

DESIGN AND SIMULATION OF THERMAL MASS FLOW METER FOR VACUUM APPLICATIONS

Submitted in partial fulfilment of the requirements for the award of

Bachelor of Technology degree in

CHEMICAL ENGINEERING

By

THIYAGARAJAN B (39690024)



**DEPARTMENT OF CHEMICAL ENGINEERING
SCHOOL OF BIO-CHEMICAL ENGINEERING**

SATHYABAMA

**INSTITUTE OF SCIENCE AND TECHNOLOGY
(DEEMED TO BE UNIVERSITY)**

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JEPPIAAR NAGAR, RAJIV GANDHI SALAI, CHENNAI - 600 119

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This is to certify that this Project Report is the bonafide work of **THIYAGARAJAN B** (39690024) Who carried out this project entitled "**DESIGN AND SIMULATION OF THERMAL MASS FLOW METER FOR VACUUM APPLICATIONS**" under my supervision from JULY-2022 to OCTOBER-2022

Internal Guide

Dr.M.KARTHIKEYAN, M.Tech, Ph.D

Assistant Professor

Head of the Department

Dr. S.Sathish, M.E,Ph.D

Associate Professor

HEAD OF THE DEPARTMENT
DEPARTMENT OF CHEMICAL ENGINEERING
SATHYABAMA
INSTITUTE OF SCIENCE AND TECHNOLOGY
(DEEMED TO BE UNIVERSITY)
Jeppiaar Nagar, Rajiv Gandhi Salai,
Chennai - 600 119

Submitted for Viva voce Examination held on _____

Internal Examiner

External Examiner

DECLARATION

I, **THIYAGARAJAN B** (39690024) hereby declare that the Project Report entitled **“DESIGN AND SIMULATION OF THERMAL MASS FLOW METER FOR VACUUM APPLICATIONS”** done by me under the guidance of **Dr.KARTHIKEYAN**, M.Tech,Ph.D (Internal) is submitted in partial fulfillment of the requirements for the award of Bachelor of Technology degree in CHEMICAL ENGINEERING.

DATE:

PLACE:

SIGNATURE OF THE CANDIDATE

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THIYAGARAJAN B

ABSTRACT

This project deals with Designing and Simulation of thermal mass flow meter for vacuum applications. A steady state, numerical model of thermal mass flowmeter for very low flow and low differential pressures (0.1 Pa) is developed and study of heat transfer phenomenon in the sensor tube, fluid flow characteristics and effects of influential parameters of mass flow for heaviest gas Tungsten hexafluoride (WF_6) was carried out.

Heat transfer behaviour of sensor tube for various gases at different temperature conditions are simulated and the results are plotted. A parametric sensitivity analysis is carried out with numerical model includes diameter of the sensor tube, length, different gas temperature, and different heater temperatures, with the results obtained, the final design of thermal mass flow meter for low differential pressure and low mass flow rates has been obtained.

To check the validity of the simulation, Nitrogen(N_2) gas is used in the simulation for which experimental data is available in literature, which is in line with the simulated results. The heat transfer analysis shows that the heat convection is the prominent mode of heat transfer, still heat conduction and radiation along the sensor are significant.

The analysis shows peculiar characteristics of the non-linearity in high flows, variation of the optimum length with process parameters and flowing gas.

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LIST OF ABBEREVATIONS

TMF	Thermal Mass Flow Meter
CTMF	Capillary Thermal Mass Flow Meter
ITMF	Insertion Thermal Mass Flow Meter
CCA	Constant Current Anemometer
PT	Platinum
SCCM	Standard Cubic Centimetre Per Minute
SLPM	Standard Cubic Centimetre Per Minute
mW	Micro Watts
STP	Standard Temperature and Pressure
min	Minute
gm	Gram
GCF	Gas conversion Factor
MW	Molecular Weight
CDTA	Constant Differential Temperature Anemometry
ΔP	Pressure Drop
WF ₆	Tungsten Hexa Fluoride
HF	Hydrogen Fluoride
Pa	Pascal

CHAPTER 1

1. INTRODUCTION

Measurement of fluid flow, either liquid or gas, is usually an important parameter in all industrial processes. Sometimes mass flow (rather than volume flow) is an important variable and is more accurate for measuring quantity of material. If mass flow rate is the quantity of interest, the conventional technologies such as differential pressure producing devices (orifice plates or pitot tubes) and linear volumetric flow devices (such as turbine, vortex, or ultrasonic flowmeters) requires additional transmitters to measure absolute pressure and temperature as well as flow calculator to calculate mass flow rate from the measured quantities. Because the individual errors of all three sensors and the flow calculator must be included, the overall accuracy of conventional technologies is low. There are two types of flow meter which can detect the mass flow of fluids directly without need of temperature and pressure measurements. They are Coriolis flow meters and thermal mass flow meters.

Coriolis flow meters, works based on the rotational dynamics, have existed for liquids for many decades but for gas flow measurement it is just emerging that too for high flow and high-pressure ranges.

Thermal mass flow meter (TMF), which is based on first law of thermodynamics and convective heat transfer effects are very popular for its accurate and economical mass flow measurement over wide ranges of flow rates and pressure conditions. The heat added, Q , is equal to the heat convected away by fluid at a mass flowrate " m ". The eqn. (1.1) shows modified form of first law of thermodynamics

$$m=Q/C_p \Delta T \quad (1.1)$$

There are two types of thermal mass flowmeters are available for gas flow measurement, one of which is applicable for incompressible fluids. The first type is capillary thermal mass flow meter (CTMF) in which heater and temperature sensors are wound outside the thin-walled sensor tube, which can also be used with a bypass containing laminar flow elements to allow higher flow rates to be measured. This type of flow meter is non-intrusive and corrosion resistance. The small diameter

of the capillary sensor tube is beneficial in minimizing the heating power requirement and also enhance the response time.

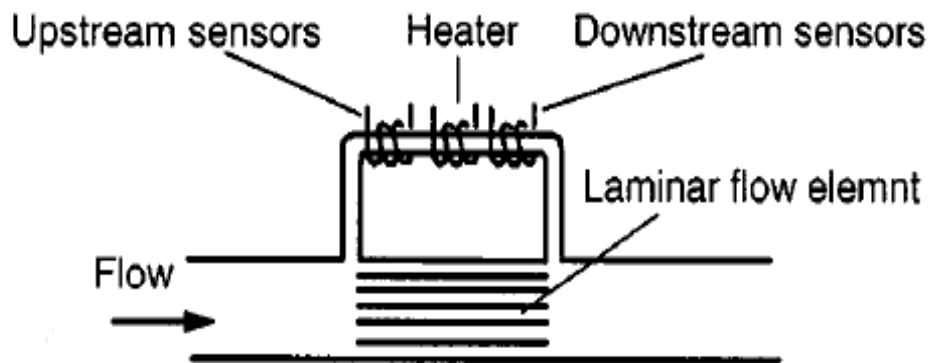


Fig:1.1: Capillary tube thermal mass flow meter

The second type is Insertion Thermal Mass Flow Meter (ITMF) in which heater and temperature sensors are inserted into the sensor tube across the flow of gas. The insertion type has some limitations. The temperature sensors and the heater must contact the fluid by inserting into pipe. Therefore, corrosion and erosion damage these elements easily. In addition to that, the robustness of the piping is affected by the intrusion into the flow, thus increasing the chances of leakage.

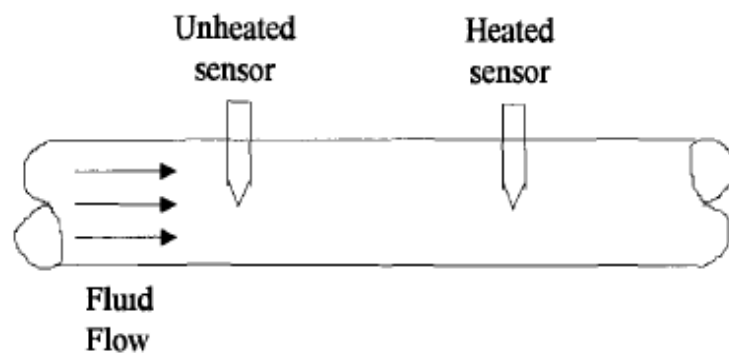


Fig:1.2: Insertion tube thermal mass flow meter

1.1 MEASUREMENT TECHNIQUE:

The amount of heat convected by the flowing gas is measured by three different measurement Techniques.

- I) Constant Power technique
- II) Constant Temperature technique
- III) Constant Differential Temperature technique

1.1.1 Constant Power Technique

In a constant power method or constant current method (CCA), the electrical power input to the heating element is kept constant. The heater temperature rises and get stabilizes. In steady state, entire power consumed will be liberated as heat into the flowing fluid. As the flow changes, the heating region temperature either increases or decreases to the new steady state temperature. Since the Q and C_p is constant in this method, the mass flow rate is inversely proportional to the change in temperature as per eqn. (1.1). The change in temperature is monitored via high temperature coefficient temperature detector (PT1200) which is connected in the Wheatstone bridge circuit to determine flow rate of fluid. At low flow rates the temperature difference is greatest. As the mass flow rate increases, the change in temperature decreases. A plot of temperature difference vs mass flow rate is shown below.

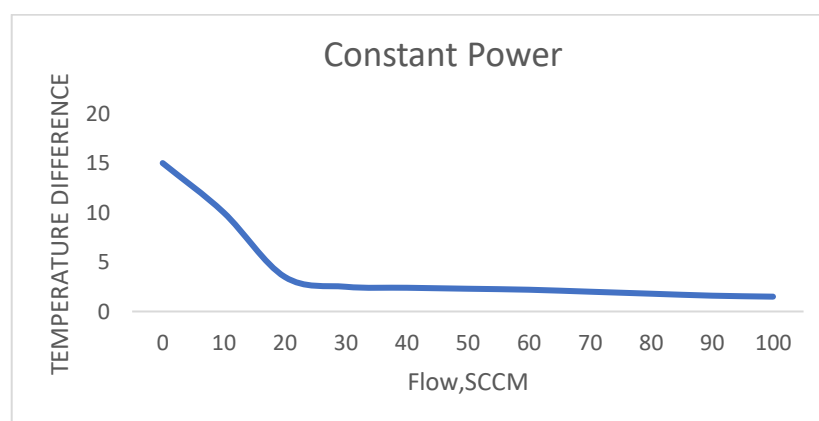


Fig:1.3: Variation of the temperature difference against flow rate for constant power

1.1.2 Constant Temperature Technique

In constant-temperature technique, the power consumed by the heater is keep on changing such that the heater maintains constant temperature. As the fluid flows, the fluid takes away more heat. Since the temperature of heater does not change, the circuit increase the power output to the heater. Since the ΔT and C_p is constant in this method, the flow rate is inversely proportional to the change in electric power(Q) as per eqn. (1.1). The heater temperature is set during the calibration to optimize the performance depends on the fluid being used. At low flow rates, the heat transfer is less thus the power required to maintain the required temperature is less. As the flow rate increases, the heat transfer to the fluid increases hence the power required to maintain the constant temperature is also

increases. The change in power will be directly proportional to the mass flow rate. A Plot of power vs mass flow rate is shown below.

