MEASUREMENT OF PRESSURE AND FLOW USING THERMOELECTRIC EFFECT

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(Measurement and Instrumentation)

By:
R. SOMAVARMA

DEPARTMENT OF ELECTRICAL ENGINEERING
UNIVERSITY OF ROORKEE
ROORKEE U.P. (INDIA)

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CERTIFICATE

Certified that the dissertation entitled 'MEASUREMENT OF PRESSURE AND FLOW USING THERMOELECTRIC EFFECT' which is being submitted by Sri R. Somavarma in partial fulfilment for the award of the Degree of Master of Engineering in Electrical Engineering (Measurement and Instrumentation) of the University of Roorkee, Roorkee, is a record of bonafide work carried out by him under my supervision and guidance. The matter embodied in this dissertation has not been submitted for the award of any other Degree or Diploma.

This is further to certify that he has worked for a period of 5½ months from February 1977 to July 1977 for preparing this dissertation at this University.

Dated : July 11, 1977

H.K. Verma
Reader,
Deptt. of Elect. Engg.,
University of Roorkee,
Roorkee (U.P.)
-247672.

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ABSTRACT

A class of materials bearing the generic name thermoelectric components exhibit a particular property when exposed to temperature effect such as development of a potential difference, a change in resistance with positive or negative temperature coefficient of resistance. These devices exhibiting thermoelectric effect, find wide applications in the measurement of temperature, temperature or difference in temperature dependent physical variables.

This dissertation deals with the applications of the thermoelectric effect for the measurement of physical variables such as pressure and flow of fluids, especially liquids, and particularly water, by applying the thermoelectric components

or devices. These devices include thermocouples and thermoresistors. Thermocouples are almost exclusively applied to measurement of temperature and very low pressures whereas thermoresistors find much wider application.

Thermocouples measure the temperature of a heated body, which is supplied with a constant energy and placed in an envelope containing a gas, which is related to the pressure of gas as a function of its thermal conductivity. In using a thermoresistor as a pressure sensing device, the heating and temperature measuring element can be combined into one single element.

For measuring flow which in effect meas: measurement of velocity, a heated body such as a metallic wire or a thermistor is placed in the path of the flowing fluid. This carries away a part of the heat, consequently the temperature of the heated body falls, which changes its resistance and hence the current flowing through it or the potential difference across it. One of these variables is calibrated in terms of velocity of flow by using some other device as a venturi meter, roto meter or measuring volume of fluid collected in a measuring tank in a given time.

Measurement of flow using thermoresistors are dealt with in considerable detail. Before going into this various conventional and not so conventional flow measuring techniques and pressure measurement are surveyed with their significant features and operating characteristics. Thermoresistors are usually used in a bridge circuit the output of which is intrinsically non linear. Among thermoresistors metal resistors are linear over a limited range whereas semiconducting thermoresistors or thermistors are non linear. The chief characteristics of these devices and their methodology of application are presented. The techniques of linearising thermistors and measuring circuit outputs using thermoresistors as sensing devices are presented. These include reducing nonlinearity through choice of values of components of a bridge circuit, compensating nonlinearity through another nonlinear function generated using diodes or transistors or converting the thermal parameters into frequency or time and using multivibrator bridge circuits.

Finally thermistor as a flow measuring element are evaluated and some of the important considerations are brought out. Two types of probes that could be used with a particular ty of thermistor are delat with. Desirable limitation of the device and characteristics, such as small size and time constant are given. In case of thermistor, it is necessary to encapsulate the bead with glass or ceramic to prevent oxidation. The power required, and the relation of the thermistor size including encapsulation and heat transfer in a typical case are worked out.

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1. INTRODUCTION

The present era is known for its technological and scientific advancement. Science discovers the laws of nature and how they operate in complex systems, whereas engineering is the application of these discoveries of science to make the world a better place for man to live and survive.

The current achievements in space exploration the landing of man on moon, the remote exploration of the moon's surface by automatic stations and other marvels of space have been made possible because of accurate, reliable and reproducible measurement and instrumentation . Lord Kelvin's

1. INTRODUCTION

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The current achievements in space exploration the landing of man on moon, the remote exploration of the moon's surface by automatic stations and other marvels of space have been made possible because of accurate, reliable and reproducible measurement and instrumentation . Lord Kelvin's warning[1] that ‘knowledge not expressible in numbers was of meager and unsatisfactory kind’ is as relevent to day as when it was made, more so since science is displacing blind beleif through enlightened knowledge made possible by the ever more accurate and newer kinds of instruments probing into the secrets of jealous nature.

Measurement and instrumentation are playing increasingly important role in our technological society and has enabled man to excercise greater control over his environment. For his well being, may be through the field of physical sciences or life sciences he is becoming increasingly dependent on measurement and instrumentation which makes possible automation, mechanisation and remote control. This becomes simpler and more convenient when the physical variables are convertable to variable electrical parameter as voltage, current, resistance, inductance or capacitance.

Nearly two third of the earth's surface is covered by water. Still one hears of shortage of drinking water or that fit for irrigation and such other purposes. That is the contradiction - in the midst of plenty there is scarcity and this is true of many other requirements of human society. This calls for study to control and distribute these commodities in an equitable manner economically, which calls in turn for accurate measurements, instrumentation and control.

Distribution entails transportation and as for as fluids are concerned with which this dissertation deals with and in particular liquids - water, interesting phenomenon are encountered, such as the kind of flow, i.e. whether the flow is pressure flow as in pipes or free surface flow as in rivers and canals, type of flow, single phase or multiphase flow and so on. Each situation calls for particular techniques of measurement and instrumentation suitable to meet the particular functional demands.

Correspondingly there exists a wide variety of conventional fluid flow meter meant for industrial, and domestic (water or gas) fluids. These range from the simple vane type of meter, to turbine type flow meter, vortex and swirl meter, the electromagnetic and ultrasonic flow meter, progressively more complex and meeting strictor specifications and special flow conditions.

Like wise to measure fluid pressure there exists a wide variety of conventional devices as the bourdon tube, bellows pressure gauge, etc. belonging to the elastic pressure transducers class, the weight gauges, manometer and the servo manometers, resistance, inductance and capacitance and piezo-electric pressure transducers force, balance devices etc., varying in complexity accuracy and reliability, for high pressure (usually above atmosphere); and thermal conductivity and ionisation gauges, for low absolute (or below atmospheric) pressures upto 10^{-8} torr.

In research as distinct from industry or demestic metering, measurement and instrumentation techniques to study and develop various facilities and make way for scientific and technological advancement of man specialised devices become necessary. In the case of fluid f flow measurement these include the thermal techniques of hot wire and hot film anemometry, and such other heated sensors as metal film or foil sensors, for measurement of very low velocities and at low Reynolds numbers of the laminar type, to high velocity large Reynolds number turbulant and or multiphase flows. The latest to arrive on the field is the Laser doppler veloci-meter[2] to aid turbulance measurement in gas or liquid. The hot wire anemometer has primarily been applied to measurement of velocities and velocity fluctuation in air.

Even here the hot wire anemometer has its disadvantage. The wire is easily liable to break or burn out and frequent replacement is a cumbersome and time consuming job. This led to the search for a solid state thermo sensitive eleme element and the thermistor with its large temperature coefficient of resistance could have been an alternative, but its time constant is too large for the purpose. It could sense average velocities and slow varying velocity fluctuation.

For low velocity and pressure measurements the thermistor has been successfully applied[3]. The quantity of flow of gases in the range of 0.2 to 20 lph and fluids to range of 0.004 to 0.4 lph have been measured using thermistors.

Thermistors, with the 'solid state' back ground is not easily liable to be burnt out, and forms an ideal replacement for the hot wire if its time constant could be reduced appreciably. Further its flow range has to be extended.

Low pressures below 10 torr could be measured using thermal conductivity and in this thermistors have found application in the range of 10^{-6} - 1 torr, whereas thermocouple is limited to 10^{-4} torr and metal resistors as in Pirani gauge to 10^{-5} torr.

In what follows a survey of conventional flow meter low pressure measuring devices, thermistor, its characteristics and applications to liquid flow measurement are presented.

Considerable attention is however devoted to measurement of flow and use of thermoresistors as sensor and an attempt is made to extend the range of particularly of thermistor as flow sensing element and to linearise the output characteristics using a thermistor probe for sensing velocity of flow.

From the simple deflecting vane type to the more complicated turbine flow meters, electromagnetic, ultrasonic vortex and swirlmeter for measuring rate of flow, to differential pressure meters such as pitot tubes, orifice plates, volume rate of flow meters, positive displacement meters of different types and tracer techniques besides techniques of pressure measurement and some of the defices for the purpose find place in chapter two. From hereon attention is concentrated mainly on thermoresistive devices as thermocoupl find little applications in measurement of flow of liquids or its pressure excepting for measurement of gas pressure below atmospheric. Further in conventional techniques, flow and pressure are inter related whereas thermal meters because of their small size does not appreciably affect flow conditions or system pressure and as such flow measurement is independent of the fluid pressure in case of incompressible fluids such as is being considered. Thus pressure measurement is also not cited any further

In chapter three thermoelectric sensors are described with mention being made of metal resistors, thermistors, diodes and transistors for temperature and temperature difference measurements. Various methodology of circuit and their application to fluid flow measurement are considered and a comparison of these is made.

In chapter four techniques of linearisation of thermistor and output circuit through piecewise linearisation, function generation and parameter conversion such as to frequency and time, multivibrator bridges and their characteristics are dealt with.

In the last but one chapter thermistor as a flow meter element is examined and some of the considerations in its application for this purpose presented. A flowmeter based on thermistor as a sensor has been developed. Its principle of operation, construction of the probe, measuring and output circuits are described. For linearisation of the meter response a novel diode function generator is introduced. Results of the tests conducted in the laboratory are also presented.

In the last chapter, conclusions on this dissertation, including the development of the flow meter and suggestions for further work in this field are brought out.

Some of the terms and definitions pertaining to the topic under discussion, and design considerations are presented in the appendices A1, A2, and A3 respectively.

2. FLOW AND PRESSURE MEASUREMENT TECHNIQUES.

2.1 INTRODUCTION :

Be it from the point of view of revenue, regulation or fair distribution, accurate and reliable method of measurement of a commodity that is under consideration becomes necessary if not essential. This becomes all the more pronounced in the case of liquids and gases of mass consumption with limited supply, whether it pertains to industry or community or individuals, and has been engaging the attention of engineers ever since men organised themselves into groups or communities to face the task of survival.

Commensurate with the various requirements of time and cause, devices were developed and continues so even today. The techniques used depend upon the quantity involved, the accuracy demanded, economics and other specifications as materials, quality and ambient conditions. Many methods and techniques of fluid flow measurement have been evolved, depending on whether it is gravity or free surface flow, pipe flow or pressure flow and, whether the fluid is compressible or non compressible besides flow conditions. Similarly methods or techniques for the measurement of pressure have been evolved depending on whether the pressure being measured is absolute or gauge pressure and the order of magnitude of these pressure . The term fluid encompasses both liquids and gases.

In the following pages various techniques used in general for fluid flow and pressure measurement are discussed with emphasis on liquid flow measurement.

2.2 CLASSES OF FLOW MEASUREMENT :

Flow measurement can be classified[5] broadly into two categories, namely :

(a) rate of flow measurement, and

(b) quantity of flow measurement

Rate of flow indicates, the rate at which the fluid passes a given section or point in its path per unit time.

Quantity of flow indicates the quantity of fluid flowing past a section or point in its path in a given duration of time.

Both the rate and quantity may be specified either in volume units or mass units and correspondingly they are termed as volume or mass flow rate and volume or mass flow respectively.

Usually the rate of flow is monitored and it is time integrated to obtain the quantity or total flow.

2.3 RATE OF FLOW METERS :

2.3.1 Deflecting vane meter

In this method a pivoted vane is placed in the path of the fluid (fig.2.1). The weight of the vane being constant, it attains a position of equilibrium depending upon the resultant force between that due to the rate of change of momentum of the liquid, which itself is a function of velocity, the weight of the vane and the reaction at the pivot. A pointer displaying the deflection is suitably linked to the vane. This device is suitable for measurement of flow of liquids and gases. It can be used to detect leakage flow in water/ gas supply systems, wherein its sensitivity to low flow rate could be advantageously used.

2.3.2 Rotating vane meter

A number of vanes arranged around the circumference of a disc or attached radially to a pivoted spindle (fig.2.2) with at least one vane in the flow stream at any time, will produce a continuous rotation. The rate of this rotation will be a measure of the velocity of the liquid through the meter. The head loss in the meter is small and it can be sensitive to flow in either direction or one direction only. This type of movement is used in case of metering domestic and industrial water supplies of small order upto about 20 m^3/h.

The spindle can be made to drive a counter, tachometer or gear train.

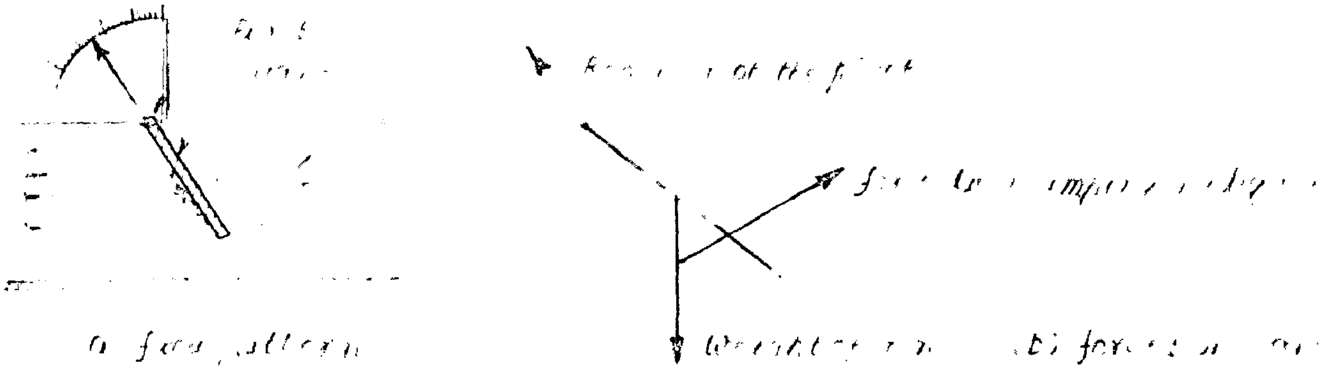


Fig. 2.1 Deflecting vane meter

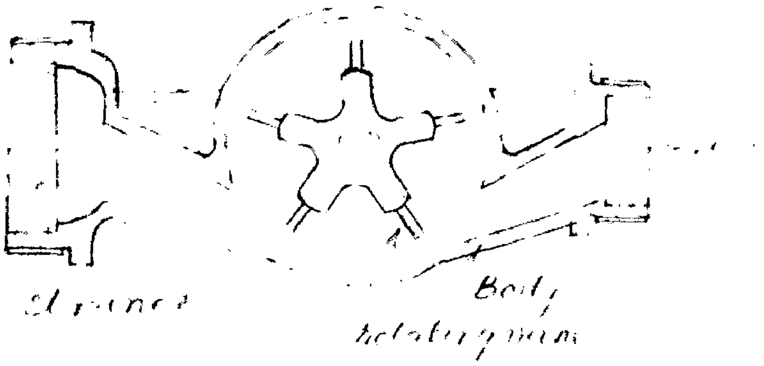


Fig. 2.2. Rotating vane meter

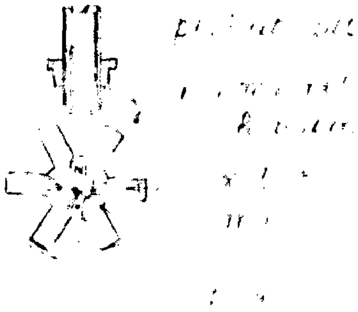
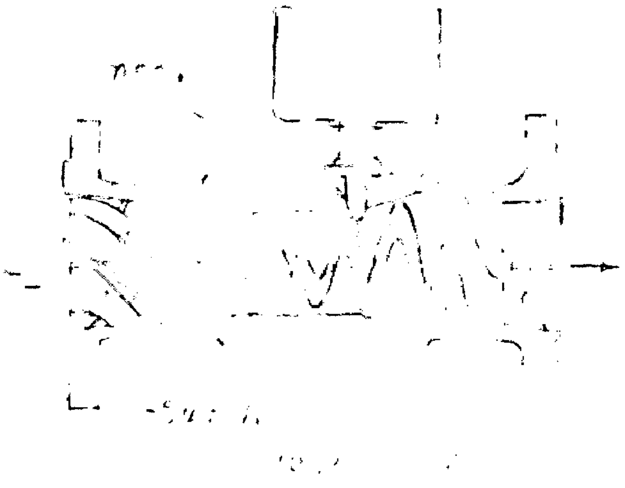


Fig. 2.3. Turbine [illegible]



[illegible] 2.4 [illegible]

F[illegible] 2.5 [illegible] meter

2.3.3 Helical vane meter

In order to measure larger quantities of liquid flow say in the range of 17 to 200 m^3/h, the rotating vane is replaced by a helical vane mounted with its axis along the axis of flow. The liquid is directed to the vanes uniformly by means of guides.

Magnetic coupling is usually employed between the under gear and the meter register. This meter is made in 40 to 150 mm size.

2.3.4 Combination meter

When the flow fluctuates widely a combination meter consisting of a large meter (helical, fan or other type) in the main, with a small rotary meter in the by pass is used. The flow is directed into the main or by pass by an automatic valve, with the main meter registering the large flows and the small meter registering the small flows, depending on the opening of the valve which responds to the minimum .limit set for the main meter. Many variations of this type of meter are available depending on the way in which the reading of the meter is arranged and housing.

2.3.5. Turbine flow meter

In this type of meter (fig.2.3) a friction free rotor is mounted along the axis of the meter tube. The rotor is designed such that its rate of rotation is proportional to the rate of flow[6] of fluid through the meter. The rotor speed is monitored by (a) a pick up coil in which a voltage is induced due to a magnet housed in the rotor or, (b) varying the reluctance of a magnetic circuit or, (c) the rotor blade rotation modulating a radio frequency circuit of which the coil forms a part.

This type of meter is made in sizes of 5 mm to 500 mm, with the smallest having a linear range of flow of 0.109 to 0.341 m^3/h and the largest having the range 654 to 6540 m^3/h.

2.3.6 Propeller type flow meter

This is a device wherein the velocity of flow imparts a rotational speed to a propeller inserted at an angle (fig.2.5) into the line. The rotation of the propeller is translated into an output signal proportional to the flow through the magnetic coupling. This meter[7] is different from the turbine meter in that,

i) the measuring element can be withdrawn from the line without removing the body of the meter.

ii) installation does not require manifolds, isolating valves, balancing valves, air, or power supplies.

This requires very low maintainence, costs less. The rangeability of the meter is 15:1 .

2.3.7 Magnetic flow meter

The onset of the magnetic flow meter[8] has eliminated the introduction of a flow disturbing device in to the flow stream and the consequent loss of head. This type of meter works on the basis of Faraday's law of electromagnetic induction. The fluid acts as a conductor and situated in a magnetic field, cuts the magnetic lines of force as it flows in consequence of which an e.m.f. is developed. The discs of conducting liquid is equivalent to a conductor of length D. The e.m.f. developed is given by

$$E = C.B.D.v \qquad \text{— (2.1)}$$

where

B = flux density ; D = length of the conductor = diameter of the pipe ; v = velocity ; C = non dimensional quantity.

so that

$$v = \frac{E}{B.C.D} \qquad \text{-- (2.2)}$$

$$Q = v.A \qquad \text{-- (2.3)}$$

where A is the area of cross section of the pipe.

If the matnetic field is alternating the voltage developed is alternating and of the same frequency as that of the magnetic field and d.c. if the magnetic field is steady.

The requirements for successful working of this instrument is that the fluid have a conductivity of not less than 0.02 uS/m. (The conductivity of tap water is of order 1 uS/m). Most of the industrial or process liquids other than insulating hydrocarbons can thus be metered successfully. Variation of flow velocity profile or turbulance does not effect the accuracy ; the head loss across the meter is equivalent to that of a straight length of pipe ; suspended solids also does not affect the flow. As such the meter is a near ideal one capable of measuring a homogeneous mixture of solid/liquid, corrosive or non -

corrossive, with practically no head loss.

This meter comes in size range of 12.5 mm to 1800 mm.

2.3.8 Variable reluctance flow meter

The variable reluctance flow meter transducer[5] operates on the principle very much similar to the linear variable differential transformer. In one system, a magnetic flow spool is suspended between helical springs in the orifice of a venturi bore. Two balanced electromagnetic coils with common centre connections are wound on the tubular body. Stream flow forces this spool down-stream until the liquid drag is balanced by the spring force. When the spool is centered between the coils the magnetic reluctance paths and the impedances are equal. Displacement of the spool causes an increase in impedance of one coil and decrease in the other with proportional changes in analogue voltages. With an a.c. input voltage to the coil, a filtered diode bridge rectifier forms a demodulating circuit to provide a standard 0-100 mV d.c. output signal proportional to flow rate. An analogue voltage integrating circuit provides pulse signals for an electronic totaliser for blending and mixing operations.

The flow meter comes in sizes 25 mm to 100 mm with flow rates of 9 to 110 m^3/h with maximum operating pressure of 340 kg/cm^2. Linearity is ± 2 % full scale.

2.3.9 Ultrasonic flow meter

An other non interfering type flow monitor is the ultrasonic flow meter. It is based on the principle that soundwaves travel through a material medium and if the medium moves the sound waves are carried with it. A transmitting transducer is located on one side of the pipe and two receiving transducers are fitted on the other side of the pipe. The sound waves will be received earlier by the receiver down stream of the transmitter than that up-stream of the transmitter. The difference in transit time may be measured as a phase difference of the sound waves arriving at the receivers or as a time difference or interval. In both cases relationship between the transit time and flow rate is linear . Alternatively bursts of sound are propagated[9] alternately in opposite directions between one pair of transducers situated diagonally along the pipeline. The signal travelling upstream is delayed, whereas that travelling down stream is speeded up by the flowing fluid.

Equipments capable of giving an accuracy of ±5% for pipe sizes 40 to 400 mm at flowrates from 3 mm/s are available. This device is mainly suitable for liquids, but devices are made for gases also.

