INVESTIGATION ON THE CAPACITANCE FLOWMETER & DEVELOPMENT OF VOID FRACTION SENSOR FOR CRYOGENIC TWO-PHASE FLOW

PROJECT REPORT

Submitted by

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to

The APJ Abdul Kalam Technological University
in partial fulfillment of the requirements for the award of Master of Technology in Mechanical Engineering with specialization in Industrial Refrigeration and cryogenics Engineering

Department of Mechanical Engineering

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MAY 2024

DEPARTMENT OF MECHANICAL ENGINEERING
T.K.M COLLEGE OF ENGINEERING, KOLLAM

CERTIFICATE

Certified that this report entitled **'Investigation on the Capacitance Flow Meter& Development of Void Fraction Sensor for Cryogenic Two-Phase Flow'** presented by **ARCHANA MOHAN, TKM22MEIR01** during **2022-2024** in partial fulfillment of the requirements for the award of the Degree of Master of Technology in Mechanical Engineering with specialization in Industrial Refrigeration and cryogenics Engineering of the APJ Abdul Kalam Technological University.

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I, Archana Mohan hereby declare that, this project report entitled **‘Investigation on the Capacitance Flow Meter& Development of Void Fraction Sensor for Cryogenic Two- Phase Flow’** is the bonafide work of mine carried out under the supervision of, **Dr. MATHEW SKARIA (**professor).I declare that, to the best of my knowledge, the work reported here in does not form part of any other project report or dissertation on the basis of which a degree or award was conferred on an earlier occasion to any other candidate. The content of this report is not being presented by any other student to this or any other University for the award of a degree.

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ACKNOWLEDGEMENT

I take this opportunity to express my deep sense of gratitude and sincere thanks to all who helped me to complete the project successfully. I am indebted to the **GOD ALMIGHTY** for giving me an opportunity to excel in my efforts to complete this project on time.

I am deeply indebted to my guide **Dr.MATHEW SKARIA.** (Professor), Department of Mechanical Engineering for his excellent guidance, positive criticism and valuable comments.

I am greatly thankful to **Dr.SHAFI K.A** Head of Department of Mechanical Engineering for his support and cooperation.

I am greatly obliged to **Dr.SADIQ A.** Professor, P.G coordinator, Department of Mechanical Engineering, for his encouragement and support.

I am highly thankful to **Mr. BINET MONACHAN**, Research Scholar (Ph.D), Department of Mechanical Engineering for his great support and guidance in the successful completion of this project.

I express my thanks to all Faculties and Technical staffs, Department of Mechanical Engineering, and all staff members and friends for all help and coordination extended in bringing out this mini project successfully in time. I will be failing in duty if I do not acknowledge with grateful thanks to the authors of the references and other literatures referred to in this project.

Finally I thank my parents and friends near and dear ones who directly and indirectly contributed to the successful completion of my project.

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ABSTRACT

Cryogenic fluids have significant growth in different industrial applications, including superconductivity, aerospace etc. Depending on the application, the cryogenic fluid flow's purpose varies greatly. Cryogens are required in the case of superconducting magnets in order to maintain the magnet material below a certain temperature and preserve the superconducting state. Currently, no one technology is capable of measuring two-phase flow throughout the entire range of flow conditions. Presenting the design and testing of the proposed two-phase flow-metering device is the goal. The concept is to use capacitance to measure the liquid's height at various locations in the channel by forcing the flow into both a laminar and stratified flow regime. In theory, the flow-rate can be inferred from these height measurements. The idea is a two-phase flow of vapor and liquid through small, parallel channels that produces a laminar, stratified flow that slopes at the liquid-vapor interface. Capacitance-liquid level devices are used in the channel to measure the liquid height. G10 printed circuit boards (PCBs) are used to create the channel walls, and the capacitor conductors are electroplated directly onto the boards to minimize channel intrusion.

Keywords: *Two-phase flow, Cryogenics*

CONTENTS

CHAPTER 1
INTRODUCTION

Two-phase flow is often referred to as the simultaneous flow of two distinct phases having a common interface in the channel. Cryogenic fluids can be found in a variety of applications, from coolants for superconducting magnets to propellants for aerospace applications to distilling and storage of industrial and life support gasses. The purpose of the cryogenic fluid flow varies significantly depending on the application. In the case of superconducting magnets, cryogens are necessary to keep the magnet material below a critical temperature so that it maintains the superconducting state. High sensitivity instruments, such as infrared detecting telescopes, require the instruments to be kept at extremely low temperatures to operate properly. In aeronautics and aerospace, cryogens are commonly seen as fuels for propulsions systems. The German V2 rocket developed in World War II was the first aerospace application developed on a large scale that used cryogenic fluids as propellants. Since then, numerous propulsion systems using cryogens have been developed.

In engineering, two-phase flow is not unusual and is a well understood concept. In cryogenics, two-phase mixtures are even more common due to the low boiling point, low heat of vaporization h_{fg}, high likelihood of heat leak, and low cavitation pressures of cryogenic fluids. Though two-phase flow is relatively well understood, it is not so easily predicted or measured. This is due to the complexity of the interaction between the phases and the number of variables that determine the flow characteristics. Measurement of common two-phase flow systems is difficult since the flow is complex, but the extremely low operating temperatures and ease of cavitation make measuring of two-phase flow characteristics of cryogenic fluids even more difficult. At present, there is no single system that can measure two-phase flow in all of its flow regimes. Many methods exist that can measure flows given specific conditions, but they rarely perform well in measurements outside of these strict design constraints. As a result, there is a large need for the development of a device that can measure the mass flow in a two-phase flow, regardless of the incoming flow characteristics.

Under this project, we propose the development of this two phase flow meter for liquid nitrogen wherein the fluid will be converted to laminar flow with the possible improvements as suggested by the author for reliable capacitance measurements. The flow rates will be in the range from 0.50 liter/min to 10 liters/ min for liquid nitrogen enabled from the self -pressurized LN_2 storage dewar of capacity of the order of 200 liters, available with the principal investigator. The measurements of the capacitance sensors in the laminar flow path will also provide the data of void fraction in the flow. The main parameters associated with the two phase flows are, void fraction, flow quality, and slip S. The void fraction is the ratio of the vapor cross sectional area to the total area of fluid flow, while the flow quality is the ratio of vapor mass flow rate to the total mass flow rate. The slip refers to the ratio of the vapor velocity to the liquid velocity. The different flow regimes have been identified by numerous maps developed for different channel configurations.

This concept follows a process that changes the incoming cryogenic fluid flow from turbulent to laminar. The liquid and vapor phases divide into a stratified flow in this laminar flow. Because of the friction in the narrow channels and the difference in viscosity between the liquid and gas, such a flow causes a slope to develop down the channel length. The mass flow rate of the fluid can be determined by measuring the height of the liquid over the known distances in the laminar flow channel. It is also possible to put several parallel plate capacitance probes in the laminar flow channel. By measuring the capacitance of these probes, one can determine the void fraction in the two-phase flow. The first task in the present work is to convert the output flow from the storage dewar of liquid nitrogen into laminar flow conditions. A laminar flow channel will be constructed for this purpose, and the dimensions of the channel will be determined by a number of factors, including the Reynolds number and fluid flow rates. Furthermore, surface tension effects are negligible in comparison to gravitational effects due to a large Bond number, which is the ratio of gravity to fluid surface tension.

Based on the design, parallel plate capacitors will be fabricated and located at equal distances over the length of the flow meter with appropriate grounding minimizing the mutual coupling between them. Capacitance measurements of individual sensors will be made by an LCR meter or by suitable bridge circuits. The above laminar flow channel will be located inside an appropriate housing and connected on either side to wider channels of cryogenic fluid flow.

LN_2 from the storage dewar will be initially cooled in a heat exchanger immersed in a liquid nitrogen bath so that the vapor fraction can be as low as possible. Subsequently it is made to enter the upstream zone earlier to laminar flow channel. A cylindrical capacitance type liquid level gauge will be used to measure the height of the liquid column of the single phase flow. Another cylindrical capacitance type liquid level gauge will also be used on the downstream side of the laminar flow channel. The measurements from these level sensors will serve to estimate the fluid mass flow rates with minimal void fraction. With the addition of external heat load applied in the flow path beyond the first liquid level sensor, the void fraction can now be varied. The measurements of capacitance sensors of the laminar flow channel can now be used to arrive at both the two phase mass flow rates as well as the void fraction in the fluid flow. The capacitance measurements will be carried out with proper shielding after minimizing the mutual coupling between the adjacent sensors.

1.1 Flow measuring instruments

A flow meter (or flow sensor) can be defined as a tool for measuring the volume or flow rate of a liquid volume (liquid or gas). The flow rate is fully accurate because the weight does not change 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 venture meter, 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.

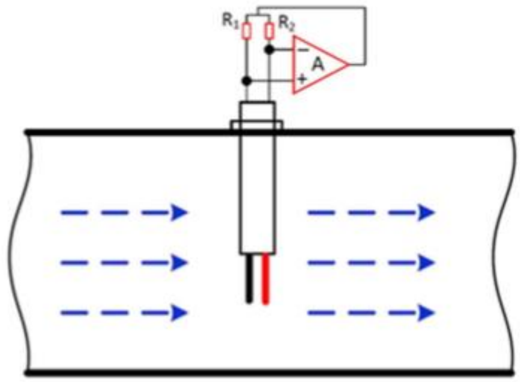

Fig. 1. Schematic of thermal mass flow meter (Moaaz Ahmed. et al,2020)

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.

