STUDY OF FLOW AND CONTROL OF GAS MIXTURE FOR THE RESISTIVE PLATE CHAMBER (RPC) PERFORMANCE IN CLOSED LOOP SYSTEM

A THESIS SUBMITTED FOR FULFILMENT OF THE REQUIREMENTS
FOR THE DEGREE OF

Doctor of Philosophy

By

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CERTIFICATE

This is to certify that the thesis entitled "STUDY OF FLOW AND CONTROL OF GAS MIXTURE FOR THE RESISTIVE PLATE CHAMBER (RPC) PERFORMANCE IN A CLOSED LOOP SYSTEM" is a bonafide record of research work carried out by **Shri. Kalmani Suresh. D**, under my supervision and guidance in the Department of Applied Electronics, Gulbarga University, Kalaburagi - 585106, Karnataka, India. The results embodied in this thesis or parts of it have not been presented for any other degree.

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Declaration

I hereby declare that, the research work presented in the thesis entitled "STUDY OF FLOW AND CONTROL OF GAS MIXTURE FOR THE RESISTIVE PLATE CHAMBER (RPC) PERFORMANCE IN CLOSED LOOP SYSTEM" has been carried out by me, under the supervision of **Dr. P. V. Hunagund**, Professor, Department of Applied Electronics, Gulbarga University, Kalaburagi for the award of the degree of Doctor of Philosophy.

Further, the results presented in this thesis have not been submitted in any University or Institute for the award of any other degree.

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Place: Kalaburagi (Research student)

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I declare that this written submission represents our ideas in my own words and where others' ideas or words have been included, I have adequately cited and referenced the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea/data/fact/source in my submission. I understand that any violation of the above will be cause for disciplinary action by the Institute / University and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been taken when needed.

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Kalmani Suresh Devendrappa

Preface

The India-based Neutrino Observatory (INO) collaboration plans to construct a large 50 K ton magnetized Iron tracking CALorimeters (ICAL) in the Bodhi hills, in the state of Tamil Nadu in an underground cavern. The key goal of this observatory is to detect, identify and evaluate the properties of omnipresent cosmic particles called *Neutrinos*. This giant particle experiment will use active large number (28,800) of gas based detectors called as Resistive Plate Chamber (RPC) of size (1.85 × 1.9) m^2 each, filled with gas mixture media within which all action takes place during an event. The performance of the calorimeter relates to performance of individual detectors and includes parameters such as efficiency of detection, sensitivity of measurement, operational life of the individual detector. The other peripheral requirements like gas consumption, pollution caused by gas leaks and the DAQ system are of prime importance and are, in a way, connected with the overall performance.

The numbers of RPCs in the ICAL experiment are 28,800; each has 128 channels (64 X-side and 64 Y-side) readout. Therefore DAQ has to process about 3.7 million channels on the arrival of predefined trigger criteria.

The total quantity of mixed gas in the ICAL calorimeter RPCs is about 200 M^3. The RPC use a gas mixture consisting of R134a ($C_2H_2F_4$), I-butane (iC_4H_{10}) and Sulphur Hexafluoride (SF_6) in ratio of 95:4.5:0.5 respectively and the mixed gas is a non–flammable and are relative expensive. To maintain the detector performance and efficiency, the gas mixture is required to flow through the RPCs continuously, maintains the composition of the gas mixture and applied HV as per the characteristics of each RPC. *The flow rate parameter is to be optimized for a proto-type detector taking into the RPC performance tests.* As the number of RPCs are large in number, letting the gas into atmosphere will contributes significantly to pollution and global warming and moreover the gas is expensive therefore it is mandatory to reuse the gas in the closed loop mode. In addition there will be logistic problems of taking this huge quantity of gas in and out of the underground experiment (cavern below 1 KM approximately).

A proto-type, PLC (Programmable Logic Controller –Siemens make) based Closed Loop gas recirculation System (CLS) is designed, which supports 12 RPCs stack of size (1.85 × 1.9) m^2 each. This system is in operation for the last 4.5 years and several factor related to the changes in the periodic atmospheric pressure changes are addressed and the system is successfully functioning satisfactorily.

The performance of the RPCs depend on environmental conditions (such as atmospheric pressure, ambient temperature, humidity), flow rate of gas mixture into the RPCs, quality of gas , the RPC input gas pressure, uniform resistivity of conductive coating on one surface of each glass, gap thickness etc. The purity of gas studies indicates a correlation between RPC performance and the quality of the gas mixture. The current drawn by the chambers can rapidly rise if the amounts of pollutants in the gas mixture increase due to poor gas quality. Also in reusing the gas in the CLS, there are several challenges that need to be addressed like pressure at the input of the RPCs in loop, gas purity, maintaining the gas composition, type of purifiers etc. In the present case an RGA300 (Residual Gas Analyzer-SRS make), a small scale mass spectrometer is connected in the closed loop gas recirculation system in the loop to continuous monitor the gas coming out of the RPCs for the moisture content, composition of the gas mixture, O_2 level in the mixture etc. The appropriate mixtures of the molecular sieves (13x, $5A^0$) are used in the purifier section in the CLS to remove and purify the impurities like the moisture, O_2 etc. The removal of N_2 is not known and remains to be unsolved. But, optimizing the leaks (air entering inside) in the CLS loop improves the performance.

The flow rate of the gas mixture into the RPC is a very important parameter. In the initial design stage design of CLS, the flow of few Standard Liters Per Minute (SLPM) was assumed and due to which several glass RPCs were damaged in the testing stage. The back ground rate for INO-ICAL is low by a factor compared to the accelerator or the surface experiments. The ICAL RPCs use glass as electrode. Therefore, a flow rate of few SCCM (Standard Cubic Centimeters per Minute) is good enough. The flow rate is one of parameter that is addressed by simulation and by performing experiments using different types of flow resistors namely the capillaries. The pressure at the input of the RPC is studied in detail, understood and is a precisely measured parameter. The tested pressure is 5 mbar and break down test value is ~12 mbar. The optimum safe operational value decided is *(2 to 3)* mbar for safe operation of an RPC chamber. The laboratories, where the RPCs are tested are temperature and humidity controlled and not pressure controlled. There is period atmospheric pressure variation in the laboratory and due to which several RPCs were damaged (buttons holding the glasses were popped up). This issue was resolved by using an external pressure sensor to correct and set the required input pressure. During a 24 hour cycle the atmospheric pressure oscillates twice about its mean value by nearly 3 mbar pressure. The pressure inside RPC detector has to follow the outside pressure to remain within specified safe pressure difference.

To control the flow of gas, the division technique using a capillary is employed to distribute gas mixture in equal quantities to each detector. The capillary is a micro bore tubular device having a large ratio of surface area to cross section area. The drag effect of inner surface of micro-bore on each component of gas as a function of concentration (partial pressure), molecular weight, density and total velocity are very important for dynamic equilibrium of gas concentrations. This device is studied in detail for material, surface finish, length of capillary, radius of curvature of flow path and bore diameter,. The feasibility of miniaturization of capillary structure within RPC assembly and without adversely affecting the uniformity of gas mixture is studied.

To summarize, a flow rate of 6 SCCM (corresponds to about 1 volume change of gas inside an RPC) with input pressure of (2 to 3) mbar and having a flow control using capillary (as flow resistor) is ideal for ICAL glass RPCs without deteriorating the performance.

The entire research work is divided into the six chapters.

Chapter 1 begins with a brief note on INO-ICAL experiment; the aim of the experiment with physics goals (measure precisely the mass of neutrino etc.) is presented. The INO ICAL experiment details are tabulated. The glass RPC construction, working principle, types and classifications, modes of operation and their applications are briefly mentioned. The gases used for the operation of RPCs are given.

Chapter 2 is devoted to the review of literature survey on RPC since invention, types of RPCs, their performances, aging issues etc. The types of gas systems used worldwide and the in-depth work done so far related to flow and control of gas mixture for the RPC performance in a closed loop system is summarized in tabular form and the objectives of the thesis is justified.

Chapter 3 discusses the entire research and development done on the thesis subject and parameters related to the RPC performance in a closed loop gas systems. We do not have much expertise in our country in building the specialized gas mixing and purification systems. Hence, the conceptual and block design parameters are chosen from the CERN gas systems documents. But the overall control parameters and the designs of the system using PLCs is indigenized and a proto-type closed loop system that supports 12 RPCs in feedback of gas mixture loop is developed and tested for parameters like flow rate, pressure and purity of gas.

The design and development work of the two types of gas systems namely, the Open Loop gas System (OLS) and Closed Loop recirculation System (CLS), including the problems and challenges which were overcome during the course of this work are described in detail. The types of purifiers used are explained in detailed and those which are readily available and being used else were, are mentioned. The gas analysis studies that are done using RGA analysis for the gas coming out of the RPCs in the loop are reported.

Chapter 4 deals with work done to justify the study of flow and control of gas mixture for the Resistive Plate Chamber (RPC) performance when connected in a closed loop system. Simulations for the flow and gas distribution inside an RPC on different platforms are presented. The experiment setup using different types of capillary for flow control is explored and described in detail.

Chapter 5 gives details of the results related to validation of CLS operation, long term stability and ageing effects studies performed using RPCs in OES and CLS.

Chapter 6 is dedicated to summary, conclusions and remarks of the research work done.

The list of references made for the research work has been put at the end of the chapter. The list of publications of the author, references made and possible upgrade and modifications for flow control in a CLS are given at the end of the thesis.

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LIST OF ABBREVIATION NOTATION AND NOMENCLATURE

µ	Micro
µm	micro-meter
abs	absolute pressure
AL 01	RPC with label as AL # 01
AL 02	RPC with label as AL # 02
CERN	European Organization for Nuclear Research, Geneva
CLS	Closed Loop System
CSC	Cathode Strip Chambers
DAQ	Data Acquisition system.
DFT	Dry Film Thickness
FC	Femto Coulomb
I-butane	Isobutane gas
ID	Inner Diameter
K ton	Kilo ton
L1, L2. ..	Layer 1, Layer 2. ..
LHC	Large Hadron Collider
m/s	meters per second
MDT	MIP Timing Detector (MTD)
MFC-6	Mass Flow Controller with label assigned as 6
mm WC	millimetre of Water Column
mm	millimetre
mV	milli-Volts
nA	Nano- Amperes
nS	Nano Seconds
OD	Outer Diameter
OES	Open Ended System
OLS	Open Loop recirculation System
P.s	Pascal-second
pC	Pico Column
ppm	Parts Per Million
pS	Pico Seconds
R134a	$C_2H_2F_4$ (1,1,1,2 tetraflouro ethane)
SCCM	Standard Cubic Centimetres per Minute
TGC	Thin Gap Chamber (TGC)
X-side	X-side read out strip
Y-side	Y-side read out strip

Chapter 1

Introduction

The elementary particle called "Neutrino" was first proposed by Wolfgang Pauli in 1930, to explain the continuous energy spectrum in beta decay. It was found in an experiment by Clyde Cowan and Frederick Reines in 1956 (Reines got the Nobel prize in physics for this work in 1995). Ever since then the research activity in this area has grown especially so in the last 15 years. This was facilitated by very important developments in particle detectors and associated instrumentation. The research on the neutrino studies has led to several Nobel prizes. There are large numbers of experiments being carried across the world to study the little known neutrino properties.

1.1 Introduction to Neutrino

The neutrino is tiny sub-atomic particle with zero electric charge. Neutrinos are the second most abundant particles in the universe, next to photons. They have a tiny mass ~ 100 m eV or about a million times smaller than an electron. In the universe there are about 300 neutrinos in every cubic centimetre. These were created during the big bang, and are also continuously produced in the Sun (about 65 billion every second passing through every square centimetre of earth), natural radioactive decays. Manmade neutrinos are produced through particle accelerators and in nuclear reactors. Neutrinos are extremely difficult to detect as they interact very weekly with matter.

There are three flavours of neutrinos and are known as electron neutrino, Muon neutrino and tau neutrino and are named after the type of particle that arises when a neutrino undergoes a charged current interaction with a nucleus or an electron. The phenomenon of changing of flavour as it propagates is known as “Neutrino Oscillation”.

The Neutrinos were produced extensively in the Big Bang and depending on their mass, can have a significant influence on how the universe evolves. Neutrinos are an essential part of the production of all the elements heavier than the iron in collapsing stars called supernovae. The Sun, which is one of the 400 billion stars in the Milky Way galaxy, is also a strong source of neutrinos of about 60 billion per square cm per second. The neutrinos which weakly interact with matter are detected through their interactions with the nucleus or electrons. The cross section of neutrino-nucleus interaction is of the order of 10–42 cm^2 making it difficult, though not impossible, to detect them. The neutrinos have zero mass in the Standard Model (SM) of particle physics and do not change their type or flavour. The Super Kamiokande group and the heavy water detector at Sudbury Neutrino Observatory (SNO) have found evidence for neutrino oscillation in measurements of atmospheric neutrino and solar neutrinos, respectively. Another consequence of these experiments is that neutrinos have a non-zero mass and that they violate flavour conservation. Thus neutrinos serve as a window to study physics beyond the Standard Model.

India was a pioneer in the field of neutrino physics, conducting experiments in the underground laboratories at Kolar Gold Fields. The first reported evidence on the existence of atmospheric neutrinos, produced by cosmic rays hitting the upper atmosphere, was observed about 50 years ago in the Kolar Gold Fields at a depth of 7600 feet. In the Standard Model of particle physics neutrinos belong to the family of leptons.

Cosmic rays enter the atmosphere (upper layer) and interact with oxygen and nitrogen nuclei in the air and produce $\pi\pm$ which decays to $\mu\pm$ which also decays. These decays of pion and Muon generates approximately two $\nu\mu$ (Muon neutrino) and one νe (electron neutrino). The cosmic ray shower is shown in Figure 1.1. The average energy of neutrino $E\nu$ ~ few GeV and the neutrino flux $\Phi(\nu) \sim 104\ m^{-2}\ sec^{-1.}$

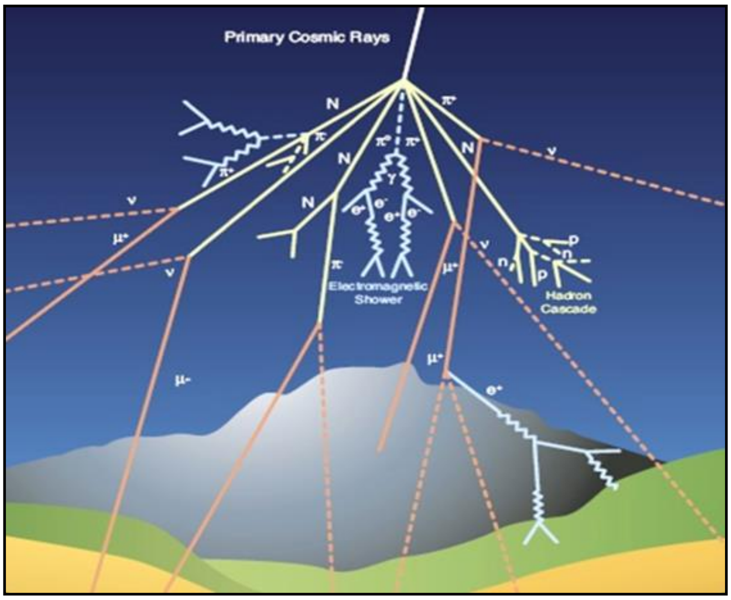

Figure 1.1: Primary cosmic ray shower

1.2 India based Neutrino Observatory

The India-Based Neutrino Observatory (INO) [1], [2] is an upcoming mega science project to study the properties of neutrinos and is an approved project by the Government of India under the research program of the Department of Atomic Energy [3]. The plan is to build a world class underground laboratory in the Bodi hills in Tamil Nadu, India. As neutrinos are weakly interacting particles it is necessary to have large mass and shield the detector to filter out all other particles interacting which are abundant. The experimental site is shown in Figure 1.2. Collaboration has been formed consisting of various institutes which have expertise in detectors, electronics, magnets, simulations etc. The proposed INO project primarily aims to study atmospheric neutrinos, namely to identify the mass ordering of the 3 neutrino mass Eigen states, in a 1,300-m deep cavern. The INO will have large magnetized iron (1.5 Tesla) as target mass (50 k ton phase I and will be 100 k ton in phase II), good tracking and energy resolution (tracking calorimeter), good directionality using the fast timing of ~ nS time resolution and charge identification.

The active detector elements will be the Resistive Plate Chamber (RPC). In the phase I, the proposed ICAL detector will have 3 modules and each module will be of size (16 × 16 × 15) m3, consisting of a stack of 151 layers with ~ 5.3 cm thick iron plates interleaved with Resistive Plate Chamber (RPC) detector layers. The conceptual design of ICAL detector is shown in Figure 1.3 and Figure 1.4 shows the RPC layout in the detector. In the phase I, a total of about 28,800 RPCs of dimension of about (2 × 2) m2 will be used for this experiment and details of ICAL are summarised in Table 1.1. The Data Acquisition (DAQ) is a VME based system and the block diagram is presented in Figure 1.5.The details of which are given in [4].

The results of one of the RPCs with continuous long term Muon tracks and image of an RPC with the actual Muons in a 12 layer stack of RPCs and is shown in Figure 1.6.

INO-ICAL is an atmospheric neutrino experiment and can be used to probe physics beyond the Standard Model. The atmospheric neutrinos in the energy range of (5 to 10) GeV is sensitive to matter effects modifying the neutrino oscillation in free space. As a result the ICAL experiment is sensitive to the ordering of the masses of the three mass states of neutrinos [5]. The other experiments in the INO cavern namely study of Dark Matter and Neutrino-less Double Beta Decay, are also in the R&D stage and will be set up in the underground laboratories of INO.

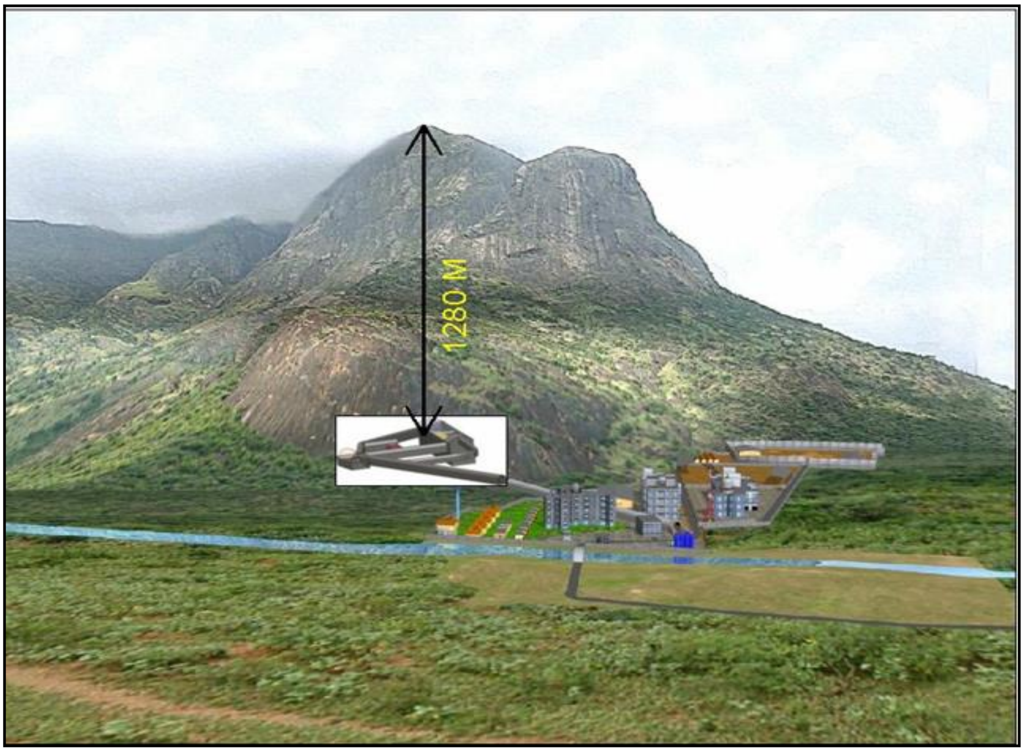

Figure 1.2 : INO ICAL site at Bhodi Hills

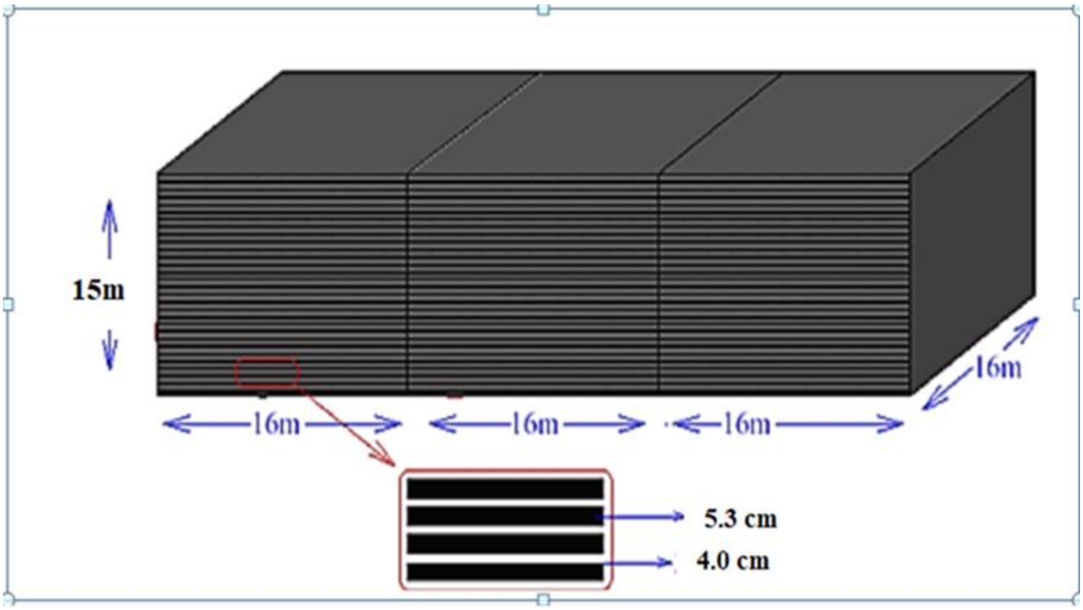

Figure 1.3: INO-ICAL Detector

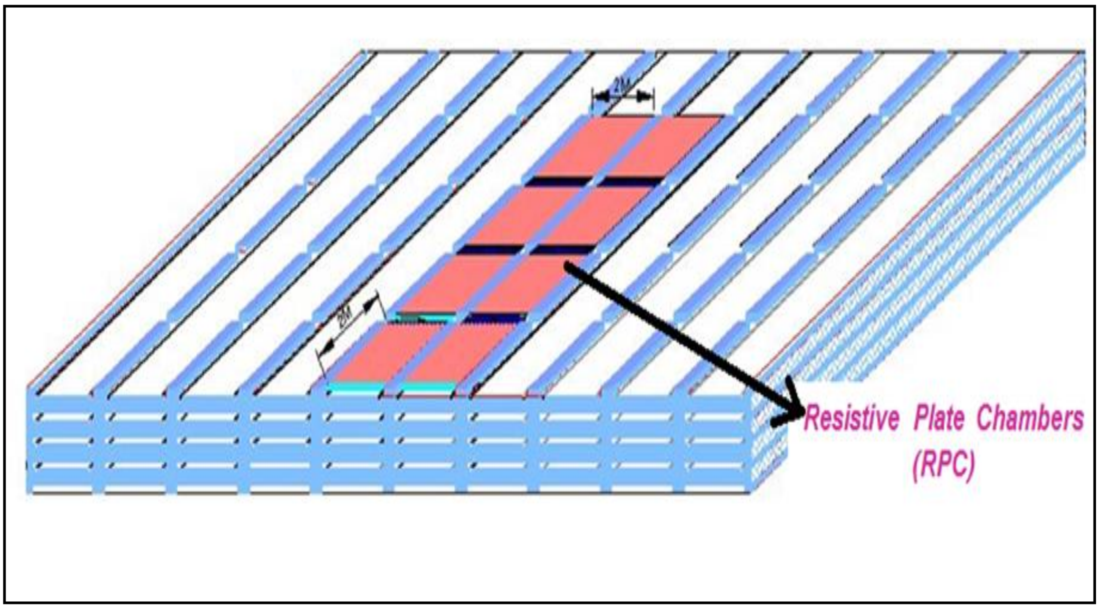

Figure 1.4: ICAL showing RPCs one road on one side

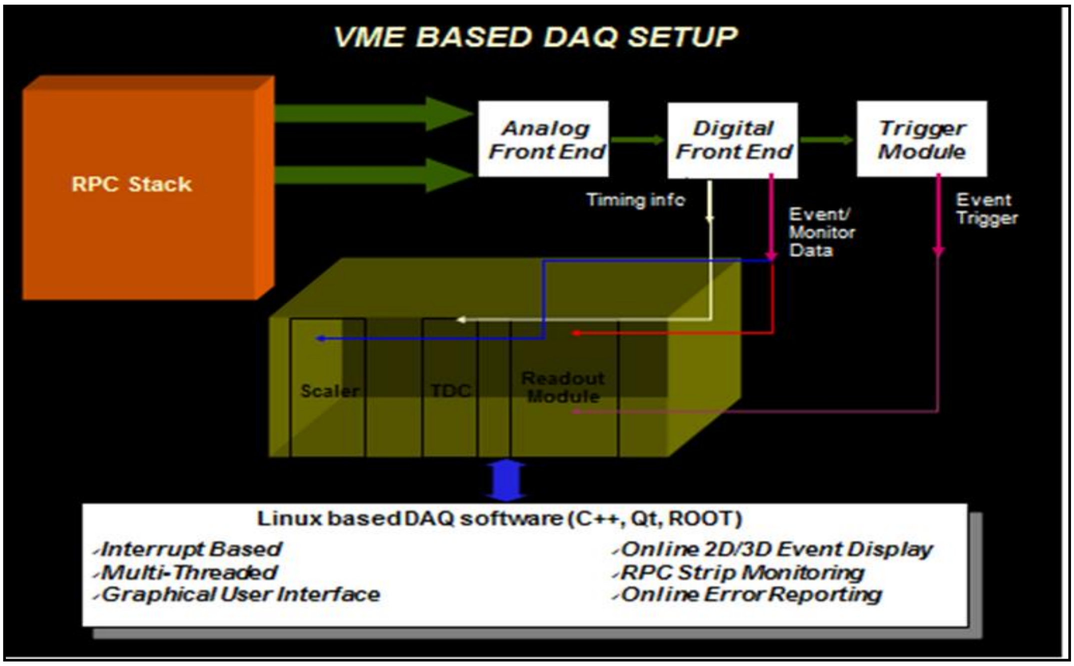

Figure 1.5: Block design of DAQ for ICAL

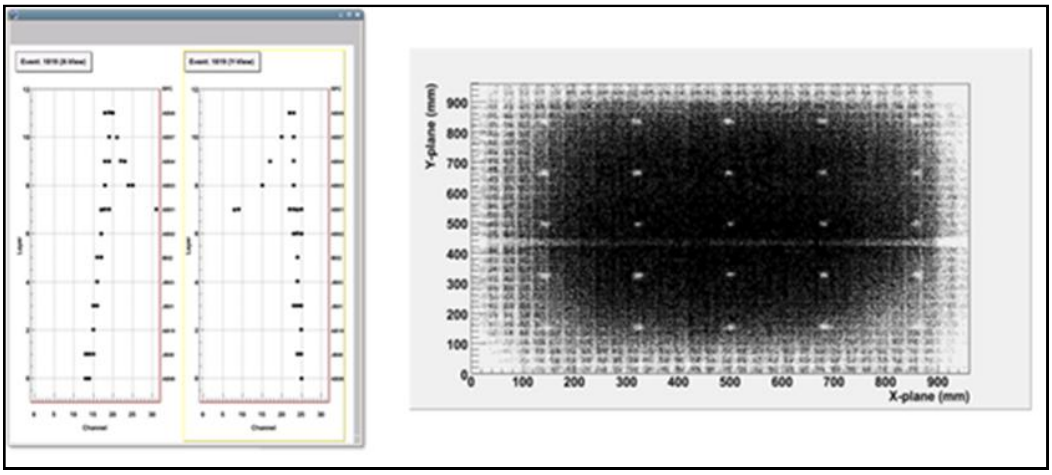

Figure 1.6 : Muon tracks and image of an RPC with Muons

Table 1.1 : INO ICAL at a glance

No. of modules	3
Module dimensions	16 m × 16 m × 14.45 m
Detector dimensions	48 m × 16 m × 14.45 m
No. of Layers	150
No. of Iron plate Layers	151
Iron thickness	5.6 cm
Gap for RPC	40 mm
Magnetic Field	~ 1.3 Tesla
RPC dimensions	1.845 m × 1.740 m
Read out strip width	3 cm
No. of RPC/Road/Layer	8
No. of Road/Layer/Module	8
No. of RPC units / Layer/Module	64
Total No. of RPCs	28,800
No. of read out channels	3.7×10^{6}

The development of RPC detectors, electronics, gas systems, the required magnetic field etc. are in the final stage due to the dedicated effort by the collaborating institution and universities.

1.3 RPC (Resistive Plate Chamber)

The RPC [6], is a gaseous ionization detector for particle physics characterized by high detection efficiency (97-98%), a very good time resolution (1.5-2 ns), a good spatial resolution (~1 cm) [7] and good reliability. It's compactness along with an industrial-supported production makes it an ideal instrument for fast response application like Muon trigger in many large experiments in involving large surface area cover [8].

1.3.1 Basic Construction of RPC

A typical view of an RPC built with a 2 mm thick float glass is shown Figure 1.7. It consists of two components, one is gas-gap and the other is signal readout panel. The gas gap of 2 mm is formed by using two glass plates having coated high resistivity on the outer surface, separated by small spacers (buttons) usually 2mm. The gas nozzles have been used to flush gas through the tiny gap. In order to apply high voltage on each plate, a resistive coating having surface resistance of about 1M ohm/square is applied [9], [10], [11], [12]. The resistance value depends on the specific application of the experiment where the RPCs are used. The tool used to measure the resistance coated on the glass is shown in Figure 1.8.The read out panels are used to collect traces of particles from gas gap, which act like transmission lines. The concept is similar to that of a capacitor.

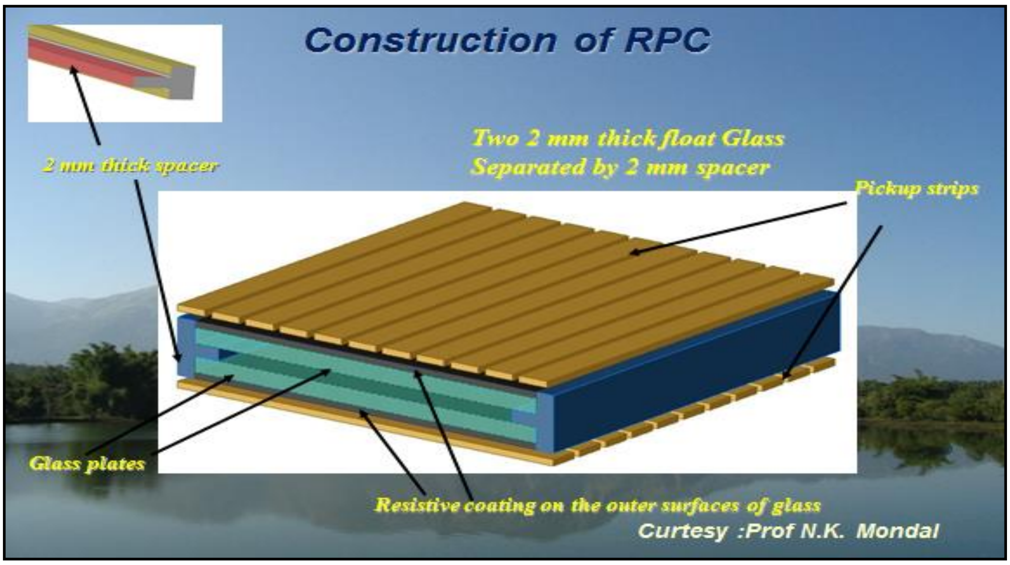

Figure 1.7: Typical RPC with pickup panels

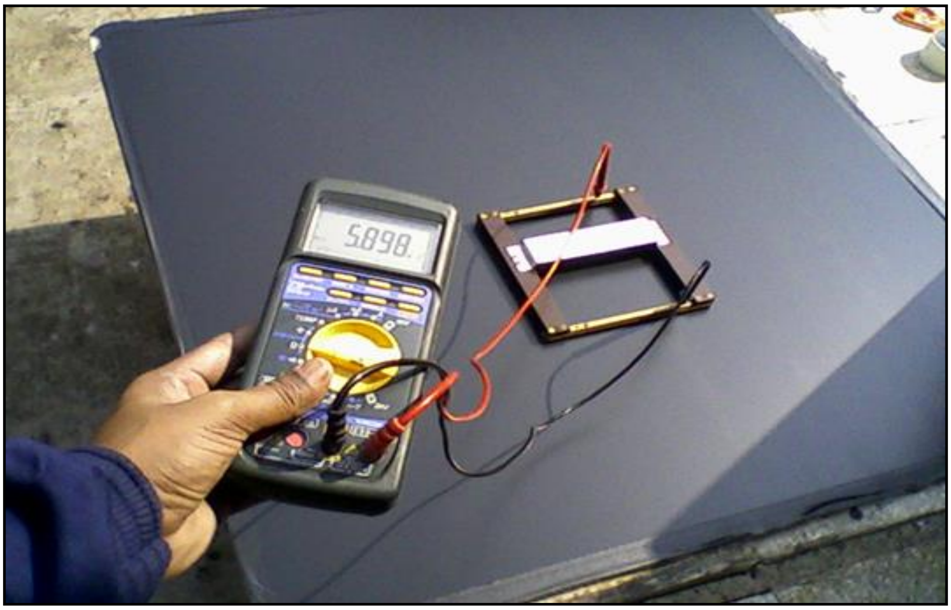

Figure 1.8: Zig to measures conductive surface resistance

1.3.2 Working principle of RPCs

The gaseous ionization detector consists of a gas gap bounded on both sides by two parallel electrodes made of commercially available float glass. The outer surface of the two glass plates are applied with a high voltage (about 10 kV) and the current drawn is of the order of few tens of nA depending on the size of the RPC. When a sufficiently energetic radiation passes through the chamber, it ionizes the gas molecules and produces a certain number of electron-ion pairs. The number (mean) of electron-ion pairs created is proportional to the energy deposited on the chamber. With the application of electric field, the electrons are drawn towards the anode and the ions are drawn towards the cathode and the charge gets collected. If an intense electric field is applied, further ionisations are produced by the primary electrons. The electrons produced in secondary ionisations are further accelerated to produce more ionisations and so on. This chain of ionizations causes a distribution of free charge in the gas having a characteristic shape of an avalanche. The recombination of electron-ion occurs, thus liberating photons, which can also initiate secondary ionisations. When series of several secondary avalanches are formed, a large amount of free charge is formed within the gas creating a streamer pulse. Then, these growing numbers of charges propagate within the gas inducing a signal in the read-out electrodes. The type of the gas mixture used plays a vital role in determining either the chamber is working in the avalanche regime or the streamer regime [13].

If n_0 primary electrons accelerated by electric field and x is the distance between anode and point of interaction then no of electrons that reaches the anode (n) is given by equation,

$$n = n_0 e^{\eta x} \text{------------ (1.1)}$$

where,

$$\eta = \alpha - \beta \quad \text{--------------(1.2)}$$

"α" is first Townsend Coefficient which represents number of ionisations per unit length and *β* is attachment coefficient which represent number of electrons that are captured by gas per unit length. The gain factor (*M*) of RPC which decides the mode of operation is defined as

$$M = \frac{n}{n0} \text{---------------------(1.3)}$$

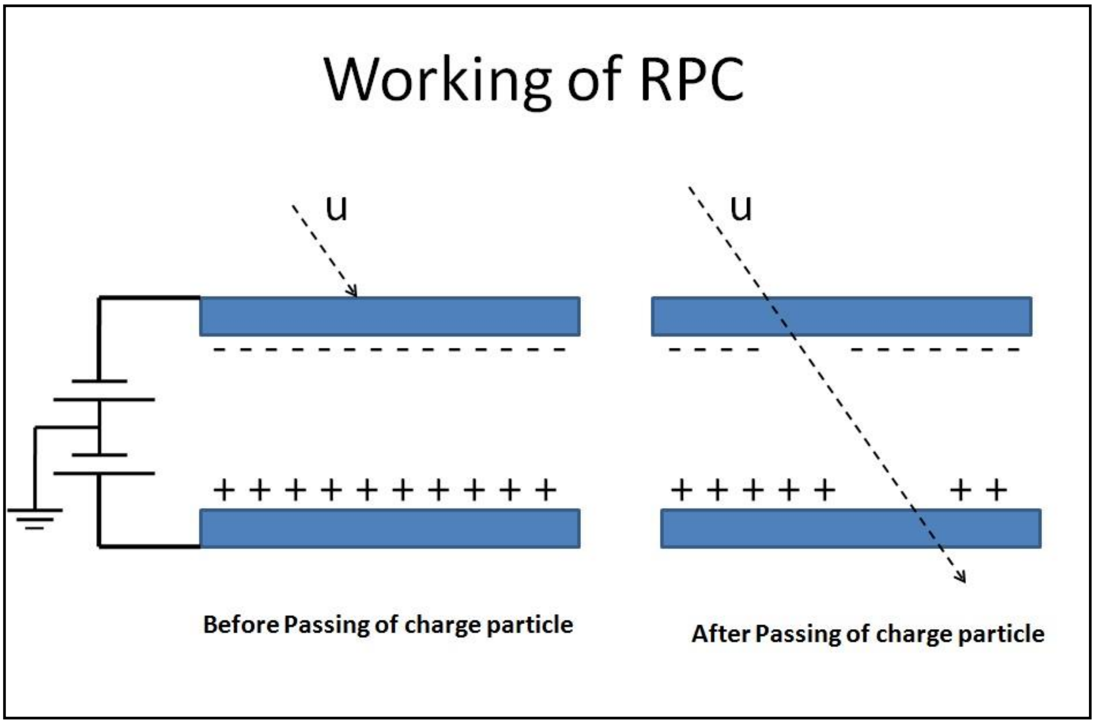

Figure 1.9: RPC showing ionisation before and after passage of charge particle

If *M* is greater than 10^8, the probability of streamer formation is more giving rise to streamer mode of operation of the RPC, while *M* less than 10^8 settles the RPC with avalanche mode of operation. The charge particle before and after passing in the detector is shown in Figure 1.9 . Discharge is localized to about 0.1 mm^2 area and it takes about 2 second to recharge the dead area of detector. Thus each discharge locally deadens the glass RPC and the recovery time called dead time (τ) can be calculated as follows.

