INVESTIGATION ON THE CAPACITANCE FLOW METER AND DEVELOPMENT OF VOID FRACTION SENSOR FOR CRYOGENIC TWO-PHASE FLOW

PROJECT REPORT

Submitted by

ABHIJITH A

Reg. No: TKM21MEIR01

to

The APJ Abdul Kalam Technological University

in partial fulfilment of the requirements for the award of the Degree

of

Master of Technology

in

Mechanical Engineering

Specialization: ***Industrial Refrigeration and Cryogenic Engineering***

DEPARTMENT OF MECHANICAL ENGINEERING

THANGAL KUNJU MUSALIAR COLLEGE OF ENGINEERING

KOLLAM-5

MAY 2023

DEPARTMENT OF MECHANICAL ENGINEERING

TKM COLLEGE OF ENGINEERING, KOLLAM

CERTIFICATE

This is to certify that the report entitled **"INVESTIGATION ON THE CAPACITANCE FLOW METER AND DEVELOPMENT OF VOID FRACTION SENSOR FOR CRYOGENIC TWO-PHASE FLOW"** submitted by **ABHIJITH A** Reg. No: **TKM21MEIR01** during **2022-23** to the APJ Abdul Kalam Technological University in partial fulfilment of the requirements for the award of the Degree of Master of Technology in Industrial Refrigeration and Cryogenic Engineering is a bonafide record of the project work carried out by him under my guidance and supervision. This report in any form has not beensubmitted to any other University or Institute for any purpose.

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DECLARATION

I undersigned hereby declare that the project report "Investigation on the capacitance flow meter & development of void fraction sensor for cryogenic two-phase flow", submitted for partial fulfillment of the requirements for the award of Degree of Master of Technology to the APJ Abdul Kalam Technological University, Kerala is a bonafide work done by me under supervision of Dr.Mathew Skaria . This submission represents my ideas in my own words and where ideas or words of others have been included, I have adequately and accurately cited and referenced the original sources. I also declare that I have adhered to ethics of academic honesty and integrity and have not misrepresented or fabricated any data or idea or fact or source in my submission. I understand that any violation of the above will be a cause for disciplinary action by the institute and/or the University and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permissionhas not been obtained. This report has not been previously formed the basis for the award of any degree, diploma, or similar title of any other University.

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ABSTRACT

Numerous sectors including nuclear, refrigeration, chemical processing, space exploration, and nuclear energy frequently experience the simultaneous movement of liquid and vapor. Due to the intricacy of the flow, instrumentation for two-phase flow metering devices for cryogenic applications has been restricted. In the present study, as an initial step, towards the development of a cryogenic flow meter, flow through a narrow rectangular channel has been analysed using Liquid nitrogen as the cryogen. Based on the concept of two-phase flow meter, the flow is passed through a number of parallel narrow rectangular channels and the flow gets converted to laminar stratified. As the flow proceeds downstream, slope develops due to the frictional interaction between the fluid and the wall. The liquid height at various locations along the channel length has been determined using capacitance level gauge sensors and the corresponding mass flow rate of the liquid phase in the two-phase flow system could be determined. The test section consists of 15 rectangular channels for 6 plate capacitance and 17 channels for 4 plate capacitance with 2mm width, 74 mm high and 305 mm long, stacked parallel.

Keywords: Flow metering device, two phase flow, Cryogenic flow meter, capacitor flow measurement, Laminar flow, Stratified Flow, Rectangular channel, Capacitance.

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NOMENCLATURE

m	Mass flow rate [kg/s]
Δp	Pressure drop [Pa]
Δx	Gap between liquid column
A	Cross-sectional area, surface area [m^2]
At	Atwood number [-]
Bo	Bond number
C	Capacitance [pF]
Ca	Capillary number [-]
Co	Confinement number [-]
D	Diameter [m]
F	Force [N]
Fr	Froude number [-]
g	Gravitational constant [m/s^2]
G	Mass flux [$kg/m^2.s$]
H	Channel height
J	Superficial velocity [m/s]
L	Length [m]
La	Laplace number [-]
Q	Volumetric flow rate [m^3/s]
Re	Reynolds number [-]
S	Slip ratio, Slope
t	Channel thickness [m], time [s]
T	Total time [s]
V	Velocity [m/s]
y	Liquid height (m , mm)

Greek Letters

μ	Absolute viscosity [Ns/m^2]
f	Friction factor [-]
α	Phase fraction in a computational cell
β	Volumetric gas flow rate [-]
δ	Slope Angle [deg]
ε	Void fraction
λ	Bakers map gas-phase parameter
ν	Kinematic viscosity [m^2/s]
ρ	Density [kg/m^3]
σ	Coefficient of surface tension [0.072 N/m]
τ	Shear stress [N/m^2]
χ	Flow quality
ψ	Bakers map liquid-phase parameter

Subscripts

l	Liquid
g	Gas
h	hydraulic

CHAPTER 1

INTRODUCTION

Cryogenic fluids are used in a variety of applications, such as cooling superconducting magnets, aerospace propulsion systems, and medical equipment. They are also used in the distillation and storage of gases for industrial and life support purposes. The specific use of cryogenic fluid flow depends on the application. For example, in superconducting magnets, cryogenic fluids are essential to keep the magnet material below a critical temperature to maintain its superconducting state. In highly sensitive instruments like infrared telescopes, extremely low temperatures are required for accurate operation. Cryogenic fluids are commonly used as propellants for propulsion systems in aeronautics and aerospace, with many rockets around the world using liquid hydrogen (LH_2) as a propellant and liquid oxygen (LO_2) as an oxidizer in first-stage launch rockets. Two-phase flow, a well-known concept in engineering, is also common in cryogenics due to the low boiling point, high likelihood of heat leak, very low heat of vaporization, and low cavitation pressures of cryogenic fluids.

Two-phase flow occurs when two distinct phases with a common interface flow simultaneously through a channel. This can include combinations of gas-liquid, liquid-liquid, and gas-solid in various industrial and medical applications. Two-phase flow is commonly observed in refrigeration, cryogenics, oil exploration, nuclear reactors, heat exchangers, atomization, lab-on-chips, and cooling electronic devices. In the chemical and petrochemical industries, gas-water and oil-water two-phase flows are often encountered. Recent technological advancements in Micro-Electro-Mechanical Systems (MEMS), biomedical engineering, and space exploration have led scientists to study two-phase flows at mini and microscale levels. Two-phase flows are also used in high altitude applications due to their powerful heat transfer capability and temperature uniformity. Compared to single-phase flows, two-phase flows are more complex in structure and combine single-phase characteristics with interfacial phenomena such as interfacial stress and contact angle. Understanding the characteristics of two-phase flow is crucial due to its many applications.

Measuring two-phase flow systems is challenging due to their complexity, and this difficulty is amplified when measuring cryogenic fluids due to factors like cavitation and extremely low operating temperatures. Although two-phase flow is reasonably well-understood, predicting or measuring it accurately is not easy because of the numerous variables that affect flow characteristics and the complicated interaction between the phases. Cryogenic flows can exhibit various flow regimes due to differences in velocity between the vapor and liquid phases. No single system can measure two-phase flow in all flow regimes, and various methods exist that can only measure flows under specific conditions. Therefore, a device capable of measuring mass flow in two-phase flow, regardless of incoming flow characteristics, is necessary. In this report, a two-phase flow meter using liquid nitrogen is tested with the capacitive method, and steps to improve the accuracy of the results are identified.

1.1 FLOW MEASURING INSTRUMENTS

A flow meter (or flow sensor) can be defined as a tool for measuring the volume or flow rateof a liquid volume (liquid or gas). The flow rate is fully accurate because the weight does notchange compared to the volume. There are many tools designed to measure the flow of water,most of which are used to measure single-phase flow. The flow rates of the two phases and the instrumentation are very limited. Most flow meters are classified according to how they measure the flow rate; whether they have a linear or non-linear relationship with flow, intrusive or can cause disruption to flow rate; how they are installed (inside or outside). The most commonly used flow meters are presented in this section.

The most common category of flow meters uses differential pressure measurement to estimate the flow rate. Some of the differential pressure flow meters include venturimeter, orifice meter, and pitot tubes. They all have different designs, but they all have the same underlying principle, which is to obstruct the flow field, measure the induced pressure difference, and use Bernoulli's equation to estimate the flow rate.

1.1.1 THERMAL MASS FLOW METER

A thermal mass flow meter is a device used to measure the flow rate of a fluid by detecting the heat transfer between a heated object and the fluid. It works based on the principle that the rate of heat transfer is proportional to the flow rate of the fluid. In a thermal mass flow meter, a heated object (such as a probe) is inserted into the fluid stream. The heat generated by the object is dissipated by the fluid, and the rate of heat dissipation is measured. By knowing the thermal properties of the fluid and the temperature difference between the heated object and the fluid, the flow rate of the fluid can be calculated.

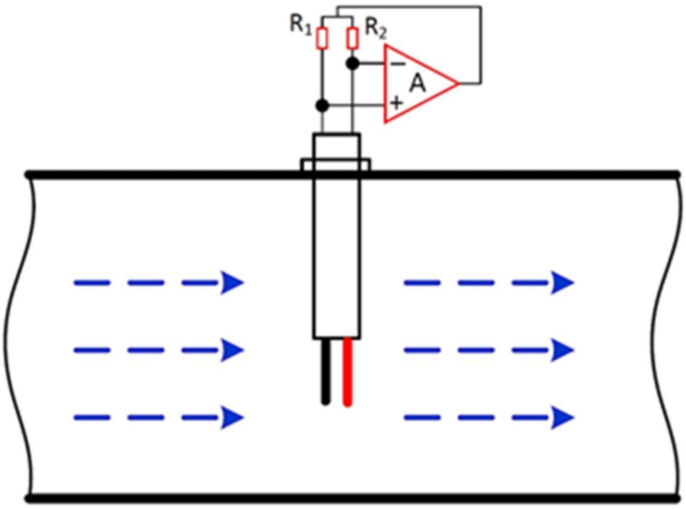


Fig. 1.1. Schematic of thermal mass flow meter (Moaaz Ahmed. et al,2020)

Some thermal mass flow meters use two platinum resistance temperature detectors (RTDs), the first sensor measures the gas temperature at immersion and the second sensor is heated to 60°F above the first sensor. The transfer of heat energy occurs to gas molecules by convection and it is based on the fluctuation of heat transfer coefficient. Wheatstone bridge, output can be used to estimate the gas flow rate. Thermal mass flow meters are primarily used for gases. Thermal mass flow meters are commonly used in industrial applications where the measurement of gas flow rates is critical, such as in the oil and gas industry, chemical plants, and power plants. They are known for their high accuracy and reliability, as well as their ability to measure low flow rates.

1.1.2 LAMINAR FLOW METER

A laminar flow meter is a collection of small tubes in which the flow rate is a direct function of pressure drop. It works based on the principle of laminar flow, which is when a fluid flows in parallel layers that do not mix.

In a laminar flow meter, a tube with a small diameter is inserted into the fluid stream. The tube is packed with a series of small screens or plates that create a laminar flow profile, where the fluid flows in parallel layers. As the fluid flows through the tube, the pressure drop across the screens or plates is measured. By knowing the fluid properties, the tube dimensions, and the pressure drop, the flow rate of the fluid can be calculated. Eq. (1.1) depicts the relationship of pressure drop and the volumetric flow.

$$Q = \frac{\pi\, d^4 (P_1 - P_2)}{128 \mu L} \tag{1.1}$$

Laminar flow meters are known for their high accuracy and precision, especially for measuring low flow rates. They are commonly used in industries such as pharmaceuticals, food and beverage, and medical devices, where precise flow measurements are critical. However, laminar flow meters are also sensitive to changes in fluid properties, such as viscosity, and can become inaccurate if the fluid flow becomes turbulent.

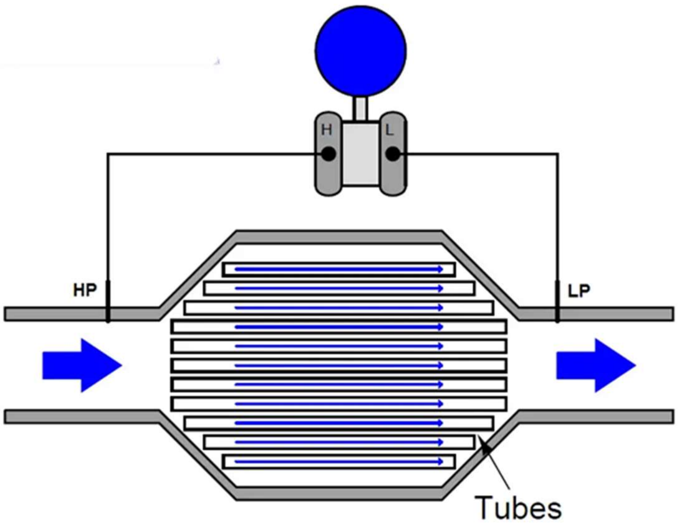


Fig. 1.2. Schematic of laminar flow meter (Instrumentationtools.com)

1.1.3 ULTRASONIC FLOW METER

An ultrasonic flow meter is a type of flow meter used to measure the flow rate of a fluid by using ultrasonic waves. It works based on the principle of the Doppler effect, which is the change in frequency of a wave when the source and the observer are in relative motion.

In an ultrasonic flow meter, two ultrasonic transducers are placed on either side of the pipe or channel through which the fluid flows. One transducer emits high-frequency sound waves into the fluid, and the other transducer receives the sound waves after they have traveled through the fluid. By measuring the time it takes for the sound waves to travel from one transducer to the other, and the frequency shift caused by the movement of the fluid, the flow rate of the fluid can be calculated.

Ultrasonic flow meters are non-invasive, meaning they do not require the insertion of a probe or tube into the fluid stream. They are commonly used in industries such as water and wastewater treatment, oil and gas, and HVAC (heating, ventilation, and air conditioning), where accurate and reliable flow measurements are critical. Ultrasonic flow meters are also ideal for measuring the flow rate of corrosive or hazardous fluids, as they do not come into contact with the fluid.

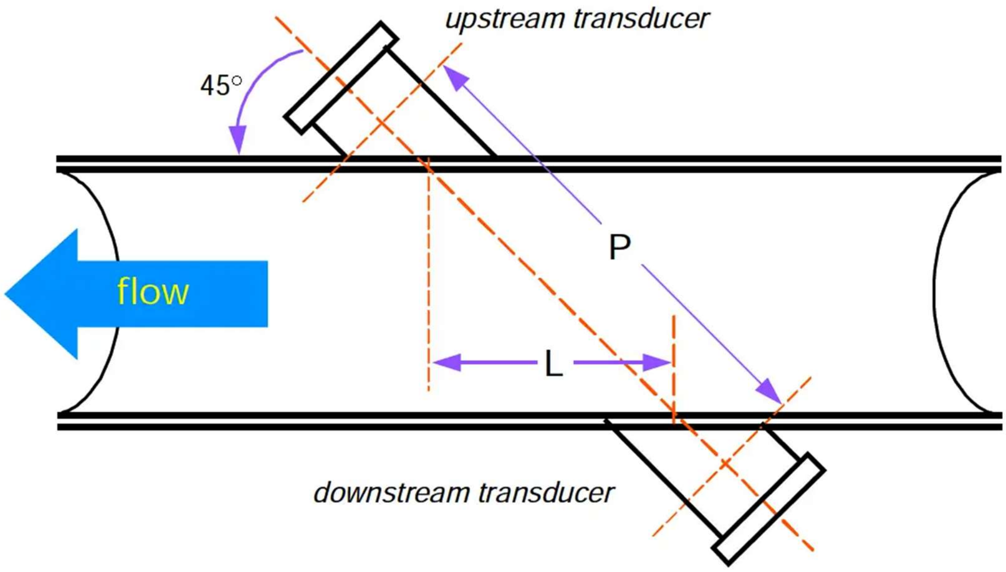


Fig. 1.3. Schematic of ultrasonic flow meter (Instrumentationtools.com)

1.1.4 ELECTROMAGNETIC FLOW METER

Electromagnetic flow meters are a type of flow meter used to measure the flow rate of conductive fluids, such as water or slurries, in pipes. They work based on Faraday's law of electromagnetic induction, which states that when a conductive fluid flows through a magnetic field, a voltage is induced in the fluid that is proportional to the velocity of the fluid.

In an electromagnetic flow meter, two electrodes are placed on opposite sides of the pipe, and a magnetic field is applied perpendicular to the fluid flow. When the fluid flows through the magnetic field, a voltage is induced in the fluid, and the electrodes measure the voltage. By measuring the voltage and knowing the magnetic field strength and the geometry of the pipe, the flow rate of the fluid can be calculated.

Electromagnetic flow meters are known for their high accuracy and reliability, even in harsh environments or with turbulent flow conditions. They are commonly used in industries such as water and wastewater treatment, chemical processing, and pulp and paper production, where accurate flow measurements are critical. Electromagnetic flow meters are also ideal for measuring the flow rate of corrosive or abrasive fluids, as they do not have moving parts and do not come into contact with the fluid.

The velocity is calculated using the Faradays Eq. (1.2),

$$E = Blv \tag{1.2}$$

where E, l, B, and v represent the induced voltage across the electrode, the distance between the electrode, magnetic flux density, and v is the velocity of the fluid.

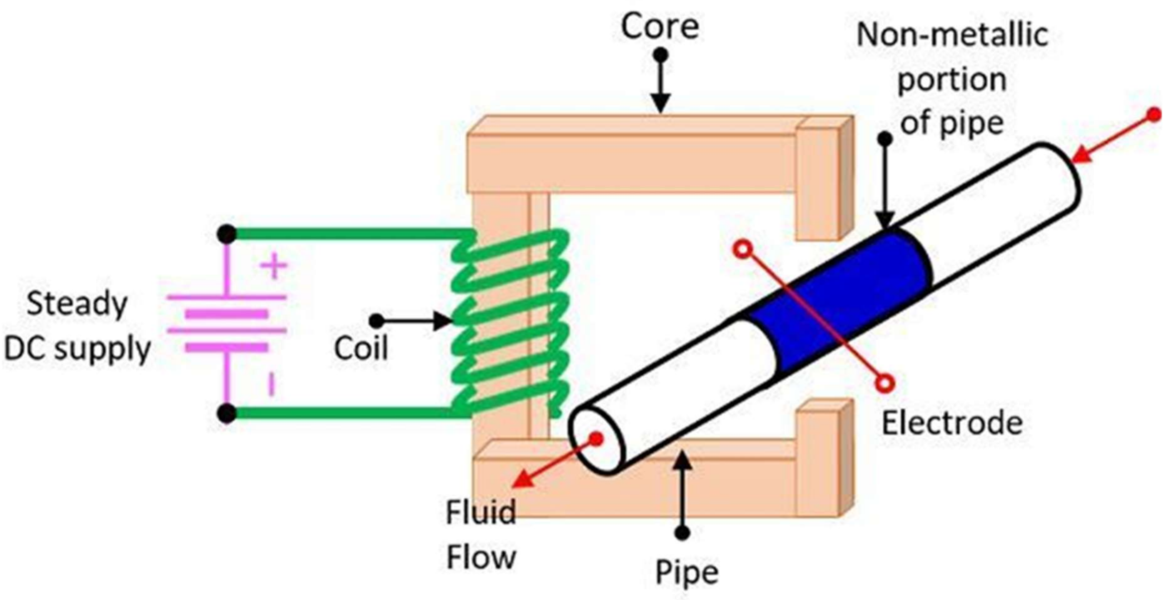


Fig. 1.4. Schematic of Electromagnetic flow meter. (circuitglobe.com)

1.1.5 CORIOLIS FLOWMETER

A Coriolis flowmeter is a type of flow meter used to measure the flow rate of a fluid by using the Coriolis effect, which is the apparent deflection of an object's path due to the rotation of the earth.