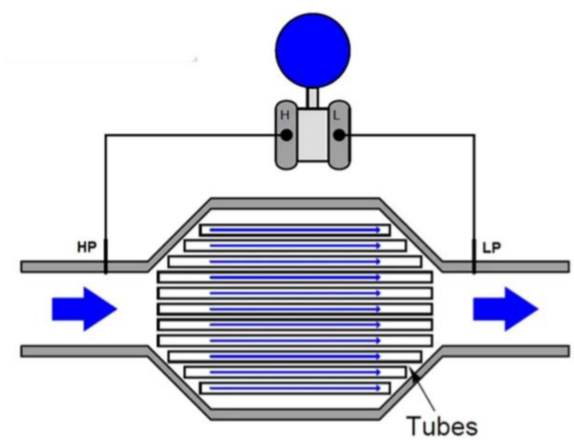

Fig. 2. Schematic of laminar flow meter (Instrumentationtools.com)

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.

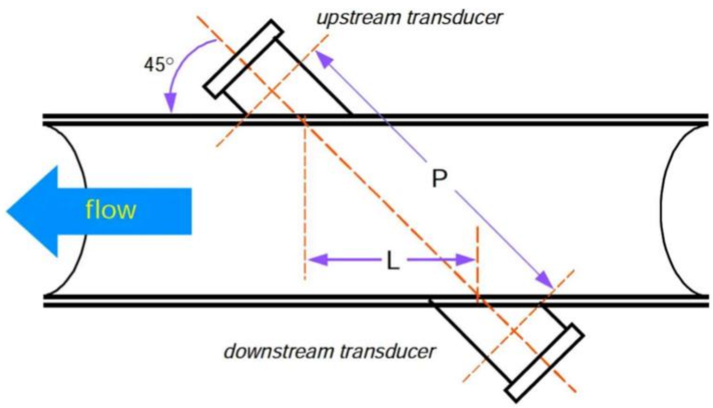

Fig.3. Schematic of ultrasonic flow meter (Instrumentationtools.com)

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 waste water 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.

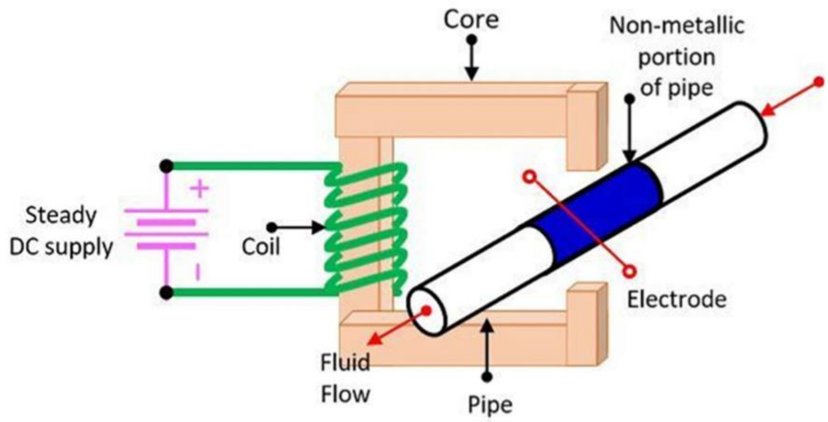

Fig. 4. Schematic of Electromagnetic flow meter. (circuitglobe.com)

1.1.5 Coriolis flow meter.

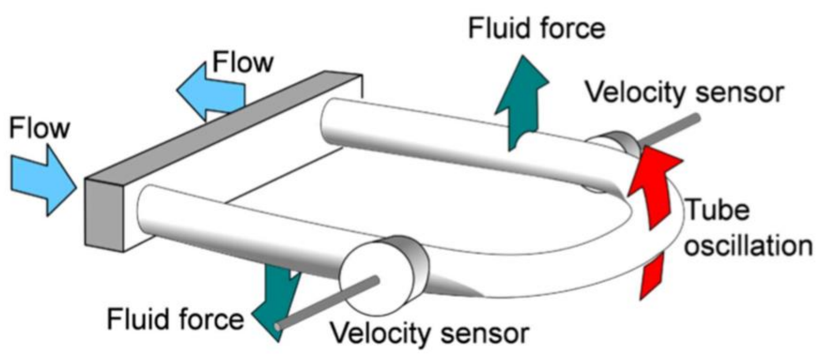

Fig. 5. Schematic of Coriolis flow meter (Instrumentationtools.com)

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.

CHAPTER 2

LITERATURE REVIEW

Two-phase flow patterns can be classified as stratified, bubbly, plug, slug, churn, or annular flow. The fluid velocities, channel dimensions, channel direction, gravity, and fluid physical parameters that define these flow patterns. To comprehend its behavior, it is crucial to forecast the flow pattern in both horizontal and vertical channels. Researchers have made flow regime maps to distinguish between distinct flow patterns in order to better understand the two-phase flow [1–8]. The original motivation to predict the flow regime was to find the minimum pressure loss for transporting petroleum products [2].

Baker [3] conducted the earlier research on two-phase flow regimes in 1954. He observed a fluctuation in the two-phase flow pressure drop over the horizontal pipe flow during the experiments, which may have been caused by modifications in the flow pattern. He then created a set of parameters that can define such transitions in order to statistically explain the change in flow regime. The mass flux of each individual phase and a phase parameter make up the two primary parameter groups of Baker's flow regime map.

A simplified flow regime map was proposed by Mandhane et al. [4] in 1974 based on experimental findings made using an air-water mixture in a horizontal tube. The main enhancement to this flow regime map was the way it was created utilizing surface velocities, which take the tube diameter into account.

A flow regime map of a small rectangular channel with a thickness of 2 mm was created in 1994 by Wilmarth and Ishii [5]. For the vertical and horizontal systems, different flow regime maps were created.

A flow map for boiling horizontal flow in a pipe was presented by Wojtan et al. [6] in 2005. Rather than superficial velocities, the new model was based on mass velocity and flow quality.

An air-water mixture was used in an experimental examination by Kim et al. [7] on a horizontal tube with a diameter of 38.1 mm.High-speed photography was utilized to depict the flow regime.

A flow regime map was proposed after a total of 263 experimental flow situations were investigated.

Using 322 data points, Jeong et al. [8] created a flow regime map for a downward flow of an air-water mixture. The investigations were carried out on a rectangular channel with a thickness of 2.35 mm. Studies on visualization have been carried out by applying an image processing approach and a high-speed digital camera. They noticed that while the flow patterns at higher liquid velocities resembled upward flow, they differed greatly from it at lower liquid velocities. These maps of flow regimes offer a more straightforward way to comprehend the flow transition.

Das et al. [9] created a novel technique that makes use of an infrared (IR) sensor to detect two-phase flow patterns. Using an IR emitter, they conducted an experimental research on a glass tube with a diameter of 4.7 mm and a wall thickness of 0.3 mm, employing infrared radiation. They discovered that the current flowing through the infrared receiver fluctuated as a result of the IR photons being refracted as they passed through the test area. The flow regime can be predicted using this variation. Using this technique, they discovered a bubbly, slug-like, stratified flow regime.

A high-speed digital camera was used to visualize the flow of liquid nitrogen (LN2) in experiments conducted by Singh et al. [10] on a horizontal pipe with a diameter of 9 mm. Compared to the Baker's map and Dukler map, they found that the Wojtan map could reliably forecast the flow transition patterns for the cryogenic flow of liquid nitrogen (LN2). The most recent developments in two-phase flow regime identification involve the use of gamma rays and artificial neural networks (ANN).

Shanthi et al. [11] employed fuzzy logic with Support- Vector-Machine (SVM) and Principal Component-Analysis (PCA) to extract the form and textural elements of the flow in order to identify and automate the flow pattern. They determined the flow regime based on the photos. Compared to SVM and fuzzy logic, they came to the conclusion that SVM plus PCA can be utilized to maximize the flow regime recognition.

An artificial neural network was utilized by Rosa et al. [12] to identify flow patterns in a vertical tube with a 26 mm diameter. After a thorough visual analysis of 73 distinct experimental flow situations, artificial neural networks are employed to identify the flow pattern.

A gamma densitometer was used by Hoffmann et al. [13] to determine the volume percentage of multiphase flow. The gathered data was subjected to multivariate analysis in order to determine the flow regime. They saw that this model clearly had trouble estimating the volume percent, but it could identify the flow regime.

An approach for determining the multiphase flow regime and volume fraction forecasts in oil-gas water systems, specifically found in offshore petroleum industry, was established by Pereira et al. [14]. They employed ANNs as an indicator for recognition by utilizing the gamma-ray pulse height distribution patterns. Four ANNs were modeled, three for volume fraction prediction and one for flow regime identification. The technique was able to forecast a homogeneous, circular, and stratified flow regime with a desirable outcome.

Hongwei et al. [15] presented a new image extraction method to recognize the flow pattern. The images are converted to grayscale and the difference between two adjacent frame area is calculated in the form of a time series. The obtained data is used to estimate the Lyapunov exponential matrix and to analyze the flow characteristics.

CHAPTER 3

THEORY

Open-channel flow theory serves as the foundation for the theory governing the laminar two-phase flow meter used in this experiment. When there is fluid moving in a channel with an exposed liquid surface—a free surface—the flow is said to be open-channel. Rivers, canals, ditches, and spillways are a few real-world instances of open-channel flow. The gadget is designed to simulate laminar, two-phase flow across multiple tall, thin channels. The liquid and gas phases in this laminar flow would also split into stratified flow. The flow then behaves as open-channel flow and as this flow travels down the channel length, as lope develops from the difference viscosity of the liquid and gas and the friction with the narrow channels. The viscous effect between the liquid phase and the wall is greater than that between the gaseous phase and the wall, so the liquid has a negative slope as it travels.