τ = RC, where R is the resistance of the glass plate given by (ρ l /A), C is the capacitance of the RPC given by ($k\varepsilon_0$ A/d)

where $\rho = 5 \times 10^{12}$ Ω-cm, l = 2m, A = 2 m^2, k = 4 and $\varepsilon_0 = 8.854 \times 10^{-12}$ F/m and d = 2 mm. Then τ = ~2 seconds of dead time.

1.3.3 Types of RPCs

There are various types of RPC [14],[15],[16] and these are classified based on the material of electrode, number of inter electrode gaps and their application.

1.3.4 Classification of RPCs based on material of Electrode

Bakelite RPCs: The Resistive plates or the electrodes are made of Bakelite, coated with linseed oil from inside and with conductive coats at the outer surface. These resistances are of few Mega ohms per square. The typical gas mixture used is 95.2-96.2% of R134a [$C_2H_2F_4$], 3.5 % to 4.5% of I-butane (C_4H_{10}) and 0.3% Sulphur hexafluoride (SF_6), with a 45% relative humidity. The water vapour is generally added to obtain a gas mixture with a relative humidity of 40–50%, which affects the resistivity of plate material. The Bakelite based, to improve efficiency at lower operating voltage and thus, avoid a degradation of RPC performance under high background conditions [17],[18] and [19].

Glass RPCs: The electrodes are made of float glass of typical thickness of 2 mm or 3 mm, coated with conductive coating at the outer surface with resistance of few Mega ohms per square. The gas volume is of 2 mm, with higher bulk resistivity and better time resolution than Bakelite. The mechanical stiffness and surface quality of glass electrode are superior to Bakelite [20]. Due to delicacy of glass, handling needs proper tools.

Hybrid RPCs: Combination of metallic and resistive electrodes is used to make hybrid RPCs. Precaution needs to be taken to avoid gas-gap confinement by metal-metal electrodes otherwise it will be "Parallel Plate Chamber (PPC) and will have violent discharge [21].

1.3.5 Classification of RPCs based on number of gas-gaps

Single gap RPC: It is basic original form of RPC which contains one gap formed with 2 electrodes. Usually the gap is 2 mm, so the required high voltage for operation will be under limit (about 10 KV). The current drawn is few nA.

Double gap RPC: It has two gaps. Double gap RPCs designed with larger number of electrode and read-out panels allows more variety in structures of RPCs. It improves the timing of detector.

Multi-gap RPCs: These RPCs are introduced in year 1996 [22].The most important feature of this design is inclusion of resistive plates electrically (floating electrodes) that divide the gas volume in to a number of individual gas gaps without the need of any conductive electrodes. It has time resolution about pS, but it requires higher voltage for operation.

1.3.6 Classification based on mode of operation

The RPCs can be operated in two modes namely the avalanche mode and the streamer mode, that differ in the mechanism in which signal is generated [23].

a.) **Avalanche mode:** The charged particles that are accelerated by the electric field, produces primary ions, which again produces secondary ionizations by collision with gas molecules. The electric field of this cluster of ionized particles is opposed by the external field and the multiplication process stops after sometime. These charges are then drifting towards the plates where from they are collected. The avalanche mode operates at a lower voltage and has less gain. Typical pulse amplitudes are of the order of few mV. In this mode, the RPCs Gain Factor (M) is below 10^8 and the secondary ionization is controlled by suitable gas mixture.

b.) **Streamer mode:** Here the secondary ionization continues to occur until there is a breakdown of the gas and a continuous discharge takes place as shown in Figure 1.10. This mode operates at a higher voltage and also results in high gain. Typical pulse amplitudes are of the order of 100-200 mV. As a result of secondary ionisation, the gain Factor (M) is more than 10^8 which gives streamer Pulses. The amplifier may not be needed for further processing the pulse information [24].

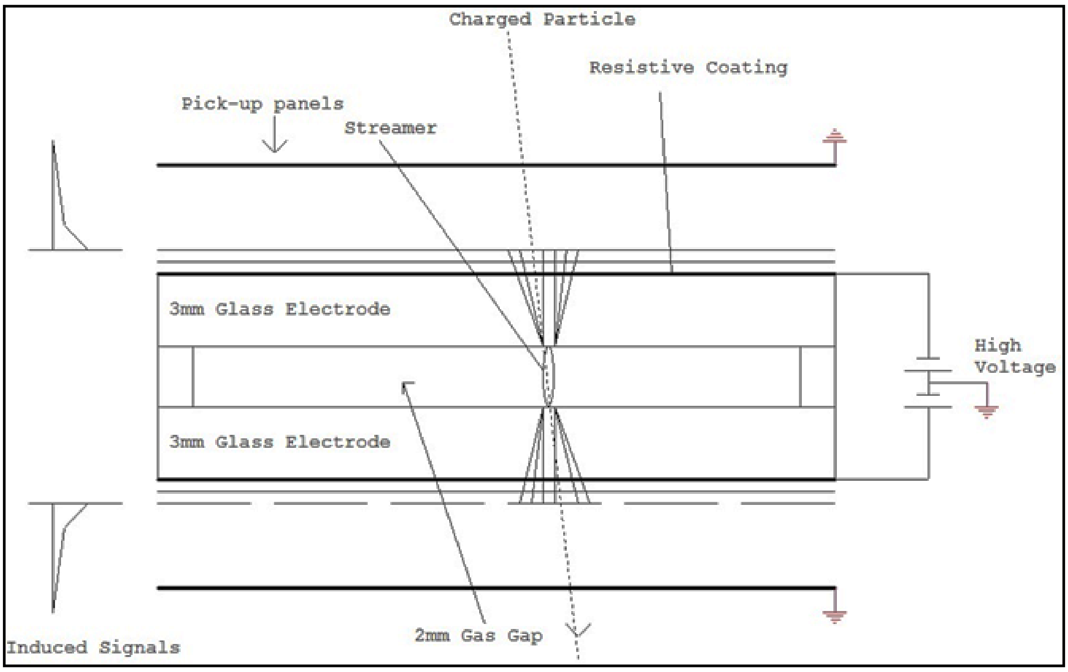

Figure 1.10: Formation of charge cluster in Streamer mode

The desired mode of operation decides the gas mixture inside an RPC. Originally the RPCs were operated in the streamer mode using Argon gas based mixture, the higher signal of few 100 pC (few tens of millivolt pulse) with high current. The streamer mode has poor rate capability of about 100 Hz/cm^2.

The avalanche mode uses Freon based mixture of gas, the signal is low with few pC (few millivolts) and low current of few n A. It also has high voltage drop at high particle rate so is useful in good rate capabilities (few kilo hertz's per centimetre square). The detector has aging issues in streamer mode and high counting rate (by an order of magnitude) applications has made avalanche mode popular than the streamer mode. It is possible to suppress the streamer formation by using quenching $C_2F_4H_2$ based gas mixtures with small quantity of SF_6. The broad comparison of Avalanche and Streamer mode is given in Table 1.2

Table 1.2: Differences between Avalanche mode and Streamer mode

Parameters	Avalanche mode	Streamer mode
Gas Composition (typical) $C_2H_2F_4$:C_2H_{10}:SF_6:Ar	95.2:4.5:0.3:0	62:8:0:30
Pulse Height	1-2 mV	More than 100mV
Charge	Few pC	About 100 pC
External Amplification	Required	Not Required
Plateau Region	9.6kV-10.5kV	8.8kV-9.6kV
Time Resolution	1 nS	1.5 nS
Stability	Long lasting	Early Aging Effect
Experiments	ATLAS, CMS, LHCB	L3, BABAR, BELLE, ARGO, OPERA, MONOLITH

The transitions from the avalanche to streamer in RPCs is studied in detail and documented by R.Cardarelli, R.Santonico et al [19]. The study was based on the direct inspection of the signal produced by the RPC. The data shows that the avalanche amplitude to be strongly dependent on the operating voltage value where the saturation occurs and streamer starts and the streamer is accompanied by a precursor pulse and according to their studies the high voltage must cause the variation of the streamer time position in two times more than in the avalanche case etc.

The measurements of avalanche size and position resolution with different resistance, avalanche to streamer transition etc. is given in [25] ,[26], [27] etc.

1.3.7 Timing RPCs

The timing RPCs were developed in late 1990's and have currently have reached a resolution of (50 to 60) picoseconds for an electrode areas ranging from about (10 to 1600) cm^2. The initial current grows exponentially in time, until the discriminating level is reached. The delay in time is independent from the position occupied by the initial charges in the gap, providing excellent timing [13]. The timing jitter dependents on the variation of the initial current (avalanche and cluster statistics) and inversely on the current growth rate is (a times *v*), where *a* is the First Townsend Coefficient and *v* is the electron drift velocity. The combination of metallic and resistive electrodes with signal-transparent semi-conductive layers, highly isolating layers and different kinds of pickup electrodes makes the RPCs with a rich variety of configurations, tuneable to a variety of requirements.

1.3.8 Trigger RPCs

In the Accelerator based experiment (CMS, ATLAS), several type of detectors (RPC, DFT, Scintillator based etc.) are employed and operation in the experiments. RPCs have an advantage of good time resolution and hence are used for triggering the events, based on certain criteria (which will also provide information on the presence and arrival time of charged particles). The RPCs used in ATLAS section of LHC are triggering RPCs and usage details are given in [21], [28], [29].

1.4 ICAL RPCs

The proposed INO-ICAL detector will be instrumented with 28,800 single gap RPCs. These RPCs are of (1.85 × 1.9) m^2 size, consists of two glass electrodes separated by 2 mm and use a gas mixture composition of R134a ($C_2H_2F_4$), I-butane (iC_4H_{10}) and sulphur hexafluoride (SF_6) in the ratio of 95.4 %, 4.5% and 0.1% respectively and are operated in *avalanche mode*. As the numbers of RPCs are large, the total gas required is of the order of about 200 m^3 and hence it is mandatory to use a Closed Loop Gas mixing System (CLS) to supply the gas into the detectors into reuse the gas coming out of the RPCs. The ICAL detailed gas requirement is shown in the Table 1.3.

Table 1.3: INO ICAL Gas requirement

No of Gas Channels/Road/Layer	2
No of Gas Channels/Layer/Module	16
No of Gas Channels/Module	2416
Total No. of Gas Channels	7248
Gas Volume /RPC/Layer	7.03 litre
Gas Volume /Layer	450 litre
Gas Volume/Module	67,500 litre
Total Gas Volume	2,02,500 litre

Each of these detectors will have 64 readout channels on X-side and similar number on the Y-side. Therefore, there will be about 3.7 million channels to be read and processed, based on criteria of trigger for neutrino studies. The RPC is a gaseous detector and its performance dependence on the quality of the gases and more over the number of these detectors are huge and considering the safety aspects, an automated CLS that will supply mixed gas and purify it after flowing through the RPC in a loop is designed, developed and is in operation for the last 5 years. The details of which are described latter.

The ICAL magnet provides target nucleons for neutrino interaction as well as it serves a medium in which secondary charge particles can be separated on the bases of their magnetic rigidity so that their momenta can be estimated. The magnetized iron calorimeter will use iron of low carbon iron (less than 0.1%) in order to have good magnetic characteristics and uniform magnetic field.

The INO ICAL design is modular so that future up-gradation is feasible and the detector readout system will have a time resolution of 1 nS and special resolution of about a 1 cm.

1.4.1 Brief construction of ICAL RPCs

INO RPCs use simple float glass as electrode having thickness of 3 mm, and area of about (2 × 2) m^2 in size with two big chamfering at two diagonally opposite corners (for electronics boards) and small chamfer at the other two corners. Usually cleaning of cut glasses is done with high purity ethyl alcohol solution and distilled water. Cleanliness is very important factor during fabrication which enhances performance of the operation of RPC. One surface of each glass is coated with conductive paint. Two methods of painting to get the required resistance on the glass surface are achieved, namely the spray painting and the screen printing. The glass surface is coated with a mask of 10mm around the edges.

In case of spray painting a special conductive paint has been developed by M/s Nerolac Kansai Paint (India) Limited [30].This paint uses 50% of slow drying thinner and the expected Wet Film Thickness of about 20µ. The second method is by screen printing using screen printing ink or called as carbon paste namely DC20 and DC1000M (which are 20 ohm and 1000 mega ohm pastes respectively) of Dozen make in the ratio of 1:5.5 used to achieve the required resistance of 1MΩ per square of surface resistance. The coated glasses are then cured at temperature of about 80-100 degree Celsius for few minutes. Two coated glasses are then used to form a "glass gas gap" (air leak tight), which will have electrodes that are separated by 72 polycarbonate buttons with a spacing of 20 mm and to maintain 2 mm gap over large area. Side spacers, big and small chamfers are used to seal the chambers. Four gas nozzles are used for gas inlet and outlet. The Epoxy of 3M make (DP190-grey) is used for gluing chambers. After leak test, these gaps are made available for assembly of RPC. The detailed poly carbonate components used to fabricate an RPC are shown in Figure 1.11.

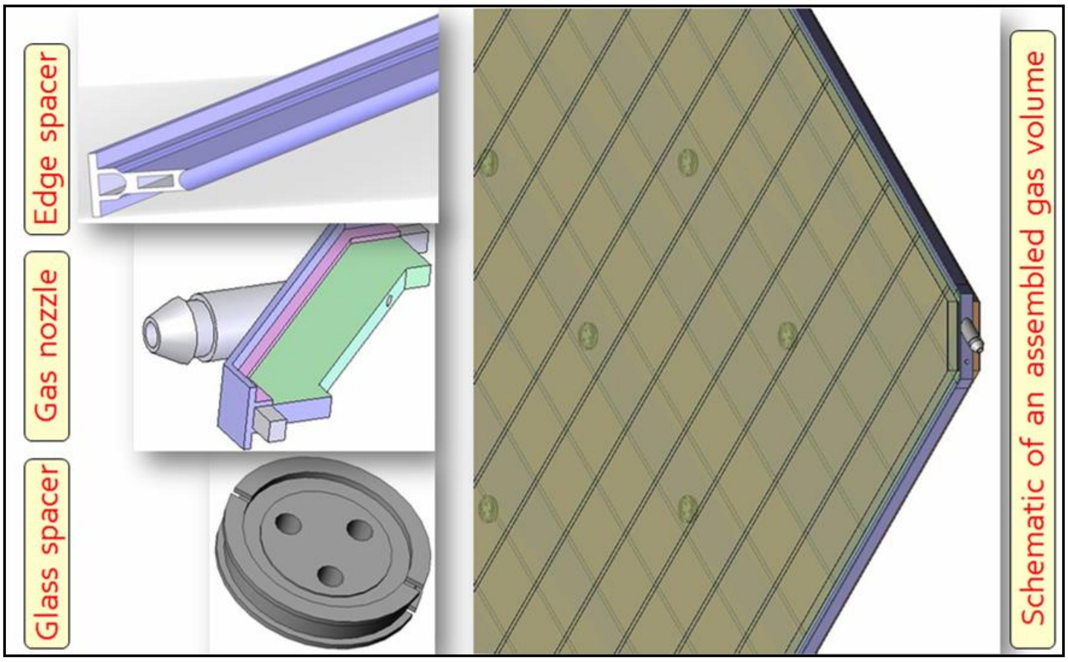

Figure 1.11: Polycarbonate components of a glass RPC

1.4.2 V-I characteristics of RPCs

A V-I characteristics study for a typical RPC is plotted and shown in Figure 1.12. It has been done to find Ohmic and discharge region of operation of this RPCs. The voltage is gradually increased and corresponding leakage current is noted down. The V-I shows that at lower voltage contribution due to leakage current through spacers is more. As the high voltages increases the gas volume contributes more in leakage current. It takes about (5 to 6) days to stabilise the current drawn by the chamber and the observed time is shown in Figure 1.13 for a typical RPC.

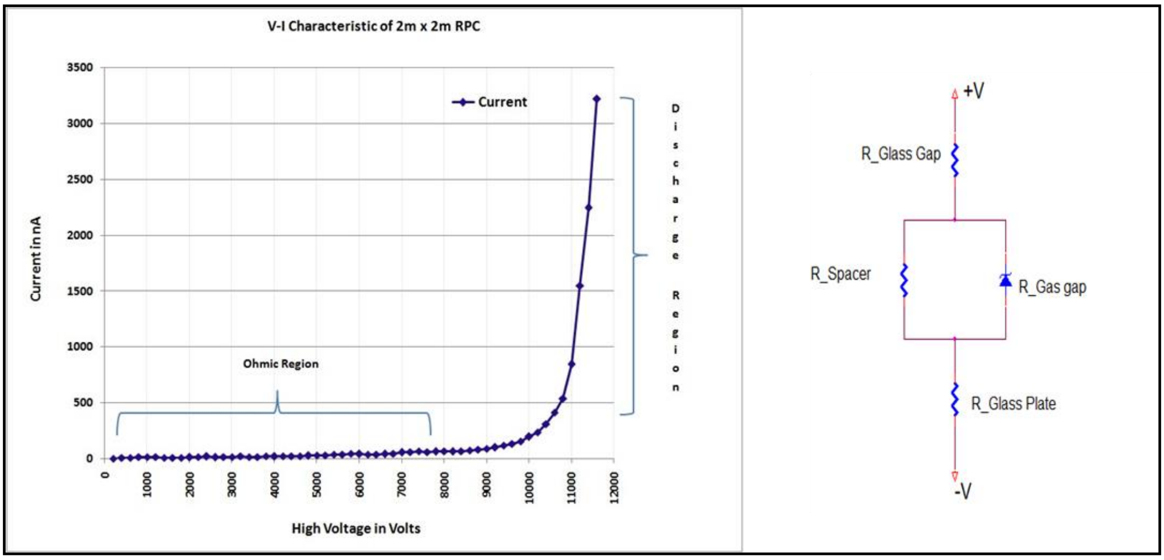

Figure 1.12: RPC V-I behaviour and equivalent electrical model

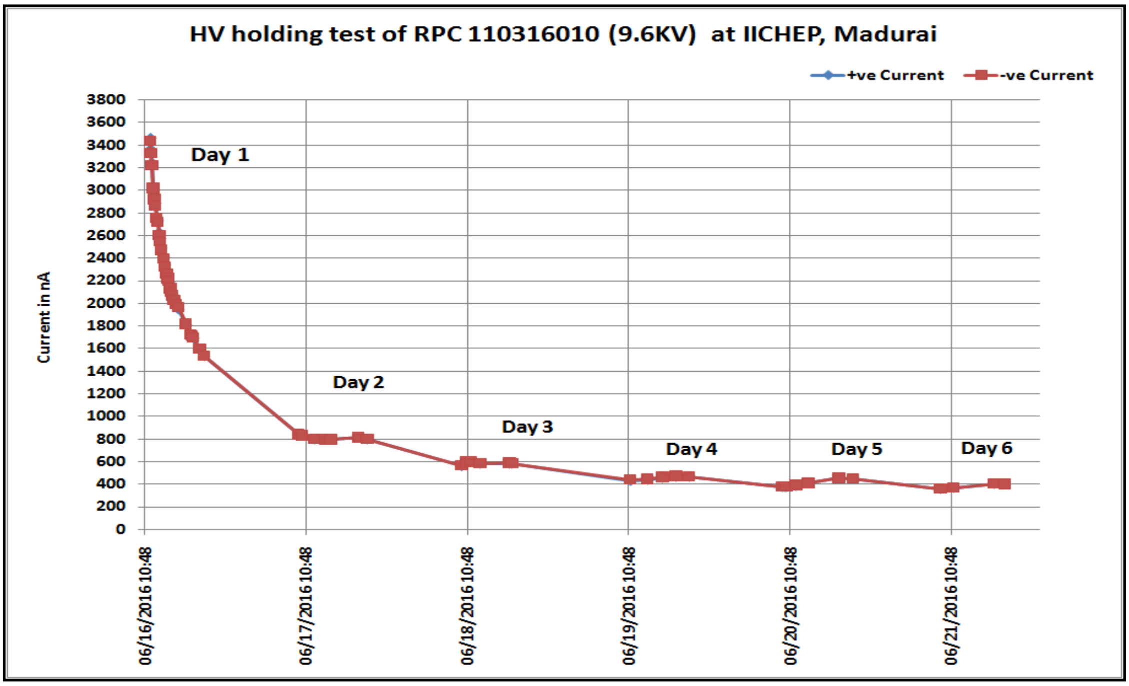

Figure 1.13: Current Stabilisation in RPC

1.4.3 Efficiency Plateauing of RPC

Each RPC before going into the stack undergoes efficiency plateau to find out operating voltage of RPCs [31]. With coincidence of (2 to 3) finger scintillator Paddles trigger has been formed and then strips under paddles are checked for Muon(s). Typical efficiency plateau plot is as shown in Figure 1.14 . The main strip and the two adjacent strips on either side are shown in the plots. It is seen that at typical high voltage of 9.9 kV, an efficiency of 99 % is achieved. The current drawn by an RPC chamber of ~ $(2 \times 2)\ m^2$ is few hundred nA.

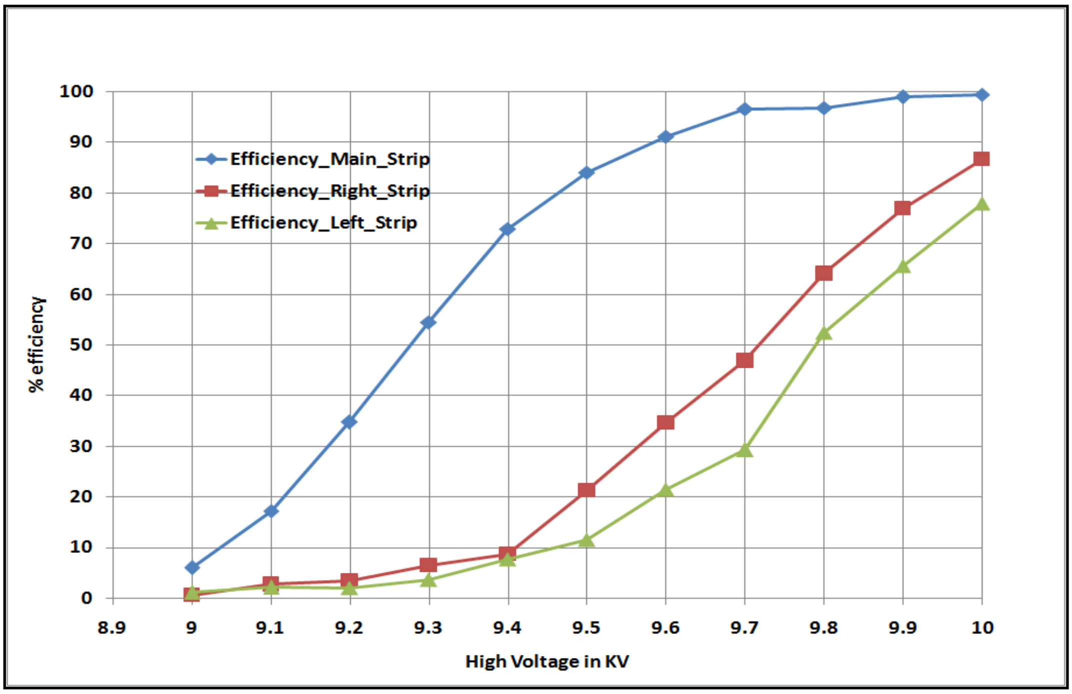

Figure 1.14: Typical efficiency plot of an RPC

The RPC is a parallel plate gas detector and in the next chapter we present the literature survey beginning with inventions of gas detectors and how RPC were evolved with time. The latest development beyond the discovery of RPC detectors is also highlighted. Why RPCs are chosen for INO-ICAL research program is addressed. Then the literature survey is followed by the Gas System and their evolution with time is highlighted. Type of Gas system and methodology of mixing gases is surveyed and finally what type gas mixing system that is best suited for INO-ICAL. Based on this literature survey formation of research problem is made.

Chapter 2

Literature survey

This chapter is devoted for the literature survey on major gaseous detectors since their invention(s) and the innovation in gas systems developed with time and their applications in various neutrinos experiment.

In the overview section, the detailed survey on the neutrino experiments that are in operation and the various types and mode of RPCs , type of gas systems that are employed in different experiments are reported in tabular form. Finally at the end of the chapter based on the literature survey the thesis topic is formulated.

2.1 Neutrino Experiments

The major neutrino experiments operational worldwide are mentioned below.

In Japan, three experiments are operation

a) HYPER Kamiokande (Kamioka Nucleon Decay Experiment).

b) Super-K(Super-Kamiokande) and

c) T2K (Tokai to Kamioka).

In USA, the experiments are

a) NOvA (NuMI Off-Axis νe Appearance)

b) MINOS+ (Upgraded electronics for MINOS)

c) SciBooNE (Scintillator Bar Booster Neutrino Experiment) and

d) MINERVA (Main Injector Experiment).

In China the experiments are

a) Daya Bay (Daya Bay Reactor Neutrino Experiment) and

b) JUNO (Jiangmen Underground Neutrino Observatory) in China

In Italy

a) ICARUS (Imaging Cosmic And Rare Underground Signal),

b) BOREXINO (BORon EXperiment) at Grand Sasso, Italy.

The other neutrino experiments are Precision Ice-Cube Next Generation Upgrade (PINGU) [32] in Antarctica, at Amundsen-Scott South Pole Station, SNO+ (SNO with liquid scintillator) at Creighton Mine, Ontario, Super-NEMO in Fréjus Road Tunnel, France and the upcoming, INO (India based Neutrino Observatory) in Tamil Nadu, INDIA.

2.2 Brief history of gaseous detector

The Nuclear and Particle Physics experiment depends upon the detection of primary particles / radiation. The interaction of particles with atomic electrons is making this detection possible. There are three types of particle detectors namely gaseous detectors, liquid based (water mineral oil etc.) and solid (scintillator semiconductor etc.) and based on the requirement like a good energy resolution, spatial resolution, time resolution etc., a particular type of detector is selected. The literature is focused on the gaseous detector as the INO collaboration has decided to use a gaseous based detector.

2.2.1 Basic operation of Gaseous Detectors:

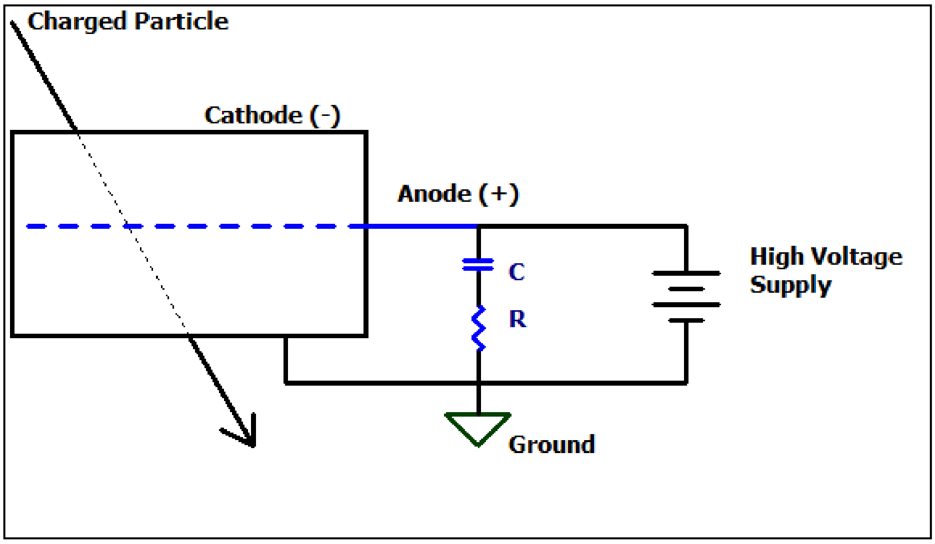

Figure 2.1: Equivalent circuit of an Ionisation Chamber

The Figure 2.1 shows the equivalent circuit of a typical gaseous ionisation chamber. The high voltage positive is applied to the central wire (anode-positive) and the negative supply to the chamber walls (cathode- negative). When the charged particle passing through the chamber ionisation of gas molecules takes place inside the chamber and produces negative electrons called as anions and positive ions as cations along the path. The charge (pulse) is collected across the resistance by increases the voltage across the resistance and reducing the voltage across the capacitor. The pulse height across resistor is [Charge due to Ionisation × Amplification factor].

2.2.2 Brief history of Gaseous detector:

Evolution of the particle detectors started with the discovery of X-rays by Wilhelm Conrad Roentgen in 1901 and Radioactivity in 1890s.

In 1908, Rutherford and Geiger fabricated the first gas detector using cylindrical electrical counter for counting alpha particles [33], which they improved in 1912 by introducing a spherical counter. Further progress was achieved in 1913, when a detector for counting beta particles was developed.

At atmospheric pressure the gases act as insulators of electricity as they don't have any free electrons to carry current. But, the free electrons are produced in gas by *ionization and* electric discharge occurs. In 1915, Townsend [34], had observed that the current in the parallel plate gap increased rapidly when the voltage is increase. He postulated that the current must be due to the positive ions and photons and these ions will liberate electrons by colliding with gas molecules and by bombardment against the cathode. Similarly, the photons will also release electrons after collision with gas molecules and from the cathode after photon impact.

In 1928, Geiger and Mueller introduced **Geiger-Mueller Counter (**G-M Counter). It is based on gas ionization in which one avalanche will trigger second avalanche and so on within a short period of time. As amplitude of collected pulses is the same, it only works as radiation induced event counter. It consists of cathode as tube surface and anode wire is supported at one end only along the axis of the cathode cylinder. Thin window made up of mica or other material provided for radiation entry. It has to support substantial differential pressure, as G-M counters and is operated below atmospheric pressure. The typical gases used are He, Ne, Ar. etc.

A study of the deterioration of methane-filled Geiger-Mueller counter by Farmer, Earl and Brown is published in [35] and the construction details are given in book edited in 2010 is by Knoll [36].

In the **Keuffel's spark counter** the high voltage is applied between two metal plates. The charged particle leaves a trail of electrons and ions in the gap and causes a spark (discharge). The time resolution is excellent about few tens of Pico-seconds.

The operating principle of spark counter with a localized discharge are described from the view point of the improvement of its time characteristics by G.V. Fedotovich, Y. N. Psetov and others [37]. The typical sizes of detectors for large physical devices are of (2 to 3) meter. The experiments have shown that the manufacturing of spark localized-discharge counters of such sizes seemed to be quite realistic. The main difficulties confronted are due to the preparation of the large, fine, non-defective electrode surfaces before assembly of the counters.

The other important task is to find new gas mixtures with better time characteristics and less prone to polymerization induced by the discharges. The comparison of various Nobel gases influence on the counter characteristics was made. Neon compared to Argon and Xenon, decreases the threshold value and has good time resolution. The low operating voltage should improve the gas mixture stability. The anode is made of semiconductor glass and the cathode is simple glass on which a copper layer is deposited A typical gas mixture consists of a noble gas with an addition of organic gases whose total absorption spectra cover a wide range of photon wavelengths below 225 nm. A mixture of gases namely, 2.5% of 1.3 butadiene; 1% ethylene; 10% I-butane and 85.6% argon under a total pressure of 12 bar, are used for one of the counter electrodes and choosing a special gas mixture which absorbs photons prior to their travelling regions of the high electric field. The spark chambers had limited size and read out was optical and electrical.

Spark chambers, on the other hand, are triggered devices and in order to sensitize the spark chamber, a high voltage pulse has to be applied immediately after the passage of a particle whose trajectory has to be determined. This requires fast high voltage trigger circuits with very high reliability (even now under up gradation and development), but it also creates a very severe electromagnetic interference (EMI) problem.

The invention of the spark chamber has led to development of parallel plate detectors.

A **PPAC (Parallel Plate Avalanche Chamber)** is a single gap gaseous detector almost similar to the Spark Counter explained latter. These are operated in avalanche mode at moderate electric field without forming a conducting channel between the electrodes (no spark but an induced signal is produced on electrodes). It normally consists of two planar electrodes made of metal or metalized ceramic or plastic, kept apart at a fixed distance of (0.5 to 2) mm by precise spacers. Its advantages include a fast response and an increased rate capability of up to 10 MHz / cm^2. The time resolution is (100 to 250) pS. Depending on the gas mixture used, a gain of about 100 can be reached with a very low discharge probability of 10^{-5} for minimum ionizing particles. The PPAC signals are small about 100 FC on an average, which results in a low signal-to noise ratio. To account for a good detection efficiency, *the front-end electronics has to support a very low-noise and very high sensitivity*, which often results in compromising the fast rise time needed for timing purposes. The possibility of using this technology for large scale applications therefore is questionable. The Parallel Plate avalanche counter (PPAC) [38], [39] was also used during this period.

Proportional (and Scintillation) counter was introduced in late 1940s by Sir Samuel Curran [40] [41] reported in 1954 and 1956 respectively, which relies on the phenomenon of gas multiplication for charge amplification originating in the gas and operates in pulse model.

The PPAC was first used in 1952 by Christiansen and reported by A. Krusche, D. Bloess, and others in 1965 [42].

It was assumed that the flow of transportation of charges through gas is similar to flow of charges in electrolytes and their motion was regarded as similar to that of ions in conducting liquids, and obeyed the ohm's law within a certain range of experimental conditions. To show the dependency of the current in a gas on the various parameters, a gap consisting of two parallel plane electrodes was filled with a known gas, pressure and temperature. A potential difference was applied. This chamber gas was irradiated by a uniform beam of X-rays. It was observed that the current rises and reaches a saturation value, which means at low voltages (weak electric fields) the number of ions created by radiation is large compared with the number of ions dragged to the electrodes. Since the speed of the ions increases with increasing field, an increasing number of ions of both signs are driven to the electrodes and the current rises. However, since the number of ions produced in a gas in unit time is finite and proportional to the intensity of irradiation, the highest rate of removal of ions can just be equal to the rate of production. Hence, a limiting value of current was obtained when every ion pair which is produced reaches the electrodes without being able to recombine in the gas. The increase of field further within certain limits does not affect the saturation current. Its value can only be raised by an increase in irradiation, a principle which is used in ionization chambers. The more detailed report (1956) is given by A Von Engel, "Electron-Emission Gas Discharges" [43].

In 1967-68, G. Charpak and F. Sauli introduced the **Multi-Wire Proportional Chamber (MWPC)** which consists of a grid of uniformly spaced thin anode wires, sandwiched between two cathode planes, the cathodes may either consist of uniform conducting foils, or of wire grids with two arrays of anode wires, stretched even at small distances from each other, sandwiched between two cathode surfaces, constitute independent detectors. The MWPCs are sensitive to position of radiation interaction. The details of development operation are summarised G. Charpak, D. Rahm, and H. Steiner, in [44].

The applications of the Multi-Wire Proportional Counter (MWPC) for wide-angle diffraction experiments and as a potential detector for protein crystallography are known. The electrostatic problems found with large area MWPC when operated at high pressure were resolved. A glass micro-strip detector can be used in place of the wire frames. The characteristic of a high-pressure Micro-Strip Gas Chamber (MSGC) was tested in a laboratory by Charpak

The details of the MWPC development is explained by Doolittle, Pollvolt and Eskovitz and is reported in 1973 [45].

The MWPC was able to track the elementary charge particle and obtain fast electronic images of photons. Charpak was awarded in 1992 with the Nobel Prize in Physics for this fantastic invention of MWPC.

In 1981, the Resistive Plate Chamber (RPC) was developed by R. Santonico and R.Cardarelli,[46] like the spark counter and the PPAC, the RPC consists of two parallel plate electrodes and had a resolution of 1 nS.

The **Micro-Pattern Gaseous Detectors** (MPGD) were developed in early 1990s as results of efforts of many groups. The invention of MPGD ,Gas Electron Multiplier (GEM), the Micro-Mesh Gaseous Structure (Micro-Me Gas), and more recently other Micro pattern detector schemes, offers the potential to develop new gaseous detectors with unprecedented spatial resolution, large sensitive area, high rate capability, operational stability etc. The applications that require very large-area coverage with moderate spatial resolutions, more coarse Macro-patterned detectors, e.g. Thick-GEMs noted as THGEM, could offer an interesting and economic solution. The new micro-pattern device appears suitable for industrial production.

The availability of highly integrated amplification with readout electronics allows for the design of gas-detector systems with channel densities comparable to that of silicon detectors. The modern wafer post-processing allows for the integration of gas-amplification structures on top of a pixel, readout chip. Due to these recent developments, particle detection through the ionization of gas has large fields of application in future Particle, Nuclear and Astro-particle physics experiments with and without accelerators.

In 1997 the **Gas Electron Multiplier (GEM)** detector was developed by Physicist Fabio Sauli. The GEMs are fabricated using Kapton foils coated with copper layer of few tens of μ m and using precision Printed Circuit Board technology for itching etc. A voltage of a few 100 V is applied and the resulting electric field strength is in the order of ~ 10 kV/cm, which is high enough for the gas amplification of tens of thousands is achievable. The detailed technical report of fabrication of GEM at CERN by Fabio is given in [47].

Presently, the GEMs are used in the COMPASS experiment, the International Linear Collider, STAR and PHENIX experiment. The GEM's amplification technique is used for position detection of ionising radiation (charged particles, photons etc.) in gas detectors. The GEMS can be used for large-area detectors as they are mechanically much simpler to implement and are versatile. The modified application details of GEM are reported 2015 and 2016 in [48] and [49].

Recent particle detectors use silicon detectors (semiconductor) as their central tracking detector. The position resolution is far better than the ionisation chambers. An individual detector module comprises silicon that has been doped to form a diode. These detectors have made impact but are expensive as of now.

In 1996, P. Fonte introduced Multi-gap RPC (MRPC) which was very useful for the time of Flight experiment.

Since then many scientists have been exploited successfully the charge information in many experiments using a wide variety of different applications and are described by F.Sauli, "Gas detectors recent developments and future perspectives and Gas detectors achievement and trends" [50], [51] and F. Flakus has also described "Detecting and Measuring ionization radiation" – A short history [52].

The development and advance research development is going on. The working principles are well understood today and also with the help of modern simulation techniques, new configurations can be easily examined and optimized before a first experimental test. Most of the gaseous detectors exploit the electric field produced by a positively charged wire. The field's strong dependence on the distance r from the wire (E α 1/r) leads to these characteristics in the detector working.

The alpha spectrometry which is instrumented and reported Hartman J. Hutsch F. Kruger et al in 2015 [53].

2.2.3 PPAC continuation of work

As mentioned above, in 1971, Pestov and Santanico started their work on PPAC (Parallel Plate Avalanche Chamber) and eventually in 1981 the Resistive Plate Chamber (RPC) was developed by R. Santonico and R.Cardarelli [46] and hence the birth of RPC detectors. The primary charges produce avalanches without forming a conductive channel between the electrodes. There is no spark induced on the electrodes.