In a Coriolis flowmeter, a tube that contains the fluid is vibrated at a specific frequency. As the fluid flows through the vibrating tube, it causes a phase shift in the vibration that is proportional to the mass flow rate of the fluid. The vibration is detected by sensors at the inlet and outlet of the tube, and the phase shift is measured. By knowing the fluid properties and the geometry of the tube, the mass flow rate of the fluid can be calculated.

Coriolis flowmeters are known for their high accuracy and precision, even with changing fluid properties such as density and viscosity. They are commonly used in industries such as food and beverage, pharmaceuticals, and chemical processing, where accurate and reliable flow measurements are critical. Coriolis flowmeters are also ideal for measuring the flow rate of fluids with high viscosity or with low flow rates.

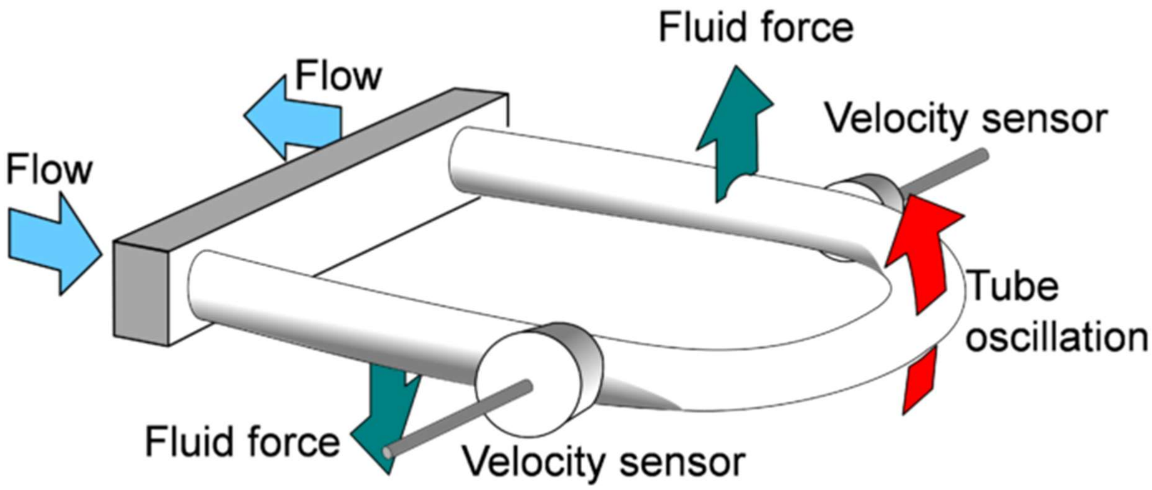


Fig. 1.5. Schematic of Coriolis flow meter (Instrumentationtools.com)

1.2 TWO-PHASE FLOW THEORY

As previously mentioned, most flow meters designed for single-phase fluids are not effective in measuring two-phase flows. Before developing a two-phase flow meter, it is crucial to comprehend the differences between two-phase and single-phase flows. This involves understanding what constitutes two-phase flow, how it occurs, and how it behaves. Two-phase flow refers to a situation in which two different phases of matter, such as solid, liquid, and gas, travel together in the same space. Liquids and gases are generally referred to as fluids because they can be deformed without external force over time. Solid particles, on the other hand, can behave like fluids when their velocity is high enough. Two-phase flow can involve any combination of the four possible fluid phases, and in many cases, the analysis of two-phase flow can be extended to multi-phase flows.

Two-phase flow does not necessarily have to involve two phases of the same substance. For instance, in coal furnaces, coal dust and air travel together as a particulate-gas two-phase flow to the furnace's firing area. However, in cryogenic flow, it usually refers to two-phases of the same substance, mainly liquid and gas. Occasionally, the flow may involve liquid-solid particles resulting from the slight freezing of the fluid, but the primary two-phase flow seen in cryogenics is liquid-gas. Therefore, for the remainder of this thesis, the term "two-phase flow" refers to liquid-gas flows unless otherwise stated.

Liquid-gas two-phase flow can occur under several conditions, and it is commonly observed in cryogenic applications due to two primary causes: heat leak in the channel or pressure drop below the single-phase boundary. However, it is crucial to understand the relationship between three essential thermodynamic variables: temperature, pressure, and volume. The pressure vs. temperature graph shows that two-phase vapor-liquid mixtures only occur on the vaporization line. The pressure vs. volume graph clearly shows "the dome," which is where vapor and liquid coexist.

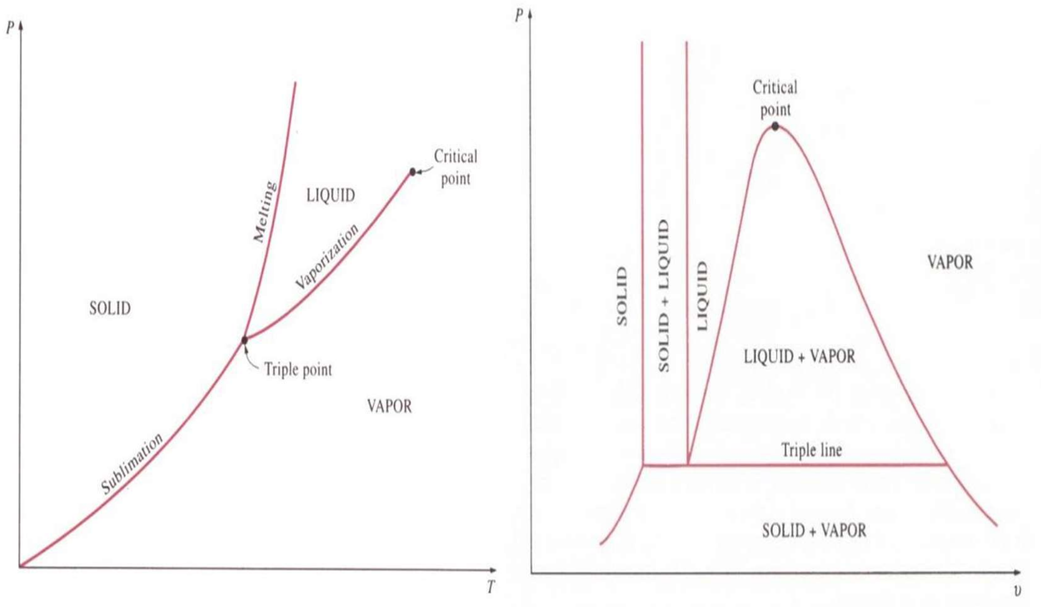


Fig: 1.6. Pressure vs. temperature diagram (left) and pressure vs. volume diagram (right) for most pure substances (Cengel. et al1997)

Although liquid-gas two-phase flow is complex, its flow patterns are distinguishable and can be consistently classified. The behavior of the flow is primarily governed by the interaction between the liquid and vapor phases, which varies as their velocities change. Fluid characteristics, such as surface tension and viscosity, play a significant role in determining the flow behavior. Additionally, the flow behaves differently depending on whether the channel is horizontal, vertical, or at an angle, and low-gravity conditions can also affect the behavior. This experiment focuses primarily on laminar and stratified flow, but it is necessary to provide a brief description of all the flow patterns.

Figure 1.7 illustrates seven common flow patterns observed in horizontal two-phase flow. However, various sources differ in their descriptions of the flow and the exact number of variations. This is because some flow patterns are either very similar or transitional regimes, and they are grouped together as one pattern. Although the flow regime cannot be determined from the void fraction or flow quality alone, the flow typically changes concerning the increase or decrease of these values.

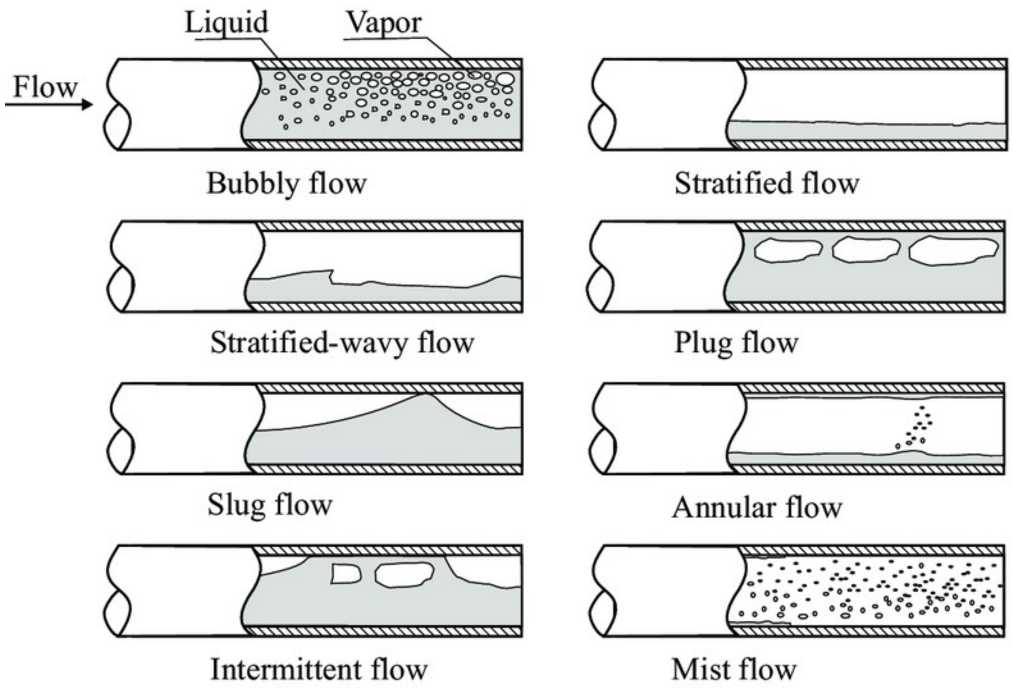


Fig1.7. The basic flow regimes for horizontal two-phase flow (Quibén. et al 2005)

A brief description of the flow patterns is given, arranged with respect to increasingflow quality

- ***Bubble flow:*** gas bubbles of various sizes flow at approximately the same velocity as the liquid. At lower liquid flow rate, the bubbles tend to travel at the top of the channel. At higher liquid flow rates, the bubbles are seen more evenly dispersed in thechannel.
- ***Plug flow:*** as the gas flow rate increases, the small bubbles begin to combine toform 'plugs' of gas in the channel.

- ***Stratified flow**:* gravitational forces separate the liquid and gas phases. The liquid- gas interface is smooth. This is the rarest type of two-phase flow because it occurs most often in larger diameter pipes and laminar flow.
- ***Wavy flow**:* increasing mass flow rates creates disturbances at the phase boundary. The amplitude of these waves increases as the massflow rates continue to increase. At the higher gas flow rates, *semi- slug flow* begins to appear and is sometimes considered a separate flow regime.
- ***Slug flow**:* Wave amplitude is high enough that the liquid touches the top of the channel. The vapor is completely separated by 'slugs' of liquid traveling in the channel
- ***Annular flow**:* At very high vapor flow rates, the liquid is forcedto the walls of the channel and the gas travels in the center. At higher gas flow rates, liquid droplets are found in the vapor flow.
- ***Dispersed flow**:* The vapor flow rate is so much higher than the liquid flow rate that the liquid is broken into small droplets and carried in the vapor stream. As the vapor flow rate continues to increase, the droplets continue to get smaller and eventually become *froth flow*.

Two-phase flow regimes are often referred to as homogeneous or separated. Homogeneous flow consists of relatively even distribution of the liquid and gas phases across the cross section of the channel. Bubble flow, dispersed flow, and froth flow can all be considered homogeneous regimes. Separated flows are the regimes where the liquid and gas phases are separated. This often refers to flows that are in a stable state and are not time dependent, like stratified or annular flow regimes. Any of the flow regimes that vary with time are called intermittent flows. These include slug flow, semi-slug flow, and plug flow.As it was mentioned, gravity and orientation have an effect on the flow characteristics. When the channel is oriented vertically and the flow is traveling upwards, the effects of gravity allow for only five flow regimes: bubble, slug/plug, churn, annular, and dispersed flows. Churn flow is a highly turbulent regime between slug and annular flow. In this flow,the liquid near the tube walls continually pulses up and down due to gravity pulling the liquid down. In microgravity flows, it is observed as dispersed bubble, bubble, slug, and annular flows. Microgravity flows are typically centered in the channels and tend to be less turbulent in their transitions between regimes thanks to the absence of gravity acting on two-phases.

1.3 TWO-PHASE FLOW TERMINOLOGIES

The mathematical model for two-phase flow can vary significantly depending on the flow regime that is in question. There are, however, some common terms that should be recognized when dealing with two-phase flows. The key factors and common terms that determine and describe two-phase flow are void fraction (α), flow quality (χ) and slip (S).

Without these values, very little can be conclusively determined about the nature of the flow.

Void fraction is the ratio of the vapor cross sectional area to the total area. This is one of the most basic commonly mentioned terms in two-phase flow

$$\alpha = \frac{A_V}{A_V + A_L} \tag{1.1}$$

Flow quality is the ratio of the vapor mass flow rate to the total mass flow rate. The void fraction and flow quality are positive values which are always less than or equal to one.

$$\gamma = \frac{m_v}{m_l + m_v} \tag{1.2}$$

Slip is the ratio of the vapor velocity to the liquid velocity. This term helps todetermine how the liquid-gas phase boundary is behaving.

$$S = \frac{U_v}{U_l} \tag{1.3}$$

It can be seen from this relationship that if the slip ratio is equal to unity, then the void fraction and flow quality are related simply by the different liquid and vapor densities. If the slip is not known, the void fraction generally cannot be determined from the flow quality or vice versa.

Attempts have been made to simplify the problem of determining the flow regime in a quantitative way. There have been numerous maps developed for different channel orientations. Some of the maps are relatively simple and use only two axes to distinguish theflow patterns, while others involve different axes for different flow patterns. Figure 1.8 shows the Baker map, the most used chart for predicting flow characteristics in horizontal flow. This chart was first suggested by Baker (1954) and was later modified by Scott (1963).

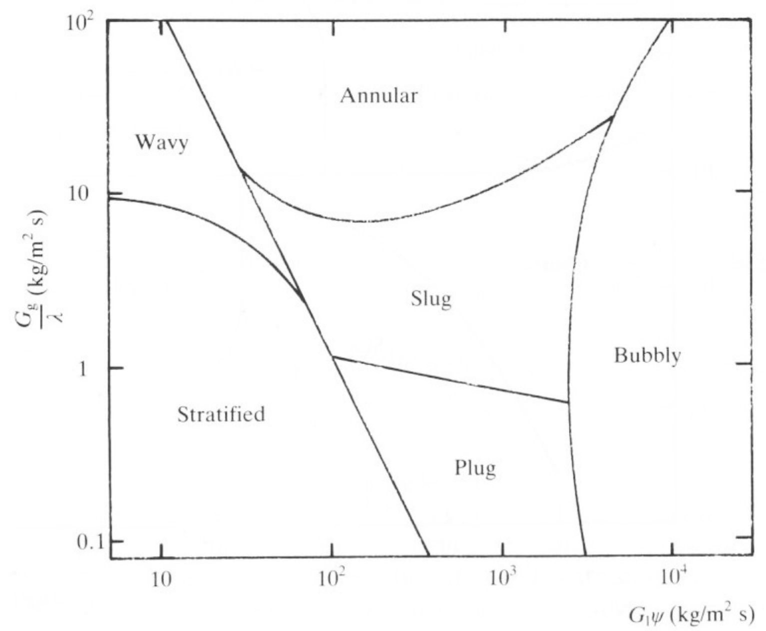


Fig: 1.8. Baker map for two-phase flow in horizontal tubes (R. H. Ashmore 2006)

In this map the vertical axes is G_g/λ and the horizontal axes is $G_l\varphi$ with:

G_g = mass flux of gas

G_l = mass flux of liquid

There has also been a large amount of work done in predicting the pressure drop in a two- phase flow system. These mathematical models of the pressure drop vary significantly from one to the other and usually require at least the void fraction and flow quality to be known. These models also usually only work for very specific flow conditions and have strict sets of assumptions that must be met for them to apply.

1.4 VOID FRACTION METERS

When comparing single-phase flow measurements to two-phase flow measurements, it is apparent that it is necessary to have more information about the flow when dealing with the two-phase system. For this, there also exists a group of devices designed to measure the void fraction or quality of the flow. As previously mentioned, the void fraction is the ratio of the cross-sectional area of the vapor to the total cross-sectional area and the flow quality is the ratio of the gas mass flow rate to the total mass flow rate. Devices that measure the void fraction are more common than quality meters in two-phase flow systems becauseit is easier to measure the ratio of the areas of the fluids than the mass flow rate.

If the gas & liquid velocities are known, and are almost equal, then the flow quality can be derivedfrom the void fraction.

Sound has been used in a couple of methods to measure the void fraction. Similar to the transit time ultrasonic flow meters, a sound wave can be sent downstream and an identical one upstream and the time of travel is measured. The difference between the amount of time it takes for sound travel upstream and downstream can be correlated to the void fraction in the channel. Another method uses the idea that the average speed of sound across a cross sectional changes as the void fraction changes. This is because the amount of gas or liquid in the channel affects the overall density of the fluid in the channel, therefore changing the average speed of sound. Passive acoustic void fraction measurements are different from the other methods that use sound. Instead of relying on the speed that the sound wave travels through the fluid, an oscillatory circuit is used to measure the resonance of the entire channel and as the void fraction changes the resonance frequency changes.

As the overall fluid density in a channel increases, the fluid’s ability to block radiation increases. This is how radiation attenuation measurement works. A photon beam is sent across the channel and a sensor measures the amount of radiation blocked by the flow to determine the void fraction. Obviously, due to the hazards from these ionizing forms of radiation, these methods can present a danger to the users. Laser attenuation methods are being developed that work on the same principle, but for the most part are still a developing technology.

Local probing devices are used to take measurements at different locations in the channel to determine the overall void fraction. Depending on the design of the device, they can be used to measure void fraction or flow quality. This tends to be a difficult method of measurementsince a moving device has to take measurements at multiple locations. If the flow is not closeto steady state, the accuracy of this method is very low.

