CALIBRATION OF CAPILLARY TYPE THERMAL MASS FLOWMETER

A PROJECT REPORT SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

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By

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CERTIFICATE

This is to certify that the project work entitled "**Calibration of Capillary Type Thermal Mass Flow meter**" by **Sriyanka Agrawal;** has been carried out under my supervision in partial fulfillment of the requirements for the degree of **Bachelor of Technology** during session 2008-09 in the Department of **Mechanical Engineering**, **National Institute of Technology, Rourkela** and this work has not been submitted elsewhere for a degree.

Place: Rourkela
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ABSTRACT

In the capillary type thermal mass flow meter the sensor is a small diameter stainless steel or constantan capillary, heated by an electric current. The heat is supplied either at the central point or over the whole length of the tube. In the absence of gas flow, the temperature profile is symmetric about the mid point. Gas flow through the capillary tube cools the entry section while heating the exit. This introduces an asymmetry in the temperature profile, which is a measure of the fluid flow rate. The asymmetry is measured in terms of difference of temperature between two suitably chosen points on the capillary tube, which are equidistant from the mid point on opposite sides. This temperature difference is a function of the direction and rate of mass flow of the fluid. The focus of this dissertation is to experimentally characterize thermal mass flow meters so as to properly understand their functioning, and to create an adequate knowledge base on the subject. It will significantly facilitate further understanding and development of these devices. Performance a capillary type thermal mass flow meter has also been studied in terms of the different operating parameters.

CHAPTER -1

Introduction

Introduction

In many process industries, mass flow rate, rather than the volume flow rate, is the desired parameter. There are two approaches to measure mass flow rate. In the first approach, volume flow rate is measured and the result is multiplied with density. Flow meters based on the first approach require additional instrumentation such as pressures and temperature sensors to infer mass flow rate. In contrast, flow meters based on the second approach provide direct mass flow measurements which are immune to variations in inlet temperature and pressure. The thermal mass flow meter belongs to the second category and offers an easy and reliable means of measuring gas flow rates.

Thermal Mass Flow meters

Thermal mass flow meters, depending upon the working range and the technique used, can be broadly classified under two categories: (i) Insertion type thermal Mass flow meters and (ii) Capillary type thermal mass flow meters.

Insertion type Thermal Mass Flow meter

These flow meters, based on measurement of heat transfer from a self-heated resistance thermometer, are suitable for high flow rates and can work in both laminar as well as turbulent flow regimes. Two fingers containing platinum resistance thermometers, one in normal operation and the other carrying a larger current for self-heating, are inserted into the flow stream. The difference of power input between the two fingers for achieving a pre-defined temperature difference is a measure of the fluid mass velocity, and thus of the fluid flow rate.

Capillary Type Thermal Mass Flow meter

The capillary type thermal flow meter operates at extremely small flow rates, the flow being necessarily laminar. Asymmetry of temperature profile in a symmetrically heated capillary tube is taken as a measure of fluid flow rate through the tube. A bypass line of large cross section and special geometry is used to increase the range of this basic instrument to work at intermediate flow levels.

Importance of Thermal Mass Flow meter

In many processes, the critical variable is mass, not volume. Volumetric flow measurements are less reliable than mass flow measurements because changes in gas temperature and pressure alter the density of the gas being metered. In contrast to rota meters, turbine meters, and other volumetric flow devices, thermal mass flow meters are relatively immune to changes in inlet temperature and pressure. These flow meter provides the most reliable, repeatable, and accurate method for delivering material at a desired rate to a process. Features, such as direct electronic read out, fast response, exceptional sensitivity at low flow rate, negligible pressure drop, no moving parts, simple installation, unobstructed straight through flow path, absence of temperature or pressure corrections and superior retain accuracy over a wide range of flow rates make thermal mass flow meters a superior alternative to conventional flow meters in many important applications. Some other advantages of this type of flow meter are wide turndown (100:1), accuracy in 2% range, low flow sensitivity, flexibility, reliability, and long life With advances in electronic technology, these flow meters are getting smarter and more capable with microprocessor computing power expanding the range of their usage. In recent years they have become the most important instruments for gas flow measurement in the process industry, offering considerably lower cost than the Coriolis alternative. The only requirement for use of this type of flow meter is that the fluid being metered should be very clean and free from solid or liquid particles that may block the sensor passage.

The technology of the thermal mass flow meter was initially inspired by the space program's need for a reliable, low power device to measure air flow in an astronaut's space suit. Today, thermal mass flow meters are used to measure the flow of gases in a growing range of applications particularly in the electronic and chemical industries. The addition of an electromagnetic control valve turns the mass flow meter into a mass flow controller.. Thermal mass flow meters are also employed for monitoring or controlling mass-related processes such as chemical reactions that depend on the relative masses of un-reacted ingredients. They are thus widely used in automotive industry, utility services, petroleum & gas industries, HVAC, R & D, raw material industries and food processing. In short, thermal mass flow controllers and mass flow meters for gases are among the standard instruments used in industrial laboratory and production processes.

CHAPTER-2

LITERATURE REVIEW

Thermal Mass Flow meters

Thermal flow meters measure mass flow rate directly. They are based on a variety of operating principles, but most involve heat dispersion. The associated physical quantity measured by the meter is the mass velocity or the mass flux that flows through a unit cross-section. A thermal mass flow sensor generates a signal output related to the mass flux [mass flux = $\dot{m}/A = v\rho$] and converts the mechanical variable (mass flow) via a thermal variable (heat transfer) into an electrical signal (current or voltage) that can be processed by, for example, a microcontroller. Fig. 2.11 illustrates the working principle. The working range for any mass flux sensor is dependent on the fluid properties such as thermal conductivity, specific heat and density, but not on the physical state (gas or liquid, temperature or pressure) of the fluid [18].

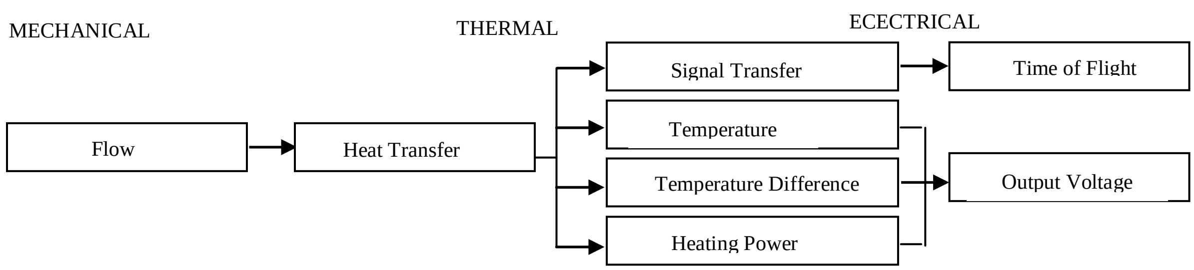


Figure 2.11: The three signal domains and the signal transfer process of a thermal flow sensor

Principles of Thermal Mass Flow meters

Thermal mass flow meters can be grouped under three broad heads. They are:

- Thermal mass flow meters that measure the effect of the flowing fluid on a hot body (increase of heating power with constant heater temperature, decrease of heater temperature with constant heating power). They are usually called hot-wire anemometers, hot-film sensors, or insertion type thermal mass flow meters.
- Thermal mass flow meters that measure the displacement of temperature profile around the heater, which is modulated by the fluid flow. These are called calorimetric sensors.

- Thermal mass flow meters that measure the passage time of a heat pulse over a known distance. They are usually called time-of-flight sensors.

Heat Transfer in the Sensor Tube

The heat transfer scenario in the sensor tube consists of heat generation in the heating wire or over the tube wall, conduction along the tube wall, convection into the gas, and heat loss to the surroundings by natural convection, all the phenomena occurring simultaneously. Most investigators have tried to describe the heat transfer phenomena in the sensor tube with simplifying assumptions. The most common assumptions are:

(1) The temperatures of both ends of the sensor tube remain constant regardless of the mass flow rate.

(2) The temperature of the tube wall is equal to the gas mean temperature in the sensor tube at any cross section.

Alternatively, the Nusselt number is 4.36 (corresponding to constant heat flux condition) at the interface between the tube wall and the gas stream over the entire sensor tube

Design and Manufacturing Features of the Sensor

Capillary type thermal mass flow meters have been designed and manufactured in a wide variety of configurations. In order to get optimum results from the sensor output, researchers have studied different designs and manufacturing methods.

Methods of Heating the Sensor

Thermal mass flow meters exploit the fact that heat transfer from the tube wall to the fluid stream is a function of mass flow rate and the specific heat of the fluid. Different designs have been used to heat the sensor of a mass flow meter. Early designs employed heating the sensor tube with constant power. Later designs included a heating device powered by a constant voltage or a constant current source. In some of the designs, the sensor tube was heated with a resistance winding to which a constant power was applied

Performance Characteristics of Flow Sensors

Many researchers have tried to improve the performance characteristics of thermal mass flow sensors. Accuracy of the sensor assembly is important for good flow control. For high accuracy, it is desirable that the differential temperature reading arises from the heat transferred through the sensor tube by the fluid, and not from other sources. One of the important characteristics of the sensor is its response time. The response of the sensor assembly relates to the speed with which the sensor assembly heats or cools after a change in heater power. A sudden change of airflow should be quickly reflected in the output signal. Quicker response allows the flow to be controlled within finer limits. Fine mass-flow control with a quick response is required for advanced semiconductor processes such as molecular organic CVD, atomic layer epitaxy etc

Gas Correction Factor

There is no accurate and straightforward method for predicting the performance of a thermal flow meter calibrated with one kind of gas but operating with another, because of the complexity of the thermal processes within the flow sensor. Use of a sensor for gases against which it has not been calibrated can lead to large measurement errors. Many times, the process gas is highly reactive or toxic. It is difficult to perform a calibration, even at ambient condition. In this case the common practice is to calibrate a flow meter on a substitute gas that is safer to handle and which matches the thermal characteristics of the process gas as closely as possible. Although most thermal mass flow meter manufacturers provide conversion factors from one gas to another, they also state that large errors can occur for process gases that have not been tested through direct calibration. Because many process gases are hazardous and difficult to handle, very little work has been done to obtain experimental data on them.