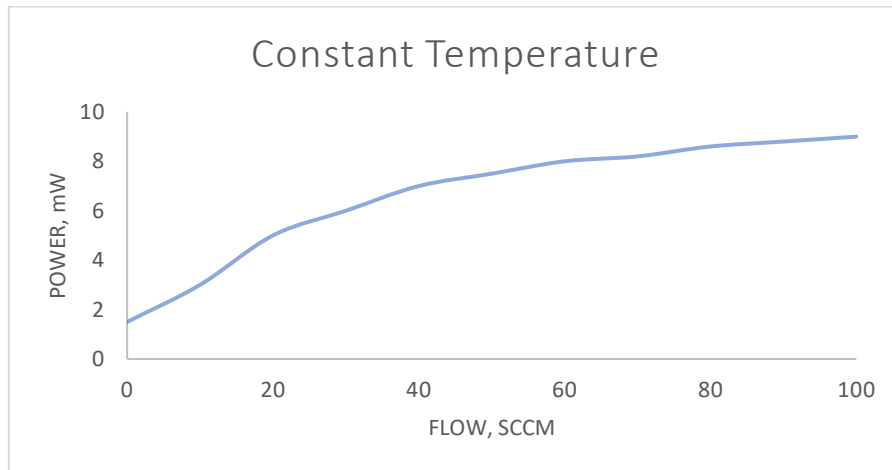


Fig:1.4: Variation of the Power against flow rate for constant temperature

1.1.3 Constant Differential Temperature Technique

Sometimes, in constant temperature mode, the heater temperature will not be set to absolute value instead setting a constant overheat with reference to the ambient temperature which also represents the average gas temperature. In that case the operating mode is called as Constant Temperature Differential technique. The advantage of this technique is that ambient temperature variation is being accounted in the flow measurement thus the overall error will be reduced.

1.1.4 Control And Evaluation Circuit:

Constant-power Wheatstone circuit with heater and sensor is shown in Fig:1.5(a). In this, the resistance of resistors R_4 & R_3 are greatly higher than sensor resistor R_1 . Hence the current passing through R_1 resistor is independent of changes in the resistance of R_1 . The flow in sensor tube cools the heating element, thus resistance of heater decreases, and unbalances the bridge. The unbalanced bridge produces a voltage output, which is calibrated to the mass flow rate. Since the output voltage from the Wheatstone bridge is very small, it has to be amplified before it is measured. The temperature coefficient for Resistor R_2 & R_1 should be the same so as to remove the reading drifts due to variation in ambient temperature. Similarly, the temperature coefficients for resistor R_4 & R_3 should also be the same.

Constant-temperature Wheatstone circuit is shown in Fig:1.5(b). The bridge is in balanced under zero-flow conditions with the variable resistor R_2 . The flow cools

the sensor tube in turn cools the heating element and decreases its resistance and balance of the bridge disturbed. The amplifier balances the Wheatstone bridge with the feedback voltage. The output signal can be calibrated to flow measurement.

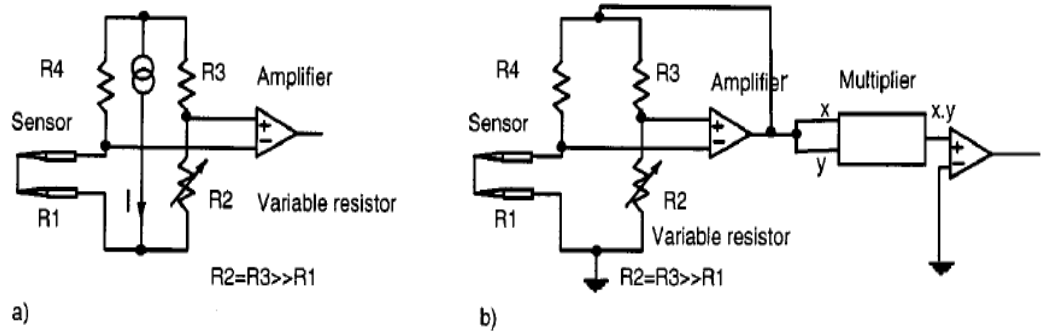


Fig:1.5: a) Constant power circuit b) Constant-temperature circuit

1.2 MASS FLOW UNITS

The unit of mass flow meters is usually referred as Standard Litre Per Minute (SLPM) and/or Standard Cubic Centimetre Per Minute (SCCM). Though it seems to be volume flow rate, we can easily convert it to mass flow by multiplying the gas density at standard conditions as per eqn. (1.4). SLPM is the volume occupied by mass of gas at standard Pressure and Temperature conditions (STP). These conditions are defined as 0°C and 1 atm. Measurements at STP conditions can be used to convert volume flow rate into mass flow by using the Ideal Gas Law,

$$PV = nRT \quad (1.2)$$

where V is volume, P is pressure, T is temperature, n is the number of moles of, and R is the gas constant. Rearranging the equation to get a density (ρ) of the gas at STP conditions,

$$\text{Density, } \rho = \frac{PM}{RT}, \text{ gm/l} \quad (1.3)$$

$$\text{Mass flow} = 1 \text{ SLPM} \times \text{Density, gm/min} \quad (1.4)$$

1.3 GAS CONVERSION FACTOR (GCF)

If the mass flow meter used for a gas other than the gas by which it was calibrated, a reading drift will occur in the output signal and in turn the mass flow rate. This is because of the difference in molar heat capacities of the two gases.

This drift can be calculated using the ratio of the molar specific heat of two gases. The output will be multiplied with this GCF will give the actual mass flow rate.

$$GCF = \frac{\text{Molar heat capacity of surrogate gas}(C_{pXMW})}{\text{Molar heat capacity of actual gas}(C_{pXMW})} \quad (1.5)$$

Where, C_p - Specific heat at sensor temperature, J/gm°C

Since the sensor temperature of mass flow meters varies with manufacturers, the conversion factor varies as the heat capacity slightly varies with temperature. They also provide a disclaimer that the inaccuracy of the conversion factor can be 10% or greater.

1.4 PROBLEM STATEMENT AND PROJECT SPECIFICATION

The disadvantage in capillary type mass flow meter is, it cannot be used to measure the flow where no or low differential pressure is required and in vacuum conditions, as the flow is through capillary tube whose diameter is in the range of 400 micron to 1.0 mm which will offer relatively high pressure drop in commercially available flow meters.

In the insertion type mass flow meter, though it can be used to measure the flow in very low pressure drop conditions, it cannot be used in corrosive environment as the sensor and heater element is directly inserted into the flowing fluid and also it is having poor sensitivity for very low flow.

This project is proposed to address the problem of measurement of mass flow in low pressure drop and very low flow corrosive gases by combining both the mass flow meter configurations.

- For optimum sensor design, a model is required which is suitably accurate to simulate the design which will be useful to gain expertise faster and cheaper without the need for expensive trial and error experiments. Modelling is considered to be economic and time efficient approach.
- To achieve the very low pressure drop, a larger diameter sensor tube is designed with suitable material of construction considering the corrosion and heat transfer properties.

- Constant Differential Temperature Anemometry (CDTA) measurement technique will be employed as it is having fastest response time compared to other techniques.
- Both the ends of the sensor tube will be anchored with heat sink of heavy mass with high thermal conductivity material which keeps the end of the sensor tube at atmospheric temperature. This will ensure that the average gas temperature is same as the heat sink, i.e., Atmospheric temperature.
- A steady state, numerical model of thermal mass flowmeter for very low pressures (1 Pa) is developed and study of heat transfer, fluid flow characteristics and effects of influential parameters of mass flow for Tungsten hexafluoride (WF_6) was carried out.
- Heat transfer behaviour of sensor tube for various gases at different temperature conditions are simulated and the results are plotted.
- A parametric sensitivity analysis is carried out in order to design and develop a thermal mass flow meter for low pressure and low flow rates.

ANSYS Multiphysics software will be used to model the entire sensor, which can simulate the fluid flow, heat transfer, energy coupling etc. While simulating, steady state method is assumed to get better approximation.

CHAPTER 2

2. DESIGN OF THE SENSOR

Geometry designing of the sensor tube includes finding the Diameter of the tube, length of the tube and thickness of the tube, heat sink thickness and length etc.

2.1 DETERMINATION OF DIAMETER OF SENSOR TUBE

To determine the diameter of the sensor tube, the following factors must be considered,

- Allowable pressure drop across the sensor
- Maximum mass flow
- Length of the sensor
- Density of gas

The required inlet pressure and mass flow rate for different application may be varied case to case and the gas is also varying. In such cases, the lowest possible inlet pressure and highest mass flow rate to be considered and lightest gas parameters to be considered while designing the geometry. The lightest gas which could be used in the sensor tube is considered, in our case it is Hydrogen Fluoride (HF). Since we are designing for very low flow and pressure, the flow can be assumed as incompressible flow as the Mach number would be <0.3 . The pressure drop in a tube for incompressible developed flow can be obtained by,

$$\Delta P = \frac{128L\mu Q_m}{\rho\pi D^4} \quad (2.1)$$

Rearranging the equation for diameter gives,

$$D = \left(\frac{128L\mu Q_m}{\rho\pi\Delta p} \right)^{0.25} \quad (2.2)$$

Where,

- D- Diameter, m
- L-Length of Tube, m
- μ -Viscosity, Pa.s
- Q_m -Mass flow rate, Kg/hr
- ρ -Density, Kg/m³

2.2 DETERMINATION OF LENGTH OF THE SENSOR TUBE

The length of the tube to be decided on the basis of L/D ratio which should be >25 to minimize the axial heat transfer and ascertain the laminar flow.

2.3 DETERMINATION OF MATERIAL OF CONSTRUCTION

Appropriate material selection is the basis for any process instruments design. The first aim of material selection is to get structural stability to prevent failure due to the process environment, normal operation exposure and upset conditions. The second objective is the cost of the design life by use of suitable construction materials. For mass flow meter applications, apart from the above criteria high thermal conductivity is also preferable while selecting the material. The selection criteria include but not limited to following factors.

- Fluid composition- Evaluation of Corrosive components
- Operating temperature, pressure, pH, velocity, dew point etc.
- Service life
- Corrosion
- Economics

Tungsten hexafluoride (WF_6) is an extremely corrosive compound that attacks any tissue. Because of the formation of hydrofluoric acid upon reaction of WF_6 with water molecules in air, the material selection should be readily compatible with hydro fluoric acid.

The selected material for handling hydrofluoric acid should be based on the concentration, temperature, velocity and aeration of the acid, and presence of impurities in the acid. As with other non-oxidizing acids, the presence of oxidizing chemicals in HF increases its corrosion attack on almost all metals. The most commonly used alloy in the chemical processes containing hydrofluoric acid is Nickel-based alloy. It is having higher tolerance for alloying elements in solid solution compared to stainless steels and other iron-based alloys but maintains good structural stability. Some alloys compatible with 10% Hydrofluoric acid & 90% N_2 mixture at 200°C are listed with its corrosion rate and thermal conductivity.

Table 2.1: Corrosion rate and thermal conductivity of various metals

Material	Corrosion Rate(mpy)	Thermal conductivity(W/mK)
Monel-400	<0.01	21.8
Nickel-200	<0.01	90.7
Inconel-600	0.07	14.9
HASTELLOY C276	0.04	9.8
SS-304	0.84	16.2
SS-316	0.2	16.3

2.4 DETERMINATION OF THICKNESS OF SENSOR TUBE

Firstly, we are required to find pipe thickness under internal pressure accordance with equation (3a) of section 304.1.2 under ASME B31.3.

$$t = \frac{PD}{2SFE} \quad (2.3)$$

Where, P- Operating Pressure, Kilo Pascal

D-Inside Diameter, mm

S-Allowable Stress for material, KPa

F-Design factor

E-Longitudinal joint Factor

t-Thickness, mm

Once the thickness has been calculated based on the internal pressure load, the corrosion allowance for 30 years life based on the corrosion data, Mechanical and erosion allowance are to be added to the calculated thickness. For seamless tube, 12.5% Mil tolerance also to be added in thickness of the tube.