Conductance probes are arguably the most common used local probing devices. These devices use the fluid in the channel as the conductor and the measured conductance-time curve is used to indicate the flow regime. The probe used for determining void fraction can be almost any device that is able to discriminate between different fluid phases and there are many other types of probes readily available: capacitance probes use capacitance to determine the flow regime, micro-thermocouple probes use small temperature sensing devices to detect phase fluctuations, hot-wire or hot-film anemometers are used for probing in the same way that they would measure flow over an entire channel, and index of refractionprobes use the change in refraction of a fiber optic surface to detect the gas or liquid phases. There have been many other types of local probing devices developed, but the underlying idea always remains similar.

Capacitance is very common in liquid level measurements and is a commonly used technique in two-phase fluid systems. In addition to being used in local probing devices, capacitors are also used to measure the average channel void fraction. The idea behind this method is that the fluid flows between two electrodes (or multiple pairs of electrodes). As the void fraction changes, so does the measured capacitance between the electrodes. This is because the dielectric constant for the vapor phase is different from that of the liquid phase, and as such, the overall dielectric of the channel changes with void fraction.
Capacitance meters work on the principle that when a potential difference is applied to two separated plates, a charge will be stored. The capacity to store charge for a given potentialdifference is the capacitance. The relationship between the capacitance, charge, and potential difference is simply:

$$C = \frac{Charge}{Potential\ difference} = \frac{Q}{V} \tag{1.4}$$

A value that affects the ability of a capacitor to store a charge is the permittivity of the spacebetween the conductors. The permittivity of free space is given as 8.85 pF/m. When insulating substances are placed in the space between the conductors they affect the ability to store a charge and are called dielectrics. The amount that the dielectric changes the capacitance is termed the dielectric constant, n. The permittivity of the space with the dielectric is given as:

$$\varepsilon = \kappa \varepsilon_0 \tag{1.5}$$

A common configuration for capacitors is the parallel-plate capacitor. This capacitor consists of two conducting flat plates that are the same size and are spaced a certain distance apart from each other. The capacitance between two flat plates is give as:

$$C = \frac{sA}{t} \quad (1.6)$$

Where A is the surface area of one of the plates and t is the size of the gap between the plates. Similar to the flat plate capacitor, a cylindrical capacitor consists of two concentric cylinders with a given space between them. The capacitance between two concentric cylinders is given as:

$$C = \frac{2\Pi sL}{ln(\frac{r_o}{r_i})} \quad (1.7)$$

Where L is the length of the capacitor, r_o is the outer conductor radius, and r_i is the inner conductor radius.

When a two-phase fluid is the dielectric between the capacitors, the effect is the same as if two different capacitors were placed in series with each other. This is because the dielectric constant for the vapor phase is significantly lower than that of the liquid phase.

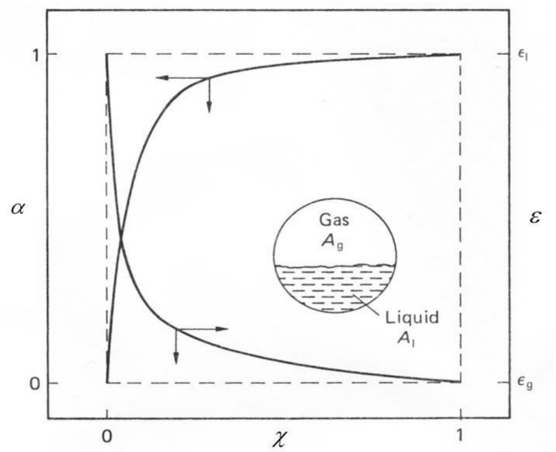


Figure 1.9. Plots of the void fraction and overall permittivity as a function of the flow quality. [20]

As the void fraction or flow quality increases, the measured permittivity decreases because of the increased fraction of the flow that is vapor. This is illustrated in Figure1.9.

Different capacitance designs have effects on the way that the capacitance corresponds to the level. Not only does the capacitor design effect the correlation, but attention must also be paid to the orientation of capacitors when used for liquid level or void fraction measurement. Figure 1.10 shows two orientations for a flat plate level gauge or void fraction meter. In this figure, the vapor and liquid sections are illustrated as two separate capacitors.

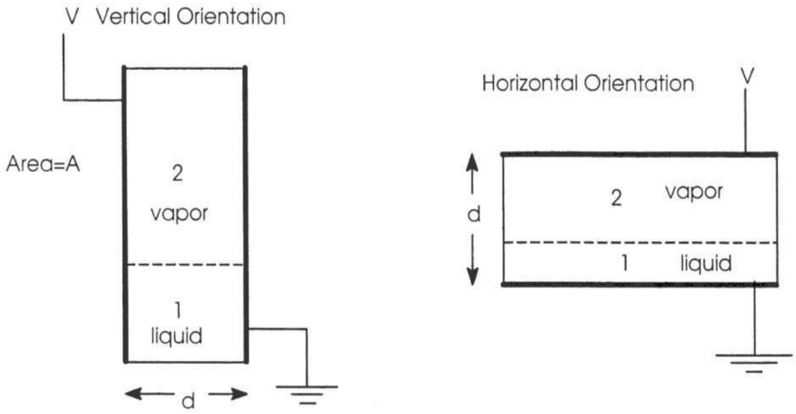


Fig 1.10: Vertical and horizontal orientation of flat plate capacitance level gauge.(J. P. Holman., 2000)

The addition of the liquid and vapor phase capacitance is not the same for the two orientations. For the vertical orientation capacitor, the equation is:

$$C = C_1 + C_2 = \frac{\varepsilon_0 A \varepsilon_{vapour}}{2d} + \frac{\varepsilon_0 A \varepsilon_{liquid}}{2d} + \frac{\varepsilon_0 A}{2d}\left(\frac{\varepsilon_{vapour}+\varepsilon_{liquid}}{2}\right) \tag{1.8}$$

For the horizontal orientation, the addition of the capacitance is given as:

$$C = \frac{1}{c_1+c_2} = \frac{\varepsilon_0 A}{d}\ \frac{2}{\frac{1}{\varepsilon_{vapour}}+\frac{1}{\varepsilon_{liquid}}} = \frac{\varepsilon_0 A}{d}\ \left(\frac{2\varepsilon_{vapour}\varepsilon_{liquid}}{\varepsilon_{vapour}+\varepsilon_{liquid}}\right) \tag{1.9}$$

After looking at the difference between the vertical and horizontal orientations, it can be seen that the vertical orientation yields a linear relationship, whereas the horizontal orientation is a nonlinear relationship. This is expected because, looking back at Figure 1.10, the vertical orientation adds as capacitors in parallel and the horizontal orientation is added in series.

A frequently used method to approximate two-phase flow is to measure the flow rate at a point when the fluid is known to be single phase, and then measure the void fraction at a point where the flow is two-phase. Since the mass flow rate is already known, the two- phase flow conditions can be better approximated by determining the local void fraction.

This method helps to approximate the flow, but it still cannot give the independent velocities of the liquid and gas phases. A method that has received attention in measuring two-phase flow is the use of void fraction measurements at more than one point in the channel. The time it takes for the same void fraction fluctuation to pass between meters can be used to approximate the flow rate. This method can determine both the void fraction and the velocity at which the gas- liquid phase boundary is moving. This method does well in intermittent flows because of the large changes seen in the void fraction with respect to time, but it traditionally does not do too well in stratified or annular flows due to the lack of time dependence of the large void fraction fluctuations. At present, there is still no single system that can measure the flow rate of the two-phase flow, regardless of the incoming characteristics. As discussed earlier there is no single device that can measure the two-phase flow simultaneously, so for this the product design has been developed.

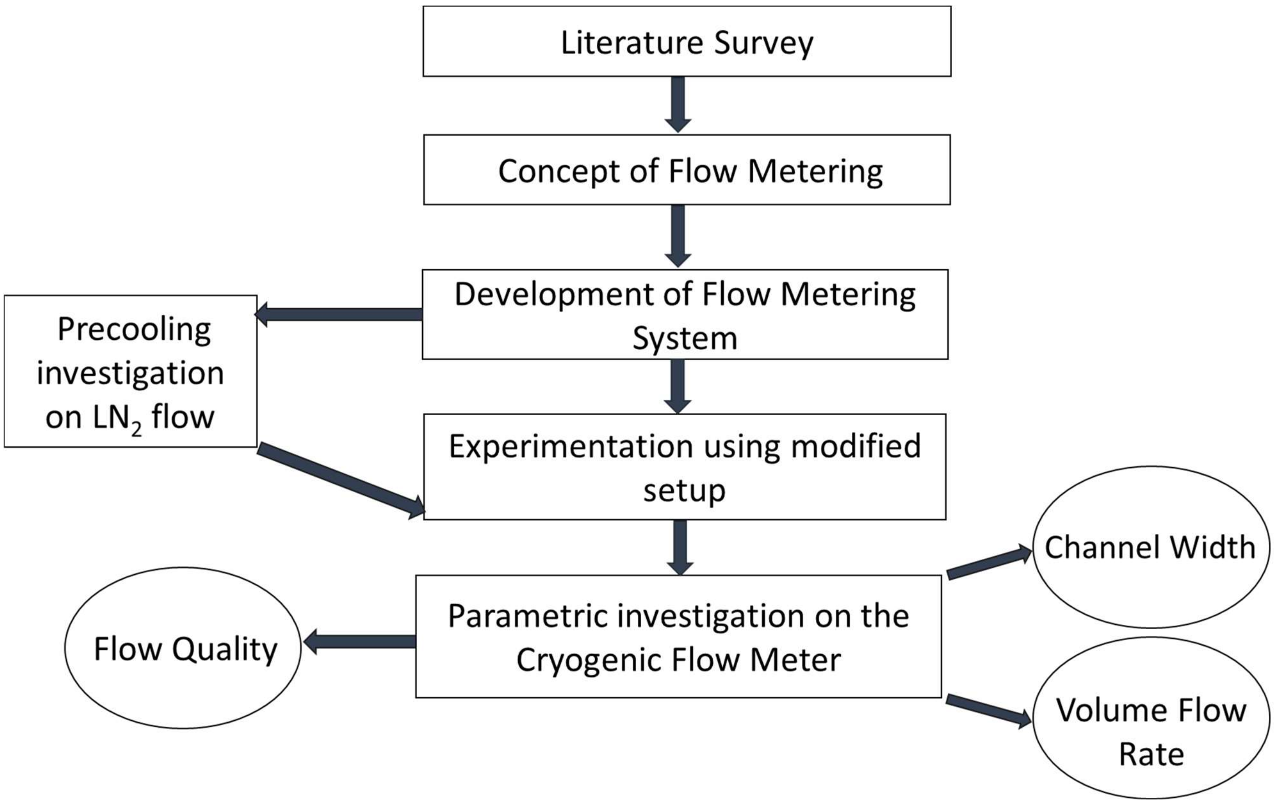
1.5 RESEARCH GAP

Most conventional flow meters are not suitable for measuring two-phase flow in cryogenic conditions. Cryogenic fluids such as liquid nitrogen, oxygen, helium, and hydrogen are essential for space and nuclear research, but there are limited instruments available to measure their mass flow. Currently, there are no devices that can measure two-phase flow throughout its flow range. Therefore, there is a need to develop a flow metering device for cryogenic applications that operates using the capacitive method. As a first step towards creating a cryogenic two-phase mass flow meter, the project has conducted preliminary research using liquid nitrogen as the cryogenic fluid.

1.6 OBJECTIVES

- To conduct parametric study on the flow meter by varying the geometric and operational two-phase flow parameters.
- To develop a precooling setup and to ensure less gaseous nitrogen to the setup.
- To develop a void fraction sensor and to calibrate it with a standard fluid .
- To improve the accuracy in the measurement of capacitance-based flow metering system for different flow rates and capacitance.

1.7 METHODOLOGY



CHAPTER 2

LITERATURE SURVEY

A separate flow regime map for the vertical and horizontal system was developed. The proposed map for a horizontal channel based on superficial velocity coordinates is shown in Fig. 2.1. Wojtan et al. (2005) presented a flow map for horizontal flow boiling in a pipe. The new model was based on the flow quality, and mass velocity rather than superficial velocities. The Wojitan flow regime map is presented in Fig. 2.2. Kim et al. (2018) performed experimental analysis using an air-water mixture on a horizontal tube having a diameter of 38.1mm. The flow regime was visualized using high- speed photography. A total of 263 experimental flow conditions was analysed and basedon the analysis a flow regime map was suggested. The new flow regime transition map is presented in Fig. 2.3. Jeong et al. (2018) constructed a flow regime map for a downward flow of air-water mixture with 322 data points. The experiments were conducted on a rectangular channel of 2.35 mm thickness. Visualization studies have been performed using a high-speed digital camera and by implementing an image processing technique. They observed that at the low liquid velocity the flow patterns were very different from upward flow but, at the higher liquid velocity the flow pattern is similar to upward flow. This is due to the dominance of buoyancy at low liquid velocity and the identified flow regime map is presented in Fig. 2.4. These flow regime maps provide a simplified methodto understand the flow transition.

Das et al. (2016) developed a new method to identify the two-phase flow patterns using an Infrared (IR) sensor. They performed experimental investigation on a glass tube of 4.7 mm tube diameter and 0.3 mm thick wall, by IR rays using an IR emitter. They found thatthe IR rays were refracted when passing through the test section and it resulted in fluctuation of current passing through the IR receiver. This variation can be used to predict the flow regime. They found a bubbly, slug, and stratified flow regime using this method. Singh et al. (2019) performed experiments using Liquid Nitrogen (LN_2) on a horizontal pipe with diameter 9mm,and flow visualization has been done using a high-speed digital camera. They concluded that the Wojtan map can accurately predict the flow transition patterns for the cryogenic flow of Liquid Nitrogen (LN_2), when compared to the Baker's map and Duckler map.

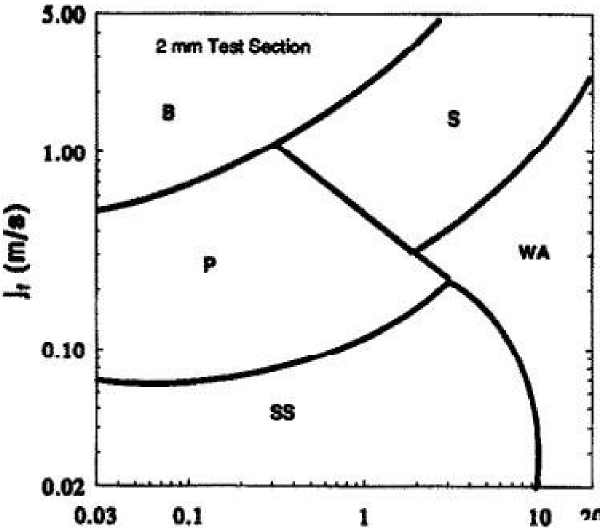


Fig: 2.1. Willmart & Ishii flow map for a horizontal rectangular channel

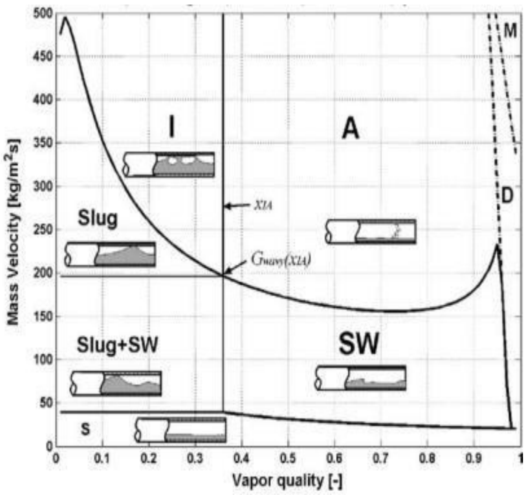


Fig: 2.2. Wojtan et al. flow boiling in horizontal channels (2005).

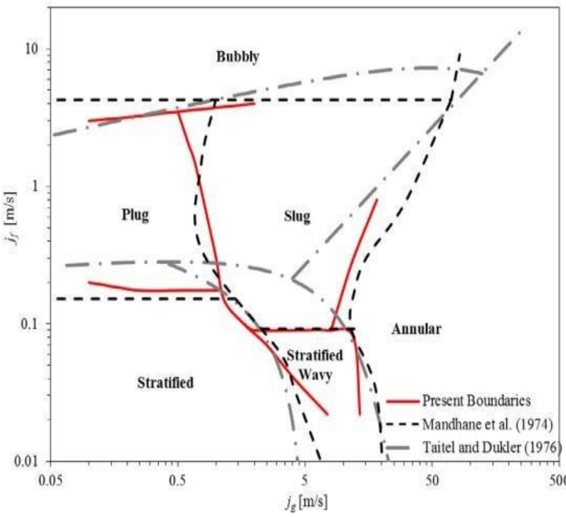


Fig: 2.3. Kim et al. horizontal air-water flow map (2015).

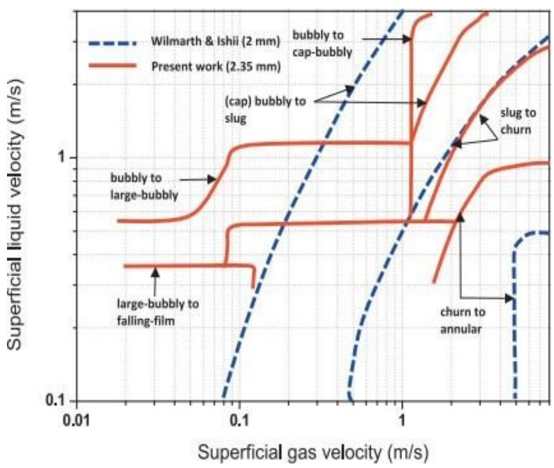


Fig. 2.4. Jeong et al. downward flowmap for a rectangular channel (2017).

The flow pattern and its characteristics vary according to channel geometry and size. The earliest attempt was to classify flow according to the tube size. Mehendale et al. (2000) suggested the following nomenclature to effectively study the flow dynamics. They classified as micro tubes (Dh < 100µm), mini tube (100µm < Dh < 6mm), and conventional tubes (Dh > 6mm). Most two-phase flow regime map was developed using a circular pipe in superficial velocity coordinates, but the flow regime in non-circular channels are different from circular tubes. Thus, there is a need to develop separate flow regime maps for rectangular channels to effectively analyze flow characteristics. Sempértegui-Tapia et al. (2017) experimentally investigated the two-phase pressure drop for non-circular geometries like square and triangle with a circular cross-section. They found a higher pressure drop for non- circular geometries when compared to circular geometries. The maximum pressure drop was noticed for the triangular cross-section followed by square and then circular geometry.