CHAPTER-3

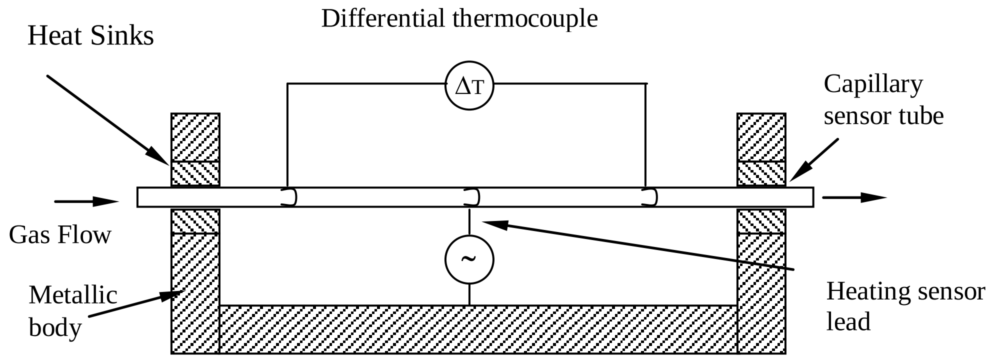
BASIC OPERATING PRINCIPLE

Capillary type Thermal Mass Flow meter

In the capillary type thermal mass flow meter the sensor is a small diameter stainless steel or constantan capillary, heated by an electric current. The heat is supplied either at the central point or over the whole length of the tube. In the absence of gas flow, the temperature profile is symmetric about the mid point. Gas flow through the capillary tube cools the entry section while heating the exit. This introduces an asymmetry in the temperature profile, which is a measure of the fluid flow rate. The asymmetry is measured in terms of difference of temperature between two suitably chosen points on the capillary tube, which are equidistant from the mid point. A fluid flow shunt (by-pass line) is added in parallel to the sensor tube to increase the range of the meter by several orders of magnitude. Flow through both the capillary as well as the by pass line are required to be laminar, often limited to Reynolds number of 50-100 in the sensor (capillary) and 500-1500 in the bypass line.

Basic Operating Principle

The schematic of a thermal mass flow meter is shown in fig. 1.1. The sensor is a small diameter capillary tube with a relatively large length-to-diameter ratio. The heating of the sensor is achieved by passing electric current through its wall or through a coil of this wire wound snugly over the tube. A differential thermocouple is use to find the temperature difference of the two points on the sensor tube. Two heat sinks are attached at the ends of the sensor tube. These heat sinks are required to keep the ends of the sensor tube at room temperature. The principle of the capillary type mass flow meter is that when a fluid flows through a capillary tube heated at the centre and the temperature difference between two suitably chosen points A and B located symmetrically on opposite sides of the mid point is measured , This temperature difference is a function of the direction and rate of mass flow of the fluid.



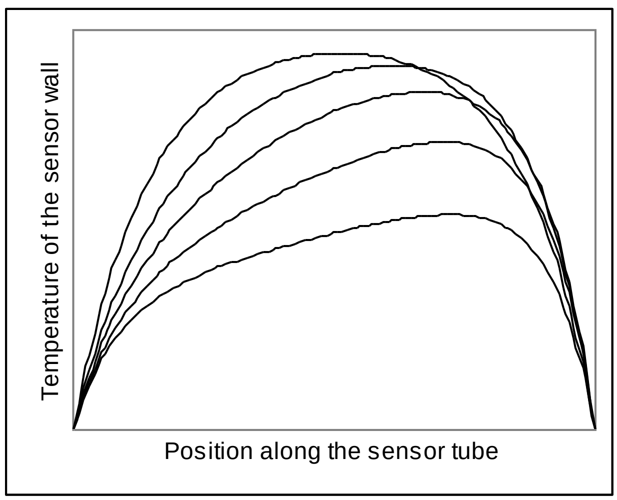


Figure 3.1: Principle of the capillary type thermal mass flow meter

In the absence of gas flow, the temperature profile is symmetric about the mid point (fig. 1.1). When a fluid flows through the sensor tube, the temperature profile gets distorted. Close to the inlet, the fluid stream cools the tube wall, and itself gets heated. On crossing the peak temperature point in the middle of the tube, the heated fluid is warmer than the tube wall; it transfers heat to the tube wall, thereby making it warmer than before. Thus, the peak of the temperature profile become lower and is shifted in the downstream direction, as shown in fig. 1.1. This distortion of the temperature profile is a measure of the mass flow rates though the capillary tube. It is measured in terms of the temperature difference between two points in sensor tube located symmetrically around the mid point. Figure 1.2 shows the typical response (in arbitrary scale) of a capillary type flow sensor in terms of the temperature difference vs. gas flow rate. It may be observed that the response is nearly linear with flow at low flow rates, which makes it possible to build an accurate flow meter based on this principle.

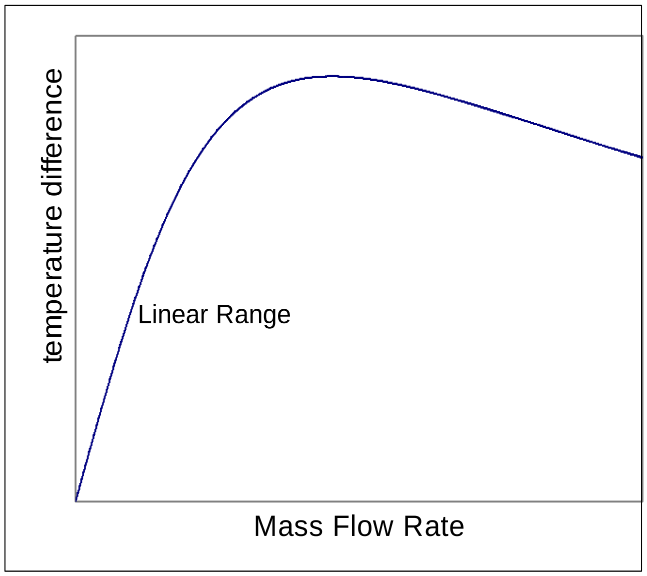


Figure 3.2: Typical response of a capillary type thermal mass flowmeter

Flow By-pass Element

For most capillary type mass flow meter designs, the limitation on flow rate to ensure linearity is approximately 120 or 20cm. To accommodate a larger range of flow and still maintain linearity of the sensor response, a laminar bypass element is employed in parallel with the sensor. In this configuration, the total flow rate through the device is the combined flow rates through the sensor and that through the bypass portion. By maintaining laminar flow within each portion, The split ratio between the sensor and the bypass flow element is maintained independent of Reynolds number, and the total flow rate through the device can be inferred by measuring only the flow through the sensor path. In operation, the laminar bypass element actually carries the major portion of the overall flow through the device with only 0.01 to 0.1% of the total flow passing through the sensing element. The capacity of a flow meter can be changed by changing the cross section of the bypass element, while using the same sensor element and associated electronics.

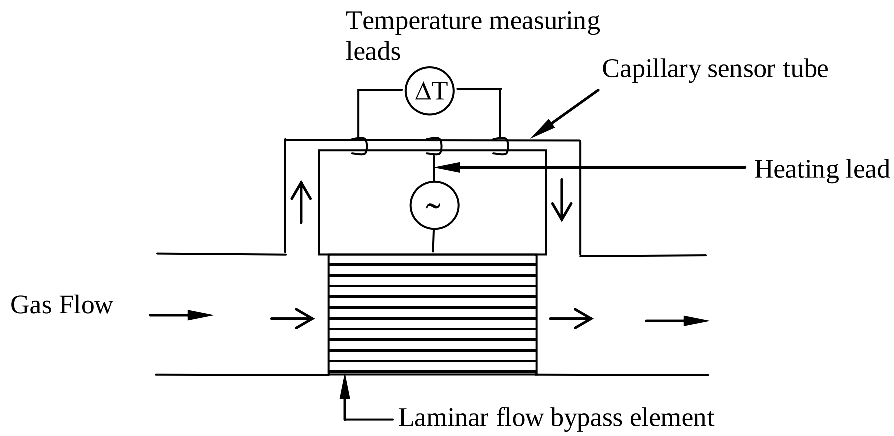


Figure 3.3: Configuration of a capillary type thermal mass flowmeter with laminar flow bypass element

CHAPTER-4

Fabrication of Prototype Flow meter

The capillary type thermal flow meter consists of the sensor assembly, the laminar flow bypass, various connectors, and a printed circuit board incorporating the electronic components. The fluid flow passage consists of the sensor and the shunt (bypass) flow paths.

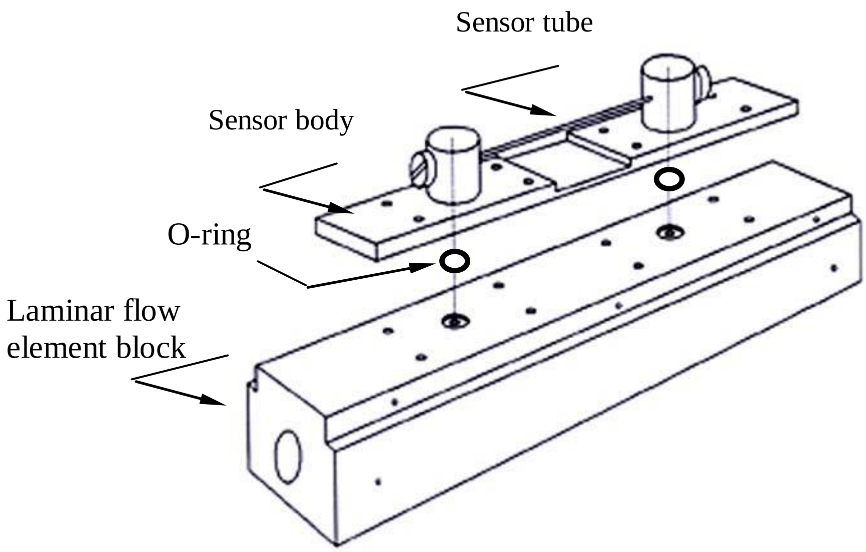


Figure 4.1: sensor body and laminar flow element before assembly

The sensor is essentially made of a thin stainless steel (SS-316) capillary tubing with thin wires embedded on the surface for heating and temperature sensing. The sensor housing, made of brass, consists of two cylindrical blocks fixed at two ends of a flat strip. The cylindrical brass blocks have central bores that serve as the passages for the fluid flowing through the sensor tube. The basic sensor can be used for measuring gas flow up to (say) 20 sccm. An aluminium block containing a laminar flow bypass element is added parallel to the sensor flow path to increase the range of the meter by several orders of magnitude. Elastomeric O-ring seals between the sensor housing and the shunt block surround the bores in the vertical brass cylinders. The brass body containing the sensor element is attached to the aluminium block by a set of screws. Fig. 4.1 shows the sensor body and laminar flow element before assembly.