Tube wall thickness calculation for external pressure or vacuum conditions required to consider stress inside the tube, compression capability of the tube, buckling, and squeezing of the tube in vacuum conditions. But tube wall thickness calculation under external pressure mainly applicable for the larger size pipes, hence this can be omitted for sensor tube thickness calculation.

CHAPTER 3

3. TWO-DIMENSIONAL SENSOR MODELLING

3.1. INTRODUCTION

The sensor tube and the internal gas flows are having following limitations

- I. The L/D ratio of the sensor is greater than 25:1
- II. The maximum velocity is less than 0.2 m/s
- III. The maximum Reynolds number is less than 100 for full scale flow.
- IV. The Mach number is less than 0.3.

Based on the above limitation, the internal gas flow has following characteristics,

1. The flow is laminar and fully developed flow distribution, and it has same heat transfer coefficient all over its length.
2. Since the Mach number is less 0.3, the flow can be considered incompressible.
3. The temperature distribution of the sensor tube and gas temperature is dependent on both axial and radial direction.

The following assumptions are made for the development of the model,

- The flow is considered to be steady state
- The properties of the sensor tube and the gas is constant.
- The heat sinks are assumed to be keep the flowing gas at ambient temperature at the inlet and outlet of the tube, temperature distribution along the sensor tube is symmetric with its centre.

3.2. DERIVATION OF TEMPERATURE DISTRIBUTION EQUATIONS

To analyse heat transfer phenomena in the sensor tube, the sensor tube is divided into two regions. One is a sensor tube region, and the other is a gas region.

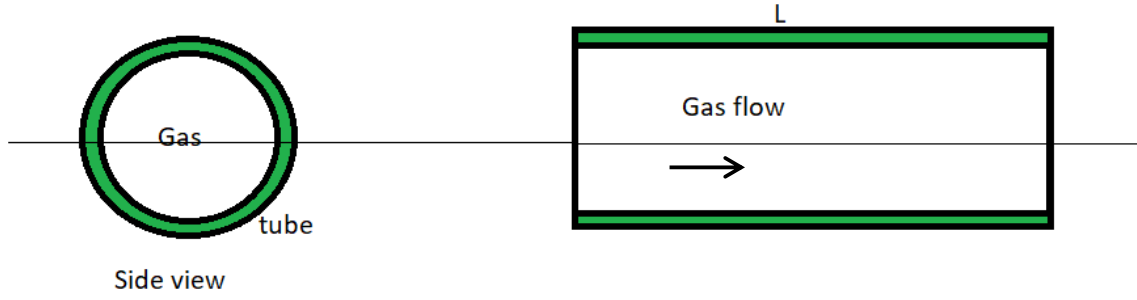


Fig:3.1: Layer structure of sensor tube

Heat transfer in the flowmeter occurs by combination of Conduction, convection and Radiation. Conduction from the outer surface to inner surface is due to temperature difference between molecules, Convection is the dominant heat transfer method within the flowmeter. Heat transfer also occurs within the molecular conduction to lesser extent. On outside of the tube, heat is dissipated by combination of radiation and natural convection, still heat transfer by radiation is insignificant.

For the energy analysis, consider the control volume of gas length of 'dx', inner radius 'r', and outer radius 'r+dr'. In laminar flow, heat is flowing by conduction into and out of the element in a radial direction, whereas in the axial direction, the energy transfer is by convection.

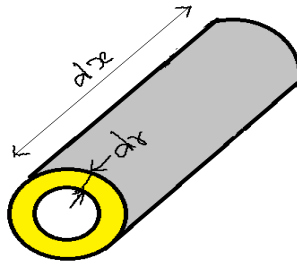


Fig:3.2: Annular element of the sensor

The heat conducted into the gas element in radial direction is given by Fourier's Law of heat conduction,

$$dq_r = -K_f 2\pi r dx \left. \frac{\partial T_f}{\partial r} \right|_{r+dr} \quad (3.1)$$

Where q is heat conducted, K_f is the thermal conductivity of gas, T_f is the temperature of the fluid element.

While the heat transfer out of the gas element

$$dq_{r+dr} = -K_f 2\pi (r + dr) dx \left. \frac{\partial T_f}{\partial r} \right|_{r+dr} \quad (3.2)$$

By Taylor's expansion series,

$$\left. \frac{\partial T_f}{\partial r} \right|_{r+dr} = \left(\frac{\partial T_f}{\partial r} + dr \frac{\partial^2 T_f}{\partial r^2} + \dots \right)$$

Net conductive heat transfer in radial direction is

$$dq_{r+dr} = K_f 2\pi r \left(\frac{\partial T_f}{\partial r} + r \frac{\partial^2 T_f}{\partial r^2} \right) dx dr \quad (3.3)$$

Similarly conductive heat transfer in axial direction is

$$K_f 2\pi r \left(\frac{\partial T_f}{\partial x^2} \right) dx dr \quad (3.4)$$

The heat convection into the element is

$$q_x = 2\pi r \cdot dr \cdot u(r) \cdot \rho \cdot C_p \cdot T_f \quad (3.5)$$

where u , p and C_p are the velocity, density and specific heat capacity of the gas respectively. The heat convection out of the element

$$q_{x+dx} = 2\pi r \cdot dr \cdot u(r) \cdot \rho \cdot C_p \left(T_f + \frac{\partial T_f}{\partial x} dx \right) \quad (3.6)$$

The net heat convection on the gas element

$$2\pi r \cdot dr \cdot u(r) \cdot \rho \cdot C_p \left(\frac{\partial T_f}{\partial x} dx \right) \quad (3.7)$$

At equilibrium,

Net heat convection = Net radial heat conduction + Net axial heat conduction

$$2\pi r \cdot dr \cdot u(r) \cdot \rho \cdot C_p \left(\frac{\partial T_f}{\partial x} dx \right) = K_f 2\pi r \left(\frac{\partial T_f}{\partial r} + r \frac{\partial^2 T_f}{\partial r^2} \right) dx dr + K_f 2\pi r \left(\frac{\partial^2 T_f}{\partial x^2} \right) dx dr$$

$$u(r) \cdot \rho \cdot C_p \left(\frac{\partial T_f}{\partial x} \right) = K_f \left(\frac{\partial T_f}{\partial r} + r \frac{\partial^2 T_f}{\partial r^2} \right) + K_f \left(\frac{\partial^2 T_f}{\partial x^2} \right)$$

$$\frac{u(r) \cdot \rho \cdot C_p}{K_f} \left(\frac{\partial T_f}{\partial x} \right) = \left(\frac{1}{r} \frac{\partial T_f}{\partial r} + \frac{\partial^2 T_f}{\partial r^2} \right) + \left(\frac{\partial^2 T_f}{\partial x^2} \right)$$

$$\frac{\partial^2 T_f}{\partial x^2} + \frac{\partial^2 T_f}{\partial r^2} + \frac{1}{r} \frac{\partial T_f}{\partial r} - \frac{u(r) \cdot \rho \cdot C_p}{K_f} \left(\frac{\partial T_f}{\partial x} \right) = 0$$

$$\frac{\partial^2 T_f}{\partial x^2} + \frac{\partial^2 T_f}{\partial r^2} + \frac{1}{r} \frac{\partial T_f}{\partial r} - \frac{m(r) \cdot C_p}{K_f A_f} \left(\frac{\partial T_f}{\partial x} \right) = 0 \quad (3.8)$$

Where $m(r) = u(r) \cdot \rho \cdot A_f$, The velocity as a function of radial length for laminar flow is given by following relation

$$U(r) = u_{max} \left(1 - \frac{r}{R}\right)^2 \quad (3.9)$$

Similarly heat balance on the element of sensor tube will be balanced by heat generation and accumulation of the sensor tube to heat loss by the flowing gas and ambient conditions.

Heat accumulation of the sensor tube is

$$Q_{Acc} = K_s A_s \frac{\partial^2 T_s}{\partial x^2} \quad (3.10)$$

Heat generation into the sensor tube is

$$Q_{Gen} = \frac{I^2 R}{2\pi r L_H} \quad (3.11)$$

Heat loss by gas molecules inside the sensor tube

$$Q_{gas} = h_i 2\pi r_i (T_s - T_f) \quad (3.12)$$

Heat loss due to ambient outside the sensor tube

$$Q_{Amb} = h_o 2\pi r_o (T_s - T_{amb}) \quad (3.13)$$

The net heat balance on the sensor tube is

$$Q_{Acc} + Q_{Gen} = Q_{gas} + Q_{Amb}$$

$$K_s A_s \frac{\partial^2 T_s}{\partial x^2} + \frac{I^2 R}{2\pi r_o L_H} = h_i 2\pi r_i (T_s - T_f) + h_o 2\pi r_o (T_s - T_{amb})$$

$$K_s A_s \frac{\partial^2 T_s}{\partial x^2} + \frac{I^2 R}{2\pi r_o L_H} - h_i 2\pi r_i (T_s - T_f) - h_o 2\pi r_o (T_s - T_{amb}) = 0 \quad (3.14)$$

Where K_s is thermal conductivity of sensor tube, A_s is the cross-section area of the tube, L_H is heating element length, h_i & h_o are inside and outside heat transfer coefficients respectively, r_o & r_i are outside and inside radius of the sensor tube respectively, T_s is tube surface temperature, T_f is fluid temperature, I is the current to the heating element, R is the resistance of the heating element.

The inside tube heat transfer coefficient is described using Nusselt number (N_u)

$$h = \frac{N_u K_f}{D} \quad (3.15)$$

Where, D-diameter of the sensor tube

K_f - Thermal conductivity of Fluid

For a fluid in a tube, which is related as in laminar Sieder-Tate equation as follows:

$$N_u = 1.80 \left(R_e P_r \frac{D}{L} \right)^{1/3} \text{ for } R_e < 2100 \quad (3.16)$$

Where R_e =Reynolds number, P_r =Prandtl number.

3.3. INITIAL AND BOUNDARY CONDITIONS

Initial and boundary conditions must be expressed for complete solution of numerical model. The temperature for left and right end of the sensor tube taken as ambient temperature. Mathematically this may be expressed as

For $t \leq 0$ for all x , $T_s = T_f = 298K$

For all t' , $x \leq 0$ for all x , $T_s = T_f = 298K$

For all t' , $x \leq L$ for all x , $T_s = T_f = 298K$

3.4. DISCRETISATION OF TEMPERATURE DISTRIBUTION EQUATIONS

The above equations and their boundary conditions are complex to solve using simple solution techniques, we have to approach the numerical methods to solve. The fig shows the two-dimensional representation of an element of rectangular grid.