2.3.10 Vortex flow meter

One of the most recent entrants into the field of flow measurement is the vortex flow meter which is predicted to cause a revolution in flow measurement techniques. It is based on the natural phenomenon known as vortex shedding. When an obstacle say a cylindrical rod, or any other bluffbody (i.e. an unstreamlined object) is present in the fluidflow path, it has been known for quite a long time that vortices are formed and these shed behind the body in the direction of the flow. The boundary layers of slow moving viscous fluid formed along the outer suffaces of the obstacle cannot follow the contour of the body on the down-stream side and the separated layers become detached and roll themselves into vortices in the low pressure regions behind the body. These vortices are shed from alternate sides of the body and the frequency at which they are shed is proportional to the velocity of flow[10].

The oscillating frequency is monitored by two electronically selfheated sensors whose temperature and thus resistance vary with localised flow. The resistance variations in the sensor are then converted into voltage signals and amplified. It is also measured by capacitance means, wherein the transducer forms part of the bluffbody itself.

This type of meter has no moving parts and can be used for measuring dirty liquids, as well as gases and slurries and highly corosive liquids. Flow rate ranges from 4.5 to 450,000 litres per minute with a given linearity of ±0.5 %, the condition being R_n (Reynold's number) minimum should be about 10,000.

2.3.11 The swirl meter

The swirl meter depends on the oscillatory nature of vortices. The swirl is imparted to the body of flowing liquid by curved inlet blades which give a tangential component to the fluid flow. To begin with the axis of the fluid rotation is the axis of centre line of the meter. A change in direction of the rotational axis takes place (precession) when the rotating liquid enters the enlarged section (fig.2.4)causing the region of highest velocity to rotate about the meter axis. This produces an oscillation or precession, the frequency of which is proportional to the volumetric flow rate.

The sensor used to measure the frequency is a bead thermistor operated in the constant current mode, to get an output voltage which is proportional to the instantaneous velocity change.

Typical liquid flow ranges are 0.36 to 3.6 m^3/h for the 25 mm size to 10.8 to 180 m^3/h. for the 150 mm size. This is also suitable for gas flow measurements. The corresponding range for gas flow is 8 to 50 m^3/h and 100 to 2500 m^3/h. The frequency range for liquids is 2 to 150 Hz and for gases 20 to 1300 Hz. Linearity is $\leq \pm 1$ % of rate and repeatability $\leq \pm 0.25$ % of rate. Operating pressure range upto 40 bar, and temperature 0 to 70°C are possible.

2.3.12 Thermal flow meter

The thermal type of flow meter has a heated sensor placed in the path of the fluid flow. The sensor is supplied with a constant heating power. The flowing fluid carries away a part of the heat from the sensor depending on the mass flowing, its specific heat, and the difference in temperature between the sensor and the fluid. A change in the mass flow rate thus causes a temperature change in the sensor. This temperature change causes a change in resistance of the sensor element leading to a change in current through the element or a change of a voltage across the element when the voltage or current respectively are maintained constant. If the temperature of the sensor is maintained constant, the resistance of the element remains constant ; with a constant current source feeding the element, for cpmstamtcy of power, the voltage drop across the element changes.

This way the following modes of oprations result -

i) constant current operation

ii) constant temperature operation

The sensor element used is usually a metallic wire - platinum-iridium , or tungstun of a few microns diameter and a few mm length in various configurations.

These methods are mainly applicable for gas flow measurements, but are also finding applications in liquid flow measurements with modified probes/sensor to withstand the mass effect and particle impact.

The sensor measures either mass rate of flow or velocity of flow

2.4 QUANTITY METERS

This type of meters gives an indication which is proportional to the quantity of fluid which has flowed in a given time. The fluid passes in the form of successive isolated quantities through the meter. Each container has known fixed capacity. The operation of the instrument is similar to that of measuring the quantity of liquid transferred from one container to another by counting the number of the measured transfers.

The quantity transferred thus may be units of weight or units of volume of the liquid or gas

2.4.1 Weighing meter

In this type containers are arranged such that when the liquid it contains reaches a predetermined level or height a container overturns and empties in succession. The number of times a container or set of containers overturns is recorded on a counter, which indicates the total weight of liquid that has flowed. This type is density and temperature dependent. Many other variations of the method are possible such as collecting tank, on a platform balance , or straingauge load cells.

2.4.2 Volumetric meters

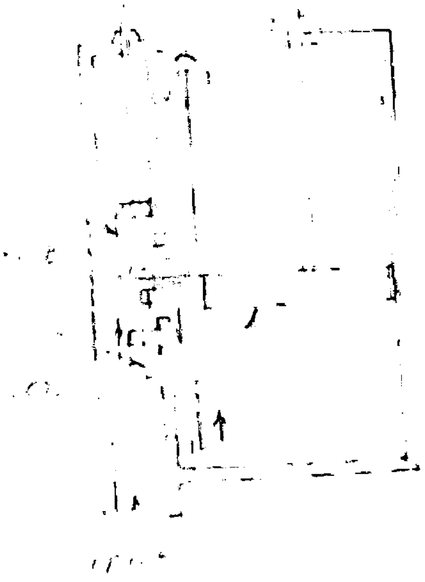
(a) Simple tank : In the simplest form of this method, a tank is allowed to fill and when the liquid reaches a level, a syphon action allows it to flow out. The number of times the liquid is syphoned out is a measure of the quantity of flow, which may be indicated by a float operated mechanism. Other arrangements include multiple tanks with automatic let-off and let-in to each tank depending upon the level in the previous tank. The number of times the cycle of filling takes place is indicated on a float operated mechanism of counter.

(b) Positive displacement meter : A class of meters derived from the previous type is the positive displacement meter. In this type of instrument, as the liquid flows through the meter it moves a measuring element which seals off the measuring chamber into a series of measuring compartments each holding a definite volume. As the measuring element moves, these compartment are successively filled and emptied. Thus for one complete cycle of the measuring element a fixed quantity of liquid is permitted to pass from the inlet to the outlet of the meter.

Positive displacement meters are used where highest degree of accuracy and good repeatability is called for. The most common forms of positive displacement meters are described below -

(b.1) Reciprocating piston type : As the name implies, a piston reciprocates (fig.2.6) inside a cylinder in much the same manner as in a steam engine , the motive power being provided by the liquid (water) pressure. The meter may have one or more cylinders. At each stroke of the piston a measured quantity of liquid is delivered at the outlet side. By suitable choice of materials, such meters are applicable to cold or hot water,oils, corrosive liquids, etc. although it is mainly intended for cold water.

As the piston reciprocates, a ratchet attached to the piston turns a pinion which turns a counter, recording the quantity of liquid flow.



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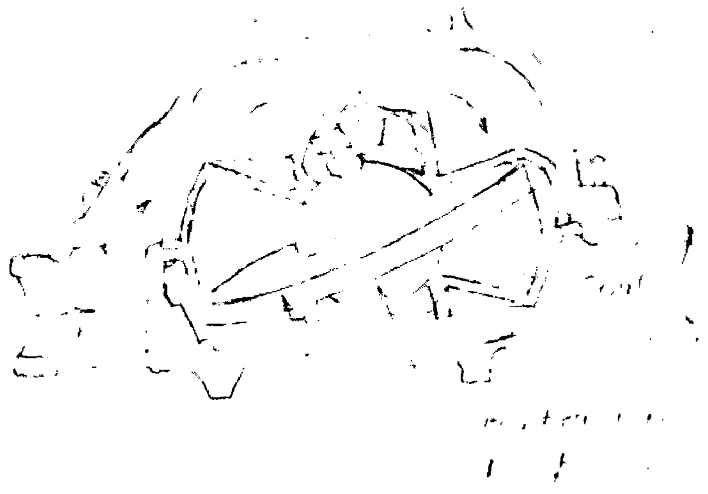

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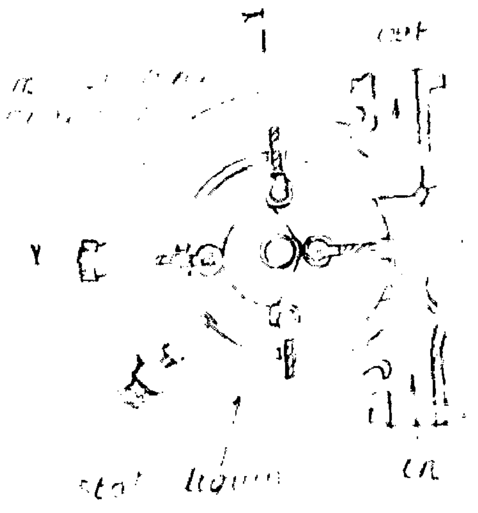
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(b.2) Rotating or oscillating piston type : This type of meter is widely used in metering domestic water supply but it is increasingly being applied to oil and chemical industries. Here the piston acts as a moving chamber (fig.2.7) transferring a definite volume of liquid from the inlet to the outlet part during each cycle of its motion.

(b.3) Mutating disc type : The water flowing through the meter, in this case gives a nutating motion (rocking motion) to a flat disc[12] which drives a gear train of the counter. The disc has radial slot into which the division plate of the measuring chamber fits. The disc is thus restrained, so that it moves up and down the separating plate, while the upper end of the disc spindle moves in a circle driving the counter mechanism. One edge of the disc is in contact with the upper edge of the measuring chamber, while the opposite edge is in contact with the lower edge of the chamber (fig. 2.8). As the liquid flows the points of contact of the disc and chamber move around the disc.

Such meters available in the range of 27 to 135 m^3/h have a metering accuracy of ± 2 % over the whole rated capacity.

(b.4) Fluted spiral rotor type : The meter consists of two fluted rotor supported in sleeve type bearings and mounted so as to rotate like gears in a liquid tight case. The impellers are carefully machined, and are in dynamic and static balance, with their relative position being controlled by two helical timing gears. The rotation of the impellers are synchronised thus, and there is no metal to metal contact, to avoid wear and tear. The shape of the rotor is such that a uniform uninterrupted rotation is produced by the liquid. The impellers in turn rotate a counter indicating the total quantity of flow.

Such meters are available in sizes from 25mm to 600 mm to cover a range of flow from 1.6 to 3200 m^3/h and pressure upto 80 bar. The accuracy from maximum to 20 % of the rated flow is of order ± 0.1 % . This type of meter finds applications in petroleum or chemical industries.

(b.5) Sliding vane type :

A set of vanes slide in and out through slots in the rotor (fig.2.9) depending on their relative position with respect to a fixed cam. The rollers at one end of the vanes follow the contour of the cam as the liquid flow causes the rotor to rotate in the meter body and around the cam. The vane nearest the inlet port begins to move outwards towards the body wall, being fully extended by the time it reaches the beginning of the measuring chamber. The vane ahead of this is fully extended. A measuring chamber is thus formed between the two vanes and the body top and bottom walls. A continuous series of chambers are thus formed for each rotor revolution (as many chambers as there are vanes).

This type of meter produces a comparitively low pressure loss and can be used upto 8.5 bar. g. pressure with a rated capacity upto 80 m^3/h. The accuracy is of order 0.1 % from rated capacity down to 20 % of it.

(b.6) Rotating vane type : The principle of operation of this type of meter is similar to that of the sliding vane type. Here the measuring chambers are formed by four half moon shaped vanes spaced equidistant on the rotor circumference. As the rotor revolves the vanes turn to form sealed chambers between the rotor and the meter body.

This type of meter is available for pressures upto 85 bar.g. with capacities ranging from 3.8 to 270 m^3/h with possible accuracies upto ± 0.1 % for flow down to 20 % of the rated capacity.

(b.7) Oval gear type : The measuring portion here consists of two intermeshing oval gear wheels rotated by the fluid passing through the meter. The rotation of the oval gear is transmitted to counter mechanism through a spindle or through the hollow spindle of one of the oval gears to a follower by means of magnets embedded in the gear wheel and follower, or it may rotate an electronic pulse generator.

Such meters are available in the range 10 to 400 mm size for pressures upto 60 bar.g and flow capacities from 0.06 m^3/h to 1200 m^3/h. Accuracies range from ± 0.25% for the smaller 10 to 65 mm sizes to ± 0.1 % for sizes larger then 80 mm.

The quantity meter described so far in this section are almost exclusively meant for liquids, more specifically for water. With suitable modifications in materials, sealants and isolation it is possible to use these meters for any type of liquids. Some quantity meters used for gas flow measurement are described below.

(b.8) <u>Bellows type gas meter</u> : A widely used commercial and gas service meter is the bellows type. It comprises four measuring compartments which operate simultaneously, some filling and some emptying sequentially usuring a uniform delivery of gas. The number of times each measuring chamber is filled and emptied is registered on a counter thereby giving an indication of the total volume in m^3 on the index. The meter register is operated from a crank that is rotated by the movement of the diaphragms. Motion of the meter mechanism occurs when there is a pressure differential of at least 2.5 mm of water.

(b.9) <u>Liquid sealed drum</u> : This meter is useful for measuring small flow of gases for analytical tests and measurements of calorific value of fuel gases. It consists of an outer chammber of tinned brass containing a rotary portion of shaped partitions forming four measuring chambers made of light tinned plate free to rotate on a centre spindle. Gas entering by an inlet near the centre leaves at the top through the outlet pipe at the top of the outer casing. The measuring chambers are sealed off by water or other suitable liquid. The level of the water is so arranged that when one chamber becomes unsealed to the outlet side, the partition between it and the next chamber seals it off from the inlet pipe. The measuring chamber will thus deliver a definite volume of gas from the inlet to the outlet of the instrument. The successive filling-sealing-and exhausting of the measuring chambers result in a rotation of the spindle which is recorded on a register, which can be calib-rated in volume units.

The type of meter is designed for volume flow of 6 to 90 litres per hour.

It is not suitable for gas at high temperature, requires maintainence, calib-ration, and periodical topping up of the sealing liquid.

(b.10) Rotating impeller type : This type of meter is very much similar to the rotating impeller type for liquids. The meter basically consists of two impellers housed in a casing and supported on rolling bearing. Wear and tear are prevented and caliberation is retained for meter life on account of the clearance of the order of few tens of microns between the impeller and casing.

The impellers are caused to rotate by decrease in pressure created at the meter outlet by the use ofgas. Each time an impeller passes through the vertical position a pocket of gas is momentarily trapped between the impeller and the casing. Four pockets of gas are therefore trapped and expelled during each complete revolution of the index shaft. The rotation of the impeller is transmitted to the meter counter by suitable gearing for the meter to read volume of gas in m^3.

Such meters are available for pressures upto 60 bar.g and flow rates of 12 m^3/h to 10000 m^3/h with an accuracy of ± 1 % over 5 to 100 % of the rated capacity.

2.5 DIFFERENTIAL PRESSURE METERS

This method, the most widely used of the flow measurement methods, is basically dependent on the difference in pressure between two sections in a flow stream. This pressure difference is created when a constriction such as an orifice plate, a venturi tube etc. are placed in the fluid flow path. Due to the constriction the area of cross section is reduced. With the law of continuity holding good, velocity at this section increases at the expense of pressure. Pressure just before the constriction, P_1 is larger than that at the constriction, P_2 and a difference of pressure exists. This pressure difference is a function of flow velocity v. Thus flow rate Q, can be deduced from a knowledge of the difference of pressure (P_1-P_2), area (at the constriction) A, through which the fluid flows and a flow coefficient C_1 for the constriction. Thus

$$Q = C_1.A.v = C_1.C_2.A.(P_1-P_2) \qquad -- (2.4)$$

where C_2 is conversion factor

Various methods are used to create the differential pressures and the pressure loss and measurement accuracy depend upon the method used.

The methods used are :

i) area is held constant : variation in head is a measure of flow, this is constant area-variable head method.

ii) flow is constant : area and head are constant, this is constant area constant head method.

iii) head is constant : Change in area is a measure of the flow, this is constant head-variable area method.

iv) head and area varies : measure of head and area indicate flow this is variable head- variable area method.

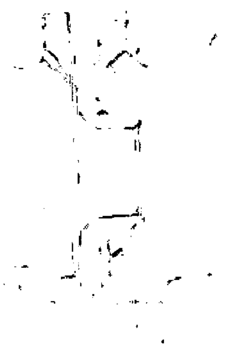
2.5.1 Constant area variable head meters

(a) <u>Pitot tubes</u> : The pitot tube (fig.2.10) is a very useful device for making temporary measurement of flow. When a tube is placed with its open end facing a stream of fluid, the fluid impinging on the open end will be brought to rest and its kinetic energy converted into pressure energy. The pressure in the tube will be greater than that of the free stream by the impact pressure and will depend upon the square of the velocity of the stream. The difference between the pressure in the tube and the static pressure of the stream will be a measure of the impact pressure and therefore of the velocity of the stream. By Bernoulli's equation, the differential pressure or impact pressure h, developed is given by

$$h = v^2/2g \quad \text{or} \quad v$$

$$v = \sqrt{2g.h} \qquad \text{-- (2.5)}$$

It is possible that the whole of the stream flowing on to the end of the tube is not brought to rest and to take care of this a coefficient C is introduced, termed pitot tube coefficient.



Hence $v = C\sqrt{2g.h}$ -- (2.6)

The most elementary form of pitot tube consists of a bent tube with a separate static pressure tapping.

Modifications include the ellipsoidal nosed standard pitot static tube, Prandtl's pitot tube, pitot venturi tube, pitot cylinder, pitot sphere and the annubar. The pitot cylinder and pitot sphere are used to measure velocity components at fixed angles to the axis of flow, the others being modifications of the basic pitot tube for better performance and coefficient .

The pitot venturi tube (fig.2.11) has two concentric venturi tubes arranged so that their openings lie in the same plane and the inner venturi commences at the throat of the outer venturi. Fluid flows through both the inner and outer venturi tubes. There is a calibrating ring on the outer venturi tube the position of which affects the static pressure at the exit of the outer venturi. These combined, develop a differential pressure of about ten times that of the simple pitot tube.

The annumbar (fig.2.12) is a more permanent type of pitot tube wherein the pressure holes are located in such a way that they measure the representative dynamic pressure of equal annuli.

(b) <u>Venturi tube</u> : The venturi or the conical type comes in three patterns. The long pattern venturi, the short pattern venturi, and the standard venturi, wherein the inlet cone angle and the outlet cone angle are different with the net loss of pressure being small, large and medium respectively. The venturi (fig.2.13) has in general 5 parts : (1) a short cylindrical accurately machined inlet section of the same diameter as the main pipe with a hole or a number of holes joined to a ring, called piezoring for measuring static pressure; (2) the entrance cone which includes an angle of 21° joined to the inlet by a smooth curve ; (3) a short cylindrical throat accurately machined, fitted with one hole or several holes and a piezoring to measure the pressure at the throat. The throat diameter is 0.224 to 0.742 of the entrance pipe diameter with a minimum of 19.3 mm ; (4) an exit cone which includes an angle of 5° to 15° ; (5) connecting flanges .

In the short pattern a standard flow nozzle may be introduced after the short inlet cylinder, in place of the inlet cone. The overall pressure loss in a venturi tube is 10 to 20 % of the differential pressure.

(c) <u>Dall flow tube</u> : This is a modified venturi tube, much shorter in length than the standard venturi tube and shorter than the short venturi tube itself. The differential pressure developed for a given flow rate is also much larger and the pressure loss is much less than that of a venturi tube (about 5 % of the loss). Fluid flowing through the tube first strikes the dam (fig. 2.14) at a , flows through a short steep inlet cone to a cylindrical section on each side of the throat slot, passes two more sharp edges at d and e, through the short recovery cone having an included angle of 15°, and finally undergoes a sudden enlargement to the pipe diameter at f. The whole device is about 2 pipe diameters long and has no smooth curves as in the venturi tube.

(d) <u>Flow nozzle</u> : In effect the flow nozzle (fig.2.15) is a very short venturi tube. It has an entrance cone which is bell shaped. It does not have an exit cone. Its flange is held between pipe flanges and pressure tappings take the form of annular rings with slots opening into the main pipe at each side of the flange of the nozzle or single hole (corner tap) drilled through the main close to the nozzle flange.

(The diameter of the pressure hole or the width of the pressure slot $> 0.03D$ where $d/D \leqslant 0.67$ and $0.02D$ where $d/D > 0.67$)

It is not suitable for viscous fluids. Its pressure loss is large, 30 to 40 % of the differential pressure.

(e) <u>Orifice plates</u>

(e.1) <u>Sharp edge orfice plate</u> : The orfice plate (fig.2.16) is the oldest and the most common differential pressure device. In its simplest form it consists of a thin sheet metal having a square edge hole which is concentric with the pipe at its centre. Other types include the eccentric orfice plate and the segmental orifice plate. The eccentric one is used when dirty fluids or fluids with suspended solids are to be metered, when the lower edge of the orifice coincides with the bottom of the pipe allowing the solids to pass through.

The orifice plates may be used for measuring flow of gases, liquids or vapours. It is not suitable for viscous fluids flow measurement or for critical flow metering.

Corner, D - D/2, and flange tapping my be used. Orifice plates are suitable for measurements of flow, for area ratio 0 to 0.5, R_n = 10,000 and upwards, for pipe dia 25 mm to 50 mm; and area ratio 0 to 0.7, R_n = 20,000 and greater and pipe dia = 50 mm and above.

The pressure loss is of the order of 50 % of the differential pressure.

(e.2) Quadrant edge orifice plate :

In this type of orifice plate, the edge is not sharp but a quadrant of a circle facing the flow. It is in between the flow nozzle and the orifice plate. The differential pressure remains constant over a wide range of R_n (500 to 20000). It is used when great accuracy is required with measurement of viscous fluids and especially where the viscosity varies or is not known.

(e.3) Dall orifice : The Dall orifice is a shortened version of the Dall tube which is about 0.3 pipe diameters long and can be bolted between pipe flanges.

(f) Gentile flow tube : The Gentile flow tube is a short pipe insert whose inner periphery is equipped with two groups of pressure nozzles. One group points up-stream and is exposed to the dynamic pressure. The other group points downstream, thereby not responding to impact pressure, but measures the static pressure. The nozzle groups are interconnected by two seperate pressure rings from which connections can be made to a conventional differential pressure meter . It is suitable for clear water, raw sewage, sludge black liquer and other fluids carrying solids in suspension (with suitable purge systems).