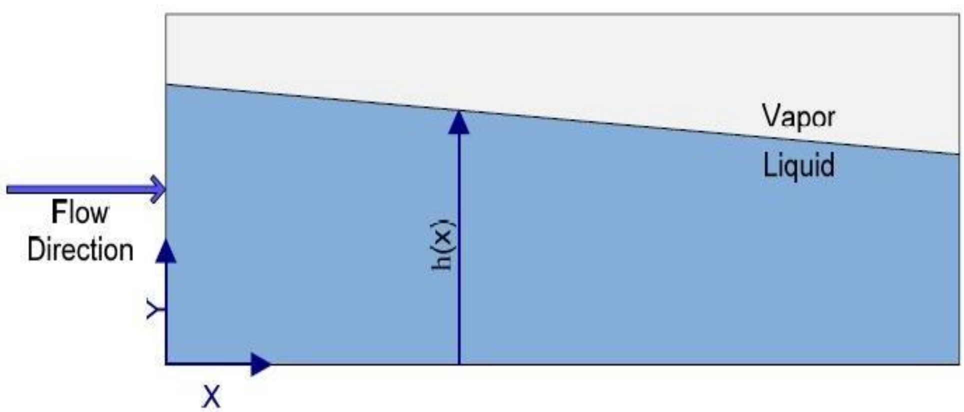

Fig.6 Stratified two-phase flow in a narrow rectangular channel

The differential in the viscous effect between the fluid and the channel walls is the main factor that enables this measurement technique. The vapor will encounter less resistance as it moves through the channel since it is far less viscous than the liquid. At the phase boundary, the liquid-vapor contact exhibits a constant slope as the two phases move through the channel. The flow rate can be determined by taking measurements of the liquid height at various locations along the channel.

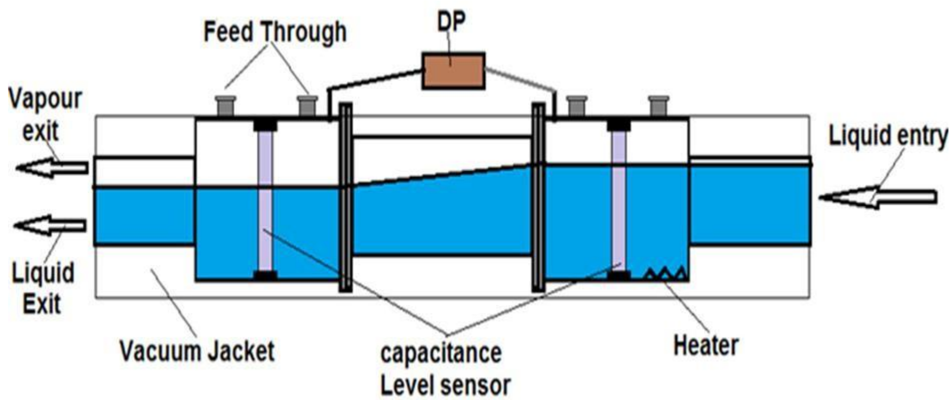

Fig.7 Schematic of Proposed Cryogenic Flow Meter

3.1 Two-Phase Flow Theory

The main objective of this proposal is to develop Capacitance type Flow meters for two phase flow of Cryogenic fluids for laminar flow conditions and verify the performance of the above system by tests with liquid nitrogen. The model for two-phase flow can vary significantly depending on the flow regime that is in consideration. The parameters associated with the two phase flows are, void fraction α, flow quality χ, and slip S. Void fraction is the ratio of the vapor cross sectional area to the total area of fluid flow and can be written as

$$\alpha = \frac{A_v}{(A_v + A_l)}$$

The flow quality is the ratio of vapor mass flow rate to the total mass flow rate and is given as

$$\chi = \frac{m_v}{(m_v + m_l)}$$

Slip refers to the ratio of the vapor velocity to the liquid velocity and is given by the relation

The slip can be related to the other parameters by the relation

$$S = \frac{\chi}{(1-\chi)} \frac{(1-\alpha)}{\alpha} \frac{\rho_l}{\rho_v}$$

When the slip ratio is unity, the void fraction and flow quality are related simply by the different liquid and vapor densities. When the slip ratio is not known, the void fraction cannot be easily determined from the flow quality and vice versa. Due to this, the flow regimes have been identified by numerous maps developed for different channel configurations. Baker map, later modified by Scott has been used by several authors for predicting flow characteristics in horizontal flow.

Void fractions can be monitored by capacitance probes by measurements between the two electrodes or multiple pairs of electrodes. The change in void fraction leads to change in capacitance in view of the changes in the dielectric constant changes between the vapor and liquid. The capacitance between two flat plates is given by the relation

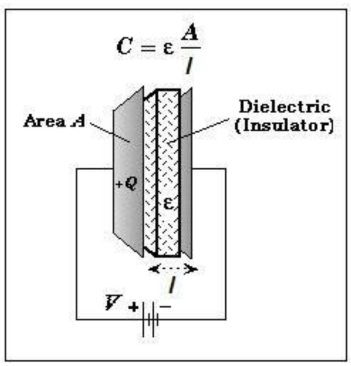

Fig.8 Parallel plate capacitors

3.2 Two-Phase Flow Characteristics

As was mentioned above, most single-phase flow meters are unusable in two-phase flows. Before a two-phase flow meter can be designed, it is first necessary to understand how two-phase flow is different from single-phase flow. This includes what it consists of, how it occurs, and how it behaves.

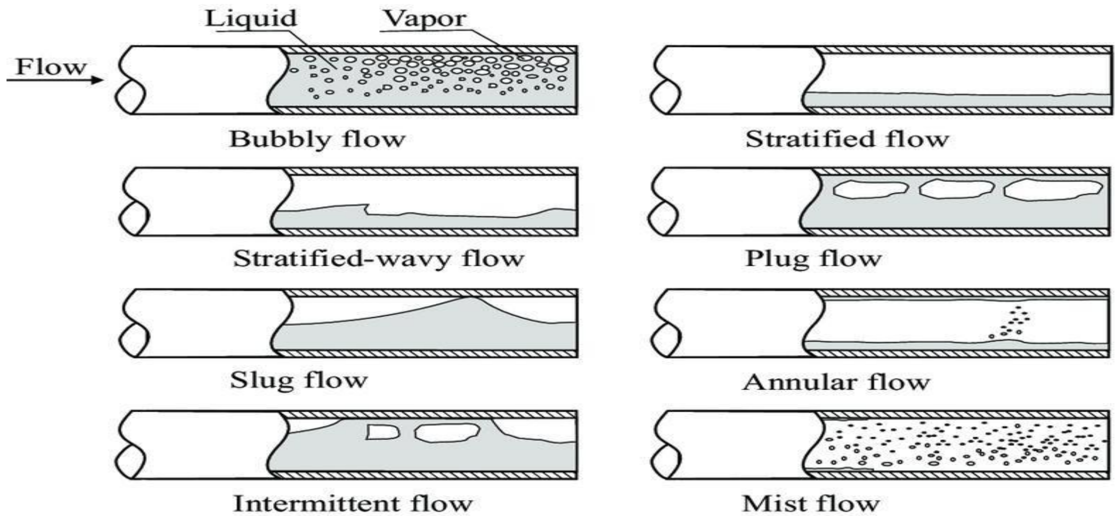

Figure.9 The seven basic flow regimes for horizontal two-phase flow

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

a) 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 the channel.

b) Plug flow: as the gas flow rate increases, the small bubbles begin to combine to form 'plugs 'of gas in the channel.

c) 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.

d) Wavy flow: increasing mass flow rates creates disturbances at the phase boundary. The amplitude of these waves increases as the mass flow rates continue to increase. At the higher gas flow rates, *semi-slug flow* begins to appear and is sometimes considered a separate flow regime.

e) 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.

3.3 Void fraction meters

It is evident from comparing single-phase and two-phase flow measurements that more flow information is required when working with two-phase systems. A collection of instruments made to gauge the flow's quality or void fraction also exists for this purpose. The ratio of the vapor's cross-sectional area to the whole cross-sectional area is known as the void fraction, and the ratio of the mass flow rate of the gas to the overall mass flow rate is known as the flow quality. In two-phase flow systems, void fraction measuring devices are more prevalent than quality meters since it is simpler to measure the ratio of the fluid areas than the mass flow rate. The void fraction can be used to determine the flow quality if the gas and liquid velocities are known and nearly equal.

There are a few techniques that use sound to calculate the void fraction. A sound wave can be transmitted downstream and an identical one upstream, and the time of travel is monitored, much like in transit time ultrasonic flow meters. The vacancy fraction in the channel can be used to determine the difference in the time it takes for sound to travel upstream and downstream. An alternative technique makes use of the notion that when the void fraction varies, so does the average sound speed throughout a cross section. This is due to the fact that the quantity of gas or liquid in the channel alters the fluid's overall density, which in turn modifies the sound's average speed. Measurements of the passive acoustic void fraction differ from other sound-based techniques. An oscillatory circuit is used to monitor the resonance of the entire channel, and when the void fraction varies, the resonance frequency changes, as opposed to depending on how quickly the sound wave moves through the fluid.

Radiation-blocking capacity of a fluid increases with channel total fluid density. The process of measuring radiation attenuation is as follows. To calculate the void fraction, a photon beam is transmitted over the channel, and a sensor measures the quantity of radiation blocked by the flow. It goes without saying that using these techniques can put consumers in danger because of the risks associated with these ionizing radiation types. Similar principle-based laser attenuation techniques are being developed, however the technology is still in its infancy.

To find the overall void fraction, measurements are made at various points in the channel using local probing devices. Depending on the device's design, they can be used to gauge flow quality or void fraction. Since a moving instrument must collect measurements at several different locations, this technique of measurement is typically challenging. This method's accuracy is quite low if the flow is not near steady state. Arguably the most widely used local probing tool is the conductance probe.

The fluid in the channel serves as the conductor in these devices, and the flow regime is indicated by the conductance-time curve that is monitored. Any instrument that can distinguish between various fluid phases can be employed as a probe to measure void fraction, and a wide variety of other probe types are easily accessible. Micro-thermocouple probes use tiny temperature sensors to identify phase fluctuations; hot-wire or hot-film anemometers are used for probing in the same manner as they would measure flow over an entire channel; and index of refraction probes use the change in refraction of a fiber optic surface to identify the gas or liquid phases. Capacitance probes use capacitance to determine the flow regime. There have been many other types of local probing devices developed, but the underlying idea always remains similar.