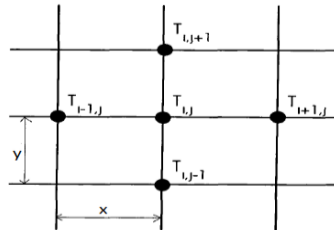


Fig:3.3: Rectangular Grid

5-point discretisation technique is used to approximate the partial differential equations formulated earlier. Forward difference method is used to calculate the first derivatives.

$$\begin{aligned}\frac{\partial^2 T}{\partial x^2} &= \frac{(T_{i+1,j} - 2T_{i,j} + T_{i-1,j})}{x^2} & \frac{\partial^2 T}{\partial r^2} &= \frac{(T_{i,j+1} - 2T_{i,j} + T_{i,j-1})}{y^2} \\ \frac{\partial T}{\partial x} &= \frac{(T_{i+1,j} - T_{i,j})}{x} & \frac{\partial T}{\partial r} &= \frac{(T_{i,j+1} - T_{i,j})}{y}\end{aligned}$$

Discretised form of energy equation of an element of gas is

$$\frac{(T_{i+1,j} - 2T_{i,j} + T_{i-1,j})}{x^2} + \frac{(T_{i,j+1} - 2T_{i,j} + T_{i,j-1})}{y^2} + \frac{(T_{i,j+1} - T_{i,j})}{r_j y} - \frac{m_j \cdot C_p}{K_f A_f} \frac{(T_{i+1,j} - T_{i,j})}{x} = 0$$

$$\begin{aligned}T_{i,j} \left(-\frac{2}{x^2} - \frac{2}{y^2} - \frac{1}{r_j y} + \frac{m_j \cdot C_p}{K_f A_f x} \right) + T_{i-1,j} \left(\frac{1}{x^2} \right) + T_{i+1,j} \left(\frac{1}{x^2} - \frac{m_j \cdot C_p}{K_f A_f x} \right) + \\ T_{i,j+1} \left(\frac{1}{y^2} + \frac{1}{r_j y} \right) + T_{i,j-1} \left(\frac{1}{y^2} \right) = 0\end{aligned}\quad (3.17)$$

For element of sensor tube is

$$K_s A_s \frac{(T_{i+1,j} - 2T_{i,j} + T_{i-1,j})}{x^2} - h_i 2\pi r_i (T_s - T_f) - h_o 2\pi r_o (T_s - T_{amb}) = 0 \quad (3.18)$$

CHAPTER 4

4. SIMULATIONS AND COMPUTATIONS

The thermal mass flow meter structure is simulated using ANSYS FLUENT Multiphysics 2022 software which is finite element-based package and it can simulate heat transfer, fluid flow, electromagnetics, structural mechanics, acoustics, and energy coupling between each of the domains. Two methods are used in simulation, i.e., steady state and dynamic state. The software uses, the basic governing equations that describe fluid flow and heat transfer consists of the well-known conservation equations for mass, momentum, and energy.

The general form of the mass conservation equation is

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_j}{\partial x_j} = 0 \quad (4.1)$$

Where ρ is the fluid density, u_j are the velocity components ($j=1,2,3$) in the x_j direction, and t denotes time.

The conservation of momentum, also known as Navier-stokes equations for laminar flow,

$$\rho \left(\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} \right) = - \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) + \Lambda \frac{\partial u_i}{\partial x_i} \delta_{ij} \right] + B_i \quad (4.2)$$

Where subscripts $i,j=1,2,3$ (denoting x, y or z), p is pressure, μ is viscosity, B_i is the body force term.

The conservation of energy can be written in terms of total energy as

$$\rho \left(\frac{\partial e}{\partial t} + u_j \frac{\partial e}{\partial x_j} \right) = \frac{\partial}{\partial x_j} \left(k \frac{\partial T}{\partial x_j} \right) - \frac{\partial p u_i}{\partial x_j} + u_j \frac{\partial \sigma_{ij}}{\partial x_i} + \phi + q'' \quad (4.3)$$

Where e is total energy per unit mass, T is the temperature, k is the thermal conductivity, p is the pressure, σ_{ij} is the shear tensor, ϕ is the dissipation function, and q'' is the internal heat generation per unit volume. These equations are general enough to account for all types incompressible fluid flow.

In Finite Element Analysis, a geometry is divided into many smaller (in the order of lakhs) elements. By balancing the forces and fluxes acting on each element from its adjoining elements, and repeating the calculation process until convergence achieved, the partial differential equations are simplified. While the results are finally an approximation, with very small elements and several iterations, the results can be consistent and accurate.

4.1 SIMULATION SETUP

The process for performing CFD analysis is outlined by the following description

4.1.1 Generate model

Once the dimensions of the thermal mass flow meter are fixed, Three-Dimensional model to be created using any 3D design software like AutoCAD inventor, solid Works or similar software and import it to the ANSYS package. ANSYS Fluent has its own 3D design software called DesignModeler.

Designed a simple straight tube of Inner diameter of 7 mm and Outer diameter of 7.4 mm. The heat sink is 40mm length from the edge of the sensor on both sides and 47mm & 7.4mm OD and ID respectively. The heating section is 10mm long at the centre of the pipe.

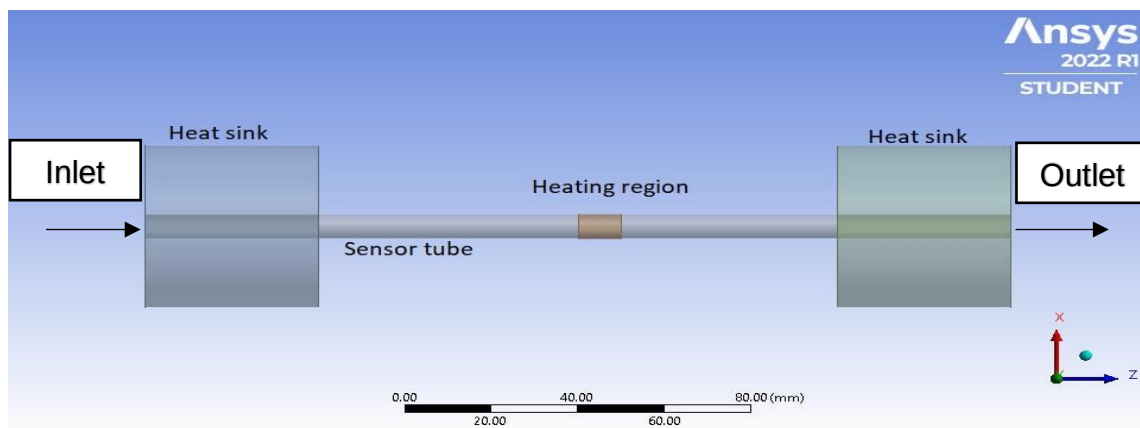


Fig:4.1: ANSYS model of a thermal mass flow meter

4.1.2 Meshing the model

This model is divided into many small elements by (grid discretization) meshing. The shapes of these elements are determined by the element type. In these computations, the shapes are tetrahedral. This step is very important, as elements that are big fail to accurately depict the model, hence the simulation may fail to converge to the required accuracy. Grids that are too small can take more

computing power and computing time to run the simulation. Meshing the thermal mass flow meter model is difficult because of very thin-film heating surface, should interact with larger fluid channel. With the auto meshing feature(inflation), the grids of the fluid near the wall will be small, and the size of the grid will increase as the distance from the heating wall increases. This is more convenient, but problems with convergence are sometimes encountered. Alternatively, if computing power are sufficiently available, small grid sizes can be used in the entire model. The element size of the mesh for this model is 0.001m and 60 mesh in radial direction.

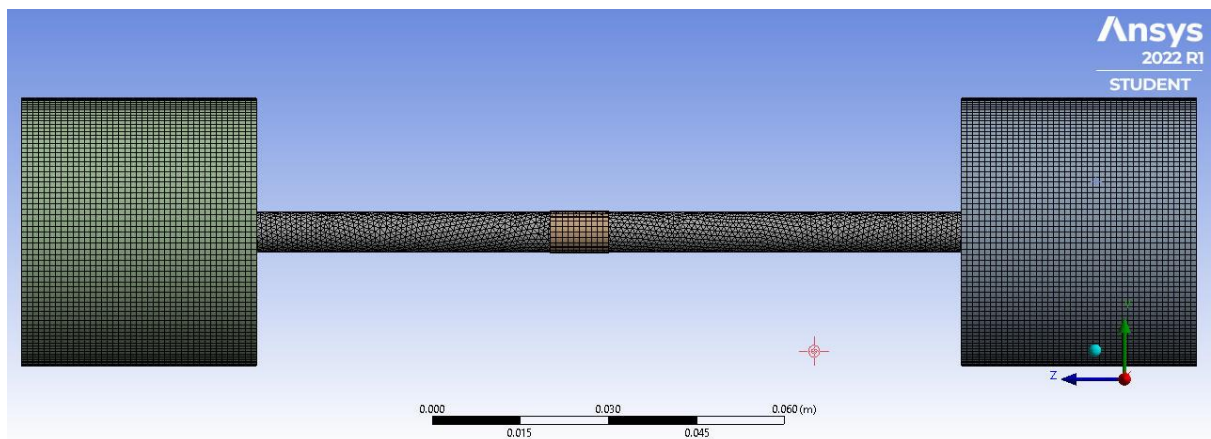


Fig:4.2: Meshed ANSYS model

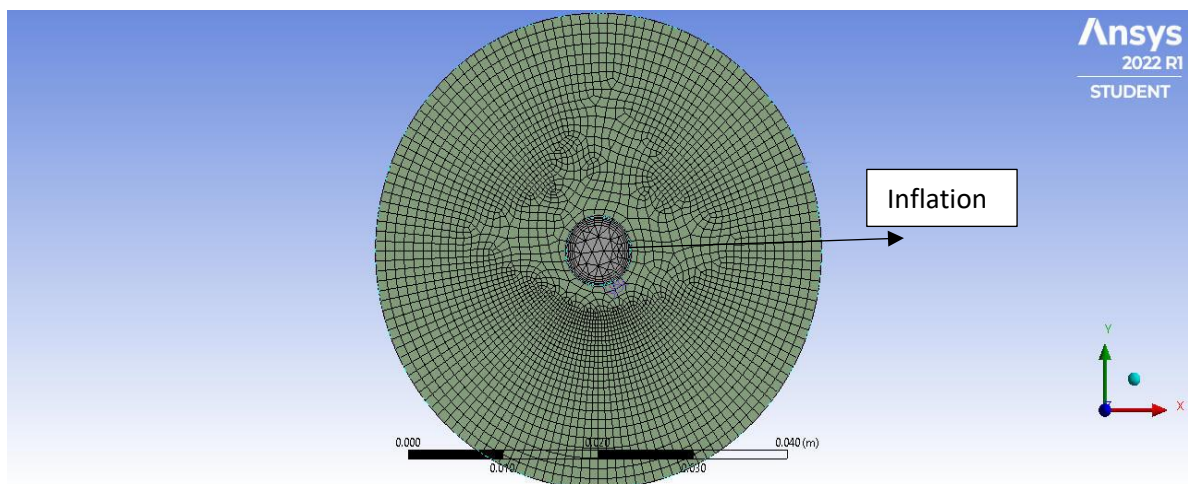


Fig:4.3: Inflation on a fluid element near the wall

4.1.3 Setup the model

In our case, energy model and fluid flow model equations to be solved. In this step, the gas pressure and mass flow to be defined. In 3-Dimensional analysis, both pressure and mass flow are defined. Fluid properties are also to be

given, which combined with the gas geometry, find the relationship between pressure and mass flow rate. To model fluid in a pipe or tube, a constraint of zero gas velocity is applied at the edge of the gas body, enforcing the no-slip flow condition.

For energy analysis, the energy generation, temperature, heat flux, and heat transfer coefficient can be given. A temperature value setting will hold a surface at constant temperature, letting it to act as a heat source or sink. Heat flux can be used to define the heat produced from a surface area, and heat generation can be used to define heat produced by a volume of surface. Constraining the heat transfer coefficient of an area is helpful in modelling heat transfer to another body of known temperature.

4.2 RUN THE SIMULATION

Once the material properties, boundary conditions, and initial conditions are entered into the program, the simulation runs with many (between 10 and 200) iterations to find the gas velocity, pressure, and temperature on elements unconstrained. The temperature of the heater varies as the gas temperature varies and maintains constant differential temperature. The simulation repeated for different flow ranges from 0 SCCM to 100 SCCM, different gases WF6, Nitrogen and Helium etc., different gas temperatures from 15⁰C to 40⁰C and different sensor tube diameters from 1mm to 7mm with different heating region length. The convergent limit for energy and continuity equation to be set as 10⁻⁶ and shown in the Fig. 4.4.