2.2.4 Resistive Plate Chambers

In 1981, the Resistive Plate Chamber (RPC) was developed by R. Santonico and R.Cardarelli, like the spark counter and the PPAC, the RPC consists of two parallel plate electrodes. At least one of the electrodes is made of a material with high volume resistivity. A charge “Q_0” that enters the resistive electrode surface, decomposes with time “t” following an exponential

$$Q(t) = Q_0 e^{-t/T} \quad (1.1)$$

where T =μμ^εφ (1.2)

The Resistive Plate Chamber, (RPC) is a parallel plate ionization detector characterized by high detection efficiency (97-98%), a very good time resolution (1.5 to 2) nS, a good spatial resolution (~1 cm) and good reliability proved in many applications. Due to its compactness and an industrial-supported production, together with the possibility of covering large surfaces, make the RPC an ideal instrument for fast response application like Muon trigger at LHC. The elementary component of a RPC is a gap, a gas volume enclosed between two resistive plates

2.2.4.1 RPC using Heat Strengthening and Tempered Glass

The glass electrode with heat strengthening and tempered is being tried out for INO-ICAL experiment, so that the handling of glass RPCs would be more feasible. The initial research and development work is reported by G. Majumder , G. Majumder, V. Datar, S. Kalmani, N. Mondal and S. Mondal [54].

The bottleneck in this development is the sagging effect of the glass due to tempering and is being addressed.

2.2.4.2 Why glass based RPCs for ICAL

The Resistive Plate Chambers (RPCs) are very much suitable for large volume experiment like INO-ICAL, CMS, and ATLAS at CERN, Argo [55] etc. The RPCs have detection efficiency of more than 96% with time resolution of about (1 to 2) nS and operating the RPCs in the avalanche mode, the aging effect on RPCs can be deferred for long periods say more than a decade [56] .

In the RPCs, the signal readout is from pick-up panels and not from electrode surface directly and hence is noise free. The signal is the image of the pulse, as the RPC functions like a capacitor. The small area on the readout strip (~1 mm) is the dead space, but rest of strip is available for detection.

The dielectric strength of glass is one order better than Bakelite, therefore has better spatial response. In Bakelite RPCs, the roughness and defects on the inner surfaces of RPC resistive electrodes can cause high dark current, high singles counting rate and breakdowns. The Bakelite RPCs require linseed oil treatment [57] which improves the smoothness of inner surface and enhances the performance. The raw glass material for electrode is cheaply and readily available therefore for about 28,800 RPC, it is very economical.

The timing performance will be crucial for detectors at future accelerators a time resolution of about 100 pS is achievable by RPCs and has helped in solution of an unambiguous bunch crossing identification at LHC experiments. Even an accurate tracking with 100 μ m resolution has been already achieved by them. RPC by virtue can be a powerful instrument to investigate electrical phenomena in gaseous media.

Keeping all above technical and economical parameters in mind, the INO ICAL collaboration had decided to use glass electrode RPC.

2.3 Brief history of Gas Systems for RPCs

Until the eighteenth century, gas was not recognized as a separate state of matter, it was Joseph Black who realized that carbon dioxide was in fact a different sort of gas altogether from atmospheric air. Latter the other gases were identified, including hydrogen by Henry Cavendish in 1766. Alessandro Volta expanded the list with his discovery of methane in 1776. It was known from a long time that inflammable gases could be produced from most combustible materials, such as coal and wood, through the process of distillation. In the last two decades of the eighteenth century, as more gases were being discovered and the techniques and instruments of pneumatic chemistry became more sophisticated, a number of natural philosophers and engineers thought about using gases in medical and industrial applications.

2.3.1 Freon gases and R134a gas (1,1,1,2-tetrafluoroethane)

Freon gas was discovered in the 1980s. It is a stable, non-flammable, moderately toxic gas and is also known as R-22. The refrigerants (R22, R-410A) used in the air conditioners are called Chlorofluorocarbons (CFCs).The CFCs are family of chemicals that contain chlorine, fluorine and carbon. The chlorine content in these compounds causes the depletion of the ozone layer. This discovery prompted to phase out the greenhouse gases which include carbon dioxide, Nitrogen dioxide, Carbon monoxide, CFCs etc. The *Hydro-Chloro-Fluoro Carbon* (HCFC) a fluorocarbon that is replacing chlorofluorocarbon as a refrigerant and propellant in aerosol cans. The R134a is also known as Tetrafluoroethane (CF_3CH_2F or $C_2H_2F_4$) from the family of HFC refrigerant. The R134a gas refrigerant is ozone friendly and is a popular replacement for R12. But, due to greenhouse effect it has been decided to stop the production of CFCs by 1995 and HCFCs by 2030 [58].

In view of the above, there is need to study and operate RPC detectors in future with Freon-less gases. There are several groups working for Freon-less gas RPCs and some of the details of which are given in [59], [60], [61] and [62] etc.

2.3.2 Gas systems for RPCs

Gas system in detectors is analogous to the respiratory system of human beings. The operating mode of RPCs depends on the mixture of gas supplied by gas system. The main functions of gas system is to mix the required gas composition precisely and then uniformly distribute it to each RPCs. Depending on the number of detectors, the gas coming out of the RPCs will be let out into the atmosphere (Open Ended system) or will purified and then looped back into the RPCs (Closed Loop recirculation System).

2.3.3 Gas systems used world wide

The major experiments at the LHC (Large Hadron Collider), CERN (European Council for Nuclear Research) are ALICE, ATLAS, CMS etc. with different physics goals, use a largest number of gas detectors like RPCs, CSC, MDT, TGC, TRT etc. which need different types of gases like CF_4, $C_2H_2F_4$, iC_4H_{10}, SF_6, Xe, Ar,N_2,CO_2, Liquid nC_5H_{12} etc. with different gas mixing compositions and are used in large quantities as the detectors are in large numbers. Most of these experiments are conducted underground at a depth of about 800 meters and a modular design approach is used for gas mixing (at surface) and circulation, distribution and purification system (underground cavern). There is massive work done on the purification and analysiss process of mixed gases. The key team players for designing and developing the different gas systems which are operation at CERN are L. Besset, F. Hahn, C. Zinoni, I. Crotty, S. Nuzzo, S. Haider, A. D'Aurai, Ch. Schaefer, M. Bosteels, R.C.A. Brown, C.R. Gregory, C.W. Nuttall, M. Treichel, S. Konovalov, G. Mikenberg, V. Polychronakos, A. Romaniouk, R. Santonico, Guidato etc. [63].

The work done on the gas systems and purification is well documented as Technical Design Report (TDR) and the publications are available for references. Some of these are M. Bosteels et al. CMS gas system proposal, CMS Note 1999/018, L. Besset, F. Hahn, S. Haider and C. Zinoni, Experimental tests with a standard closed loop gas circulation system, CMS Note 2000/040, RPC gas distribution layout by I.Crootty, F.Hahn et al, detailed, ATLAS gas system proposals by LHC gas working group (ATLAS Technical Design Report) etc.

The other experiments like BaBar IFR detector at SLAC use gas systems that are in operations [64] etc. The Gas system and its up-gradation are discussed in the paper by Wolfgang Menges [65]. As a part of upgrade of the forward end cap Muon detection system (IFR) a gas distribution and monitoring system was installed at SLAC [66]. Here about 300 gas circuits are controlled and monitored. The returned gas flow is monitored by digital bubblers which use photo-gate electronics to count the bubbling rate. The bubble rates are monitored in real time and recorded in a history database allowing studies of flow rate versus chamber performance. It is an open ended system (OES) and the mixed gas is produced from the tanks of argon, Freon, and I-butane and distributed via low-pressure manifolds to gas distribution boxes mounted on the detector. The gas flow is measured using bubblers before venting the gas into the atmosphere. The typical flow rates used are (3 to 8) volume changes per day.

The BELLE detector at KEK experiment uses a similar gas distribution system as mentioned above and is Open Ended System (OES) type. The flow resistors and electronic bubbler that are used are given reference [67].

In gaseous detectors, gases play a major role in the output signal quality. Hence special attention has been paid to select suitable gas mixture and its circulation system. The MWPC uses “Magic Gas” consisting of Argon (75%), I-butane (24.5%) and

Freon-13, B1 (0.5%) where the proportions are in volume. Some gas mixture studies carried have been carried out by NASA [45].

Most of the LHC experiments uses closed loop gas system and its up-gradation has been described in R. Guida et al [68].

An ARGO experiment set up at high altitude to study mainly cosmic gamma-radiation (TIBET, CHINA), at energy threshold of 100Gev, use RPCs as active element and three types of gases are used. The gas system is a OES and is by developed by R. Santanico and his team [55].

The RPC performance with new purifiers in closed loop system has been studied for LHC experiment noted down by M. Capeans et al [69] and the ageing process is known as the degradation of their performance under the exposure to ionizing radiation is studied [70].

The experience of the operation of the Gas Gain Monitoring system (GGM) of the CMS RPC Muon detector has been described by S. Colafranceschi et al [71].The purpose of GGM is to monitor any shift of the working point of the CMS RPC detector.

The Gas systems used in various LHC experiments are summarized in Table 2.1.

2.3.4 Types of Gas mixing Systems

There are various methods by which, one can mix the required composition of gases. The number of RPCs in an experiment will decides the type of gas mixing system that is required.

2.3.4.1 Open Ended gas System (OES)

In an open ended gas system, the mixed gas is let into the atmosphere after the usage in the detector. The OES are suitable where the numbers of gas detectors are few tens in number. An OES consists of input section with mass flow controllers (MFCs) to provide gas with proper proportions, input manifold for gas mixing, capillary tubes for balancing flow and safety bubblers for avoiding the damage caused to RPCs if there is any obstacle to flow through RPCs. Output section consist of isolation bubblers which are helpful to isolate system pressure from atmospheric pressure and useful to indicate gas flow and output manifold which collected the gas and sent it to vent. The technical details is described in the reference [72].

2.3.4.2 PRE-MIXED gas mixing system

The offline mode of gas mixing technique is used is known as Pre-mixed gas systems. In this gas system, a large volume supply cylinder (say of 15 Litres) which is filled with the required composition of gas. Then the supply cylinder is connected to the RPC or any Gas detectors. When the pressure drops the mixed gas is refilled.

Table 2.1: Gas System at LHC

Active Element	RPC	CSC	GEM
Experiment	ALICE, ALAS,CMS	CMS	LHCb
Gas Mixture	$C_2H_2F_4$, iC_4H_{10}, SF_6	Ar, CO_2, CF_4	Ar, CO_2, CF_4
	95%, 4.5%, 0.3%	40%, 50%, 10%	45%, 15%, 40%
Gas Volume	~15 m^3(each)	~90 m^3	<1 m^3
Gas Recirculation	(ALICE - OES)	(CLS)	(OES)
Greenhouse contribution	75%	10%	6%

2.3.4.3 Closed Loop gas System

In a Closed Loop gas System (CLS), the gases are mixed as per the required composition, then fed into RPC stack and the output gas from the RPCs is purified and recirculate back into the RPC stack. In CLS the gas is reused in the detectors continuously after purification [73], [74]. The impurities which get accumulated in the gas mixture due to leaks or formation of radicals are removed by suitable filters in the purifiers section.

2.3.4.4 The Open Loop System (OLS)

The open loop system recirculation system is based on the separation and recovery of major gas components after passage of the gas mixture through the RPCs, and has the advantage that it does not need filters for removal of impurities. However our studies have indicated that the CLS is found to be more efficient than OLS. The research and development under taken for feasible study is reported in [75].

2.4 Gas System for INO-ICAL

The INO ICAL experiment uses a large volume of gas mixture (~ 200 m^3) of three gases namely R134a, I-butane and SF_6. Both from the operation point of view and economic point of view an automated Closed Loop System (CLS) is better option and is mandatory. It also helps in maintaining the environment clean and pollution free.

2.4.1.1 Simulation studies for Gas flow distribution inside an RPC

There is huge work done by several simulation groups who have presented their work on the RPC behaviour, performance, operation function, gas gap variation, characterization, effect of SF_6 variation[76], [77] etc. in an RPC. But, the literature survey related to the distribution of gas, flow rate of gas mixture, variation of composition of gases, nozzle positions for inlet and outlet of the gas for an RPC which are some of the parameters which help in improving the performance of an RPC, only a single paper is available that too it deals with the distribution of gas inside an RPC (Bakelite) by the CDF team at CERN [78]. Hence, there is a wide scope to understand the parameter mentioned above by simulation.

2.4.1.2 RPC performance studies

The performance of an RPC depends on the following factors;

a) Making the RPC gap (type of electrode used may be Bakelite or Glass) [79]: Where in the uniform thickness of electrodes used and the thickness of gas gap throughout the area of the gap (specially all the edges), cleanliness of the electrodes, proper curing of the glue that is used to hold the spacers etc., uniform surface resistance, nozzle position and leak prof gas gap with the target leak rate of 5×10^{-4} SCCM (say pressure drop of less than 1.75 mm WC in more than 33 hours) [80].

b) The pickup panel having precise matching impendence, so that signal does not get attenuated or buried.

c) All chambers should have uniform flow of gas distribution. The function of the gas flow rate through the chambers and the environmental conditions, such as atmospheric pressure, ambient temperature and air humidity etc. are to be optimized [81]. The performance measures include the noise rate as well as the detection efficiency and pad multiplicity for cosmic rays.

d) The aging effect, a long-term aging test of a Resistive Plate Chamber (RPC) was carried out with an intense gamma 137 Cs source and the RPC performance was monitored under cosmic rays. The detailed aging studies are presented in [82], [83], [84], [85], [86], [87] and [88].

e) The composition of gas mixture and the quality of gas analysis in a Closed Loop system in detail are reported in [89], [90], [91], [92], [93] and [94]. These are referred and the details are mentioned latter.

2.4.2 Overview of the literature survey

In this chapter, a detailed report on the literature survey of gaseous detectors, since their inventions and their recent developments are discussed. The Figure 2.2, shows how the gaseous detectors evolved with improved capabilities of their usage (position sensitive or imaging etc.) with time. The Table 2.2, summarises the history of development of gas detectors.

The gas based detectors like the GM counters, Spark chambers, PPAC detectors, MWPC etc., are highlighted with the principle of operations in this chapter. The Spark chambers, Parallel Plate Chamber, Resistive Plate Chambers and GEM's are ideal the large scale experiments and for the high accuracy tracker Gas Micro-strip Chambers and Micro-Pattern chambers are suitable.

The details of the experiments operating worldwide, the type of RPCs, composition of gases used, the types of gas systems interfaced is summarized in the Table 2.3.

Out of these gaseous detectors mentioned above, the INO-ICAL collaboration team has decided to use glass RPC, as it has good detection efficiency, fast rise time (order of 1 nS), fine spatial response and from the economic point of view, glasses RPCs are cheaper than other detectors and has the advantage of simple to fabricate, assemble and test RPCs.

As RPC require gas mixture for ionization, so we have also gone thrown the documents and literature to known about the various gas systems developed by several institution around the globe. The large scale experiment at LHC in CERN have developed and integrated several gas mixing systems for their different experiments with different types of gases and different compositions. There is also enormous work on gas purifications at CERN and most of their work is well documented.

The RPC performance and gas quality in CLS for new purifiers at LHC are studied by M.Capeans, R.Guida, S.Haider etc. and documented in [69]. This work is focussed for Bakellite RPCs (not glass), and gas breakdown radicles using gas chromatography under electric and high radiation background.

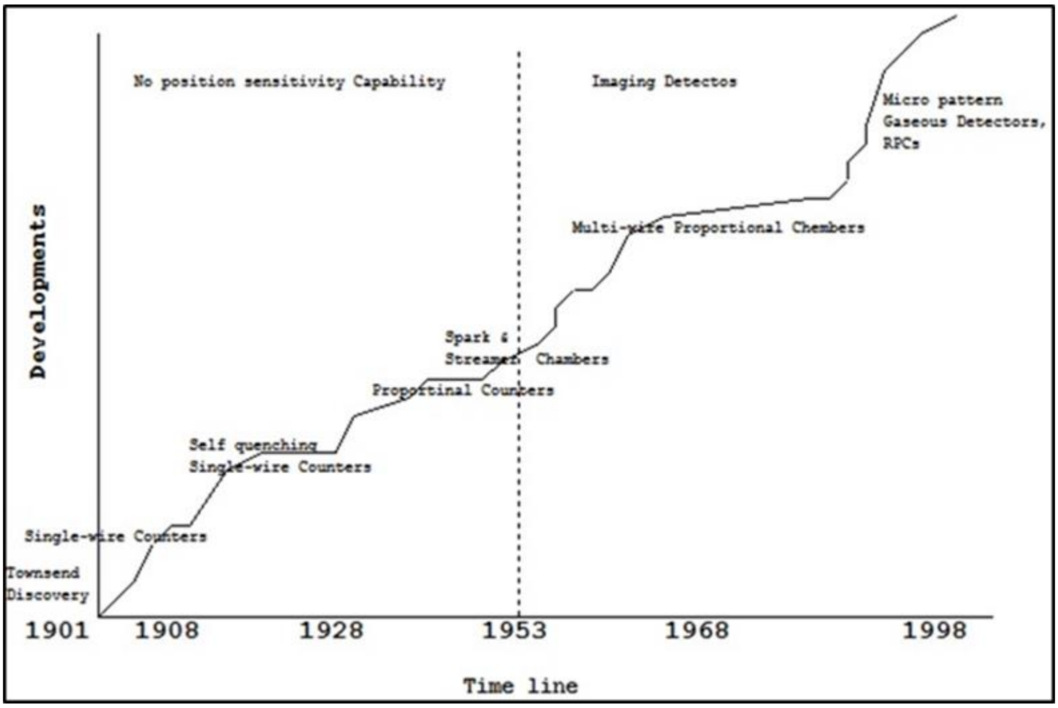

Figure 2.2 : Time line chart (Detector Development)

Table 2.2: Important Inventions of Gaseous detector

Year	Discovery	Scientists/ Inventor(s)
1908	Geiger Counter (GM)	Hans Wihelm Geiger
1940	Proportional Counter (PC)	Samuel Curran
1948	Parallel Plate Counter (PPC)	Leon Madansky & Rohat Padd
1949	Parallel Plate Chamber/Keuffels Spark Counter	Keuffel
1968	Multi Wire Proportional Chamber (MWPC)	George Charpak
1974	Time Projection Chamber (TPC)	Dy Nygel
1982	Pestov Counter / Planer Spark Chamber	Pestov
1982-83	Resistive Plate Chamber (RPC)	Santanico
1988	MicroStriop Gas Chamber (MSGC)	Oed
1996-97	GEM (Gas Electron Multiplier) and Micomegas	Fabio Sauli

Table 2.3: Large Scale Experiments using RPC and type of gas mixtures

Experiment(s)	RPC-Area(m^2)	Electrode	Gap thickness (mm)	No of gaps	Mode of operation	Purpose	Gas System	Gas Mixture (approximate ratio)
CBM TOF	120	Glass	0.25	10	Avalanche	Timing	Open End	$C_2H_2F_4$(85%)+ C_4H_{10}(5%) +SF_6(10%)
ALICE MUON	140	Bakelite	2	1	Highly satuated Avalanche	Trigger	Open End	$C_2H_2F_4$(89.7%)+ C_4H_{10}(10%) +SF_6(0.3%)
ALICE TOF	170	Glass	0.25	10	Avalanche	Timing	Closed Loop	$C_2H_2F_4$ (90%)+ C_4H_{10}(5%) +SF_6(5%)
L3	600	Bakelite	2	2	Streamer	Trigger	Open End	Ar (58%) + I-butane (39%) + $CBrF_3$ (3%).
BESIII	1200	Bakelite	2	1	Streamer	Trigger	Open End	Ar (50%)+ $C_2F_4H_2$ (42%) + C_4H_{10} (8%)
BaBar	2000	Bakelite	2	1	Streamer	Trigger	Open End	Ar (61.2%) + $C_2H_2F_4$(34.4%)+ C_4H_{10}(4.4%)
Belle	2200	Glass	2	2	Streamer	Trigger	Open End	Ar (30%) + $C_2H_2F_4$(62 %)+ C_4H_{10}(8 %) (butane silver)
CMS	3750	Bakelite	2	2	Avalanche	Trigger	Closed Loop	$C_2H_2F_4$(95.2%)+ C_4H_{10}(4.5%) +SF_6(0.3%)
OPERA	3200	Bakelite	2	1	Streamer	Trigger	Open End	Ar (75.4%)+ $C_2F_4H_2$ (20%) + C_4H_{10} (4%) + SF_6 (0.6)
YBJ-ARGO	5630	Bakelite	2	1	Streamer	Trigger	Open End	Ar (15%)+ $C_2F_4H_2$ (75 %) + C_4H_{10} (10%)
ATLAS	7500	Bakelite	2	1	Avalanche	Trigger	Closed Loop	$C_2H_2F_4$(94.7%)+ C_4H_{10}(5%) +SF_6(0.3%)
Daya Bay	640	Glass	2	1	Streamer	Trigger	Open End	Ar (65.4%)+ $C_2F_4H_2$ (30%) + C_4H_{10} (4%) + SF_6 (0.5)
INO-ICAL	97505	Glass	2	1	Avalanche	Trigger	Closed Loop	$C_2H_2F_4$(95.2%)+ C_4H_{10}(4.5%) +SF_6(0.3%)

The preliminary results on optimisation of gas flow rate for ICAL by M. Bhuyan, S. Kalmani, N. Mondal, S. Pal, D. Samuel, and B. Satyanarayana is reported in [74]., where in the studies done are using glass RPCs which are sealed after filling a mixture of gas in it and then operated in the OES system and CLS.

2.4.3 Why need to study the flow and control of gas mixture for the RPC performance in a closed loop system?

As seen from the above literature a huge work has been carried out by the scientist in the field of gaseous detectors. The earlier inventions of gaseous detectors were of sealed type and the gas is stagnant in the detector for the period of operation and due to temperature and pressure variations leaks and the efficiency will degrade. But these detectors were portable and easy to operate.

The literature study indicates that, there is not much detailed research work done around the globe on the RPCs which use glass as electrodes, except for the BELLE experiment in which a few hundreds of them were used in OES and NOT in CLS, while most of the bigger experiments at CERN use Bakelite based electrode RPC.

In view of the above, the INO-ICAL collaboration has decided to use glass based RPCs and as the number of RPCs is huge and quantity of gas is about 200 M^3, hence it is mandatory to use a CLS.

In India, we do not have expertise to design and build the CLS for the research program like INO ICAL. In 2012, a conceptual design and prototype testing of Open Loop recirculation gas System (OLS), a new technique based on condensation and separation of the mixed gas was presented by the ICAL team and it was loudly appreciated by the RPC community [75]. But due to technicality, feasibility, time schedule, cost involved expert man power issues etc. OLS was differed and a CLS was decided to be built and tested by INO collaborators. Some additional work to enhance the performance of the OLS using centrifugal separation of gases is done by us, which is highlighted in this thesis.

Survey of literature shows that the flow rate studies for ***glass RPC*** in CLS environment is very rare in the literature. The INO RPCs will be used in low back ground radiation (underground cosmic rays only) and hence the flow rate will be different when compared to the other accelerator based experiments. The atmospheric pressure variations will be different in India and hence the control study is included.

In view of the above “Study of flow and control of gas mixture on the performance of the RPC in Closed Loop System” is being persuaded.

Chapter 3

Analysis, development and testing of Gas system

In this chapter we briefly describe the research and development work done on the various gas systems that were designed, fabricated and tested for the INO-ICAL research program. The detailed work done on Closed Loop System (CLS), some tools developed for testing the gas systems are explained. The gas analysis using Residual Gas Analyser (RGA a small scale mass spectrometer) in a CLS is described.

3.1 ICAL-RPC Gas Systems

In the initial stages of testing RPCs, the gas mixture was procured form industries in a cylinder with the required concentration of gas mixtures and it was very expensive and did not have leverage to have different concentration of gas at the user end. Therefore several types of mixing and distribution gas systems were developed and evolved with time.

3.1.1 Gas Properties of the gases used for RPC

The gases used for the ICAL glass RPCs are R-134, I-butane and Sulphur-hexafluoride for avalanche mode of operation (streamer need additional argon gas) and their properties are studied.

A prototype CLS for 12 RPC stack is designed and tested for the study of flow and control of gas mixture for the RPC performance.

3.1.2 Types of Gas mixing System

The basic function of the gas system for RPCs is to mix the required gases as per the required composition of gases and then latter distribute the mixture to the individual chambers. The ICAL gas detector volume (~200 m^3) is required and the relative expensive gases make a CLS essential and mandatory. The studies have shown that some of the major parameters that affect the performance of RPCs are the quality of gas mixture, composition of the gases and the flow rate. The poor quality of gas mixture inside the detector increases the current drawn by the RPCs which turn increases the background noise rates, due to which the RPC performances deteriorate. The composition of the required gas mixture can affect the RPC pulse shape and hence mode of operation (could go into streamer mode). The simulation studies have shown that the "Dead Zones" pockets inside an RPC are created, where the gas does not, so the flow rate, quality and purity of the gas are very important parameter.

3.1.2.1 Open Ended gas System (OES) type gas mixing system

In the OES, the discharge of the gas coming out of the RPC is let out in to atmosphere as shown in Figure 3.1. This type of system is suitable when the RPC detector volume is few tens of cubic meters i.e. RPCs are just less than few tens.

3.1.2.2 Pre-mixed Gas Mixing System by partial pressure method

The detail of the Pre-mixing system is shown in Figure 3.2. In this mixing system the gases are filled into a cylinder by partial pressure method.

A few rota-meters are used to indicate the flow of each gas into the mixing cylinder and a pressure sensor is used to indicate the filling pressure on the cylinder [1].

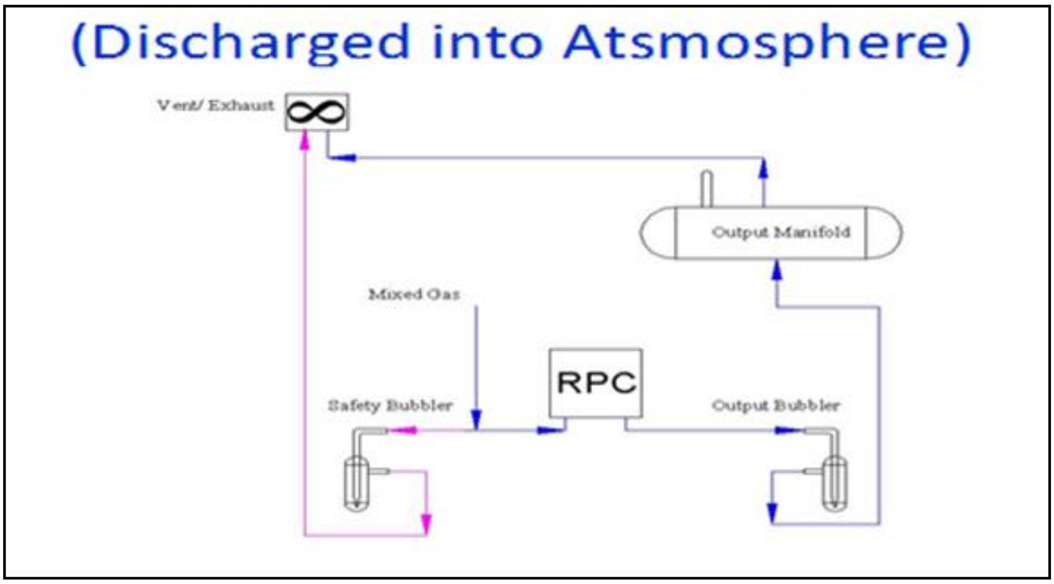

Figure 3.1: Schematic of OES

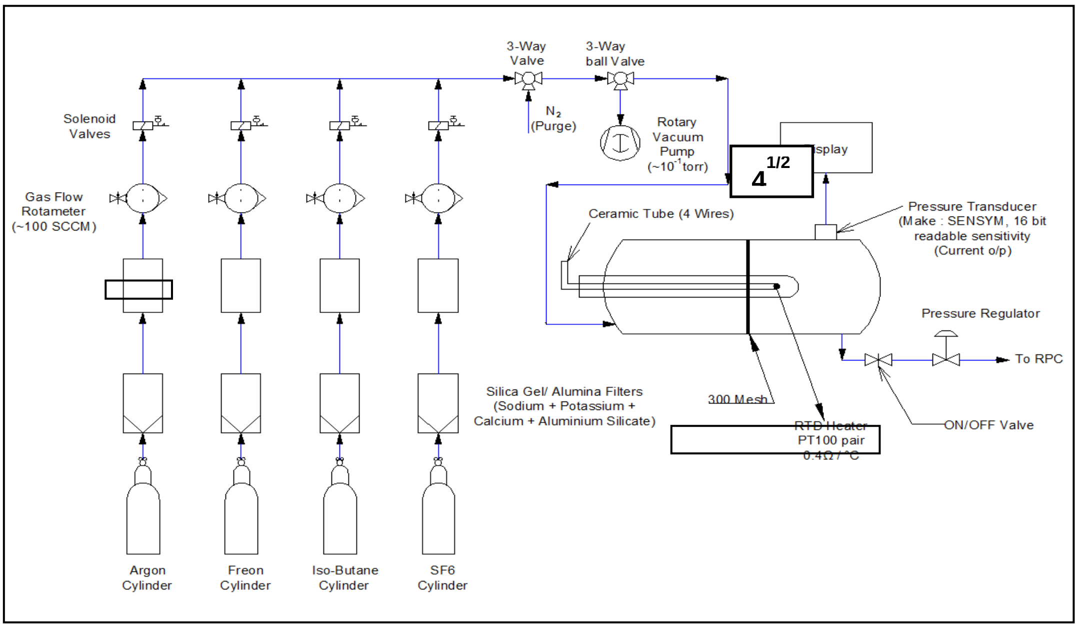

Figure 3.2: Line diagram of a Pre-mixed gas mixing system

Procedure of mixing:

If the required gas concentrations are R134a is 95%, I-butane as 4.5% and SF6 of 0.5%. Then the mixing procedure is as followed.

Firstly, the cylinder (20 litres.) is evacuated to 10^{-1}Torr, assuming the required pressure needed is 2 atmosphere (abs) after mixing all the gases.

The required total pressure would be pressure of (R134a + I-butane + SF_6) = 2 atmosphere (abs), which is displayed as 10,000 counts on display.

The Pressure of SF_6 will be equal to [2 atmosphere × 0.5%] = 0.01 atmosphere [50 counts] is filled, as the needed concentration is 0.5%.

Next, the pressure of I-butane = [2 atmosphere × 4.5%] = 0.09 atmosphere [450 counts] and lastly the pressure of R134a =2 atmosphere × 95% = 1.9 atmosphere [9500 counts] is filled.

This system has provision for Argon gas, when required. This system helped in filling the gas in house and performed well.

3.1.2.3 Volumetric method an OES (Open Ended System)

The pre-mixed gas system described above has a disadvantage of dead time; the flow of gas into the RPCs has to stop for refilling the supply cylinder when it becomes empty. Hence an online OES, using volumetric method of mixing the required gas concentration of gases (and distributing the same to 16 channels) was developed. It is a Mass Flow Controller (MFC) based system and has a provision for mixing four gases. The outlet of gas from the RPCs is let out into the atmosphere and hence the name Open Ended System.

3.1.2.4 Open Loop Recirculation System (OLS)

Another type of gas recirculation system namely the Open Loop recirculation System (OLS) has been implemented as an alternative to CLS. The basic difference between these gas systems is that in OLS major gas component (R134a) is extracted from the gas stream and reused while the remaining small quantity of gas mixture is chemically treated into safer compounds. In case of CLS the minor components (impurities and radicals) are trapped through several filters and removed from gas stream while remaining major part of gas mixture is recirculate. In OLS R134a gas contained in the gas mixture flowing out of RPC outlet is converted into liquefied state and separated from gas mixture. Selective condensation and separation of R134a is achieved by maintaining gas mixture under specific combination of pressure and temperature. Liquefied R134a at -10 °C is filled in container and sent back to inlet of gas mixing system. Cold liquefied gas in the container is heated to room temperature, develops pressure due to heating and reused. In this way R134a gas is being re-circulated, not in a direct loop but by batch type transfer, hence the name "Open Loop". This type of system does not require the filters or adsorbents for individual impurities, delicate loop pressure control or any precision chemical analysis to decide the top-up gas quantities. A moisture sensor placed at the outlet of RPC is sufficient to indicate amount of moisture which serves as indicator to ingress of air into gas mixture by leakages. In this method the mixed gases coming out of RPCs are separated, purified, stored and reused. The gases are separated from the mixture is accomplished by using differences in their physical and chemical properties. For example: I-butane and R134a can be liquefied at temperatures above -30 °C, whereas Argon and SF_6 are still in gas phase at that temperature. R134a is a saturated compound but I-butane retains substantial chemical affinity. In gas phase SF6 is 2½ times heavier than Argon. The conceptual functioning could be demonstrated, but due to cost and time schedule a new CLS was designed, developed and tested as its feasibility of operation was seen at the LHC, CERN experiments.

3.1.3 Closed Loop Gas mixing and recirculation system

A Closed Loop System (CLS) capable of purifying and recirculating gas mixture in a loop is more suitable when the numbers of chambers are large. In a CLS the gas mixture, after having flown through detector is not let out into atmosphere but looped back to the detectors after purification and re-pressurization. The impurities that get accumulated in gas mixture due to leak or formation of radicals are removed by suitable filters. The efficiency of CLS is defined as ratio of difference between total gas mixture volume and gas volume lost as leakage and formation of radicals, to total gas mixture volume. Typical efficiency of a closed loop system is in range of 85 % to 95 %. However for setups with small number of detectors working under cosmic luminosity this value is found to be near 97%.

We do not have much expertise for designing and developing a CLS in our country and therefore, it becomes difficult for fabrication of bigger gas systems that would be required in the INO project.

In view of the above, the conceptual design of the CLS which are being used at CERN for the CMS, ATLAS [63], [68], [69], [71], [95], [96], [97], etc. experiments are chosen by us for a proto-type CLS for a stack of 12 RPCs. But, the overall detailed control designs, fabrication and instrumentation using PLCs (Programmable Logical Controllers) is indigenized designed and developed.

The basic function of the CLS is to mix the gas as per the required composition, distribute the mixture of gas in to the individual chambers and have purification system in the loop of the gas flow. The CLS is operated with a fraction of fresh mixture continuously injected into the system. The fresh gas quantity that needs to be flushed precisely is yet to be determined. Usually it is about 5% of the volume of gas. The CLS is depended on pneumatic parameters; hence many pressure sensors are used in process control and operation.

A typical CLS consists of 4 major blocks namely, gas mixing (on-line), gas recirculation, gas purification system and control system. The Schematic and conceptual designs are shown in Figure 3.3 and Figure 3.4. The detailed line diagram of CLS is shown in Figure 3.5. The experimental set up of the flow of gas to the RPCs and back to the CLS is shown in Figure 3.6.

3.1.3.1 Gas mixing unit

The gas mixing block will have a gas mixing system with capacity to deliver gas mixture into a stack of 12 RPC's of (1.85 × 1.9) m^2 size, with an total internal volume of ~96 litres and total capacity of 140 litres and will deliver a mixed gas of R134a (~95%), I-butane (~5%), argon (if used ~30%) and sulphur hexafluoride, which will be less than 1% with a flow range (20 to 1000) SCCM.

3.1.3.2 Gas recirculation unit

In a CLS the pressure control is crucial. If pressures say more than few mbar's are exerted, then it will damage the RPC. The pressure exerting on any RPC (glass) under test say should not be more than (4 to 5) mbar in the closed loop.

The system has a vent (exhaust); so that gas can be thrown into the atmosphere frequently (breakdown gas radicals etc.) and a provision to discharge the gas completely say after a month and refill at a higher rate the fresh gas. A port in the CLS loop is provided for online monitoring of gas sample in the loop for an RGA.

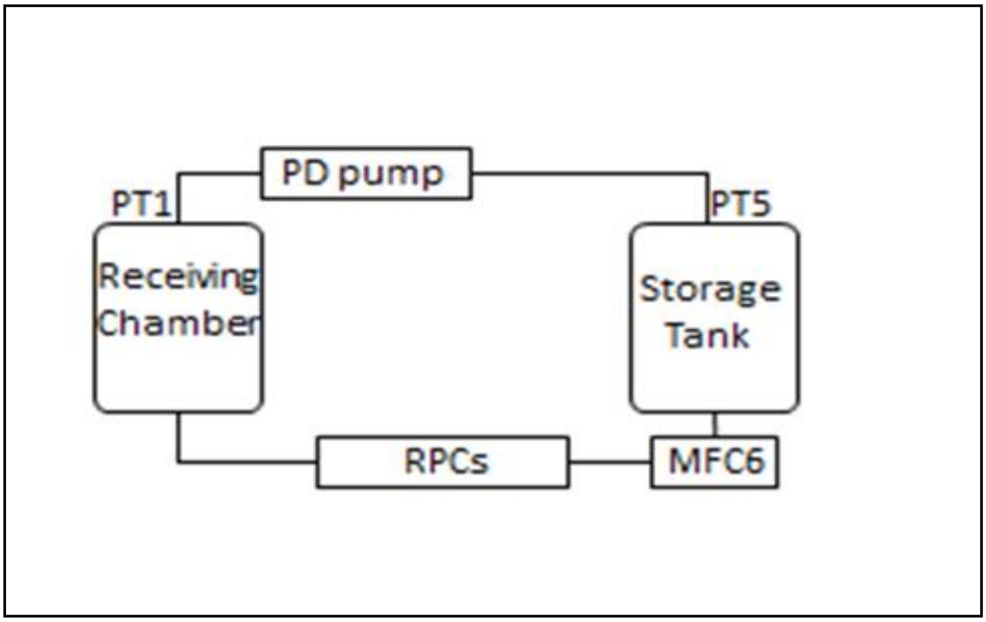

Figure 3.3: Conceptual Designs of CLS

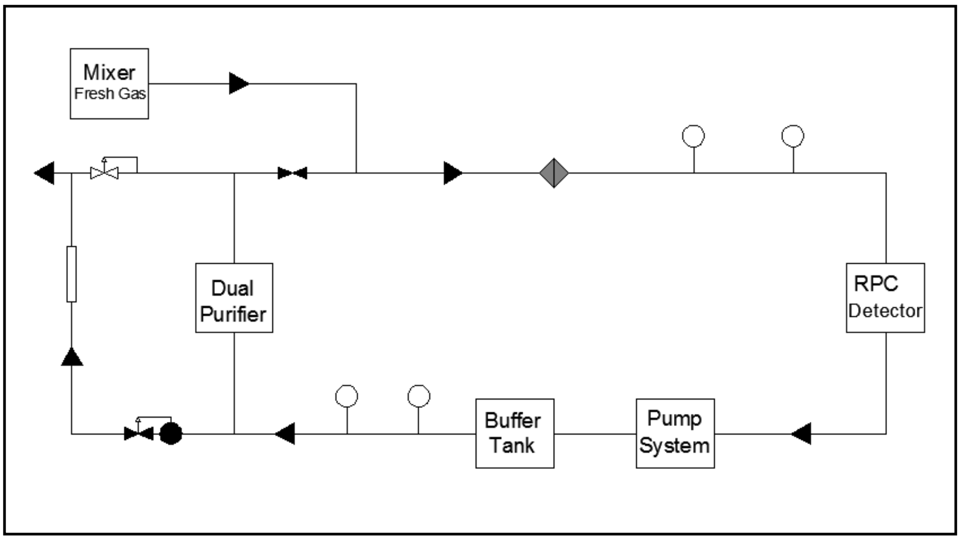

Figure 3.4: Schematic Design of CLS

3.1.3.3 Gas Purification unit

To remove the moisture, trace of oxygen and fluoride (halide) radicals from gas mixture of I-butane, R134a, Argon and $SF_{6,}$ a continuous duty gas purification system is incorporated in the system. It has a dual column type with thermal swing. The system need to achieve a contamination removal down to 2 ppm or less concentration. The $3A^0$ and $5A^0$ combination of molecular sieves are used in continuous duty purifier for removal of water.

