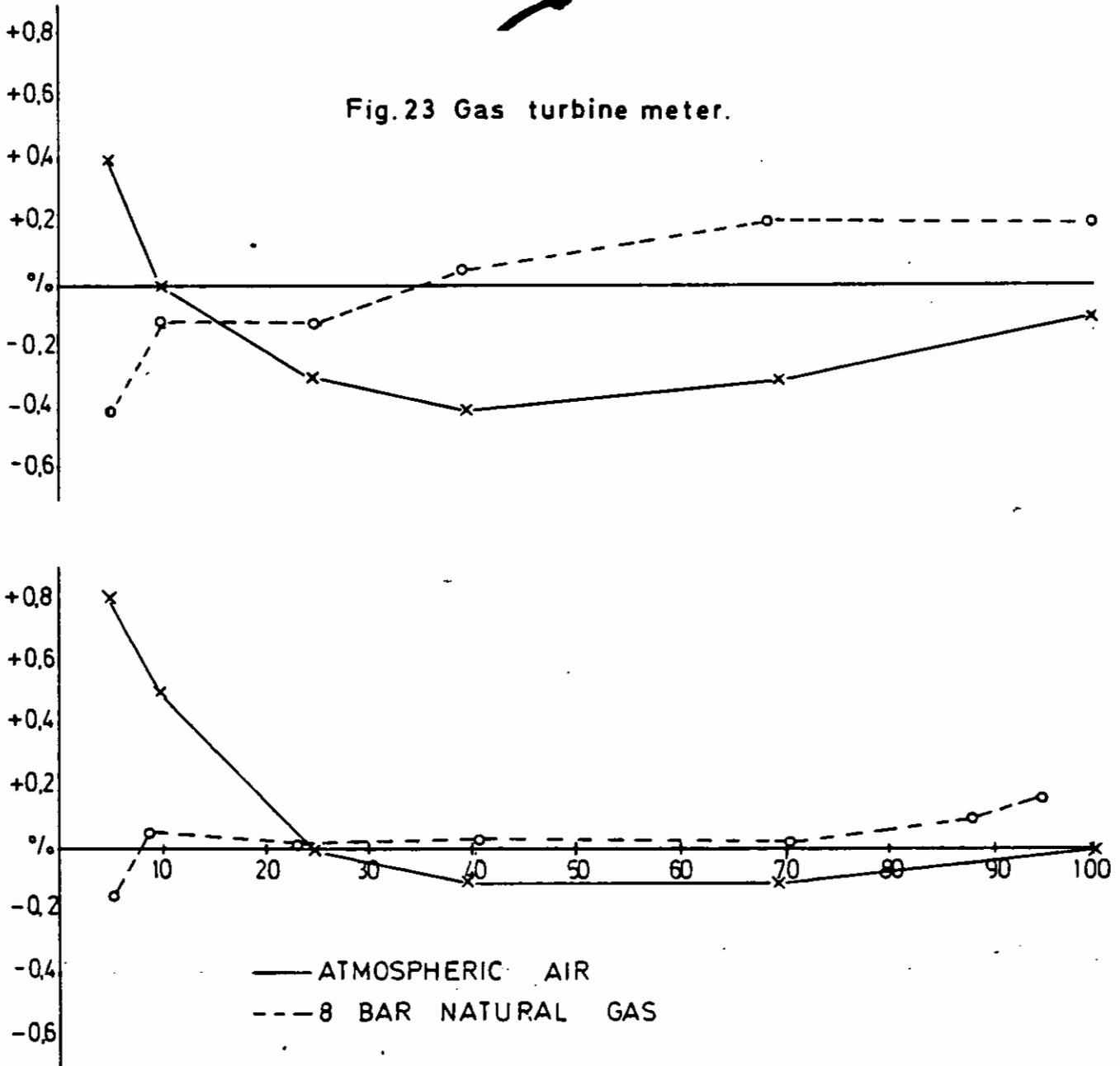


Fig. 24 Calibration curves for two identical meters.