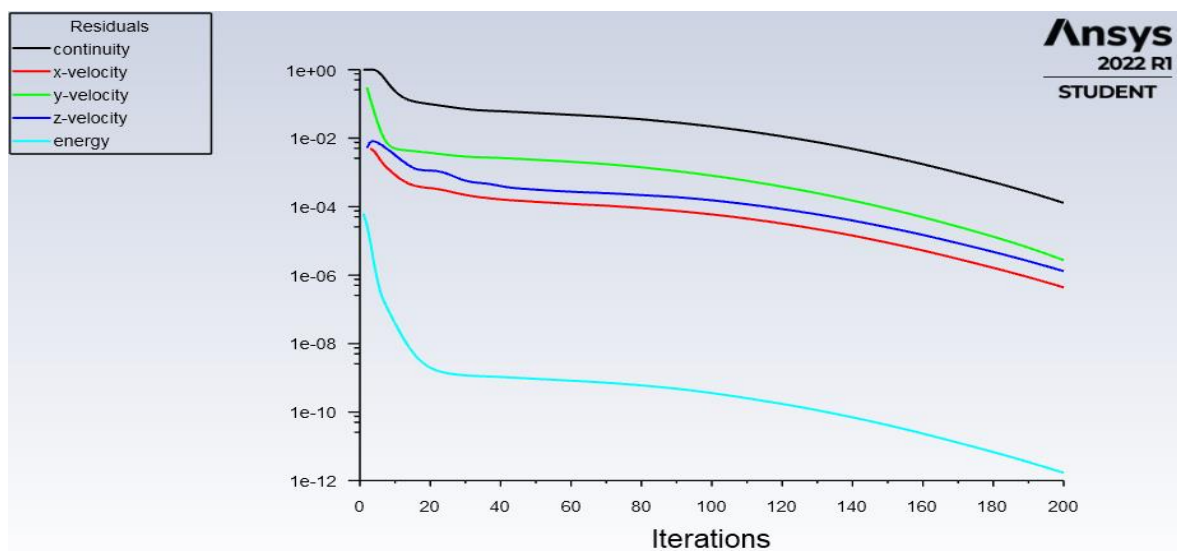


Fig:4.4: Scaled Residuals charts

4.2.1 Boundary conditions:

Inlet- The mass flow inlet type is selected for the inlet; the absolute pressure is selected as 0.1Pa and the rest values will be as per the requirement. Inlet temperature kept as atmospheric temperature(288K).

Outlet - The outlet is selected as a mass flow outlet; the outlet temperature kept as atmospheric temperature(288K).

Wall: The wall motion is stationary, and the shear condition is no-slip, and thermal condition chosen as temperature, both heat sink temperature kept as atmospheric temperature(288K) and wall thickness kept as 20mm for conduction solution heat generation rate kept as 0. The heater temperature kept as 40K higher than the gas inlet temperature.

4.2.2 Setup of the model

Table 4.1: Input Parameters for ANSYS Fluent

Parameters	Settings	Reason
Solver	• Type: Pressure-based • Time: Steady-state	➤ Pressure- It is for incompressible fluid flow. ➤ To study the velocity profile at given time.
Model	• Viscous Laminar • Energy ON	➤ Involves Laminar fluid flow. ➤ Involves heat transfer calculation.
Materials	• Tungsten Hexa Fluoride (WF6) • Hydrogen Fluoride (HF)	➤ Density (13.25 kg/m³) and dynamic viscosity (1.72e-05kg/m.s) ➤ Density (0.893 kg/m³) and dynamic viscosity (1.99e-05kg/m.s)
Boundary conditions	• Mass flow-inlet: 0-100 sccm • Supersonic/ Initial Gauge Pressure: -101324 Pa	➤ Mass flow is 0-100 sccm ➤ Initial pressure into pipe is 0.01 mbar.
Solution methods	• Scheme: Coupled • Momentum: Second order	➤ Coupled scheme is used for Temperature, velocity and pressure corrections to obtain a more accurate pressure field.
Solution Initialization	• Hybrid initialization	➤ Used for single-phase flow

CHAPTER 5

5. RESULTS AND DISCUSSIONS:

5.1. DIAMETER OF THE TUBE:

While calculating the diameter, the lightest gas which is flowing through the sensor is to be considered, in this case Hydrogen Fluoride (HF) is the lightest gas which could flow through the sensor tube as the WF_6 is highly hygroscopic in nature which liberate HF while reacting with moisture in atmosphere.

For 4 gm/hr HF flow with pressure drop of 0.1 pa and 20cm length, the diameter is

$$D^4 = \frac{128 \times 0.2 \times 1.99 \times 10^{-5} \times 1.38889 \times 10^{-6}}{0.893 \times 3.14 \times 0.1}$$

$$D^4 = \frac{7.07556 \times 10^{-10}}{0.280544}$$

$$D = (2.52208 \times 10^{-9})^{0.25}$$

$$\boxed{D = 7.0 \text{ mm}}$$

For different gases, the sensor diameter is tabulated for 4gm/hr flow,

Table 5.1: Gas density Vs sensor diameter

Gas	Density (Kg/m ³)	Diameter(mm)
Helium	0.179	10.02
Hydrogen Fluoride	0.893	6.70
Carbon Di Oxide	1.964	5.32
Butane	2.59	4.97
Carbon tetrafluoride	3.929	4.47
Hexafluoroethane	6.16	3.79
Sulfur hexa fluoride	6.518	3.81
Tungsten hexafluoride	13.25	3.29

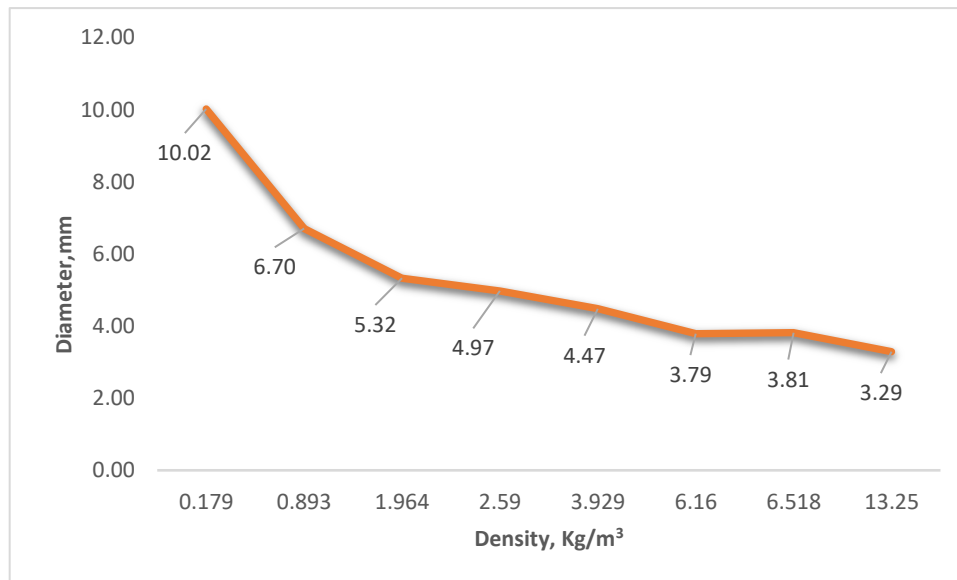


Fig:5.1: Gas density Vs sensor diameter

The graph depicts, the diameter of the sensor tube inversely proportional to the gas density. As the density increases, the sensor diameter is decreases to get the same level of pressure drop. The disadvantage of the higher diameter is sensitivity will be less. To make it up we need to increase the heater temperature. But heater temperature also cannot be increases beyond certain limit

5.2. THICKNESS OF SENSOR TUBE

For Thermal mass flow meter application

Operating Pressure- **100 KPa**

Inside Diameter- **7 mm**

Allowable Stress for material-**70000 KPa**

Design factor- **0.72**

Longitudinal joint Factor- **1**

$$t = \frac{100 \times 7}{2 \times 7000 \times 0.72 \times 1} = 0.007mm$$

The thickness comes around **7μm**. But sum of allowances for threading, grooving, corrosion, and erosion to be given. Considering the allowance and Manufacturability the thickness chosen as **0.20 mm (200 μm)**

5.3. SIMULATION RESULTS:

In this section, the results of the two-dimensional numerical simulation of different configurations presented.