2.1 RECENT DEVELOPMENT IN TWO PHASE METERING

Meribout et al. (2020) developed an ultrasonic based new multiphase flow composition metering device. The new concept flow meter is non-invasive and non-radioactive which is very critical in oil fields. The device generates an annular flow regime using a swirl separator in which the outer phase is surrounded by liquid and gas at the core. This is followed by a clamp-on ultrasonic device to measures flow rates using ultrasonic signals. This device is compact and real-time results are achieved compared to the traditional liquid-gas separator. Morales et al. (2004) developed an algebraic model for gas-liquid two-phase flow meter using a Venturi tube. They performed analysis on air-glycerin and air-water mixtures at lower volumetric void fractions. They also carried out numerical simulation using a two-fluid method and validates using experimental results. They concluded that the flow meter can work in an upward bubbly flow regime in a Venturi tube with a reliable error. Cater et al. (2020) simulated geothermal two-phase flow for six different types of flow meters namely orifice and Venturi- tube type differential pressure flow meters. They found that Venturi meter has the lowest turbulent kinetic energy when compared to others also Venturi and nozzle meters had the lowest pressure drops. Thus, they concluded that Nozzle and Venturi flow meters can measure geothermal two-phase flow however convergent cylindrical throat of the nozzle may result in scale deposition of minerals. Segmental orifice meters somewhat show promising results for geothermal use when compared to orifice meters. Yang et al. (2018) analyzed the performance of an electromagnetic flow meter in two-phase flow situations by using a phase-isolation method. This method is used to convert the incoming flow into a symmetrical swirling annular flow where the gas-liquid phases are separated and then used the electromagnetic device to measure the flow rate. "Measurement of Two-Phase Flow in a Cryogenic Loop Using a Capacitance-Based Flow Meter" (2019) by D. K. Kim et al. This study investigated the use of a capacitance-based flow meter for measuring the flow rate of cryogenic two-phase flow in a loop. The results showed that the capacitance-based flow meter was able to accurately measure the flow rate in both liquid and gas phases

2.2 SUMMARY OF THE LITERATURE SURVEY

Measurement of cryogenic two-phase flow has become an important area of research due to the increased use of cryogenic fluids in various industrial applications, such as liquefied natural gas (LNG) transportation and storage. Here is a summary of recent literature on the measurement of cryogenic two-phase flow:

1. *Capacitance-Based Flow Metering*: Capacitance-based flow meters have been extensively studied for measuring cryogenic two-phase flow. In particular, researchers have focused on the development of high-precision capacitance-based flow meters that can accurately measure cryogenic fluids at low temperatures and high pressures.
2. *Ultrasonic Flow Metering*: Ultrasonic flow meters have also been studied for measuring cryogenic two-phase flow. Researchers have focused on the development of ultrasonic flow meters that can operate at low temperatures and pressures, and that can accurately measure the flow rate of both liquid and gas phases.
3. *Differential Pressure Flow Metering*: Differential pressure flow meters, such as venturi meters and orifice meters, have been used for measuring cryogenic two-phase flow. However, these flow meters can be difficult to use at low temperatures, as the viscosity of the fluid increases and may cause blockages in the meter.
4. *Electrical Impedance Tomography (EIT) Flow Metering*: EIT has been studied as a non-invasive imaging technique for measuring the flow of cryogenic two-phase fluids. EIT has been shown to be effective in measuring the flow of cryogenic fluids in pipelines and storage tanks.
5. *Coriolis Flow Metering:* Coriolis flow meters have been used for measuring cryogenic two-phase flow. Researchers have focused on the development of high-precision Coriolis flow meters that can accurately measure the flow rate of both liquid and gas phases, even at very low temperatures.

Overall, recent literature on the measurement of cryogenic two-phase flow has focused on the development of high-precision flow meters that can operate at low temperatures and high pressures, and that can accurately measure the flow rate of both liquid and gas phases. Ongoing research is focused on improving the accuracy, reliability, and versatility of these flow meters for a range of industrial applications.

CHAPTER 3

GENERAL PRINCIPLE

3.1 CONCEPT

The two-phase flow meter is originated or is built around the open-channel flow theory. In open flow channel the fluid flows through a channel and it has a free surface i.e., a liquid surface which is exposed. Canals, ditches, rivers are some of the examples of open flow channel. The principle is that there is a laminar, two-phase flow which is passed through a number of narrow, parallel, tall channels. The laminar flow is also made stratified. Following these conditions, the flow behaves as an open flow channel flow and as it flows along the length of the channel, a slope is developed due to the difference in viscosity of the liquid and the friction formed between the liquid-vapour system with the surface of the narrow channels. The viscous effect or force which is formed between the liquid and the surface is greater than the viscous effect between the gaseous phase and the surface, so as a result a negative slope is generated as the flow travels down the channel length. Fig.3.1 shows the slope of liquid in an open channel flow.

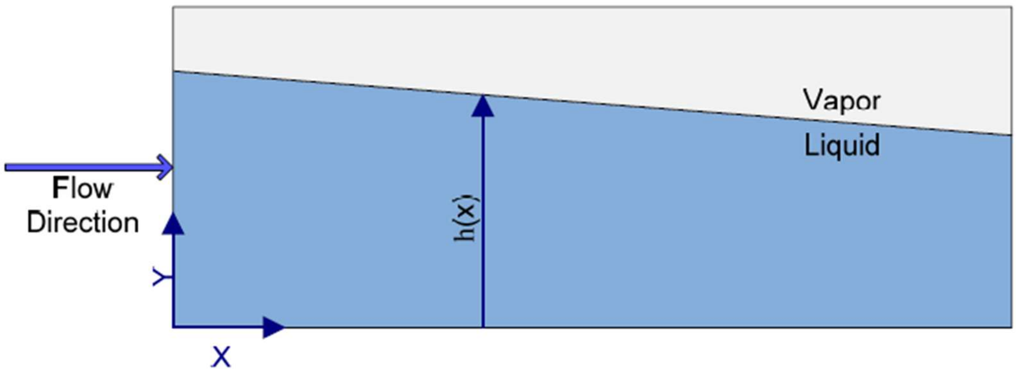


Fig. 3.1 Open channel flow

The main reason for this measurement method to work is the viscous effect between the fluid and the channel walls. Due to the low viscosity of the vapour phase, it will only have less resistance when it flows through the channel. As the two-phase flow progresses, a constant slope of the liquid-vapour interface is seen at the phase boundary. Height is measured at different points of the channel and from this the flow rate is calculated.

One of the assumptions to consider in this theory is that there is no phase change happening in between the channels or inside it. So, it means that the vapor mass flow rate and the liquid mass flow rate are separate values and are constant values. The second assumption is that the variation of pressure is only along the x-axis, and it does not change with respect to the y-axis or z-axis. The last assumption is that the system is considered to be in a steady state, or in a quasi-static state and the time dependence is neglected over short periods.

3.2 DESIGN OF FLOW METER

In the laminar two-phase flow meter concept, a number of parameters must be considered. These factors include flowrates at which the device will be required to control, the fluid that may be measured, the specified pressure drop across the system, the system accuracy, and also the method by which the liquid level are measured. The fluid properties are the primary things that has to be considered before determining the physical dimensions of the channel, this is often because different fluids have different viscosities, densities, dielectric constants, and other properties which will directly affect the design of the device. The properties of both the liquid and therefore the vapor phases of the fluid to be utilized in the channel must be considered.

Reynolds Number is a non-dimensional number that is used in determining if the flow is laminar or turbulent which means it is possibly the most important value to know for the experiment.

$$R_e = \frac{\rho v 2t}{\mu} \tag{3.1}$$

Where ρ is the density, μ is the viscosity, V is the fluid velocity, and t is the distance between the parallel plates.

The Reynolds number has a very large part in determining the channel dimensions. Equation 3.1 assumes the flow is between two parallel flat plates with either an infinite length, or a very large channel height to width ratio. While some sources vary slightly, the common approximation for the transition from laminar to turbulent flow is at the Reynolds numberof $1x10^3$.

The flow rate through the channel goes to be slow because it must remain within the laminar flow region. For a flow meter to use this theory, it should contain numerous parallel channels to permit for measurement of any reasonable mass flow rates. The mass flow rate range which will be measured by the device will have an outsized effect on the amount of channels used and also the exact dimensions of the channels. One option for determining the flow rate is to measure the height in each of the channels and add the individual mass flows to find out the whole mass flow rate. Another choice is to take the average of the height measurement across all of the channels to find the overall mass rate.

The Bond Number is a non-dimensional number which shows the ratio of the effect of gravity on the fluid to the surface tension.

$$Bo = \frac{(\rho_l - \rho_v) g t^2}{\sigma} \tag{3.2}$$

where $\rho_l$is the liquid density, ρ_v is the vapour density, g is the gravity, t is the channel width, and σ is the fluid surface tension.

The Bond number is beneficial when viewing the capillary effect of fluid in a channel. The higher this number is, the less the system is suffering from physical phenomenon, this value is primarily employed in standing flow and is typically not as important in moving flows. Since this experiment deals with low flow rates through narrow channels the Bind number has to be considered while determining the channel dimensions, the channels have to be narrow enough in order that the viscous effect of the fluids will create the required slope. If there are too narrow, capillary effects will govern the fluid behavior, this implies the measured liquid slope might not be a reliable indicator of the flow.

Since the system is modelled as open-channel flow, the pressure drop is primarily due to the viscous interaction between the fluid and also the channel walls, The pressure drop across the flow meter may be a function of the fluid viscosity, fluid velocity, channel width and channel length. This implies that while pressure drop must be taken under consideration when determining the channel width, it also encompasses a large effect on determining the channel length. The pressure drop due to single phase fluid flow during a channel is

$$\Delta p = \frac{12 \mathrm{V} \mu \mathrm{L}}{\mathrm{t}^2} \tag{3.3}$$

Where Δp is the pressure drop along the length of the channel, V is the fluid velocity, μ is the fluid viscosity, L is the channel length, and t is the channel width. In the pressure drop equation which is mentioned above, a clear relationship between the pressure drop and the channel length is observable. In addition to this it is observed that a proportionality between the pressure drop and the fluid velocity is attained. As the length of the channel increases the pressure drop increases and this is an important factor, but in orderto get more accurate results the slope should be measured over longer lengths and at morelocations.

3.3 MATHEMATICAL THEORY

The calculation used here is same as that of open-channel flow and obtained a clear relationship between the liquid mass flow rate and height change. Here gradually varied flow concept is used for the flow analysis. The assumptions taken here are that the bottom slope of the channel is slowly changing, the liquid depth is slowly changing i.e., there is no hydraulic depth, a slowly or unchanging cross section, the velocity distribution is taken as one-dimensional and hydrostatic pressure distribution is considered along the length of the channel.

The change in the liquid height with respect to the x-position is given as

$$\frac{dy}{dx} = \frac{S_0 - S}{1 - Fr^2} \tag{3.4}$$

Where S_0 is the slope of the physical channel, but the present experimental channel is horizontal, so this value is taken as zero. The slope of the liquid surface is a function of the velocity and is affected by the ratio of friction coefficient of the fluid to the channel dimensions and is given as

$$S = \frac{fV^2}{4tg} \tag{3.5}$$

And the friction factor is given for flow in a rectangular channel

$$f = \frac{96}{\mathrm{Re}} \tag{3.6}$$

Inserting the hydraulic diameter and friction factor into the slope, we see that the slope of the liquid surface is a function of the mass flow rate. The resulting slope is given as

$$S = \frac{12 v_l \dot{m}_l}{t^3 \rho_l y g} \tag{3.7}$$

Froude's number is the non-dimensional number that is commonly used in comparing the wave-making component of fluid movement. Typically, it is presented as the square of the number

$$Fr^2 = \frac{\dot{m}_l^2}{y^3 t^2 \rho_l^2 g} \tag{3.8}$$

Where y is the height of the liquid.

After substituting the simplified slope and the Froude's number, the equation for the change in liquid height becomes

$$\frac{dy}{dx} = \frac{\frac{-12 v_l \dot{m}_l}{t^3 \rho_l y g}}{1 - \frac{\dot{m}_l^2}{y^3 t^2 \rho_l^2 g}} \tag{3.9}$$

After rearranging terms

$$t^3 \rho_l y g \int_{y_1}^{y_2} y \, dy - \frac{\dot{m}_l^2 t}{\rho_l} \int_{y_1}^{y_2} \frac{1}{y^2} \, dy = -12 v_l \dot{m}_l \int_0^{\Delta x} dx \tag{3.10}$$

Integrating this

$$\frac{\dot{m}_l^2 t}{\rho_l} \left(\frac{1}{y_2} - \frac{1}{y_1}\right) + 12 v_l \dot{m}_l \Delta x + t^3 \rho_l y g (y_2^2 - y_1^2) = 0 \tag{3.11}$$

which is a quadratic equation with the solution

$$m_l = \frac{-B_1 + \sqrt{B_1^2 - 4A_1 C_1}}{2A_1} \tag{3.12}$$

where the coefficients are

$$A_1 = \frac{t}{\rho_l} \left(\frac{1}{y_2} - \frac{1}{y_1}\right) \tag{3.13}$$

$$B_1 = 12 v_l \Delta x \tag{3.14}$$

$$C_1 = \frac{t^3 \rho_l g}{2} (y_2^2 - y_1^2) \tag{3.15}$$

Equations 3.12,3.13,3.14 and 3.15 show that the mass flow rate is determined by measuring the change in liquid height at two channel locations (y_1 and y_2) with a known distance (Δx) between them. This is done at multiple points in the channel and the average of the results is taken. This means that a longer channel gives a more accurate flow rate measurement because the average can be taken over more length increments.

Table 3.1. Properties of Liquid Nitrogen at normal boiling point at 77 K

Density (kg/m^3)	808.9
Heat of vaporization (kJ/kg)	198.3
Specific heat (kJ/kgK)	2.04
Viscosity (kg/ms x 10^6)	157.9
Thermal conductivity (W/mK)	139.6
Dielectric constant	1.434

CHAPTER 4

EXPERIMENTAL SETUP AND PROCEDURE

4.1 FABRICATION

4.1.1 DEVELOPMENT OF FLOW METER

The goal of this project was to develop an apparatus that could measure mass flow in two-phase cryogenic applications using the concept presented in Chapter 3. Experimental setup contains three sections – Inlet , Outlet & Test section respectively .Here the material used is SS304 for the development of inlet, outlet, and the test section. The dimensions and CAD model of the sections are illustrated below.

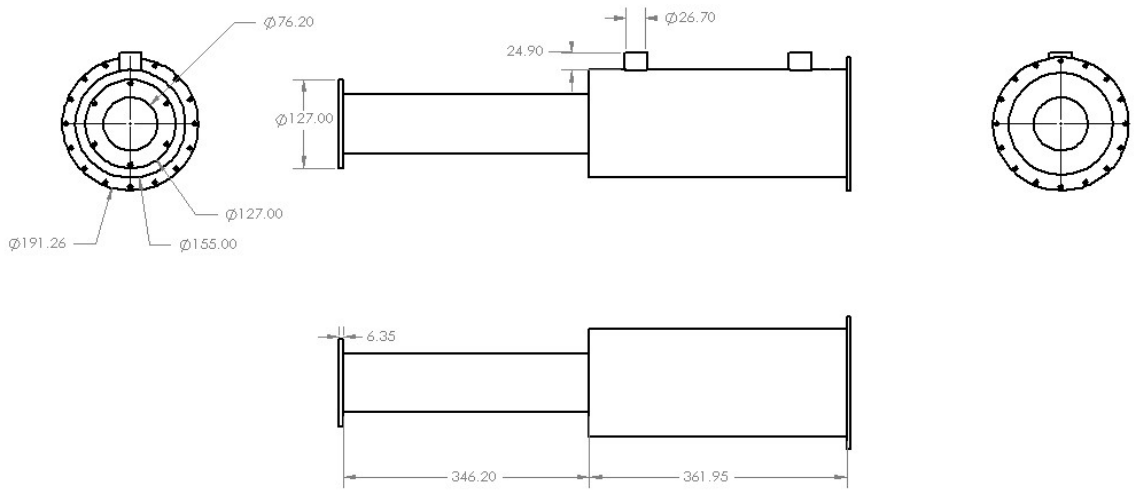


Fig: 4.1. CAD drawing of Inlet section (dimensions)

Fig: 4.2. Inlet section CAD assembly

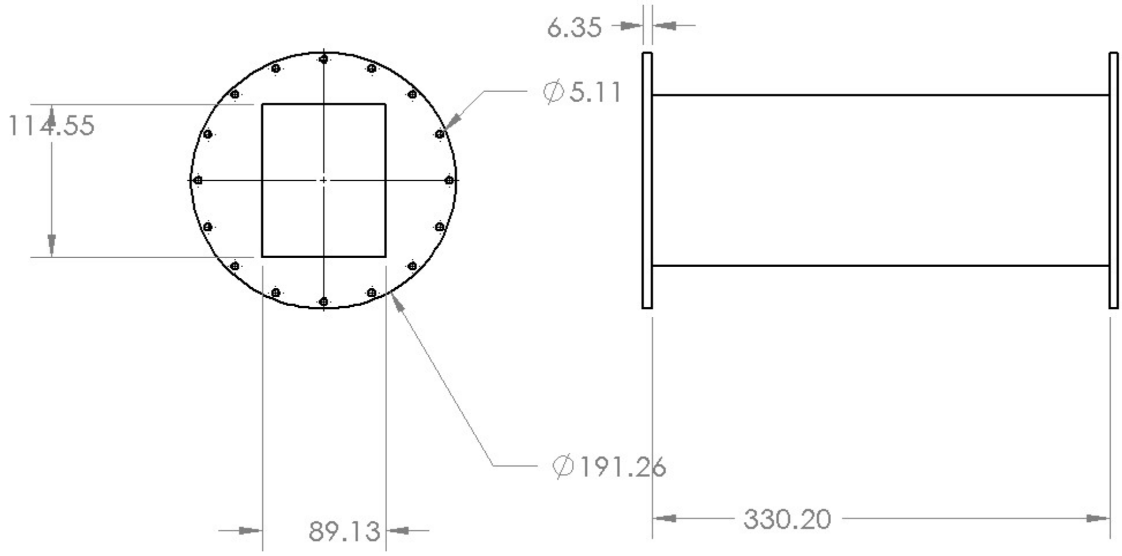


Fig: 4.3. CAD drawing of Test section (dimensions)