In two-phase fluid systems, capacitance is a frequently used technique for liquid level measurements. Capacitors are employed not only in local probing devices but also in the average channel void fraction measurement. The fluid flows between two electrodes (or many pairs of electrodes) according to the theory underlying this procedure. The measured capacitance between the electrodes varies in tandem with the vacancy %. This is because the vapor phase's dielectric constant differs from the liquid phase's, and as a result, the channel's overall dielectric varies with the vacancy fraction. The basis of capacitance meters' operation is the idea that a charge will be stored when a potential difference is introduced to two separated plates. The capacitance is the amount of charge that can be stored for a specific potential difference. The relationship between the capacitance, charge, and potential difference is simply:

$$C = \frac{charge}{Potential\ difference} \tag{1.4}$$

CHAPTER 4

METHODOLOGY

4.1 Development of Cryogenic Two-phase Flow Meter

The required test section is modeled on Solid works and Welded assembly is attached with it. In the cryogenic system aluminum is used as base and G10 plates are used as separator.

4.2 Modeling of Aluminum base

The aluminum base is having size 75mm x 10mm x 305mm. 16 slots are made by using CNC machining for 15 channels. The size of the slots are 2.5mm depth and 1.7mm width.

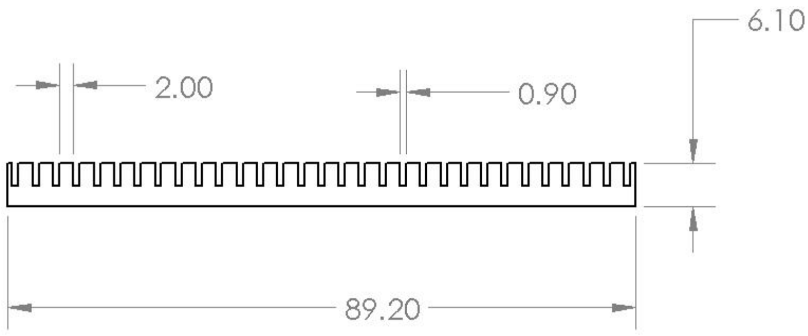

Fig.10 Aluminum base solid works model (side view)

Fig.11 Aluminum base

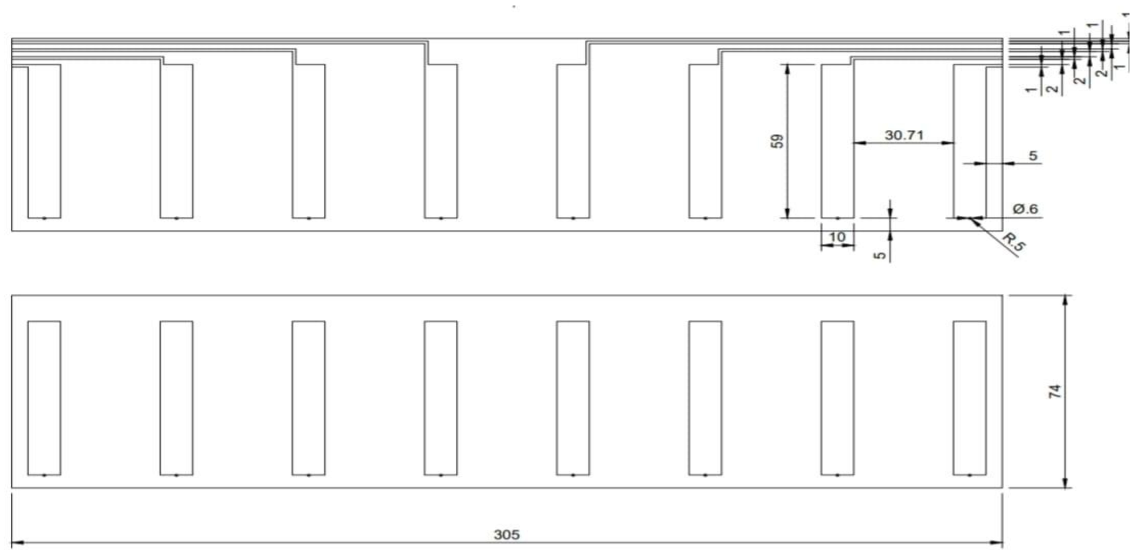

Fig.12 Copper etched PCB

The design of copper plates and leads are made and it is created in the glass epoxy board with double side copper coating by using masking and etching. The work is done at Microcircuits, Tripunithura, Ernakulam. The test section contains copper etched PCBs mounted in the aluminum base plate for channel width of 1.5 and 2 mm. The copper plates used here are 8 plate capacitors. The test setup with the PCB and the aluminum base plate is placed into the section.

Fig.13 Plates arranged parallel in the Aluminum base plate

4.3 Void fraction sensor

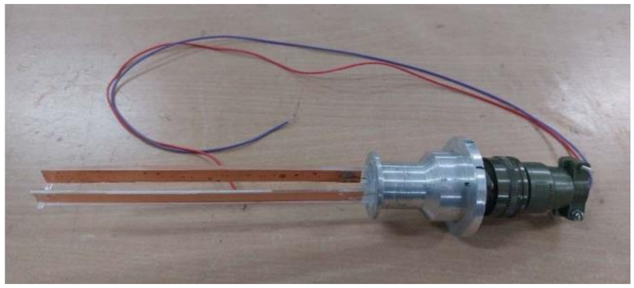

Fig: 14. Void Fraction Sensor

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.

4.4 Test section and connections

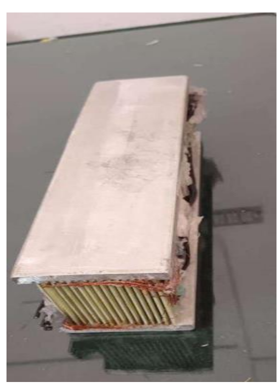

Fig.15 Picture of rectangular narrow channel formed with capacitor plates and Aluminum base plate

The copper plates are placed in the slots and need to fix with suitable sealant. The leads are taken out using enameled copper wires. Out of the four copper leads, 2 leads are taken to one side and other 2 are taken to the opposite side. Since the capacitance obtained during flow is pF (10-12 F), the capacitance due to wire is also getting affected. In order to reduce the effect of capacitance due to the lead wires single core shielded wires are used. The earth wires are connected to the ground in LCR meter. The aluminum base plate has been used as the top and bottom channel wall. The aluminum has slots provided in it to accommodate the 8 capacitor configuration plate. The assembled narrow channel has been provided with connections using soldering the co-axial cables for eliminating the effect of stray capacitance. The connection from the capacitor plate has been taken towards the co-axial cable using enameled wires. The enameled wire has been soldered to the capacitor plates. The soldering is done with utmost care so that no shorting of the connection occurs with the aluminum base plate. Moreover, Kapton tape has also been used at the top and bottom of the 8-capacitor configuration plate before fixing it in the base plate for eliminating any chance of shorting.. The rectangular channel installed in the test section has been calibrated using the LCR meter as seen in Fig 16.

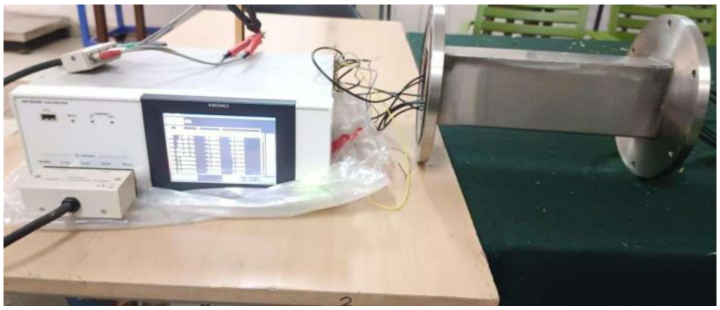

Fig.16 Testing of the capacitors using LCR meter

An experimental setup has been developed to evaluate the performance of the proposed flow meter using parallel narrow rectangular channels. The narrow parallel channels consist of capacitors arranged along the length of the channel. To study the performance of the capacitors arranged in the channel, calibration tests were carried out for different heights of standing liquid nitrogen for the determination of capacitance of the system. The height of the liquid was varied between 0 to 100% of the height of the capacitor plates used in the channel and corresponding capacitance values have been recorded. After proper calibration of the capacitors, the test section has been assembled with the inlet and the exit section through flanged connections as shown in Fig. The assembled setup is leak tested and insulated by using MLI, to ensure that there is minimal amount of heat in leak to the system.

Fig.17 Flow meter with connections for capacitors

Fig.18. Flow meter with connections for capacitors with proper support in the cryostat.

To create vacuum, diffusion pumps as shown in Fig. 19 were used and a vacuum of 10^{-3} mbar has been produced. The vacuum pump has the capacity to create a vacuum close to 10^{-6} mbar. The pump was developed by VR Technologies Bangalore and consist of both rotary and diffusion pump. Initially vacuum has been created by running the rotary pump and after attaining certain level of vacuum, the diffusion pump is switched on. Proper cooling water has been circulated through the outside of the diffusion pump setup to extract the heat from the oil that move upwards from the oil sump.

Fig 19 Vacuum pump

Fig 20.Cryostat connected to vacuum pump for insulating the system

The cryostat shown in Fig.20 has couplings provided on the outer flange to incorporate the inlet pipes and also the connections. Moreover, 16 pin connectors were also used to ensure leak free connections from the inside capacitors to the LCR meter. The flanges are been provided with O rings to ensure perfect sealing and low temperature grease has also been used for more perfect sealing. The liquid nitrogen supply is taken from self-pressurizing Dewar vessel. The LN_2 has been obtained from liquid nitrogen production facility installed in DST-FIST lab of TKM College of Engineering Kollam. In order to ensure 100% liquid in the supply line, the flow from the transfer line is pre-cooled in a vacuum insulated vessel. The pre-cooled liquid nitrogen is given to the flow meter experimental setup as illustrated in Fig.21 for evaluating the authenticity of the proposed concept of two-phase flow metering.