4.2 Fabrication of the Sensor

The sensor is the most vital component of the thermal mass flow meter. Geometrically, as well as from fabrication point of view, it is also the most crucial component of the system. A thin walled stainless steel tube has been used for the sensor because of appropriate thermal properties and easy availability. The selected tube is 60mm long, 0.58 mm in outer diameter with 0.30 mm in inner diameter. A photograph of the sensor has been shown in Fig. 4.2.

Figure 4.2: The Sensor tube

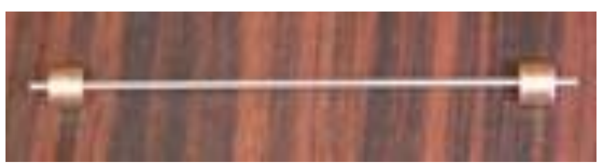


Figure 4.3: Sensor tube with copper blocks

Two small copper blocks are attached to the two ends of the sensor tube to act as intermediate heat sinks. The copper blocks are brazed at the two end of the sensor tube in such a way that the distance between the blocks is 50 mm, which becomes the effective length of the sensor tube. The sensor assembly containing the two copper blocks and the SS tube has been shown in Fig 4.3. Two constantan wires of diameter 40µm are embedded on the exterior of sensor tube at optimally chosen locations to serve as the differential thermocouple. A copper wire of diameter 150µm is attached at the centre of the sensor tube to serve as the lead for the heating current. This sensor tube sub assembly is further attached to a large brass housing, which acts as structural support, and electrical ground and heat sink. Heat sinks are required to maintain the two ends of the capillary at near room temperature. The design of the housing is such that there is a provision for cleaning the sensor tube if it gets clogged accidentally. It consists of two holes of large diameter at the two ends in line with the sensor. The holes are normally closed with screws, which are removed if cleaning of the sensor is necessary.

Fabrication of the sensor element offers many challenges because of its small size and the precision required. Innovative solutions have been employed when demanded by the fabrication process.

Sensor Tube

The dimensions of the capillary sensor tube are given in table 4.1

Table 4.1: Geometrical details of the capillary sensor tube

Feature	**Value**
Part name	Sensor tube
Outer diameter	0.58mm
Inner diameter	0.30mm
Length	64 mm
Material	Stainless Steel (SS316L)
No off	1

The sensor tube stock is cut to size using EDM process. EDM technique is employed to ensure sharp and burr-free ends. To attach the heating and thermocouple wires to the sensor tube at the calculated locations, three grooves of width 0.16 mm and depth of 0.04mm are made on the sensor tube with the help of a watch marker’s lathe. A special hand brazing technique has been devised to attach the heating and the sensing wires to the capillary tube. Hydrogen gas is used in this brazing operation. A special torch was fabricated for the purpose of providing fine control. The tip is made of a short length of 0.19mm ID capillary tube. The advantage of using hydrogen is that it provides a very small but stable flame and eliminates the possibility of carbon deposit. A clean and effective joint is obtained every time. Care has been taken to see that there is no extra braze alloy deposited on the sensor tube. For this purpose, three stainless steel rings are placed over the groves on the sensor tube and a layer of (anti brazing) mould release powder is applied on the tube. When the mould release is dry, the stainless steel rings are removed. The anti brazing powder coating covers the whole surface of the sensor tube except the three grooves. A mixture of powdered silver brazing alloy (43%Ag) and flux is made in the form of a paste. The heating wire and the thermocouple wires are dipped in this paste. A small quantity of the paste is also applied on the grooves. The three wires are gently placed in the respective grooves and the paste is allowed to dry. The flame of the heating torch melts the flux and the brazing alloy, and thus gives a very clean and effective joint of the wires on the tube. The use of mould release powder stops the flow of brazing material outside the grooves on the sensor tube. Figures 4.5 (a) to 4.5 (f) show the procedure followed in the fabrication of the sensor subassembly.

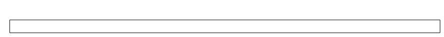


Figure 4.5 (a): Sensor tube cut to size the with help of EDM machine

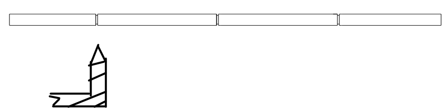


Figure 4.5(b): Marking of heating and sensing points with grooves on the sensor tube using a watch maker's lathe

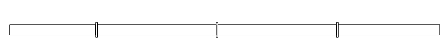


Figure 4.5(c): Process of masking of the heating and sensing points with the help of steel rings and application of anti brazing mould release material around the grooves at these points

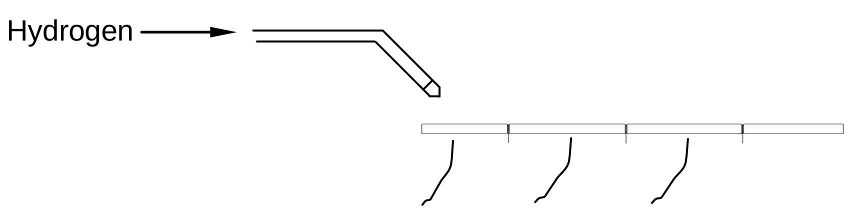


Figure 4.5(d): Brazing of heating and sensing wires at the respective locations

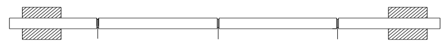


Figure 4.5(e): Brazing of small copper blocks at the end of the sensor tube

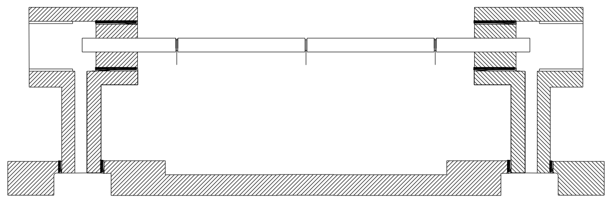


Figure 4.5(e): Soldering of the copper blocks to the brass body

The copper blocks are machined out of a commercially available high thermal conductivity copper rod. The Inner diameter of the copper blocks is about same as that of outer diameter of sensor tube, with a clearance of 0.1 mm or less on the radius to allow flow of molten brazing alloy.

Figure 4.6: Watchmaker's lathe

The blocks are also made on a watchmaker's lathe shown in Fig. 4.6.

The geometrical details of the copper blocks is given in Table 4.2

Table 4.2 – Geometrical details of the copper blocks used as heat sinks.

Feature	***Value***
Part name	*Copper block*
Outer diameter	4mm
Inner Diameter	0.70mm
Length	4mm
Material	Copper
No off	2

Figure 4.7 and 4.8 shows the copper heat sinks.

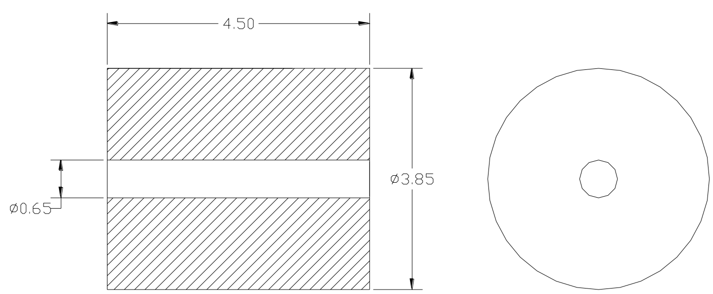


Figure 4.7: Copper blocks

Figure 4.8: Photograph of copper blocks

Ideally, the heat generated in the sensor tube should be conveyed to the flowing fluid or the heat sinks at the ends. But in practice, because of the large exposed surface area, a significant amount of heat is lost by natural convention to the surroundings. To minimize this effect the sensor should be effectively insulated. Adding a solid insulation is not advisable, because it increases the thermal mass of the sensor. Therefore, we have loosely wrapped the sensor tube with some low-mass synthetic cotton and covered it with a thin cap all around the sensor tube. A pictorial view of the insulation cap which encloses the sensor tube is shown in Fig. 4.7. Its dimensions are given in Table 4.3.

Table 4.3: Dimensions of sensor cover

Feature	**Value**
Part name	Sensor cover
Length of the cover	48mm
Width of the cover	16mm
Height of the cover	15mm
Material	Aluminium sheet
No off	1

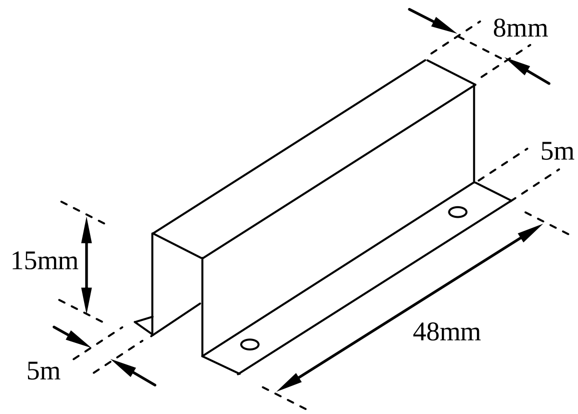


Figure 4.9: Sensor cover

Screws are used to hold the cover on the sensor housing.