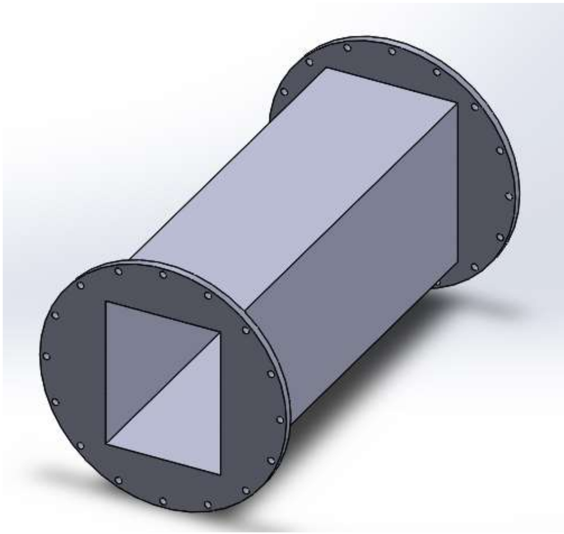


Fig: 4.4. Test section CAD assembly

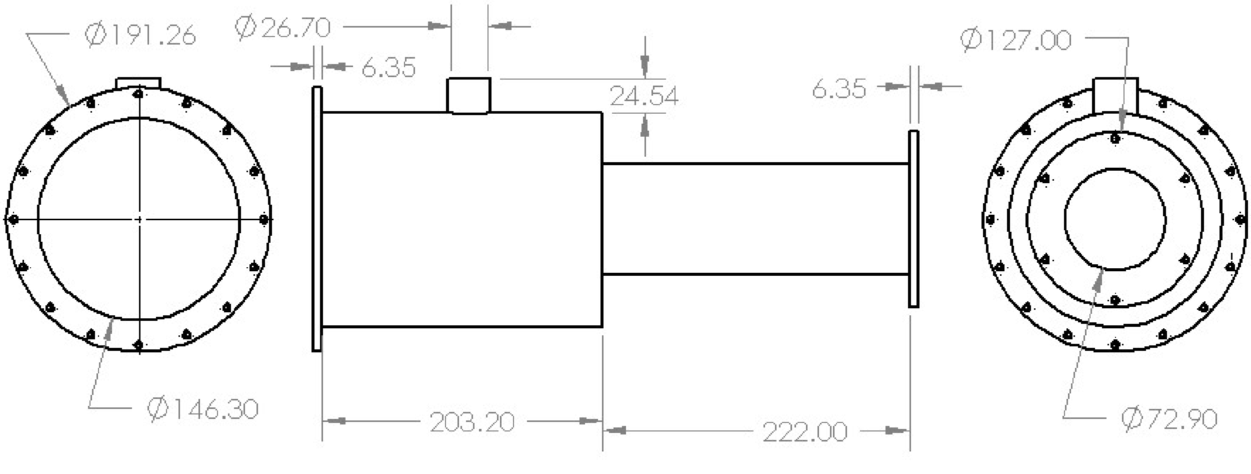


Fig: 4.5. CAD drawing of Outlet/Exit section (dimensions)

Fig: 4.6. Outlet/Exit section CAD assembly

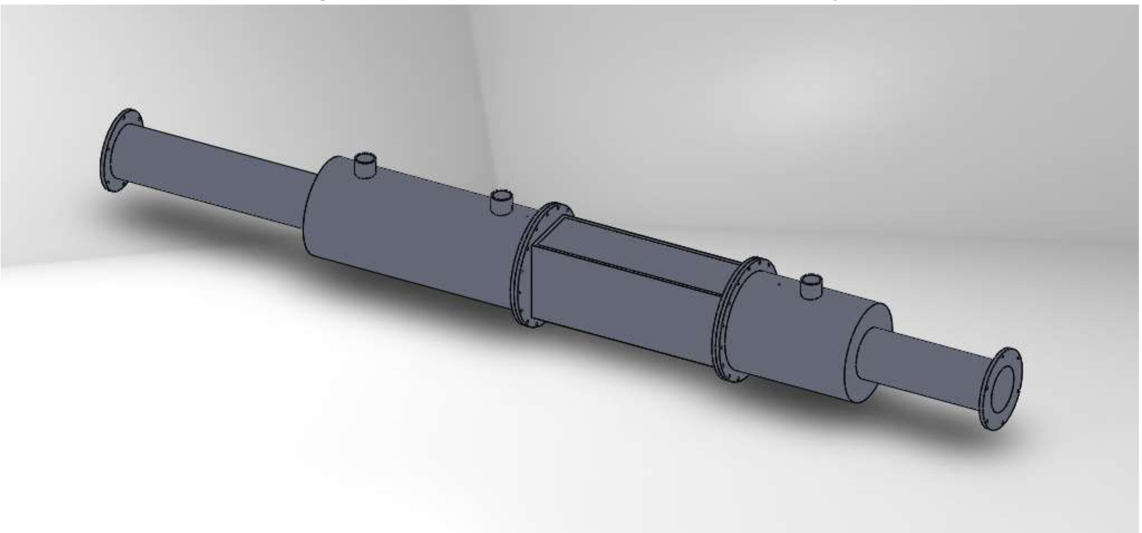


Fig: 4.7. Final Setup CAD assembly

4.1.2 TEST SECTION MATERIALS & SETUP

Aluminium 3004 is the material used for the test section that hold the capacitor plates .The metal is machined by groove cutting to hold the capacitor plates. This is selected because it is an extremely versatile metal with several advantages, it is recognized for being lightweight and flexible. It also has easiness of cutting small slots in the plates is also considered while selecting this type of material. The alloy has a higher strength than 3003 aluminium, which makes it suitable for use in applications that require higher strength and pressure resistance. The aluminium is used as the base plate. The grooves of 2 mm and 1.5 mm were machined by using CNC Miller Cutter.

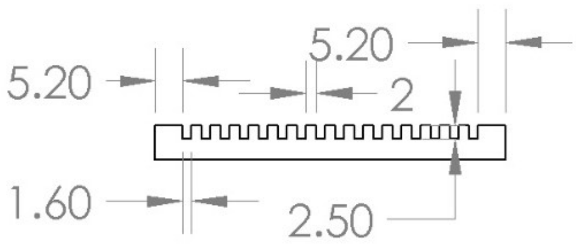


Fig: 4.8. CAD drawing of aluminium base plate for 2mm channel width

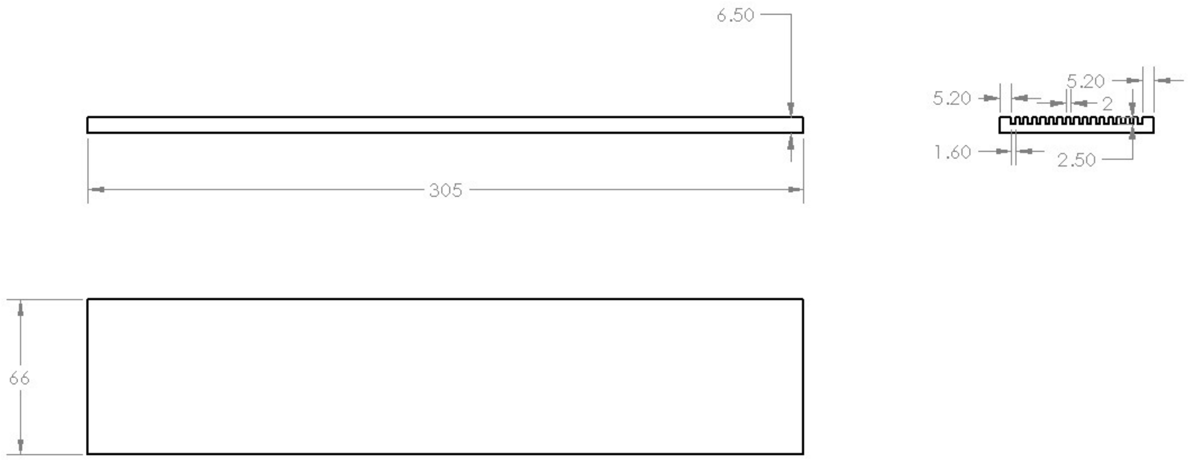


Fig: 4.9. CAD drawing of aluminium base plate for 2mm channel width (multiple views)

Fig: 4.10. Machined aluminium base plate for 2mm channel width

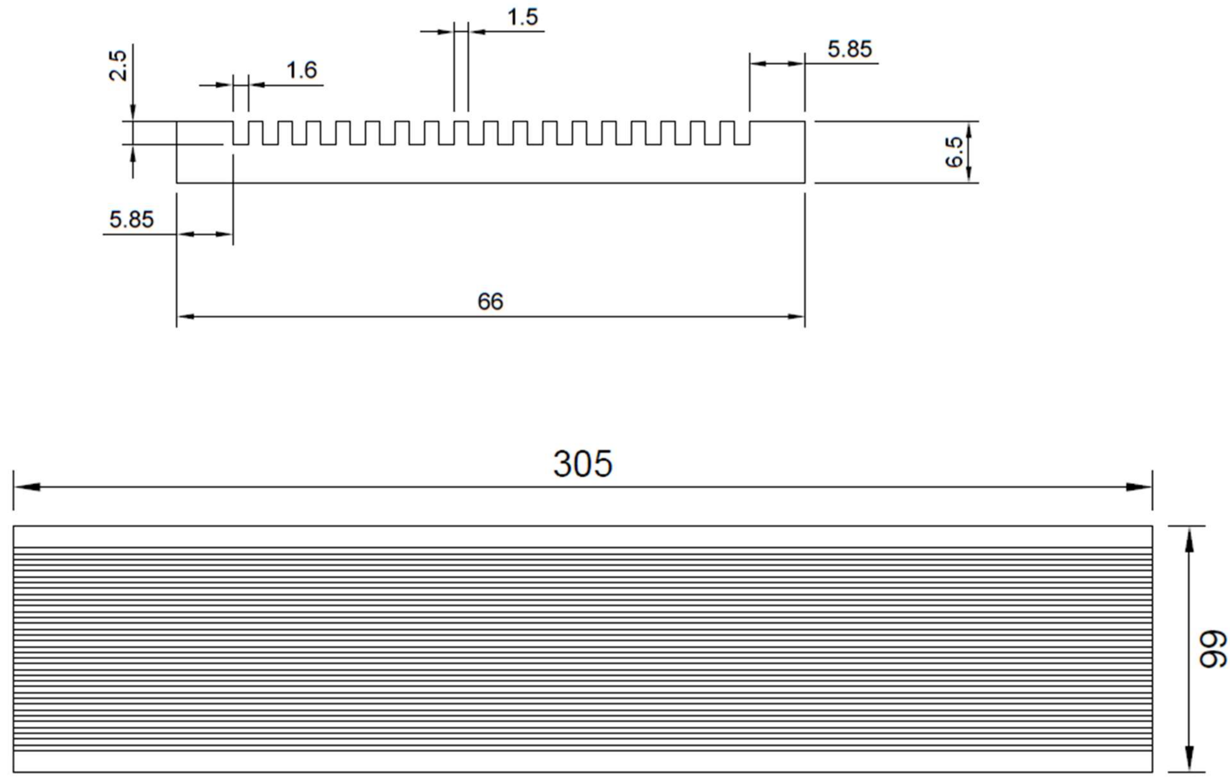


Fig: 4.11. CAD drawing of aluminium base plate for 1.5 mm channel width

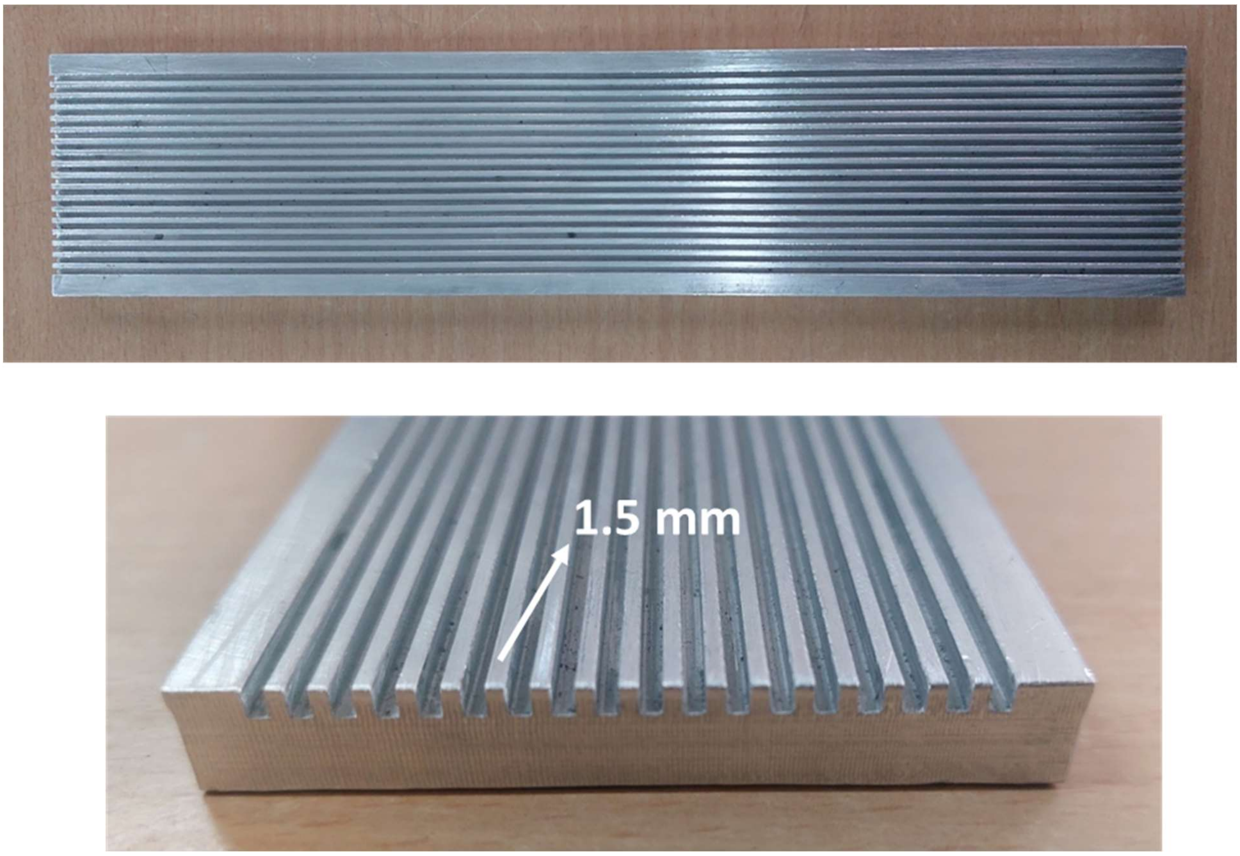


Fig: 4.12. Machined aluminium base plate for 1.5 mm channel width

The test section contains copper etched PCBs mounted in the aluminium base plate for channel width of 1.5 and 2 mm. The copper plates used here are 4 plate and 6 plate capacitors. The test setup with the PCB and the aluminium base plate is placed into the section.

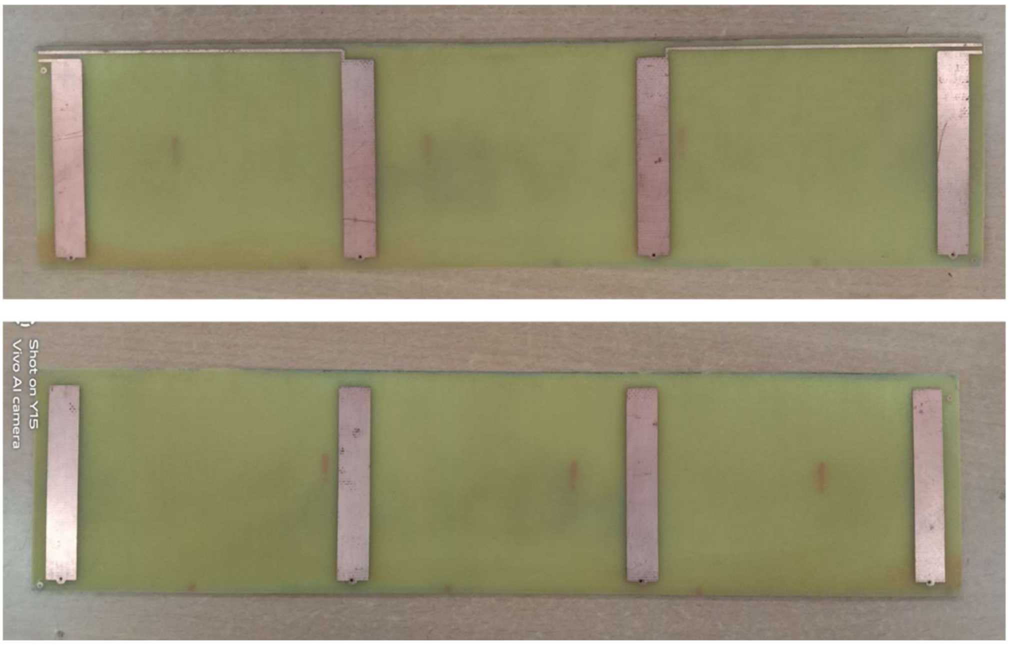


Fig: 4.13. Four plate copper etched PCB

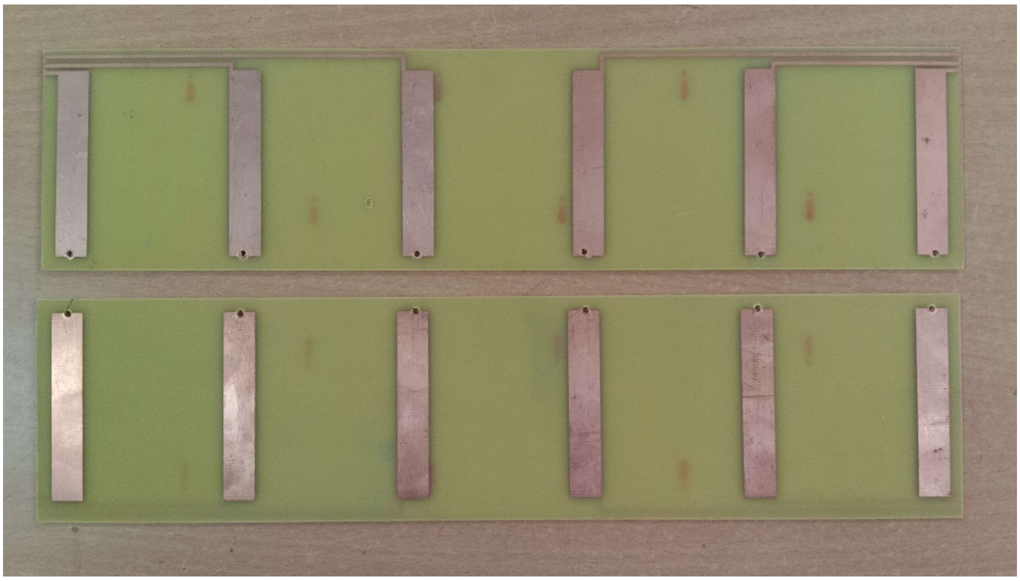


Fig: 4.14. Six plate copper etched PCB

The dimension of PCB is 305 x 74 x1 mm. In each plate 4 copper etch of dimension 60 x 10 mm is made so that it act as the plate of a capacitor. The thickness of copper etch are neglected. Aluminium base plate act as holder for the plates, and in total 18 plates are arranged parallel in the aluminium slots to form 17 channels for the fluid flow through channel width of 1.5 mm while that of 16 plates arranged in 2 mm channel width to form 15 channel flow. Connections are taken out from the copper plates using enamelled copper wire. Wire leads are soldered at the top and bottom of the copper adhesive tapes such that the flow of fluid is not obstructed. Each consecutive plates are given positive and negative charges, and the positive and negative leads are taken from the top and bottom side of the plate respectively. This is done for avoiding any short circuit in the system.