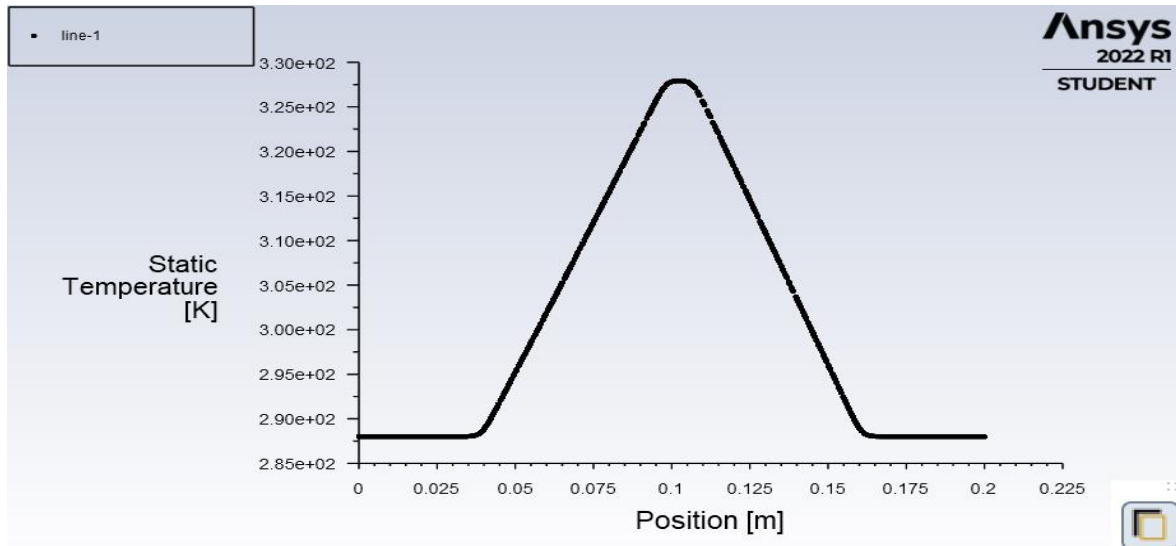


Fig.5.2: Axial temperature distribution of the sensor

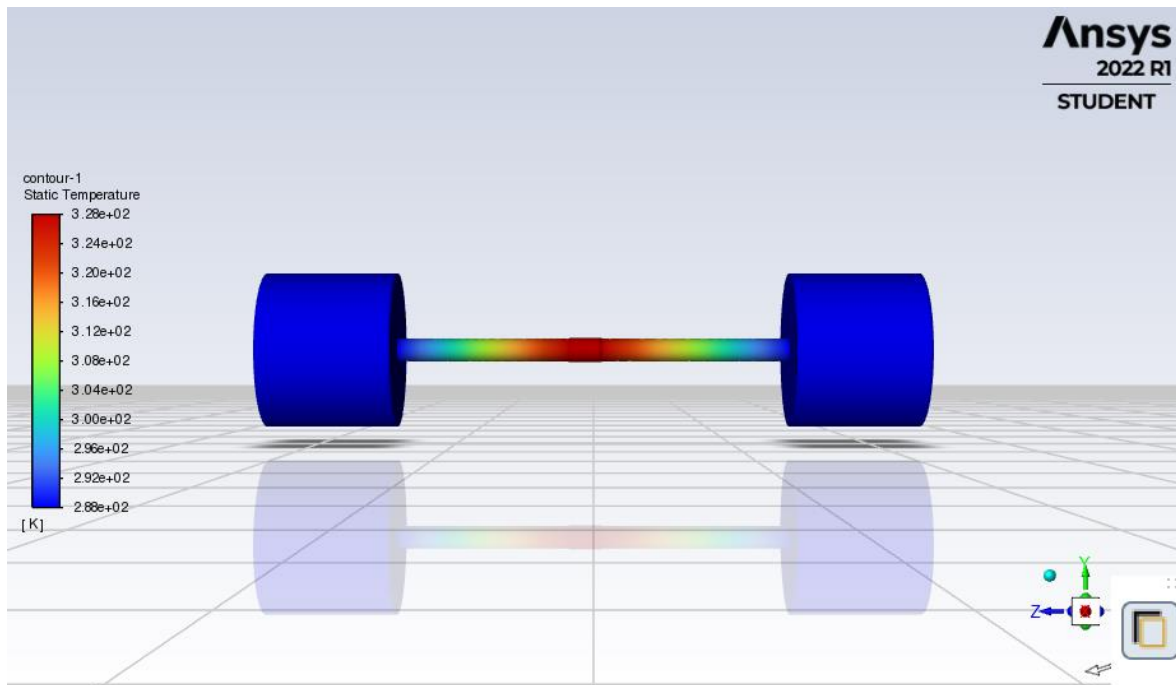


Fig.5.3: Contours of Axial temperature distribution of the sensor

The temperature distributions in Fig. 5.2 are related to those found in thermal mass flow meter. The mountain-like shape of the axial temperature distribution of the sensor is formed by the heat generated by the platinum coil windings in the centre portion of the tube and heat removed by conduction of heat sinks at its two ends.

In zero flow, the axial temperature distributions are identical and symmetrical with respect to the centre of the tube. When there is flow in sensor tube (flow is to the right), the temperature profile become asymmetrical and slightly moves towards outlet. The power required to maintain the peak temperature constant for different flow is actually small, still it has excellent sensitivity in providing the mass flow measurement.

The gas entering the sensor has the temperature equal to inlet heat sink temperature and the inlet of the sensor tube, as shown in Fig. 5.2 & Fig. 5.3. When the gas experience the increasing temperature profile of the sensor tube in the upstream half of the sensor, the gas temperature continually increases to slightly cooler than the sensor wall temperature. So, in upstream half of the sensor, heat is transferred from the sensor tube wall to the gas by convection. This heat is absorbed by the gas via its molar heat capacity, and the gas temperature continues to increase.

After gas reaching the centre of the sensor, the gas encounters the decreasing temperature profile in the downstream half of the sensor (due to its dominant heat conduction), but retains the heat it has absorbed in the upstream half. So, the gas temperature is always higher than that of the sensor tube, and heat is transferred from the gas to the sensor tube by convection. The heat transferred into the downstream half of the sensor tube is that which is carried in the gas via its heat capacity, and the gas temperature continues to decrease as the gas transfers its heat.

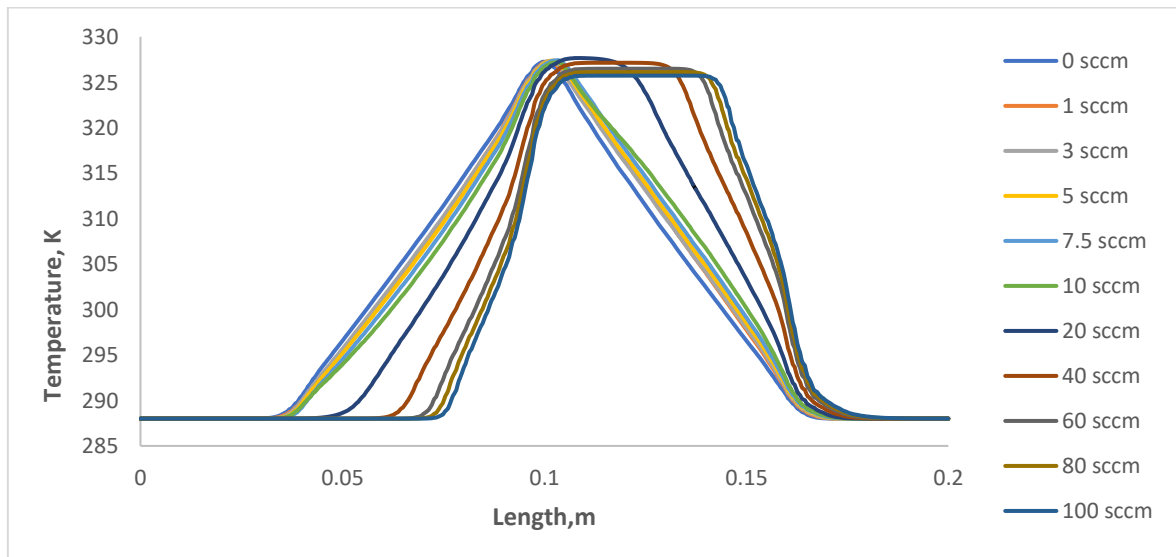


Fig:5.4: Temperature distribution of the sensor of 7mm dia. for various flow(10mm)

In fig.5.4, shows the temperature distribution of sensor tube of 7mm diameter and 230mm² heating surface area at the center for different flow of WF₆ from 0-50 SCCM. The heating coils wound for 10mm at the center. As can be seen, the peak temperature(327K) of the sensor keeps shifting towards right and slightly reduces as the flow rate increases and the length of the peak temperature also increases due to poor thermal conductivity in turn poor conduction of the gas from and to the sensor tube. As can be seen in the graph, till 5 sccm there is no any appreciable change in the axial temperature distribution and almost equal peak temperature. After 5 sccm the peak temperature slightly reduces, the power supplied to maintain the constant peak temperature will be linearized to the mass flow reading. Though the larger diameter sensor gives very low pressure drop, it has poor sensitivity to very low flows. For flow higher than the 60 sccm, the total heat capacity of the gas becomes high resulting in higher skin temperature in the outlet of the sensor and the difference in peak temperature is also very less, thus it is achieving the saturation limit.

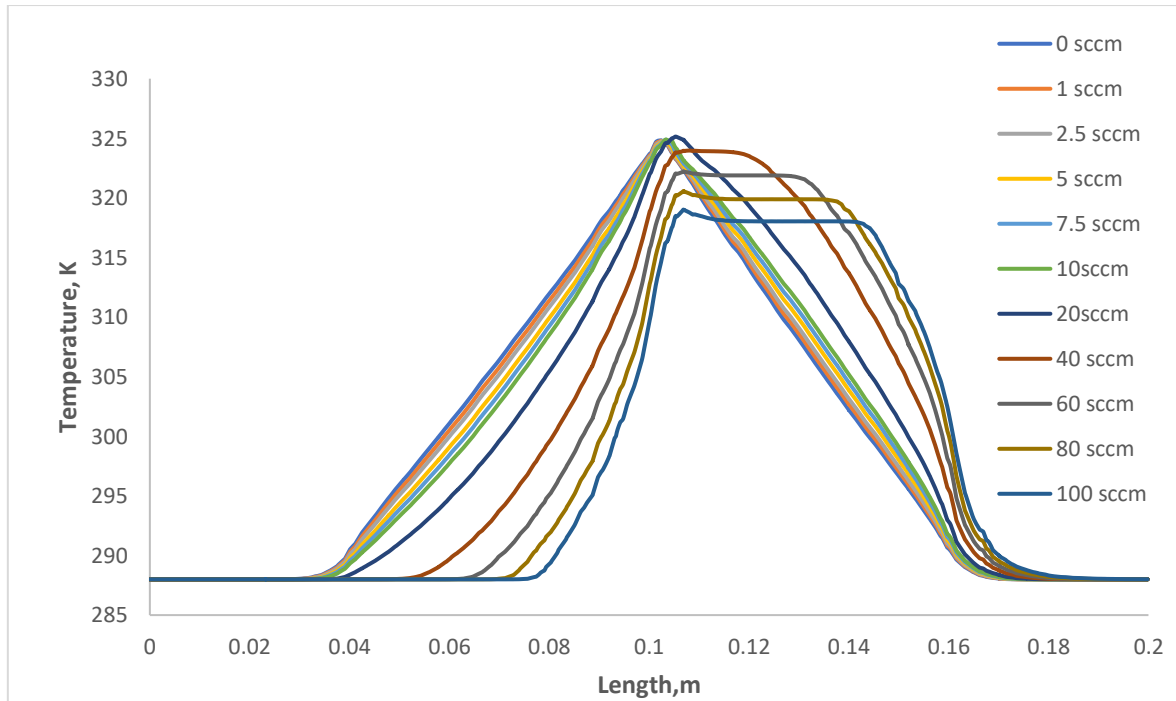


Fig:5.5: Temperature distribution of the sensor of 7mm dia. for various flow(5mm)

In Fig.5.5 shows the temperature distribution with change in the length of the heated region(5mm) with same diameter sensor for WF₆ gas. The peak temperature(325K) is less compared to earlier configuration(327K), hence the power required to maintain the peak temperature is high compared to the earlier configuration. As earlier graph, till 5 sccm mass flow the axial temperature

distribution and the peak temperature is unaltered, after that there will be a distinguishable variation in the axial temperature distribution and the peak temperature. The power required to maintain the constant peak temperature will be linearised with respect to mass flow reading. Unlike earlier configuration, till 100 sccm, there will be appreciable change in peak temperature and the temperature distribution.

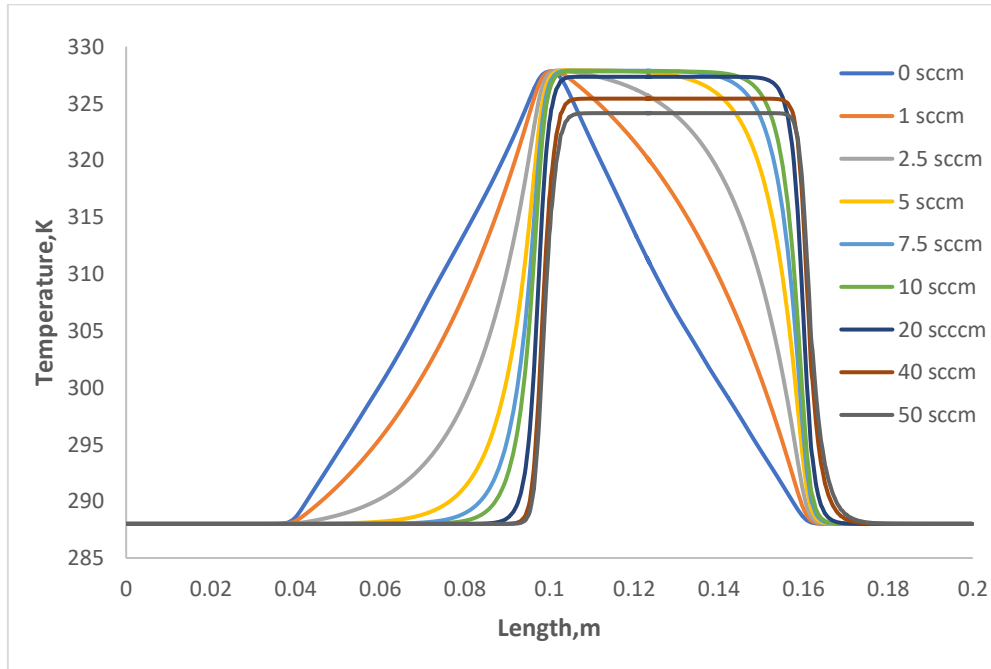


Fig:5.6: Temperature distribution of the sensor of 5mm dia. for various flow

The simulation repeated for 5 mm diameter sensor with 200mm length and 10mm heating region at the center. Boundary conditions applied to the model is Mass flow inlet, mass flow outlet, Heat sink temperature (Atm. Temperature) kept as 288K and the heated region is 40K higher than gas inlet temperature (heat sink temperature) at center. The temperature distribution along the axial direction for WF_6 gas is shown in Fig.5.6. Unlike 7 mm diameter sensor, It is having high sensitivity even for 1 SCCM but the variation in temperature will get saturated with 40 SCCM, there after the change is very less. But the problem with 5mm diameter sensor compared to 7 mm sensor is, it offers high pressure drop comparatively. The advantage is high sensitivity whereas the disadvantage is high pressure drop and low range.