(g) Centrifugal type : Fluid flowing through a right angled bend in a pipe, where the bend is in the form of a smooth segment of a circle, has tendency to continue to move in a straight line. The pressure of the fluid on the outer radius of the pipe wall will be greater than that on the inner radius. The difference in pressure depends upon the fluid density and velocity. The mass flow rate W is given by

$$W = C.A. \sqrt{\rho\,(P_1 - P_2)} \qquad \text{-- (2.7)}$$

where ρ = mass density of the fluid.

(h) Linear resistance flow meter : Linear resistance flow meter, also referred to as laminar[13] were specially developed for measuring low flow rates of fluid. Here the resistant elements (primary or flow meter element) are generally made up of either porous plugs, or devices of sintered bronze, or in some cases of capillary tubes.

In the laminar flow through porous materials, the axial pressure gradients $\Delta h/\Delta x$ is directly proportional to the mean filter velocity v, by means of Darcy's law

$$\Delta h/\Delta x = \mu\, v/k \qquad \text{-- (2.8)}$$

where $v = Q/A$, $A = \pi d^2/4$

The main characteristics of these flow meters may be modified on the basis of the thickness of the porous element, type of tube, resistant element diameter ratios, and different characteristics of the porous material, thus combining the advantages of linear resistance flow meter with the positive characterstics of the orifice plates.

Tests results presented show a near true linear relation between Q and Δh for the range of flows upto 8 lpm, where Δh ranges from 0 to 600mm of the water.

Figure 2.17 gives comparative performance for the orifice plate, flow nozzle, venturi tube and venturi nozzle.

2.5.2 Constant area constant head meters

In a given installation the flow through a primary element will remain constant so long as the area of the element and the differential pressure across the element remain constant. This is the principle of the constant area constant head meters such as the funnel meter, the flow prover and the constant flow niveu, mainly used in gas flow measurement.

(a) Funnel meter : The funnel meter consists of a series of orifices, in a plate in the end of a tank or in the large end of a funnel, which discharges into the air. For a particular test the differential pressure across the meter is held constant and rate of flow is controlled by the number of orifices that are open. Thus both the differential pressure and the area remain constant for a particular test. It is usual to calculate the differential pressure to be used from an empirical formula involving specific gravity and pressure of gas to calculate the rate of flow.

(b) Flow prover : The flow prover is an improved funnel meter consisting of a pair of orifice meter flanges fitted with inlet and outlet section and of 8 to 10 pipe diameters in length. Between the flanges a number of interchangeable orifices of different sizes may be fitted. Other orifices are calibrated under a differential pressure, calculated from an empirical formula with a gas of known density, and nominal rate of flow is established. This meter is then used for checking other gas flow meter installations.

(c) Niveu : In its usual form the niveu is a constant area variable head meter. It has an orifice in the bottom or side of a vessel and the flow varies as the height of liquid above the orifice which is measured by sight glass, float or other suitable device. The usual equation for orifice meters apply in this case.

In the constant flow niveu the height of liquid above the orifice is arranged to be constant by means of an over flow arrangement which is adjustable. The flow through the orifice will then remain constant as long as the orifice is not altered due to wear and tear or dirt collection.

2.5.3 Variable area -Constant head meter

By maintaining the differential pressure across an orifice constant, by adjusting the area of the orifice, the area of the orifice will be an indication of the rate of flow.

In this case the rate of flow can be arranged to be directly proportional to the area of the orifice and consequently several difficulties with constant area, variable head meters including the square law flow relation are overcome. Such meters have also been designed in which accuracy is independent of the rate of flow and viscosity of the fluid. Some of these types of meters are described below.

(a) Gate type area meter : In this meter (fig.2.18) a gate is introduced into the flow stream and the area of the orifice (of flow) is varied by raising or lowering the gate which can be done either manually or automatically so as to maintain a constant pressure drop across the orifice. This pressure drop is measured by two taps in the main pipe, one each side of the gate. As the rate of flow through the orifice increases, the area of the orifice is increased. The position of the gate is indicated by a scale which gives the rate of flow. This rate of flow is not linear due to the velocity of approach increasing with increased rate of flow. This is overcome by measuring the impact pressure at the up-stream end than by the usual static pressure.

(b) Orifice and plug meter : This type of meter, shown in fig. 2.19 consists of a circular orifice into which a tapered plug fits. The form of the plug is such that the area of the annular space between the plug and orifice is proportional to the lift of the plug. When the fluid flows past the plug, the plug rises, and the amount by which it rises is a measure

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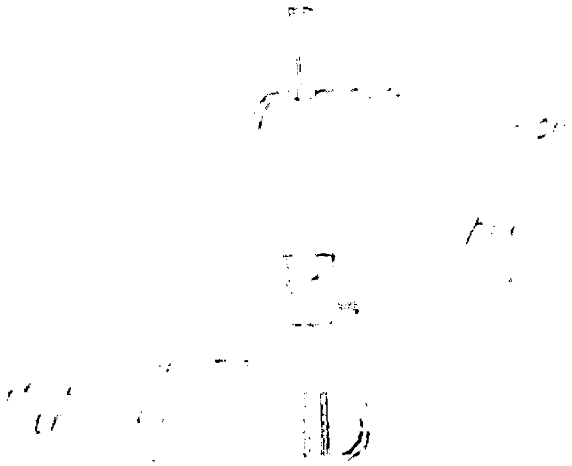

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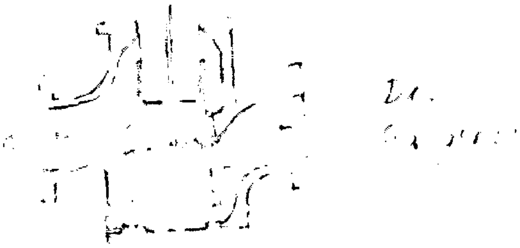

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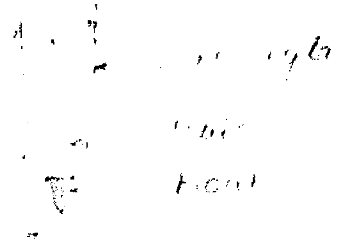

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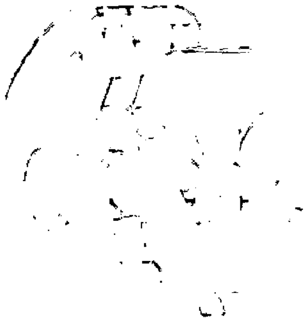

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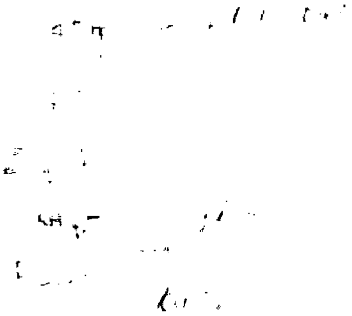

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of the rate of flow.

A modified form of this meter is the cone and disc type (fig. 2.20). Here primary element is a piston or disc moving in a conical chamber so that the force due to the differential pressure between the two sides of the disc balances the weight of the disc. By suitably shaping the chamber the flow can be made proportional to the lift of the disc.

(c) Variable area meter (Rota meter) : This type of meter consists of a long uniformly tapered graduated glass tube with the smaller section at the bottom and the longer section at the top, with the axis of the tube vertical. A float the simplest of which is in the shape of a plumbbob moves freely within this tube centrally along a guide.

As the rate of flow increases the float (fig.2.21) rises in the tube increasing the annular space and keeping the differential pressure across the float at a fixed value. By suitable design of the float a constant flow pattern and discharge coefficient for all flows having R_n above 40 has been achieved. The instrument thus has the capacity of giving a very large range of flows and for large range of viscosities of the metered fluid. It can also be arranged to give an indication of weight independent of small changes in specific gravity of the metered fluid.

When metering opaque liquids or when glass cannot be used, the tube and float are made of non magnetic steel and the float position indicated by an extension of the float carrying a magnet, the movement of which is picked up by a follower magnet and transmitted to the indicator.

The accuracy achieved is ± 2 % over a 10:1 range of flows. Glass tube rota meters have flow ranges from 30 to 450 mlph upto 1.36 to 13.6 m^3/h (liquids). Pressure range is 8 bar for larger one and upto 32 bar for the smaller one.

Metal tube rota meter can go upto 2000 bar, and capacities as large as 410 m^3/h.

2.5.4 Variable head, variable area meters

The range of the usual differential pressure flow meter is of the order of 10:1 . To obtain greater flow range and at small differential pressures a meter was developed in which the orifice area increases as the flow increases. With this it is possible to measure flows down to $\frac{1}{1000}$ of the meter maximum with an accuracy of better than ± 1 % of the range when the meter is used in the semilogarithmic mode. Meters with linear relationship give a flow range of 100:1.

This type of meter (fig.2.22) has a casing to which is fixed one end of a bellow, the other end of which is fixed to the orifice housing. At the orifice opening there is a shaped plug whose position is fixed. As the differential pressure changes, the bellow expands or contracts altering the annular gap between the plug and the orifice. The plug is called the central control member. The displacement of the bellow consequently that of the orifice attached to it causes a change area will change in flow rate and differential pressure. For a given meter the relation between these three parameters is unique. In the no flow condition the orifice remains closed.

Suppose with an orifice plate differential pressure at 10 % of the maximum given a rangeability of 3:1 on flow, then this element called gilflo primary element, will give a rangeability of 10:1 (i.e. the linear element) and the wide range element (semilogarithmic) a rangeability of 30:1.

The chief advantage of this device is that for 1 % of the maximum differential pressure the linear element will measure 1 % of meter maximum flow while the wide-range element will measure 0.1 % of the maximum flow.

These meters are available in sizes 2mm with flow rate 24 l.p.h to 600 mm size with flow rate upto 3000 m^3/h. In all sizes the differential pressure at maximum flow is 250 mm Hg.

2.5.5 Target flow meter

To measure the flow of highly viscous fluids at elevated temperature the meters dealt with so far are inadequate. In such cases the target flow meter is used (fig.2.23). Here the differential pressure connection is eliminated and is used for the measurement of flow of hot asphalts tars, oils and slurries at pressures upto 100 bar. g at R_n as low as 2000.

A target or a disc is placed in the flow path. The liquid impinging on this disc or target will be brought to rest so that the pressure increases and a force F is existed on the target. This force

$$F = \frac{K \rho v^2 A_t}{2} N \qquad (2.9)$$

where ρ = mass density

A_t = target area

v = velocity of liquid through the annular ring between target and pipe.

K = is constant

and is balanced by air pressure in the bellows so that a 0.2 to 1 bar signal proportional to the square root of the flow is obtained. The circular square edged target is attached to the force bar so that the target is concentric with the pipe forming an annular orifice.

The range of this meter varies from 0 - 52.7 to 0 - 123 l.p.m for the 19 mm size at temperatures of 400°C to, from 0-682 to 0-2273 l.p.m for the 100 mm size at temperatures to 260°C The overall accuracy is ± 0.5 % .

2.5.6 Current meter

Current meters have a rotor or propeller that is driven by the fluid flow. It measures the velocity of the fluid. Current meters find wide application with measurement of velocity of flow in large pipes, open channels and irrigation canals. Basically the number of revolutions made by the impeller is counted by lead phone, ringing of bell, lighting up of a lamp etc. for every few say ten revolutions of the propeller in case of small velocities and electro mechanical/electronic counters in case of large velocities. They come in sizes of rotor ranging from about 10 mm or less to 100 mm and for flow velocities in the range of about 1 cm/s to about 150 cms/s. The rotor may be cup shaped in the larger sizes and vane type, helical or screw type in small sizes and for large velocities.

2.6 OPEN CHANNEL FLOW MEASUREMENT

The methods of flow measurement so far described pertain to measurements where in the fluid in flow is bounded. In flow system where the fluid has a free surface (i.e. one surface of the fluid is open to atmosphere) flow measurements are carried out using weirs and notches where in the quantity of flow is a function of head over the weir or notch and the area of flow. The area itself is a function of head of flow. Some of the devices used for this type of flow measurement are discussed below. These are generally applicable to water flow measurements.

The weir provides a form of restriction in the flow path and have a variety of shapes. Depending upon the shape of the opening these are classified as rectangular weir, rectangular or square notch, V notch, traposoidal or cippoletti weir, logarithmic weir etc.

The simplest is the rectangular weir - straight edge over which the liquid flows. The name weir is used where large flows are being metered and the flow width is large.

For measuring medium/small flows a rectangular notch is used. When the flow is small say upto about 200 m^3/h a V notch is used, this notch having angle $\theta = 30$ to 90°. Usually a 90° V notch is used.

When the flow contain suspended solids a Venturi type (called Parshall flume) is used.

The head of flow in these cases is the height of the free surface from the edge of a rectangular weir of the apex of the V notch measured at a point ahead of the notch where the level just starts dropping.

In case of large flumes or canals gangs of current meters are used distributed along the width of the canal to measure velocity distribution. Tracer techniques are also adopted for velocity gauging in canals and river sections.

2.7 TRACER TECHNIQUES

In cases where the velocity of stream along a desired length of section as for example in canals or rivers or in pipes in case of viscous liquids tracer[14] and dye dilution techniques are used. A soluble chemical that is inert is introduced at a certain section of a given concentration and its concentration at two other sections down-stream are measured, which gives concentration as a function of velocity. One of the notable method is Allen salt dilution method and an other is the dye injection method.

Radioisotope gauges are used for measuring velocity of homogeneous material in a closed system such as a pipe line. Here the radio isotope is injected into the flow-stream and its position is detected by means of G M counters or NaI (TI) scintillation detectors.

For measurement of flow of gases the different absorptivity of infra-red frequency spectrum by various gases is made use of. A tracer gas is injected into the stream by a pump consisting of a reciprocating differential area piston driven by line gas pressure . Infra red detectors placed inside the pipe line at two different points use a small electric heater element to generate infra red radiation which is passed through a saphire window to a spherical mirror. Radiation is reflected from the mirror through a second saphire window, a mechanical chopper and an optical filter, before being received by the detector. Nitrous oxide and carbon monoxide have been used as tracer gases. Accuracy of 0.12 % have been achieved and it is unaffected by changes in pressure, temperature or velocity.

To detect the flow rate of liquid hydrogen while fueling a rocket it is measured experimentally by tagging the fluid magnetically and timing its travel between tracer and detector point. In this case the pipe line carrying the gas passes between the poles of a permanent magnet and two r.f. coils surround the pipe line a short distance apart. The up-stream coil is momentarily energised by a square wave oscillator and magnetically tags a segment of the precessing magnetic dipoles of the fluid. The tagged segment emits an r.f. signal of the same frequency as the processing dipoles and its presence is detected by the down-stream pickup coil. The time taken for the fluid to travel between the two coils is measured by an electronics counter and is a measure of the fluid velocity.

2.8 CLASSES OF PRESSURE MEASUREMENT

Measurement of pressure can be classified into two categories namely-

(i) pressure above atmospheric
(ii) pressure below atmospheric

Instruments that measure the pressure above atmospheric pressure are called pressure gauges and that below atmospheric pressure as vacuum gauges.

2.8.1 Pressure gauges.

Pressure may be measured directly,

(a) by balancing the pressure produced against a column of liquid of known density or
(b) by allowing the pressure to act over a known area and measure the resultant force. This force which is equal to pressure x area may be measured by balancing it against a known weight or by the strain or deformation it produces on an elastic medium.

Depending on the technique used pressure measurement may thus be classified as -

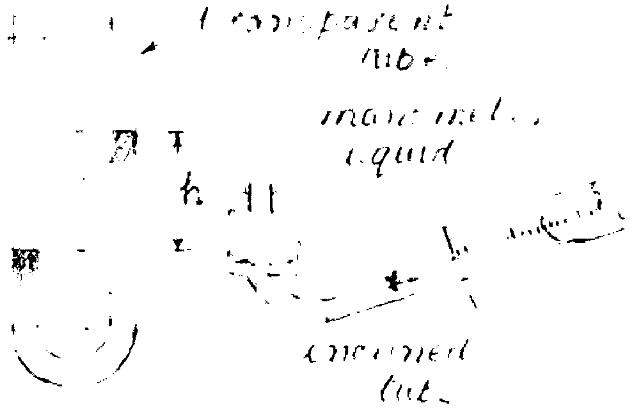
(a) Pressure measurement by balancing against a column of liquid of known density which includes.

Simple U tube with vertical or inclined limb (fig.2.24). Here a simple transparent (glass or polythene) tube is partially filled with a liquid of known specific gravity. The fluid whose pressure is to be measured is let into one of the limb, with the other open to atmosphere in which case the pressure measured is that relative to the atmosphere or the other limb may be connected to another pressure line when the measured pressure will be relative to this reference pressure. Various liquids such as mercury, transformer oil, Carbon tetrachloride, bromoform etc. are used as the manometric fluid depending upon the range of pressure to be measured and the resolution needed.

When very low pressures are to be used one of the limb is inclined so that for a given pressure a greater displacement length of liquid is available depending upon the angle of inclination.

By sealing one limb and filling the tube with the required liquid, absolute pressure can be measured. This is similar to barometer and the pressure measured is that relative to the Torricellian vacuum.

Thus by using U tube manometer it is possible to measure pressure above the atmosphere, below the atmosphere, absolute



IG. 2.24.U-tube manometer

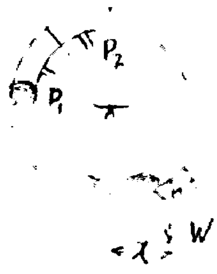
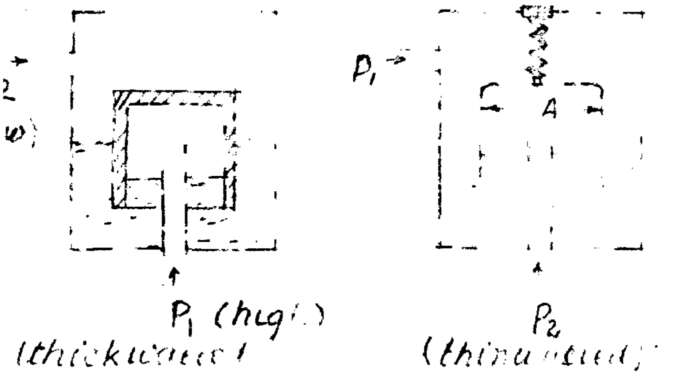


FIG 2.25 Ring balance type pressure gauge



IG. 2.26 Bell type pressure gauge

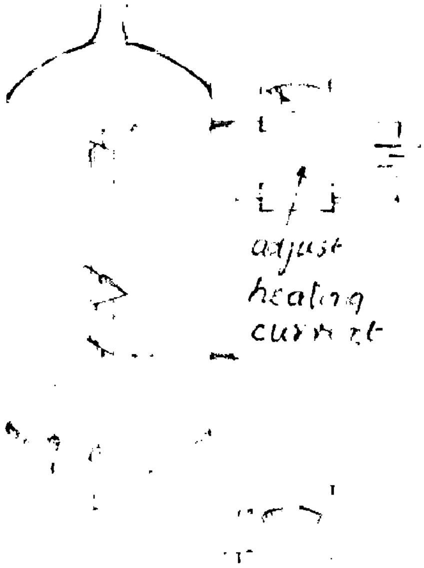
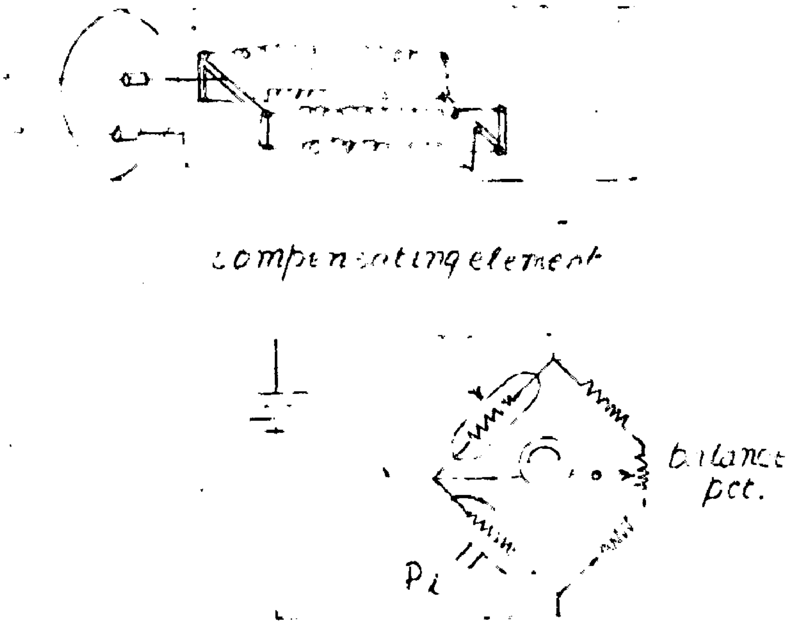


FIG. 2.27. Thermocouple vacuum gauge



IG. 2.28 Pirani vacuum gauge

pressure or differential pressure.

For industrial usage such devices come in a rugged and standardised form.

(b) Pressure measurement by balancing against a known force which includes

(b.1) Piston type pressure gauge

In this case the pressure to be measured is applied to one end of a piston of known area of cros-section which is free to move inside a cylinder. The piston experiences a force and it is displaced. It is brought beck to the original or reference position by adding weights to the piston. The pressure is thus given by the (weight added + weight of the piston) ÷ the area of the piston. This is also called dead weight tester and is used in calibrating other pressure gauges. This is suitable for pressures upto from 1 to 1100 bar g.

(b.2) Ring balance type pressure gauge.

This type of instrument is used wherein pressure differences of order 100 mm or less of water gauge are to be measured. It consists of a hollow ring (fig. 2.25) of circular section partitioned at its upper part and partially filled with a liquid in order to form two pressure measuring chambers. The body of the ring is supported at its centre on Knife edge or roller bearing. The fluid whose pressure difference is required is led into the ring by fluxible connection. The ring devices which measure pressure indirectly. The pressure is made to act on a diaphragm to which strain gauges are fixed and connected in the form of a half bridge or full bridge circuit. The pressure acting on the diaphragm causes strain to be induced in it which is a measure of pressure, available in the form of an electrical output voltage due to bridge unbalance.

The pressure may be made to act on a piezo electric crystal (quartz) cut in a special way and placed between two plates one of which may be fixed and pressure to be measured is applied on to the other plate, when an e.m.f. will be set up between the plates which is a measure of pressure. This method is used for measuring very high pressures.