For 4 plate capacitor there are 8 copper capacitor in a single plate and only 4 connections are taken out while for 6 plate capacitor there are 12 copper capacitor in a single plate and only 6 connections are taken out using enamelled copper wire. The other four connections are avoided intentionally because large number of leads taken out will provide stray capacitance to the circuit, that deteriorates the accuracy of the system. The length of the enamelled copper wire leads used are very small as possible to avoid the effect of stray capacitance. RG 174 cables are used to take connection from the enamelled copper wire to LCR meter, which gives us the value of capacitor. From the capacitor value obtained from the LCR meter value of liquid height is estimated and thus the mass fraction can be obtained. In total in a test section four positive and four negative leads are taken out. It indicates four capacitor readings along the flow direction.

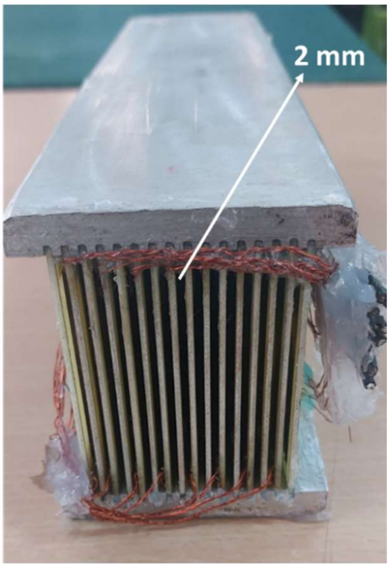


Fig: 4.15. Final test setup for channel width of 2 mm

4.1.3 VOID FRACTION SENSOR

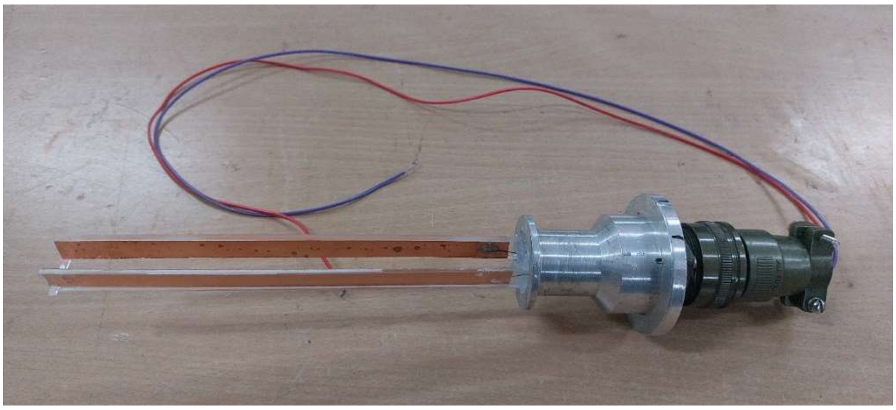


Fig: 4.16. Void Fraction Sensor

The copper is etched on acrylic plates with width and length of 10 mm & 150 mm. The copper plates are placed apart a distance of 10 mm . The plates are joined in an electrical connector via insulated copper wire. The etched copper on the acrylic plates acts as the conductive surface, creating a capacitor. The distance between the plates and the area of the plates affect the capacitance value. By varying the distance and area, the capacitance can be changed, which in turn affects the rise in liquid level between the plates. The wire leads are connected to LCR to obtain the capacitance. The rise in liquid level between the plates shows variation in capacitance. This setup is commonly used in various applications, such as liquid level sensors, where the change in capacitance is utilized to detect the presence or level of a liquid. The etched copper plates provide a sensitive and adjustable capacitor, while the LCR meter accurately measures the resulting capacitance variation.

4.1.4 EXPERIMENTAL APPARATUS

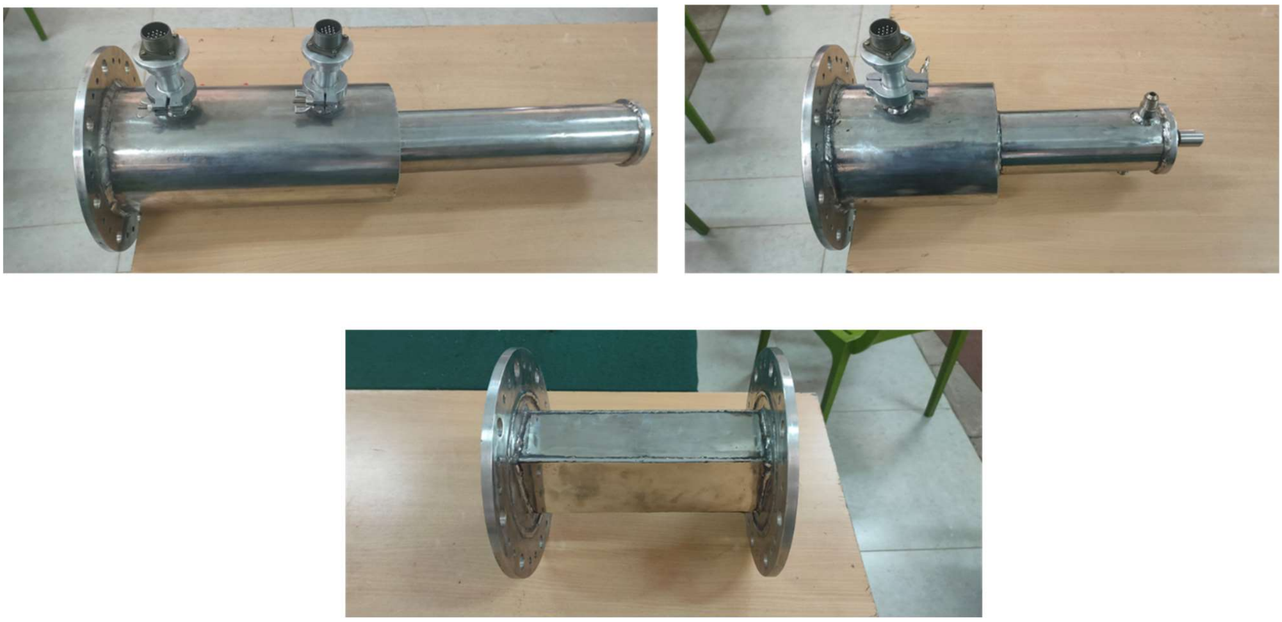


Fig: 4.17. Fabricated Inlet , Outlet & Test section

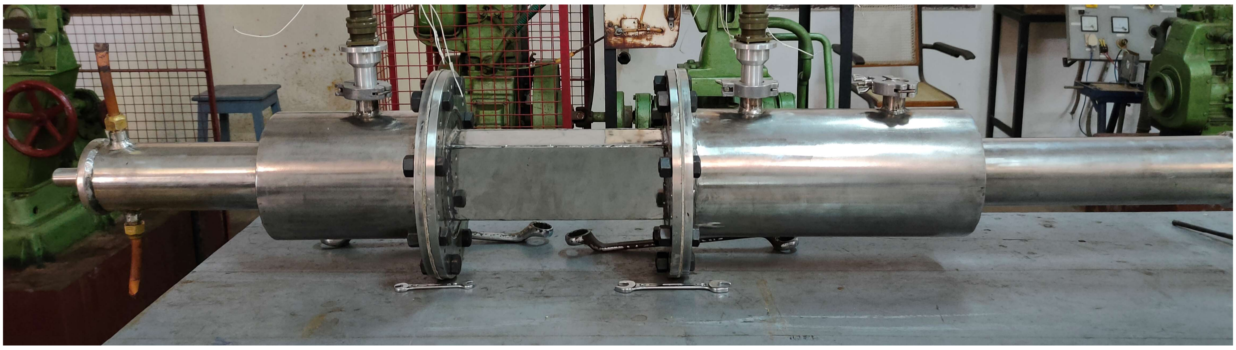


Fig: 4.18. Assembled Section

Fig: 4.19. Assembled section after applying multi-layer insulation

Fig: 4.20. Assembled section after applying Nitrile Rubber

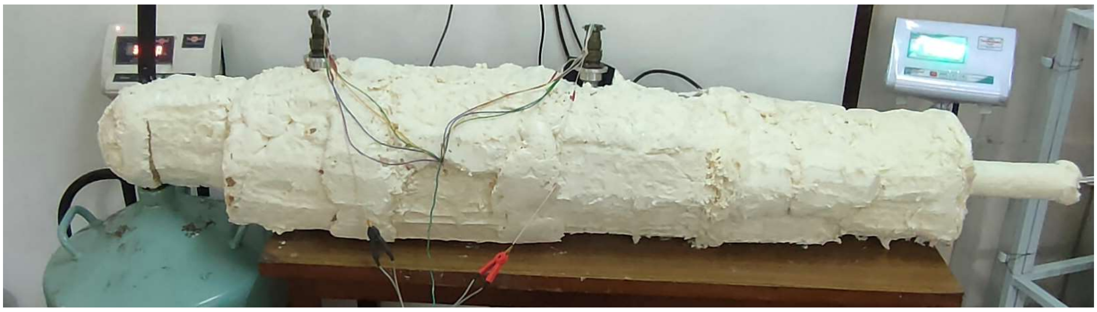


Fig: 4.21. Assembled section after applying PU Foam insulation

The completed sections are assembled with the test setup installed in the test section and is subjected to a multilayer insulation. It consists of multiple layers of thin sheets of reflective material, such as aluminum or Mylar, separated by spacers or insulation materials. The reflective layers help to reduce radiative heat transfer, while the spacers and insulation materials reduce conductive heat transfer. And after that beneath the multilayer insulation nitrile rubber is wrapped around as another layer of insulation. Finally, it is wrapped with Polyurethane foam (PU Foam) as a last layer of insulation.

Fig: 4.22. Polyurethane Foam & Nitrile Rubber insulation

Fig: 4.23. Cryogenic storage tanks (230 L & 120 L)

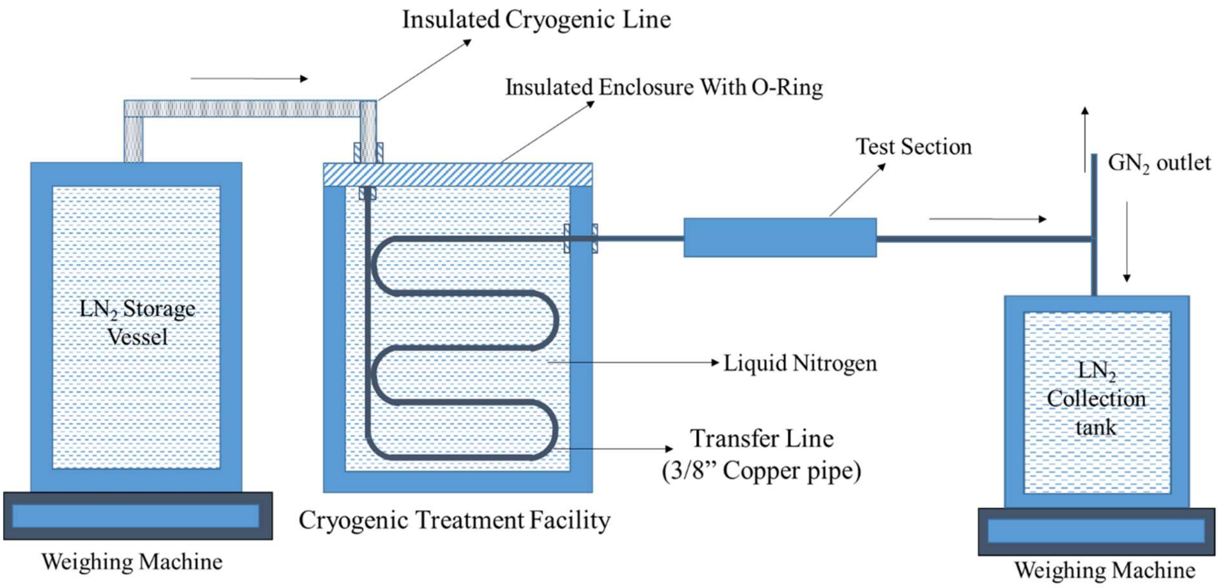


Fig: 4.24. Schematic of Precooling Setup

The above figure illustrates the precooling of the liquid nitrogen to ensure 95% Liquid nitrogen into the test section. For that a precooling bath is installed in between the cryogen transfer line and was filled with liquid nitrogen so that when LN_2 passes through the bath it gets cooled again.

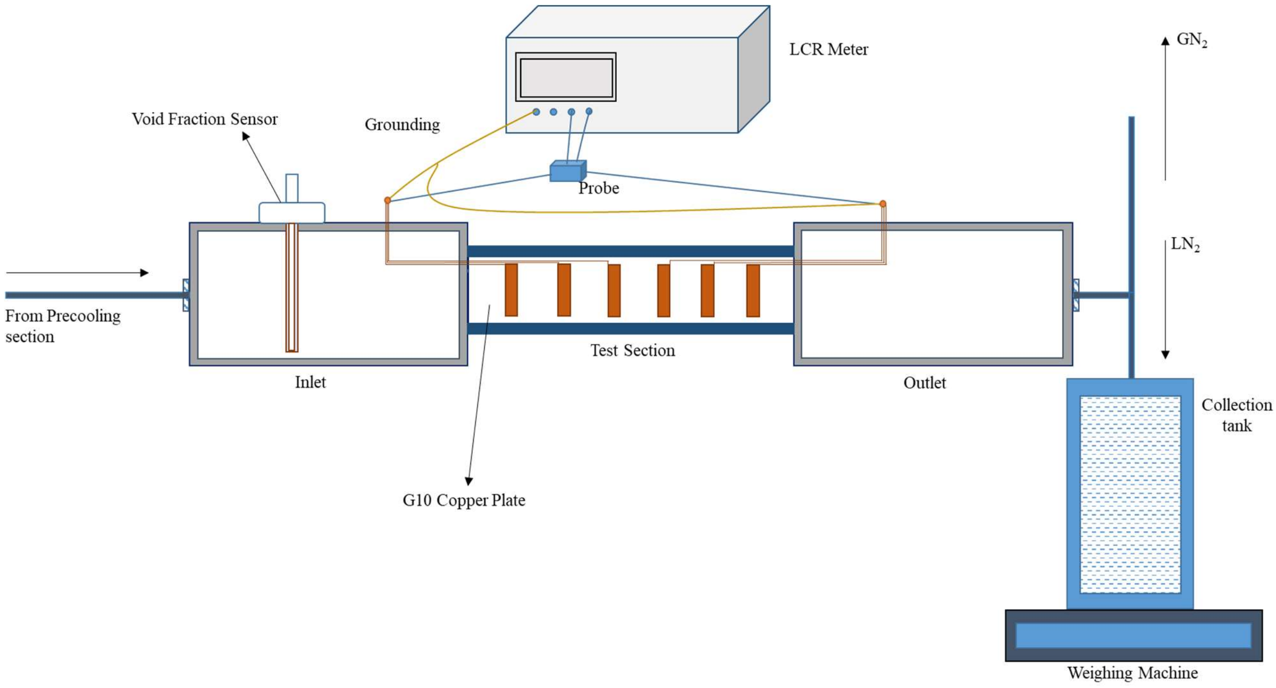


Fig: 4.25. Schematic of Experiment Setup for 6-plate capacitance of 2 mm channel width

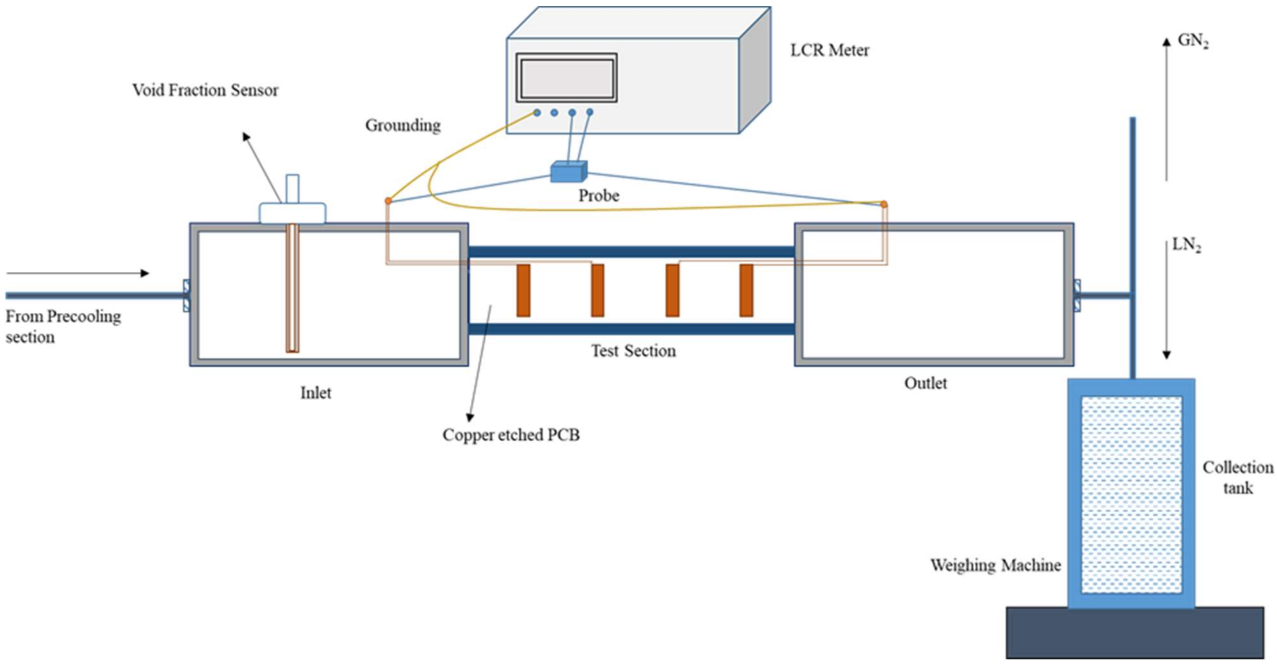


Fig: 4.26. Schematic of Experiment Setup for 4-plate capacitance of 1.5 mm channel

Proper grounding of aluminium base plate is done usingcopper wire wound around the aluminium plate. Effect of mutual capacitance us reduced by ground all the capacitor except the one, which is measuring. RG 174 cables has shielded wires which can be used to reduce the stray capacitance acting on the system.

Fig: 4.27. LCR meter

LCR meter is used to find out the value of parallel capacitance, it also has provision to ground the unwanted signals. Fig shows the LCR meter used in the experiment. It is a product of the company "HIOKI" and the serial number is IM 353.

4.2 EXPERIMENTAL PROCEDURE

The test section design and its fabrication has already been covered in the chapters earlier now we will see the procedure for doing the experiment and how the test section is setup The main instruments that used for the setup are LCR meter ,weighing machine.