Fig 21. Liquid nitrogen production facility

The liquid nitrogen supply is taken from self-pressurising Dewar vessel. The LN_2 has been obtained from liquid nitrogen production facility installed in DST-FIST lab of TKM College of Engineering Kollam as shown in Fig. 21.

The system is tested for liquid flow rate ranging between 0 and 150 g/s. Initially, no heat load is provided inside the experimental system and the insulation provided on the measurement system ensures that there is only minimal chance for any heat in leak from the ambient atmosphere. The LN_2 flow has been varied from 0 and 150 g/s by regulating the liquid line valve provided in the Dewar vessel and corresponding capacitance readings has been taken using the calibrated LCR meter. The liquid nitrogen flow is controlled manually by regulating the valves. For every liquid nitrogen flow, the corresponding capacitance at each of the specific locations along the channel length has been recorded.

Fig 22.Experimental setup for evaluating the performance of the cryogenic flow meter

4.5 Experimental Analysis on Cryogenic Flow Meter

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. 23 illustrates the pre-cooling of the liquid nitrogen to ensure 95% Liquid nitrogen into the test section. For that a pre-cooling 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.

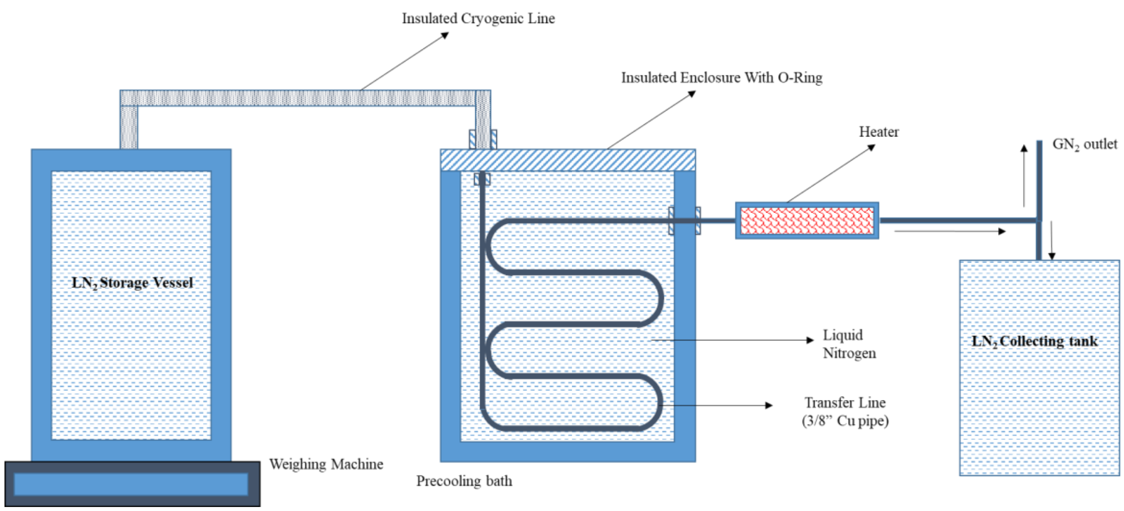

Fig.23 Schematic of Pre-cooling Setup

Fig.24 Cryogenic Treatment Facility

Fig.25 Brazed coil pre-cooling setup

CHAPTER 5

RESULT

Fig. 26 shows the variation of capacitance along the channel length for different level of standing liquid nitrogen. Four capacitors were arranged along the channel length for estimating the capacitance at different positions in the channel. It may be noted that the first and the last capacitors showed almost similar capacitance values for all liquid levels. Meanwhile the capacitors in between those outermost capacitors showed fairly higher values. Moreover, the capacitance increases with location starting with the outermost positions and reaching a maximum at the centre position.

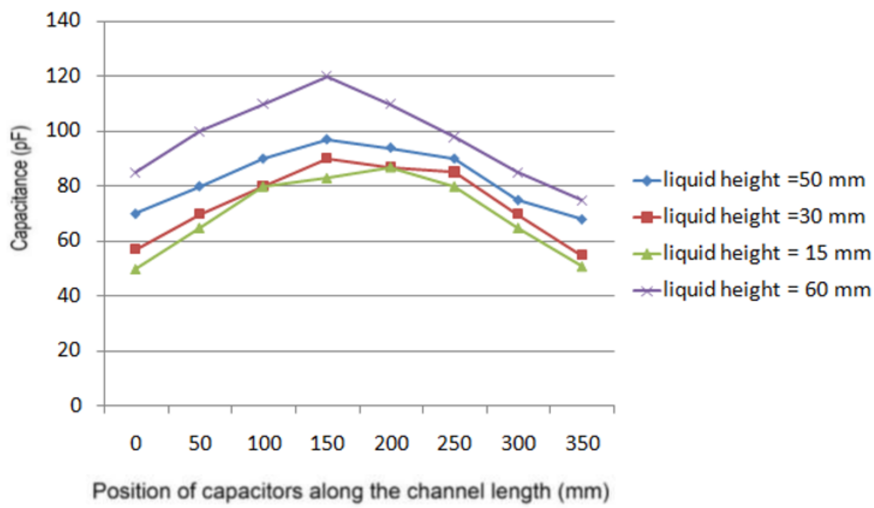

Fig.26 Variation of capacitance along the channel length without shielding.

Since the capacitance varies along the channel length, the effect appears to be from mutual capacitance. Therefore, it may be noted that the capacitor being measured also considers the capacitors around it and the measured capacitance becomes higher than would be expected. Consequently, proper grounding needs to be given to eliminate such undesirable effect on the system. Therefore, the coaxial shields were grounded for further test and it was expected that after proper adequate shielding the effect would no longer be affect the system. The effect of shielding could be easily understood from Fig.27, where by all the capacitors arranged along the channel length recorded comparable capacitance within a variation of ±7.9%. Moreover it may be noted that the variation in capacitance with change in liquid height is lower. The minimum and maximum capacitance recorded ranges between 40 pF and 75 pF during the calibration test.

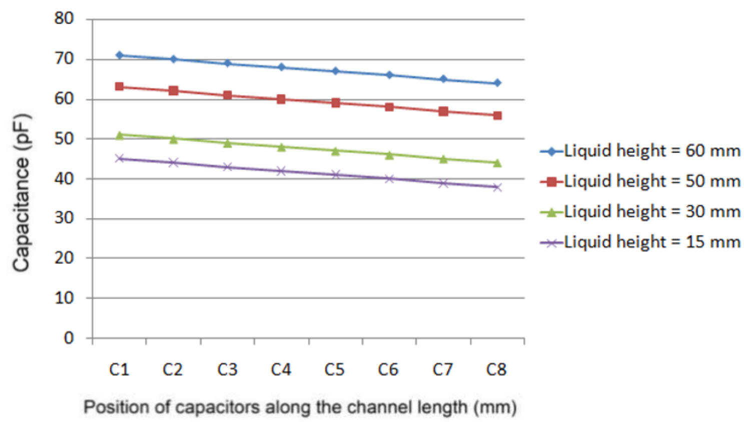

Fig.27 Influence of shielding to eliminate mutual capacitance effect on the system.

After evaluating the effect of mutual capacitance and proper calibration, the experimental facility described in the previous section is assembled for further analysis. The test section was assembled with the inlet and the exit section using flanged connections. Feed-through were used for taking out all the terminals of the capacitor plates. Since capacitors are having significant sensitivity to any noise source, all the connections were done using soldering to ensure best possible contact between them. The inlet, test and the exit section were bolted and lead reinforcement gasket has been provided in between each flange of different sections to make a good sealing of the system. The assembled setup is leak tested and insulated by using MLI, nitrile rubber and PU foam respectively to ensure that there is minimal amount of heat in leak to the system. In the beginning of experiment the liquid nitrogen is introduced to the experimental setup which is having a higher temperature than the cryogenic fluid. The liquid undergoes rapid evaporation and the small liquid slugs present reside on a thin layer of vapor formed at the lower side of the flow meter system. This is referred to as film boiling and it would continue until system gets cooled down to the temperature of the fluid. The system needs to cool down until the temperature sensors in the experimental section read a sufficiently low temperature equivalent to that of the liquid coming from the vessel. As the temperature of the surface lowers, liquid droplets remains at bottom surface.Heat is transferred during film boiling from the pipe wall to the fluid primarily by conduction through the vapor film and by radiation from the hot pipe wall. After the cool down the experimental setup has been tested with different flow rates using self-pressurizing Dewar vessel having a storage capacity of 230 L. All of the instruments on the experiment system have been tested to make sure there are proper connections. Typically as the system gets cooled down, the lower part of the test setup gets filled with liquid with vapor above it resulting in a two-phase flow. As more liquid enters the inlet section, a laminar stratified flow occurs and a slope gets developed as the flow proceeds downstream.