Sensor Housing

The sensor housing is made of brass Fig. 4.10 shows the basic components before assembly and brazing. The components are assembled as shown and brazed together to make a single block. Figures 4.11 and 4.12 shows the schematic and photographic views of the sensor housing and Table 4.4 gives the dimensions

Table 4.4: Geometrical details of the sensor housing

Feature	**Value**
Part name	Sensor Housing
Length of the housing	150mm
Width of the housing	20mm
Height of the housing	15mm
Material	Brass
No off	1

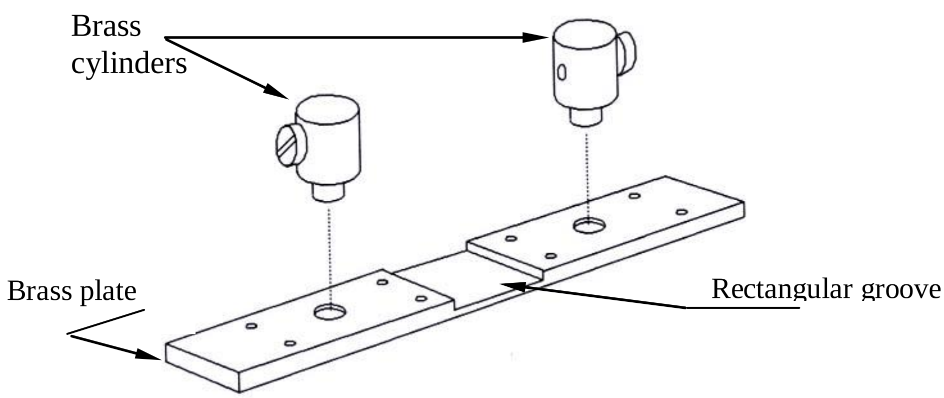


Figure 4.10: Basic components of sensor body before brazing

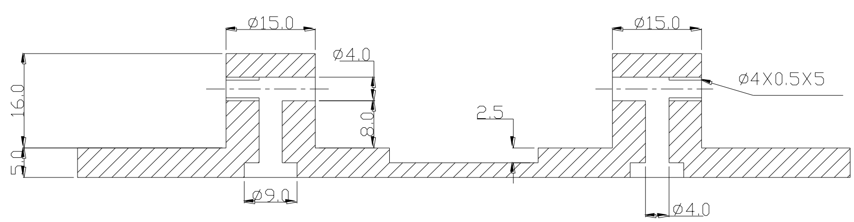


Figure 4.11: Schematic of the sensor housings

(a)

(b)

Figure 4.12: Photograph of the sensor housing (a) top view, (b) front view

The sensor housing consist of two brass cylinders of diameter 16 mm and length 21 mm. Brazed to a plate of width 20 mm and thickness 5 mm. Figure 4.10 shows the basic components before assembly and brazing. The components are assembled as shown and brazed together to make a single **nonlithic** block. The brass plate is machined on a milling machine, while all the components have been made on a lathe, following standard machining methods.

A rectangular groove of 25X20X2.5 mm (marked 3 in fig 4.12 a) is made in the middle of the base plate to accommodate a small PCB that provides the anchors for the heating wire and the thermocouple connections. The PCB is cut to size and glued inside this rectangular groove. The electrical connection to the heating and sensor wires are made through this PCB, which provides the required strength and mechanical rigidity.

4.3 Fabrication of the Laminar Flow Bypass

The laminar flow bypass consists of a rectangular aluminium block having a through central hole along the length to contain the laminar flow cartridge and a rectangular groove on the side to contain the electronic PCB. The laminar flow catridge is made of a bundle of 190 capillary tubes each having outer diameter of 0.90 mm and inner diameter of 0.60mm. These capillaries are placed inside a hollow stainless steel tube of diameter 13 mm. This precision laminar flow element preserves constant ratio between sensor and total flow rates.

For fabricating the laminar flow cartridge, first the calculated number of capillary tubes are cut to a size greater than the cartridge shell length with the help of a standard cutting or shearing process. We used a simple hand shear to cut the capillary tubes.

During this cutting operation the ends of the capillary tubes are bent and squeezed, thus blocking the passages. The tubes are then placed on a tray where an epoxy adhesive (ARALDITE) is applied on the middle portion of each tube with the help of a brush. The reason for application of the adhesive is to block the narrow triangular passages formed between the capillary tubes on assembly. Blocking the triangular gaps ensures stable flow through the tubes and reproducible performance. These capillaries are then inserted into the shell in such a way that small lengths protrude from both ends of the shell. The protruding parts of the capillaries need to be cut to size without leaving any burrs or creating distortions in the tubes. After the epoxy has set, electro-discharge machining (EDM) process has been used for cutting the tubes to size. We have used both wire EDM and die-sinking EDM with success. Because the adhesive is an electrical insulator, the wire EDM process sometimes becomes slow and erratic. The die sinking method, however, gave consistently good results. A photographic views of the laminar flow element is shown in fig. 4.13 and the dimensions are given in table 4.5.

Figure 4.13: Photographic view of laminar flow catridge

Table 4.5: Geometrical detail of laminar flow element

Feature	**Value**
Part name	Laminar flow element
Length	65mm
Diameter	13mm
Material	Stainless steel
No off	1

The Specifications of the wire EDM machine used in this operation are given in Table 4.6.

Table 4.6: Specifications of EDM machine

MAXI CUT (Electronica M/C Tool, Pune, India)	
Maximum work piece dimensions	$400 \times 300 \times 150$ mm^3
Maximum work piece weight	200 kg
Travel X of table	200 mm
Travel Y of table	300 mm
Travel of U axes	±15 mm
Travel of V axes	±15 mm
Wire electrode diameter	0.25 mm std., 0.15, 0.2, 0.3 options.
Wire feed rate	10 m/min (max.)
Table displacement per step	0.001 mm
Outside dimensions of machine	$1250 \times 945 \times 1730$ mm
Net weight of machine	1300 kg approx.

The die sinking type of EDM machine was an old imported machine and no specifications were available.

Fabrication of Laminar Flow Element Housing

The housing of the laminar flow element has been designed to contain the laminar flow catridge and to support the PCB containing the electronic circuitry. The housing also serves to hold the inlet and outlet connectors. This housing has been machined out of a rectangular aluminium block (150x35x35mm). Use of aluminium as material of construction is prompted by its light weight, high machinability and good corrosion resistance. Outline dimensions of the housing is given in table 4.7

Figure 4.14: Photographic view of the housing of the laminar flow bypass

As shown in the photographic view of the housing, (fig 4.14) the upstream and downstream holes marked 1 and 2 serve as the connections into and out of the sensor tube. The ports for inlet and outlet of the main (total) fluid stream are at the ends are not visible in the picture.

Table 4.7: Outline specifications of the housing of laminar flow element

Feature	**Value**
Part Name	Laminar flow element housing
Length	150mm
Width	35mm
Height	35mm
Material	Aluminium
No off	1

Eight blind threaded holes of nominal diameter 3 mm and depth 4 mm are made on the top of the laminar flow element housing to attach the sensor housing. A rectangular groove of size 150X5X10mm is made on one side of the housing to accommodate the PCB that carries the electronic circuitry. The inner bore of the housing contains threaded portion at both ends to accommodate the brass connectors, which connect the laminar flow divider to the flow line.

Fabrication of Brass Connectors

Two special connectors are machined out of brass bar stock to connect the flow meter to the flow line. Figure 4.15 gives the details of their construction.

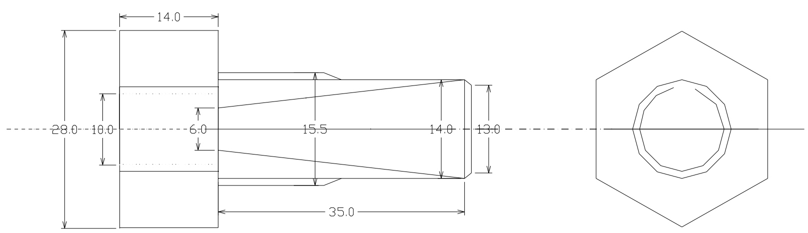


Figure 4.15: Pictorial view of brass connector

While one end is provided with pipe thread, the other end is made for a ferrule connection. The connector has a tapered bore to ensure that the inlet flow is uniformly distributed over the cross section of the laminar flow bypass cartridge.

Fabrication of the Electronic Circuitry

A major positive feature of the thermal flow meter is the electrical voltage output and direct digital read out proportional to the mass flow rate through the sensor. This is ensured by providing an appropriate electronic circuitry. All the electronic components are mounted on a PCB (130X76x1.5mm), which is attached to the body of the flow meter. The main functions of the electronic circuitry are:

(a) to provide heating current to the sensor, and
(b) to sense, amplify and display the thermocouple output voltage

Figure 4.16 shows a block diagram of the electric circuit.