Fig: 4.28. Assembled Experimental setup

The process of measuring the capacitance values using an LCR meter in a capacitive two-phase flow meter involves several steps. Firstly, the LCR meter is calibrated to ensure accurate results, and the frequency of the meter is set appropriately. This is essential to obtain reliable data for the experimental setup. The experimental setup for the capacitive two-phase flow meter consists of a test section with four output wires that give four capacitive values as output. Each output consists of an aggregate value of 17 capacitors for 4 plates and an aggregate of 15 capacitors for 6 plates. Two test sections with different channel widths of 1.5 mm and 2 mm are fabricated, and liquid nitrogen is fed through the inlet. As part of the calibration process, the LCR meter is connected with each test section with only stagnant air in the system (initially no flow of liquid nitrogen is given). Capacitance values are noted with and without grounding the system, and four outputs can be obtained with each test condition. During the measurement, only one capacitor is energized at a time. After finding the importance of grounding, liquid nitrogen is taken in a rectangular thermocol box with different heights of fluid in it, and the test section is immersed in it. The value of capacitance is found using the LCR meter, and different values of capacitance can be obtained with different heights of nitrogen in the rectangular box.

Next, the flow of nitrogen at different flow rates is given, and capacitance values are noted. The liquid nitrogen is passed onto a constricted flow channel, and as the viscous force precedes, it makes the flow laminar and stratified. As the level of the cryogenic fluid increases, it starts to flow through the parallel channels, and due to the viscous force, a negative slope is formed. the LCR meter, the capacitance value is measured at each part of the test section, and it is recorded. This enables the determination of the ratio of cryogenic fluid at different parts of the test section, which can provide valuable information for further analysis of the flow behavior of two-phase fluids in cryogenic conditions.

CHAPTER 5

RESULTS AND DISCUSSION

The setup that was assembled was used to determine the mass flow rate for various channel widths, specifically those with widths of 1.5 mm and 2 mm . The mass flow rate was parallelly measured by using the weight calibration method i.e., by measuring the weight from the inlet flow tank of liquid nitrogen in grams per second to the outlet collecting tank .The liquid height along different positions on the channel is calculated from the capacitance measured during the flow measurement is correlated with the empirical relation to estimate the flow rate for each case of the experiment.

In order to ensure that the test setup received the appropriate amount of liquid nitrogen, the precooling setup was adjusted and calibrated to deliver between 95% and 98% of liquid nitrogen to the test setup. Additionally, the void fraction sensor was calibrated to ensure accurate readings of the liquid-vapor nitrogen present in the experiment.

To begin with, the capacitance value is determined by measuring the stagnant air inside it, and four capacitive output readings are recorded. To improve the accuracy of the measurements, the unused capacitor output and the aluminum base plate are grounded. When measuring one capacitive output, the other three output terminals and the baseplates of the test section are properly grounded. The readings obtained represent the sum of the capacitors acting in parallel mode. Therefore, to obtain the capacitance value of a single capacitor, the output value of the LCR meter is divided by channels between them. This provides the individual capacitance value, which is measured in the range of Pico Farad (pF) in the LCR meter when there is stagnant air inside the capacitor.

5.1 MASS FLOW RATE ESTIMATION

The experiment was done for test sections of channel width of 1.5 mm and 2 mm for 4 plate and 6 plate capacitance. The mass flow rate was estimated experimentally by using the setup and also by using weight calibration for the reduction in weight from the inlet flow tank to the outlet collection tank.

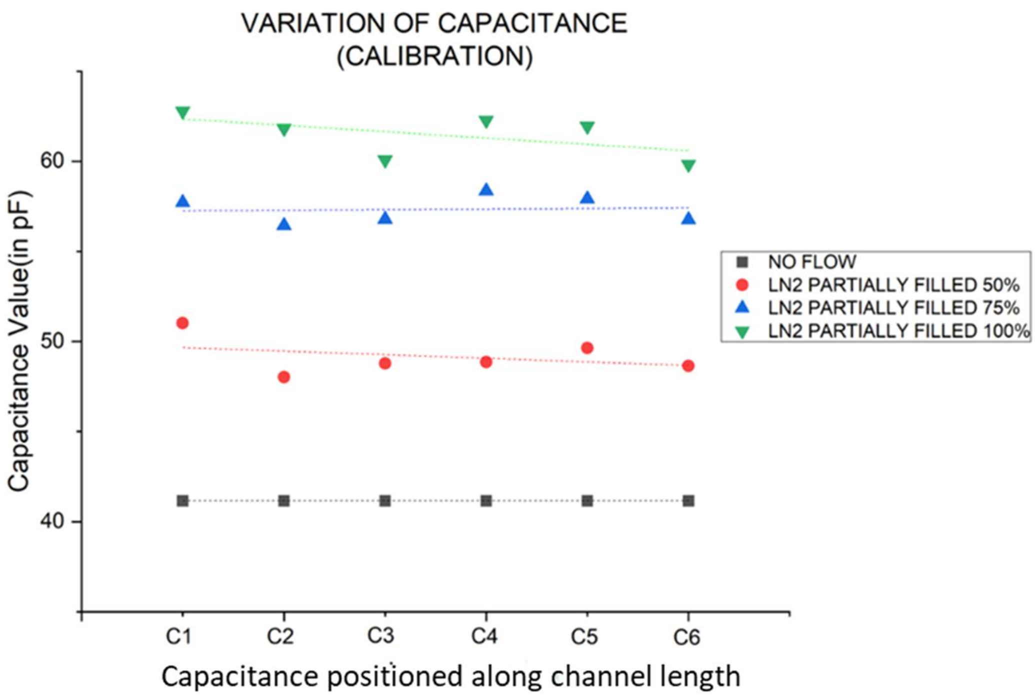


Fig 5.1. Test section calibration-variation of capacitance along channel length

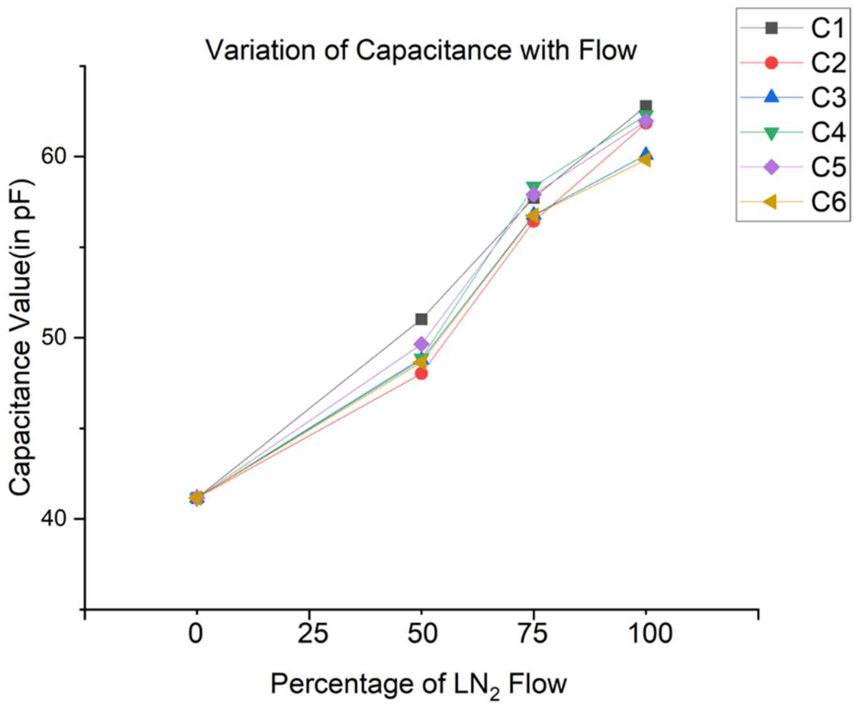


Fig 5.2. Test section calibration -variation of capacitance with LN_2 flow

Fig 5.1, 5.2 shows the calibration of variation of capacitance of test section of 6 plate capacitance of 2 mm channel width. It shows the value for different capacitors placed along the channel length over the test section. The calibration was precise that for each increase in the level of cryogen a higher capacitance value is obtained. For stagnant air the value was same for all the capacitors and was found to be 41.16 pF.

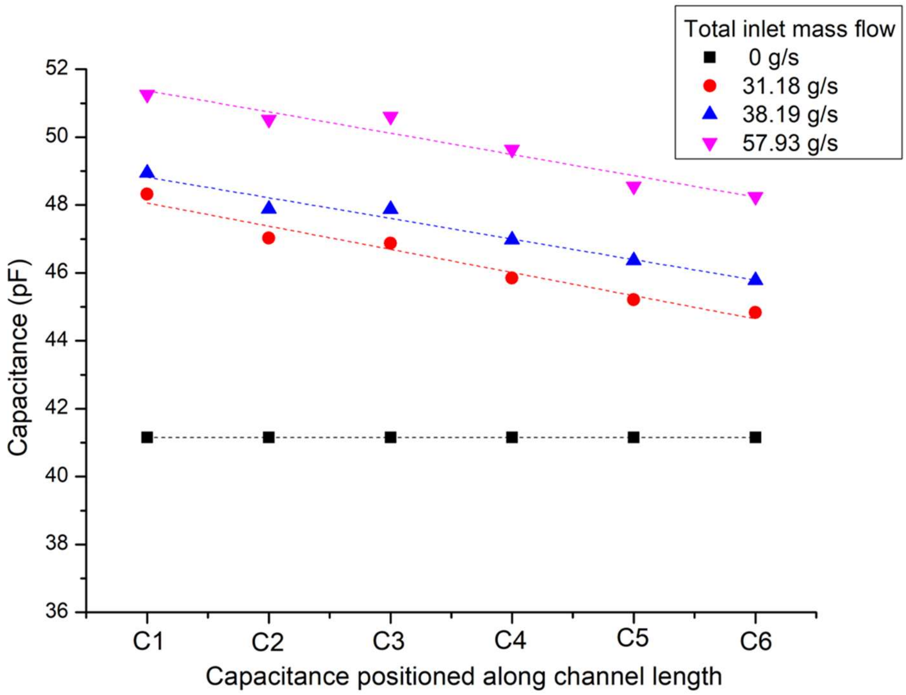


Fig 5.3.Variation of capacitance along the channel length for different inlet mass flow (2mm Channel width - 6 plate capacitance)

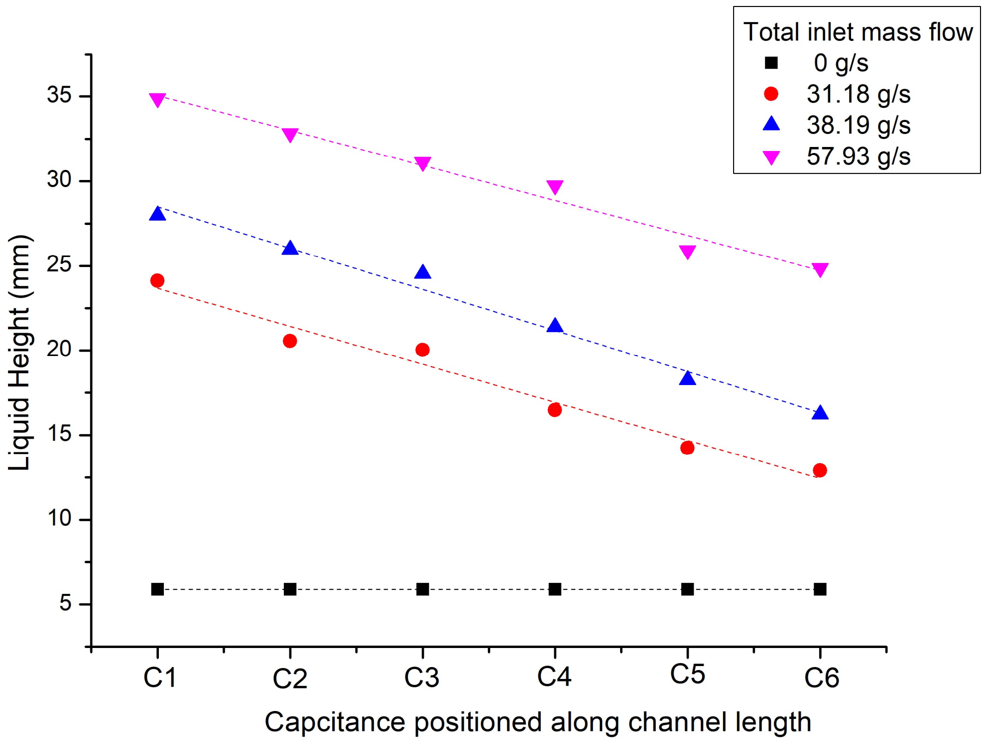


Fig 5.4.Variation of height along the channel length for different inlet mass flow (2mm Channel width - 6 plate capacitance)

Fig 5.3 shows the experimental results for the test section for 2 mm channel width and 6 plate capacitance. The test section comprises 16 plates that contain 15 flow channels. The experiment was conducted using three different flow rates, and the maximum capacitance recorded was 51.43pF. According to the open channel flow theory, when flow occurs in a certain direction, a slope will be created along the flow direction, resulting in a decrease in capacitance output value in that direction. This implies that the capacitance value at C1 is always greater than that at C6 when the flow is from C1 to C6.

By analyzing the graph depicted in Figure 5.3, it can be inferred that the difference in capacitance between consecutive capacitors increases with higher flow rates. This is attributed to the fact that the slope of water in the channel also increases with the flow rate, resulting in a greater difference in capacitor values. As the flow progresses along the channel, the capacitance value decreases due to the decreasing slope. Additionally, the slope value decreases as the channel width increases. By using the capacitance values obtained from the LCR meter, it is possible to estimate the liquid height in each column, and subsequently determine the mass flow rate through each channel. The height calibrated form the capacitance is shown in the figure 5.4 and has decreasing slip along the length.

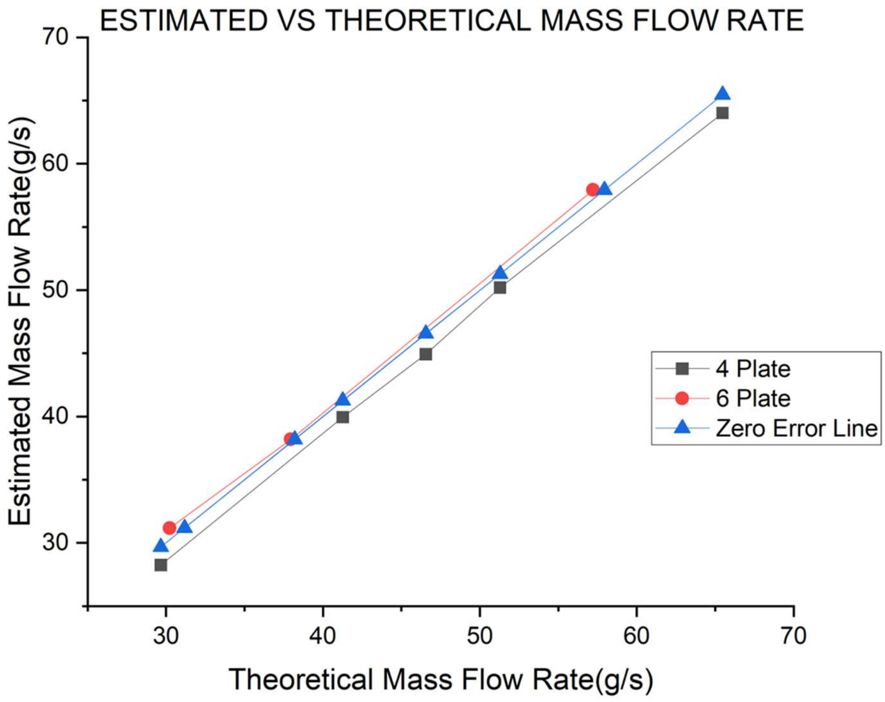


Fig 5.5. Mass flow rate comparison of 4-plate vs 6-plate capacitance

The estimated mas flow rate from the capacitance was found out and theoretical mass flow rate using the empirical formula was found out for the 6 plate PCB .The results were compared with the 4 plate PCB. The six plate has higher flow rate accuracy as there are a greater number of sections to be calibrated than the 4 plate PCB. Therefore, the mean average mean error was obtained as ±5% for six plate capacitance and 7% for the four-plate capacitance.

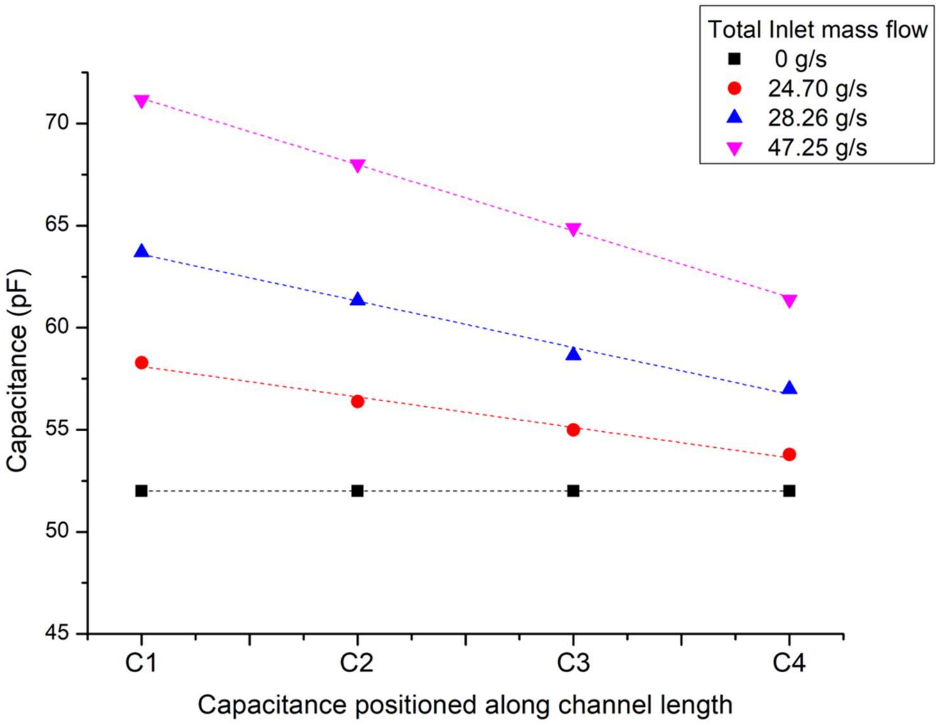


Fig 5.6.Variation of capacitance along the channel length for different inlet mass flow (1.5mm Channel width - 4 plate capacitance)

Fig 5.6 shows the experimental results for the test section for 1.5 mm channel width and 4 plate capacitance. The test section comprises 18 plates that contain 17 flow channels. The experiment was conducted using three different flow rates, and the maximum capacitance recorded was 72.53pF. Based on the graph provided, it can be inferred that a decrease in channel width results in an increase in capacitance difference between two consecutive capacitors in the direction of flow. This leads to a steeper slope when compared to a test section with a wider channel width. As it is clear from the more accuracy of the flow is obtained for minimum channel width. The reason why a decrease in channel width results in an increase in capacitance difference between two consecutive capacitors in the direction of flow is that a narrower channel width results in a higher electric field strength between the plates, which in turn leads to a larger capacitance change for a given flow rate. This increase in capacitance change results in a steeper slope in the capacitance versus flow rate curve for narrower channel widths.