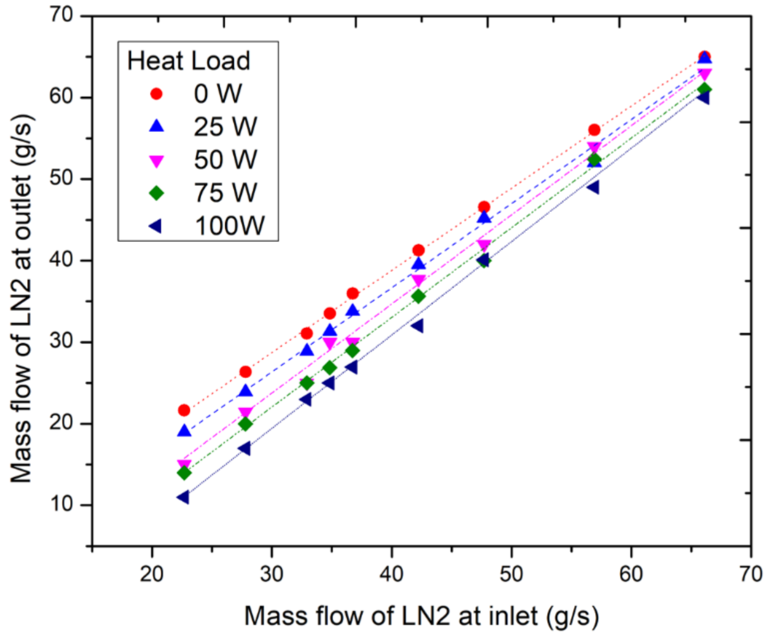

Fig.28 *Mass flow rate at inlet vs mass flow rate at outlet*

A heater was installed along the transfer line and has regulated the heater input for the liquid nitrogen. The results obtained are shown below. 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.28 shows that for 100W of heat input the mass flow rate decreases to about 50%. Fig. 29 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.

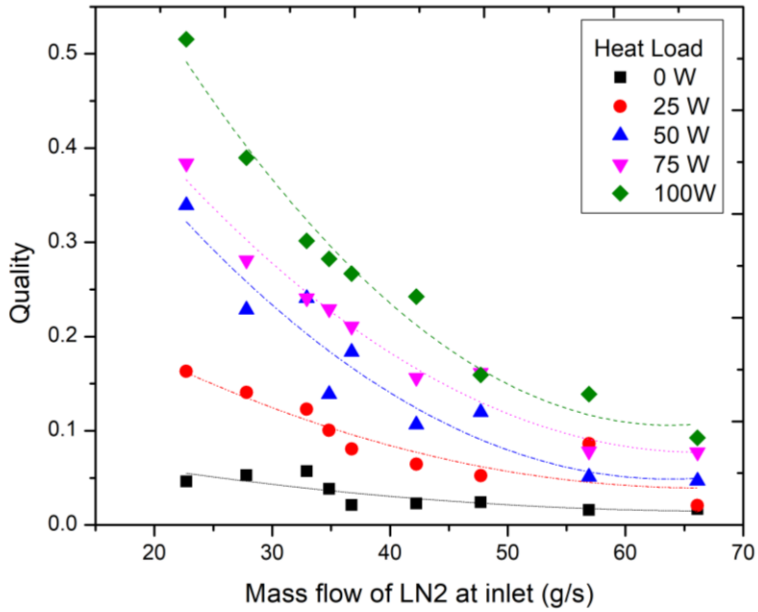

Fig.29 *Flow quality vs .Mass flow rate at inlet*

The system is tested for liquid flow rate ranging between 0 and 250 g/s. Initially, no heat load is provided inside the experimental system and the insulation provided on the measurement system ensures that there is only minimal chance for any heat in leak from the ambient atmosphere. The LN_2 flow has been varied from 0 and 250 g/s by regulating the liquid line valve provided in the Dewar vessel and corresponding capacitance readings has been taken using the calibrated LCR meter. To ensure 100% liquid at the inlet of the flow meter system, a pre-cooling arrangement is provided. The liquid nitrogen flow is controlled manually by regulating the valves. For every liquid nitrogen flow, the corresponding capacitance at each of the specific locations along the channel length has been recorded. Fig.30 represents the capacitance measured at each of the capacitors positioned in the channel for every flow rate given from the Dewar vessel. It may be noted that with increase in liquid flow, the capacitance recorded at each capacitor increases. As the liquid flow increases more and more layers of fluid enters the channel and the fraction of vapor in the channel decreases. Therefore, the effective dielectrics between the capacitor electrodes changes. Since the dielectric constant of liquid phase is higher than that of vapor phase, with increase in liquid holdup the effective dielectrics increases. Consequently, the capacitance value obtained at each of the capacitor for every flow rate would change and it increases with increase in the flow rate provided at the inlet of the flow measurement system.

Figure 30 represents the capacitance measured at each of the capacitors positioned in the channel for every flow rate given from the Dewar vessel. It may be noted that with increase in liquid flow, the capacitance recorded at each capacitor increases. As the liquid flow increases more and more layers of fluid enters the channel and the fraction of vapor in the channel decreases. Therefore, the effective dielectrics between the capacitor electrodes changes. Since the dielectric constant of liquid phase is higher than that of vapor phase, with increase in liquid holdup the effective dielectrics increases.

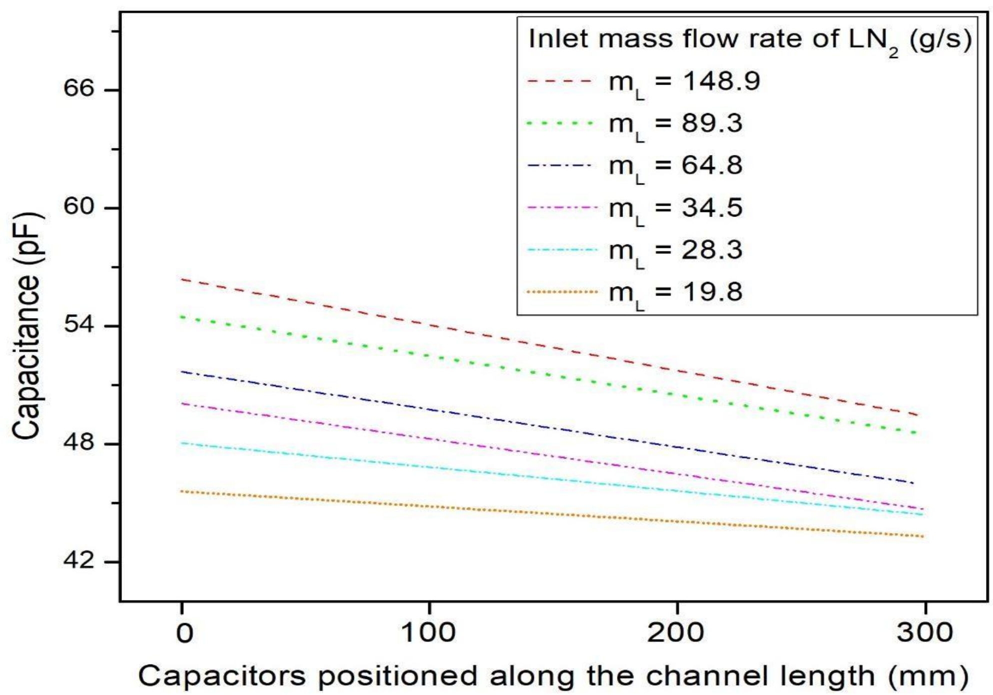

Fig.30 Capacitance recorded for different capacitors positioned along the channel length.

Consequently, the capacitance value obtained at each of the capacitor for every flow rate would change and it increases with increase in the flow rate provided at the inlet of the flow measurement system.

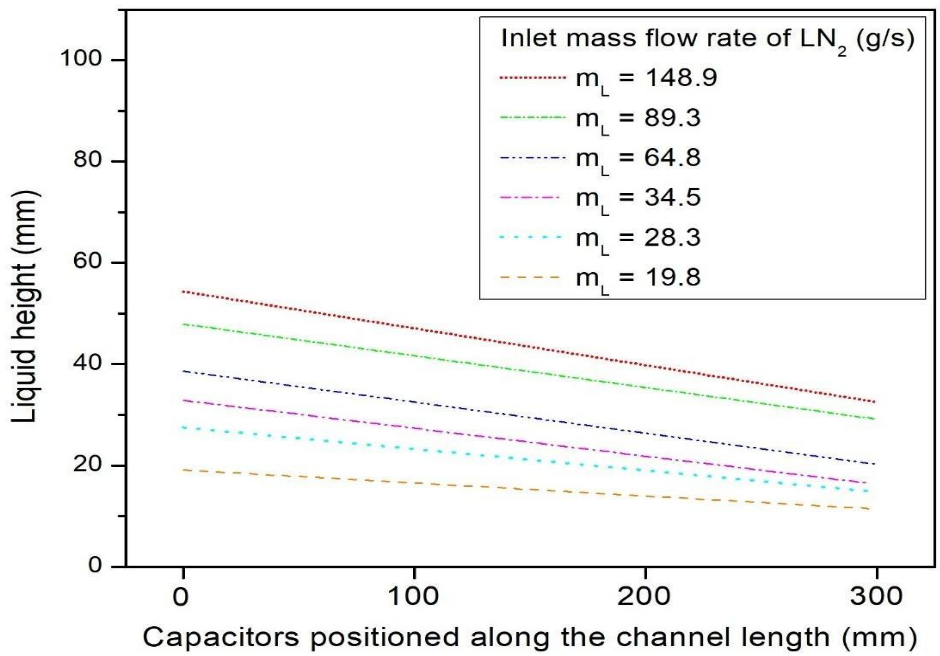

Fig.31 Variation of height of liquid along the channel length for different liquid flow at the inlet.

The capacitance measurements obtained from the LCR meter has been converted to liquid height by using the correlation between capacitance, dielectric constant and height. The capacitance and the corresponding liquid height are having linear relationship and follows a similar trend as depicted in Fig.31 With increase in inlet liquid flow from the Dewar, more liquid enters the channel. Consequently, more number of fluid layers are formed which would increase the liquid height throughout the channel length. With increase in number of fluid layer, more frictional interaction would happen between them and therefore, the increase in liquid height would be higher comparatively than that downstream. The increase in liquid height at the inlet of the test section with increase in inlet flow from 18 g/s to 35g/s is approximately 100%. Meanwhile the increase in liquid height at the exit of the test section is around 70%only.Moreover, with increase in total flow at inlet the slope developed in each of the narrow rectangular channel also increases. The slope at the liquid vapor interface is obtained from the liquid height determined at the inlet and the exit of the test section. For the inlet total flow range considered for the experimental study, the slope varies from 2° to 7° respectively as illustrated in Fig.32. It may be noted that the slope developed at the interface is having a linear relationship with the inlet flow given from the Dewar vessel.