The measured pressure may change the capacitance between two plates by changing the area between the plates or displacing the dielectric, which is given out as an a.c. bridge output voltage or frequency and calibrated in terms of known pressure by other methods. By this method, very low pressures to very high pressures can be measured.

Other indirect pressure measurement include variable inductance, variable reluctance and the linear variable differential transformer.

All the above pressure measuring techniques could be used in conjunction with the differential pressure flow metering devices.

is balanced by a control weight which is at its lowest point when the pressure is the same on both sides of the partition.

(b.3) Bell type pressure gauge.

In this type of pressure gauge (fig.2.26) the force produced by the difference of pressures on the inside and outside of a bell is balanced against a weight or against the force produced by a compression spring (fig.2.26).

(c) Pressure measurement by balancing the force produced on a known area against stress in an elastic medium.

In this category are included the Bourdon tubes of the 'C' type, the spiral type, and the helical type. This is the commenest type of pressure measuring device and is applied to measurement of pressure above atmoshpere below atmosphere and differential pressure depending on the construction. Usually it measures pressure above atmosphere i.e. from 1 to 70 bar g. when the joints are soft soldered or brazed ; upto 350 bar g. when the tube is solid drawn heat treated beryllium copper with brazed joints, and upto 6000 bar g. when the tube is alloy steel with screwed or welded joints.

Another type of device in this category is the diaphragm type either stiff metallic diaphragm or bellows, or slack diaphragm and drive plate.

(d) Other methods of pressure measurement.

In this category of pressure measuring devices are included

2.8.2 Vacuum Gauges

(a) Thermal Conductivity Gauges

These are designed primarily for operations below atmospheric pressure and are based on the principle that thermal conductivity of gases in the region where the mean free path is not negligible compared with the distance between the heat source and sink. The Knudson formula can be written as

$$Q/t = \lambda S P T^{-1/2} \Delta T \qquad (2)$$

where Q/t = heat transfer rate,

P = gas pressure

S = surface area of the heat source,

T = ambient temperature

ΔT = temperature difference between heat source and sink.

λ = constant

Transducers based on this principle lose their sensitivity above 10 torr when conductivity becomes independent of gas pressure.

(a.1) Thermocouple vacuum gauge

The thermocouple vacuum gauge consists of a hot surface, either a thin metal strip or wire whose temperature may be controlled by varying the current passing through it. For a given heating current and gas, the temperature assumed by the hot surface depends on pressure. This temperature is measured by a thermocouple welded on to the hot surface. The glass the Pirani gauge. Instead of the metallic resistance elements the temperature sensitive thermistors are used. These gauges have a range of 10^{-6} to 1 torr.

(b) Ionisation gauges :

When a high energy electron strikes a gas molecule there is a definite probability that it will drive an electron out of the molecule leaving it as a positively charged ion.

In the ionisation gauge a stream of electrons emitted at the cathode strike gas molecules in its path of travel and liberate secondary electrons, leaving the gas molecules as positive ions. The number of positive ions thus formed is directly proportional to the electron current i_e and the gas pressure. Having a fixed value of i_e the rate of production of ions is, for a given gas a direct measure of the number of gas molecules per unit volume and thus of pressure. The positive ions are attracted to a negatively charged electrode, which carries the ion current.

When ionisation occurs as a result of the electrons emitted due to thermal energy applied to the cathode it is referred to as thermonic ionisation gauge. Their range is from 10^{-3} to 10^{-8} torr.

Instead of hot cathode if a radio active source emitting α particles are used to ionise the gas in the gauge it results the radioactive ionisation gauge which is used in the range of 10^{3} to 10^{-3} torr.

2.8.2 Vacuum Gauges

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(a.2) Resistance thermometer gauge (Pirani gauge).

In this type of gauge (fig.2.28) the function of heating and temperature measurement are combined in a single element. The resistance element is in the form of four coiled tungsten wires connected in parallel and supported inside a glass envelope to which the gas whose pressure is to be measured is admitted. The cold or reference temperature surface is the glass tube. Generally two identical tubes are used, wherein one is highly evacuated and sealed and to the other gas is admitted. The sealed tube acts as a reference gas tube, and compensates for temperature changes and bridge excitation voltage changes on the output reading. Current flowing through the measuring element heats it to a temperature depending on gas pressure. The electrical resistance of the element changes with temperature and this resistance change causes a bridge unbalance. The bridge is initially balanced in a given gas and at very low pressure. A change of pressure will unbalance the bridge and this unbalance voltage is a measure of the gas pressure. These gauges are available in the range of 10^{-5} to 1 torr.

(a.3) Thermistor Vacuum Gauges :

Thermistor vacuum gauges operate on the same principle as the Pirani gauge. Instead of the metallic resistance elements the temperature sensitive thermistors are used. These gauges have a range of 10^{-6} to 1 torr.

(b) Ionisation gauges :

When a high energy electron strikes a gas molecule there is a definite probability that it will drive an electron out of the molecule leaving it as a positively charged ion.

In the ionisation gauge a stream of electrons emitted at the cathode strike gas molecules in its path of travel and liberate secondary electrons, leaving the gas molecules as positive ions. The number of positive ions thus formed is directly proportional to the electron current i_e and the gas pressure. Having a fixed value of i_e the rate of production of ions is, for a given gas a direct measure of the number of gas molecules per unit volume and thus of pressure. The positive ions are attracted to a negatively charged electrode, which carries the ion current.

When ionisation occurs as a result of the electrons emitted due to thermal energy applied to the cathode it is referred to as thermonic ionisation gauge. Their range is from 10^{-3} to 10^{-8} torr.

Instead of hot cathode if a radio active source emitting α particles are used to ionise the gas in the gauge it results the radioactive ionisation gauge which is used in the range of 10^{3} to 10^{-3} torr.

In another type the Philips Penning ionisation gauge high temperature filament and the problems associated with it are tackled by using a cold cathode tube and a high accelerating potential. A superimposed of magnetic field causes the electrons objected from the cathode to travel in long helical path to the anode which results in more collisions with gas molecules and thus greater ionisation. This type of gauge is useful for measurement in the range of 10^{-2} to 10^{-5} torr.

2.8 COMPARISON

In this chapter various types of devices and techniques used in flow measurement have been dealt with. These are invariably the primary elements as for example the deflecting vane, the rotating vane, vortex meters, swirlmeter, sliding vane, weirs and notches etc. These are in other words the flow sensors. The venturimeter by itself cannot give any useful flow data.

Pressure measuring devices such as mercury manometers, bourdon and diaphragm gauges, bellows and bell pressure gauges suitable for a wide range of pressure or differential pressure were also covered briefly, besides some of the electrical techniques like strain gauge and capacitance type pressure transducers Vacuum measuring devices like Pirani gauge, thermocouple gauge etc. have also been dealt with briefly.

These mechanical gauges are being used extensively in conjunction with differential pressure flow meters. It is time that electrical/electronic transducers find a much wider application with their fluxibility at signal processing.

The mechanical devices mentioned are the time tested and proven devices. Devices such as the vortex meter, swirlmeter, thermal meter are of comparitively recent origin undergoing further developments towards reliability ruggedness and better performance.

With mechanical devices the distance to which information about the measurand is transmitted is restricted. This can be overcome by using electrical output transducers, in place of the usual mercury manometer or pressure gauges, such as strain gauge or L.V.D.T. type pressure transducers and consequently totalisation/integration can also be performed remotely.

The use of a device depends on the nature of flow measurement problem to be tackled. When loss of head cannot be tolerated and aggressive fluids have to be metered the conventional flow meters have essentially to yield place to the electriomagnetic or ultrasonic flow meter or the vortex or swirl meters with their electrical detectors avoiding moving parts in the liquid.

In most of the meters discussed other than those wherein mention has been made, viscosity, density and compressibility affect the meter accuracy, as also temperature which affect all these properties to some extent. These provide an incentive to the development of a meter which is insensitive to the maximum number of undesired variables.

Thermal flow meters especially thermistor flow meters with no moving parts, least affecting the flow pattern, due to its small size, with the glass encapsulation resisting chemical action could possibly aspire to be an ideal flow meters. This ofcourse seems to have a long way to go as yet by way of development and application.

This chapter could not be complete without a mention of one of the latest advances in flow measurement technique. namely the laser doppler velocity meter, a competitor par excellent of the conventional pitot tube and hot wire/film measurement. In this case the velocity measurement is direct, besides requiring no physical object to be placed in the flow path coupled with low sensing volume and high frequency response. The cost and complexity is the vital question that has confined this method to the Research and Development Laboratories - that too rich.

3. THERMOELECTRIC SENSORS FOR FLOW MEASUREMENT

3.1 INTRODUCTION :

Electrical resistance of a conductor signifies that current flow through the conductor resulting from a potential difference applied across it is inhibited. This resistance to the flow of current causes heat to be developed in the conductor or the resistor. In case the heat builds up without being able to be dissipated quickly enough into the surroundings, a rise in the temperature of the resistor manifests.

This increase in temperature brings into play interesting phenomenon. The resistance of the conductor increases in some cases as in metals like copper, aluminium, platinum, iron etc. whereas the resistance decreases in materials like carbon, insulating materials and semiconducting oxides.

The change in resistance consequent with change in temprature per degree centigrade is termed the temperature coefficient of resistance of a material, usually denoted by α. When there is an increase in resistance with increase of temperature the material is said to have a positive temperature coefficient (P.T.C.) of resistance. When there is a decrease in resistance with increase in temperature the material is said to have negative temperature coefficient of resistance (N.T.C.).

Temperature sensitive materials manifesting a change in their electrical characteristic or state or more appropriately exhibit thermo-electric-effects are broadly grouped under the generic name thermoelectric devices and include thermocouples, metal thermo resistors, and semiconductor thermo resistors. Of these the thermo couples are almost exclusively used for temperature and its other application, low pressure measurement has already been covered.

3.2 THERMOELECTRIC DEVICES

3.2.1 Metal resistors

Some of the common metals used as temperature sensitive resistors include platinum, copper, aluminium, nickel, chrome alloys, tungston etc. Of these platinum and its alloys find wide application as temperature sensors, in fluid velocity measurements, turbulance measurements as with hot wire anemometry and so on.

The general expression giving the resistance temperature relation for metal resistor is

$$R_T = R_a (1 + \alpha_a \Delta T + \beta_a \Delta T^2 + \gamma_a \Delta T^3 + \dots) \qquad (3.1)$$

where R_T = Resistance at temperature T

R_a = Resistance at a reference temperature T_a

$\alpha_a, \beta_a, \gamma_a$ = Constants at reference temperature T_a

ΔT = Change or difference in temperature $(T-T_a)$

To a first approximation valid generally in the range of 0 - 100°C this equation may be simplified by omitting higher powers of T to

$$R_T = R_a (1 + \alpha_a \Delta T) \qquad -- (3.2)$$

which is, a linear function.

Platinum has a temperature coefficient of resistance of 0.3 % per degree centigrade and tungston 0.4 % per degree centigrade. The thermal time constant depends on the dimensions, material used and the ambient media and conditions, and range from 2 ms to 60 seconds or more.

3.2.2 Thermistor

From the atomic theory of matter it is well known that with increase in temperature the lattice vibrations increase and more electrons become avialable for conduction and hence conductivity of semiconducting and insulating materials increase.

In semiconductors in addition it is possible by proper choice of the alloying or dopant element and impurity concentration to obtain resistors with desired value of α in a given range. Since resistance decreases with increase in temperature α is negative. In some cases it is possible to get a positive α.

The resistance temperature relation of semi-conductor thermo resistor otherwise known as thermistor is exponential in nature. In case of NTC thermistors, under zero power conditions i.e. under the condition when current flow is small enough as not to cause increase in internal temperature of the thermistor its resistance can be represented by[15]

$$R_T = R_a \, e^{B\left(\frac{1}{T} - \frac{1}{T_a}\right)} \qquad \text{-- (3.3)}$$

The power dissipated is $P = VI = D(T - T_a)$ -- (3.4)

where D = a constant of proportionality termed dissipation constant or thermal conductance.

B = Material constant

V = Voltage across the thermistor

I = Current through the thermistor

and e = Base of material logarithm = 2.7183

With a thermistor material having a heat capacity C, the heat transfer equation is,

$$C \frac{dT}{dt} = - D(T-T_a) \qquad \text{-- (3.5)}$$

when power dissipation in the thermistor is appreciable the more general equation is,

$$C \frac{dT}{dt} = P - D(T-T_a) \qquad \text{-- (3.6)}$$

The temperature coefficient of resistance of thermistors range from -4 % per°C to + 60 % per°C and this has made its application to measurement systems more attractive, because of larger output and reduced signal conditioning.

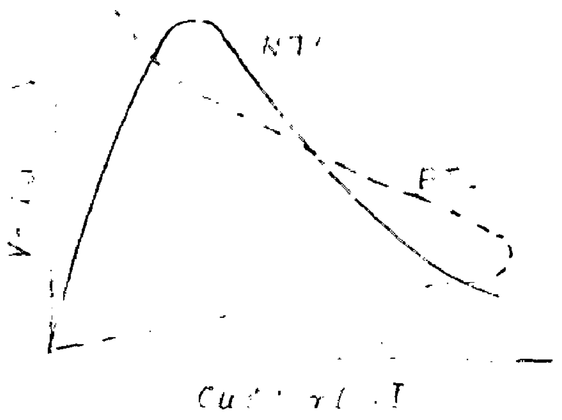
Thermistors are made from sintered mixtures of metal oxides or mixture of metal oxides such as cobalt, copper, iron, magnesium, tin, uranium, boron etc. and come in various shapes and configurations. The earliest thermistor was of UO_2 followed by $MgnO_2$, Ag_2S and leading to transition metal oxide systems. Barium, boron, germanium and silicon oxides exhibit NTC characteristic while doped $BaTIO_3$, Bi, yttrium and other rare earth elements Sb, W etc. exhibit PTC characteristic. The PTC exists only over a limited temperature range.

Thermistors find wide applications in the measurement of temperature, temperature compensation in biasing circuit of amplifiers, amplitude stabilisation in oscillators, distant or remote switching etc. At present thermistors are available to operate up to 300°C and work to develop these for temperatures upto 900°C are under way.

The thermal time constant of thermistor which is a function of the heat capacity C, the material, shape and mass range from 1 to 200 seconds for encapsulated ones. With uncapsulated thermistors time constants of 0.01s have been realised.

Some thermistor characteristics :

The V-I characteristic of the NTC thermistor is shown in fig. 3.1. For very small currents through the thermistor, the voltage drop across it varies linearly (for a given temperature) upto a certain point. In this region the thermistor



3.1 Static V-I characteristics [illegible]

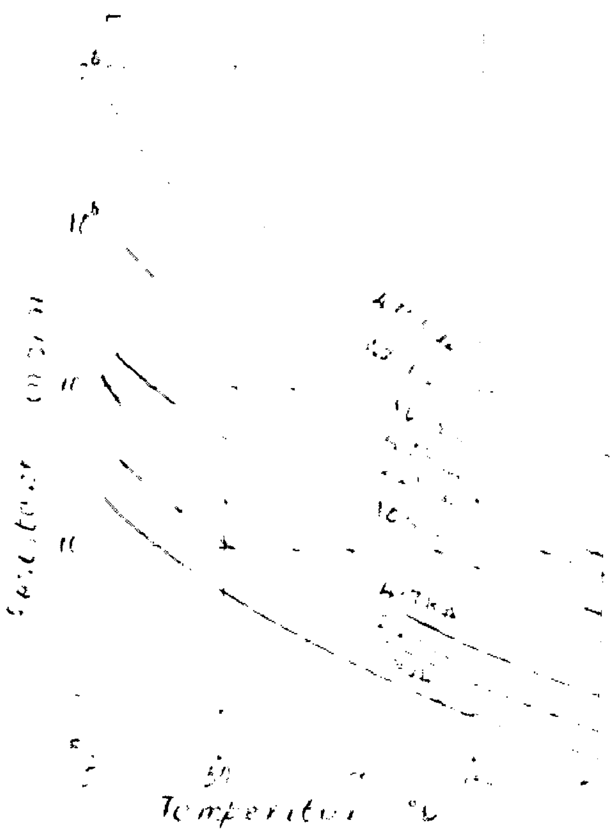
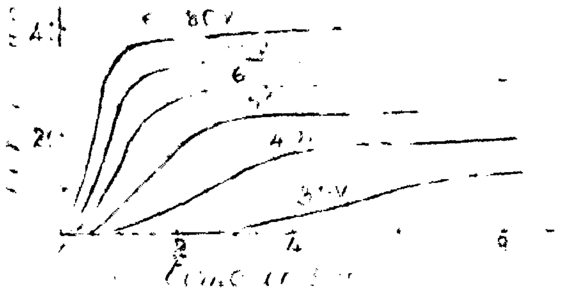


Fig 3.2 Typical [illegible] curves for [illegible] the [illegible]



3.3 [illegible] characteristic [illegible] typical thermistor

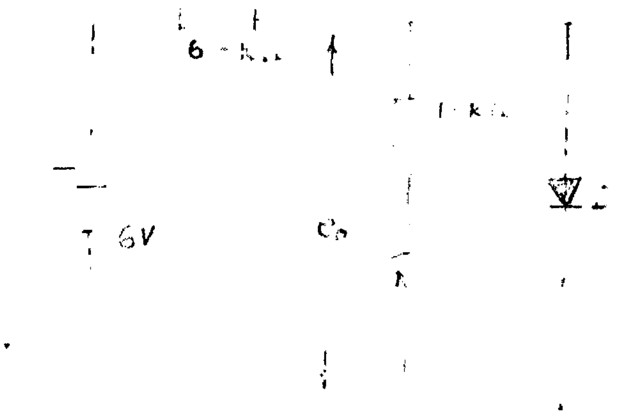


Fig 3.4 [illegible]

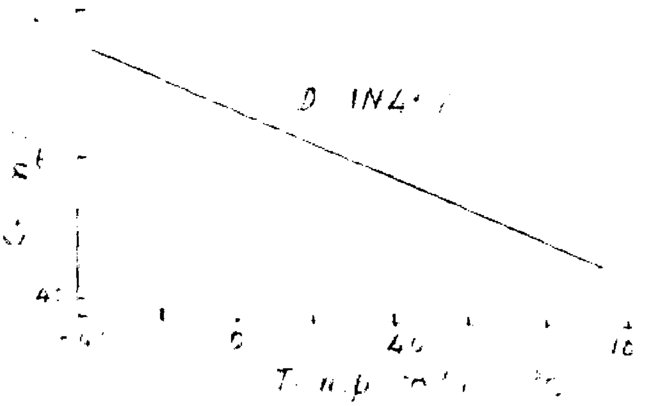


Fig 3.5 [illegible] Characteristic

behaves as a linear resistance and obeys ohms law. When the current is further increased the characteristic bends over and begins to drop. Further increase of current causes a decrease in voltage which remains almost a constant after a certain current. The current at which the voltage just begins to decrease is referred to as the threshold voltage.

The R-T characteristic is shown in fig (3.2). In the early part of the exponential curve the thermistor is quite sensitive to temperature ; dR/dT is large, and as temperature is further increased the change in resistance almost becomes negligible after a certain temperature i.e. dR/dT → 0. For e.g. for a certain thermistor the change in resistance from $180^\circ C$ to $190^\circ C$ is approximately 1 ohm whereas in the range of say 40° to $50^\circ C$ it is about 150 ohm . In other words dR/dT is steep and gradually becomes almost flat. Like threshold voltage it may be said there is a threshold temperature and may be defined at a certain dR/dT when dR/dt tends to become constant or in other words dR/dT begins to increase rapidly at less than this temperature.

Another characteristic which is of interest but not usually presented is the current time characteristic[14] shown in fig. (3.3). When the voltage applied across a thermistor - resistance combination is varied, the current is determined by the resistance of the series resistor and the resistance of the thermistor. The current flowing in the thermistor causes internal power dissipation and consequent lowering of resistance which further increases the current. This process will continue till the thermistor reaches its maximum temperature possible for the amount of power avialable at which a steady state will begin to exist. The time it takes for a thermistor to heat up to its maximum temperature for a given power is a function of its mass, value of the series resistance and the applied voltage.

3.2.3 Diodes :

In germanium and silicon the most commonly used semiconductor materials, thermal energy is sufficient even at ambient temperature to enable few electrons to break the covalent bond and cause diffusion current, which is temperature dependent. As a p.n. junction is subjected to varying temperature it is found that this diffusion current increases exponentially and almost doubles for every 10°C rise in temperature for both silicon and germanium.

This temperature sensitivity of commercial p-n junction (diodes) have been made use of[16] to measure temperature changes in the range of -40°C to + 100°C in conjunction with a micro ammeter used as a mV meter, both with Ge and Si diodes. With the configuration shown in fig. 3.4 the output voltage ranges from 200 to 450 mV for Ge and 450 to 750 mV for Si. The volts output - temperature relation is almost truly linear(fig.3.5).

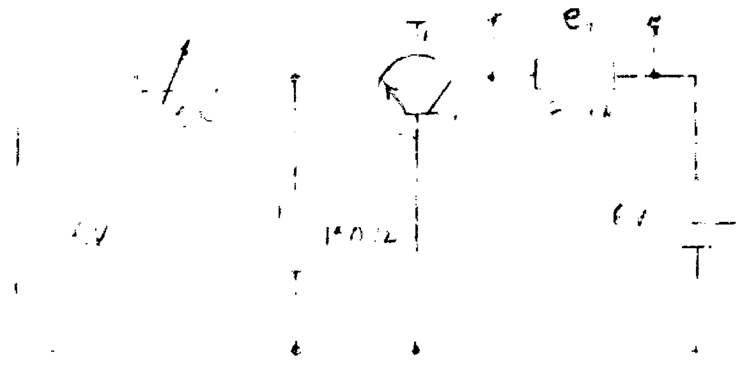
The variable temperature is that of the ambient or that of a bath in which the diode is immersed and temperature is varied gradually and the outputs are recorded. The relation between self heating at the junction due to diode forward current and attendent cooling in a flow stream appear not to have been studied. This study together with the frequency response and time constant could prove useful in its application to flow measurement problems.