3.1.4 Control System features

a) Mass flow control system for preparing and injecting gas mixture of I-butane, R134a, argon and SF_6. The design value of flow range is (10 to 1000) SCCM gas mixtures.

b) Pressure/Vacuum Control system for maintaining ± 2 mbar (Gauge) pressure within +/- 0.1 mbar at inlet and outlet of detector stack.

c) A high pressure (2 bar.) at the storage cylinder to low pressure regular (few mill bar) at the RPC input.

d) Master controller with PC based software, graphic display of parameters, data logging and remote control, Ethernet connectivity.

3.2 Basic Function of CLS

The MFCs with designated numbers as MFC 1, MFC 2, MFC 3, and MFC4 are for the flow control and filling of gases Ar., R134a, SF_6 and I-butane gases respectively and theses cylinders are placed outside the laboratory. The composition of the required mixture (presently RPCs operated in avalanche mode) is R134a (95.4 %), I-butane (4.5 %) and SF6 (0.1%) and these values are set through a data logger PC connected to the CLS system. Initially the mixed gas is filled in the loop automatically through the PLC system. The total gas in the circuit is (a) 20 litres in the supply cylinder having a pressure sensor PT5 (b) 20 buffer or receiver cylinder having PT1 pressure sensor attached to it and (c) the two purifiers cylinders are of 5 litres each.

The supply cylinder is filled to a 1.6 bar (again settable through the data logger PC or the HMI connected to the series of PLCs - details explained later).

The MFC 6 (at a set flow rate) connected to the high pressure cylinder (storage tank output) supplies the mixed to the RPC stack as shown in Figure 3.6 and through the RPCs the gas the flows back into the receiver tank and the pneumatic pump sucks the gas from the RPCs through the buffer cylinder and based on the pressure PT1 developed due to gas flow inside it and then this gas is pushed into the dual purifier section and back into the storage tank after purification. This way the loop continues and frequently as and when required the fresh gas is topped up into the CLS depending on the on the pressures PT5 and PT1 (difference being 0.300 abs bar). This top-up gas is about 5 litres.

3.2.1 Specifications and settings of the pumping module

The pumping module is the most important vital device in the CLS. It sets up the gas flow across closed loop and through the 12 RPCs. The operating values in detail for the CLS (pressures, speed of pump etc.) are given in Table 3.1 and the pressures and flow settings (minimum and maximum) needed for Aanlog Input (AI) modules are shown in Table 3.2 (analog settings).

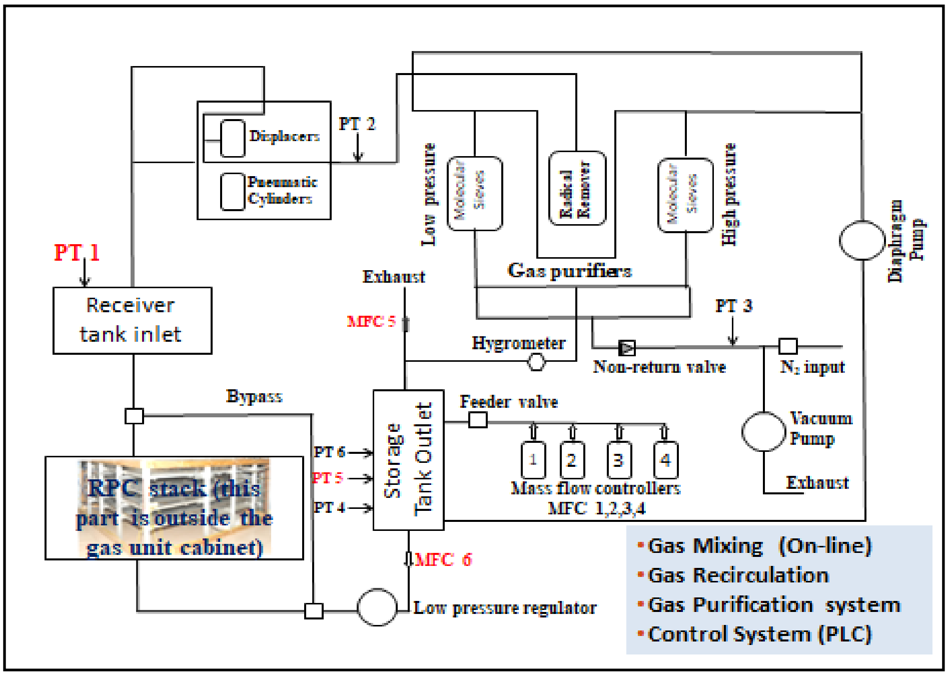

Figure 3.5: Line diagrams of Proto type CLS

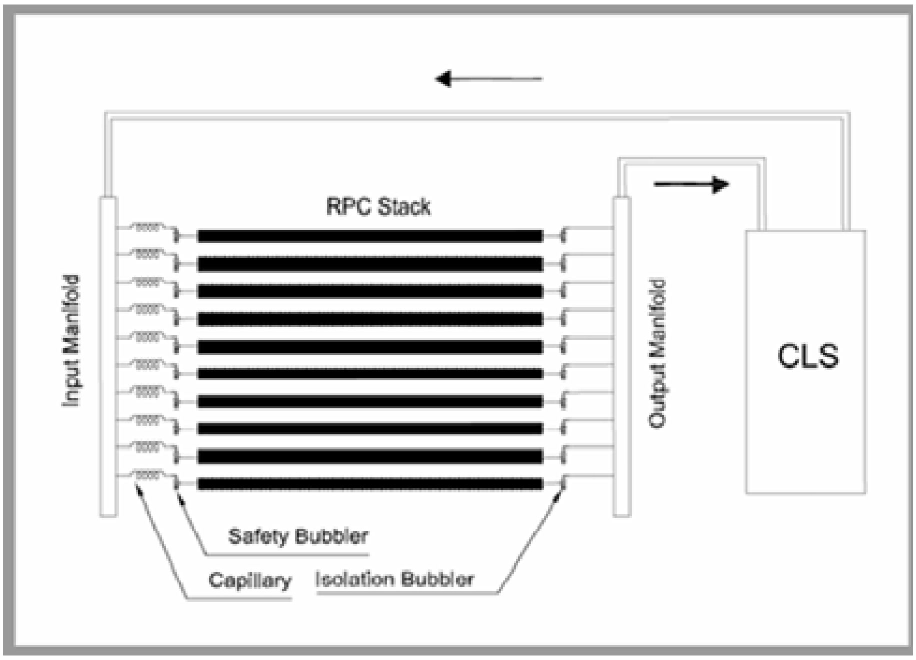

Figure 3.6: Experimental Setup (RPCs connected in CLS)

Table 3.1 : CLS operating values

1	SP1	1.007 bar	Maximum value for PT1 (Receiver Pressure)
2	SP2	0.997 bar	Minimum value for PT1 (Receiver Pressure)
3	TF1	12 sec	Waiting time for delivery stroke
4	TF2	18 sec	Waiting time for suction stroke
5	FP1	Nil	Flow setting for Argon
6	FP2	14.0 SCCM	Flow setting for I-butane
7	FP3	304 SCCM	Flow setting for R134a
8	FP4	1.6 SCCM	Flow setting for SF6
9	FP5	Nil	Flow setting for Exhaust Flow
10	FP6	0.700 SCCM	Flow setting for Loop flow (one RPC)
11	PBS	1.150 bar	Minimum storage-tank pressure for top-up start

Table 3.2: CLS Analog data settings

Sl.no.	Device No.	Minimum	Maximum	Description
1	PT1	0	2.447 bar	Receiver pressure transmitter
2	PT2	0	5.0 bar	Pump pressure transmitter
3	PT3	0	6.10 bar	Vacuum pump pressure transmitter
4	PT4	0	2.447 bar	Low pressure transmitter
5	PT5	0	6.10 bar	Medium pressure transmitter
6	PT6	0	6.10 bar	Comparative pressure transmitter
7	MT1	0	5000	Moisture transmitter
8	MFC1	0	Argon	mass flow controller
9	MFC2	0	243 SCCM	I-butane mass flow controller
10	MFC3	0	1500 SCCM	R134a mass flow controller
11	MFC4	0	1.6 SCCM	SF6 mass flow controller
12	MFC5	0	100 SCCM	Vent gas mass flow controller
13	MFC6	6 0.0	100 SCCM	Loop-flow mass flow controller
14	LP1	0	320	Exhaust Pressure transmitter
15	BT1	0	10	Baratron transmitter

3.2.2 Components of the loop

a) *Pneumatic Pump:* It is a dual cylinder Positive Displacement (PD) Pump. It can suck and deliver gas at (0.5 and 5) bars. The stroke of the pump starts a new cycle. The compression ratio, stroke speed and wait time can be set and adjusted through the main PLC. Two directional check valves in the outlet keep the gas moving in and out in a positive direction.

b) *Gas Purifier:* It has 3 cylinders of 5 litre capacity. The purifier cylinder contains activated basic alumina (Al_2O_3 mixed with small proportion of Al $(OH)_3$). This purifier removes the unwanted radicals formed in the gas mixture (for e.g. SF_2, SF_4 etc.) which may cause damage to the detector by forming complex compounds with the RPC glass. The other two cylinders have Molecular Sieves (mainly aluminium silicate) with 4A (pore size $4A^0$) and 13X (pore size $10A^0$) type in the ratio of 90:10. The $4A^0$ adsorbs moisture, SO_2, $C2H_4$, C_2H_6, C_3H_6, ethanol but not higher hydrocarbons. Some 5A sieves (pore size $5A^0$), are also used for adsorbing normal (linear) hydrocarbons up to n-C_4H_{10} (not the Iso-compounds). The 13X sieves is used for purification of higher hydrocarbons. The purifier has set of six valves which can isolate each cylinder or put them in parallel. The heaters along with PT-100 (temperature transducers) are attached to the cylinders for the purpose of regeneration. The gas purity after purification is in the range of 2 ppm water vapour or better.

c) *Moisture Sensor*: The moisture transmitter senses the moisture content of the gas stream, in series. Its output is in the form of current of (4 to 20) mA. , that is proportional to the moisture content.

d) *Storage Tank:* This is about 30 litres Stainless steel storage tank which can hold up to 90 litres of gas mixture (3 bar abs). This tank has four pressure transducers (BT1, PT4, PT5, and PT6) which are used to fill it at different pressures. This way a volumetric ratio of mixture of gas can be prepared. The concentration of each phase can be calculated as a pressure ratio of filling pressure to full pressure. The tank is fitted with two mass flow controllers, The Mass Flow Controllers; *MFC5* for allowing a small flow of gas mixture into vent and MFC6 to set up a flow rate in the loop as per number of RPCs connected.

e) *Low Pressure Regulator:* This is a specially designed device to maintain a small positive pressure at the inlet of RPCs. It converts the high pressure (~1.5 bar abs) from supply cylinder (PT5) to low pressure of (2 to 10) mbar at the input of RPCs. No capillary impedance is required at the inlet (to drop the pressure) because we are already maintaining the pressure low. The regulator takes inlet pressure from the storage tank through MFC6 and reduces it to adjustable range (2 to 10 mbar) as per design.

f) *Three way valves:* Pneumatically operated three way valves isolate the RPCs from the loop in case of maintenance and emergencies like when pressure becomes greater than SP1 value. Both valves operate together simultaneously.

g) *Vacuum and diaphragm Pumps:* These are used to extract gases for recovery and regeneration. Vacuum is also used to clean the system prior to filling.

h) *Mass flow controllers (MFC):* Mass flow controllers are used to prepare a premix as well as online mix for the top up. The setting is given for top-up flow (re-filling of the RPC when pressure at storage tank reaches a min. point). MFCs are connected together with isolation valves and one common feeder valves. The top-up starts when PT5 value reaches PBS value (here typically kept at 1.15 bars) and sends a gas-mixture in the (user-defined) ratio 95:4.5:0.5 of R134a, I-butane and SF_6.

i) *Receiving chamber:* This is similar to storage chamber, difference being it works near atmospheric pressure. The pressure transmitter PT1 monitors its pressure (which is also the output pressure from RPC). It acts as buffer tank for pressure regulation. It works between the max and min values set by SP1 and SP2 respectively (max being around 1.004 (1.007 bar and min being around 0.997 to 1.001 bar).The pump module sucks the gas from Receiving chamber and puts it back in the loop.

3.3 PLC based Instrumentation of CLS

The pressure parameters play a crucial role in the design of CLS. The basic block diagram of CLS is shown in Figure 3.5. The CLS is completely automated and has provision to mix four types of gases (only three used) in the appropriate ratio as required by the user, typically R134a (95.2%), I-butane (4.5%) and sulphur hexafluoride (0.3%) with a set flow rate of 6 SCCM to each detector and maintain a safe pressure of 3 mbar for the normal operation of the RPCs. Initially the designed flow rate was very high (few SLPH). The purification process in the loop is automated by using dual purifiers. The safety aspects like over pressure, and isolation or cut-off of flow of gas into the RPC detector stack due to blockage of gas is implemented.

3.3.1 Principal of operation and Design Criteria

There are two basic pressures, PT1 measured on the receiver tank pressure and PT5 on the storage or delivery tank pressure. The pressure observed by the PT1 (sensor) is lowest in the loop while PT5 is highest. The suction pump is a reciprocating type of pump that sucks gas from receiver tank and delivers it to purifier tank. The receiver tank acts like a buffer tank. The reciprocating pump is used for better discharge rate control and its suction is not continuous as it would have been in case of a rotary or centrifugal pump. The pressure seen at PT1 reduces, when the suction stroke is ON and it increases due to return flow when suction stroke is OFF. The PT1 being the lowest pressure in the loop and it can be assumed that the pressure inside RPC is greater than PT1 and is allowed to change within a band of pressures which is about 3 mbar. This means pressure inside RPC cannot change more than 3 mbar. The lower limiting value is termed as SP1 which is in the range of 0.998 bars to 1.003 bars. The upper pressure range is SP2 and can be set at (1.000 to 1.006) bar abs, depending upon the allowable pressure band. When pressure falls below the value of SP1, the pumping stops and further lowering of PT1 does not take place and the flow is full as per set point on the MFC 6 (Mass Flow Controller) which supplies the gas into the RPC stack with the set flow rate of 6 SCCM. Due to this action PT1 tends to rise. When pressure goes above or equals SP2, the flow stops completely through MFC 6 hence PT1 cannot further increase. The pumping is kept ON so that it helps in lowering PT1 to a pressure below SP2.

The flow is proportional to the band of (SP2-SP1) and actual value of PT1 can be given as the Flow rate = MFC6 *((SP2-SP1)/PT1))

The storage tank pressure (PT5) is monitored to obtain and estimate the leak rate, and the amount of gas available for recirculation. The limits are set on PT5 such that is should not be less than 1.150 bar (abs) and more than 1.450 bar (abs). This limit of 300 mbar is constant and is internally set. So for every refill the gas pumped / top-up is 300 mbar in a 20 litre storage cylinder. The lower pressure range is termed as PBS and is adjustable. When PT5 reaches a value of 1.150 bar due to leakage or bleed through MFC 5 (exhaust MFC), the backfill is activated .The selected valves which are not shown in drawing namely SV10 (I-butane) SV11 (Freon) and SV12(SF6) are opened along with SV13 which is a discharge valve. When the pressure PT5 reaches (PBS + 300) mbar i.e. 1.450 bar abs, the backfill stops. All along the backfill, the normal function of pumping and PT1 is ON along with all interlocking actions.

The pump used to suck gas from the storage cylinder is a reciprocating type (piston based) and driven by a pneumatic cylinder. The stroke is 100 mm and its bore is 18 mm. The stroke lengths (both forward and return) can be adjusted by the position of reed switches provided on the body of pump. The speeds, both forward and reverse are controlled by unidirectional needle valves which are provided on compressed air tubes. The supply pressure of 5 bars is required to operate the pumps.

To keep the flow uniform throughout the pumping cycle and similarly the pressure should also be kept constant. A HPLP regulator was installed in the loop to reduce pressure from PT5 (1.45 bar abs) to an adjustable (20 to 30) mbar constant pressure (safe operation of RPCs). But (20 to 30) mbar pressure is too low for MFC 6 to work on downstream of low pressure regulator. Hence we have to keep it on the upstream side of LP regulator. During a condition PT5>SP2, the MFC6 flow stops completely and this action starves LP regulator of gas sending it into unstable control.

During evacuation of the system the entire volume comes under vacuum, including low pressure regulator. As this is a large area device, vacuum produces tremendous forces on the diaphragm which might get ruptured or may lose smoothness of pressure control.

The storage tank delivers low pressure gas to the RPC which is collected in the receiver tank and pumped and returned to the storage tank. A set of MFCs are used to mix gas at appropriate flow rate. The system operates between (1.15 to 1.45) bar abs where the top up starts at 1.15 bars and stops at 1.45 bars abs. The RPC is maintained between 1.006 to 1.009 bars with (2 to 3) mbar ratio difference. The flow rates can be adjusted for (1 to 100) SCCM. The room pressure variation is periodic and observed pressure variation is (1.004 to 1.010) bar and twice a day.

In the purifier section the removal of radicals by disposable activated Alumina and the removal of Oxygen by CuZn and Ni-NiO on activated Alumina/Silica by continuous duty purifier (standard cartages available) and the moisture level and oxygen level is maintained less than 2 ppm.

3.3.2 Instrumentation details of CLS

The key components of the CLS are PLC units namely the master controller CPU (model SIMATIC-S7-1214C), digital input (SM 1222-DC), digital input and out module (SM 1223- DC / DC), Analog input modules (SM 1231 AI) and Analog output module (SM 1232 AQ). The other components are the Shavison make, AS 775 (8 Channel, solenoid driver with input 24VDC/15mA and Output of 24VDC/2.5A), AS 773 and AS 333 (power distribution module), TAON-30s/60S, TATP-180SAS 622 namely solenoid valve controller, solenoid drivers, power distribution modules, timers, Analog timers, isolated coils, respectively, Schneider make relays (24V) MCBs, GE Pan metrics transmitter, Tylan make MFCs (Mass Flow Controller), pressure sensors (MSI make Model M5256-000012), RTDs, purifier units, heaters for regeneration etc. The storage tank and receiver tank are of about 20 litres, to deliver mixed gas to RPC stack and receiver tank to receive exhaust gas from RPCs, a High Pressure to Low Pressure (HPLP) regulators (to control and regulate the flow and pressure of the mixed gas into the RPCs). The front view is pictorially represented in Figure 3.7 and details of the PLC and peripherals are represented in the form of block diagrams as shown in the Figure 3.8 and Figure 3.9

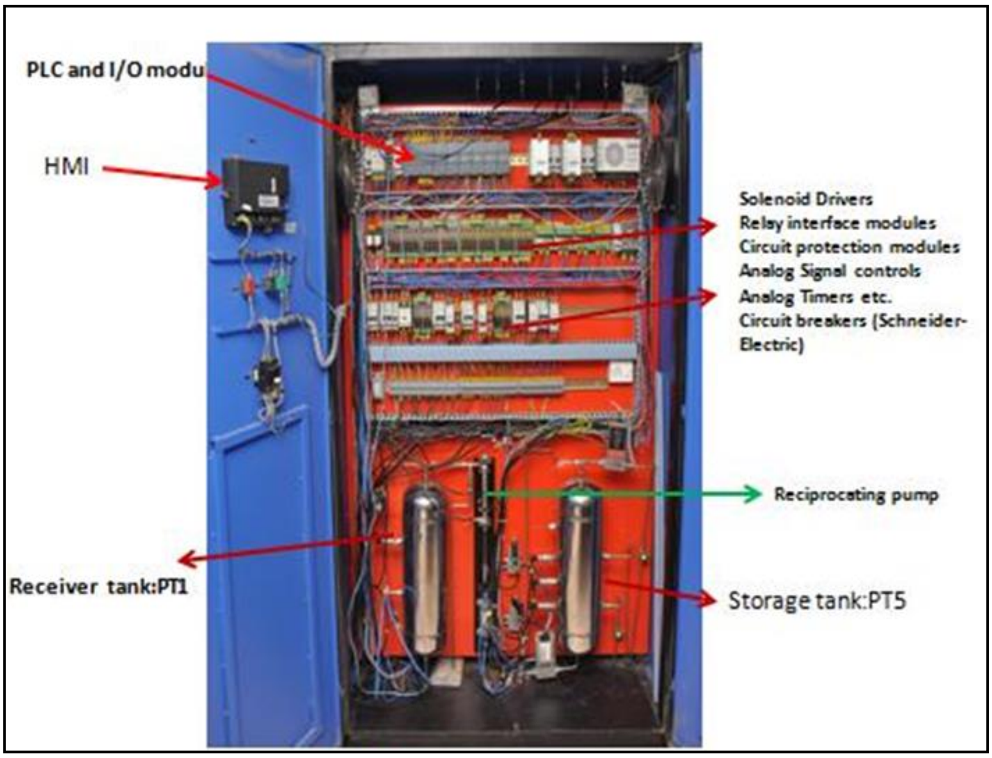

Figure 3.7: CLS showing different components

The pressure transducers have (4 to 20) mA current output are used for receiver tank (PT1), radical remover tank (PT2), regeneration of molecular sieve cylinders (PT3), Storage tank (PT5 and PT4), laboratory pressure monitor (PT6) and similarly the mass flow controllers MFC1 to MFC4 are for refilling of gas, MFC 5 for control of exhaust gas and MFC 6 for control of flow of gas into the RPCs. The relays are used to shut off the valves of MFCs to completely stop the flow of gas. The over current relays are used for the compressors, vacuum pump, electrical heater for regeneration and diaphragm pump. The timers are used to make heater ON or OFF and are used for controlling the displacement pump to start and stop and wait for particular position. A gang of solenoid valves are used for pumping of displacement pump and to control MFC supply.

There are two Analog inputs that are connected to the CPU from the RTDs which are used for monitoring temperature of gas purifier chambers. These parameters play a crucial role during recharging / regeneration of molecular sieves which are used for purification of gases.

The main CPU has six bit-operated digital inputs and 2 bit operated digital output. It is also providing 8 digital outputs as independent channels. Digital output of CPU and Signal Module are given to solenoid driver which is used to operate solid state relays controlling heaters, air compressor, metering and vacuum pump and solenoid valves of purifier units. The LAN interface has been controlled using CPU1214C.

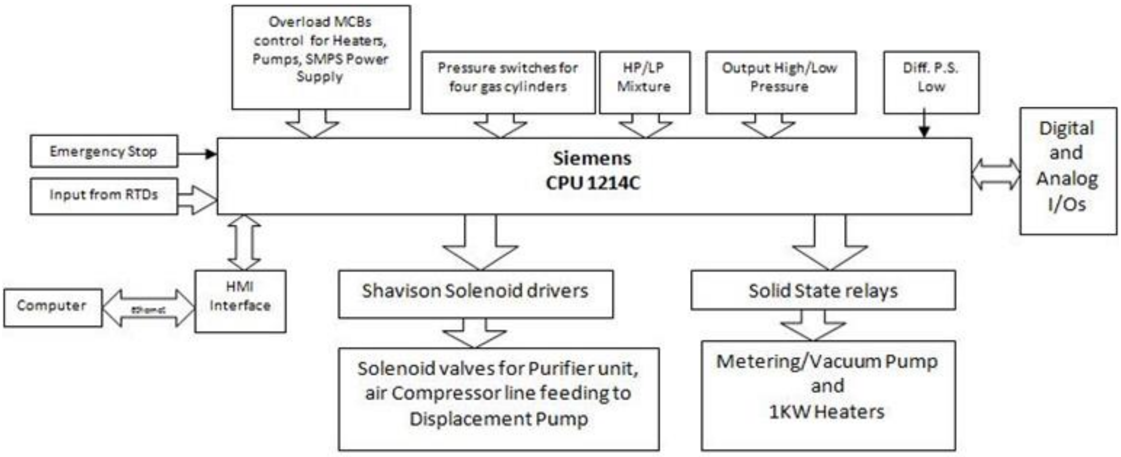

Figure 3.8: PLC based CLS control components

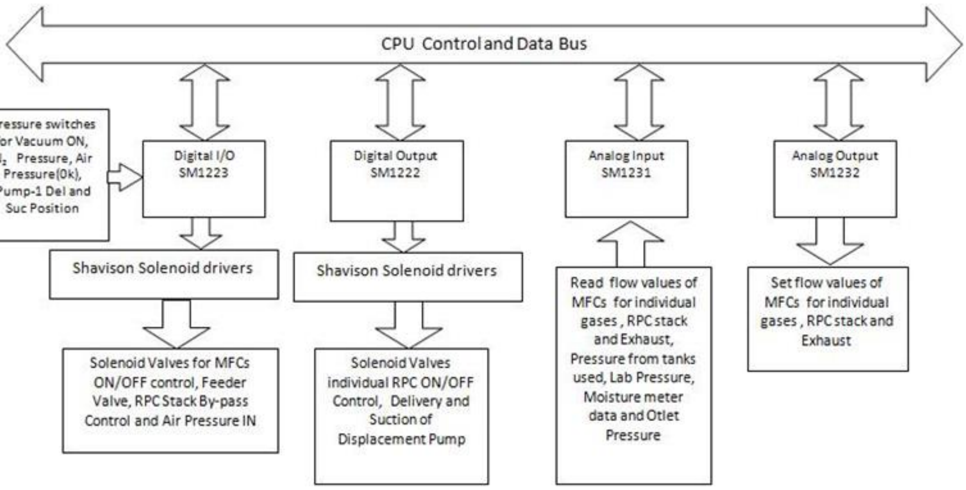

Figure 3.9: PLC modules and peripherals

The SM1223 DC-DC Digital I/O is used to get five inputs from Nitrogen (N_2) cylinder pressure input, air pressure, Pump-1 position delivery and Pump-1 position suction. Its eight outputs are connected to solenoid driver which controls the solenoids valves of MFC for on/off operation, feeder valve, air compressor and RPC stack By-pass operation.

Digital output unit (SM1222 DO) used to drive 16 solenoid driver circuit (Shavison AS775) which controls the gas flow ON/OFF operation of individual RPCs. It also drives positive displacement pump. Apart from these modules two Analog output modules (SM1232 AO) connected to exhaust MFC, RPCs flow MFC and individual gas MFCs to provide Analog control voltage in proportional to set gas flow.

One Analog input module (SM1231 AI) has seven inputs from storage tank pressure (PT5), laboratory pressure (PT6), moisture meter (used to check quality of gas), exhaust MFC (MFC 5), RPC flow MFCs (MFC 6), mixture tank-2 (controller) and outlet pressure. The other SM1231 AI module is used to get the control Analog voltage read values which corresponds to actual gas flow through the MFCs. The receiver tank pressure sensor (PT1) output, Purifier suction pressure(PT2) , regeneration Pressure(PT3) , storage tank pressure(PT4) have been monitored through this module.

A Human Machine Interface (HMI) is a platform which permits communication between PLC based CPU and computer interaction between users and automation equipment. It has 7 inch TFT LCD display with flash ROM of 128 MB and 30 MB system memory, a total of 82 MB user memory and 16MB backup memory is available. A RS-232/485/433 communication link is also present in this model and has in build feature of saving data through USB) without connecting it to PC. It provides 8 levels of passwords to set user security to prevent improper use.

A monitoring PC is connected to CLS CPU through Ethernet via DOP e-Server data collection software. There are 28 monitoring data (pressures PT5, PT1, mass flow rates, refilling time etc.) parameters that are stored every 3 minutes (can be set as per requirement) in an excel sheet for offline analysis. The CLS are built at other INO-ICAL collaboration institutions, but with few functions and a fully automated one.

3.4 Performance of CLS

. The ambient pressure variation cycle has great impact on the gas flow operation of CLS in absolute mode of operation, which in turn has effected on current, noise rate of the RPCs and a few RPCs were damaged. A differential mode of operation was then introduced to overcome the problem.

3.4.1 Results and Conclusion related to CLS

The Gas flow is controlled efficiently using PLC based instrumentation. All the peripherals of PCL-CPU are operating as per design with added modification for the last 4 years. The auto refill cycle of 12 days has been achieved with minimum a leakage which corresponds to about 5 litres of gas to top-up. The leakages of the gas at the several joints were further reduced by gluing and reduction in auto-refill cycle period was observed.

In the process of modifications the HPLP regulator is replaced by a capillary at each input of an RPC, the details of which are presented in the next chapter. The flow rate optimisation results are described in chapter 5.

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3.5 Tools developed during the development of gas systems

Several tools for testing and analysis of gas were developed for smooth function of the CLS. The gas flowing through the detector was monitored by using a bubble counter was developed and briefly explained below.

3.5.1 Bubble counter

As a part of R and D work for INO-ICAL development, several type of gas mixing systems open ended, open loop, closed loop etc., mixing systems were developed to study the flow and control of gas mixture into the RPCs. In the process several tools were developed and one such tool namely a bubble counter was developed making use of a microcontroller 89C51 (Philips make), to test the flow of gas into the RPC.

In an open ended gas system, the gas coming out of the RPC is left out into the atmosphere through a bubbler(s) made of borosilicate glass containing non-degassing oil DC706 (ρ = 1.08 gm./cc). The outlet of the RPC is connected to an Isolation bubbler and at the input bubbler is called as the safety bubbler [72].When there is a block in the flow path, due to dust particle or any impurity in the RPC, the safety bubbler releases the gas into the atmosphere and thus protects the RPC. The oil levels in the two bubbler is such that, the level in the safety bubbler is double (10 mm) that of the isolation bubbler. When the gas flows through the RPC, bubbles are seen the isolation bubbler and indicate that the system is functioning well (not leaky) which means there is continuous flow of gas through that RPC. Therefore, counting these bubbles indicates, there is a flow of gas in the RPC and the number of bubbles will indicate the quantity of gas flowing through it. To count these bubbles a microcontroller based system has been developed and successfully integrated during initial studies of Gas system and RPCs tests. The detail of electronics tool developed is given below.

3.5.2 Instrumentation

A simple LDR has been used to detect bubble shadow which is cutting light of LED seating opposite of LDR. The LED light is obstructed by the bubble passing through the light passage. When this happens there is resistance change in the LDR. This change is registered is processed to register a bubble count Figure 3.10.

The electronic tool to count the bubbles is divided into three sections namely (a) Sensor section (b) Signal conditioning and (c) Readout section.

In the sensor section, bubbles are detected using LED and LDR combination. The LDR and LED are kept face to face on the wall of glass bubbler containing oil as shown in Figure 3. The LED light falls on the LDR through the oil. When bubble comes out of bubbler, it blocks the light falling on LDR which in turn increases the resistance of the LDR. In the signal conditioning section, the small variation of resistance is sensed in terms of voltage by connecting it to the comparator through a buffer. The comparator output is connected to microcontroller port. Isolation is provided between the microcontroller and the signal conditioning circuit section by using an op to-coupler.

In the readout section, an LCD display of 16 × 2 lines is used to read the counts through the microcontroller and display it. The first line on the display is the bubble count which is updated as and when it is registered and second line shows the count of the bubbles per minute. The code has been written in assembly language and then the hex file has been loaded in Microcontroller using application called flash magic.

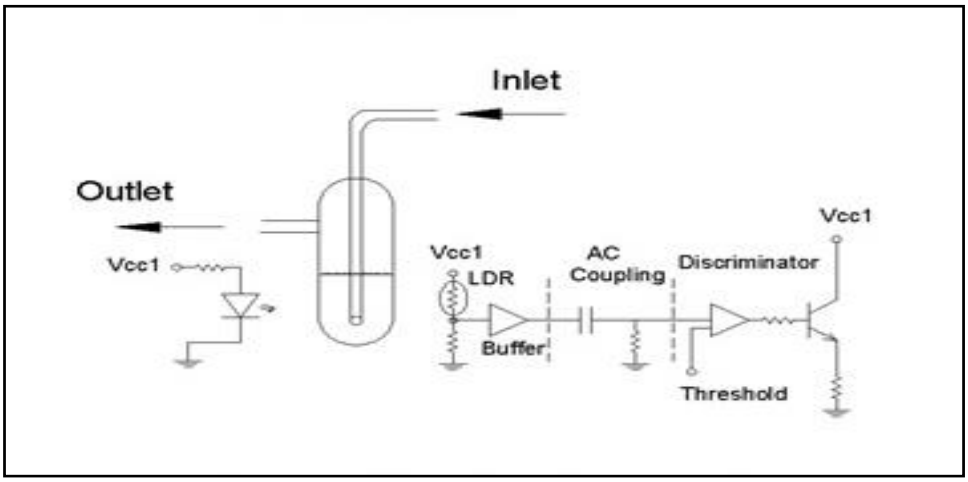

Figure 3.10: Principal of operation of the counter

The Digital bubbler that has been designed, fabricated, integrated and tested and is very useful for keeping track of gas flow through the RPCs. We are able to estimate the gas loss and hence check leakages by the bubble count measurements. The total gas used is 8 litres per day and from this value, one can estimate as to how many bubbles are expected. It is observed that the diameter of each bubble was about 4 mm, and then we expect 3 bubbles per second for 8 litres of gas in a day. Within a 5 to 10 % error we could use this digital counter at the initial phase of testing the gas system. The system supports 999 bubbles per minutes that could be counted. The data logging could also be done with this microcontroller based. A similar system Digital bubbler is developed by BaBar IFR detector at SLAC [67] but the technique and sensor is different.

3.6 Study of gas mixture inside an RPC using Residual Gas Analyser

The sophisticated gas analysers like the Gas Chromatographs are used at CERN experiments for studying the breakdown radicals of gas mixture coming out, after the usage from an RPC and several results are reported in [96], [98], [99], [100]. But the Chromatographs are expensive. In lieu of the chromatograph a simple Residual Gas Analyser (RGA) which is a small scale mass spectrometer is used by us. It is connected directly to a vacuum system (vacuum chamber) and whose function is to analyse the gases inside a vacuum chamber. It can be used for complete characterization of a vacuum environment that requires the detection of all the component gases present, as well as measurement of the total pressure.

A Stanford Research Systems (SRS) incorporation make RGA (Residual Gas Analyser) probe was purchased by us. This probe was then hooked to a turbo vacuum pump (Pfeiffer make) along with an assembly of chamber with ports which was designed by us. It is interfaced to a PC through an RS232c port. The library for basic analysis is provided by the SRC.

3.6.1 RGA Principle of operation

A small fraction of the gas molecules are ionized (forming positive ions), and the resulting ions are separated, detected and measured according to their molecular masses (mass to charge ratio of ion). To accomplish these, a typical RGA has three major parts, namely, an ionizer, a mass analyser (here it is a quadruple filter), and an ion detector as shown in Figure 3.11. (*This figure is adapted from the SRS manual).*

The output of an RGA is a spectrum that shows the relative intensities of the various species present in the gas. This output is known as a mass scan or mass spectrum. From these mass spectra one can identify the different molecules present in a residual gas environment and, when properly calibrated, it can be used to determine the concentrations or absolute partial pressures of the components of a gas mixture.

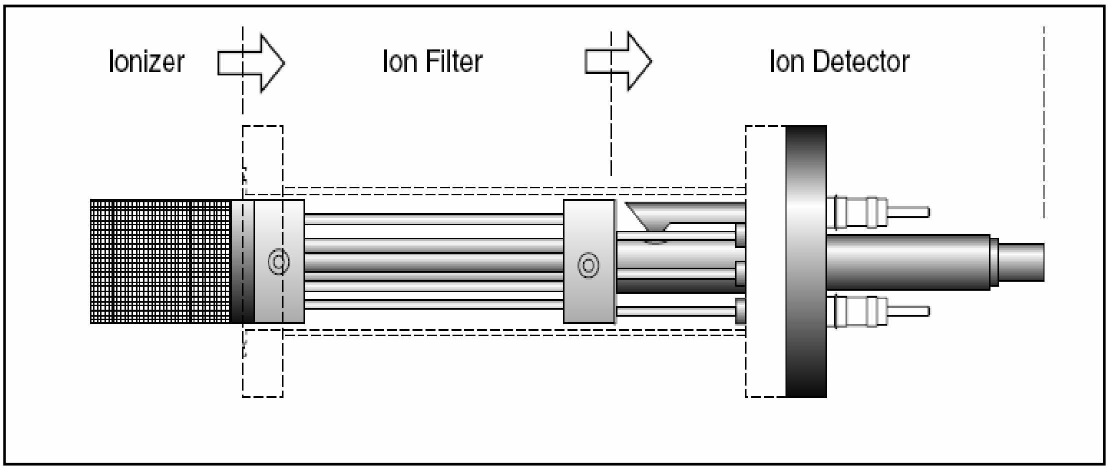

Figure 3.11: Major Components of an RGA

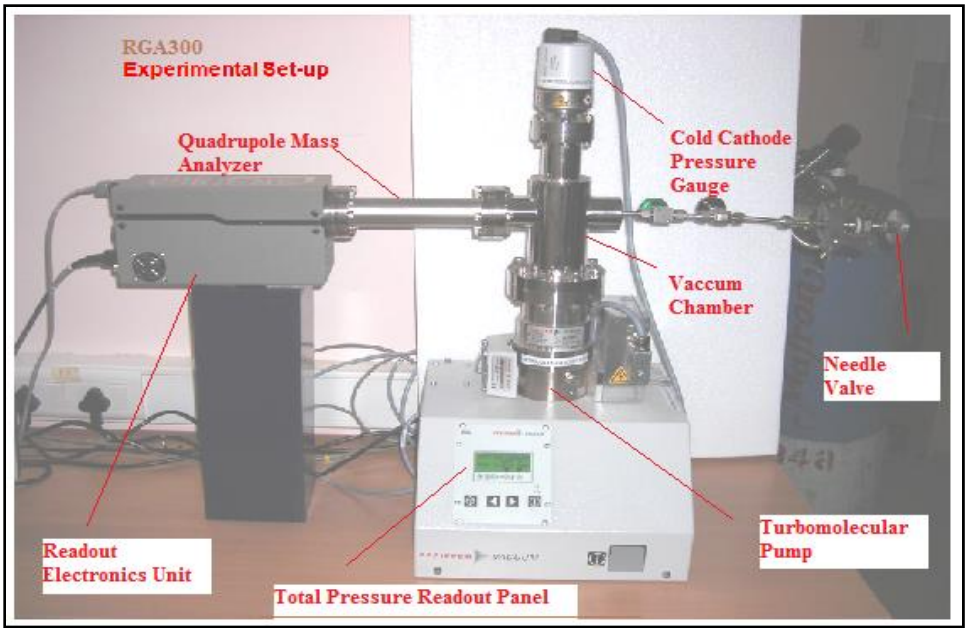

Figure 3.12: Experiment setup of RGA system

3.6.2 Procedure to obtain mass spectra of Gas or Gas Mixture

The complete experimental setup is shown in Figure 3.12. The fabricated vacuum chamber whose one end is connected to the RGA probe and the other end is connected to the RPC gas (to be analysed) output through *a* fine tune needle valve. The chamber is evacuated to a very low pressure of the order of 10^{-8} mbar.