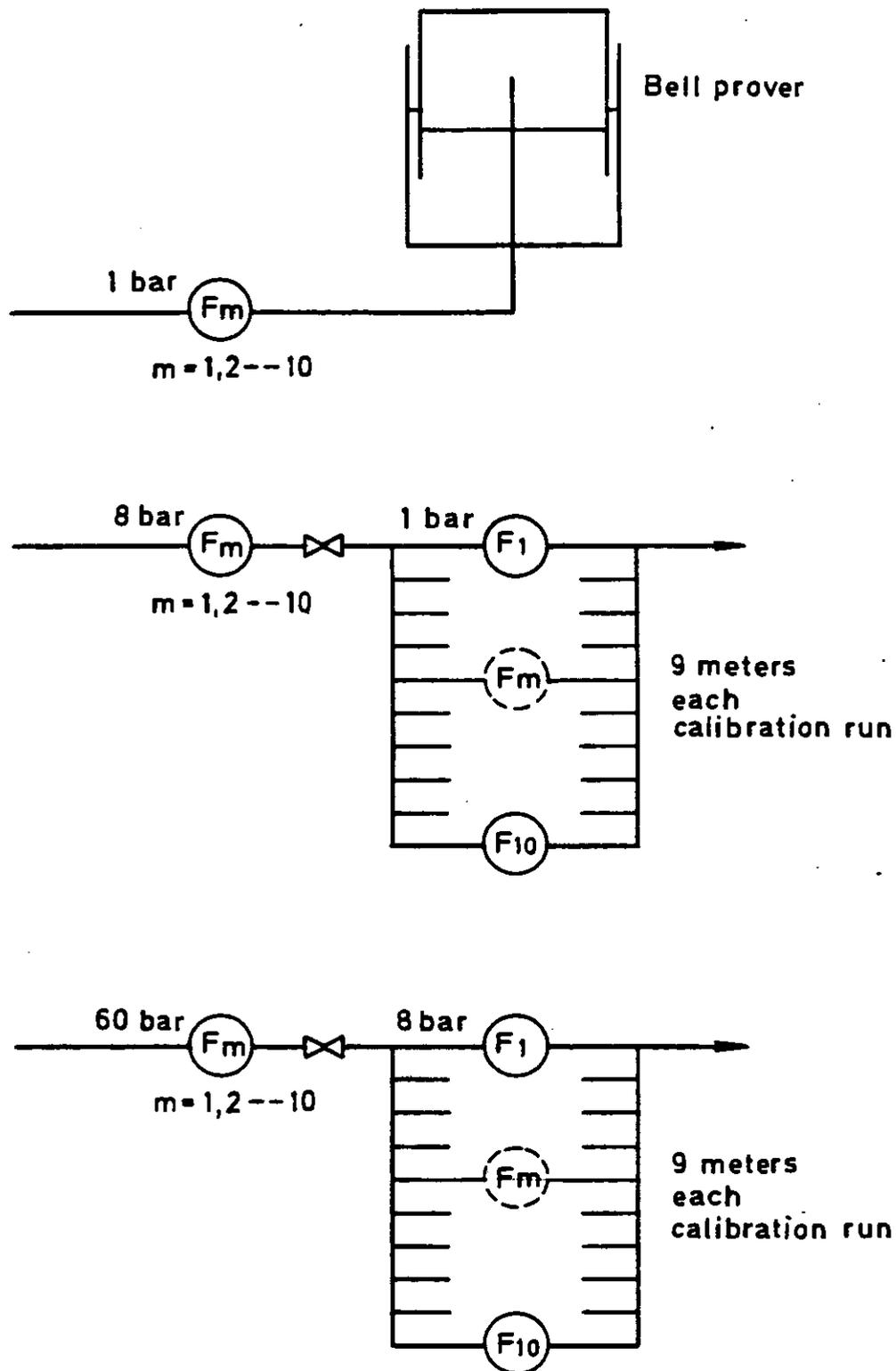


Fig.25 Stepwise calibration of high pressure turbine meter

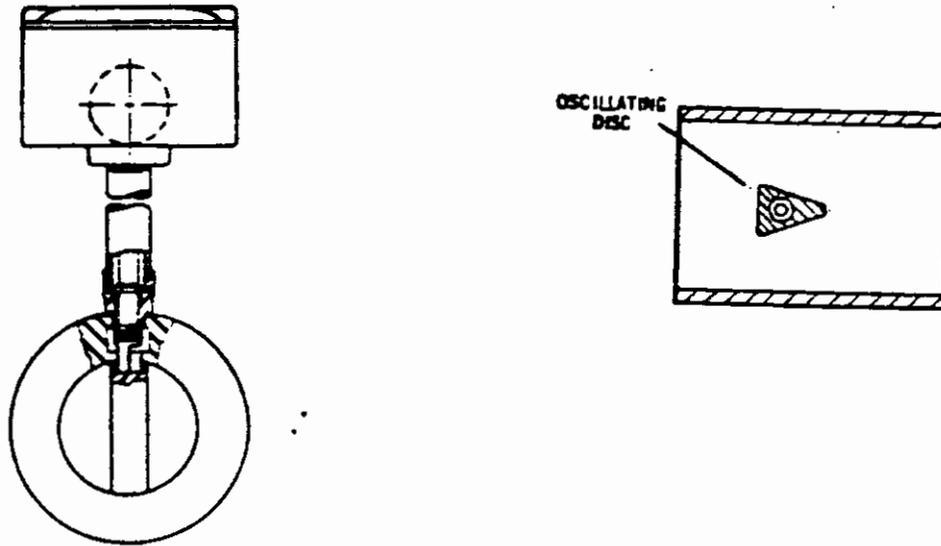


Fig. 26 Vortex meter

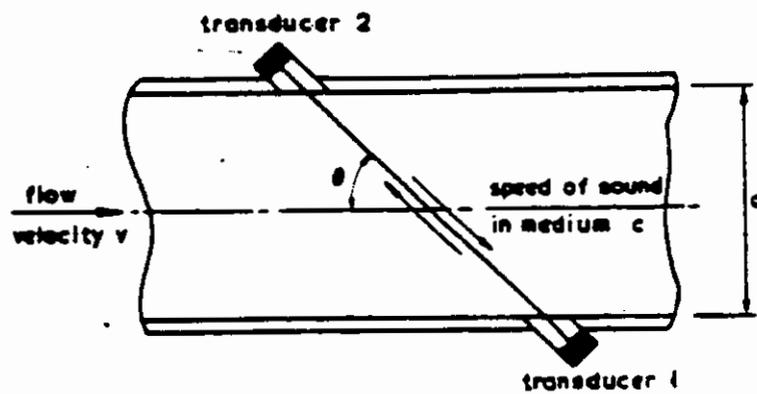


Fig. 27 Diagonal-beam
Ultrasonic Flow Meter

References

[1] Paper presented at the North Sea Flow Measurement Workshop, a workshop arranged by NFOGM & TUV-NEL

Note that this reference was not part of the original paper, but has been added subsequently to make the paper searchable in Google Scholar.