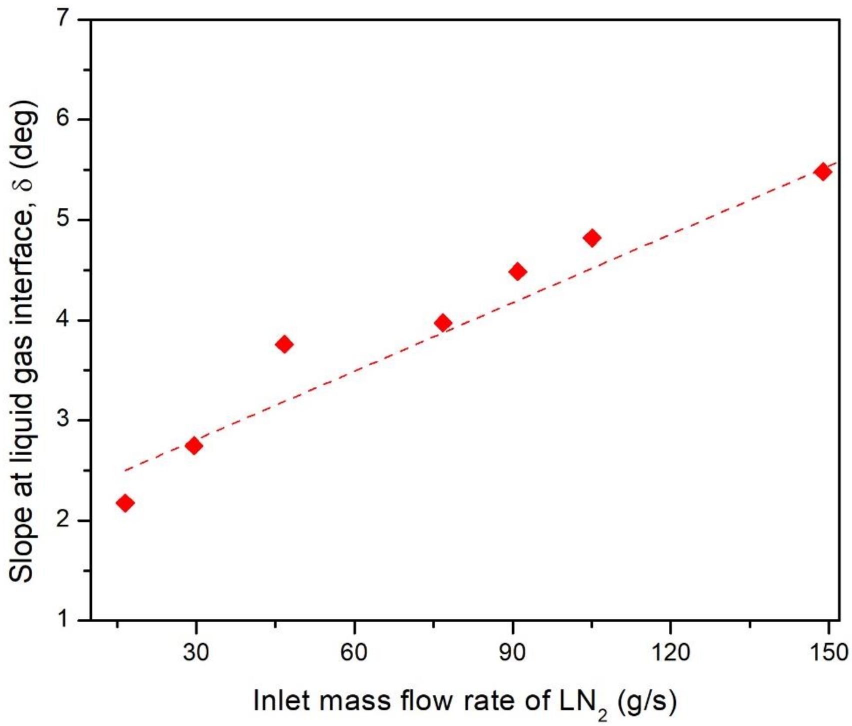

Fig.32 Slope developed at the liquid-vapor interface for different inlet total flow of liquid from Dewar vessel.

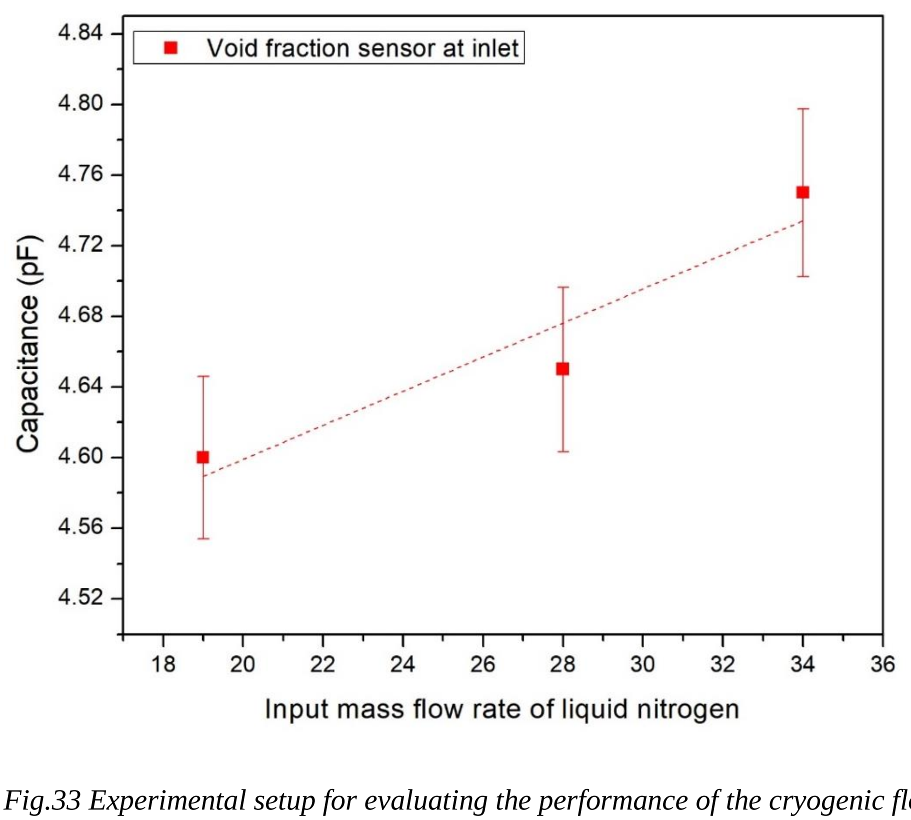

Fig.33 Experimental setup for evaluating the performance of the cryogenic flow meter.

Void fraction sensor has been developed and incorporated at the inlet and exit section of the cryogenic flow meter. The void fraction sensor typically measures the liquid height just before it enters the test section. Therefore the void fraction sensor at the inlet section typically gives the liquid height at the inlet of the test section. Also the void fraction sensor positioned near the end of the test section would give approximately the liquid height at the exit of the test section. These liquid height measurements would typically reflect the data necessary for determination of mass flow rate of the liquid phase through the flow meter. Both the void fraction at inlet and exit section have been calibrated and ensured that the connections have been made properly. Moreover to further reduce the mutual capacitance effect the connections have been made with co-axial cable.

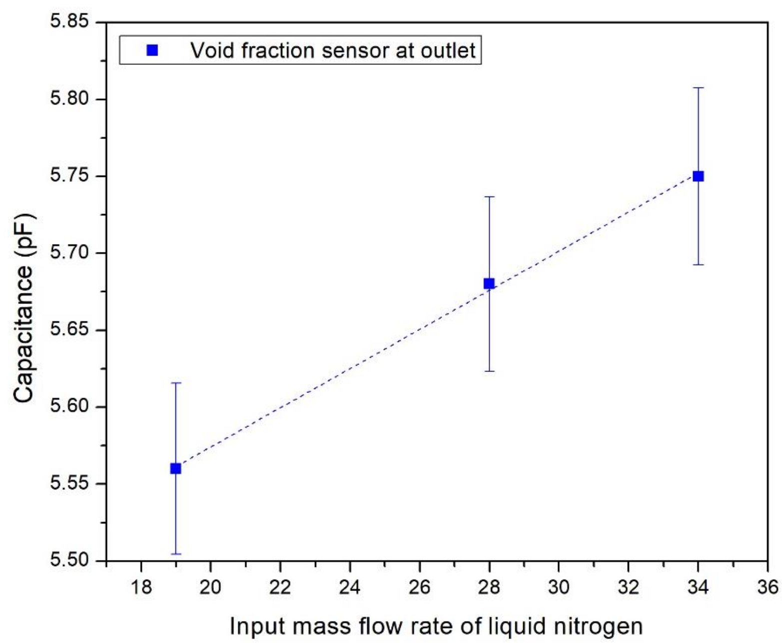

Fig.34 Experimental setup for evaluating the performance of the cryogenic flow meter.

Figures 33 and 34 illustrates the variation of void fraction sensor reading obtained using LCR meter for different input mass flow rate of liquid nitrogen given from the self-pressurizing Dewar vessel. It may be noted that with increase in input mass flow from Dewar, the number of layer of liquid would increase and hence the capacitance recorded would be higher. The capacitance value obtained has been converted to liquid height data by using the principle of adding the capacitance provided by vapor and liquid together. The total height of the sensor electrodes are known and based on that total height the height of the liquid could be measured. Similarly the void fraction sensor at the exit section also shows increasing trend as the input mass flow rate from Dewar has been increased. As input mass flow rate is increased more layers of liquid enters the channel and therefore the liquid height at the entrance of the test section would be higher. As the number of liquid layer is increasing, the frictional resistance between the layers would be higher and hence a higher slope would be obtained. Therefore the variation in the slope at the interface could also be obtained from the void fraction sensor used with the cryogenic flow meter. The liquid height obtained from both the void fraction sensors has been represented in Fig.35.

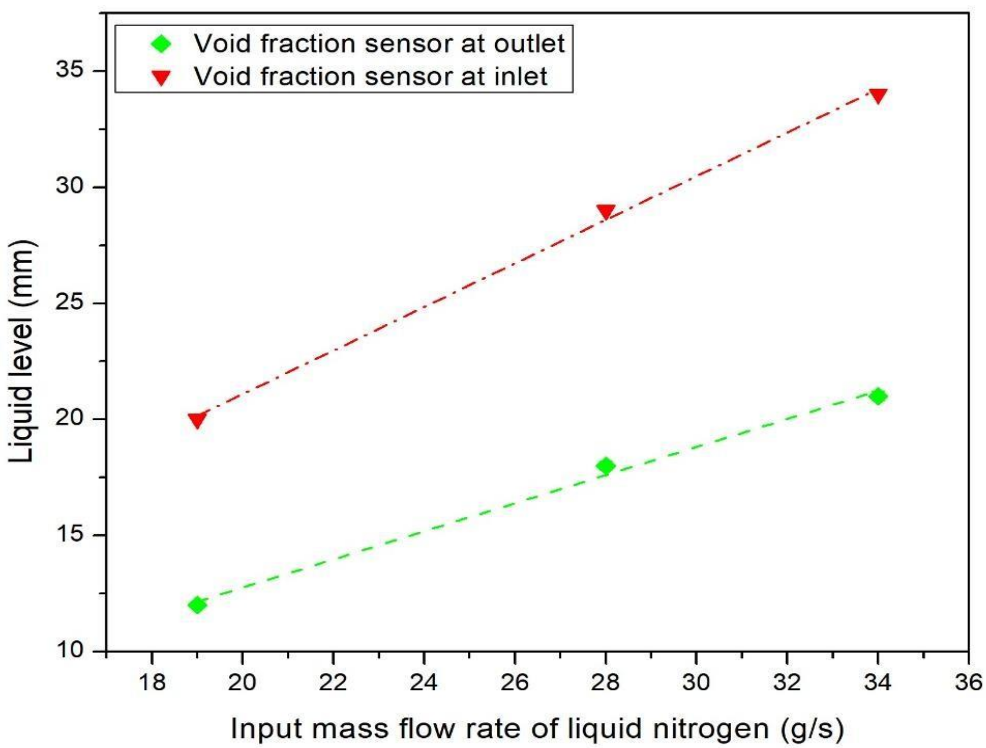

Fig.35 Experimental setup for evaluating the performance of the cryogenic flow meter.