The needle valve is used for fine tuning the flow of gas inside the chamber. Initially it is turned off not letting any gas to enter the chamber while the chamber is being evacuated.

After sufficient flushing for hours together, the needle valve is opened such that the gas to be analysed enters the chamber at a pressure of order 10^{-5} mbar. Again to remove traces of impurities that might be present inside the chamber, the chamber is flushed with the gas to be analysed at pressure of order 10^{-5} mbar for a couple of hours. Since flushing process takes time hence the entire process of taking a mass spectrum becomes time consuming.

Then the RGA is turned on and then the filament is switched on, such that it heats up. The RGA is operated via a computer interface where mass spectra data is collected. A typical mass spectrum is shown below where X-axis corresponds to mass by charge ratio in atomic mass unit and Y-axis corresponds to the ratio of pressure at a particular m/e to the total pressure represented in terms of percentage.

3.6.3 Procedure for analysis of gases using RGA

The vacuum pressure at maximum (closing all the valves) should reach about 1.2×10^{-8} mbar. The RGA system is connected to PC via the RS232C and then the filament is switched on and set the mode as histogram and the scan parameters stop mass to 150 (since SF6’s molecular mass is 146). Start the scan, set the ‘analyse’ window (In utilities) on the screen so that you can analyse the gases present in it. After every 10 scans save the ASCII data (In file) for analysis. Save at least four to six ASCII data [about 50 to 60 scans].The ASCII data gives all the masses (150 masses) versus its partial pressures. Create an excel file and import the ASCII data [It will give you partial pressures of all the 150 masses]. Normalize each mass pressure with total pressure (sum of partial pressures). For example, if total pressure = 1.2×10^{-8}, partial pressure for a mass number = 3×10^{-9}. Then the normalization = $(3 \times 10^{-9} \times 100) / 1.2 \times 10^{-8}$. Normalize each mass pressure with highest partial pressure. Plot molecular mass Verses percentage of gases in actual normalization and highest gas normalization. For each of the gases the cylinders are connected and gases are flushed for about 2 hours and the vacuum pressure obtained is in the range of 2.2×10^{-5} to 5.4×10^{-5}.

3.6.4 Results of gases analysis

The RGA analysis results of (a) R134a gas, (b) I-butane and (c) SF_6 gases in the pure form directly obtained from the cylinder(s) are shown in Figure 3.13, Figure 3.15, and Figure 3.17. As per the National Institute of Standards and technology (NIST) Chemistry web book reference [101], the plots for R134a and I-butane are shown in Figure 3.14, Figure 3.16 and the RGA spectrum for SF_6 is available in the Library of the SRS system itself so we have used the for analysis and comparison. It is shown in

Figure 3.18 and all are normalized plots. The results for the 3 gases are summarized in, Table 3.3, Table 3.4 and Table 3.5 which shows the complete breakdown fragment of each gas. There is good correlation between the two plots except for addition of moisture seen in the acquired plots.

3.6.4.1 RGA spectrum of R134a gas

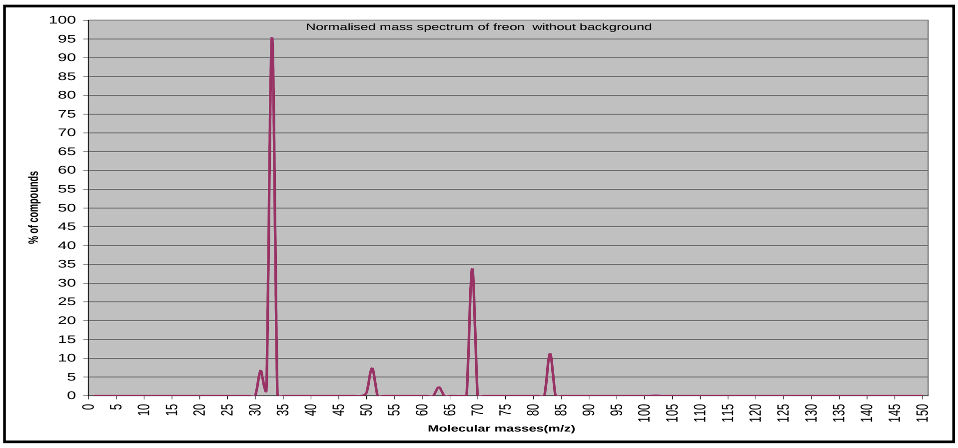

Figure 3.13: RGA spectra of R134a gas

As per NIST (Chemistry web book) the spectrum is considered for cross-checking

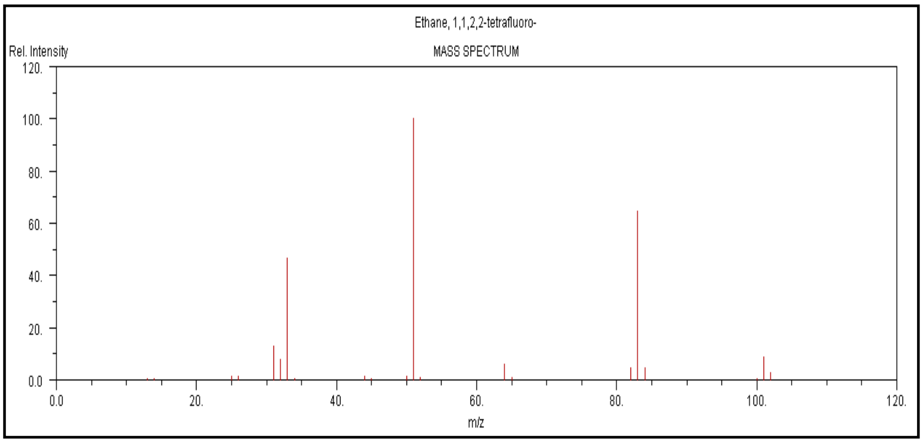

Figure 3.14: RGA Spectrum as per NIST Chemistry web book

Table 3.3: R134a (CH_2FCF_3) Fragments

Molecular mass	Fragments	Actual Percentage (with background)	Actual Percentage (w/o background)	Normalized percentage (with background)	Normalized Percentage (w/o background)	NIST Library
33	CH_2F	52.52	51.37	100	95.42	47.1
69	CF_3	18.7	18.24	35.69	33.85	NA
83	$C_2H_2F_3$	6.31	6.1	12.1	11.24	64.6
31	CF	5.26	4.46	10.019	6.84	12.8
51	CHF_2	4.43	4.17	8.454	7.37	100
63	$C_2H_2F_2$	1.53	1.38	2.9	2.35	NA
32	CFH	2.14	1.52	4.07	1.64	8.3

3.6.4.2 RGA Spectrum of I-butane

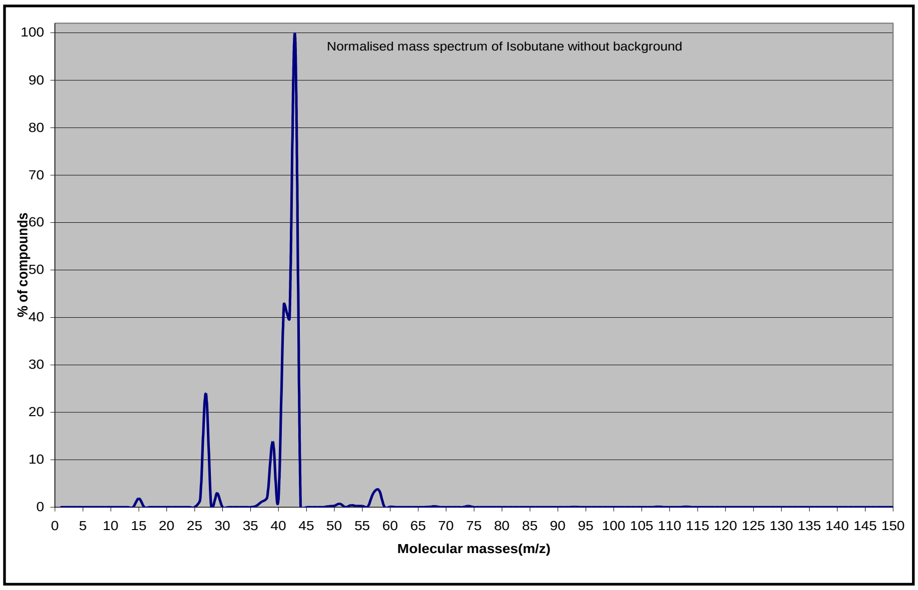

Figure 3.15: RGA I-butane pure gas spectrum

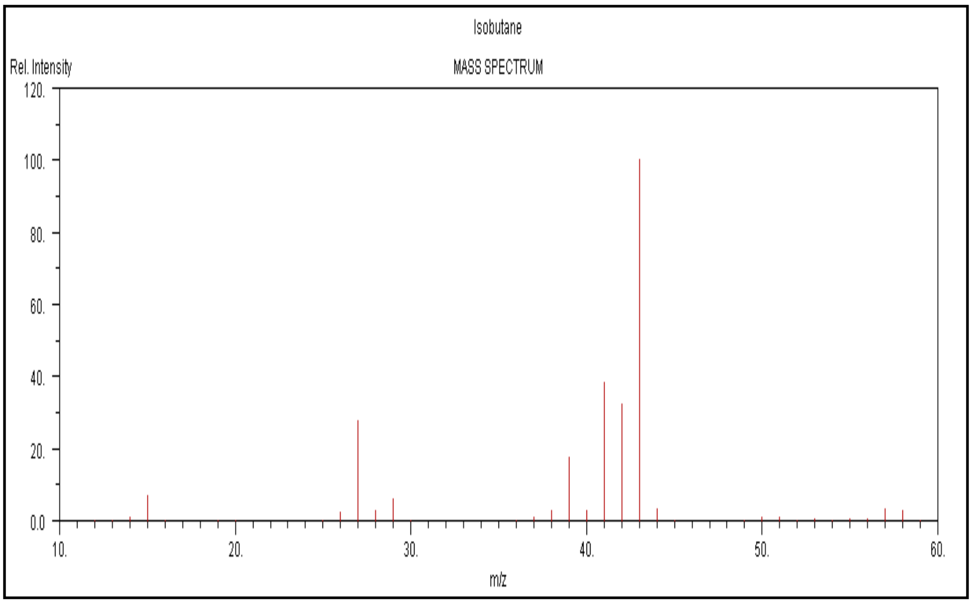

Figure 3.16: RGA for I-Butane Spectrum as per NIST Chemistry web book

3.6.4.3 RGA spectra of gas mixture

In the CLS, the R134a, I-butane and SF6 gases are mixed in fixed proportions and are flown through RPC. The RGA spectrum is obtained using one of the outputs connected to RGA system via fine tune needle valve (to attain a stable low pressure). The output will be always going through a bubbler ensuring flow of gas. Also we have collected the spectra of gas coming out of RPC, with similar arrangement. The normalised plots are shown in Figure 3.19 and Figure 3.20 are expected and calculated.

We generated the mixed gas RGA (Calculated output) spectra from the known mixing ratio of the gases, using individual pure spectra. It is well matching with the Spectra collected gas (which is input to RPC). But it was not matching with the spectra collected with gas which was coming out of RPC. Also the spectra of mixed gas and RPC output gas are not matching in some mass number like 28, 18. The plots are shown in Figure 3.21. The reason could be due to plastic tubing that is used for the gas coming out of RPC and may be prone to moisture and air and also somewhere gas may be leaking.

Table 3.4 :I-butane (Fragments)

Molecular mass	Fragments	Actual Percentage (with background)	Actual Percentage (w/o background)	Normalized percentage (with background)	Normalized Percentage (w/o background)	NIST Library
43	C_3H_7	36.28	36.05	100	99.27	100
41	C_3H_5	15.76	15.54	43.44	42.76	37.9
42	C_3H_6	14.62	14.47	40.29	39.821	32.3
27	C_2H_3	9.27	8.76	25.55	23.945	27.7
39	C_3H_3	5.1	5.01	14.062	13.79	17.5
29	C_2H_5	2.13	1.21	5.88	2.95	6
15	CH_3	1.48	0.77	4.08	1.82	6.9

3.6.4.4 RGA Spectrum of SF_6

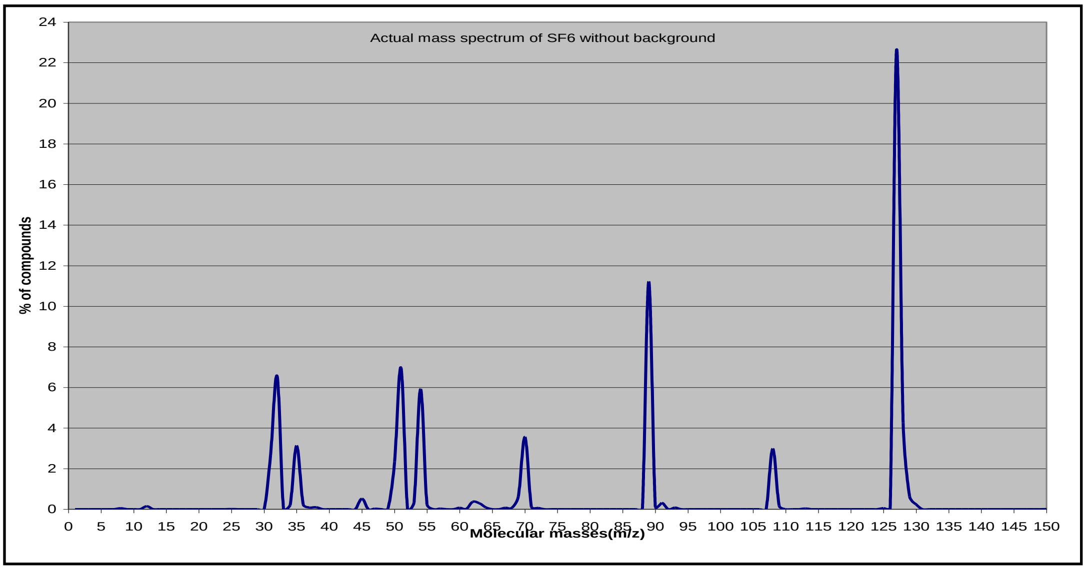

Figure 3.17: SF_6 RGA Spectrum

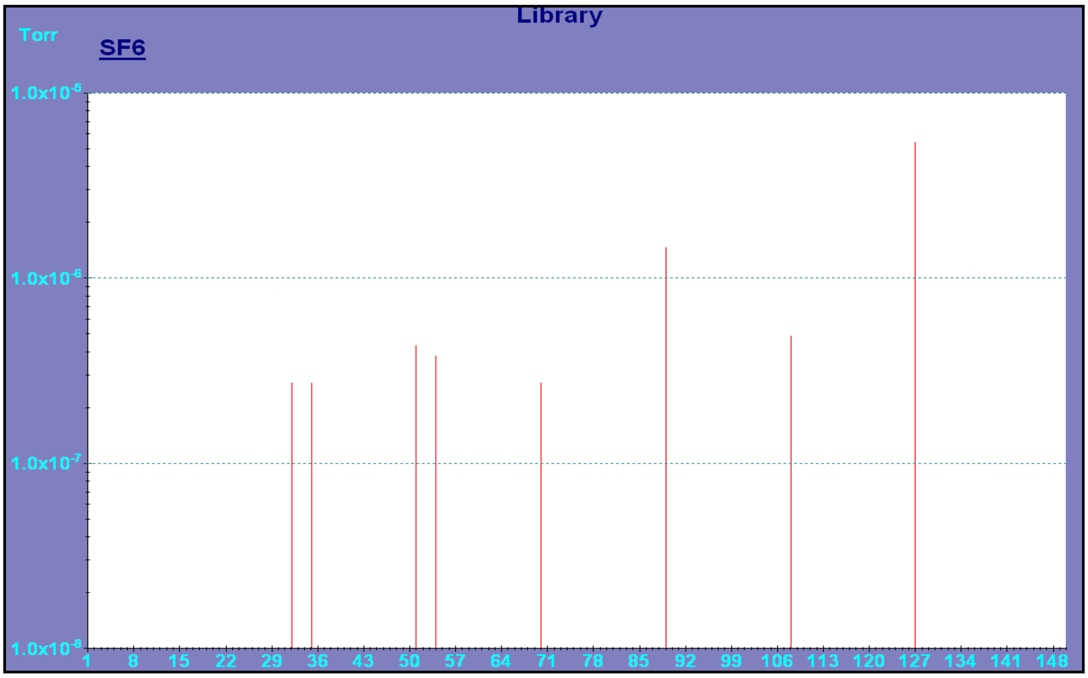

Figure 3.18: RGA SF_6 pure gas spectrum (SRS Systems Library)

Table 3.5: SF_6 gas Fragments

Molecular mass	Fragments	Actual Percentage (with background)	Actual Percentage (w/o background)	Normalized percentage (with background)	Normalized Percentage (w/o background)	RGA Library
127	SF_5	22.69	22.63	100	99.81	60.241
89	SF_3	11.29	11.2	49.75	49.47	16.241
51	SF	6.91	6.96	30.52	30.68	4.81
32	S	7.1	6.54	31.34	29.55	3.01
54	SFH_3	5.83	5.9	25.73	25.93	4.21
70	SF2	3.56	3.55	15.69	15.67	3.01
35	SH_3	3.22	3.12	14.2	13.91	3.01
108	SF_4	2.95	2.97	13.012	13.09	5.421

3.6.4.5 RPC mixed gas RGA analysis

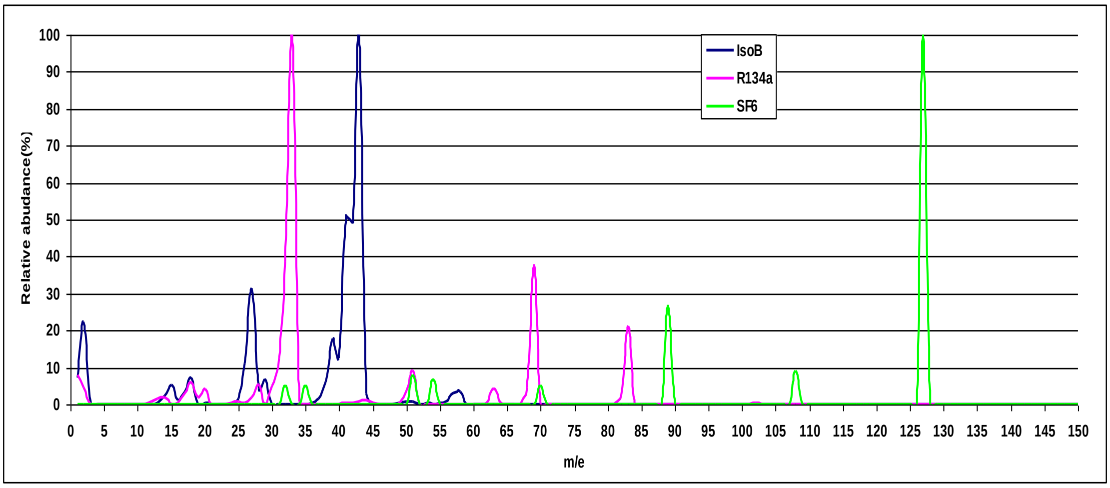

Figure 3.19: Mixed gas (R134a + SF_6 +I-butane) RGA spectrum

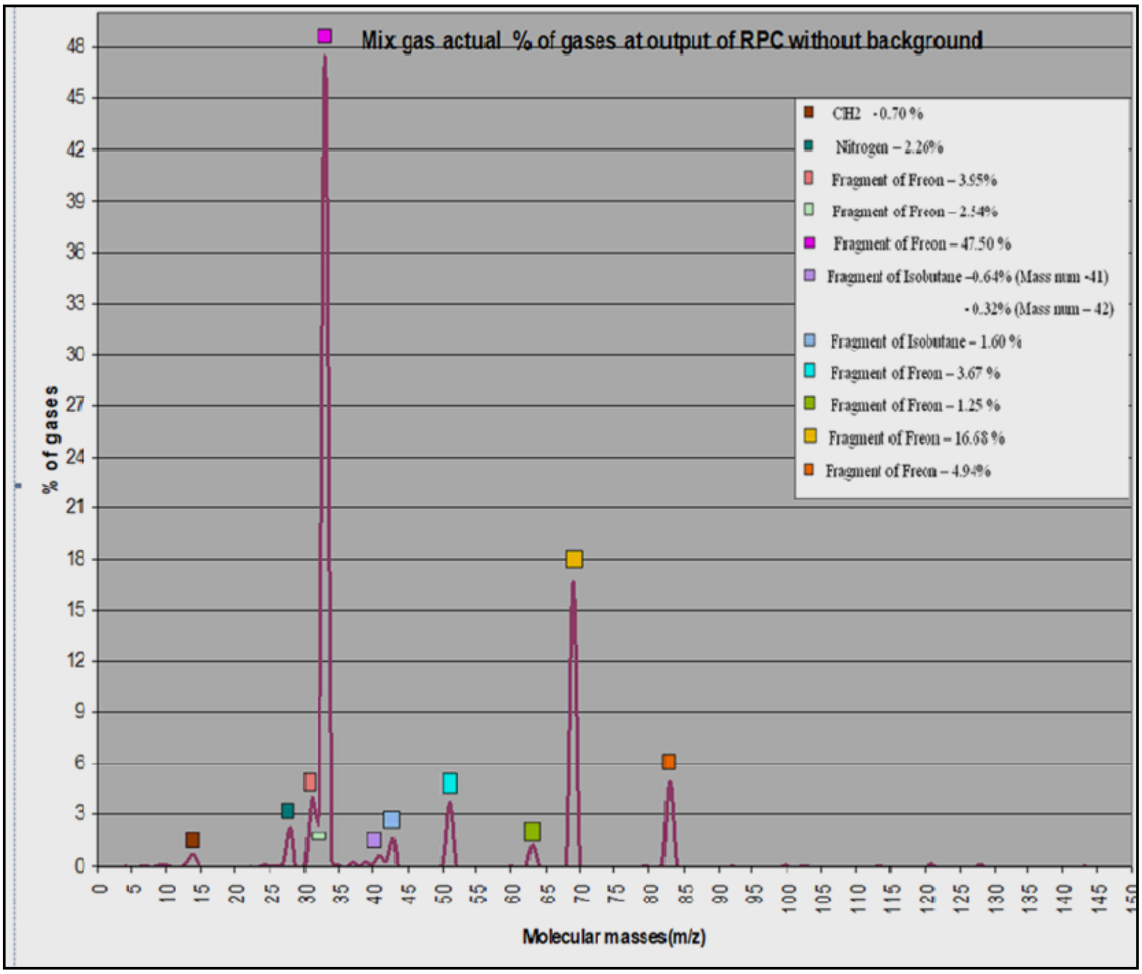

Figure 3.20: RPC output mixed gas Normalised spectra in CLS

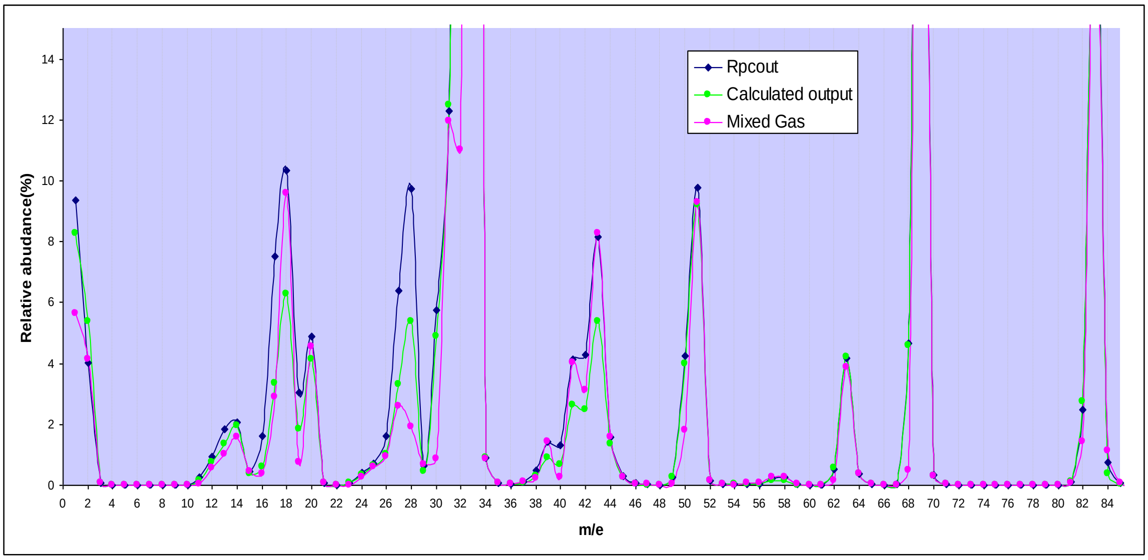

Figure 3.21: Mixed Gas (RPC output Calculated and Observed)

3.6.5 Studies using "Sealed RPC"

The RGA was interfaced in the loop of the 4 RPC stacks of 4 RPCs in the CLS and operated for the last several years. We have not observed any breakdown radicals from the gas mixture in the CLS loop. The moisture level was found to increase gradually, but the current and noise was found to be in acceptable range. This could be attributed to the leakages in the plumping and flow rate.

Unlike the proportional counter, where the mixed gas is sealed inside the chamber, the mixed gas is flowed inside the RPCs and is removed through the exhaust nozzles continuously (there is no stagnant gas). An interesting result was observed when an RPC was sealed (both input and output nozzles were closed after filling gas in it) and the efficiency, current and noise rates (background noise signals) were monitored round the clock for 4 months. Its efficiency was found to have declined from 90% to over 80% over the period of 4 months. This decline in efficiency is attributed to decline in gas mixture quality. Yet, no breakdown radicals were observed, during operation of 4 RPCs in a CLS for more than a year. One of the reasons could be due to the low background rate and moreover the set flow rate may be lower than required.

3.6.6 RPC performance with gas mixture

a) The studies done by sealing the RPC output and the input, after filling it with a mixing gas show that the efficiency of the detectors has not decreased substantially over the period of 4 months. So fresh gas need not need be frequently flushed or topped up in the system.

b) We need to monitor regularly the concentration of gas mixing ratio, gas flow rate, bubblers, proper circulation, pressure variations, leaks etc. and the long term reliability of cylinder exchanges, replacement or regeneration of molecular sieves, all safety parameters related to detectors, system leaks, working place and working staff.

c) The periodic pressure changes in the atmosphere were addressed and the system is successfully functioning over the last 4 years and the results are reported here.

d) Using RGA 300 (Residual Gas Analyser-SRS make), a small scale mass spectrometer is hooked in the loop of gas flow in the CLS to monitor continuous the gas coming out of the RPCs and the moisture content, concentration ratio of the gas mixture, O_2 etc. are studied in detail. Appropriate molecular sieves are used in the purifier section in the CLS to remove and purify the impurities like the moisture, O_2 etc. *The removal of N_2 is not known and remains to be solved. But, optimizing the leaks (air entering inside) in the CLS loop improves the performance.*

e) The flow rate of the gas mixture into the RPC is a very important parameter. In the initial design of CLS system, the flow of few litres per minute (LPM) was assumed and designed (as in the case of LHC experiments), several INO glass RPCs were damaged as the flow set was of the order of few LPM. The back ground rate for INO-ICAL at the underground will be very low and the electrodes of the INO RPC, being a simple glass float a flow rate of few SCCM was found to give satisfactory RPC performance results.

f) Some studies on the gas mixture and high voltage monitoring are described in [93] which are not addressed by us so far.

g) The design feature and studies performed on CLS system may be used as bench mark for future up-gradation and most of the thesis work pertains to this work

Chapter 4

Experimental studies on flow resistors and Simulation of gas flow inside an RPC

In this chapter, we describe the experimental studies on different flow resistors namely the capillaries [102], [103] and simulations. We have fabricated various types of capillaries to study the effect of capillary as a dynamic impedance element on the differential pressure across RPC detector in a CLS. The simulations related to the parameters like the flow rate, gas distribution of the gas mixture inside an RPC and nozzle positions on the RPCs are studied on various platforms like Solid-Works, COMSOL and CDF are performed.

The performances of the RPCs depend on various parameters like environmental conditions (such as atmospheric pressure, ambient temperature, humidity, radiation etc.),[86], [104], [70], [105], [106] etc., flow rate of gas mixture into the RPCs, concentration or the composition of the gas mixture (which should be maintained throughout the operation of an RPCs), quality of gas, the RPC input gas pressure, uniformity of conductive coating on the surface [12] uniform gas gap thickness, nozzle positions, electrode thickness, ageing [31] etc. In the previous chapter the studies related to the purity of the gases, concentration of gas mixtures and analysis is addressed.

In this chapter, we have tried to address the optimum flow rate that would be required and type of flow limiting register that could be used suitable for the RPCs without deteriorating the performance in a CLS environment.

4.1 Experimental studies with Capillaries

The problem of balancing the flow of gas mixture into the RPCs using a flow resistance viz. capillary is done. Several different sizes of capillaries are fabricated and studied so that the optimum dimension of capillary that could be used in the RPC tray in the final ICAL. In the following, we describe the design and test carried out with different types of capillaries and their behaviour with different gases.

4.1.1 Design of capillary and testing

A capillary tube is a long, narrow tube of constant diameter and acts as a flow limiter and majoring the chamber impedance so as to make the individual flow independent on the chamber impedance. The capillary is used in medical applications and widely used in gas detectors in large experiments like CMS and ATLAS at CERN. The capillary acts like high impedance source in an electrical system, where the pressure drop is analogous to the voltage and the flow to current. It obeys a linear relationship. Therefore, if we need to supply uniform flow into multiple RPCs from a common source (manifold) which is at high pressure, then a capillary at the input of each RPC would act like a high current source and the flow would be uniform in all RPCs having different impedances (due to the different lengths of tubes connecting them at the input).

A standard flow of 6 SCCM is being used based on the study done so far, corresponding to about one volume change per day with a safe differential pressure of 2.5 mbar across the input of an RPC.

Started fabricating the first capillary, assuming the input pressure to be 1.002 bar abs (which is a requirement of MFC used in the CLS), the length of stainless (SS) tube to be 2500 mm, pressure difference required to be say about 2.5 mbar for a flow rate of 6 SCCM and considering the viscosity of the R134a gas (which is the major component). The diameter of the capillary tube using Hagen-Poiseuille Law (as given below), is about 300 microns and offers 1 PSIG resistance to a flow of 6 SCCM. The flow is assumed to be laminar, viscous and incompressible.

The flow rate, Q, is given as per the following equation

$$Q = \frac{\pi \times \Delta P \times D^4}{\mu \times 128 \times L} \qquad (1)$$

where D = diameter of tube in meter, L = length of the tube in meter, μ = dynamic viscosity of gas (Pa), ΔP = Pressure Difference (Pa.); Capillary bore is about 300 micron. This capillary is wound on a bobbin for safe handling.

Several other capillaries with different diameters and lengths were then fabricated as mentioned below and the following tests are carried out with these capillaries using different gases.

4.1.2 Types of capillaries under test

To study the effect of capillary as a dynamic impedance element on the differential pressure across the RPC detector in a closed loop gas system, two sets of capillaries were fabricated and tested.

a) 3 capillaries namely C2, C5 and C6 having inner diameter (ID) of 300 micron and outer diameter (OD) of 1000 micron and having lengths of 150 mm, 600 mm and 2500 mm respectively and

b) 3 capillaries namely C1, C3 and C4 having ID of 1800 micron and OD of 3100 micron and having lengths of 1500mm, 1200mm and 600mm respectively as shown in Figure 4.1.

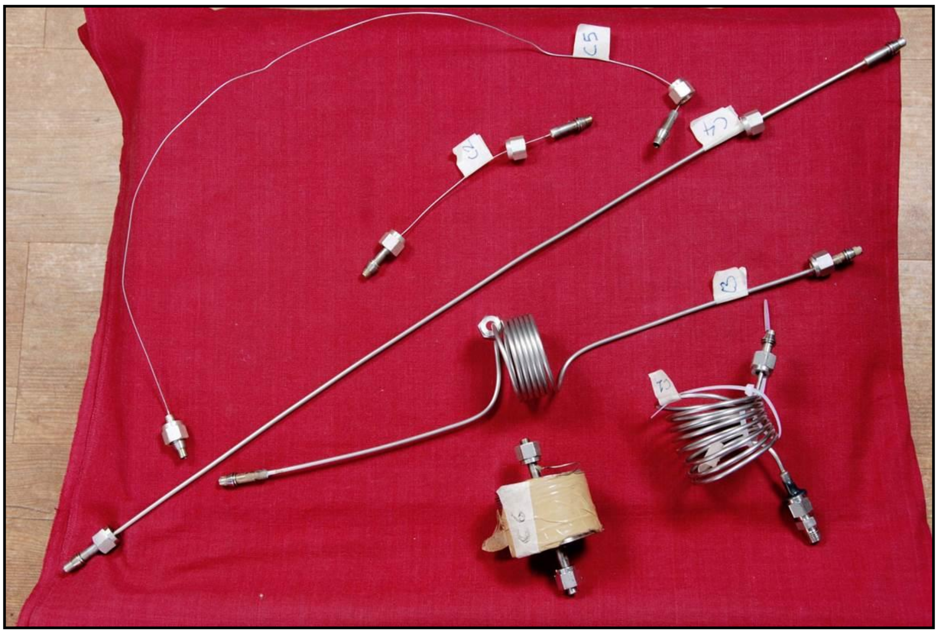

Figure 4.1: Capillaries C2, C5 and C6 of 300 microns C1, C3, and C4: 1800 micron

4.1.3 Experimental Setup

A simple AURDINO microcontroller is used having open ended source. The experimental setup is as shown in Figure 4.2 and as seen in the block diagram, under observation test, there is a provision to connect different capillaries and if required an RPC can be connected in lieu of capillary to measure the differential pressure. The components in the loop are two Mass Flow Controllers (MFC), differential pressure sensors and a microcontroller (Arduino-Uno) board with an add-on 16 bit ADC (ADC 1115), interfaced via USB to a computer.

The studies are performed by flowing 3 gases namely $C_2H_2F_4$ (R 134a), C_4H_{10} (I-Butane) and SF6 (Sulphur hexafluoride) into the capillary and measuring the pressure across set flow. The data is recorded at a rate of (17 to 20) samples per second in a PC operated in the Linux platform.

We had two old MFCs of Tylan make, having full scale of 45 SCCM meant for nitrogen gas. The minimum operating pressure is 2 bar abs and one of them is used at the input, to set and control of the flow of gas and it is called as the control MFC, while the second MFC function is to read only and hence we call it a meter MFC at the output of the capillary. The two MFCs are calibrated using water displacement method for each of the gas and a typical calibration plot for SF6 gas is presented in Figure 4.3. It is seen from the calibration plot that a flow of 10 SCCM (nitrogen gas) corresponds to 2.69 SCCM for SF_6 gas as the MFC is meant for nitrogen, while being used for SF_6 etc. A factor of 0.26 needs to be considered for SF_6 and similarly the calibrated factor are 0.25 and 0.28 for I-butane and R134a respectively.

We started the experiment with a pressure sensors namely (a) XLdp, Ashcroft made, which is a diaphragm based, having a differential pressure range of ± 61.3 mbar with a current output of (4 to 20) mA and having a resolution of ± 0.005 mbar. At a later stage we have used SM5852, Silicon Microstructures Inc. make, a fully amplified, and calibrated and temperature compensated sensor and having a range of ± 100 mbar, with full scale of 0.5 volts to 4.5 volts (amplified digital output) with a resolution ± 0.1 mbar. The second pressure sensor had to be used due to the limitation in the range of the first one, as it was getting saturated beyond the range as seen in the plot Figure 4.4, which also shows the I-butane gas behaviour with different capillary.

4.1.4 Ohmic law for pressure versus flow

The Ashcroft made sensor has an out current of (4 to 20) mA and using a multi meter the current is recorded against each flow rate set, and in parallel the current values measured by converting the same current by (RCV420) to voltage and calibrated to differential pressure are noted. The equivalent current read value(s) to the pressure difference value is plotted in the same Figure 4.5, which is a linear plot and also follows the equivalent Ohmic law for pressure versus the flow.