3.2.4 Transistors :

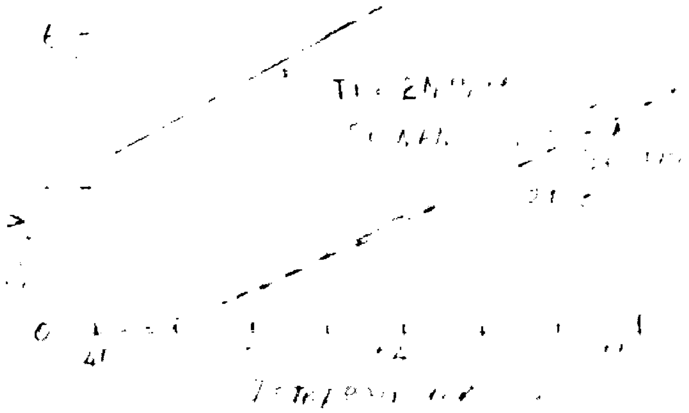
Like diodes, transistors composed of p-n junctions, are also affected by temperature. The parameter affected thus are noted by, the base current I_B, the collector current I_C, and the current gain β or h_{FE}.

A simple transistor thermometer circuit is shown in fig.(3.6) and the temperature vs volts output with the transistor itself acting as a single stage amplifier is shown in fig.(3.7). For the circuit configuration shown (fig.3.6) the relation between output and temperature is linear from 20°C to +70°C approximately for Ge transistors and -40 to + 100°C for Si. The outputs for these cases range from 0 to 6 V and 1.5 to 6 volts respectively. For the cases shown time constants of 1.5 seconds in liquid media and 30 seconds in air have been reported.

Transistors do not seem to have found application as temperature sensors yet, perhaps on account of the more competative thermistor, not withstanding its own ability to amplify and regions of linearity. A transistor thermometer is



[illegible] 3.6 Transistor Thermometer Circuit



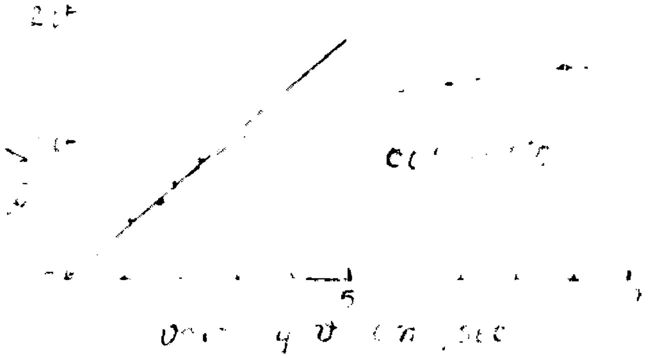
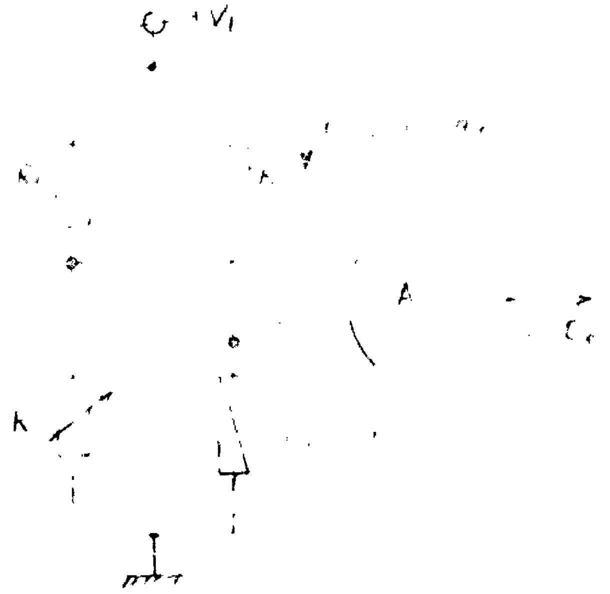


Fig. 3.7 [illegible]

Fig. 3.8 Thermistor bead calibration curve, e_0 vs [illegible]



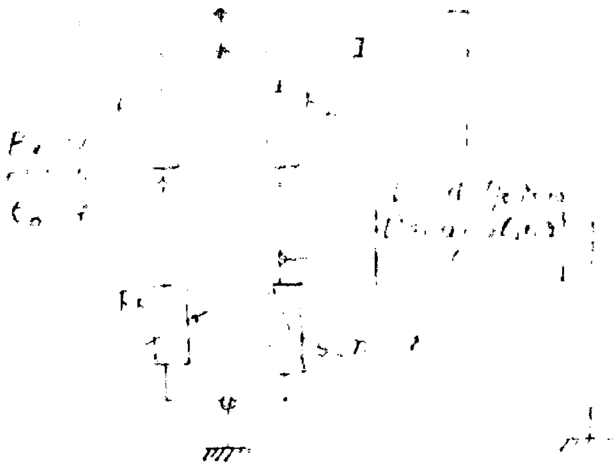


Fig. [illegible] Constant temperature-resistance system

[illegible] Constant Current System

reported and experimental results made available[17]. To become an effective temperature sensing device, the time constant of the transistor needs to be reduced and packaging designed for the purpose.

3.3 METHODOLOGY OF APPLICATIONS

Thermo resistive elements whether of metal or of semi-conductor such as thermistors, are arranged in different circuit configuration depending upon the requirements. Then include (a) constant curve circuit ; (b) constant temperature circuit ; (c) mixed operations. Each of these methods has its own advantages and short comings. Each of these type of operation is described in some detail and finally a comparison is made of these different configurations.

3.3.1 Constant current method

The constant current method [18-21] is the oldest and most widely used method with anemometry . In this method the current through the sensor is maintained, essentially constant usually by connecting a large resistance in series with the sensor (fig. 3.8), so that the current flow is controlled by this series resistance. The change in current flow due to the sensor resistance change is made of the order of 1/100th or less as to be inconsequential. The operating temperature of the sensor for a given condition is selected by the choice of the series resistor.

This condition of operation is applicable to any heated sensor more particularly to metallic wire sensors as in hot wire anemometry wherein platinum or its alloys of upto 0.15 mm dia and 1.5 mm log are used as sensors with typically 5 ohms sensor resistance under operating conditions..The sensor is heated by a constant current and heat is developed. This heat is transferred to the surrounding fluid as a function of the fluid flow velocity. At the elevated sensor temperature its resistance is increased and with flow velocity temperature reduces, so that resistance reduces, and consequently with constant current flowing through the sensor, the voltage developed across the sensor reduces. This voltage is related to flow velocity by calibration for a given probe configuration and flow media.

In place of the wire sensor thin films of the same metals (now a days aluminium film is also used) are deposited at the tip of specially shaped quartz, silica or other insulating rods and are used in liquid flow measurements, with the main aim at turbulance measurements.

The constant current mode of operation is resorted to in the case of thermistor sensors also. In the design of instruments, wherein heated thermistor are used, the characteristics of importance are the sensitivity to changes in the fluid temperature and sensitivity to relative velocity[20].

The sensitivities are defined as the fractional rate of change of thermistor voltage with respect to one variable, the other variables remaining constant.

The steady state heat transfer equation (3.6) for a thermistor can be written as

$$i^2 R_a \, \epsilon^{B(1/T - 1/T_a)} - D(v)[T - T_x] = 0 \qquad (3.7)$$

where $D(v)$ = velocity dependent dessipation constant

T_x = ambient temperature of the liquid

Considering T as a function of the parameter i and the variable T_x and v,

$$\partial T/\partial T_x = [\,1/(1 + BP/DT^2)\,] \qquad (3.8)$$

$$\partial T/\partial v = [\,-(\partial T/\partial T_x)\,(P/D^2)\,(dD/dv)\,] \qquad (3.9)$$

The voltage sensitivities are

$$S_T = (1/\mathcal{E})(\partial \mathcal{E}/\partial T_x) = -(B/T^2)\,[1/(1+BP/DT^2)\,] \qquad (3.10)$$

$$S_v = (1/\mathcal{E})(\partial \mathcal{E}/\partial v) = -[\,(S_T . P/D^2)(dD/dv)\,] \qquad (3.11)$$

where S_T = sensitivity to temperature change

S_v = sensitivity to velocity change

When the thermistor heating current is small, the sensitivity to temperature variation is large, approaching αx as i tends to zero. At the same time the sensitivity to fluid velocity variation is small and tends to zero with the current tending to zero.

With increase in heating current, the temperature sensitivity decreases monotonically, and approaches the limit

$$S_T \doteq 1/T = D(P + DTx) \qquad (3.12)$$

The sensitivity to speed variations increases with current approaching the value

$$S_v \doteq 1/D \; (dD/dv) \qquad (3.13)$$

Thus by proper choice of the thermistor bias current, it is possible to make it sensitive to flow velocity or to ambient temperature changes. This fact is also clear from the R - T curve of the thermistor. When the thermistor is operated in its region of high resistance change (fig.3.2) it is very sensitive to temperature changes. In the low resistance change region it is not sensitive to temperature. The particular region of operation along the R - T curve can be realised either by external heating of the thermistor or by internal heating due to power dissipated in the thermistor, this being achieved through a proper bias resistor for a given supply voltage.

3.3.2 Constant temperature method

In this method the temperature of the sensor is held constant and as a consequence the resistance of the sensor remains constant. This method is otherwise referred to also as the constant resistance method.

In the case of metal sensor either the wire or the film type an increase in fluid velocity causes a greater heat dissipation into the fluid media as a result the temperature of the sensor tries to fall increasing the resistance. This alters in fact, reduces the current through a meter connected in series with the sensor. The reverse of this takes place when there is a reduction in fluid velocity. Thus the current through the meter is a measure of the flow velocity.

A typical scheme for this type of operation[21] is shown (fig.3.9). The sensor forms part of a bridge circuit, with a fixed ratio arm and the remaining arm has either a resistor identical with the sensor or a control resistor. The current through the sensor is adjusted to maintain the required temperature. As the flow velocity increases past the sensor, it will tend to cool, the resistance decreases, causing the voltage across the sensor to decrease, which in turn reduces the voltage input to the amplifier. The phase of the amplifier is such that this decrease in voltage will cause an increased output from the amplifier, to increase the sensor current. A high gain amplifier will tend to keep its input very close to the balanced condition . Thus any change in the resistance of the sensor is immediately corrected by an increase or decrease in the current through the sensor.

The output could thus be either the current through the sensor detected by a suitable ammeter or the voltage output of the amplifier to send this current through the sensor. With the feed back control the resistances in the bridge circuit an constant and the voltage across the bridge is directly proportional to the current through the sensor i, and power

$$P = i^2R \qquad (3.15)$$

Therefore, the square of the voltage measured on top of the bridge is directly proportional to the instantaneous heat transfer between the sensor and its environment.

Thermistors also can be operated at constant temperature and the varying current through the thermistor being used as an indication of fluid velocity or temperature. As in the case of the wire or film sensor much shorter response time could be achieved with this type of operation. The response time is virtually controlled by the servo system or amplifier in the feed back, that control the thermistor current.

Considering T as a parameter, in equation (3.7) the constant temperature resistivities are defined as

$$I_T = 1/i \,.\, \partial i/\partial Tx = 1/2(T-Tx) \qquad (3.16)$$

$$Iv = 1/i \,.\, \partial i/\partial v = 1/2D \,.\, dD/dv \qquad (3.17)$$

where I_T = current sensitivity to temperature

Iv = current sensitivity to flow velocity.

3.3.3 Mixed mode of operation

In this method of operation neither the current nor the temperature of the sensor is maintained constant. The sensor resistance is one leg of a d.c. Wheat Stone bridge. The unbalanced bridge voltage e_o is a measure of the flow velocity v.

Two arms of this bridge have resistance of value R and the third arm has a decade resistance box, to balance the bridge. The balanced value R_3 of this arm is the resistance of the thermistor subjected to fluid flow velocity.

In operation the bridge is balanced under no flow conditions. Then a flow velocity v causes a bridge unbalance voltage $-e_o$. D(v) is obtained as a function e_o i.e. D now becomes a function of flow velocity v.

The relationship between v and e_o is shown (fig.3.10) for thermistor type TX1647, with the glass encapsulation removed to obtain superior thermal time constant, and having a resistance of 3500 ohms at 273°K. The flow during calibration was linear with R_n will below 1200 and for the fluid CCl_4 held at 0°C. Power dissipation at $v = 0$ is 16.6 mW.

3.4 Comparison

Metal wire and film anemometry, especially the former is well established for flow measurement, particularly turbulance measurement, in air or gases. The wire with modifications and film with quartz coating are available for liquid flow measurements.

Thermistor has not found wide spread applications on account of its large time constant, thermal inertia and its irreproducible characteristic even for a given type leading to replacement difficulties entailing the whole range of readjustments and calibration. This defect has to a very large extent been overcome in present day thermistors, but time constants have not yet been reduced comparably. As such thermistors are suitable for low velocity, steady state flow measurements and have been applied to blood flow measurement[23] the nature of which is pulsatile ,satisfactorily.

The question of the advantage of using one or the other type, whether constant current, constant temperature or mixed mode, therefore is pertinent more to the wire and film type rather than the thermistor. But the arguments are applicable to thermistor measuring systems as well.

The constant current system although the oldest of the systems employed has the disadvantage that matching of the frequency characteristics of the amplifier to that of sensor is required to obtain a flat frequency response. With this matching the frequency response extends to several hundred KHz. Another major draw back is that the frequency response of the sensor depends not only on the sensor characteristics but also on the flow characteristics. This leads to the necessity of adjustment of the frequency compensation when ever the mean flow changes. This limits the use of the constant current system to situation where the fluctuations in velocity are small compared with the mean velocity.

The feed back loop in the constant temperature method eliminates or overcomes the above difficulty. Further it has the advantages of reduced sensor burn out and temperature compensation possiblity, the output is direct d.c. and is suitable for large fluctuations in velocity.

In the cases of the thermistor applications cited, the maximum velocity attained is about 0.5 m in water. In these cases the thermistor at the tip of a bent glass rod has been rotated inside a dewar jar[20] containing the liquid, with the assumption that the temperature gradient $\delta Tx/\delta s$ remains constant. In the other the thermistor probe is introduced into a pyrex tube in which CCl_4 or methanol was the medium kept at $0^{o}C$. Both these methods obviated the need for temperature compensation.

In practice however, in the process of prolonged measurements it is quire possible the fluid ambient temperature changes and temperature compensation becomes essential inviting changes to the system of experimental measurement, increasing the complexity although not in surmountable. These reports[20,22] have made available data for further work than providing a flow measurement system as such.

Data on response time of a thermistor flow meter using boron bead thermistor fabricated for the purpose is reported[24]. Numerical solution of the nonlinear differential equation (3.6) is presented and a relationship between the response time and thermal time constant is attempted . It has been found convenient to bias the thermistor at high current to achieve good sensitivity and response to velocity.

4. LINEARISATION TECHNIQUES.

RODUCTION :

he output of most of the transducers are non linear, ple, the d.c. bridge output, semi conductor Strain hermistor, and hot wire bridge outputs etc. In many ns it is desirable or even essential that the final ndication be a linear function of the input variable.

physical system is said to be linear if the relation the forcing function and its output response can be d by a linear differential equation. If the forcing is x and the response to this, of the system is y o may be related by an equation of the type

$$y''' + ay'' + by' + cy = dx' + gx$$

where a, b, c, d, g are constants.

Further, if the forcing function x_1 causes response y_1 and a forcing x_2 causes a response y_2, then a forcing function $ax_1 + bx_2$ causes a response $ay_1 + by_2$, where a and b are constants. Thus linearity also implies that the principle of superposition is valid.

Linearisation means approximation of a given characteristic by a straightline over the range of expected variation of the variable or over given elemental ranges.

4.1.1 Classes of linearisation

Linearisation can be divided into four classes :

i) null balance bridges with sensing devices to provide a constant rate of change of slope of the set point resistance.

ii) function generation technique, which use passive devices to generate the required curve.

iii) deflection methods which are non nulled bridges, which combine the curve of the output current of a bridge with the curve of a sensing element (plus on occasions curves of other variables) to provide constant output slopes.

iv) nonlinear dial displays which set spacing of the dial to give correct readout.

The main feature of a good linearisation methods are

i) provision of some minimum required worst case tracking error, depending on the application.

ii) be physically realisable implying economy, ease of maintainence, etc.

iii) be applicable in a variety of situations.

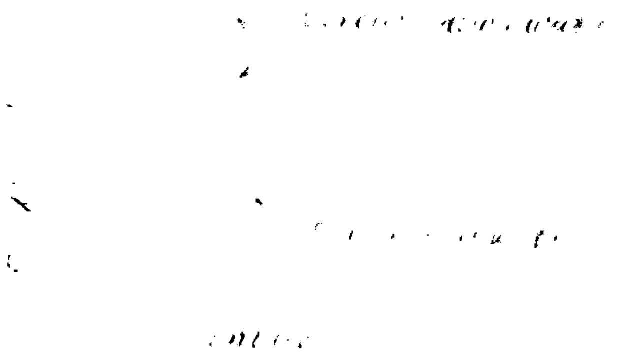
iv) ability to lend itself to simple calibration and adjustments.

4.1.2 Linearisability

Suppose a resistance transducer responds to a physical quantity such as displacement or temperature or pressure etc., of value say x either directly or indirectly, it is shown[27] that the relationship of the transducer output y to the input x can be linearised by linear methods if and only if both the resistance and conductance of the transducer are concave upward functions of the variable x (fig.4.1). This result applies to either deflection output or null balance output.By the linear methods it is possible to linearise thermistors and linear metals (e.g. copper), in terms of the physical quantity say temperature, but not platinum.

Platinum and other sensors can on the other hand be linearised in terms of the reciprocal of the absolute temperature.

Linearisation is often a convenience for readout rather than an absolute necessity for making measurements.



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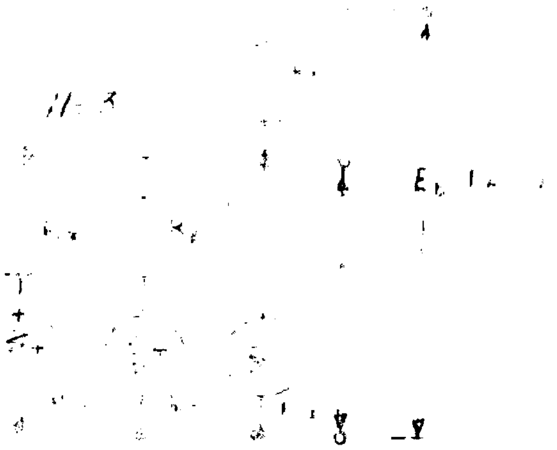

e = 1.05V at 0C

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Fig 4.2 [illegible] vs temperature [illegible]

Fig 4.3 Basic Wheatstone Bridge

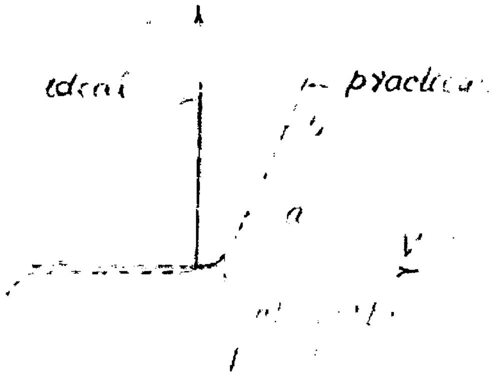
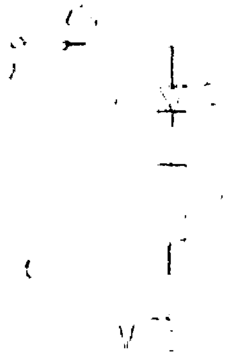


Fig 4.4 Diode characteristics



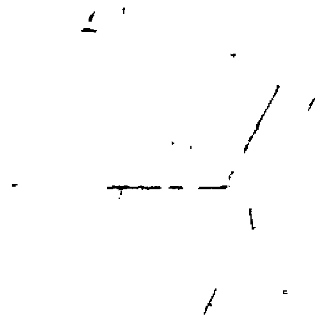


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fig 4.[illegible]

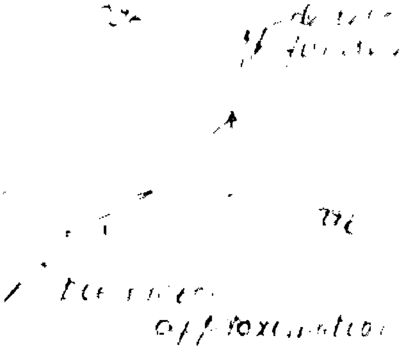


Fig 4.[illegible] [illegible]

4.2 LINEARISATION OF SENSOR

4.2.1 Metal resistor

The resistance-temperature relation of pure metallic elements can be represented by an equation (3.1)

i.e. $$R_T = R_a (1 + \alpha_a \Delta T + \beta_a \Delta T^2 + \gamma_a \Delta T)$$

Usually as a first approximation these elements are considered like linear and represented by

$$R_T = R_a (1 + \alpha_a \Delta T)$$

over a limited range of temperature.

Invariabily these elements are used in bridge circuits for temperature measurements. By suitable choice of the bridge components and configuration limited linearity could be achieved. A common technique of linearisation also known as hybrid linearisation, is to suppress the negative second term nonlinearity β ($\beta = -5.08 \times 10^{-7}$) by connecting the platinum sensor in series with a nickel sensor ($\beta = 6.535 \times 10^{-6}$) . This way with a ratio of Pt/Ni of about 19, a linear 100 ohm sensor with a sensitivity of 0.4056 ohm K^{-1} can be achieved[28]. Where the fluctuation in temperature is large, the greater nonlinearity is smothered by using other techniques as linearising circuits using diodes or transistors (valves in older circuits) to generate a nonlinear function, the resultant of these together giving a linear output. Such techniques are described in subsequent sections.

4.2.2 Thermistors

Thermistors as already mentioned are used to a very large extent in the measurement of temperature, because of its large temperature coefficient of resistance. Where other quantities such as pressure, velocity etc. are to be measured using thermistors, its change of resistance due to a change in its temperature, brought about as a result of interaction of heat transfer to or from the surrounding medium or variation of its dissipation constant, or its V - I characteristics are made use of.

In the measurement of flow (flow velocity), for instance the thermistor is either directly heated (self heated), or indirectly heated (i.e. seperately heated through a heating element which is in thermal contact, but electrically insulated from it), to a certain temperature or its obtain a certain value of resistance. The flow of the fluid carries away a part of the heat thus reducing the temperature and increasing the resistance. Basically, this means the thermistor is temperature dependent.

Methods of linearisation have consequently been developed to a large extent as applied to temperature measurement. These methods could however be applied equally well to measurement of other variables, with slight modifications to suit the particular operating conditions. Technique of linearisation thus becomes dependent upon the variable being measured and the law connecting the variable to the thermistor parameter.