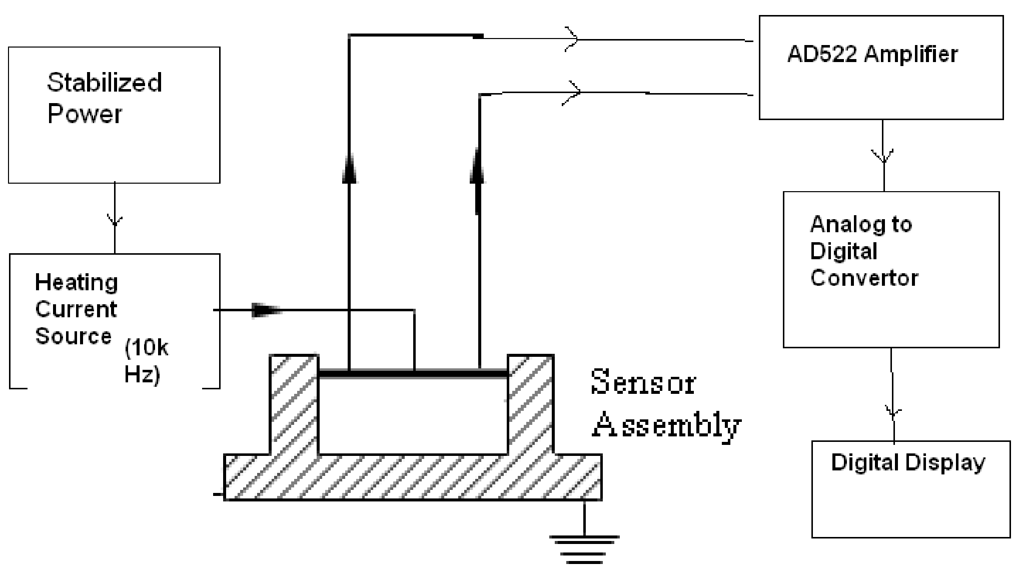


Figure 4.16: Block diagram of electronic circuit of the capillary type thermal mass flow meter

The main sections of the electronic circuit are as follows:

1. DC Power Supply
2. AC Current Source (10 kHz Approx)
3. Sensor Assembly
4. Instrumentation Amplifier (AD522)
5. Analog to Digital Converter and Display

(1) Power Supply

The power supply circuit has been designed for an input voltage of 24 V ± 10 % which is stabilized to 18 V DC. It is built using IC 7818-type voltage regulator, a few capacitors and diodes. The IC LM7818 is a 3-terminal Voltage Regulator, which holds the load voltage constant even if the load current and source voltage are changing. It needs a minimum input-to-output difference of 2 V i.e. $(V_i – V_o) \geq 2$ V. For obtaining a regulated output of 18V the IC needs an input voltage between 20 and 37 volt. A diode is used at the input for protection against accidental polarity reversal.

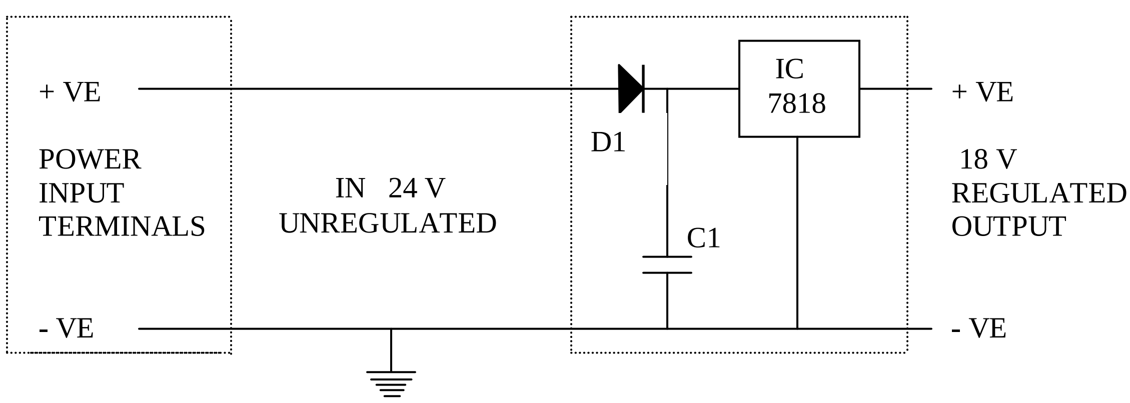


Figure 4.17: Circuit diagram of a regulated power supply

We have used a 1N4007 diode with a forward bias voltage drop of 0.7V. Thus 20.7V is the minimum input voltage at which the regulator maintains 18V at the output. We have specified the input voltage to be 24V ± 10% i.e. 21.6 V to 26.4V. The maximum output current of the IC is 500 mA. Actual dissipation in the proposed circuits has been estimated to be less than 200 mA. A small heat sink appropriate to the current requirement has been fitted with the IC. The power supply unit is fabricated on the same PCB.

(2) Current Source

A high frequency current source is used for heating the sensor tube. The heating element (sensor tube) is of very low resistance (50 mΩ) (taking into consideration that the two halves of the capillary tube, each of length 25 mm, come in parallel across the heating current source). An equivalent electrical circuit of sensor tube is shown is Fig. 4.18.

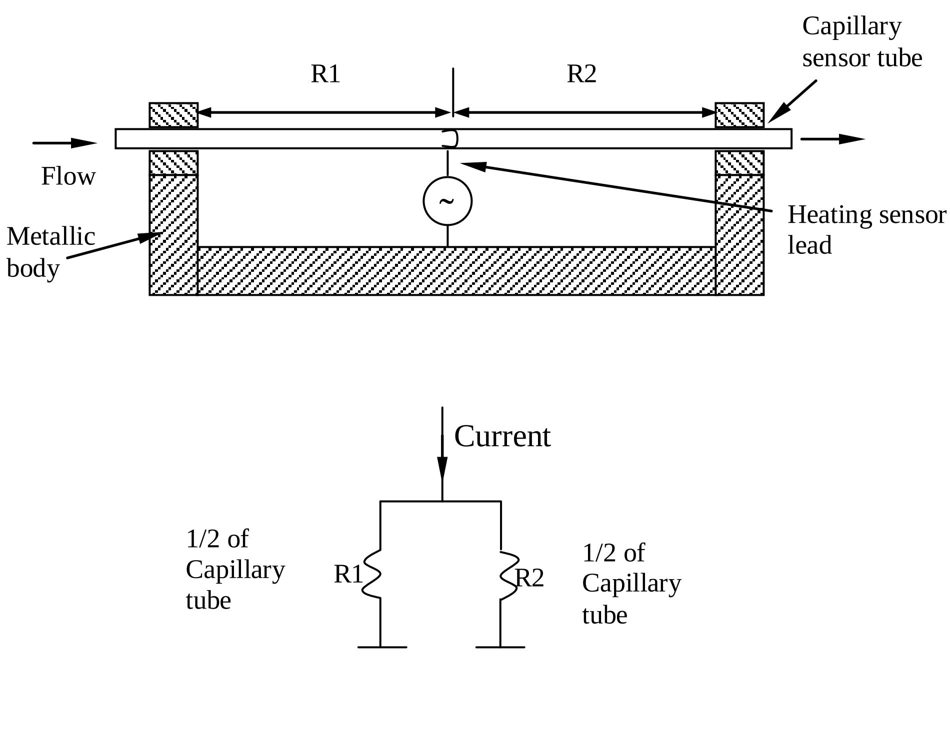


Figure 4.18: Equivalent electrical circuit of sensor tube

For delivering a steady power of approximately 0.25 W, either alternating or direct current could be used. But if a DC voltage is applied, it will be indistinguishable from the thermocouple voltage generated and therefore it will be impossible to measure the temperature asymmetry over the sensor tube. We have used a 10 kHz AC as the heating current so that its remnants can be easily filtered out from the thermal emf during measurement. The frequency of 10 KHz has been chosen as a trade off between transformer size and frequency handling capacity of the active devices (IC, transistor etc). We have used the PWM IC SG3525 as the oscillator with 10% dead time between commutations. A ferrite ring transformer is used to convert the power into low voltage and high current (0.15 V RMS, 3A). This transformer also provides isolated voltage supply for other sections (Amplifier, ADC, Display) through auxiliary windings and rectifiers.

IC SG3525 is a pulse width modulator (PWM) designed for use with switched mode power supply (SMPS). The reason of choosing this modulator is the simplicity of external circuitry necessary for its operation. Another useful feature of this chip is the control over the dead time [when the conduction state flips from one output level to the other there is a “both off” condition. This feature protects the conducting devices from mutual loading. The frequency is set to 10 KHz and dead time at 10%]. When a high frequency of 10 KHz is used, self-impedance of the coil is high and hence the device draws a rather small amount of current from the power supply.