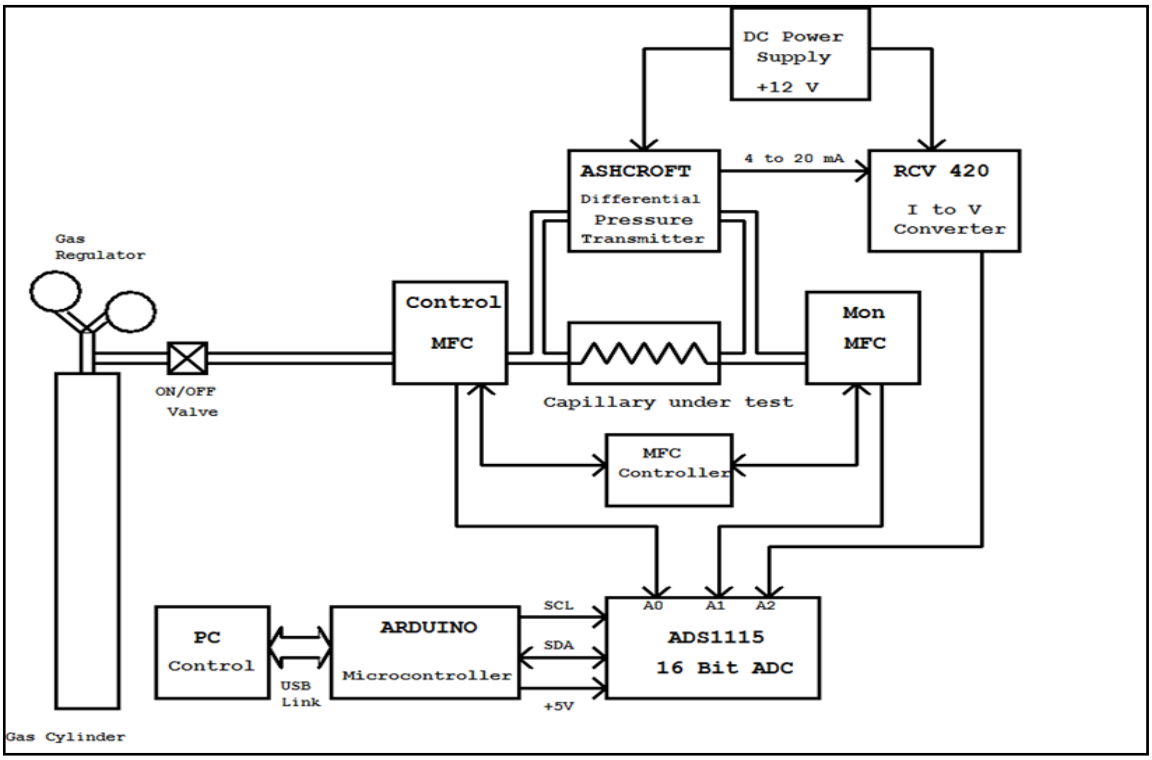

Figure 4.2: Experimental Setup

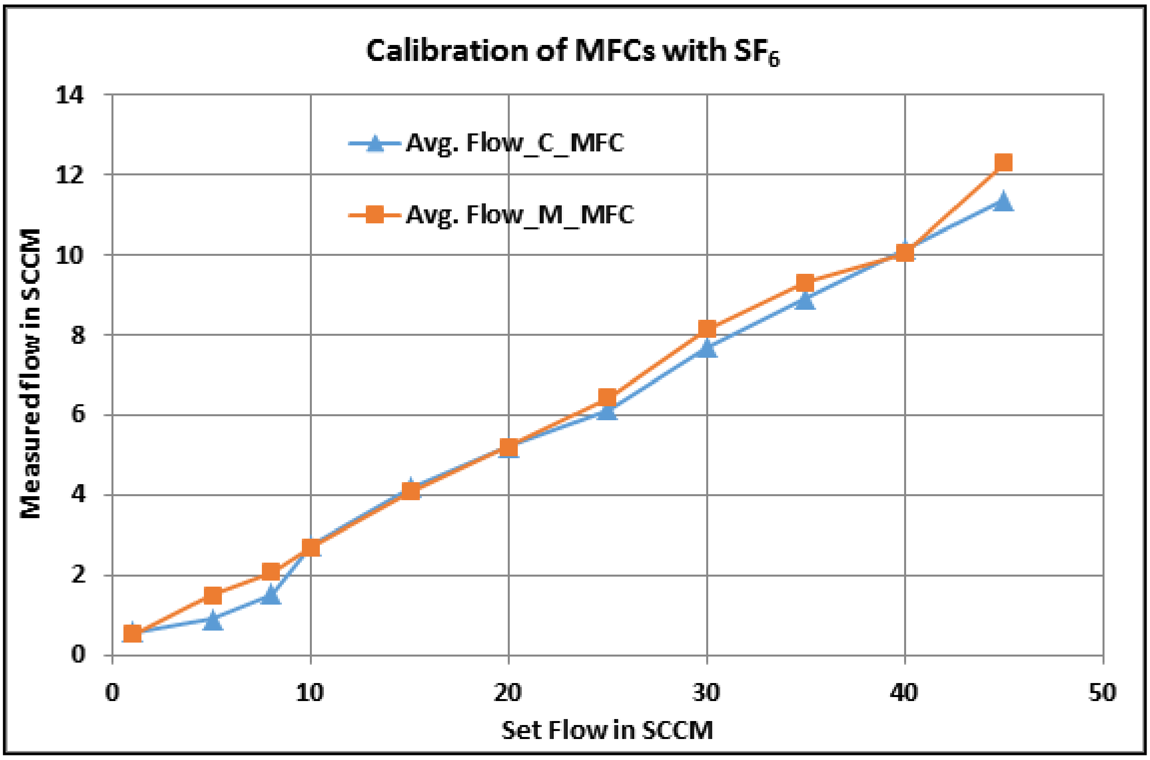

Figure 4.3: MFC calibrations for SF_6 Gas

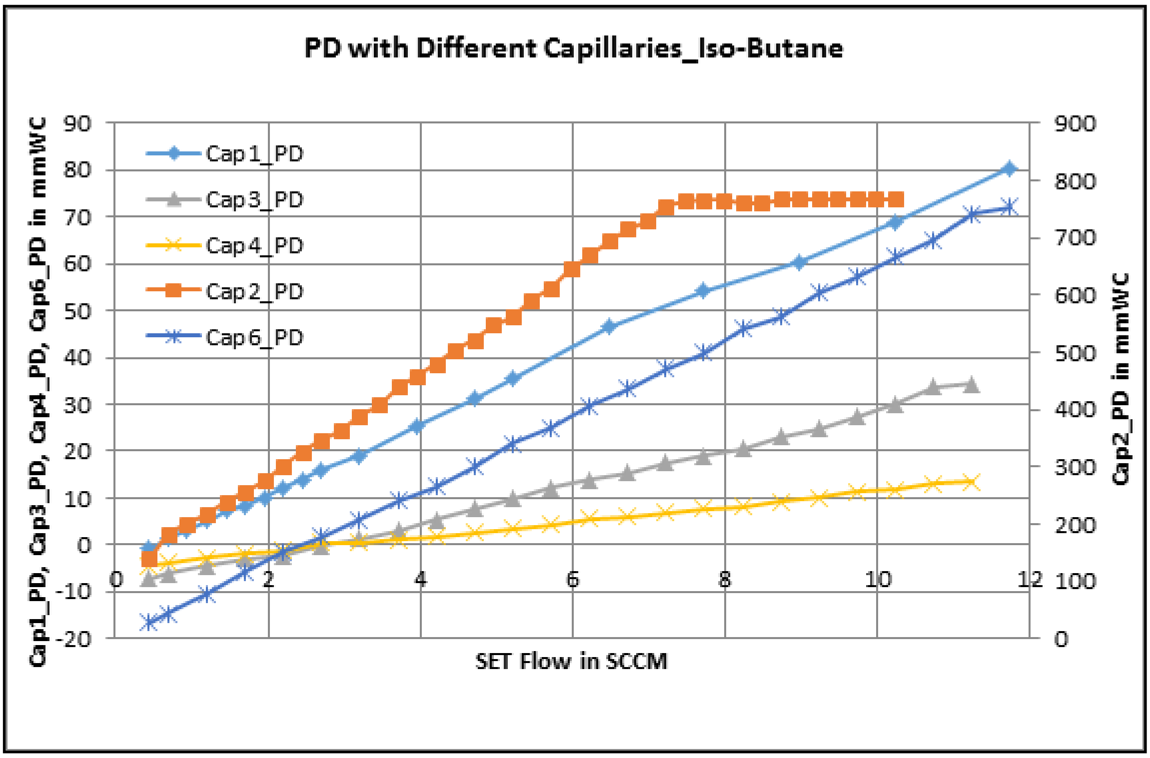

Figure 4.4: Results with Ashcroft Differential Pressure Sensor

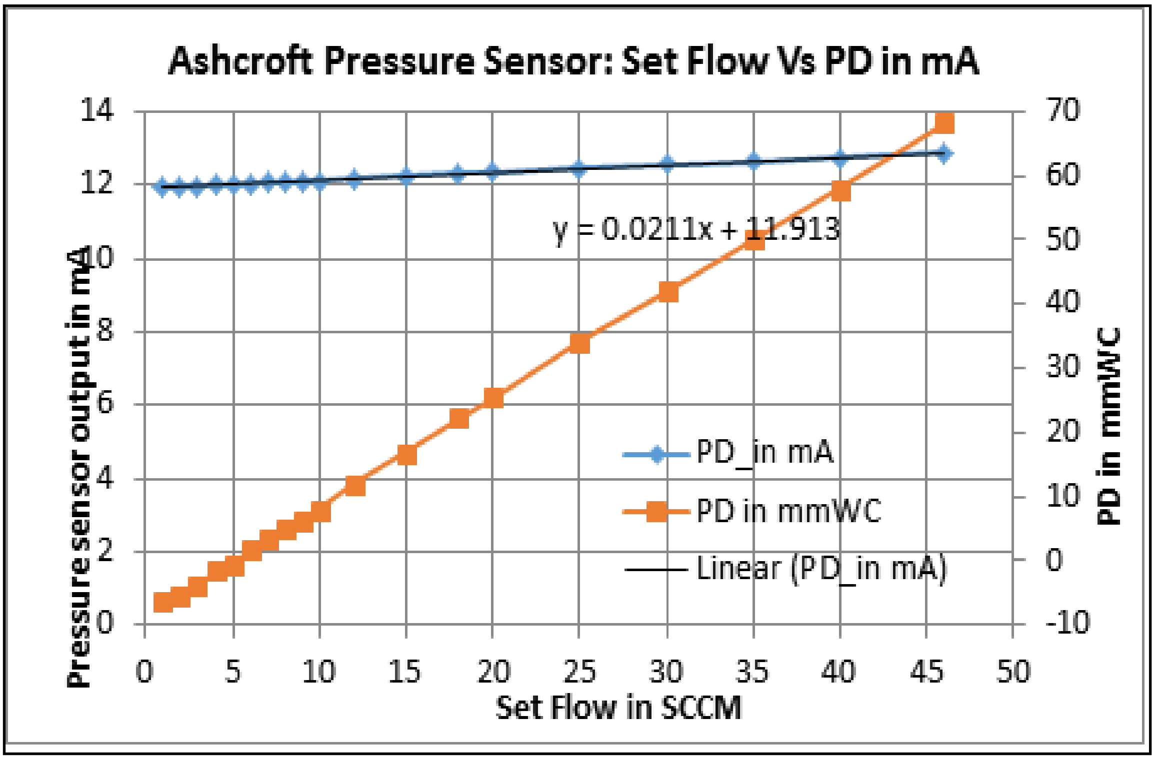

Figure 4.5: Flow to current relation using Ashcroft Pressure Sensors

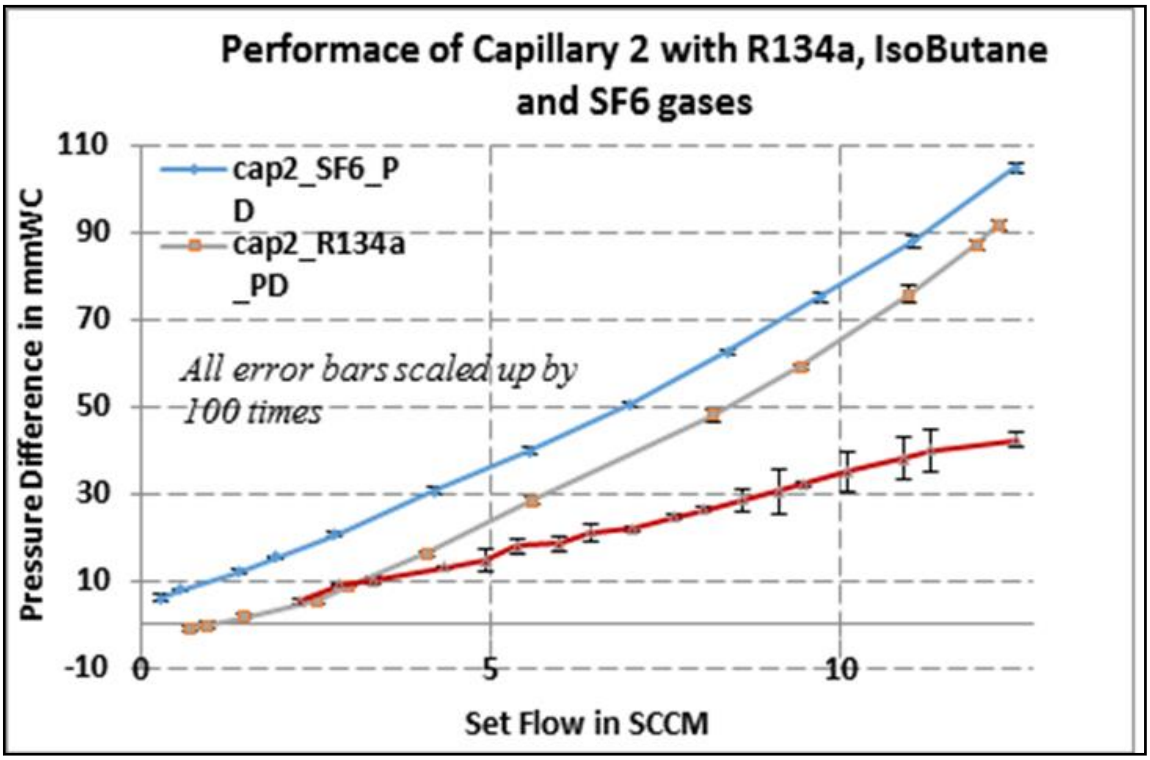

Figure 4.6: Capillary C2 Results with R134a, I-butane and SF_6 gases

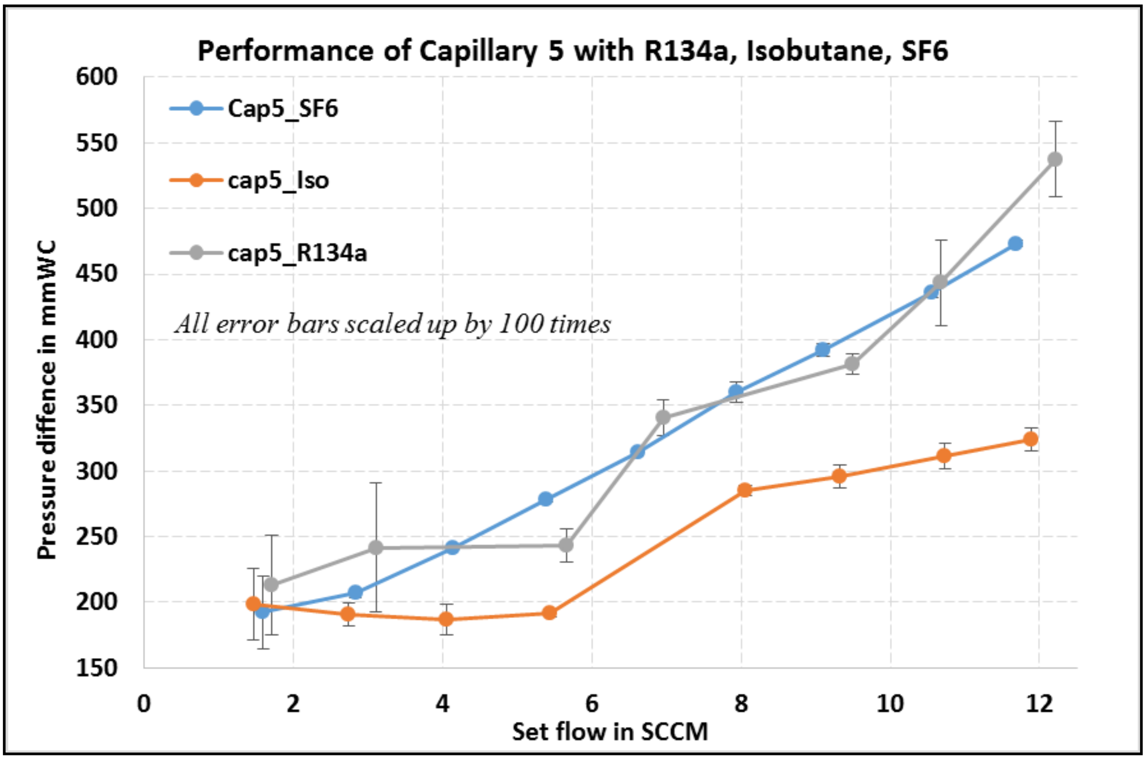

Figure 4.7: Capillary C5 Results with R134a, I-butane and SF_6 gases

4.1.5 Flow rate versus pressure difference

In the Figure 4.6, it is seen that, I-butane which has the lowest viscosity among the three gases produces the lowest pressure drop for a given flow rate. The same results are observed in Figure 4.7 and Figure 4.8 that the dependency of the viscosity of the gases with capillaries C2, C5 and C6 which are having same diameter (300 micron), but of different lengths.

The longest capillary C6, which is wound on a bobbin, shows ideal performance and could be the most suitable one for INO RPCs where the flow rate is about 6 SCCM; it can function well for the increased flow rate to 25 SCCM. But if space is to optimised then C2 and C5 could also be used which will have less impedance and higher flow than C6.

The capillaries C1, C3 and C4 did not show any pressure difference at low flow rates of few tens of SCCM are not suitable when these are to be used for impendence matching.

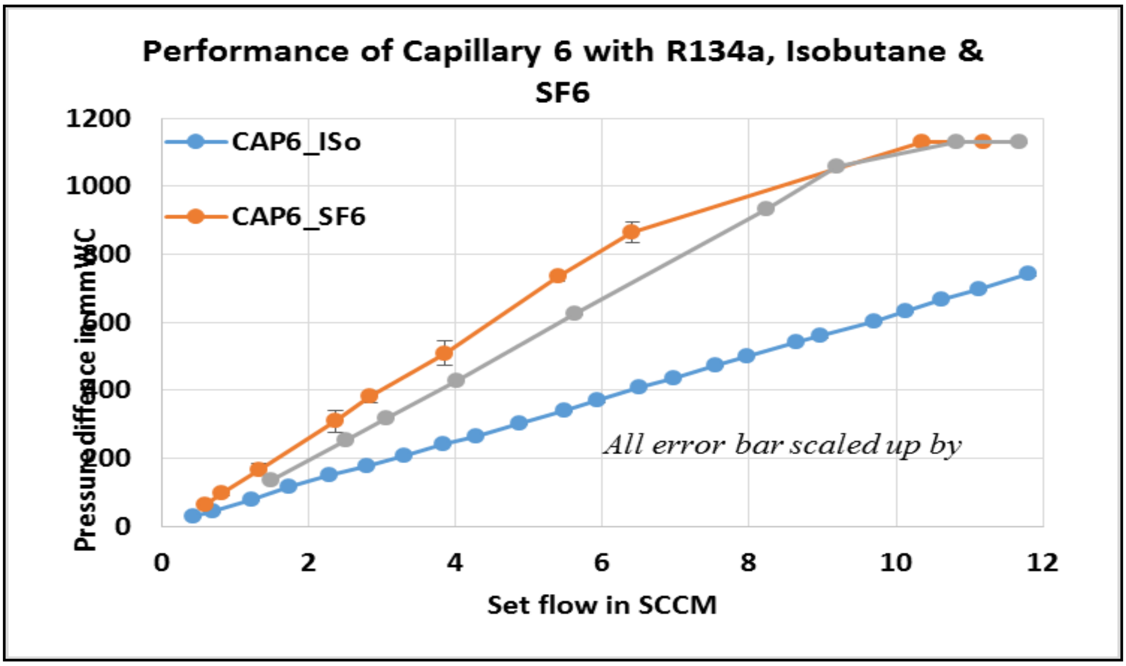

Figure 4.8: Capillary C6 Results with R134a, I-butane and SF_6 gases

4.1.6 Measurement of pressure difference across an RPC

To study the pressure drop across the RPC for given flow rate, a RPC of (1 × 1) m^2 in lieu of capillary (as shown in the setup) is connected. An input flow rate of 6 SCCM was applied to the RPC under test and it was observed that, the output flow rate reached the input in few tens of seconds. The pressure drop of about 0.1 mbar across the RPC was observed. The input nozzles have a termination on the side spacer of an RPC with an opening of [(0.7 mm) height × 2.55 mm width × 11 mm length], which would give a resistance to the flow inside the RPC gap. But looks this termination has marginal effect of the capillary.

4.1.7 Flow balance in a multiple RPCs

It is observed from our studies of the RPC stacks that, with a flow rate of 6 SCCM per RPC and using capillary of 300 μ and of length 600 mm, the performance parameter like the noise rate and current are stable over a long period several years.

The noise rates for one strips each from X-side and of Y-side of the latest data as shown in Figure 4.9 and observed noise rate is about (100 to 150) per second. The current drawn by the RPC is shown in Figure 4.10, which is about (100 to 150) nA and the current are stable for six months. The flow rate of 6 SCCM per RPC is very low by a factor, as compared to that of Bakelite RPCs at CERN and elsewhere and may cause segregation of SF6 (heavy gas) in a CLS, whose concentration is very low and hence a longer study may be needed.

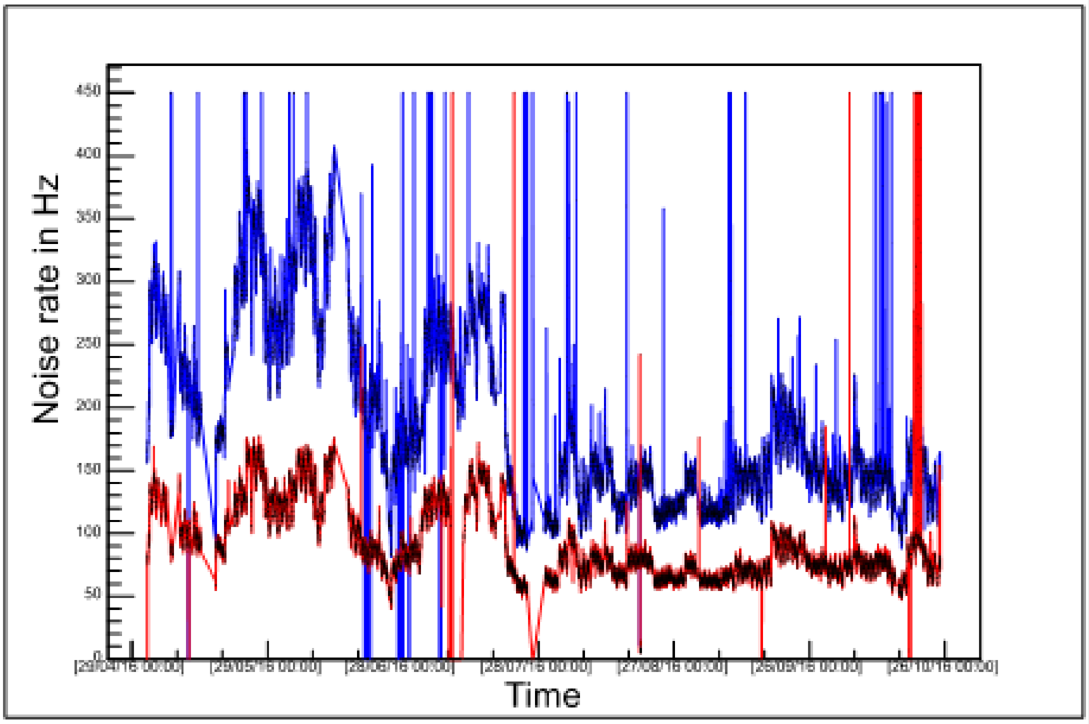

Figure 4.9: Strip Count / Noise Rate

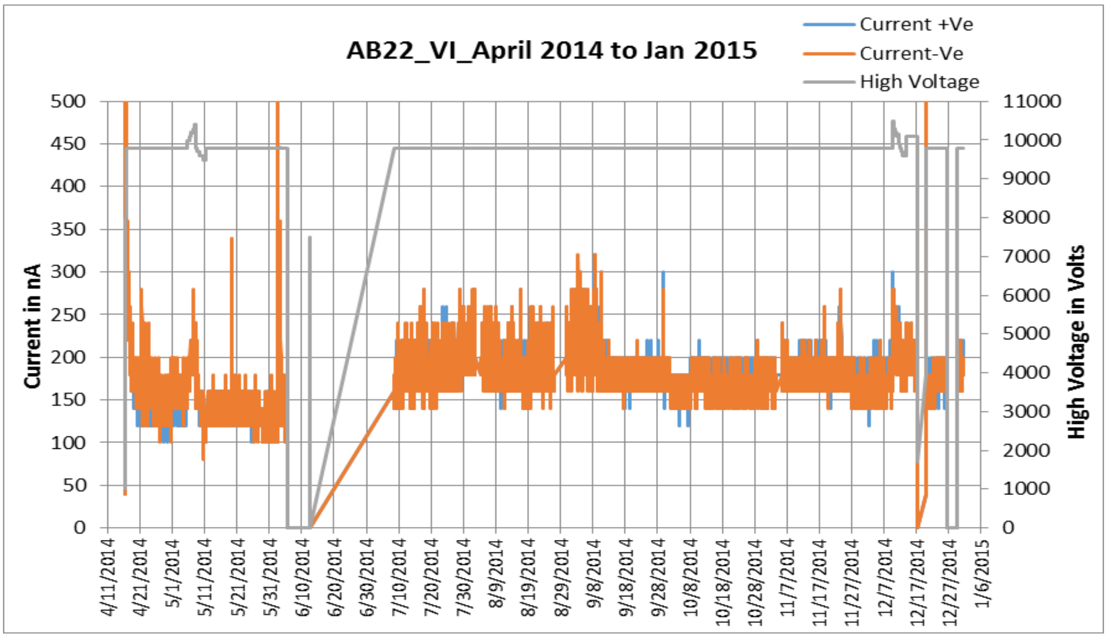

Figure 4.10 : Current and voltage

4.1.8 Capillary Conclusion and Results

The function of flow resistor depends on the type of gas that flows through it. It is very prominently observed that, higher the gas viscosity of the gas, then higher is the pressure difference required across it. If the plot of flow rate versus pressure difference is linear then the slope is given by $D^4/(nL)$, if it is not a straight line then we have to use the compressible fluid equation and the measurements of input and output has to be on an absolute scale (barometric pressure). With the present setup it could not have been possible to measure.

The flow through the capillaries namely C2, C5 and C6 is laminar and hence obeys Poiseuille's principle for fluid and gases. The flow rate of 6 SCCM is in the linear region. In the present CLS, the capillaries C6 and C5 appear to be ideal and could be used inside the RPC tray with a suitable design to accommodate them in an RPC tray and multiple connections to match impedances of the different RPCs.

The RPC performance parameters,, the current and noise rates (back ground cosmic ray rate) are shown in Figure 4.9 and Figure 4.10 above are with the capillaries C5 and C6 used in the loop.

4.2 Simulation studies for flow of gas distribution within an RPC

Some of the important parameters affecting the performance of an RPC are uniform flow of gas, gas distribution, gas purity inside the chamber, the nozzle positions and the flow rate etc. The earlier studies have indicated [68] that the current drawn by the RPC (chambers) can rapidly rise, if the amount of pollutants in the mixture increases due to poor gas quality and breakdown radicals of gases etc. Also in reusing of the gas in the CLS, there are several challenges to be addressed like gas purity (purifiers used) and concentration of the gas mixture which may vary with time. The gas purity at the outlet need to be continuously monitored using gas spectrum analysers and controlled through a set of gas purifiers. The estimate of progress of partial pressure gradient of a gas mixture or the radicals generated over a period of time of transit during process of detection. Hence a number of studies on controlling and optimisation of the gas flow through an RPC is required. Few of these parameters namely, the flow rate or the velocity of gas inside the gas gap, position of the input and output nozzles on the gap etc. are simulated and studied.

*The simulation studies have been performed on the 3 platforms namely SolidWorks, COMSOL and CDF (*CFX*) with different goals. Each of these packages has some limitation and some benefits to some extent are exploited for the gas flow studies.*

4.2.1 Objectives and Goals of simulation

a) To study the flow dynamics in the gas distribution system in order to ensure uniform gas flow in the entire chamber volume.

b) To study and correlate the effect of spacers, button and nozzle location on residence time distribution, density stratification, existence of dead zones etc. in the RPC gas gap.

c) Gas distribution effect of position(s) of the nozzles on the gas gap.

d) Optimise the input gas flow rate etc.

4.2.2 Simulation using Solid-Works

The basic tools for various numerical techniques, which are commercially available for fluid analysis, are Solid-Works, COMSOL, CFD (*Computational Fluid Dynamics*) etc. As a beginner for the simulation work, the Solid-Works platform was preferred due to the use age of this package in other applications and the availability of license version and was a learning curve. The Solid-Works, 2014-2015, version is used in 3 dimensions, to simulate the flow velocity within a RPC gap assuming the dimension of an RPC gas gap considered is $(1.85 \times 1.9)\ m^2$ with a gap of 2 mm and with 3 mm thick floats glasses which are used as electrodes in the construction of an RPC gas gap.

Each gas has different property such as density, viscosity and diffusivity at operating temperature and therefore a concentration gradient will setup within the gas mixture. The segregation of gases under different velocity conditions may occur. Therefore to avoid this, it is necessary to maintain minimum velocity of a gas mixture especially when I-butane is used.

In the Solid-Works platform the study is done on all the three gas using flow rates of 3 SCCM (half volume changes per day) and 30 SCCM (5 volume changes).

4.2.2.1 Schematics of an RPC

A schematic diagram of a glass RPC gap, dimensions, components and the detailed cross of a spacer used in simulation are shown Figure 4.11 (typical RPC), Figure 4.12 (actual dimensions of glass with chamfering shown), Figure 4.13 (poly carbonate components used for making a RPC-gap) and Figure 4.14 (side spacer dimensions showing the hole of nozzle).

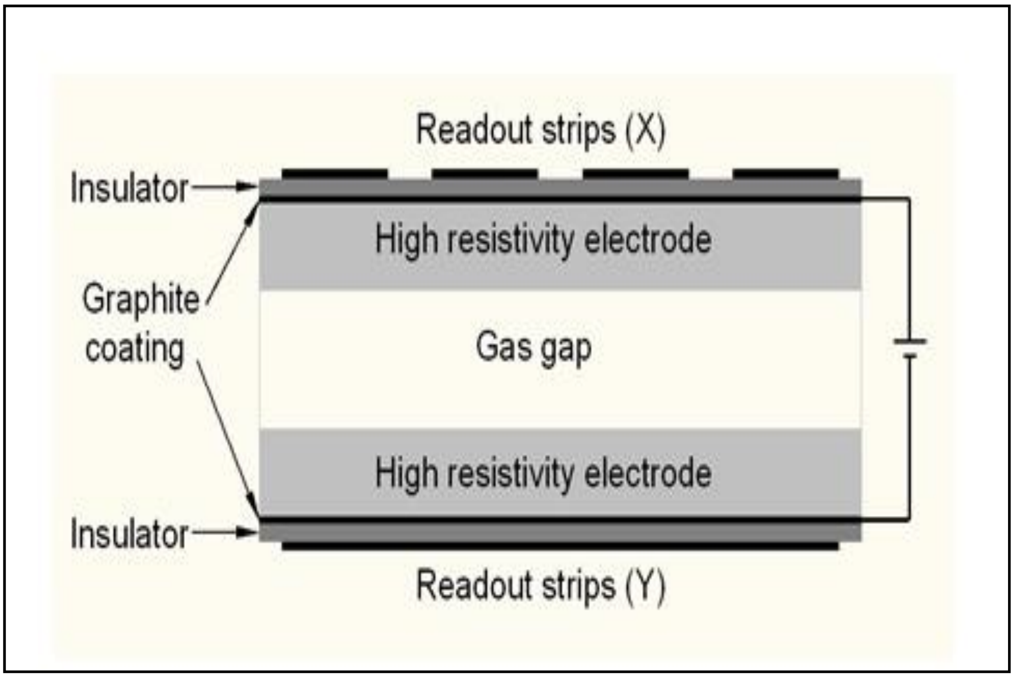

Figure 4.11: Typical RPC

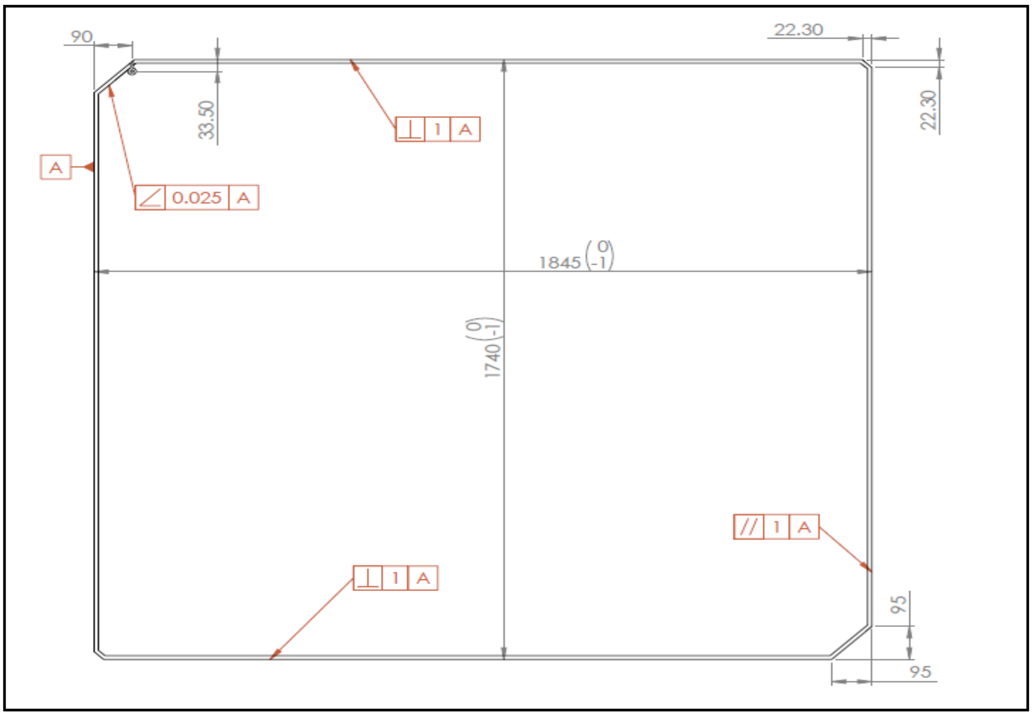

Figure 4.12: RPC glass dimensions and position of Nozzle

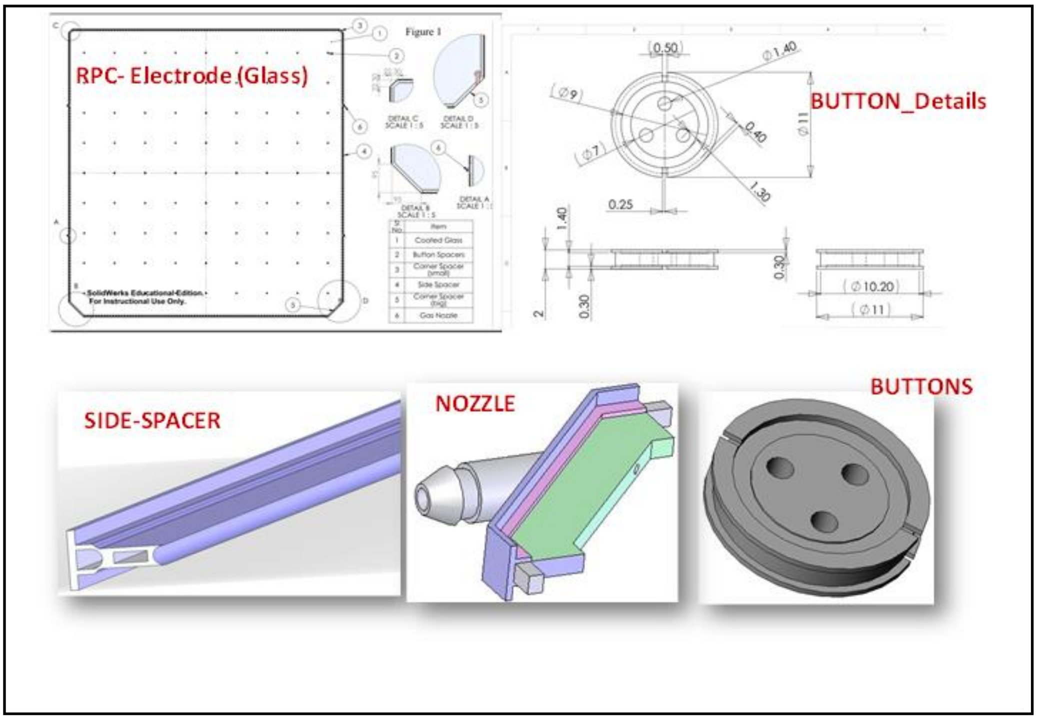

Figure 4.13: Poly carbonate components for making RPC gas gap

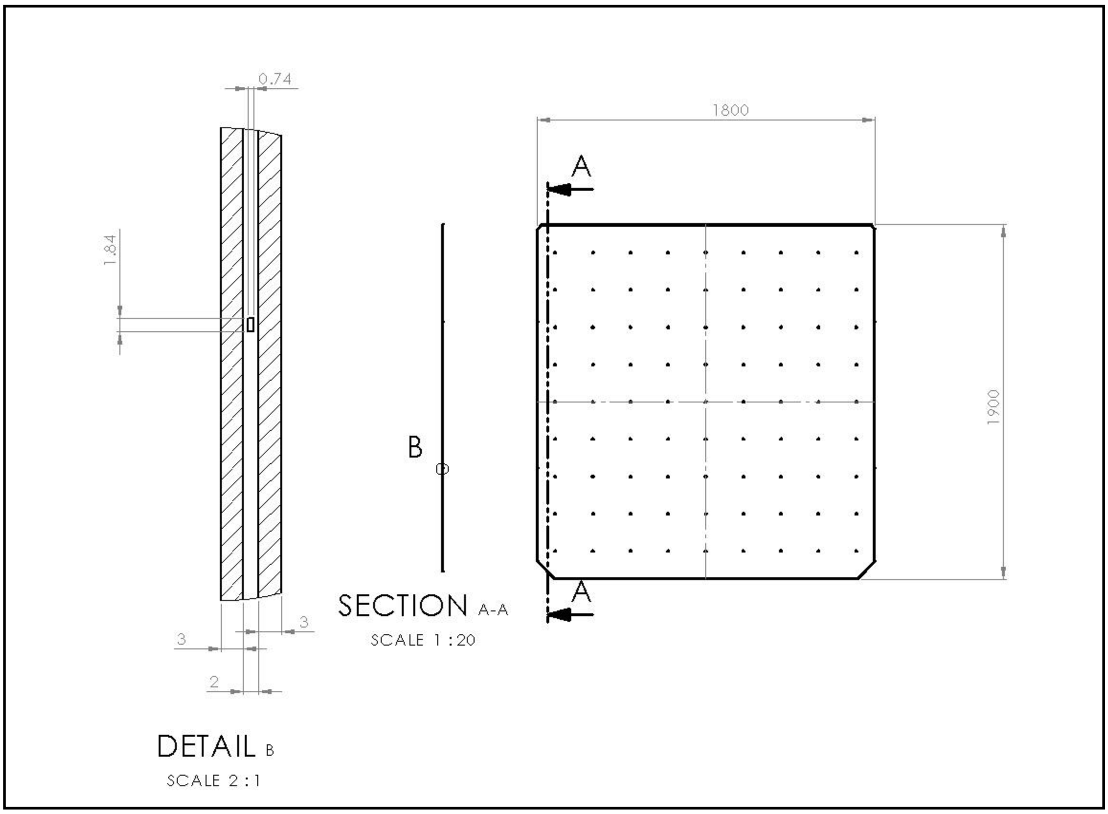

Figure 4.14: Simulation parameters

4.2.2.2 Hardware details and Software assumptions

The basic components of an RPC gas gap are the float glass of 3mm thickness, polycarbonate buttons of 2 mm thickness and of 11 mm diameter, the T-shaped side spacers and gas nozzles. The geometry has been simplified for simulation purpose. The float glass wall is assumed to be adiabatic and having roughness of 0.05 μ m. The buttons that are placed inside the chamber at 200 mm spacing are considered to be cylindrical of the exact height of 2 mm. The button height plays a crucial role in maintaining the gap or thickness throughout the area of RPC gap, so that the applied field is uniform. The side spacers are of T-type,these side spacers help in holding the glass and act as sealants, so that the glass gap so formed has leak proof sealing, but one can see that, the rectangular section only of T-side spacer comes in the contact of gas, hence in modelling the spacers are considered to be rectangle. The two gas nozzles are placed for the entry and exit of gases. There are four in numbers and in *lieu of* *full nozzles the input rectangular holes are considered as two dimensional entry points having nozzle end dimensions of 1.81 mm hole.* The entry point position and the orientation are identical to that of nozzle.