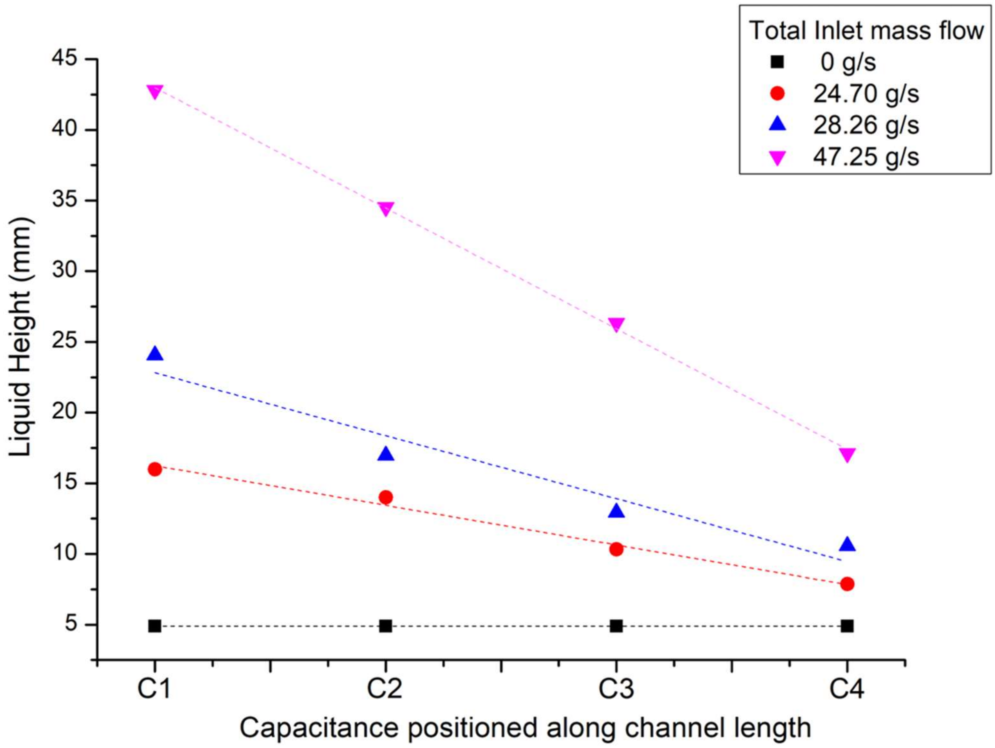


Fig 5.7.Variation of height along the channel length for different inlet mass flow (1.5mm Channel width - 4 plate capacitance)

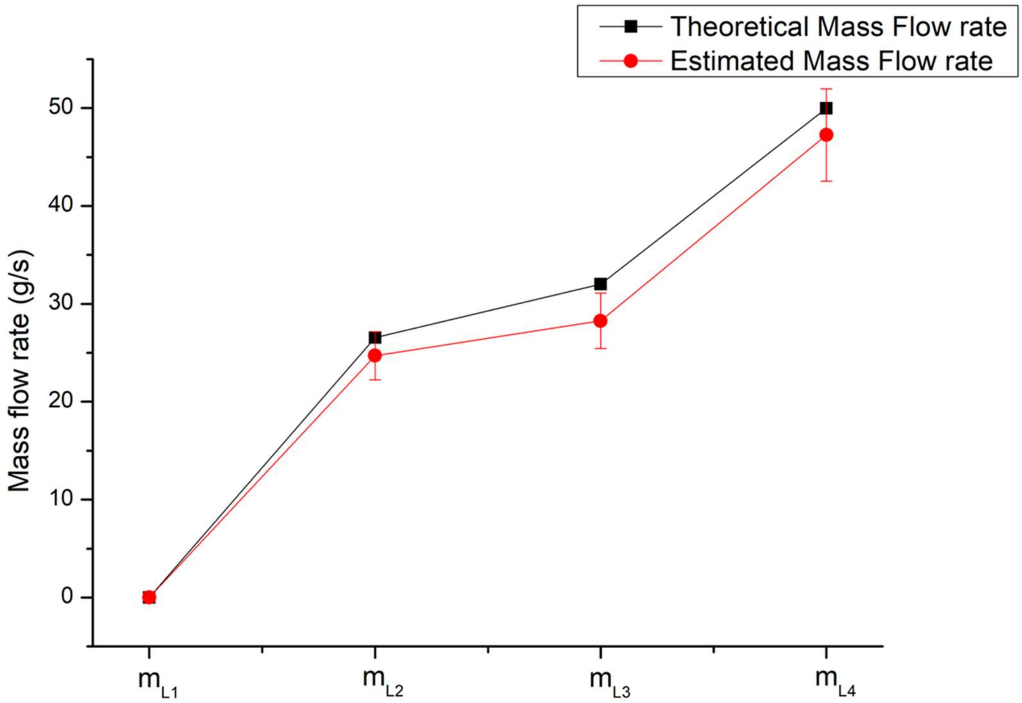


Fig 5.8. Estimated vs Theoretical mass flow rate (1.5mm channel width)

Fig 5.8 depicts the graph of the Estimated vs Theoretical mass flow rate for 1.5mm channel width. An error of ±7% was obtained from the estimated mass flow rate.

5.2 PRECOOLING & VOID FRACTION SENSOR CALIBRATION

A heater was installed along the transfer line and have regulated the heater input for the liquid nitrogen. The results obtained are shown below.

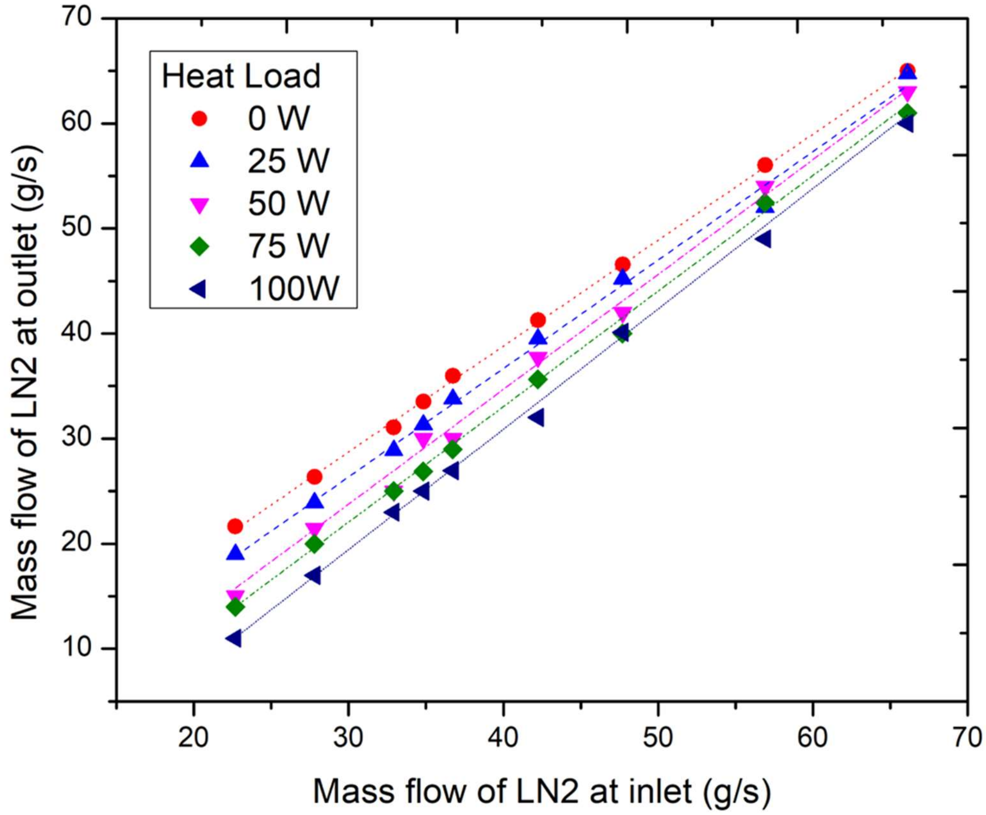


Fig 5. 9. Mass flow rate at inlet vs mass flow rate at outlet

From the graph it is observed that with increase in heat input the mass flow rate of LN_2 decreases at the outlet. For heat input of 25 W there is a decrease in mass flow rate of about 17.39%. Similarly for the heat input of 50,75 & 100W there is a decrease in mass flow rate of 34.78%,43.47% & 56.52%.From the graph, it can be concluded that there is an inverse relationship between heat input and mass flow rate of LN_2 at the outlet. This finding is important for understanding the behavior of LN_2 under different heat inputs and can inform the design and operation of LN_2 systems in various applications. From the fig 5.9 shows that for 100W of heat input the mass flow rate decreases to about 50%.The figure 5.10 shows the different flow quality for heat input. Flow quality can be expressed as a percentage or a fraction, with a flow quality of 0 indicating pure liquid & a flow quality of 1 indicating pure vapor.

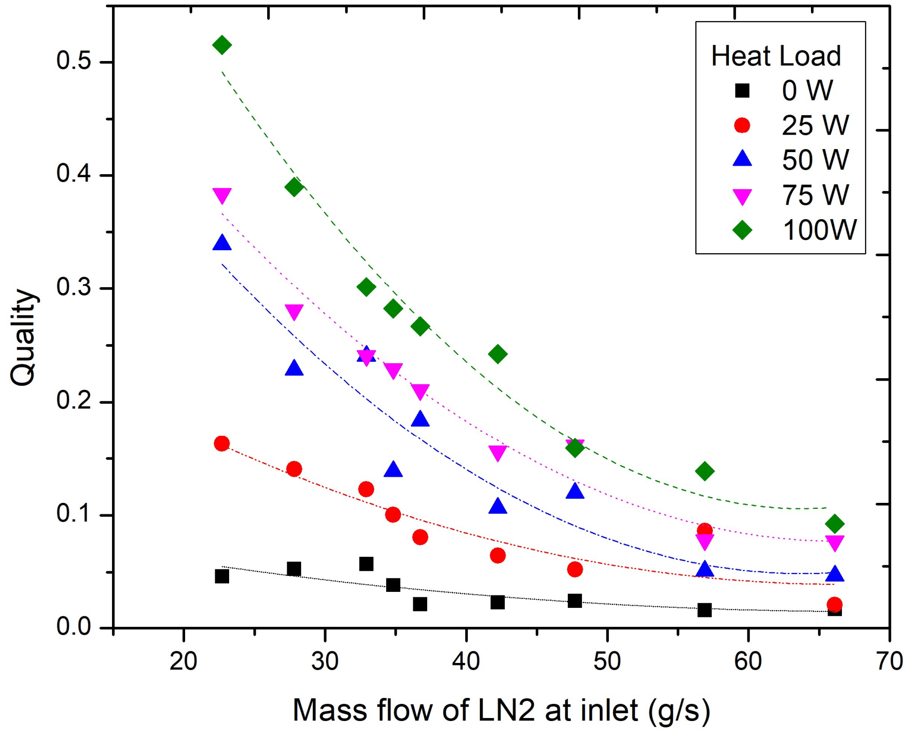


Fig 5.10. Flow quality vs .Mass flow rate at inlet

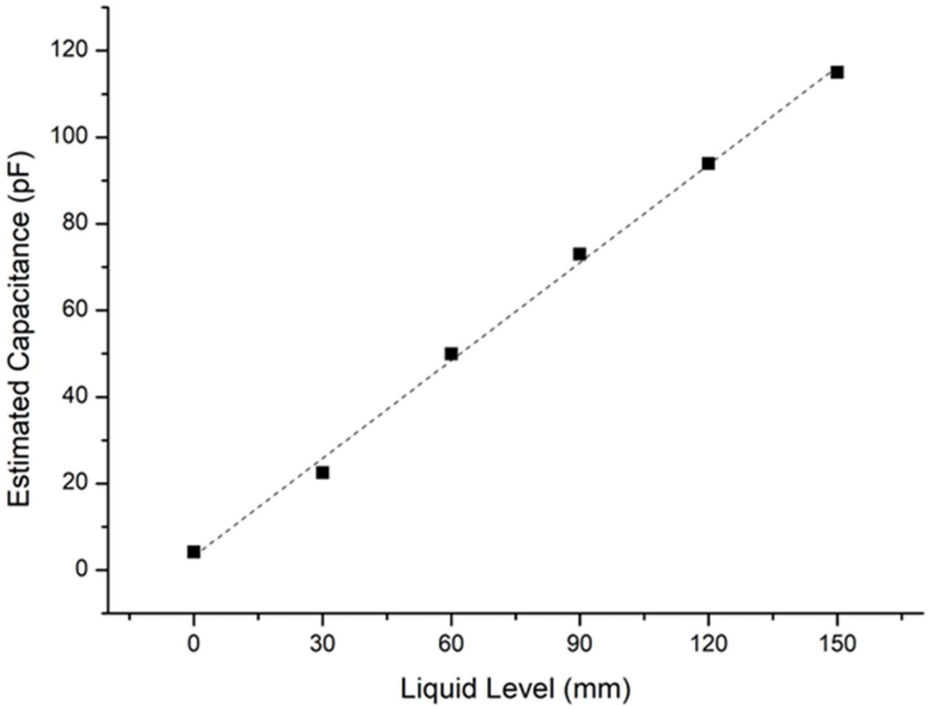


Fig 5.11.Void fraction sensor – Estimated capacitance vs Liquid Level

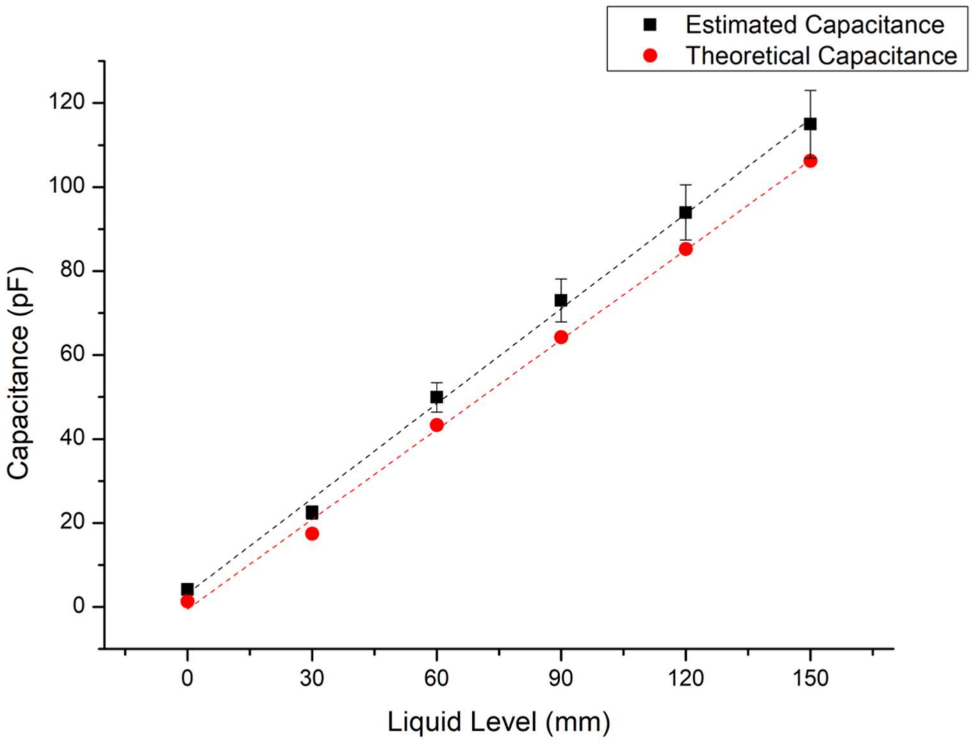


Fig 5.12. Estimated vs Theoretical Capacitance along Liquid level

Figures 5.11 and 5.12 depict the calibration process of a void fraction sensor using water as the reference fluid. The void fraction sensor is designed to measure the percentage of the volume of a two-phase flow that is occupied by gas or vapor, which is also known as the void fraction. During the calibration process, the liquid level is increased gradually, and the capacitance values of the void fraction sensor are recorded at each level. The capacitance changes linearly with the increase in the liquid level, and this linear relationship is used to measure the void fraction of two-phase flow accurately. The calibration results show that the void fraction sensor can accurately measure the void fraction of two-phase flow. This is an essential finding because the accurate measurement of the void fraction is crucial for the design and operation of many industrial processes involving two-phase flow. The error in the calibration of the void fraction sensor is stated to be ±10%. This means that the readings obtained from the sensor could be off by up to 10% due to the inherent error in the calibration process. To minimize this error, calibration should be done with great care, and the sensor should be periodically recalibrated to ensure its accuracy.

CHAPTER 6

CONCLUSION

The accuracy of flow rate is higher for the six plate compared to the four plate due to the availability of more number of capacitance placed along the channel length . While the four plate has only four capacitance along the channel, the six plate six capacitance, enabling the average to be taken over more length increments. Therefore, the average error value is also lower for six plate capacitance. The experiments revealed that the average error for six plate capacitance is ±5%, whereas it is ±7% for the four plate capacitance. Though the measurement accuracy can be improved by increasing the number of capacitance, only eight capacitance can be installed due to the limited length of the plate.

Increasing the length of the channel would cause a greater pressure drop in the flow due to an increase in wall shear stress. However, elongating the channel would facilitate precise flow measurement since the slope can be measured at various points along the channel. The average slope of liquid is higher for the 1.5 mm channel width than for the wider channel width of 2 mm. Thus, the experiments demonstrate that reducing the channel width results in a more accurate flow rate estimation. The experiments were conducted to determine how grounding affects the capacitance output. Grounding can enhance the flow meter's repeatability. The estimated flow rate for the channel width of 1.5 mm was found to be 3 LPM and for 2 mm was found to be 5 LPM.

The results of the experiment indicated that proper grounding of both the aluminum base plates and unused capacitance can enhance the precision and dependability of the flow meter. The width of the channels plays a crucial role in regulating the capillary effect and frictional resistance on the fluid by the channel walls. If the channel is too narrow, the flow characteristics would be controlled by the capillary effect, which might lead to an inaccurate representation of the fluid flow rate. On the other hand, a broader channel might produce a laminar flow, but the slope downstream would be decreased due to reduced frictional resistance imposed by the channel walls and the fluid, and a pressure drop would occur in a wider channel.

The slope created at the interface of LN_2-GN_2 is directly related to the mass flow rate of LN_2. The ideal channel width is between 1mm to 2mm, but narrow sections are challenging to produce and can lead to flow blockage. The void fraction sensor was calibrated, and an error of ±10% was observed.

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