In linearising thermistors the common technique has been, to assume[29], as a starting point the relation

$$R = A\,e^{B/T}$$

Next the output from the network containing the device is expanded in terms of ascending powers, and the condition under which the first of the nonlinear expansion term vanishes is determined. From this condition the design values of the circuit parameters are obtained.

Finally the error is estimated by determining the value of the remainder terms.

The basic draw back with the method is the initial assumption of the resistance temperature relation and its ability to fit well the experimental curve. The other draw back is omission of the higher order terms in the series expansions.

The earliest method of compensation or the nonlinear R.T characteristic was by means of a passive shunt[28]. By means of low parallel or high series resistance with the thermistor a point of inflection is developed about which near linear effects are possible over a reasonable range of operation[30].

This method was improved upon to achieve greater linearity and ease of setup[31] (which was not so with previous one). Here the thermistor is used in a bridge with an easily varied external resistance which is used to set the bridge voltage for a particular temperature. When the resistivities at both ends of the scale are made equal it is found that the linearity requirements are fairly well satisfied. The bridge output voltage equation is expanded in series as usual after inserting the assumed thermistor characteristic.

A network of N thermistors in series with fixed resistors $R_1, R_2, \ldots, R_N$ have been able to meet the requirements for a linear characteristic, maintaining still sufficient sensitivity over intervals exceeding 100°C (fig.4.2).

Linearisation has also been achieved by balancing the non linear effects of the sensor output against a generated non-linearity rather than by simply reducing it[29]. Here a R -T relation of type

$$R_T = R_a \left[1 + \frac{\Delta T}{a + b\Delta T} \right] \qquad (4.1)$$

which is proved to be linear, is assumed. This equation is fitted to three of experimental points from the characteristic of the device and the error between the assumed equation and the experimental curves of the sensing device is estimated. The nonlinear output terms (of the bridge output equation) are equated to zero, and from this the desired values of the circuit parameters are obtained involving no approximation.

4.3 LINEARISATION OF MEASURING CIRCUIT OUTPUT

Sensors by themselves cannot give measurable output. They need to be used in a network comprising of other components as resistors, inductors, capacitors and active circuit elements. In linearising it becomes necessary that the entire network be linearised. The most common network used is a bridge circuit, the output of which is intrinsically nonlinear. By configuring and choice of component values properly, such as for example having a high ratio between the fixed and variable arms of magnitude greater than ten, the change in the sensor itself being small, the bridge output can be made linear. Other techniques of linearisation include generation of a nonlinear function, and compensating with it the sensor network output, placing the sensor in an environment similar to and simulating the change in variable as required in a measurement system; conversion of the network output voltage or current into other parameter as time, frequency or phase in a linear manner and so on. Some of these techniques are examined in some detail hereunder.

4.3.1 Bridge circuits

The most common form of bridge circuit is the d.c. Wheat Stone bridge circuit (fig. 4.3) R_1, R_2, R_3 are standard resistances, R_4 is the thermoresistive sensor. The bridge could be of null balance type in which case one of the resistor say R_3 is made variable (i.e. a decade resistor box or a multi turn linear potentiometer). The bridge is balanced each time R_4 changes either manmually in simple cases, or be means of servo control in cases where continuous and fast responses are required.

The other mode of bridge operation is to initially obtain bridge balance under standard condition and allow the bridge unbalance voltage to develop. This unbalance bridge voltage e_0 is a function of R_4, change i.e. a function of the change in the measurand

The first method is called the null method and the second one the deflection method. In the null method a calibrated variable resistor R_3 is required and error due to change in bridge supply voltage V is not introduced, whereas in the deflection method change in V introduces an error.

In the measurement of non electrical quantities by electrical methods the deflection method has been finding greater application on account of its simpicity although at the sacrifice of accuracy of an order of magnitude of that of the null method. In this case linearity is existent when change in the sensor resistance say $R_4 \ll R_4$, so that i_m the current through the detector can be assumed proportional to the change.

The unbalance or measuring current may be written as

$$i_m = R_2 E_0 \frac{\Delta R_4}{a \Delta R_4 + b} \qquad (4.2)$$

where a, b are constants for a given bridge and is a function of

R_1, R_2, R_3, R_4 and R_m so that $i_m = f(\Delta R_4)$ and is a nonlinear function.

With a NTC thermistor the R-T relation being exponential it is possible that the bridge can supply nonlinear output to cancel the sensor nonlinearity[32]. A variation of this method uses sensors in two adjacent bridge arms.

In fig (4.3) if $R_1 = R_4$, and $R_2 = R_3 = nR_1$ and R_4 changes by + R_4 and R_1 by − R_1 then the bridge output current i_m is given by,

$$i_m = \frac{V_o}{R_1} \frac{\Delta R_4/R_4}{2(1+n) - (\Delta R_4/R_4)^2} \tag{4.3}$$

The relative nonlinearity of the detector scale is given by

$$D = \frac{1}{2(1+n)} \frac{R_4}{R_4} \tag{4.4}$$

From this equation it is evident that higher the value of n the lesser the nonlinearity; i.e. by having a high ratio of R_2/R_1 the bridge output nonlinearity can be reduced to incosequence if not eliminated.

4.3.2 Piecewise linearisation

(a) Function generation using diodes

Linearisation of output through a linearising function matching an actual calibration curve for a specific type of sensor and system, is finding greater usage because of the inherent high accuracy as compared to linearisation based on empirical laws connecting input-output relation of a system of measurement.

Linearising function is generated using active and passive devices. In early linearising circuits diode valves were being used. These gave way to semiconductor diodes, being more reliable and requiring low voltages.

The V-I characteristic both the ideal and the practical, of a semiconductor diode is shown in fig. 4.4. A little above the cut in voltage in the region a - b the characteristic is linear. If the length of the segment is reduced the linearity is more pronounced. Diodes are used to generate linear segments of a nonlinear function [34] the slope of the segment being decided by resistor networks.

The basic principle of diode wave shaping is illustrated in fig. 4.5 where there is a biased diode and the circuit characteristic is shown in fig. 4.6 Here the diode connection determines the permissible current flow and direction, and the battery voltage only sets the break point location. The combined circuit response of the elements is found directly from Kirchoffs voltage and current law. For the circuit of fig.4.6,

$$v_i = v_d + v_r + V$$

$$v_{i1} = V + i_a R \quad \text{for } i_a \geqslant 0 \text{ or } v_a \geqslant V$$

$$v_{i2} = V + v_d \quad \text{for } i_a \leqslant 0 \text{ or } v_a \leqslant V$$

The magnitude of V determines the point at which the diode starts to conduct.

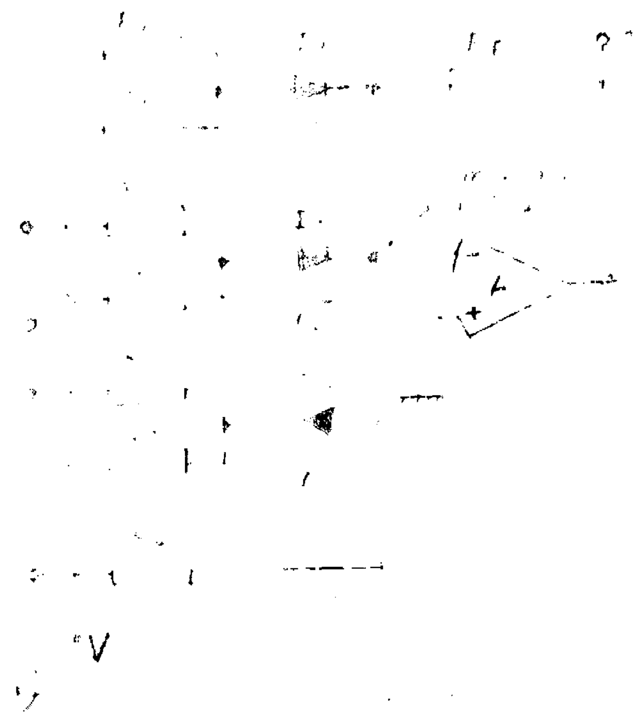
The advent of operational amplifier has simplified the wave shaping circuitry. The closed loop gain of an operational amplifier for the inverting mode of operation is given by

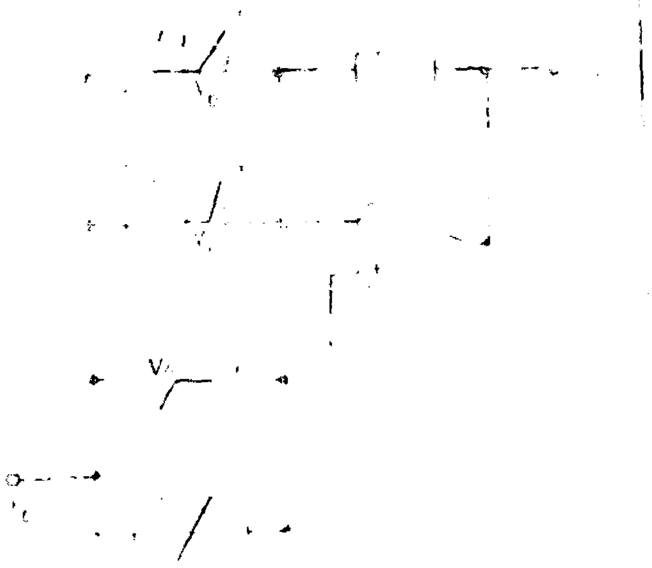
$$A = -\frac{R_F}{R}$$

The inverting input is also referred to as a summation point in that the output is a sum of the inputs at this point.

The approximation of nonlinear functions is achieved with operational amplifiers by the use of appropriate nonlinear feed back network. The most general way of generating such functions is through the use of piece wise linear approximation as shown in fig 4.7. The accuracy of the approximation depends upon the number of segments used, being greater, the greater the number of segments. The complete curve is obtained by summation of the individual line segments, whose breakpoint voltages and slopes are determined seperately for each segment.

Fig. 4.8 shows a general circuit diagram of a function generator which has three limiter networks[36] plus a direct input resistor R_4. Each of the four paths to its summing junction has a particular short circuit transfer conductance as shown in the block diagram of fig.4.9. The upper three paths create the break points V_A, V_B, V_C (fig.4.10) with three associated components of output slope. The total transfer characteristic





[illegible] 4 [illegible] fig 4.2

[illegible] of fig 4.2

[illegible] 4.1[illegible] [illegible] characteristic
[illegible] 4.11

is proportional to the total short circuit transfer characteristic or transfer conductance formed between v_i and the summing junction. Fig. 4.10 shows the resulting over all transfer characteristic. With reference to fig. 4.8, the resistor R_3, r_3, with the diode D_3 provides the break point,

$$V_A = - \frac{V.R_3}{r_3} \qquad (4.5)$$

for $v_i < V_A$, D_3 is ON, D_1 and D_2 are OFF.

$$S_A = - R_F \left(\frac{1}{R_3} + \frac{1}{R_4} \right) = S_B - \frac{R_F}{R_3} \qquad (4.6)$$

Here the slope is established by both R_3 and R_4

In the interval when $V_A < v_i < V_B$ the slope is determined only by R_4 (all the diodes are off) ; hence

$$S_B = - R_F/R_4 \qquad (4.7)$$

The next break point V_B occurs when D_2 comes ON when

$$V_B = \frac{V.R_2}{r_2} \qquad (4.8)$$

and in the interval $V_B < v_i < V_C$

$$\text{slope} \quad S_C - R_F \left(\frac{1}{R_2} + \frac{1}{R_4} \right) = S_B - \frac{R_F}{R_2} \qquad (4.9)$$

The last break point is $V_C = \dfrac{V.R_1}{r_1}$ (4.10)

and for $V_C < v_i$ both D_2 and D_1 are on

$$\text{slope} \quad S_D = - R_F \left(\frac{1}{R_4} + \frac{1}{R_2} + \frac{1}{R_1} \right) = S_C - \frac{R_F}{R_1} \qquad (4.11)$$

A general purpose diode function generator, with adjustable slopes and break points is shown in fig. 4.11. The transistor emitter followers prevent loading the breakpoint setting of potentiometers R_4, R_5. For $R_1 = R_2 = 12K$, and $R_7 = R_8$ the break poihts are merely $2V_1$ and $2V_2$. It is possible to have slopes of both +ve and -ve polarities.

Diode function generators are used to deal with a wide class of functions including muli variate functions[37].

(b) Function generator using transistors

Fig. 4.13 shows a circuit diagram in which transistors are used to generate nonlinear functions. The base of each transistor Q is connected to the input while each emitter is connected through a bias resistor R_K to a potential V_K produced by the resistor chain r_B, $r_1, \ldots\ldots, r_K, \ldots\ldots, r_N$. The bias voltages V_1, $V_2, \ldots\ldots V_K, \ldots\ldots V_N$ are formed by passing a constant current i_o through the resistor chain. The output is essentially the total current i. The voltage drop iR_L across R_L is used for convenience.

In designing the circuit two assumptions are made[38]

i) The resistors r_1, $r_2, \ldots, r_K, \ldots, r_N$ that produce the bias voltages are small as compared to the emitter series resistances R_1, $R_2, \ldots\ldots, R_N$ or that $(i/i_o) \ll 1$.

ii) The transistor base-emitter voltage is independent of the collector current and a collector emitter current ratio $\doteq 1$,

$\alpha \doteq 1$.

Semiconductors being inherently temperature sensitive temperature stabilisation or compensation needs to be provided. In the function generator referred two temperature compensating elements are provided, one to take care of temperature dependent collector leakage current under cut-off conditions, and the other the base emitter voltage V_{BE} although assumed constant is temperature dependent, which has the effect of shifting the input voltage to the entire chain.

4.3.3 Linearising amplifier

Thermal flow meter used in physiological and pharmacological research are based on heat convection, which means that the temperature difference between the measuring and compensating device is related hyperbolically to the flow velocity[39]. In this case linearisation will be necessary to obtain a direct reading instrument.

To measure the temperature difference between the heat convecting element of the flow meter and passing blood two matched thermistors are mounted as adjacent arms of a bridge change in temperature of the convecting element produces a directly proportional variation of the output of the bridge depending on the sensitivity of the thermometery. This is approximately 4 % resistance change per degree centigrade.

The bridge is fed by a pulse generator so that heat production in the thermistor is considerably reduced. The output of the bridge is amplified and linearised by an antilog operator followed by a peak detector.

The log and antilog amplifier make use of the approximately logarithmic relation between current and voltage in a semiconductor p n junction[40] which is given by

$$i = I_o \, e^{v/\eta V_1} - I_o \qquad (4.12)$$

I_o = temperature dependent term related to reverse bias current.

V = temperature equivalent of voltage = KT/Q_e = $T/11{,}600$

η = is an empirical parameter related to device composition having a value $\simeq$ 1 for Ge and 2 for Si.

Such a junction either of a diode, or of a transistor Q_1 with its base circuit grounded is used in the feed back path of an operational amplifier A_1 to get a log function. To provide teperature compensation the output of this amplifier is connected through another similar transistor Q_2 to the input of a second operational amplifier A_2 with a base biased through a temperature compensating resistor. In the antilog circuit the position of Q_1 and Q_2 are interchanged Q_2 now is in the feed back part of A_1 and the grounded base transistor Q_1 is connected to the input of A_2. The output voltage

$$v_{02} = C \log^{-1} (D \, v_{in} / \gamma T)$$

for the antilog operator. Where v_{02} is the output of A_2

$C = R_y \cdot i_R$

D = input divider fraction

Y_T = temperature variation term appearing in the input voltage V_{in}.

The antilog operator used in the flow meter referred to is Philbric Nexus 4350 type.

4.3.4 Simple operational amplifier circuit

Fig. 4.14 shows a single operational amplifier used with a differential input and a common reference voltage. R_3 is the thermistor used to measure temperature. With this arrangement[41] one side of the thermistor can be grounded and electrically insulated from the heat source being measured. The output voltage e_o is given by

$$e_o = E\left(1 - \frac{R_2K}{R_3}\right) / (1 + R_2/R_3) \qquad (4.14)$$

where $K = R_F/R_1$

or $$e_o = E\,(1 - R_2\,K/\,Ae^{-BT})/(1 + R_2/\,Ae^{-BT}) \qquad (4.15)$$

putting $R_2/A = C$,

$$e_o = E\,(1 - (K+1)\,Ce^{BT}) \,/\, (1 + Ce^{BT}) \qquad (4.16)$$

Equating the second derivative of $Ce^{BT}/\,1 + Ce^{BT}$ which is independent of K to zero

$$e^{BT} = 1/C \qquad (4.17)$$

indicating that a given BT fixes the value of C. Further this function can be made linear over a range of values of BT, and the output voltage equation (4.15) will be linear with respect to T over this range of RT. By this way linear temperature indication has been obtained over a range of 10 to 50°C

4.3.5 J.F.E.T. Linearising circuit

The output of a transducer of the form

$$E_t = at + bT^2 \tag{4.18}$$

can be linearised[42] if voltage controlled resistor (VCR's) are used in the feed back amplifier circuit when the output

$$e_o = \gamma t \tag{4.19}$$

for the input given by eqn (4.18). The necessary conditions for this is

$$R_S/R_P = \left[1 + (b/a\gamma)\, e_o \right] \qquad (4.20($$

when b/a is positive (b, a being constants), and

$$R_S/R_P = \left[1 - (b/a\gamma)\, e_o \right] \tag{4.21}$$

when b/a is negative.

p - channel J.F.E.T's are used for +b/a and n-channel J.F.E.T'S are used for -b/a.

4.3.6 Astable multi vibrator bridge

The use of multivibrator bridge for measurement of temperature or temperature differences has advantages over the conventional methods in that sensitivity and linear range of operations can be increased considerably[43].

In the usual astable multivibrator circuit the pulse duration of interval can be combined by a change in either R_1, C_1, R_2 or C_2. If $R_1 = R_2$, $C_1 = C_2$ the pulse time is given by

$$t_1 = R_1C_1 \log_e 2 = t_2 = R_2C_2 \log_e 2 \qquad (4.22)$$

where a small change occurs in any of these components R_1, R_2, C_1 or C_2 t_1 will differ from t_2 by Δt. A high impedance d.c. voltmeter connected between points A and B will indicate a small out of balance voltage e_o. If E is the amplitude of the square pulse

$$e_o = \frac{E(t + \Delta t) - Et}{2t + \Delta t} = \frac{E\,\Delta t}{2t + \Delta t} \qquad (4.23)$$

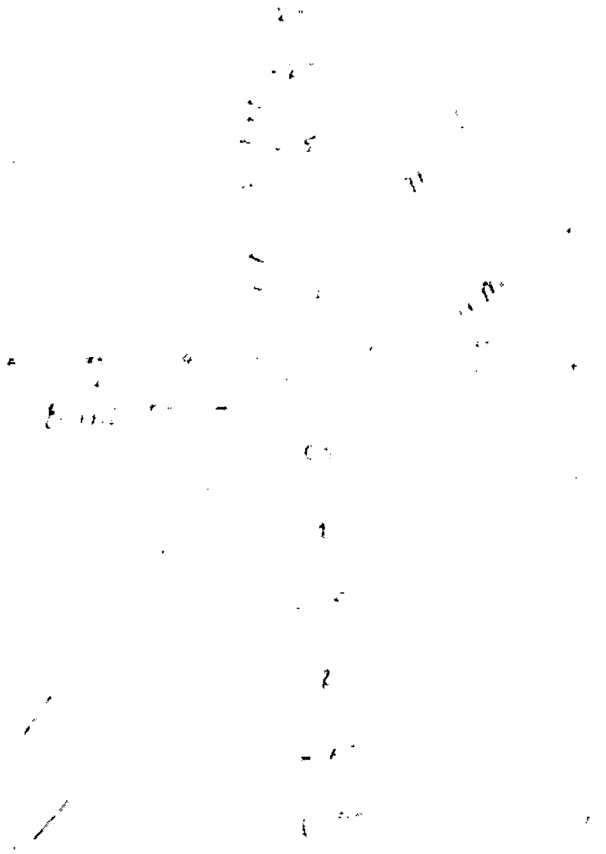
t being dependent on ΔK or ΔC

$$e_o = \frac{E\,\Delta R}{2R + \Delta R} \text{ or } \frac{E\,\Delta C}{2C + \Delta C} \qquad (4.24)$$

If R_1 or R_2 is substituted by a non-linear resistor, it was found to introduce a curvature into the calibration of opposite direction to that due to the natural nonlinearity of the bridge itself. As a result the output of the bridge is proportional to temperature over a much wider range than a linear resistance of similar resistivity.

P.T.C. sensistor, Silicon transistor and Germanium transistor have each been substituted for R_1 or R_2, the transistor in the open base configuration. Sensitivities of 73 mv/°C for P.T.C. resistors and 83 mv/°C for silicon transistor (2N3638) from 15 to 40°C and 650 mv/°C for Ge transistor over an 18°C have been reported (fig.4.16).

[illegible]



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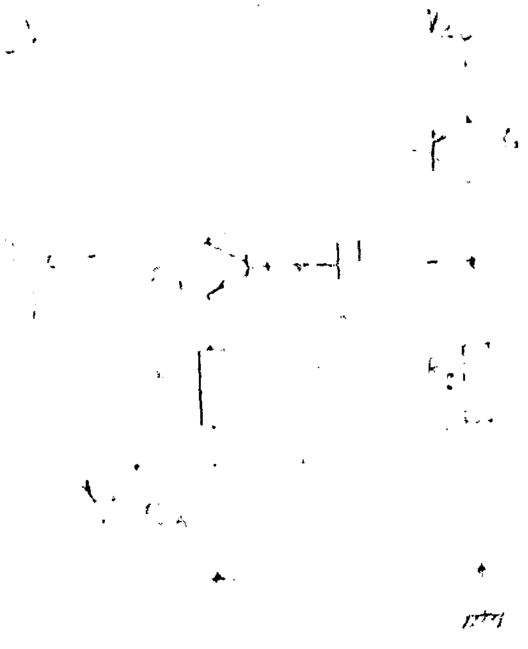
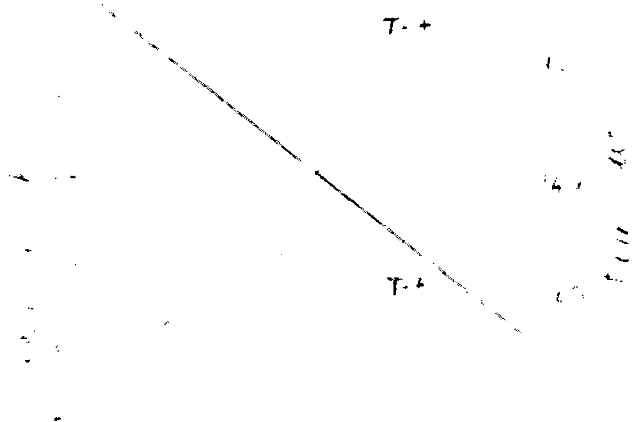




[illegible]

The disadvantages of the transistor are their bulk and the large time constants of 20 s or more, which limits their application to slowly varying temperature and for measurements of temperature gradients.