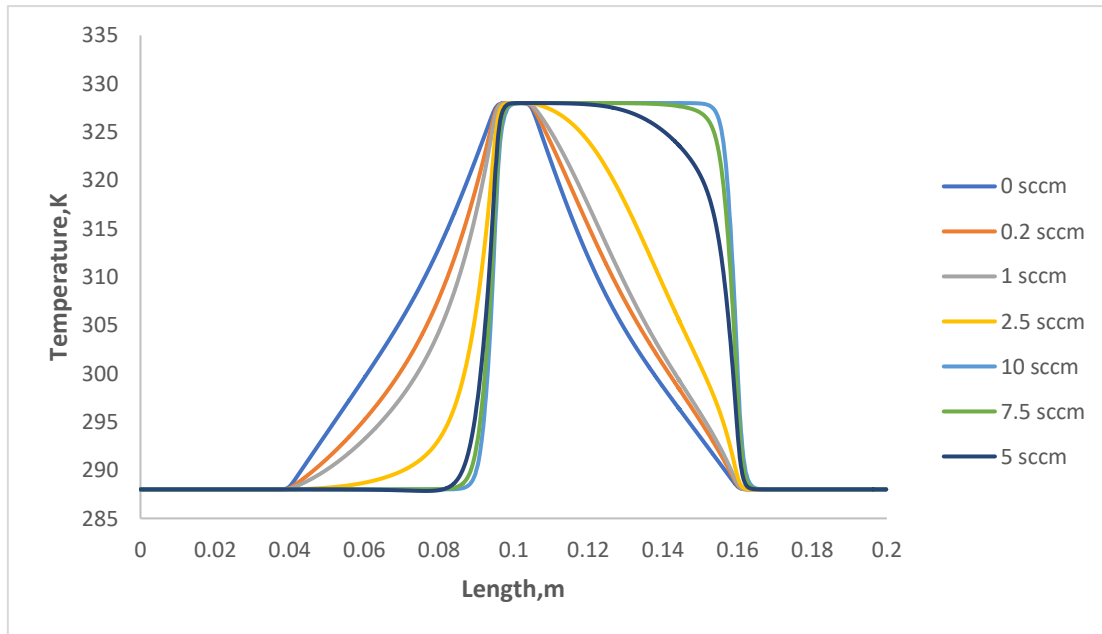


Fig:5.7: Temperature distribution of the sensor of 3mm dia. for various flow

The Fig.5.7 shows the temperature distribution of the 3mm sensor tube. It can be observed that reduction in tube radius increases the sensitivity for low flow. This phenomenon is easily explained from the sider-Tate equation for heat transfer coefficient between the tube and flowing gas. A reduction in the tube diameter increases the “h” value due to increase in N_{Re} value, which makes the heat transfer to the gas more effective, but ΔP and the range limits the selection. In this 3mm sensor gives the sensitivity even for 0.2 sccm but it gets saturated with 7.5 sccm, beyond that the temperature distribution is almost same for all flows.

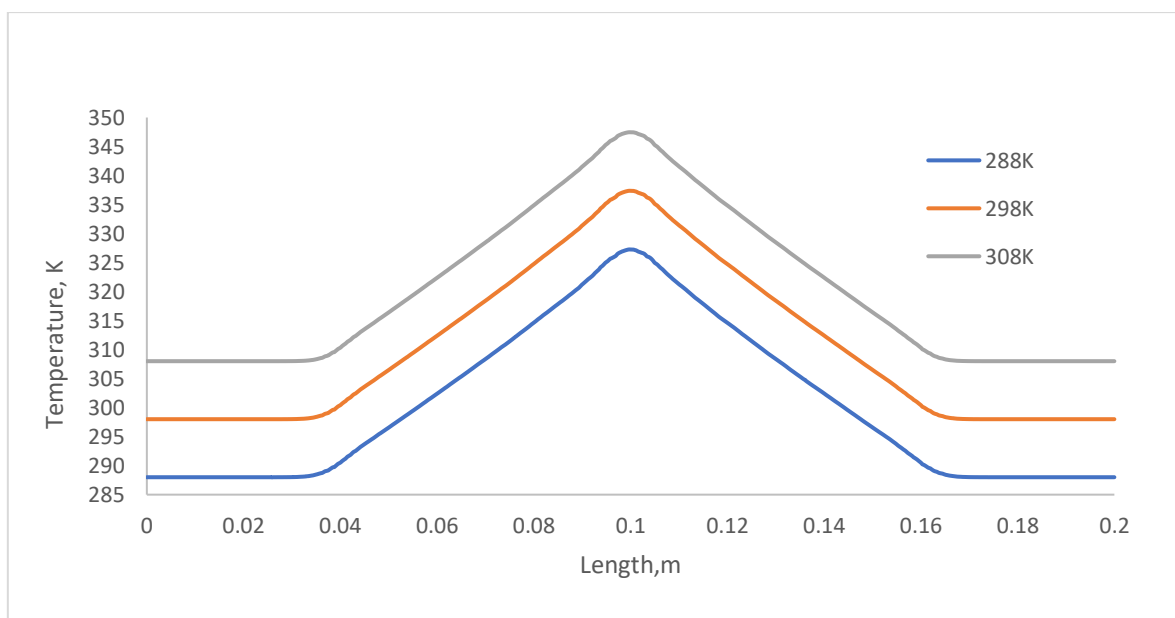


Fig:5.8: Temperature distribution of the sensor for various atm.temperature

As the resistance values of heater and the gas temperature sensor is chosen such that the circuit will always get balanced at the constant differential temperature. As can be seen in the graph, the constant differential peak temperature is maintained by the electronics for different gas temperature. The temperature distribution is shown in Fig.5.7. If the gas temperature is 288K, then the heater temperature maintained is 328K (i.e., 40K higher than gas temperature). Similarly, when the gas temperature is 298K due to ambient variation or due to some process variation, the heater temperature will be maintained 338K, and when the gas temperature is 308K, the heater temperature will be maintained 348K. Since both heater and sensor resistance value changes simultaneously, the power supplied to the circuit will be unaltered, hence the error due change in gas temperature is greatly reduced.

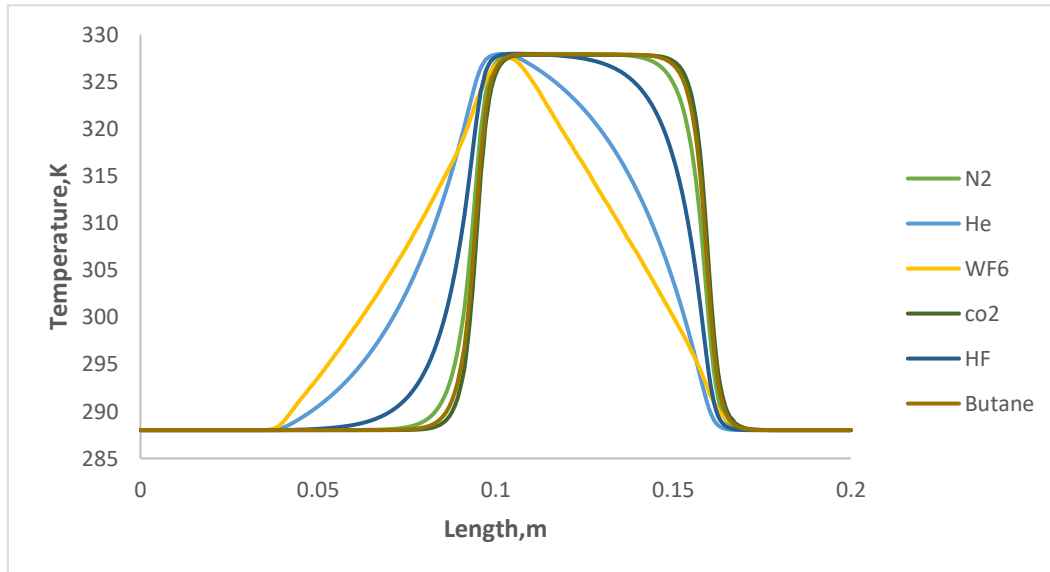
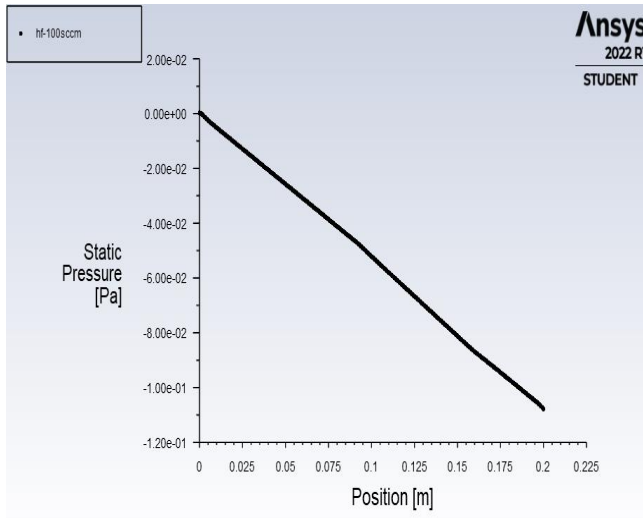


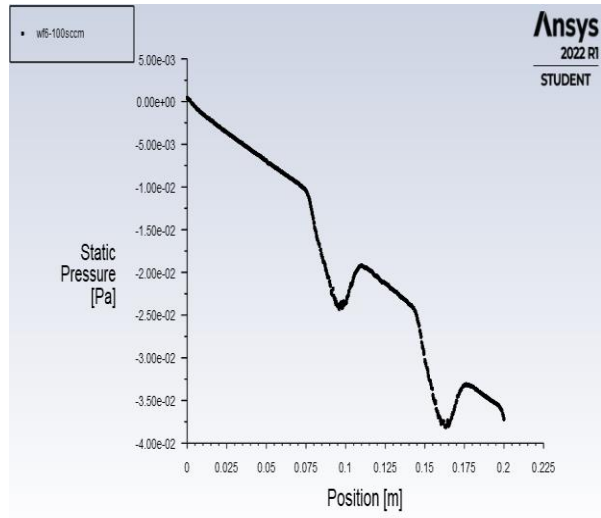
Fig.5.9: Temperature distribution of the sensor for different gas.