The gas mixture used is R134a, I-butane and SF_6. The assumption considered is that, the major concentration of gas mixture is R134a which is 95% and hence it would replicate as a single gas for simulation purpose. The gas properties namely the density and viscosity are considered. The boundary conditions used are the flow rate at the input taking into consideration the volume changes that would take place for an RPC. Since the laboratory where the RPCs are used, is maintained at a controlled temperate and pressure, the base thermodynamic parameter like pressure is taken to be 1 bar abs and temperature as 24^0 C, for all simulation purposes.

A 3D simulation is done and assuming flow is symmetrical about the mid plane in Y-directions that is the thickness and taking into consideration the configuration of the PC used for number crunching and flow calculation, the fluid cells are numbering to 10813 and partial cells are 1024515. The number of iterations done is about 214 for each set of calculations a symmetry condition is applied to the mid plane in the Y-direction i.e. the width of gap (2mm).

4.2.2.3 RPC performance parameter

The desired performance of an RPC are (a) detection efficiency of about 97-98% (b) time resolution of about 2 nanosecond and spatial resolution of less than 1 cm and the low leakage currents of few n A. (c) Long term stability over a long period. (d) The breakdown radicals are produced during operation of RPC. *The residence time of the radicals within a gap is related to the drift and diffusion properties of gas flowing* *inside an RPC. The least residence time for radicals is desirable for extended life span of a RPC.*

4.2.2.4 Function of each gas in an RPC

The R134a acts as a main ionization gas. I-butane gas helps in absorbing the secondary UV photons and SF_6 helps in absorbing electrons and stops the streamer formation. The quencher (i-C_4H_{10}) and electronegative (SF_6) gases will help in containing the charge development and reducing the streamer probability, the more the I-butane better is the performance, but more than 8 % is not permitted due to safety issues. If the percentage of SF_6 is increased to greater than 0.3 %, the noise rate gets reduced and effectively the efficiency is also reduced and the time resolutions of the RPC operation deteriorate. If R-134a concentration is reduced the efficiency and noise rate is reduced and hence timing gets affected. *Hence it is important that, the appropriate concentration of gases is to be maintained. The current increases, if the percentage of air (due to leakage) is more.*

Therefore it is mandatory that the air must be completely displaced by the gas mixture in the entire gap of the RPC detector. The concentration of I-butane should not vary by few per-cents. The concentration of SF_6 should not vary more than 1 %. The optimized ratio of the gas mixture for ICAL glass RPC gap is 95.0:4.5:0.5 , R134a, I-butane and SF_6 respectively to get the best performance of the RPC.

The gas mixture ratio is required to be maintained uniformly throughout the volume of the RPC detector. If any deviation is seen within localized area such as pockets, then the performance would be affected in a localized area of RPC.

4.2.2.5 Interpretation of simulation Plots

The simulation has been carried out with following flow rates which are within the ranges of operation. The flow trajectories have been plotted considering gas in the pure form.

a) The flow studies with R134a with flow rate of 3 SCCM, 30 SCCM and at 300 SCCM are simulated. These are shown in Figure 4.15, Figure 4.16 and Figure 4.17 respectively.

b) The flow studies with I-Butane with 0.3 SCCM, 3 SCCM and 30 SCCM are shown Figure 4.18, Figure 4.19 and Figure 4.20. The Swirls seen around the buttons is shown in Figure 4.21.

c) Flow simulation for SF6 at 3 SCCM and 30 SCCM are shown in Figure 4.22 and Figure 4.23

d) The simulation studies performed by the CERN, CDF [68] team are shown in Figure 4.24. This Figure is adapted from CDF data.

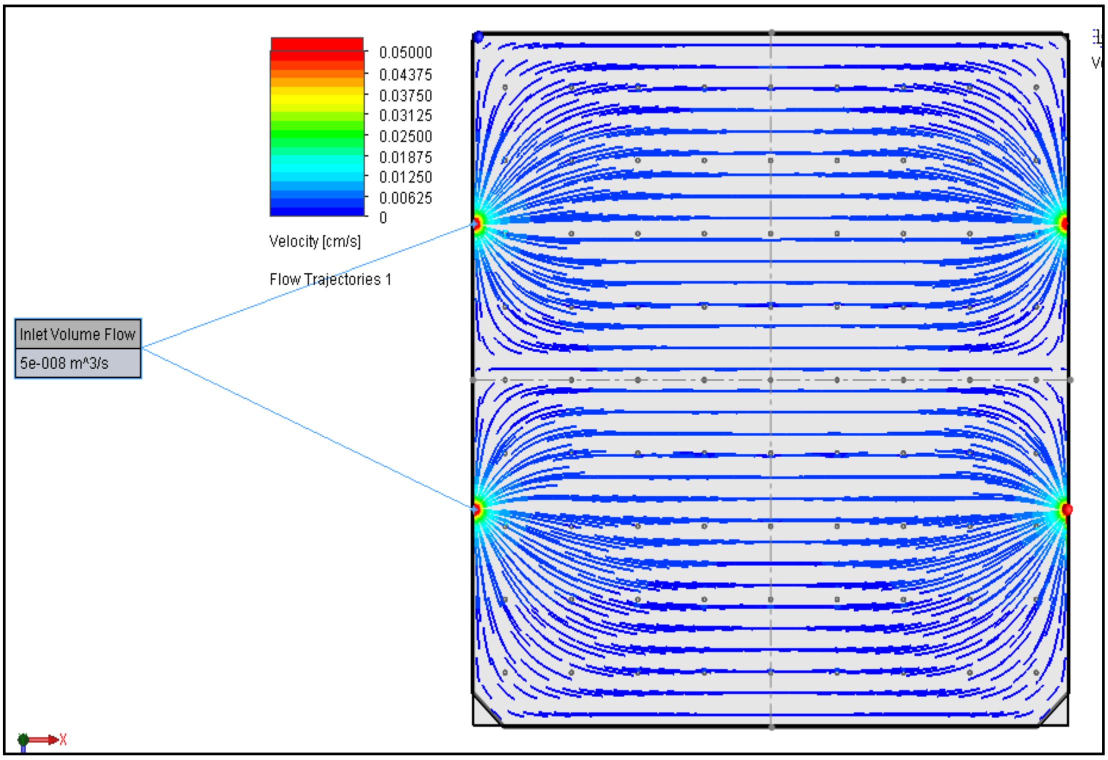

Figure 4.15: R134a at 3 SCCM

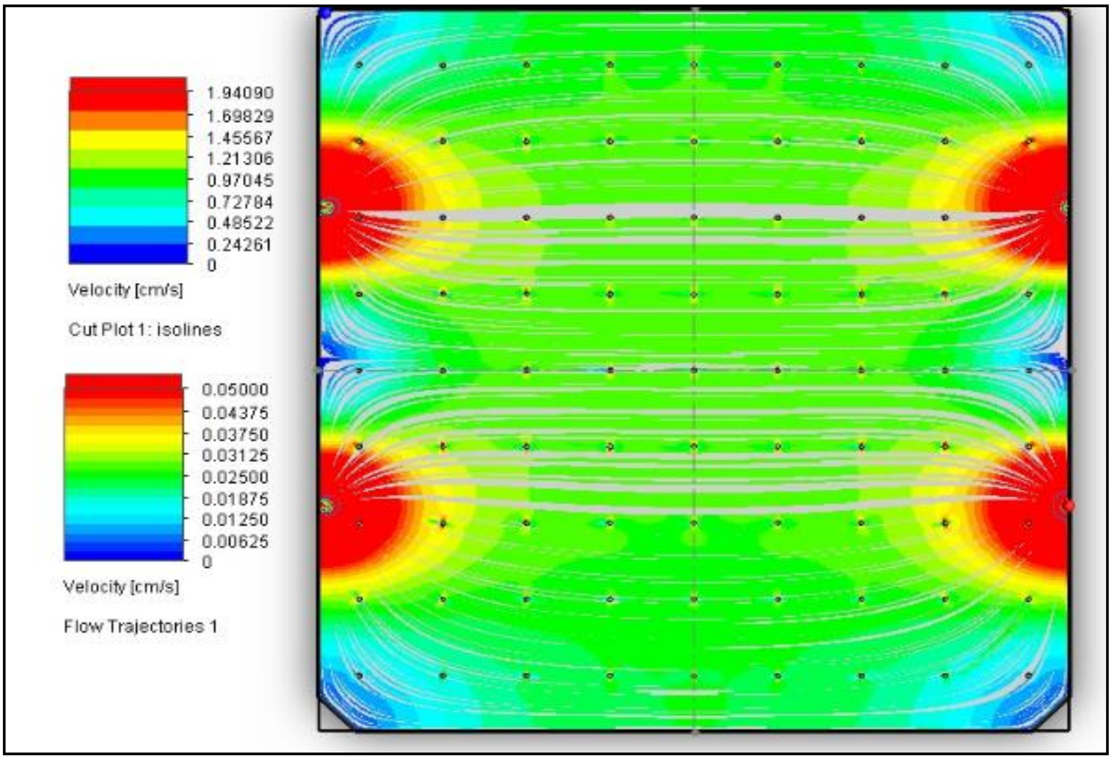

Figure 4.16: R134a at 30 SCCM

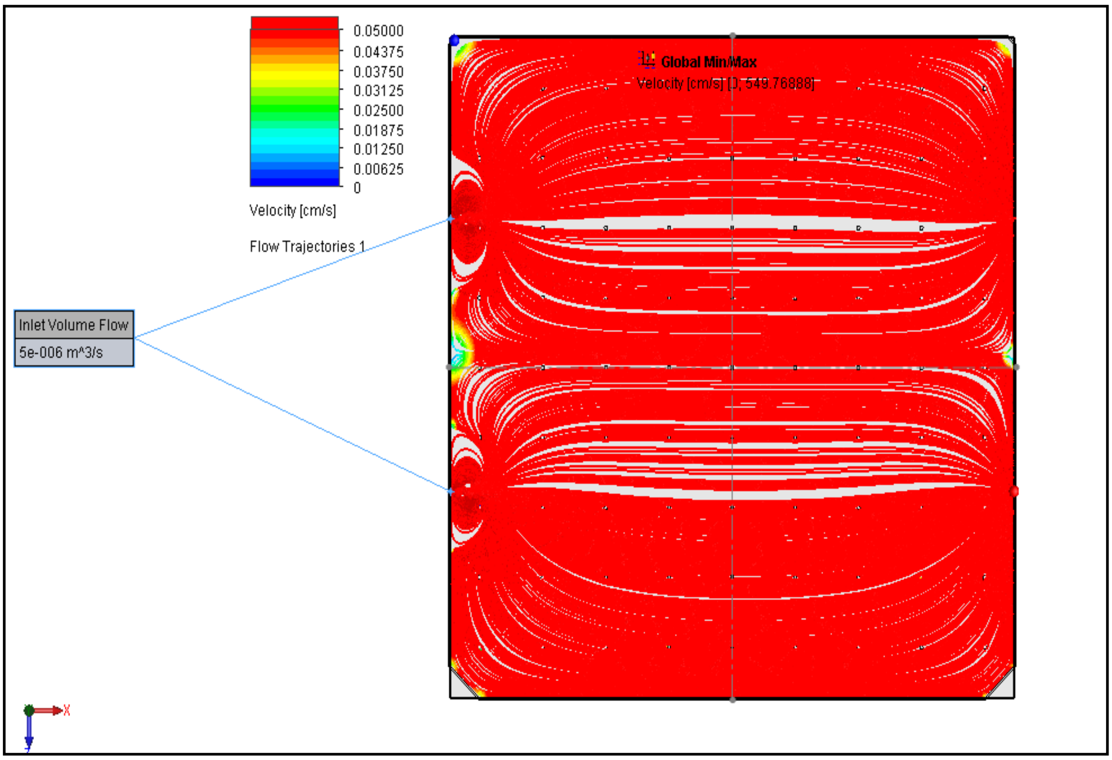

Figure 4.17: R134a at 300 SCCM

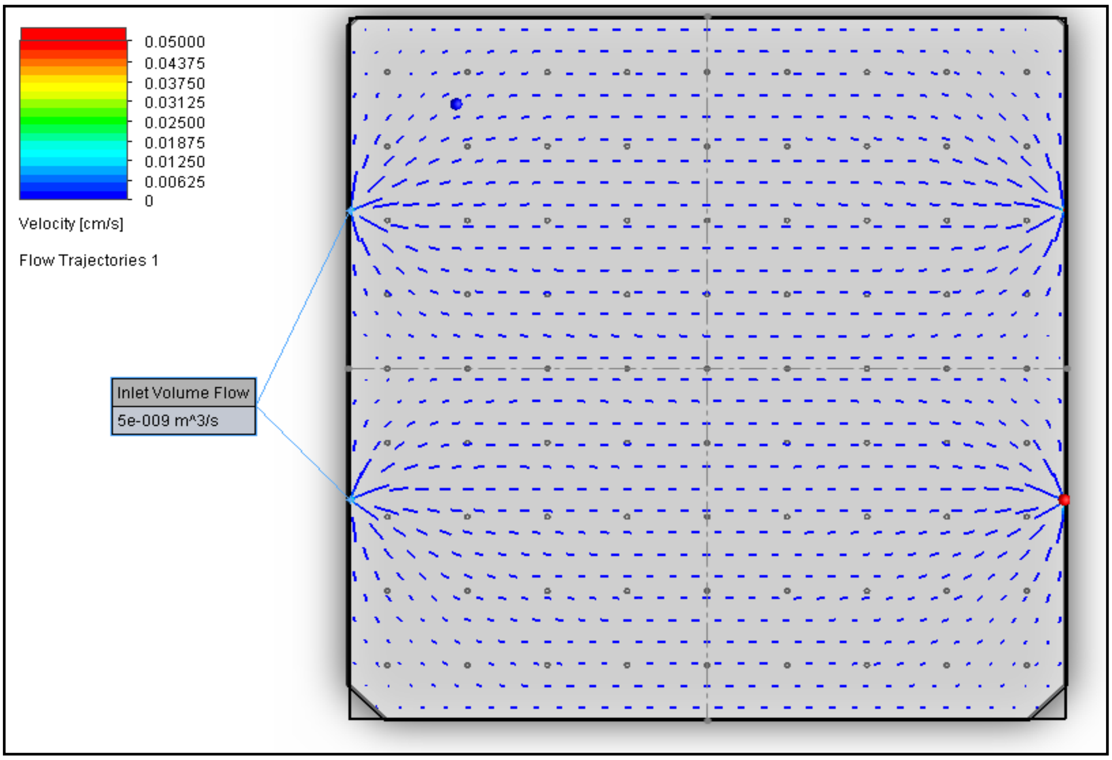

Figure 4.18: I-butane at 0.3 SCCM

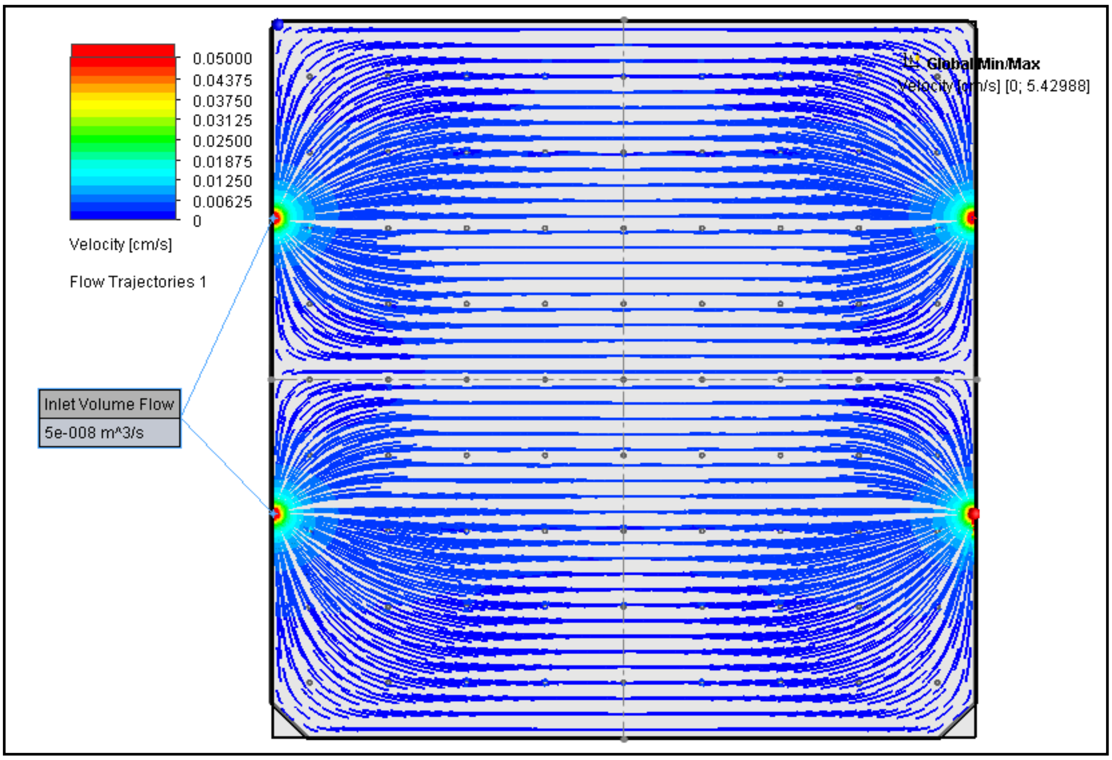

Figure 4.19: I-butane at 3 SCCM

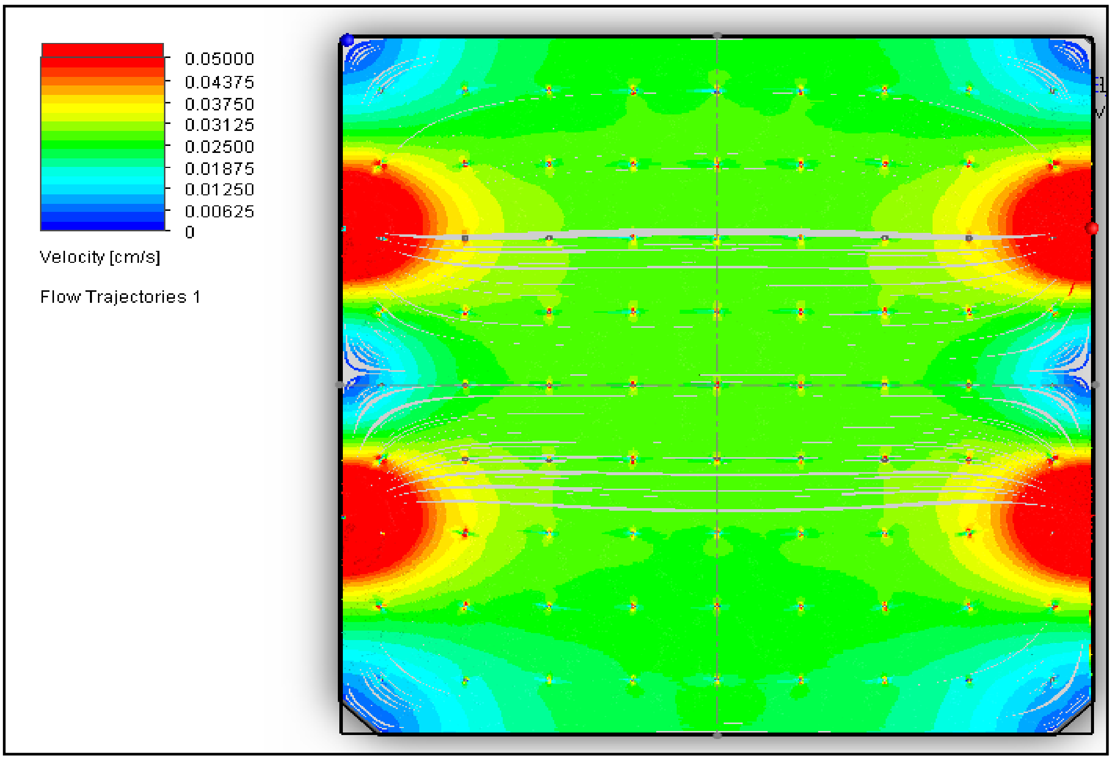

Figure 4.20: I-butane at 30 SCCM

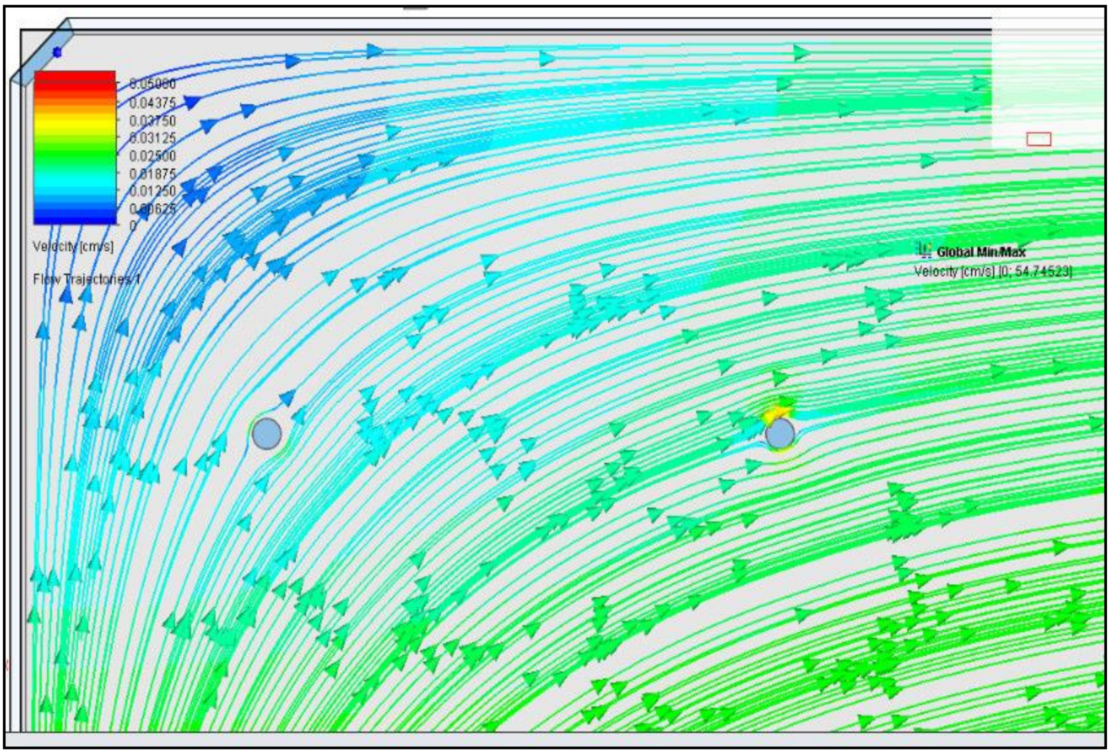

Figure 4.21: Swirls seen around the buttons

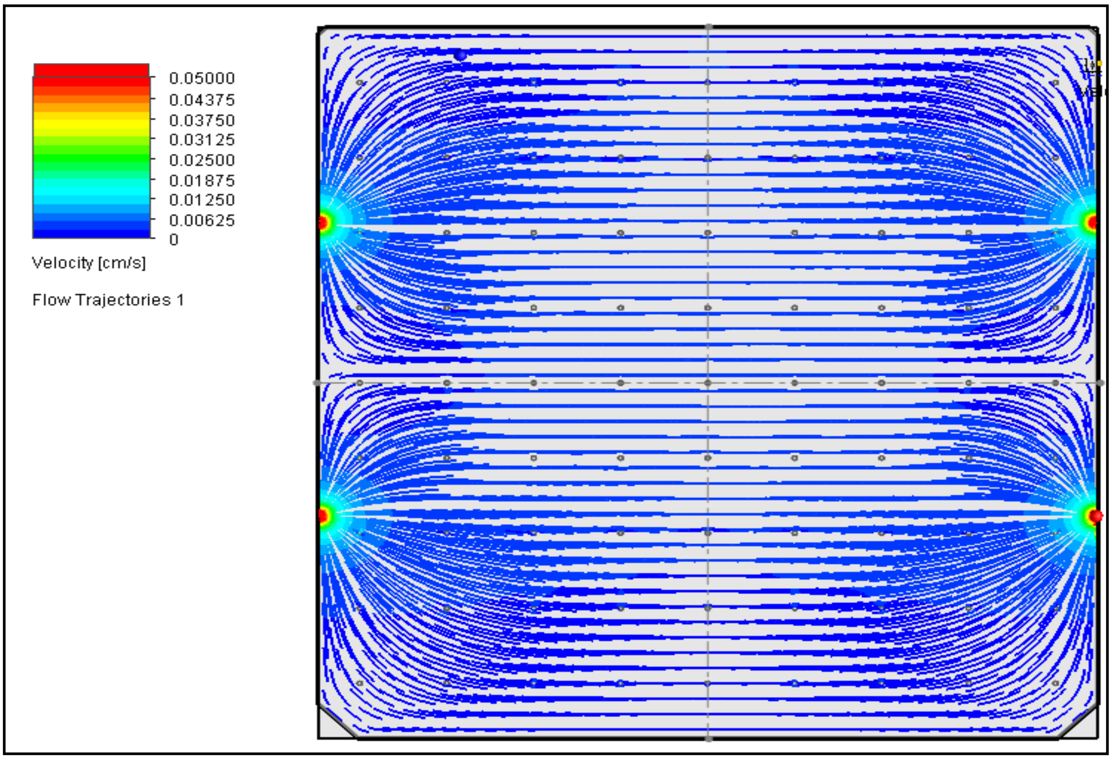

Figure 4.22: SF_6 at 3 SCCM

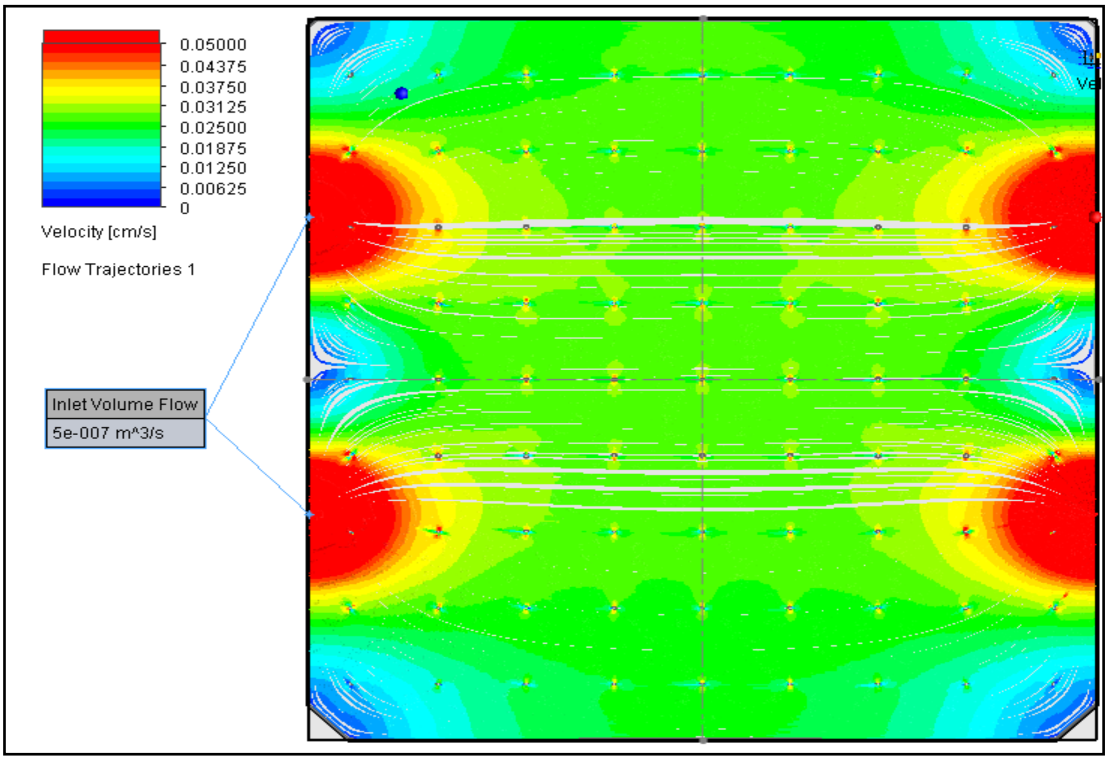

Figure 4.23: SF_6 at 30 SCCM

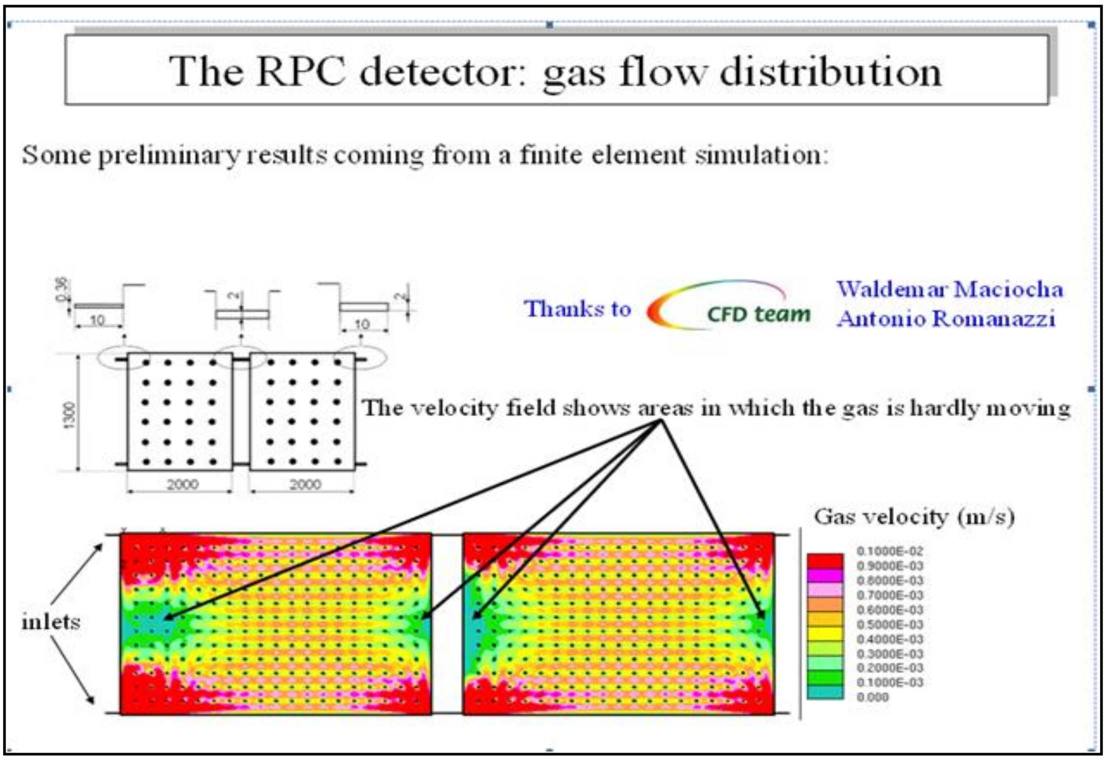

Figure 4.24: CERN CFD team flow distribution

4.2.2.6 Analysis and Comparison

The Dead Zones are observed on the four corners and on the surface of the gap along the nozzles, where the flow of the gas is almost zero. For comparison of the observed data with that of CERN data, following points are to be noted.

a) RPC size: CERN RPC is (1.3 × 2) m^2, while INO RPC is (1.85 × 1.9) m^2

b) The nozzles for the CERN RPC are located at the corners and are 4, while that of ICAL RPCs are located along the edges and are also 4.

c) The average velocity over large working area (nearly 70%) is 0.4×10^{-3} meters/sec at flow rate of 6 to 10 SCCM, while for INO RPC it is between 0.1875×10^{-3} and 0.3125×10^{-3} at 30 SCCM

d) The radiation intensity to which CERN RPC is subjected is many times higher than for the INO RPC, hence CERN RPCs need large number of volume changes of fresh gas per unit time. This requirement may not be strictly applicable with ICAL RPC. The INO RPCs has glass as electrode while the CERN RPCs are of Bakelite, therefore in view of low background radiations, the ICAL RPC can be operated at flow rates much lower than CERN RPCs.

e) Hence a flow rate of less than 30 SCCM appears to be adequate for INO RPCs under cosmic radiations.

4.2.2.7 3 SCCM flow rate of R-134a

a) The velocities all over RPC are in a range of 0.0625×10^{-3} m/sec to 0.1×10^{-3} m/sec.

b) Only very near the nozzles the velocities are in the range of 0.3×10^{-3} to 0.5×10^{-3} m/sec.

c) The average velocity over 90% of area is nearly (1/7th) of the average velocity inside CERN RPC.

d) This flow rate will cause 1 volume change every 2 days. It will take about 3 to 4 volume changes for the RPC to become operative. Therefore to reduce the flushing time 6 to 10 SCCM of flow rate is sufficient.

e) To supplement the leakages from RPC some excess flow is required to maintain a concentration gradient.

Hence from the simulation studies, a flow rate of 6 to 10 SCCM gas mixture may considered as optimum for a (1.85 × 1.9) m^2 size RPC running under cosmic radiation.

4.2.2.8 R-134a, I-butane and SF_6

Maintaining the uniformity of gas mixture ratio's within the RPC comparison between R-134a, I-butane and SF_6 distribution at various flow rates. The SF_6 and R-134a flowing at 3 SCCM individually show the identical velocity of 0.06 × 10 e $^{-3}$ m/sec distribution and therefore they will not undergo the separation.

4.2.2.9 Effect of buttons on the flow patterns

From the velocity plots Figure 4.21, it can be seen that,

a) The highly localised Swirls are caused by the buttons to the extent of causing velocity in Z direction (along the width of the gap).

b) The magnitude of swirl velocity is 2×10^{-9} meters/ sec at maximum.

c) The swirl causes flow in Y direction

d) The magnitude of linear velocity in X – Z plane is 0.06×10^{-3}, which is nearly 10^4 times higher than the swirl velocity.

The swirl velocity is considerably low as compared to the linear velocity and hence has no significant effect of drift or diffusion to alter the gas distribution.

4.2.2.10 Conclusions (Solid-works simulation platform)

The preliminary results show that, there are “Dead Pockets” (where the drift velocity of gas is Zero) in the RPC detector. The time taken by the gas mixture to completely refill the dead zones will be longer for the larger dead zone. The Dead zones can be smaller at high flow velocities of gas, but cannot be Zero. The same can be used for validating the large scale models. A flow is a combination of drift and diffusion (the drift is the movement of gas atoms caused by pressure difference and the diffusion is the movement of gas atoms caused by concentration difference) and hence a Dead zone may have contained small fraction of gas which has diffused.

a) The flow rates of 3 SCCM to 10 SCCM are adequate to initiate the RPC in reasonable time and sufficient to operate them under cosmic radiation conditions.

b) The objects in the path of the gas flow such as nozzles, buttons do not cause turbulent conditions at flow rates near 3 SCCM.

c) The “Reynolds’s Number” (Rd), a dimension less quantity and an important characteristic of fluid under motion using the following formula:

   Rd = (Density of fluid × Velocity of Fluid × diameter of pipe)/Dynamic Viscosity.

   Then, in the case pipe diameter is 2 mm i.e. gap between glasses. The calculations show that, the Reynolds Number for all gases between 0.06 to 6.0 for flow rates between 0.3 SCCM to 30 SCCM is less than 2500 and *hence the* *flow pattern is considered as Laminar and NOT Transient (2500 to 3000) or Turbulent (above 3500)*

d) The Separation of gases does not take place even in the dead zones at flow rates of 3 SCCM or more. The flow rate of 4 to 9 SCCM can be simulated to find the precise flow rates required to operate RPC under optimum conditions.

e) Improvement in gas nozzle design, simulations of scaled up version of RPC to provide final recommendation for design of internals of an RPC.