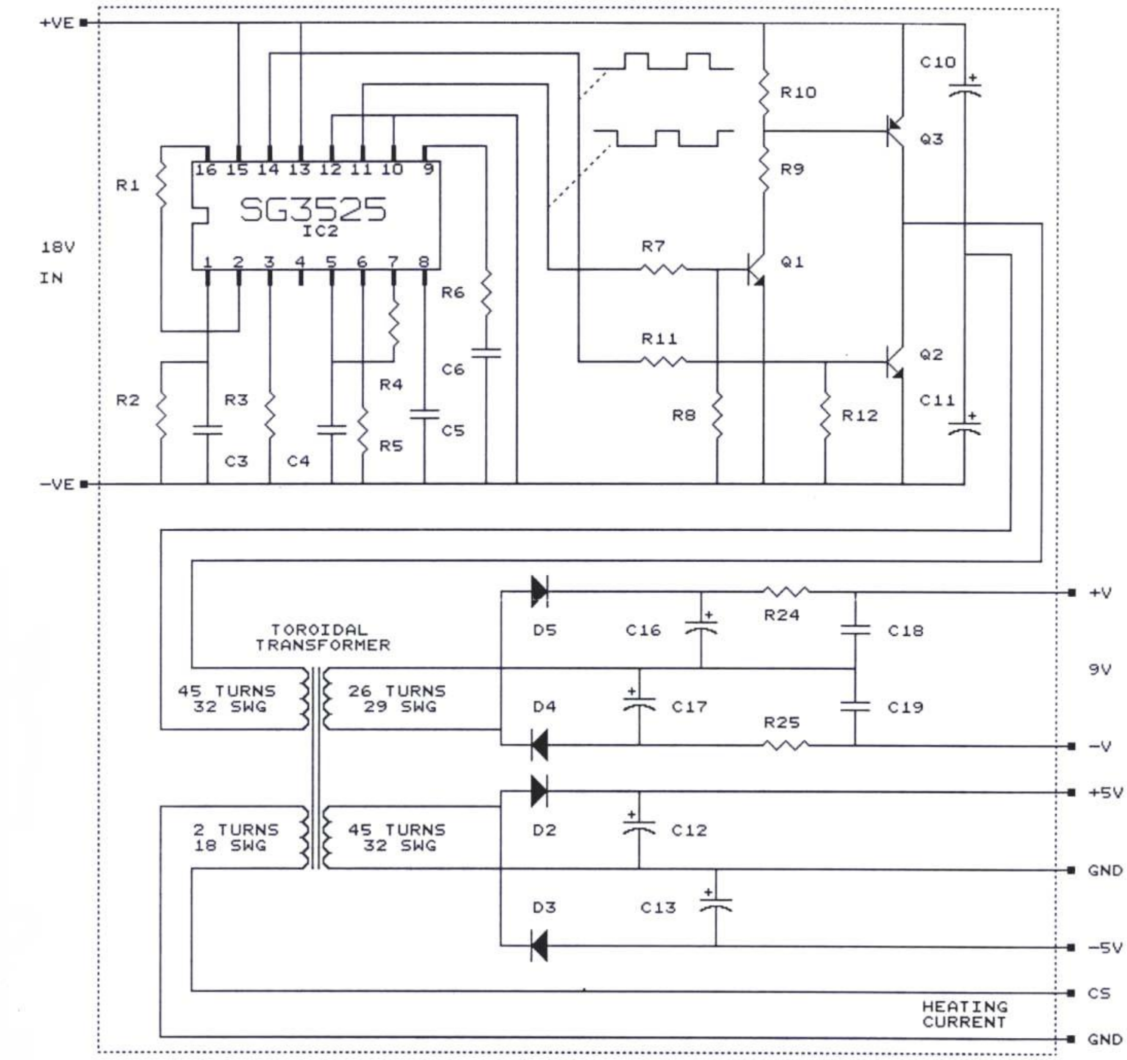


Figure 4.19: Current source and auxiliary power supply

By using high frequency, the audible noise effects from the transformer due to magnetostriction are also eliminated. At higher frequency the transformer size becomes smaller for the same power output, but at the same time the electronic devices in the circuit consume more power. The two-phase output of the IC is buffered (isolated from the following circuits) through transistors (BC 547, BEL 187, BEL 188) to drive the primary winding of the toroidal transformer (Ferrite Core). The prime output of the transformer in the thick secondary winding is 0.15 V RMS and can provide 3 Amperes of current. This output is used to heat the sensor. Two more auxiliary windings provide isolated voltages of ± 5V and 9V for the amplifier and meter sections. Rectifiers BA157 and 10 µF capacitors are used for DC conversion. We have used the following values for the resistors and capacitors in our current source and auxiliary power supply circuit.

Table 4.8: Values for the resistors and capacitors used in current source and auxiliary power supply circuit

R1=10KΩ	R8=10KΩ	C3= 0.001µF	C13=10µF/25V
R2=10KΩ	R9=1KΩ	C4= 0.01µF	C16=10µF/25V
R3=10KΩ	R10=2.2KΩ	C5= 0.01µF	C17=10µF/25V
R4=220Ω	R11=1KΩ	C6= 0.001µF	C18= 0.047µF
R5=6.8KΩ	R12=2.2 KΩ	C10=10µF/25V	C19= 0.047µF
R6=100KΩ	R24=100Ω	C11=10µF/25V	
R7=10KΩ	R25=100Ω	C12=10µF/25V	

(3) Sensor Assembly

The heating current source is connected to the centre of the capillary tube and the return path of the current is through the brass body of the sensor assembly. Thus the sensor tube is split into two equal parts and the current through each half of the tube becomes half of the current supplied by the source. The potential difference between the points A and B (which are located at equal distance from the mid point C) vanishes all the time, and the thermal emf generated by temperature asymmetry can be measured comfortably. The small alternating potential difference caused by fabrication errors and resulting current asymmetry can be filtered easily.

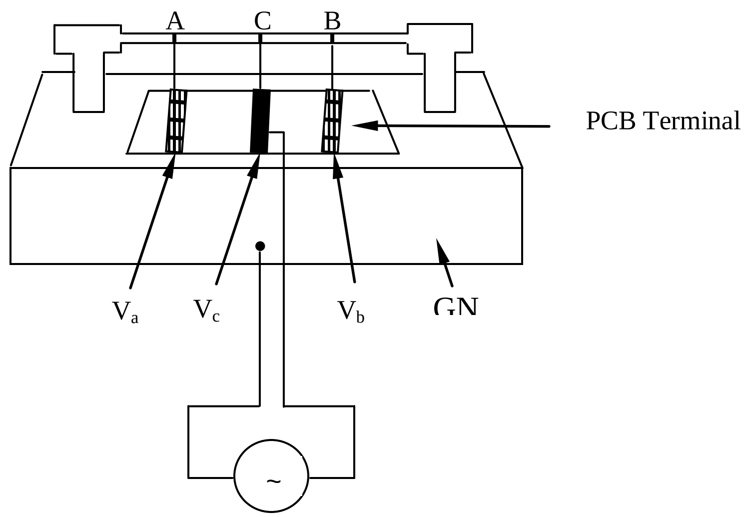


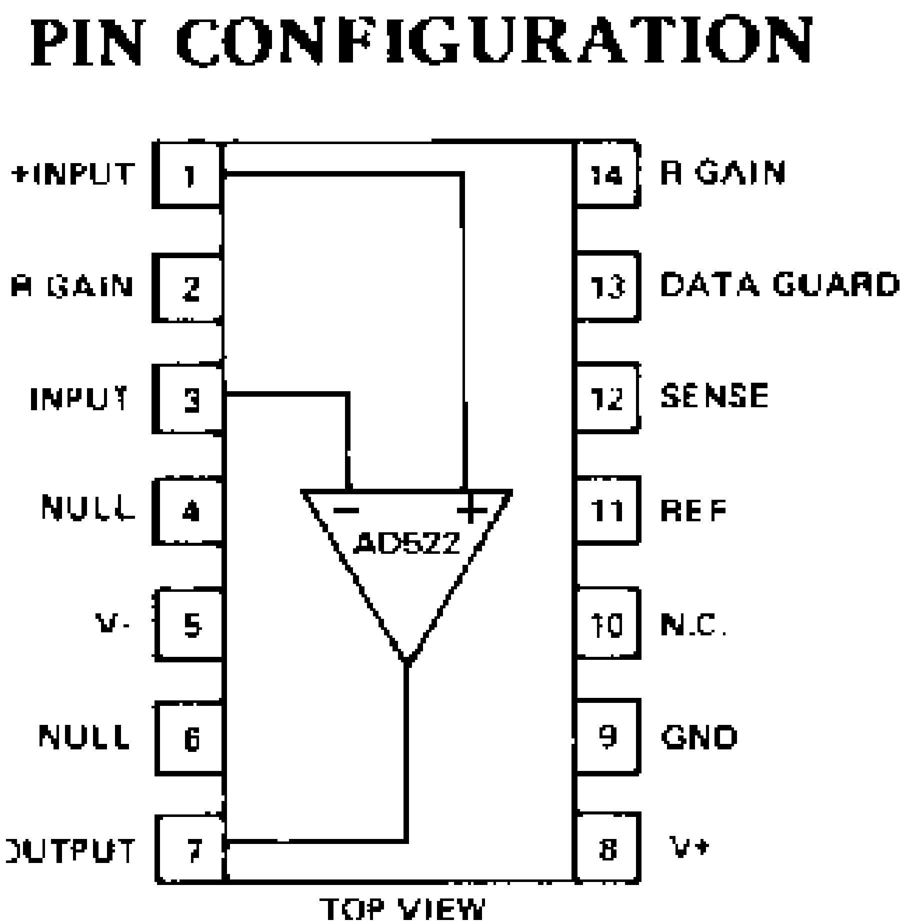
Figure 4.20: Sensor assembly

Constantan wires are brazed at optimized locations (A and B) to make the constantan-SS-constantan differential thermocouple. Connections (Va, Vb and Vc) from thermocouples and the mid point are terminated on a small PCB at the base of the sensor body.

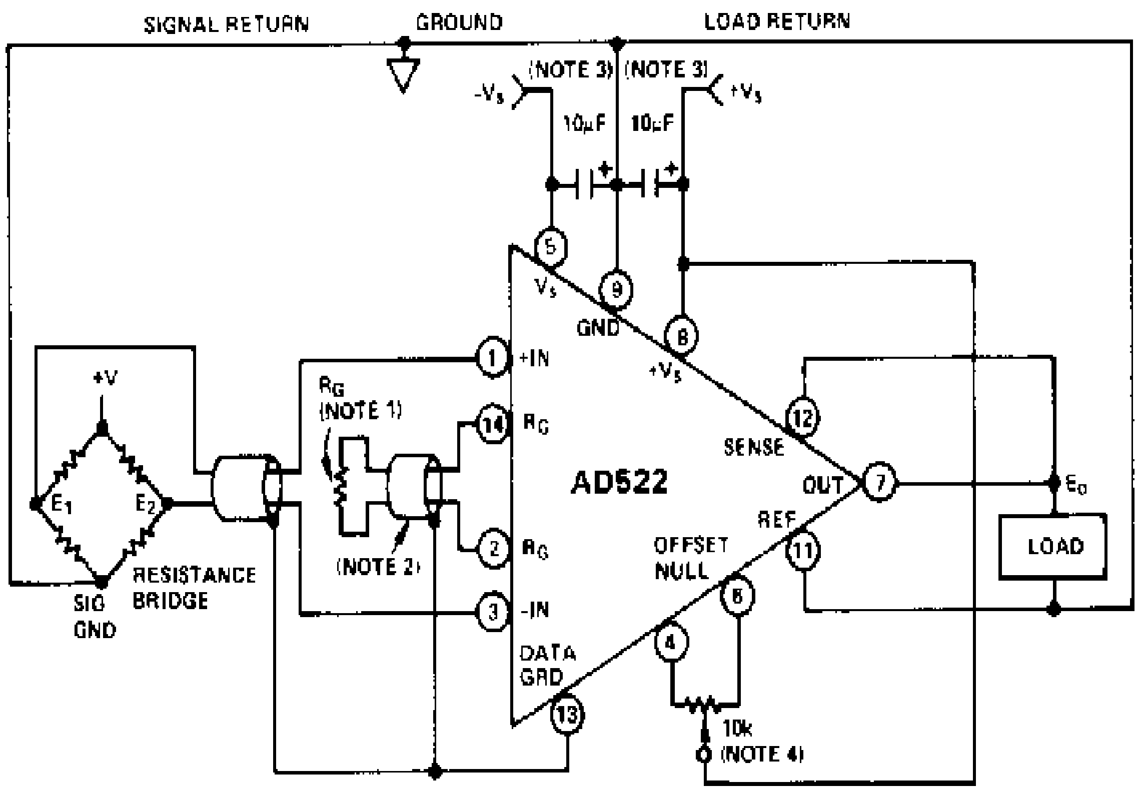
Instrumentation Amplifier (AD522)