The capacitance value obtained has been converted to liquid height data by using the principle of adding the capacitance provided by vapor and liquid together. The total height of the sensor electrodes are known and based on that total height the height of the liquid could be measured. Similarly the void fraction sensor at the exit section also shows increasing trend as the input mass flow rate from Dewar has been increased. As input mass flow rate is increased more layers of liquid enters the channel and therefore the liquid height at the entrance of the test section would be higher .As the number of liquid layer is increasing, the frictional resistance between the layers would be higher and hence a higher slope would be obtained. Therefore the variation in the slope at the interface could also be obtained from the void fraction sensor used with the cryogenic flow meter. The liquid height obtained from both the void fraction sensors has been represented in Fig.35

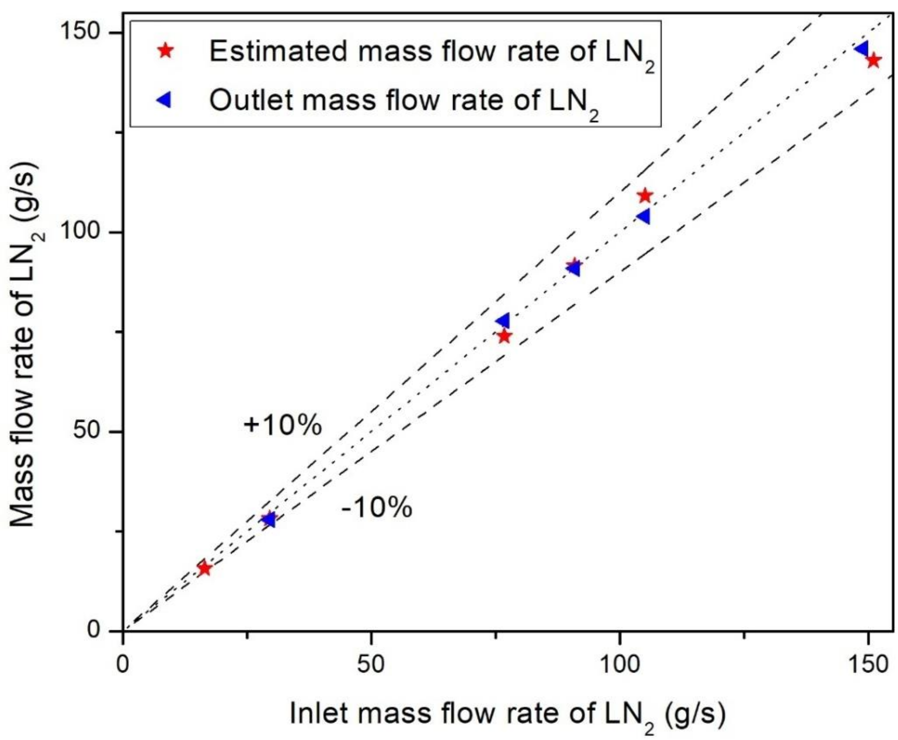

Fig.36 Comparison of measured mass flow rate with inlet flow condition for evaluating the performance of the cryogenic flow meter.

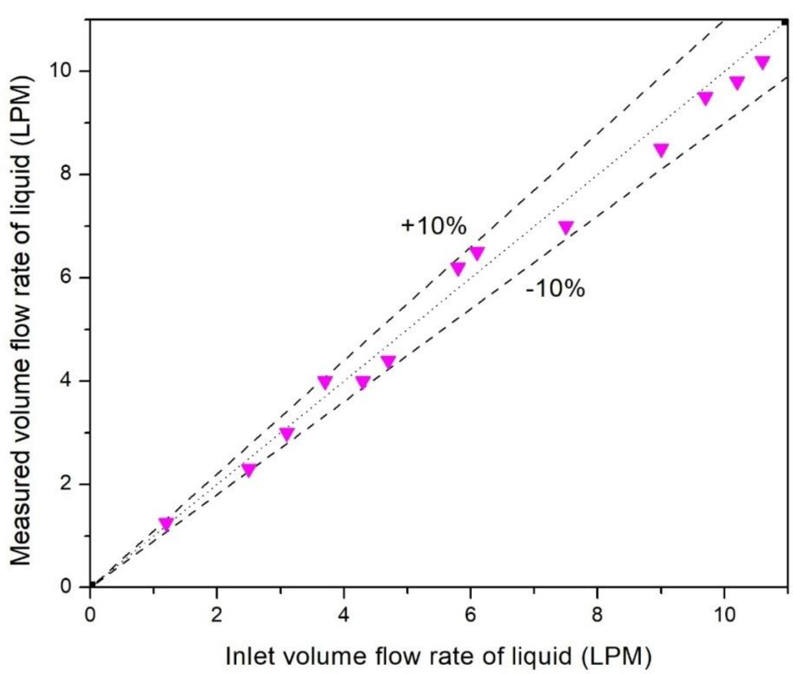

Fig. 37. Comparison of measured volume flow rate of liquid with inlet flow condition for evaluating the performance of the cryogenic flow meter.

Figures 36 and 37 represents the comparison of mass flow rate of liquid nitrogen determined from the correlation and also the outlet flow rate obtained by measuring the amount of liquid collected at the cryogenic container. The liquid height obtained from the capacitance at the inlet and the exit of the narrow rectangular channel has been used to estimate the mass flow rate of the liquid phase alone. The liquid height obtained would be the average liquid height in all the 15 narrow rectangular channels provided in the test section. Therefore the mass flow rate of liquid obtained would be the average mass flow rate of liquid in one channel. The estimated average mass flow rate obtained multiplied by the total number of channels would give the total mass flow rate of liquid nitrogen in the whole system. The total mass flow rate of the liquid is compared with both the mass flow rate at the inlet and exit section of the measurement system and it is found to have good agreement. The variation is well within ±5% and the maximum error encountered in the mass flow rate estimation was 3.41%. Since the measurement system works on the basis of laminar flow transition, the flow rate range that the flow meter could measure accurately depends on the number and the width of the narrow rectangular channel. The flow measurement system should be designed in such a way that the flow inside the channel would be strictly laminar for the proposed system to perform accurately.

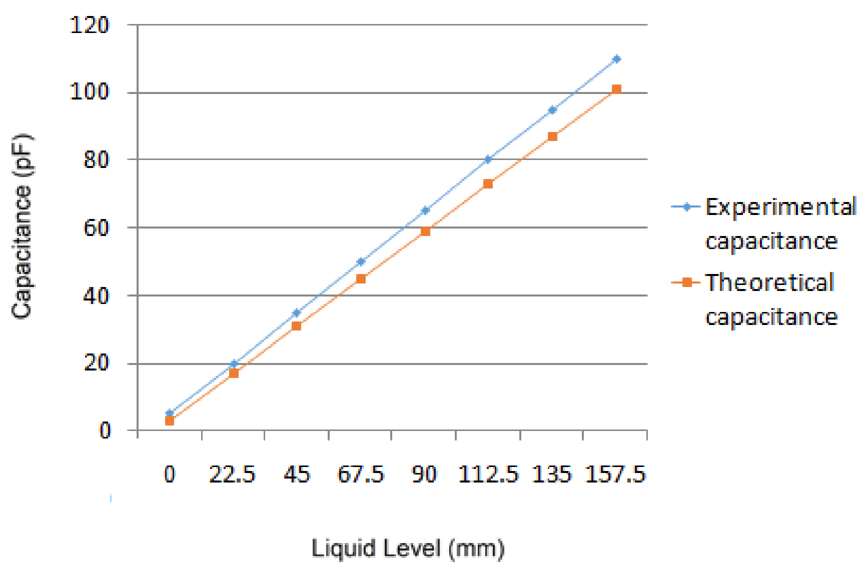

Fig 38 Experimental vs Theoretical Capacitance along Liquid level

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

1. Capacitance type flow meter for the two phase flow of the cryogenic fluids for stratified laminar flow conditions has been developed and the performances with liquid nitrogen have been verified.

2. Since the liquid phases are more viscous than the gaseous phases, LN_2 introduces more friction on the walls. Therefore, the wall shear stress increases with an increase in the velocity of LN_2. The wall shear is responsible for the development of pressure drop inside the channel.

3. The liquid nitrogen is flown through a rectangular narrow channel for its characterization. In all cases, a stratified flow is observed as it can be characterized by a separate gas-liquid region and a defined interface between the phases. The viscosity differences between both phases and the friction with the narrow channels trigger a negative slope downstream in the test sections of models.

4. The capacitance and liquid column height has a linear relationship with flow rate that makes the proposed concept absolutely feasible for a flow meter.

5. Void fraction sensor has been developed based on parallel plate capacitor configuration.
6. The effect of channel width was studied, and it is found that 1.5 mm is better than 2.00 mm in calculating the theoretical mass flow rate.

7. Void fraction sensor has been developed based on parallel plate capacitor configuration. It is worth notable that the liquid data shows considerable agreement within ±5%. Therefore both the void fraction sensors could be reliable indicator of the mass flow rate of the liquid phase.

8. The developed capacitance based flow meter has been tested with liquid nitrogen flow ranging from 0 to 10 litres/min along with void fraction measurements using the LN_2 supply from the pressurized liquid nitrogen storage dewar of 230 litre capacity.

CHAPTER 7

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