As already stated, linearity is achieved over a limited range of temperature. Greater linearity has been obtained by linearising the astable multivibrator around the point of its inflection, the condition being[44]

$$R_2C_2 = C_1R_o (B - 2T_o) / (B + 2T_o)$$

This gives for output voltage at inflection point

$$V_{To} = V_p(2To/B)$$

At the point of inflection, the a.m.v bridge is unbalanced having output voltage independent of bridge element relations. At the inflection point the sensitivity of the a.m.v bridge is twice that of the wheat stone bridge and there are only two adjustable parameter R_1 C_1 and R_2 C_2, the two time constants t_1 & t_2 in this case, compared to four elements in the Wheat stone bridge.

4.3.7 Monostable multi-vibrator bridge

The monostable multivibrator bridge (mmb) with constant triggering pulse frequency has a linear resistance voltage characteristic. Because of this reason a linear temperature to voltage characteristic could be obtained if thermistor with linearised temperature resistance characteristic is used (parallel connection of passive resistor with thermistor).

The thermistor m.m.b with constant triggering pulse frequency represents a simple linear temperature to time converter.

If the triggering pulse for the m.m.b are supplied by a linearised amb[45] i.e. by a linearised temperature to frequency converter still higher sensitivities could be obtained.

The mmb linearly measures frequency deviations of the triggering pulses. It's sensitivity is higher than the amb and the mmb with constant triggering pulse . The temperature-voltage characteristics of these bridges are shown in fig. 4.17.

4.3.8 Complementary multivibrator

By using thermistor in place of the resistance determining frequency of the complementary multivibrator[46] temperature and temperature differences could be converted directly into frequency or time.

Fig. 4.18 shows a complementary astable multivibrator the frequency of which is controlled by the temperature sensitive current generator consisting of transistor Q_3 and thermistor network $R_e(\theta)$. The thermistor is linearised by the network. The conversion of temperature (T) to frequency (f) enables digital readout facility which is slowly but steadily displacing the analogue readout.

4.4 COMPARISON

Various techniques of linearisation of the sensor itself invariably of the semiconductor thermoresistor - thermistor has been dealt with. In certain situations where the operation is restricted to a limited range of temperature these techniques could easily be applied with the concomitant simplicity in circuitry and economy. Where the range of operation is wide, greater accuracy and sensitivity are desired the other technique, function generator to match the total output characteristic could be applied. This appears to be the most versatile method as far as analogue signal conditioning is concerned. The logarithmic and antilogarithmic operators could in this light be considered as a special or specific form of function generators. All these techniques become perhaps absolete in the charisma of the digital technology which is fast replacing analogue techniques of display largely due to computer facility and ease of interfacing with it besides the more psychological satisfaction of dealing directly with numbers rather than positions or lines. In this context the multivibrator bridges could find greater application as the output could be obtained in the form of pulses and the frequency can be counted by an electronic counter, or digital display for the specific purpose could be built in directly with out going through the process of A/D conversions. In spite of this it appears the analogue system could not be thrown over board as still the method of permanent recording in easily recognisable and direct access form is the strip chart recording may be with ink or inkless type. Although other system of recording such as tape or micro film is possible the same cycle of conversion back has to be gone through to make the data available again, with accidental loss being perhaps a salient feature.

Finally the choice of the particular linearising technique is dictated by the requirements of the measuring system and for all that may needs not to be resorted to.

5. DEVELOPMENT OF THERMISTOR FLOWMETER

5.1 INTRODUCTION

Basic works to facilitate the development of thermistor flowmeter have been available. A thermistor flowmeter developed for the measurement of blood flow and cardiac output has been reported. Here a silver tube is heated by means of a heating coil and the thermistors constituting two arms of a bridge circuit measure the temperature difference between the heated body and the passing blood. The thermistors act as differential temperature thermometer. The bridge is supplied with pulsed voltage of fixed amplitude and the current through the thermistors is limited so that self heating is negligible. The power dissipated, in other words is limited to a few microwatts. In other cases the ambient fluid temperature fluctuation is eliminated by establishing the relative fluid velocity by rotating the thermistor probe in a dewar bottle containing the liquid[20] or by passing the liquid at constant temperature[22] through a pipe wherein the thermistor probe is situated. These obviate the need for self compensation due to ambient temperature variations.

In other thermal flow meter also it appears compensation for temperature changes of the fluid is not provided. For example, in the case of velocity measurement in air using hot wire anemometer, the probe measures the stream velocity and the temperature at the stagnation point is seperately measured and corrections applied or velocity is obtained from graphs or tables for given temperature changes.

The problem of self compensation becomes more accentuated when thermistors are used in the self heated mode compared to the indirectly heated or non self heated modes (as in thermometry).

If a thermistor flow meter is to operate successfully and on a continuous basis, i.e. if it is to become an effective competitor to the conventional flowmeters, it is important that its indication be true under practical conditions of operations. This implies in other words that reference to graphs and charts or periodical calibration be not resorted too often. For this requirement self compensation for fluid temperature fluctuation is necessary. Further the flow rate has to be direct on an indicating meter and be susceptible to recording and or time integration for purposes of flow totalisation.

The velocities encountered in practice are rather large and flow is invariably turbulant especially in pipe or pressure flows where Reynolds number is of order $5x10^5$ or greater. Laminar flow is rarely encountered (Reynold number < 2400). The data sofar available has been in addition to the restrictions on temperature, been limited to a maximum liquid velocity of 75 cms/sec.

In this chapter an attempt is being made to further extend the operating range of thermistor flowmeter and linearise it to give output directly in terms of velocity.

5.2 PRINCIPLE USED.

A bead thermistor, is self heated by the passage of current through it to a temperature higher than that of the liquid media, in which the velocity or flow measurement is to be made. Due to the flow velocity the heat from the thermistor is removed, its temperature reduces, therefore its resistance increases. This increase of resistance changes the current through the thermistor and the voltage across it. By measuring one of these and calibrating the probe for a set of conditions it is possible to measure flow velocities in other similar situations.

The heat from a heated body, placed across the flow, (thermistor) is mainly removed by forced convection[47] and the amount of heat removed depends on the difference in temperature between the thermistor (or its encapsulation surface) and the flowing liquid, the thermal conductivity of the fluid, and certain nondimensional parameters[48] as Reynolds number (R_n), the Prandtl number (P_r), and the Nusselt number (N_u). A theoretical calculations of the flow velocity and heat transport relation is quite complicated and therefore it has not been attempted here.

The thermistor probe is calibrated instead , under different flow conditions and ambient temperature variations, to evaluate its performance. Based on these results signal conditioning is attempted to provide an indication of flow velocity directly. The object is to achieve flow measurement as simply as possible. Further the measurement is limited to average flow velocities. Rapidly fluctuating or instantaneous turbulent flow velocities are not considered because of the relatively large time constants of practically all thermistors. Even for this it is advantageous to have thermistors with short time constant so as to respond to slow variations.

The liquid that flows over the velocity sensing probe also flows over a temperature compensating thermistor around which a stagnation chamber is created so that it is not subjected to flow velocity, thus providing compensation to fluid ambient temperature change .

5.3 FLOWMETER SCEMATICS.

Fig. 5.1 shows the block schematic of the flowmeter. A thermistor probe introduced into the flowing fluid unbalance a bridge and its output e_o is given to an amplifier which raises the voltage level suitable to feed in the linearising amplifier. The linearising circuit also amplifies the input signal v_i and its output is fed to a moving coil voltmeter, which reads directly the velocity. It can be scaled to read flow directly provided the area of crosssection of flow and a section is created where at velocity distribution is uniform.

5.4 SENSOR.

5.4.1 Thermistor Selection.

The thermistor is self heated and placed in flowing water to measure its velocity. Due to velocity of flow the heat is carried away by the liquid. The quantity of heat generated should be such as to develop the thermistor temperature to a particular value for a particular velocity. In other words temperature drop must be a function of velocity. The heat developed in the thermistor due to flow of current is given by

$$q_1 = i^2R_i \text{ watts} \qquad 5.1$$

$$= C_q.i^2R_i \text{ heat units} \qquad 5.2$$

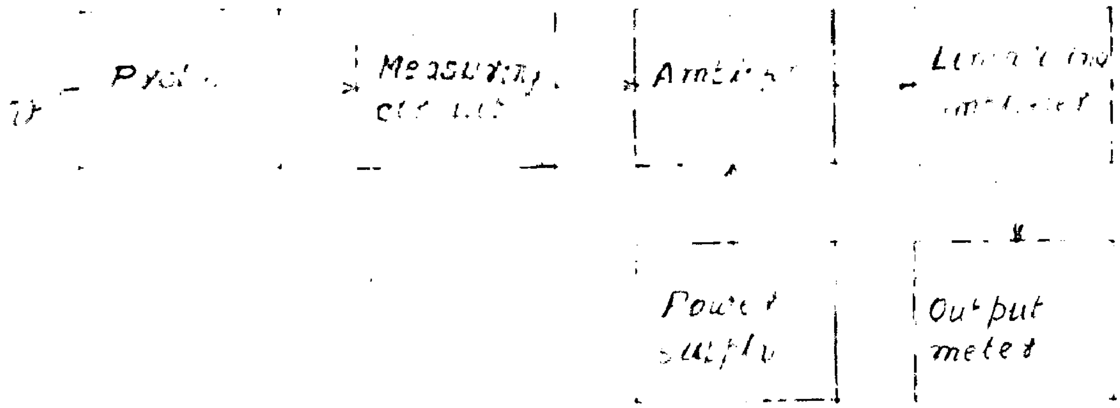


Fig. 5.1. Block schematic of flow meter

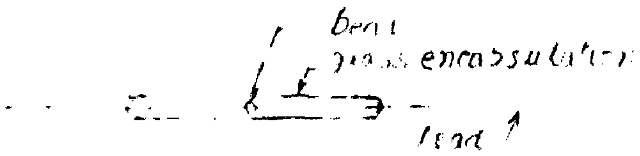


Fig. 5.2 Thermistor

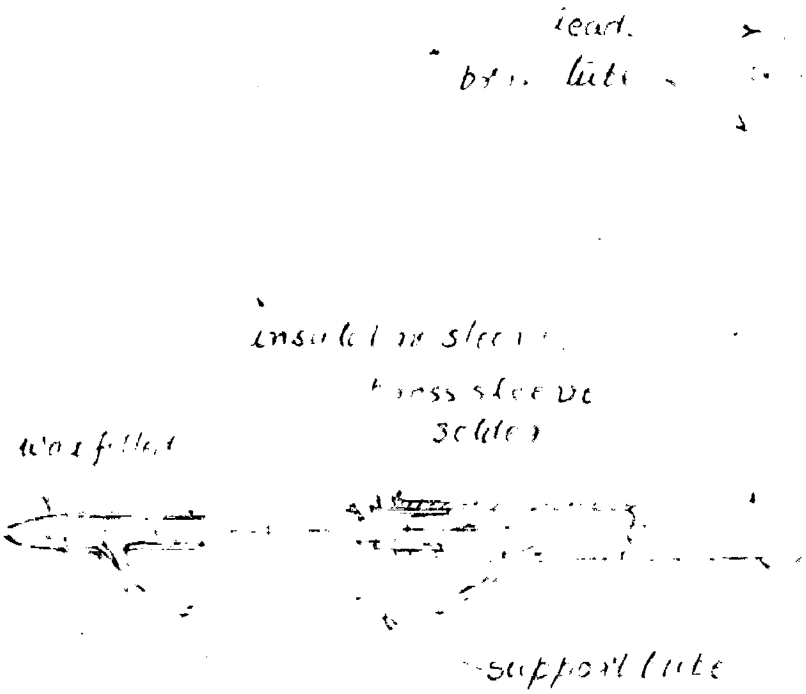


Fig. 5.3. Thermistor probe 'A'.

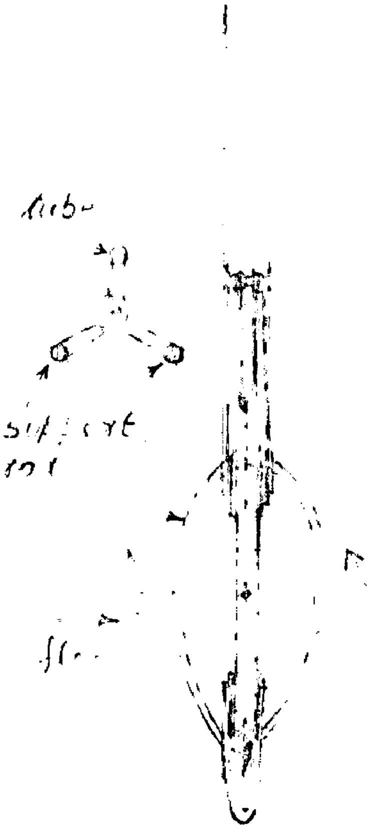


Fig. 5.4 Thermistor probe 'B'

where R_i is the thermistor resistance at current i

C_q is a conversion factor for electrical power to heat unit.

The heat transferred from the heated thermistor, the thermistor being considered as a cylinder of diameter (D_o) and length (L) is dependent on Nusselt number, Prandtl number of fluid P_{rf} and Reynold's number R_{nD} where suffix D here stands for diameter of the thermistor outer most heat convecting surface.

These factors are related by the equation[50]

$$\frac{\bar{h}_c D_o}{K_f} = K.\, R_{nD}^{\ m} \cdot P_{rf}^{\ n} \qquad 5.3$$

where $\bar{h}_c$ = heat transfer coefficient.

K_f = thermal conductivity of the fluid at mean film temperature T_m

P_{rf} = Prandtl number for the fluid at T_m

K, m, n have values given in the table below -

R_{nD}	K	m	n
0.1 - 50	0.91	0.385	0.31
50 - 10,000	0.60	0.5	0.31

From this relation the heat transfer coefficient as a function of velocity can be obtained. Calculate the quantity of heat required as a function of velocity and thereby determine the range of current for the given velocity range of interest from equation 5.2 and 5.4. Thus

$$q = C_3 v^{1/2} \pi D_o^{1/2} L \Delta T \qquad 5.4$$

$$\text{or} \quad q = C\sqrt{v} \qquad 5.5$$

From 5.4 it is evident that the cylindrical surface D_oL proportionately effects the quantity of heat or power. To limit this within reasonable limits and thermistor ratings D_oL has to be reduced to the minimum. This is also a function of R_{nD} and smaller R_{nD} the smaller is the quantity of heat required and power dissipated. As a rough indication for a bead thermistor of diameter 1 mm and length 1 mm the power required is 210 mW for a velocity of 0 - 0.5 m/s as shown at A 3.

As thermistor of the required dimensions could not be procured, experiments were conducted with an available glass encapsulated bead thermistor

5.4.2 Thermistor Specifications

Type = Glass encapsulated type BA21K5
Material constant = B = 3000
Power dissipation = 0.06 W
Temperature = 200°C
Resistance R_{25} = 1500 ± 20 %

Resistance in ohms at	0°C	50°C	100°C	150°C
	3750	690	200	36

Dissipation constant = 0.35 mW/°C

Time constant = 5 secs.

Current at P_{max} = 40 mA.

Threshold voltage at 25°C = 2.2 v

These thermistors are of the axial lead type. The overall length of the glass encapsulation is 32 mm and diameter 2.5 mm with the thermistor bead situated at about the middle of the glass tube (fig. 5.2).

5.4.3 Probe Construction

Two types of probes were fabricated. In type A the thermistor is mounted such that it is parallel to the flow (fig. 5.3). In type B the thermistor is mounted so as to be perpendicular to the axis of flow (fig. 5.4).

Probe A is of bent brass tube of inside diameter of 4 mm and outside diameter of 5 mm. It has an auxiliary tube of 1.5 mm I.D. by 2.5 mm O.D. with a tip tube of 3 mm I.D. acting as a mechanical support for the glass tube and carrying the lead. This tube is soldered on to the main brass tube through the inside of which both the leads are taken out. A small piece of very thin brass tube (2.5 mm I.D. x 3 mm O.D.) is inserted with a cambric sleeve to make it fit tight into the main tube and limit heat conduction. Leads are taken out through the main tube and the support tube, the thermistor leads are soldered to this and carefully pushed in and its body seated in. Wax is melted and poured over the open end of t the support tube and over the cambric sleeve to form a water sealant and lead insulation.

Probe B is also like wise made. Here the thermistor is perpendicular to flow or along the axis of the main support tube. Three supports are provided, two of steel rods and the other a small brass tube through which lead is taken as in type A. The supports are spaced 120° apart on the tube surface.

5.4.4 Preliminary Studies on the Sensor

Preliminary experiments were conducted to determine the thermistor characteristics and choose the operating point. The thermistor V-I characteristics is plotted for ambient temperature in water and in air (fig. 5.5). From this plot a curve of current Vs Resistance of the thermistor was derived. From the resistance temperature curve of the thermistor its resistance at a given temperature is used. From the I Vs R curve at this resistance value the current is known. Thus for any desired temperature the current to be passed through the thermistor is known or the thermistor bias current can thus be decided to produce a certain temperature at the thermistor surface. From the data, the over heat ratio, that is the ratio of the thermistor temperature to the water temperature can be decided. The heat transfer from the thermistor to the water depends on the difference in temperature between these two and hence the velocity measurement

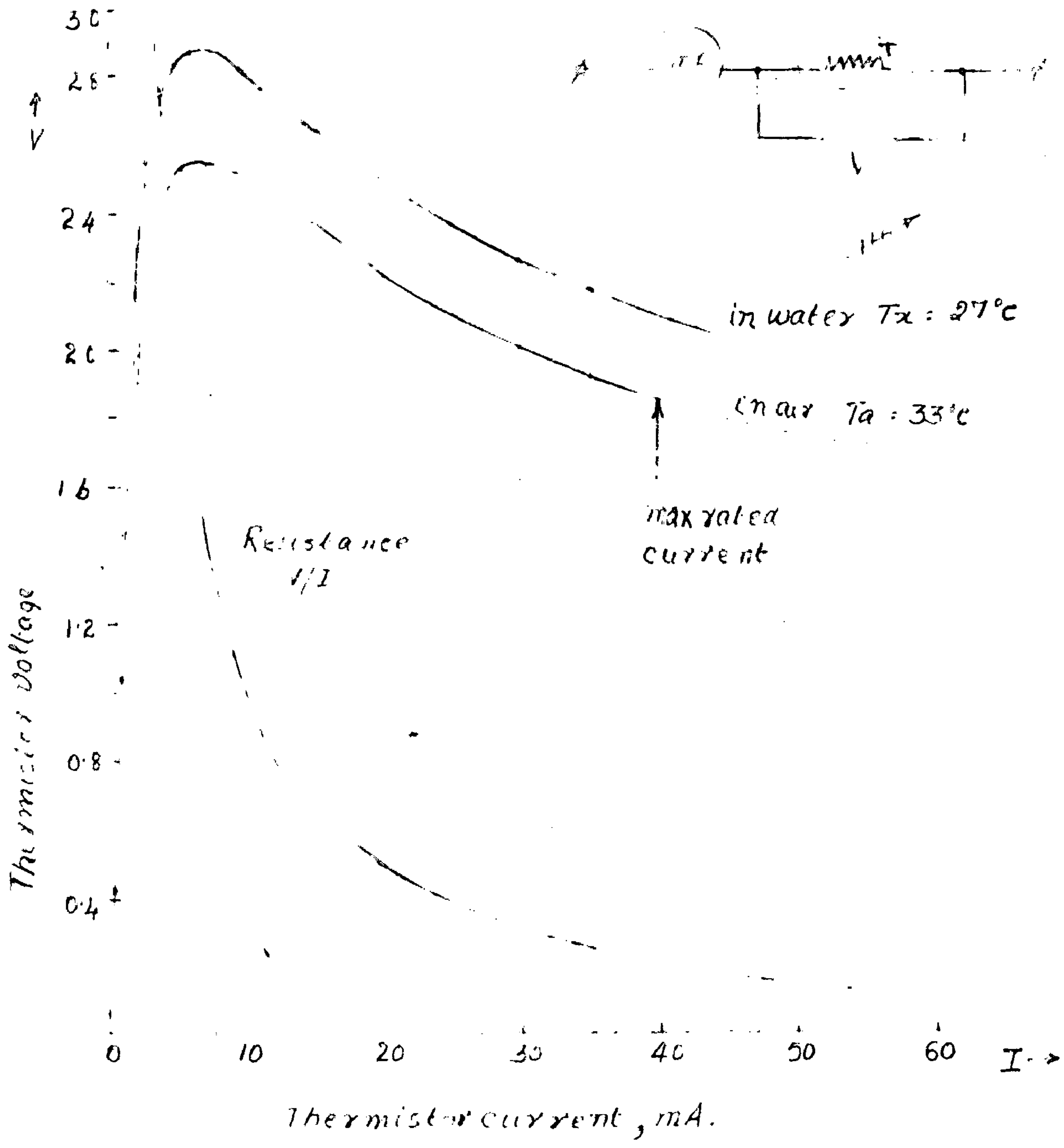


FIG: 5.6. Thermistor V-I characteristic

range.

A bridge circuit is assembled consting of two thermistors in adjacent arms. The temperatures of these thermistors are varied by using a constant temperature bath. For various difference in temperature the bridge output is shown in fig.5.6. The maximum temperature to which the thermistor have been exposed is 74°C. For the same differences in temperature but different reference temperatures, the bridge outputs agreed closely with the curve fig 5.6 if not coincided.