The AD522 is a precision IC instrumentation amplifier designed for data acquisition applications requiring high accuracy under worst-case operating conditions. An outstanding combination of high linearity, high common mode rejection, low voltage drift, and low noise makes the AD522 suitable for use in many 12-bit data acquisition systems. An instrumentation amplifier is usually employed as a bridge amplifier for resistance transducers (thermistors, strain gages, etc.) found in process control, instrumentation, data processing, and medical testing. The operating environment is frequently characterized by low signal-to-noise levels, fluctuating temperatures, unbalanced input impedances, and remote location which hinders recalibration

Pin Configuration of AD522:



Circuit diagram of 14 pin single chip Instrumentation amplifier AD522



$$E_O = \left(1 + \frac{200k}{R_G}\right)\left[\left(E_1 - E_2\right) - \left(\frac{E_1 + E_2}{2} \times \frac{1}{CMR}\right)\right]$$

NOTES:

1. GAIN RESISTOR R_G SHOULD BE <5ppm/°C (VISHAY TYPE RECOMMENDED).
2. SHIELDED CONNECTIONS TO R_G RECOMMENDED WHEN MAXIMUM SYSTEM BANDWIDTH AND AC CMR IS REQUIRED, AND WHEN R_G IS LOCATED MORE THAN SIX INCHES FROM AD522. NO INSTABILITIES ARE CAUSED BY REMOTE R_G LOCATIONS. WHEN NOT USED, THE DATA GUARD PIN CAN BE LEFT UNCONNECTED.
3. POWER SUPPLY FILTERS ARE RECOMMENDED FOR MINIMUM NOISE IN NOISY ENVIRONMENTS.
4. NO TRIM REQUIRED FOR MOST APPLICATIONS. IF REQUIRED, A 10kΩ, 25ppm/°C, 25 TURN TRIM POT (SUCH AS VISHAY 1202-Y-10k) IS RECOMMENDED.

Figure 1. Typical Bridge Application

Analog to Digital Converter and Display

An Analog to digital converter is used to convert the Analog output of the differential thermocouple into a more sophisticated and easily readable digital display. An inbuilt three and half digit LCD panel meter has been used to cover both ADC and Display.

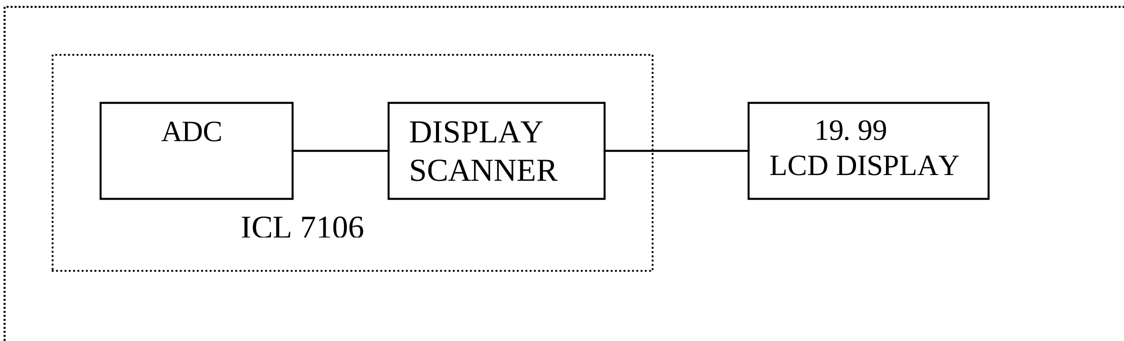


Figure 4.23 Analog to digital converter and display block diagram

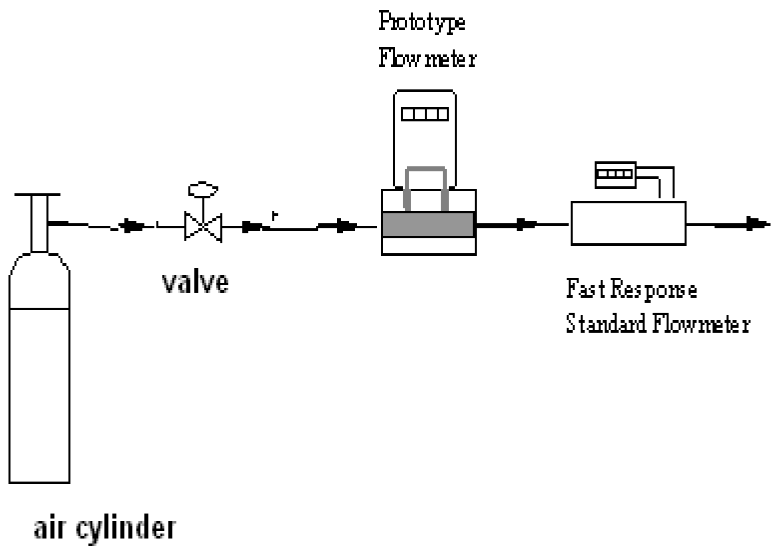
The input sensitivity of the meter is 200 mV DC FSD. The output display gives a direct read out for the flow rate. The digital display cannot exceed the three and half digits 1999. Hence it can read a maximum flow rate of 19.99 slpm. If the flow rate exceeds 19.99 slpm the right most 3 digits will be blank and only the left-hand “1” will appear on the display indicating an “over-range” condition. After the over range condition has been removed, it may take several seconds for the flow meter to recover and resume normal operation. This will not harm the instrument.

CHAPTER-5

EXPERIMENTAL STUDIES

Performance of Prototype Flow meter

The performance of the prototype flow meter is studied by comparing with that of a standard flow meter connected in series with it. Various performance parameters such as accuracy, linearity, repeatability, short-term reproducibility of the prototype instrument have been studied.



Experimetal set up

Study of Accuracy, Linearity, Repeatability and Short- Term Reproducibility of Prototype Thermal Mass Flow meter

This experiment is designed to determine the accuracy, linearity, repeatability, and short-term reproducibility of the prototype thermal mass flow meter. The experiemntal set up as shown in Fig. 5.20 is employed. After the installation of the experimental unit and covering the electronic warm up period test loop is purged with clean, dry nitrogen gas for a minimum of 5 minutes. The flow rate is maintained at the full-scale reading of the prototype flow meter.

Once the set up is ready, the flow rate is varied over full range of the instrument in discrete steps both in increasing and decreasing order. The readings on the test and standard instruments are noted down and analyzed for precision, accuracy, linearity and repeatability.

Accuracy

The Bias in a set of readings is defined as the average difference between the readings of the prototype flow meter and a standard flow meter.

$$B = \frac{\sum_{i=1}^{n}\left(m_i - m_{s,i}\right)}{n} \tag{5.1}$$

where $m_i =$ flow rate reading in the prototype flow meter,

$m_{s,i} =$ Flow rate reading in the standard flow meter,

all readings being taken near the specified nominal flow rate.

Precision of a reading is usually defined in terms of the standard deviation of a set of readings corresponding to the same true value. Extending the concept a little further, we define precision in terms of the standard deviation of the difference in readings between the prototype and the standard flow meter. In other words,

$$P = \sqrt{\frac{\sum_{i=1}^{n}\left\{(m - m_s)_i - B\right\}^2}{n}} \qquad (5.2)$$

Where

$P =$ Precision of a reading

$m_i =$ Flow rate reading in the prototype flow meter,

$m_{s,i} =$ Flow rate reading in the standard flow meter,

$n =$ Total number of readings at flow rates close to the specified value.

$B =$ Bias

Accuracy is defined in terms of bias B and precision P as:

$$A = \left(P + |B|\right)\frac{B}{|B|} \qquad (5.3)$$

Accuracy has the same sign as bias B and is larger than B by the value of precision P. The accuracy of the secondary standard employed in this study is not known, but is expected to be much better than that of the prototype instrument. Therefore, the accuracy computed in this study can be taken as the accuracy of the instrument itself. Table 5.5 summaries all the readings under 10 flow ranges. All readings falling within a given range of flow rate have been processed to compute bias, precision, accuracy and short term repeatability.