Thermal mass flow meters are giving good accuracy (<1%), if they are calibrated with original process gas. But all the calibrations cannot be performed with actual process gas due to various reasons like toxicity, corrosiveness, non-availability etc. In that case, it is common practice to use a reference gas like Nitrogen, Air for calibration and use the conversion factor for the actual gas. Fig.5.9 shows the axial temperature distribution of sensor tube with 10 SCCM flow of different gases. Since the heat generated by the heater is constant for all gases, the heat carried away by the flowing gas depends on the molar heat capacity. As it can be seen from the graph, different gases show different temperature distribution for same mass flow rate due to the fact that, all gases don't have same molar heat capacity. The gas which has low molar heat capacity will get heated up very soon as well cools down very easily. Similarly, the gas which have high molar heat capacity will get heated

up very slowly as well cools down very slowly. Since the heat capacity is a function of the temperature, the conversion factor will be varying with peak temperature of the Thermal Mass Flow Meter.

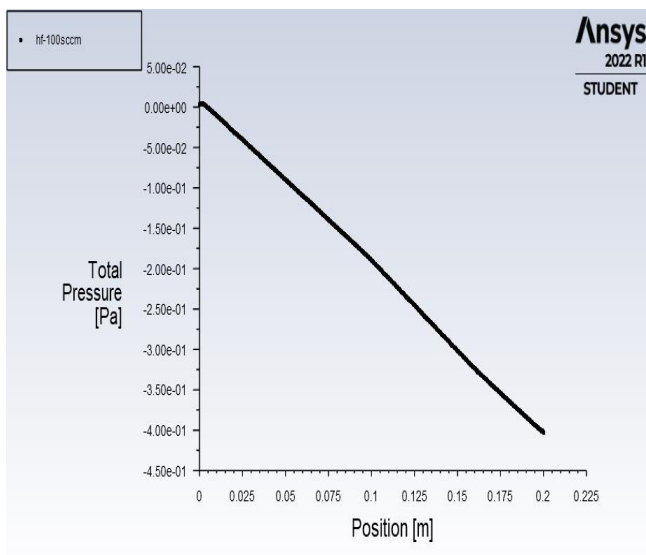


(a)

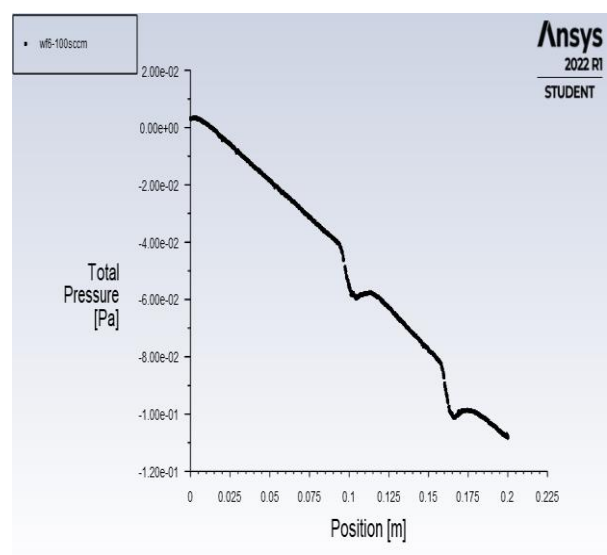


(b)

Fig.5.10: Pressure drop profile of 7mm sensor tube (a) Hydrogen Fluoride (b) WF6

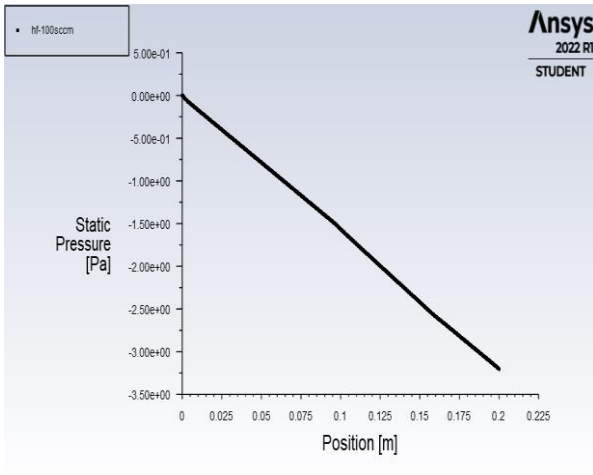


(a)

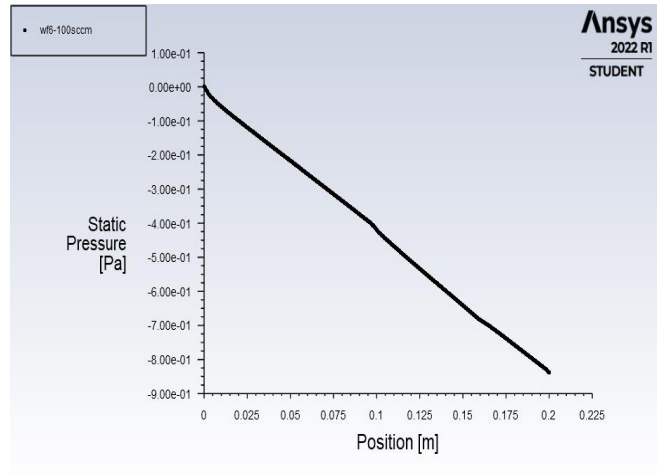


(b)

Fig.5.11: Pressure drop profile of 5 mm sensor tube (a) Hydrogen Fluoride (b) WF6



(a)



(b)

Fig:5.12: Pressure drop profile of 3 mm sensor tube (a) Hydrogen Fluoride (b) WF6

Fig. 5.10 (a) shows the pressure drop across the thermal mass flow meter of 7 mm diameter for 100 SCCM(5.35gm) of Hydrogen Fluoride gas. Simulation shows that there is a pressure drop of **0.11 Pa** absolute. Similarly, Fig. 5.10 (b) shows the pressure drop for 100 SCCM (20gm) Tungsten Hexa Fluoride (WF6) gas, is **0.04 Pa** absolute.

Fig. 5.11 (a) shows the pressure drop across the thermal mass flow meter of 5 mm diameter for 100 SCCM of Hydrogen Fluoride gas. Simulation shows that there is a pressure drop of **0.425 Pa** absolute. Similarly, Fig. 5.11 (b) shows the pressure drop for 100 SCCM Tungsten Hexa Fluoride (WF6) gas, is **0.11 Pa** absolute.

Fig. 5.12 (a) shows the pressure drop across the thermal mass flow meter of 3 mm diameter for 100 SCCM of Hydrogen Fluoride gas. Simulation shows that there is a pressure drop of **3.25 Pa** absolute. Similarly, Fig. 5.12 (b) shows the pressure drop for 100 SCCM Tungsten Hexa Fluoride (WF6) gas, is **0.91 Pa** absolute.

CHAPTER 6

6. CONCLUSION AND FUTURE WORK:

6.1. . CONCLUSION:

Development of thermal mass flow meter for low pressure drop and corrosion resistant application in vacuum environment has played a significant role in semiconductor manufacturing sector. Since very limited suppliers manufacture low pressure drop thermal mass flow meter used in industrial practice since late 1950's, researches conducted on this type of flow meters are limited. This is especially true for the computational fluid dynamics of a Thermal mass flow meters.

Therefore, the CFD of Thermal Mass Flow Meter has been developed in this project using ANSYS Fluent 2022 R1 software. ANSYS Fluent is a sophisticated CFD simulation tool to study temperature, pressure and flow profile of a model. By developing Thermal Mass Flow Meter based on the real dimension and geometry, the result of this model would be closely related to nowadays application. This simulation can then provide a platform to conduct study on the possibility of usage of these type of Thermal Mass Flow Meter in other fields and applications.

The comparison of different configuration of thermal mass flow meter were modelled and simulated. From the results, for a given pressure drop and flow range, 7 mm diameter sensor with 5 mm heater length is most suitable. It has high sensitivity (1 sccm) as well as range till 100 SCCM. To optimise the mass flow meter, the design should aim to minimize the power by reducing the heat loss to the environment. The sensitivity can further be increased by increasing the sensor over heat temperature.

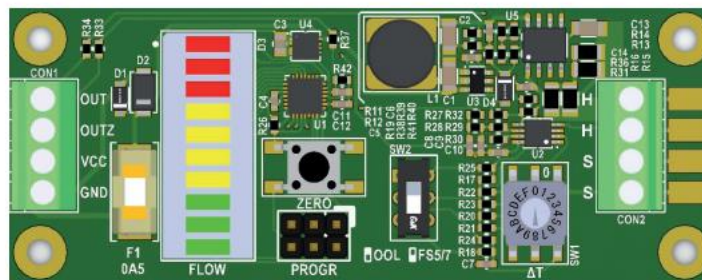
6.2. . FUTURE WORKS:

- To assess how well the ANSYS simulations translate to true behaviour, fabricated sensors should be made and tested.
- The constant power circuit board as shown in Fig.6.1 can be procured from “Innovative Sensor Technology” and can be used to characterize the actual circuits similar to the characterization done in ANSYS.
- For heating element, Polyamide insulated Platinum wire has to be used as per the circuit board specifications. For heater-PT45 and for sensor-

PT1200. PT45 means, the resistance of the wire is 45 ohms at 0°C, similarly PT1200 means,1200 ohms at 0°C.

- For different flow rates, the sensor will set and deliver a constant temperature, and the input power to heater is measured. The power divided by overheat temperature is equal to the heat conductance. The heat conductance trend can be fitted to King's Law, and used as calibration for the sensor.

Front side of Flow Demo Board:



Back side of Flow Demo Board:

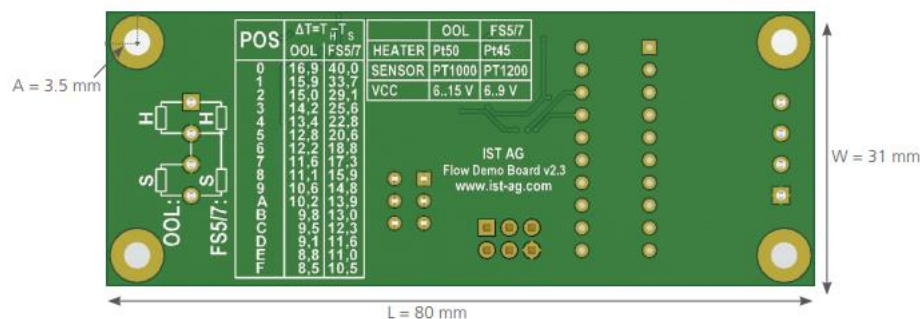


Fig:6.1: Flow demo circuit board for thermal mass flow meter

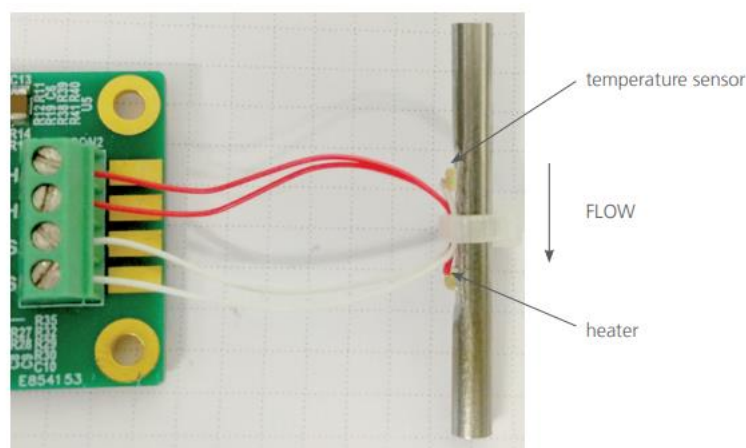


Fig:6.2: Model sensor tube

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