5.5 LINEARISATION

The actual velocity Vs bridge output curve could not be obtained for reasons already mentioned. Hence for the purpose of completing the flowmeter, a curve of the type shown in fig. 5.7 is assumed for the velocity Vs bridge output voltage relation on the basis of the previous works and the curve is linearised.

The principle of the diode function generator has been described earlier in section 4.3. Here a five segment diode function generator is designed to give the inverse curve of that shown in fig. 5.7 and denoted assumed linearising curve in fig. 5.8. In the region 0 - 1 m/s in fig 5.7 the slope of the curve de_0/dv is large and in the linearising curve this slope must be small so that the resultant of the two is midway between these two curves. In the same manner the slope required at other points are determined and fixed by the resistor network.

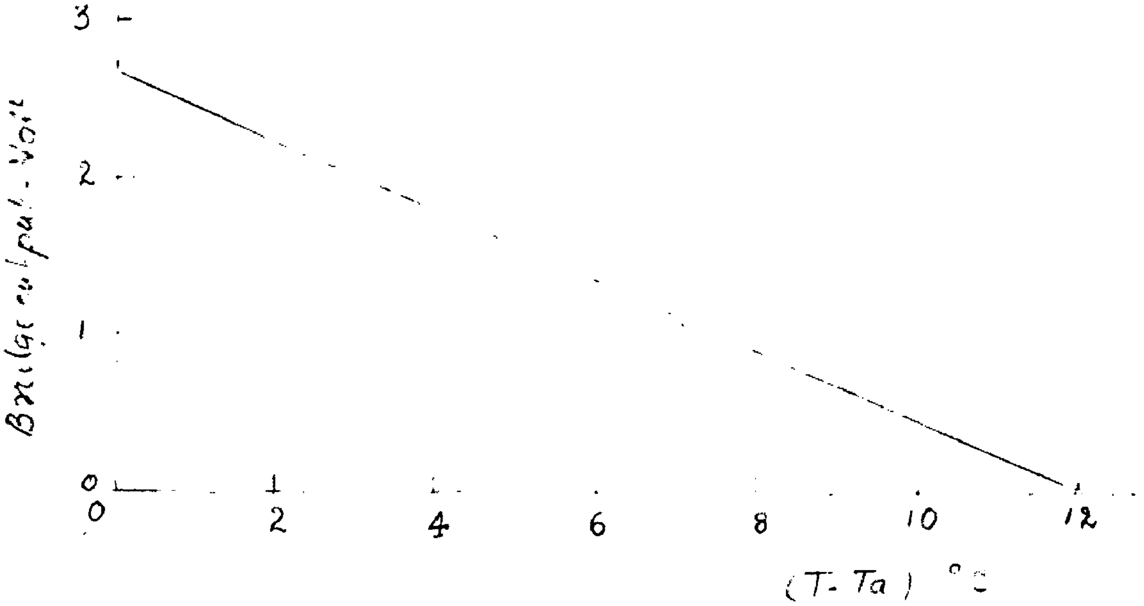


FIG.56 Bridge output vs temperature difference

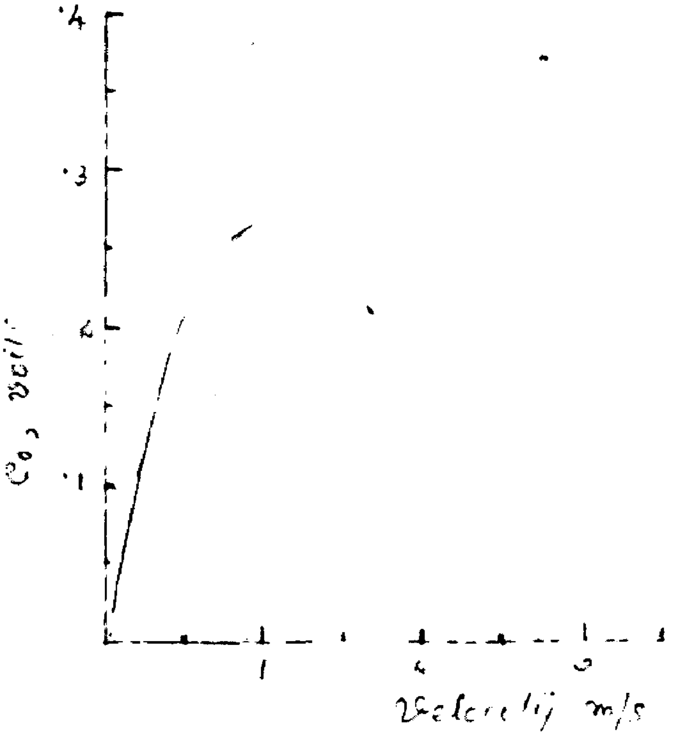


FIG. 57 Assumed V vs Eo Curve

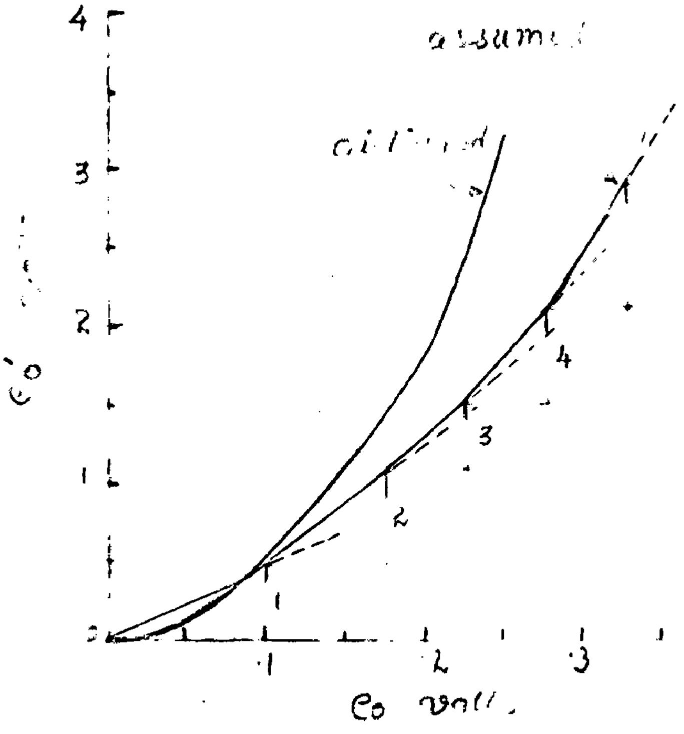


FIG 58. Linearizing curves

5.6 COMPLETE CIRCUIT OF THE FLOW METER

The complete flow meter circuit comprises of a Wheat Stone bridge circuit employing thermistor in one arm (fig.5.9) or two thermistors in adjacent arm (fig.5.10) incorporating temperature compensation , a bridge supply, bridge amplifier and linearising amplifier (fig.5.11).

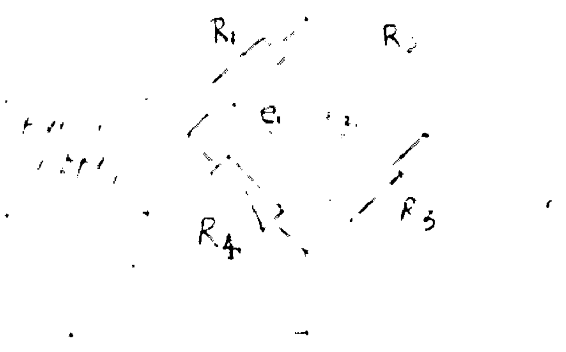
5.6.1 Bridge Supply

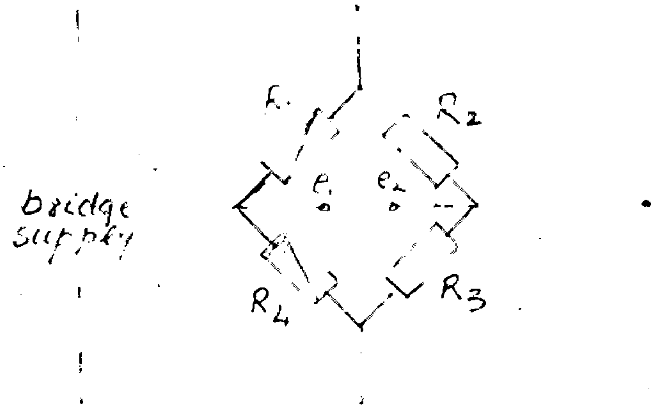
The thermistor bridge used is that shown in fig.5.10 i.e. the two thermistor temperature compensating type. The bridge is supplied through a constant current source.

This constant current source (fig. 5.11) consists of a transistor Q_1, an emitter resistance comprising a fixed value resistors R_{11} to limit the maximum current in series with a variable resistance R_{12}, so that current in the range of 5 to 50 mA could be supplied to the bridge. This transistor base is biased through R_{10} and zener diode D_0, so that the base bias remains constant for small changes in the supply voltage.

5.6.2 Bridge amplifier

The bridge amplifier consists of an operational amplifier A_1 operated in the differential mode, to which the bridge unbalance voltage is connected. The gain of this amplifier is set, decided by R_{14} and R_{13}. This amplifier output is thus $(e_1 - e_2) \frac{R_{14}}{R_{13}} = v_1$. This is the voltage applied to the linearising amplifiers . The bridge output for temperature





… 5.9 Bridge with one thermistor Fig: 5.10 Bridge with two thermistors

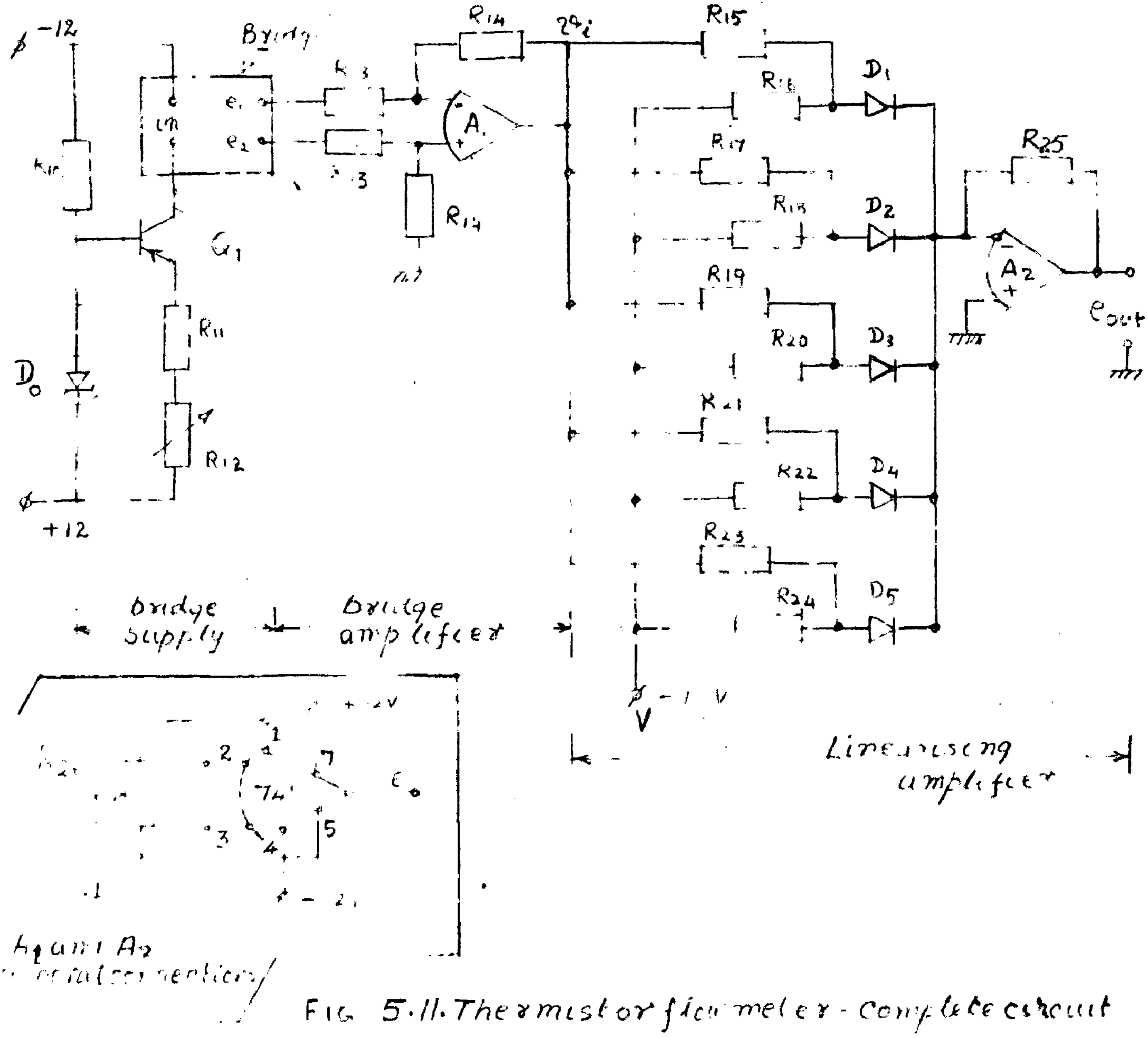


FIG. 5.11. Thermistor flowmeter - complete circuit

difference has been obtained as shown in fig.5.6

5.6.3 Linearising amplifier

The basic linearising circuit has been described earlier. This linearising amplifier is a network of diodes, diode biasing resistors and slope deciding resistors. The diodes start conducting in succession when v_i excludes the diodes reverse bias. The linearising circuit is a five segment diode function generator.

The linearising curve necessary for the assumed velocity Vs output relation is shown in fig. 5.8. Points 1.2...5 denote the position at which slope for the linearising circuit are determined. In the circuit the slope is determined by the ratio of R_{15}, R_{17}.... to R_{25} and the corresponding break points to these positions are decided by the chain of resistors R_{16}, R_{18}.... R_{24}. These are in all 5 diodes, 5 break point resistors and 5 slope resistors in this 5 segment function generator.

For the output meter a milliammeter converted to read 0 - 5 volts full scale is used.

5.7 TEST RESULT

Some of these results have already been presented. In fig.5.8 is shown the V.I. characteristics of the thermistor

In fig. 5.8 is shown the curve obtained for known inputs at the linearising amplifier input. The curves differ slightly because of the deviation in component values. The curve is smooth and without sharp corners that are present due to segmentisation on account of the cut in part of the diodes being not sharp and well defined as in the idealised diode characteristic, which is all the more better for this purpose.

6. CONCLUSION

In the preceeding chapters, a survey of various types of conventional flow meters some pressure measuring devices and some not so unconventional flow measuring devices, their range and applications have been dealt. The number and types of these devices dealt with are quite large but is not likely to be complete .

The thermal flow meter of the hot film and hot wire type and the grid or foil type[49] which is an alternative to the hot film type of device being more rugged and less susaptible to burn outs have been mainly intended for gas or air flow studies. The film and the foil type have been tried on liquid flow measurement but not found satisfactory.

The sensitivity of thermistor to flow velocity and fluid temperature fluctuations and their limiting values have been brought out. Linearisation of the nonlinear output characteristics have been considered.

A flow probe using thermistor was constructed and assuming hyperbolic velocity output relation this characteristic has been linearised based on piecewise linearisation through function generation using diodes. It is possible to adjust the slope and cut-in points by introducing presents in series with the resistors determining the break point (r's) and with slope deciding resistors (R) (fig. 4·8), and also have either positive or negative slopes. Thus this technique of linearisation could be applied practically to any type of output curve to obtain linearity.

Thermistors have been used to measure low velocities in the laminar region. The aim here has been to extend this to higher velocities and also to turbulent conditions of course not minding the low frequency response of the thermistor

In the literature cited, velocity measurement appears not to have been the prime purpose, but measurement of temperature at various levels as the probe was lowered at a certain speed into the ocean in oceanographic studies.

It is felt if thermistor are to be successfully applied to velocity measurements, other techniques have to be tried.

In this context it is possible, semiconducting oxide film deposited on a ceramic substrate, like the hot film probe, and glass coated, may be in a position to measure fluctuating fluid velocities more successfully. The dimensions have to be quite small in order that R_{nD} is small and the power requirements are with-in the thermistor ratings. If only commercial thermistor are to be used, the smallest available should be examined from the point of limiting R_{nD} for the values of velocities to be encountered.

For temperature compensation it is not necessary to use an identical thermistor as the velocity measuring one, but one having similar temperature coefficient of resistance as the velocity sensing thermistor in its operating range, which need not be small unless the temperature fluctuation of the liquid also are rapid which in practice is not likely.

The future course of work, hence, profitally could be devoted to thin film thermistor deposition on ceramic substrate and temperature compensation through a commercial thermistor. After all innovation is the call of times. If the time constant could be effictively reduced to a few milliseconds or less, this could prove itself to be a very useful flow study device. Directional sensitivity could also be achieved by depositing the thermistor on a ceramic substrate. These measures it is felt could reduce if not eliminate the short falls of the thermistors in fluid flow applications. Further by employing one of the multivibrator bridge circuits and frequency counting or voltage to frequency conversion of the bridge output voltage e_o and frequency counting the current trend towards digitisation and digital readout can also be met with.

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8. APPENDIX

APPENDIX - A1

FLUID PROPERTIES/ TERMINOLOGY

Some of the terms and nomenclature used in connection with fluid flow are given below :

1. Mass density is the mass per unit volume and is generally denoted by

$$\rho = \frac{\text{Mass}}{\text{Volume}}$$

2. Weight density or specific weight is the weight of fluid mass per unit volume and is denoted by or

$$\gamma = \frac{\text{Weight of fluid}}{\text{Volume of the fluid}} = \frac{W}{V} = \frac{M}{V} \cdot g$$

where g = acceleration due to gravity

3. Viscosity is that property of a fluid which resists relative motion of its adjacent layers. The relative velocity between adjacent fluid layers introduces shear stress f_s which is proportional to the velocity gradient, dv/dy

The shear stress $= f_s = \mu \cdot \frac{dv}{dy}$

Here μ is called coefficient of viscosity or simply viscosity.

4. Kinematic viscosity is the ratio of the absolute viscosity to the mass density and is denoted by

$$\nu = \frac{\mu}{\rho} = \frac{\mu}{w/g}$$

Both μ, ν vary with temperature

5. Reynolds number R_n is the ratio of inertia forces to viscous forces. It is an important non-dimensional number

$$R_n = \frac{v.d}{\nu}$$

where v = velocity of the fluid

d = significant dimensions

ν = kinematic viscosity

The dimensions of importance in case of thermistor in fluid path is its diameter and the Reynolds number is R_{nD}.

6. Laminar or viscous flow is one in which fluid particles move in layers or laminae and there is no exchange of particles

between adjacent layers. The flow of fluids in pipe when R_n is less than 2100 is laminar.

7. Turbulant flow is one wherein the velocity varies from point to point in the flow path in both direction and magnitude and from instant to instant. The flow of fluid in pipe when R_n is greater than 3000 is turbulant.

8. Bernoulli's theorem :

The total energy of a flowing liquid comprising of kinetic energy, potential energy and elevation energy remains constant.

Considering two points 1, 2 in a flow path, where p, v, Z denote respectively the pressure, velocity and elevation the Bernoulli's equation is

$$\frac{p_1}{\gamma} + \frac{v_1^2}{2g} + Z = \frac{p_2}{\gamma} + \frac{v_2^2}{2g} + Z + h_{12}$$

where h_{12} is the loss of head between points 1 and 2.

APPENDIX - A2

HEAT TRANSFER

Flow measurement using thermal techniques depend on the heat transfer from the heated sensor, either wire, film or the thermistor to the surrounding body. This heat transfer the most important being convective heat transfer as far as liquids are concerned is governed by the heat transfer coefficient between the heated body and the surrounding fluid. Some non-dimensional numbers of importance in this regard are given below

Nusselt number (N_u) is the ratio of the temperature gradient in the fluid immediately in contact with the surface to a reference temperature gradient.

$$N_u = \frac{\bar{h}cL}{K_f}$$

where L is a significant length

K_f is the conductivity of the fluid at mean film temperature.

Prandtl number (P_r) is a function of fluid properties. It is defined as the ratio of Kinematic viscosity of the fluid to the thermal diffusivity of the fluid

$$P_r = \frac{\nu}{a}$$

where a is the thirmal diffusivity of the fluid or the molecular diffusivity of heat $= K_f/c_p$

where c_p is the specific heat at constant pressure

$$N_u = f(R_{nD}, P_r)$$

APPENDIX - A3

THERMISTOR SELECTION CONSIDERATION

Considering a thermistor bead of diameter (Do) 1 mm, length (L) 1 mm with glass encapsulation and uniform surface temperature, neglibible conductive and radiant heat transfer,

$$Nu = \frac{\bar{h}_o . D_o}{K_f} = K . R_{nD}^{m} . P_{rf}^{n} \qquad A\ 3.1$$

Further assuming R_{nD} in the range of 50 to 10000,

$m = 0.5$, $n = 0.31$ and $K = 0.6$

Let the fluid temperature = Tx = 30°C

Let the bead surface temp. = T_s = 60°C

The difference in temp = T = 30°C

$$\text{The mean film temp.} = \frac{30 + 60}{2} = 45^{\circ}C$$

At this mean temperature $K_f = .37$

$$q = \bar{h}_o . A . T. \text{ heat units/hr} \qquad A\ 3.2$$

$$\bar{h}o = \frac{K . K_f}{D_o} . \frac{v^{1/2} . D_o^{1/2}}{\nu^{1/2}} P_{rf}^{.31}$$

$$= \left(\frac{K . K_f P_{rf}^{.31}}{\nu^{1/2}} \right) \left(\frac{v}{D_o} \right)^{1/2} \qquad A\ 3.3$$

at a given temperature K_f, P_{rf}, ν are constant so that

$$\bar{h}o = C_2 \left(\frac{v}{D_o} \right)^{1/2} \qquad A\ 3.4$$

and $q = C_2 \left(\frac{v}{D_o} \right)^{1/2} \pi D_o . L . \Delta T$ or

$$q = C_3 v^{1/2} D_o^{1/2} L \Delta T. \qquad A\ 3.5$$

here C_3 includes a conversion factor to the electrical power in watts required. It is clear q is directly proportional to $D_o^{1/2} L$ for a given velocity.

Hence the conclusion that D and L should be as small as possible to limit thermistor power dissipation

For the example considered

$$q = .308 \sqrt{v} \text{ watts}$$

For a velocity of say .5 m/s power required is

$$q = .308 \sqrt{.5} = .21 \text{ or } 210 \text{ mW}.$$