Table : Summary of calibration data of the prototype flow meter [M: Nominal flow rate; X1: Average reading of standard instrument, X2: Average reading of prototype flow meter, B: Bias; P: Precision; A: Accuracy; STR: Short term repeatability]

Sr No	M (slpm)	Range (slpm)	No.of Obs.	X1 (slpm)	X2 (slpm)	B (X1-X2) (slpm)	P (slpm)	A (slpm)	STR (slpm)
1	1	0-2	5	1.27	1.29	0.02	0.15	0.19	0.15
2	3	2-4	5	3.12	3.18	0.06	0.27	0.33	0.09
3	5	4-6	5	4.96	5.00	0.04	0.17	0.22	0.03
4	7	6-8	5	7.15	7.19	0.04	0.24	0.28	0.03
5	9	8-10	5	9.35	9.39	0.04	0.24	0.31	0.02
6	11	10-12	5	11.06	11.09	0.04	0.17	0.21	0.01
7	13	12-14	5	12.96	13.01	0.05	0.26	0.33	0.02
8	15	14-16	5	15.19	15.22	0.03	0.20	0.25	0.01
9	17	16-18	5	17.09	17.13	0.06	0.26	0.32	0.01
10	19	18-20	5	19.23	19.25	0.02	0.21	0.26	0.01

Results :

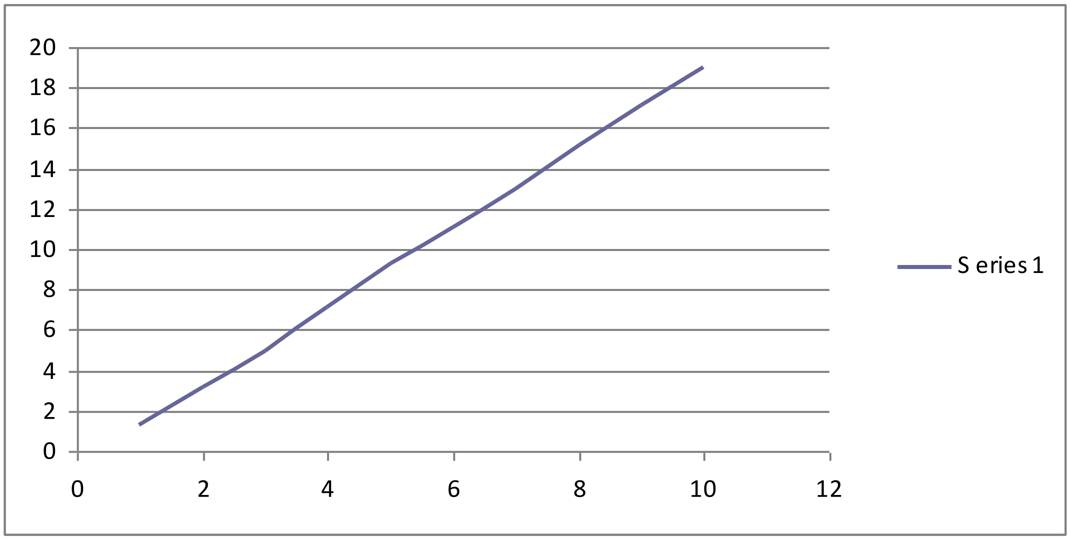


Figure -5.1

graph for prototype flow meter(x-axis :observation no and y-axis: reading on prototype flow meter)

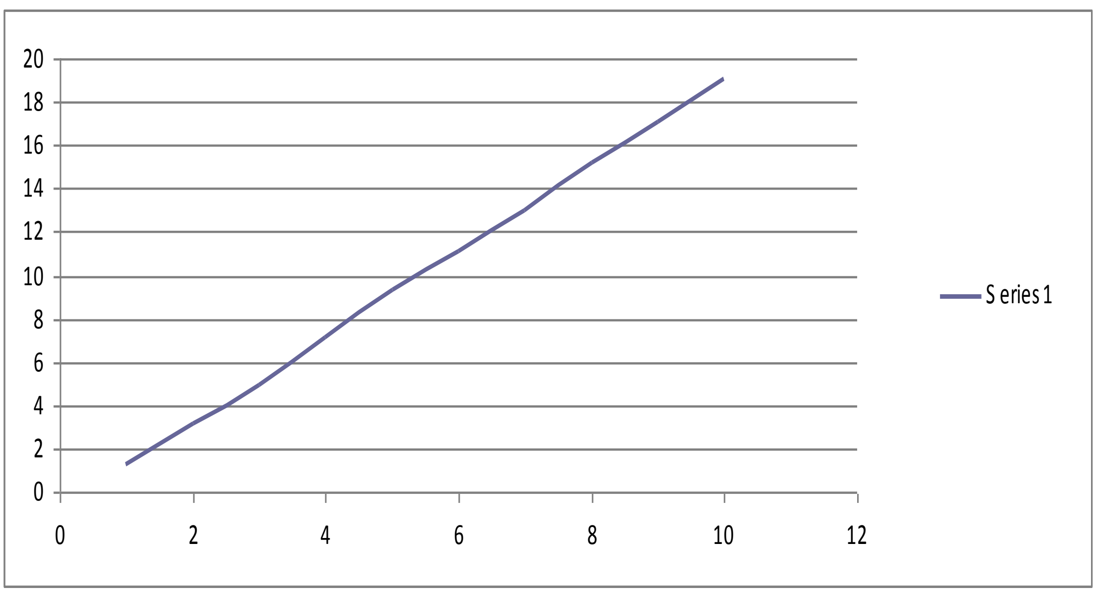


Figure-5.2

graph for standard flow meter(x-axis :observation no and y-axis: reading on standard flow meter)

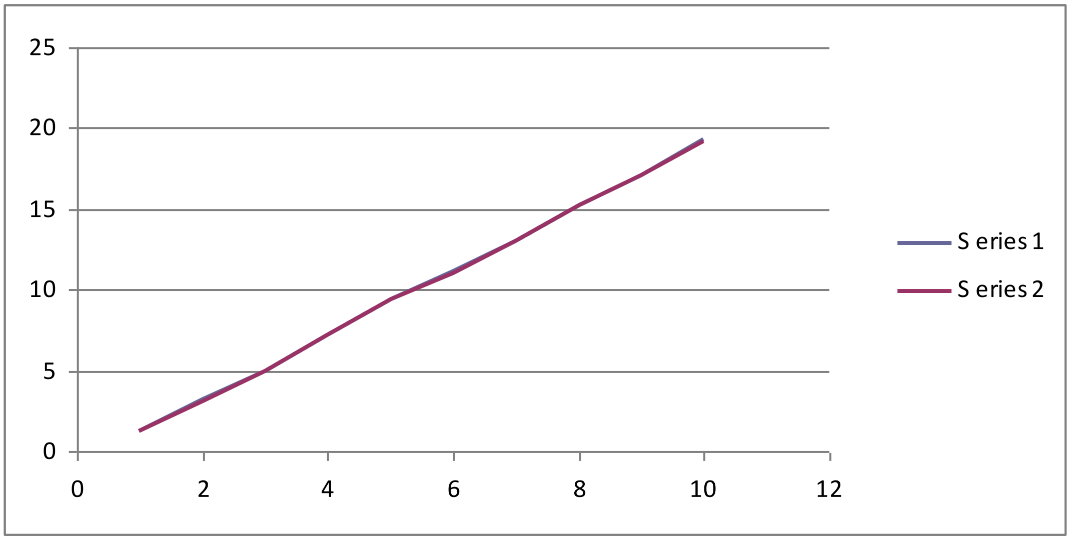


Figure-5.3

Combined graph for both standard and prototype flow meter
(BLUE- Standard Flow Meter and RED- Prototype Flow Meter)

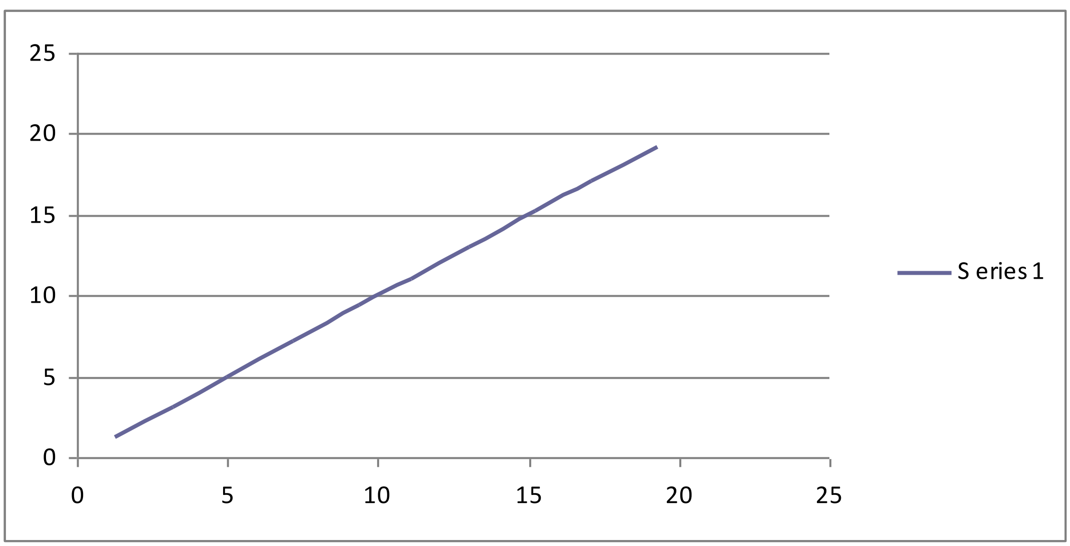


Figure-5.4

Response curve of the thermal mass flow meter
(The straight line shows an ideally linear relation and the dots shows the actual calibration)

Conclusion

The results obtained from experimental studies are given in chapter 5 in tabular form and are shown by plotting graphs. The curves obtained form fig.5.1 and 5.2 are almost parallel. Again when the readings of both the standard flow meter and prototype floe meter were plotted on a single graph they were overlapping (shown in fig 5.3).Hence the reading obtained from proto type flow meter is almost same to that of the standard flow meter and the flow meter is calibrated. The multiplication factor is 1 as the graphs are overlapping. In Fig 5.4 the graph is platted between the standard flow meter readings (as x-axis) and prototype flow meter readings (as y-axis). This shows that the variation of prototype flow meter reading to that of standard flow meter is linear.

In the prototype flow meter the 741 op-amp was replaced by single chip instrumentation amplifier AD 522 which helped us getting better result.

Future Scope:

1) Developments in gas correlations and microprocessor technology will provide more field adjustable functions. It will also reduce the cost to produce the instruments
.

2) Another emerging trend is adding multivariable capability to the instrument. Multivariable flow meters are one of the fastest-growing segments of the flow meter.

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6) AD522 DATA SHEET

7) ICL7106 DATA SHEET