4.3 Simulation using COMSOL

The Simulation is also done on a platform of COMSOL Multiphysics® version 5.1 in 2 dimensions, to study the flow velocity of gas within a RPC gap with dimensions are $(1.85 \times 1.9)\ m^2$ with a gap of 2 mm and assuming 3 mm as thick glass. The emphasis on the simulation results are related to the (a) Transient flow pattern of gas inside the RPC detector say form 0 second to 60 seconds using R-134a (R22) gas (major component of a mixed gas). (b) Gas flow inside the RPC detector for small flow rate few SCCM (velocity from 0.01meters/second to 0.18 metres/second), as the glass RPCs are very efficient in low flow rate when the outside environment of operation has low radiation for the underground ICAL experiment, while in LHC-CMS it is quite high due to collusion of photons and antiprotons.

The gas used in the simulation is R22 (assuming that the flow pattern would be similar to R134a), as it was available in the library of COMSOL package. The major concentration of gas mixture is Freon which is 95% and hence it would replicate as a single gas for simulation purpose. The boundary conditions used are the flow rate at the input taking into consideration the volume changes that would take place for an RPC. As the laboratory is maintained at a fixed temperate and pressure the earlier modules generated in Solid-Works platform are imported in the COMSOL and the simulation is done in 2D and it is assumed that the flow is symmetrical about the mid-plane in Y-directions i.e. thickness and taking into consideration.

A schematic diagram of the glass RPC gap dimensions considered are similar to that used in Solid-Works.

4.3.1 Software tools and Criteria

The main objective is to conduct a simulation study and understand the gas flow patterns inside an RPC chamber at low velocities and initial gas distribution profile. The COMSOL platform is used in this analysis as this will give some cross verification for the simulation work done earlier using Solid-Works and to decide for further details studies if it can be used.

4.3.2 Interpretation of Graphs

The Part A of simulation consists of plots showing Flow lines called ‘Iso-flow’ for from (5.45 to 60) seconds. An Iso-flow is defined as a line joining points of equal magnitude of gas velocities in a 2D plane or 3D space, bunched to form a particular range flow velocity. A single component gas flow is introduced at time t=0 into the gap. The subsequent development of Iso-flow lines through different part of the gap after a period starting from t = 5.45 sec. to t = 60 sec are reported here and simulation results are shown in Figure 4.25 for 5.45 seconds, Figure 4.26 for 32.72 seconds and Figure 4.27 for 60 seconds.

The distribution of gases after introduction through the inlet nozzle is under study. This is important from many points such as how each component of gas mixture is going to develop its partial pressure over a period of time from inlet to the outlet of the detector.

This model can also be applied to the inward leakage of impurity from air such as moisture and oxygen and the distribution as if from an infinite source. For the flow rate of few SCCM, the Iso-flow lines develop stronger in the middle and less at edge initially. The steady state condition is achieved before 60 sec.

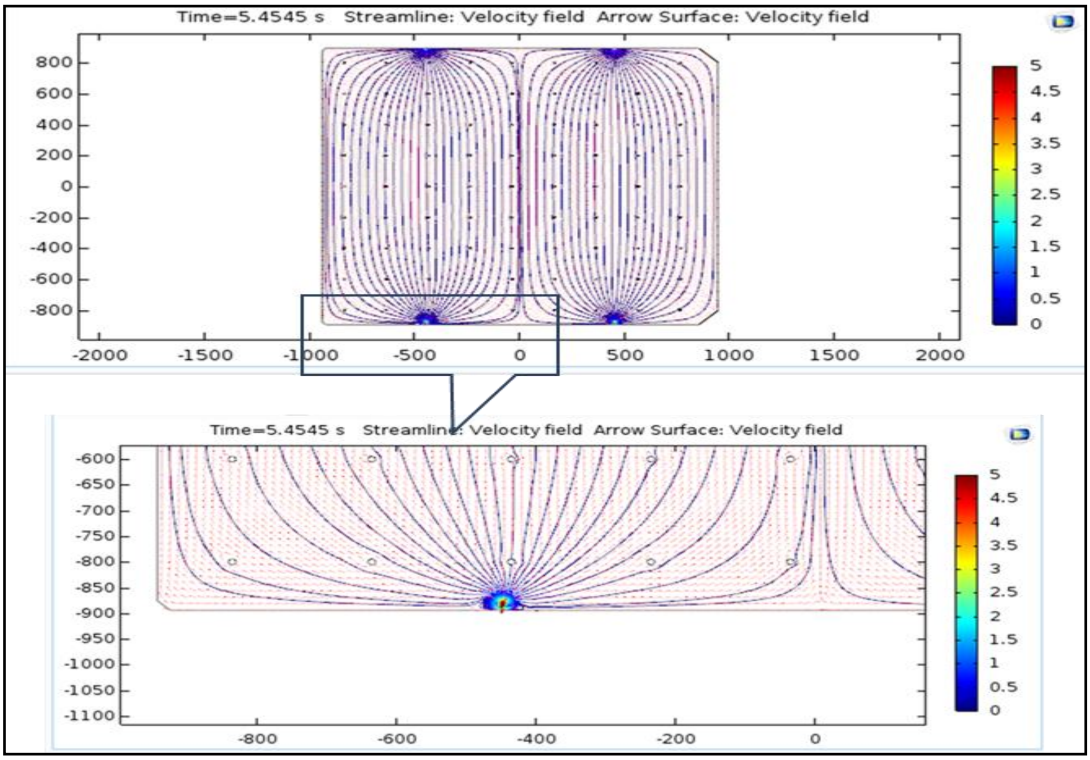

Figure 4.25: Streamlines at 5.45 seconds

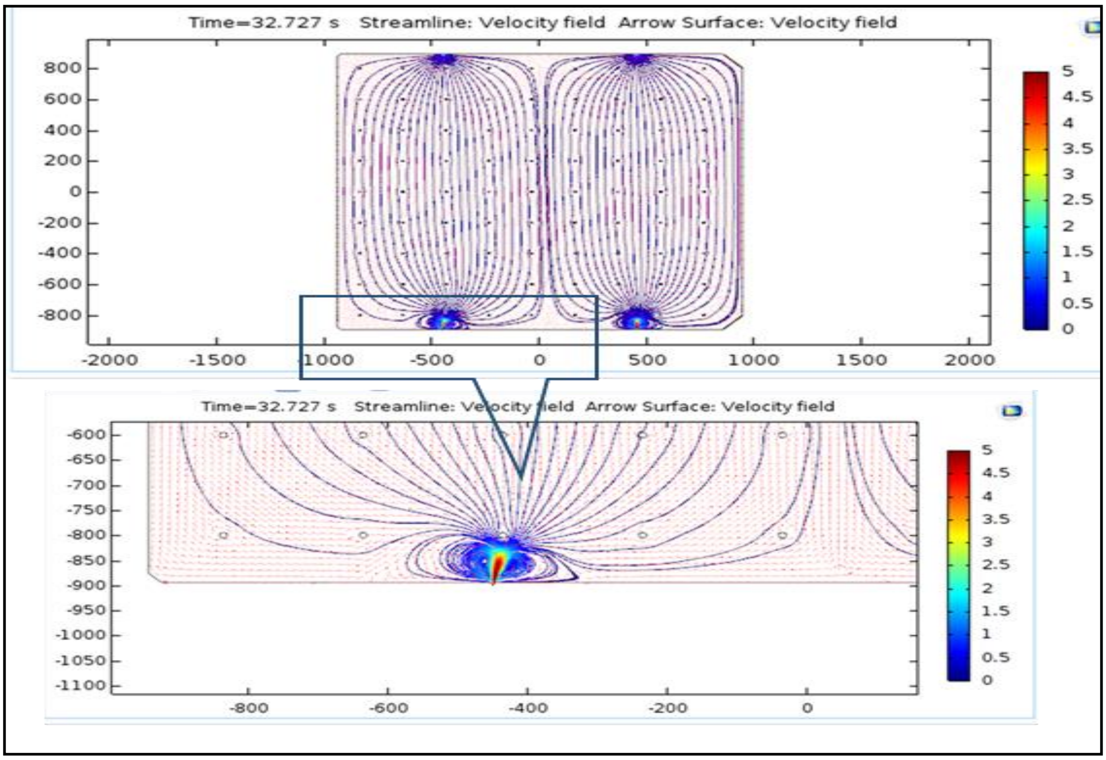

Figure 4.26: Streamlines at 32.72 seconds

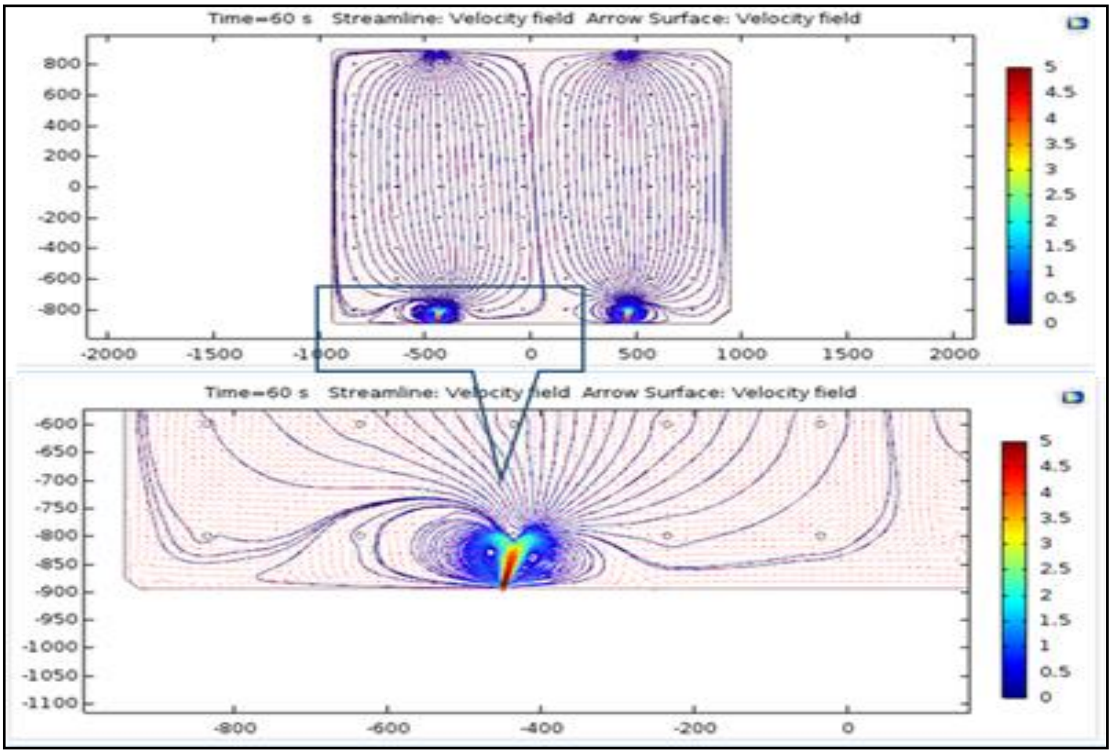

Figure 4.27: Stream lines velocities at 60 seconds

4.3.2.1 Flow simulation for different velocities

In the Part B simulation i.e. the “iso-flow” distribution is studied after steady state conditions have been reached. The “iso-flow” distribution is studied for different velocities starting from 0.02 meters/second (1.51 SCCM) to 0.17 meters/second (12.852). The plots in Figure 4.28 and Figure 4.29 represent the simulation reports for flow of gas at low flow rate of (1.5 to 6) SCCM in an glass RPC. The gas flow distribution looks to be identical for the low flow rate.

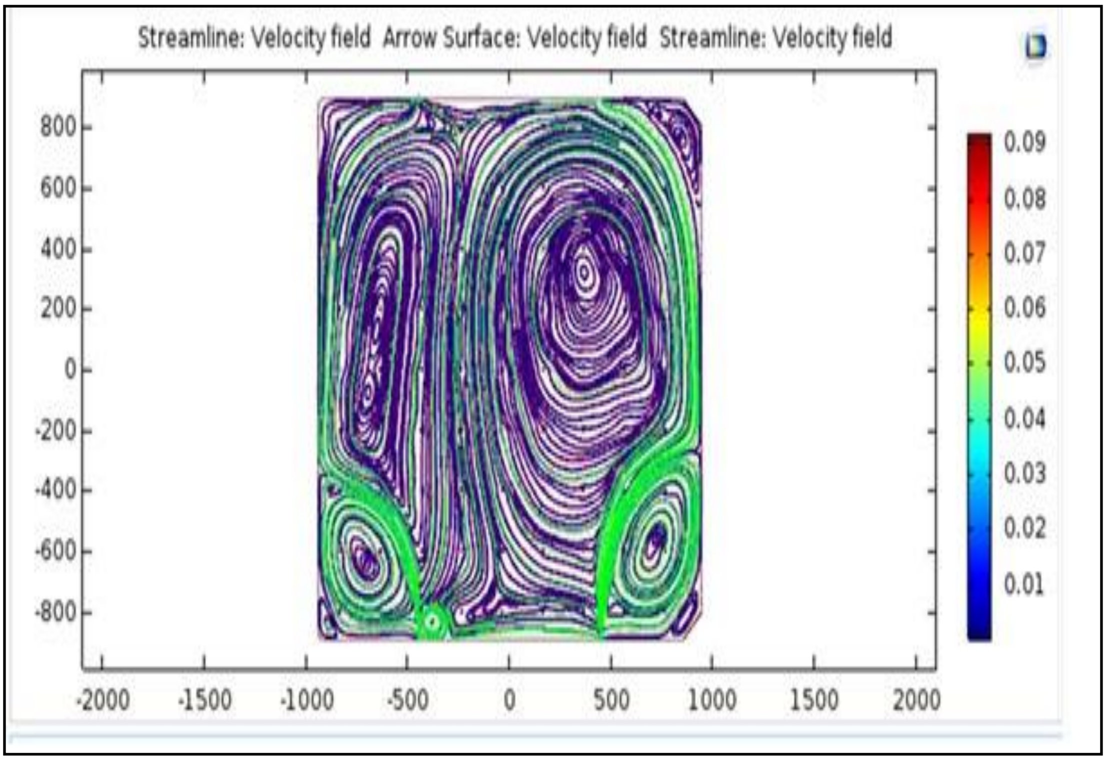

Figure 4.28: Velocity flow distribution at 1.5 SCCM

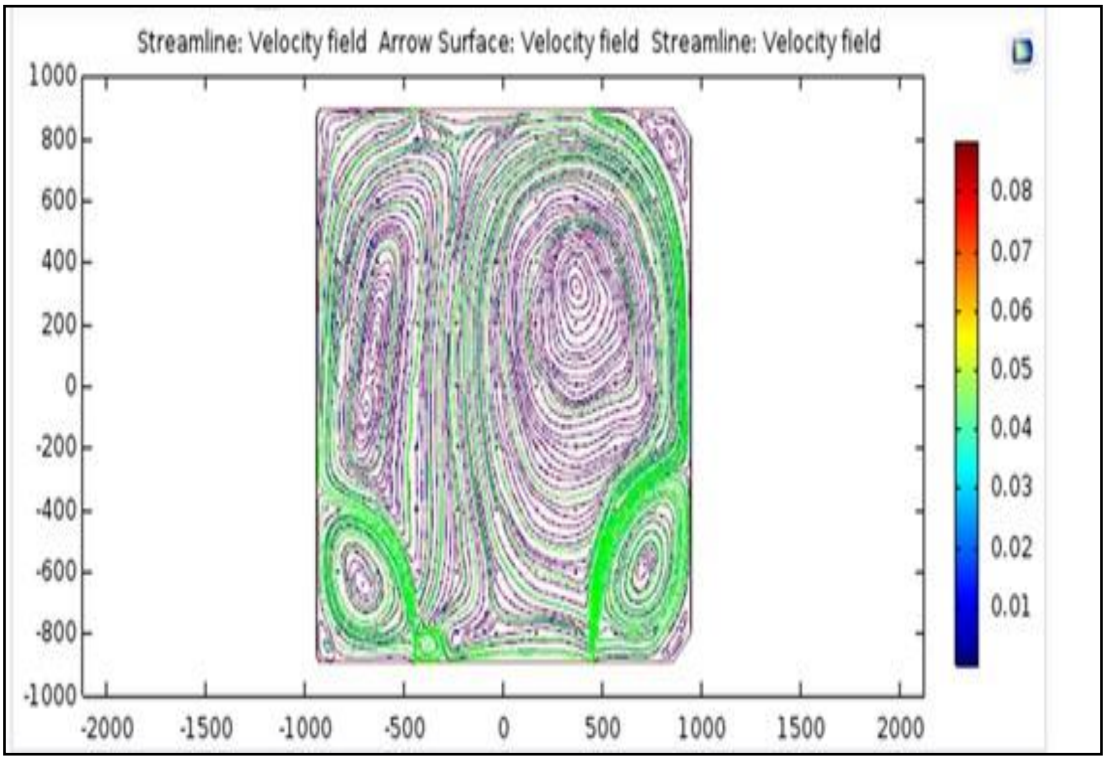

Figure 4.29: Velocity flow distribution at 6SCCM

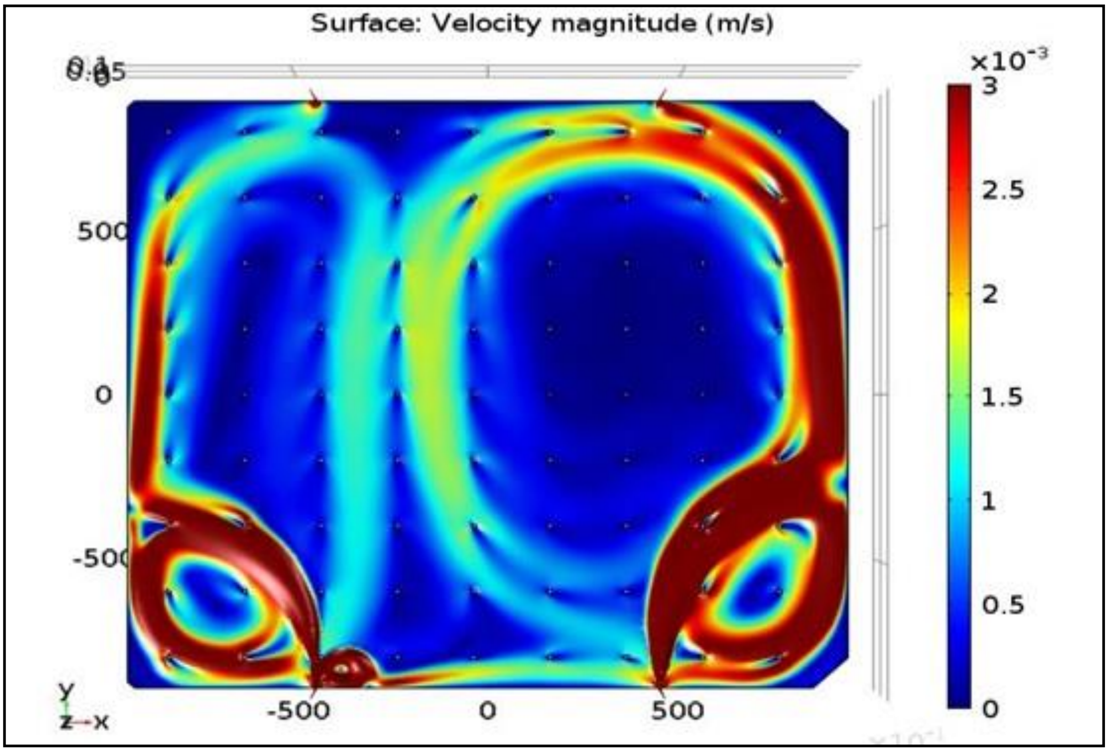

Figure 4.30: Velocity magnitude showing unequal flows

4.3.2.2 Velocity magnitude

In the Part C simulation, the surface height velocity magnitude plot is shown in Figure 4.30. There are two inputs gas nozzles and two output nozzles and it looks that the flow of gas reaching at both the output nozzles is different and to verify this an experimental is performed.

4.3.3 Experimental Setup

To verify the simulation result (velocity magnitude plot) that the flow of gas is more in one of the output nozzles of the RPC gap, the following experimental setup was done:

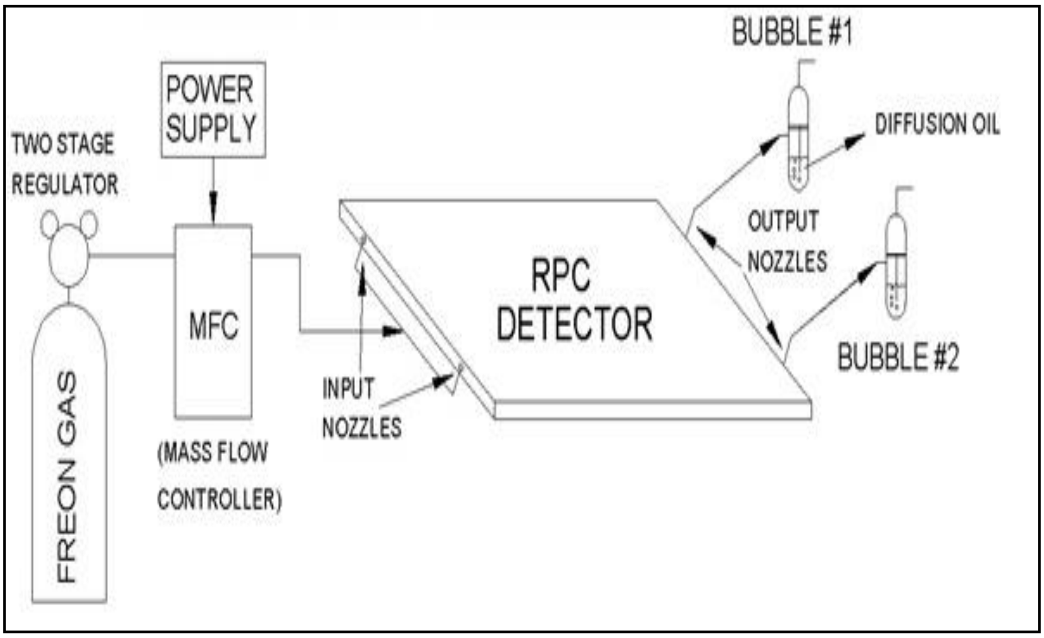

Figure 4.31: Experiment setup to study the flow of gas at the output nozzles

The experimental setup is shown in Figure 4.31. The RPC gap under test is a (1 × 1) m^2 gap having two inputs and two outputs and the R-134a gas is used. The MFC flow is set as per the composition of gas (from few SCCM to tens of SCCM) to the RPCs under test. The gas flows through the RPC and then moves into the bubblers connected at the output. The tube lengths going to the input and output of the RPC used are of equal lengths to make sure that equal quantity of gas is flown into the gap. The number of bubble's are counted in each of the bubbler. It is observed that the number of bubbles in each bubbler was found to be EQUAL and moreover the bubbler counts remain same even when the bubbler connections are interchanged. Hence the simulation result of flow rate in each out nozzle does not match with experimental setup and may be because of the inadequate and precise measuring tool that may be needed to match the simulation results and also the flow may be unequal in the initial stage which we are not able to count or observe. A more detailed study may be required.

4.3.4 Results

a) The COMSOL package is more complex in nature, than the Solid-Works for the beginners. It was just a learning curve.

b) The transient and steady flow of gas could be done easily in the COMSOL package.

c) The flow of gas is not equal at the out nozzles using the available resources it could not verified by the experimental setup. May be different and more precision tool of measurement is needed. The simulation gives a high degree of precision and there could be a possibility of different flow rates at the output of the RPC detector.

4.4 Simulation using CDF

In order to validate the studies done using so far and to incorporate the new dimensions, a study of the flow of the gases through RPC gas gap, using the CDF (CFX / FLUENT) is done by a team of members including a summer vacation project student.

Some changes in the RPC dimension and position of the gas nozzles are implemented due to design and space constraints. In the latest designs of RPC, *nozzles are not placed at the corner, but are placed on the one side (input nozzles) of the gap and the outlet nozzles are on the opposite side of the RPC gap and they are placed inclined by 45°.*

The CFX and FLUENT are the options for CFD analysis. The CFX solver is preferred, due to lack of time and the other advantage of the using CFX is the volume of control is assembled around the nodes (cell vertex), where each element is divided in sub volumes.

An RPC is constructed by using the latest dimension of (1.850 × 1.738) m^2, the sheets (resistive plates) of 3 mm thickness and a gas gap of 2 mm between glass sheets which is maintained by button spacers of height 2 mm and diameter 11 mm and are placed at distances of 200 mm along X and Y directions and the side spacers used are of thickness of 2 mm, on the four edges to make glass gap. These buttons maintain a uniform gap throughout the area of RPC gap, so that the applied field is uniform.

The elementary component of an RPC is the gas gap, the gas volume enclosed between two resistive plates. There are two inlets and two outlets for gas flow as shown in the Figure 4.32 and Figure 4.33 for the top and bottom gap of an RPC respectively. The top and bottom are different as the RPC gap is rectangular and the nozzles are placed on the longer end and in opposite directions. The shows Figure 4.34 the details of the chamfering of 4 side of RPC glass electrode. The inlet nozzles are 45 degrees inclined clockwise, while the outlet nozzles are inclined at anti-clockwise 45 degrees. The current design of RPC glass gap is referred as design 1.

4.4.1 Nozzle positions

Two design position of placing the nozzles are studied. The details of design 1 are shown in Figure 4.32 and Figure 4.33 for top and bottom glass respectively. The distance between the left edges and left nozzle is lesser, compared to the distance between the right nozzle and the right edge. During the initial design of the RPC gap, nozzle positions were different. In the design 2, the nozzles are placed in such way, that the distance between the left nozzle and the left wall is equal to the distance between right nozzle and right wall and also the distance between two nozzles is twice the distance between nozzle and the nearest wall.

The final design of ICAL may have a parallel flow for 4 RPCs with in a road, from a common source of gas manifold.

4.4.2 Fluid Simulation

The previous simulation using COMSOL platform, was done for a single gas which was for R22 (assuming it is equivalent of R134a for simulation purpose). In present study, simulations are done for all the three gases individually that are being (used in avalanche mode), for the mixed gas and then the nozzle position variation is also considered. The inlet velocities for the gases are kept at 0.17 m/s (as it was kept in the previous studies), 0.085 m/s (one fifth of 0.17) and 0.85(5 times of 0.17).

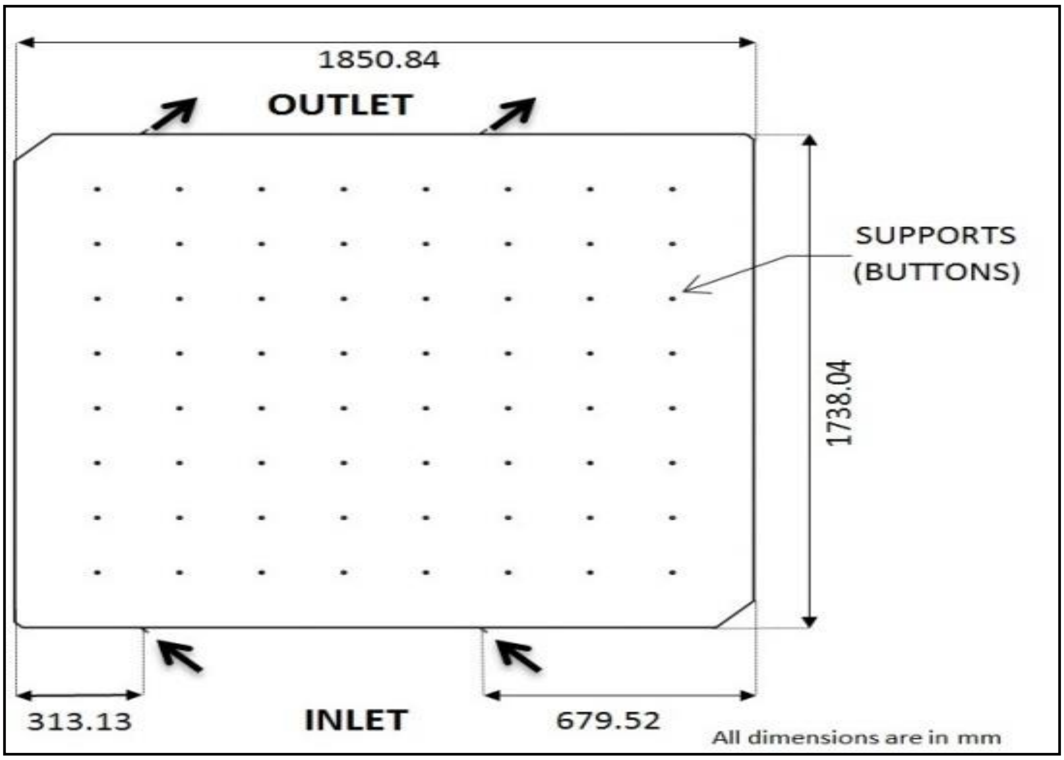

Figure 4.32: Top glass of an RPC gap

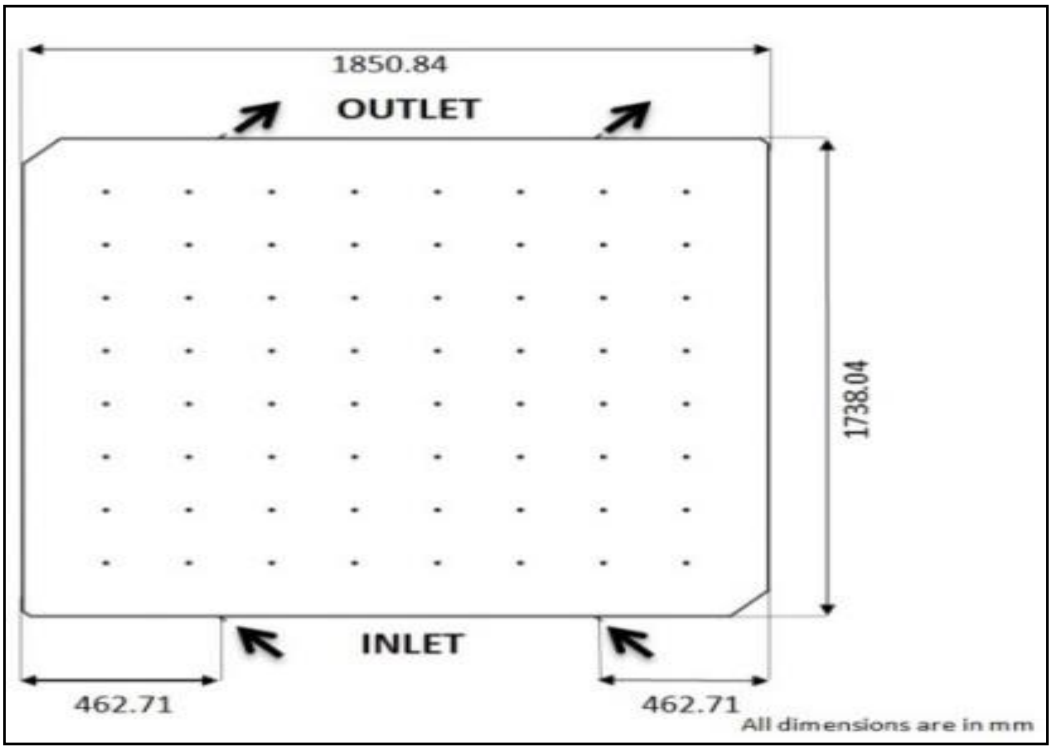

Figure 4.33: Bottom glass of an RPC gap

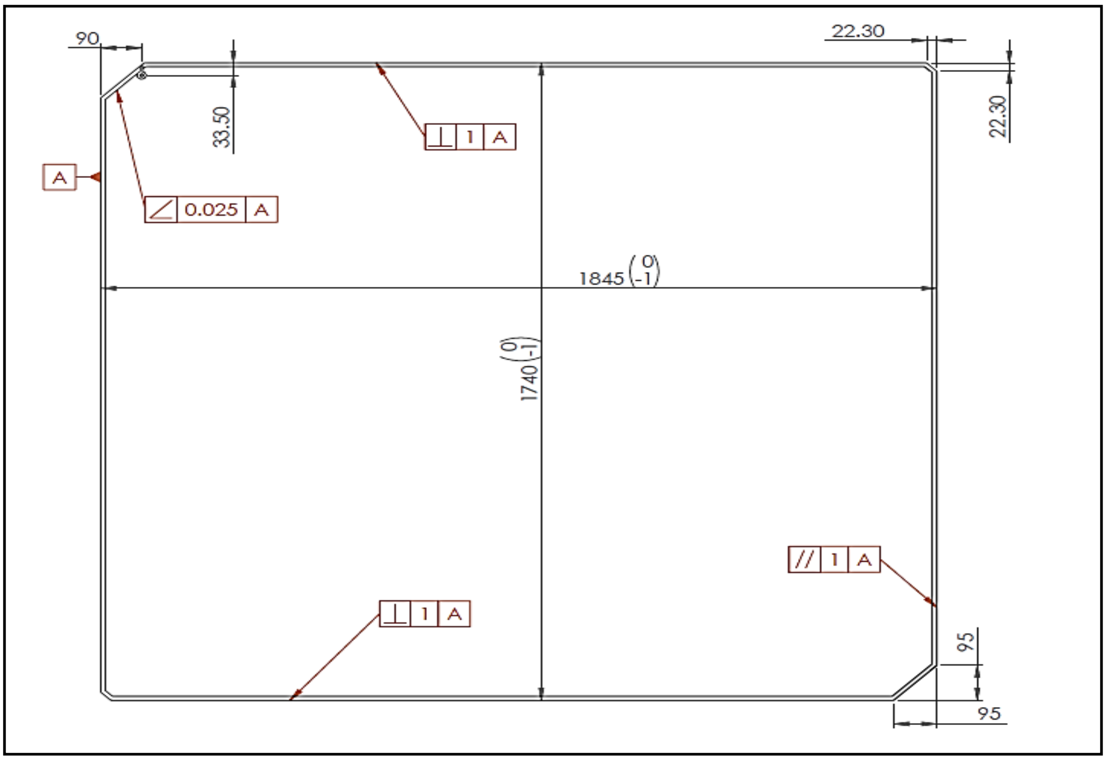

Figure 4.34: Chamfering detail of glass

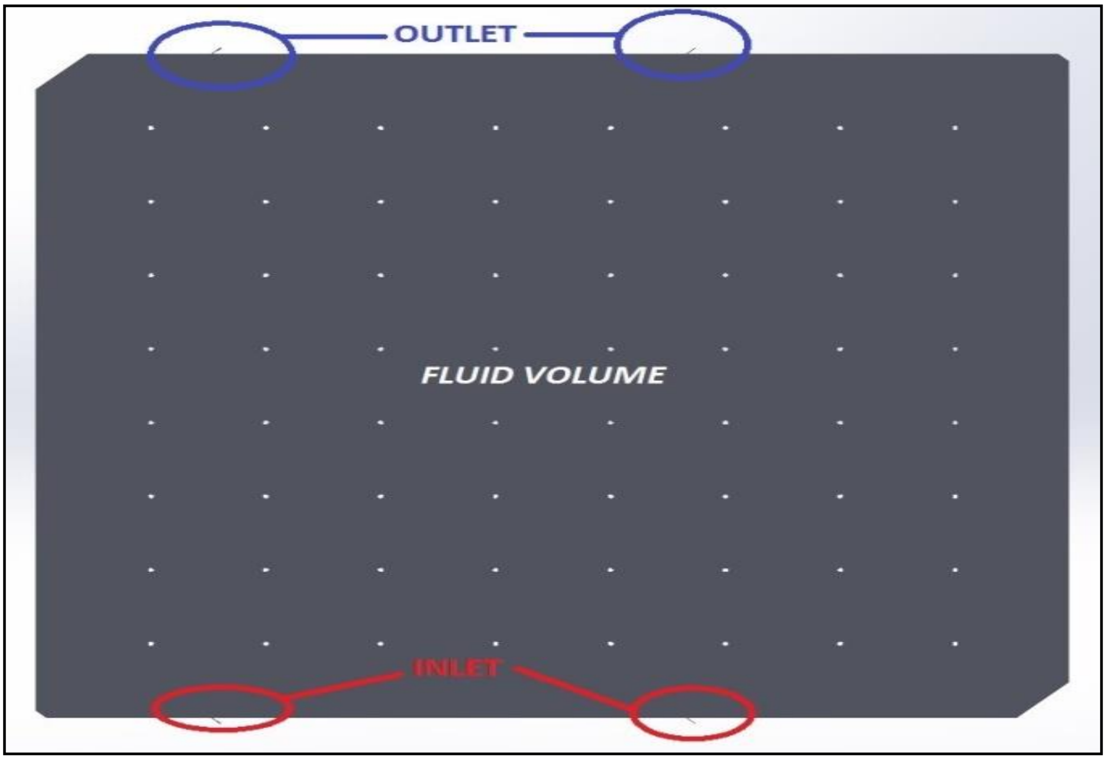

Figure 4.35: Assumption for simulations

The nozzle angle is also considered. The mixed gas flow simulation for the flow of 6 SCCM is considered. The fluid volume assumption is as shown in Figure 4.35.

4.4.3 Gas Simulation of R134a

The boundary conditions are

a) Inlet velocity of 0.85 m/s

For 25 litres / hour volumetric flow, velocity is kept as 0.85 m/s.

25 litres / hour = 25,000 cm^3/sec

For one second the flow will be 25,000 cm^3/3600 sec = 6.94444E-006 cm^3/sec

This is the flow through two nozzles, through one nozzle the flow will be

6.94444E-006 /2 cm^3/sec = 3.47222E-006 cm^3/sec

Diameter of the inlet nozzle is 2.30 mm Therefore Area of the inlet is

$$\pi \times (1.15 \times 10^{-3})^2 = 4.15475E\text{-}006$$

Inlet velocity is

$$\frac{3.47222E{-}006\ \text{cm3/sec}}{4.15475E{-}006\ \text{m2}} = 0.845 m/s \text{ (Aapproximately 0.85 m/s)}$$

b) Inlet velocity of 0.17m/s

The initial velocity of 0.17 m/s (which is one fifth of the 0.85 m/s) the volumetric flow will become one fifth and that is 5 litres / hour.

c) Inlet velocity of 0.085m/s

The velocity 0.085 meters /second is one tenth of the 0.85.The volumetric flow will also be one tenth and will be 2.5 litres / hour

d) Outlet conditions applied

The outlet is defined as opening for all simulations and the gauge pressure is kept as Zero bar abs.

4.4.3.1 Material Properties

Freon (R134a)

Molecular Weight - 102.03 g /mole

Density - 4.25 kg /m^3

Dynamic viscosity - 11.6E-006 Pa.S

4.4.3.2 Inlet velocity of 0.17 m/s

a) With the residual of 10^{-4} : Velocity contour
b) With the residual of 10^{-6} :Velocity contour and streamlines

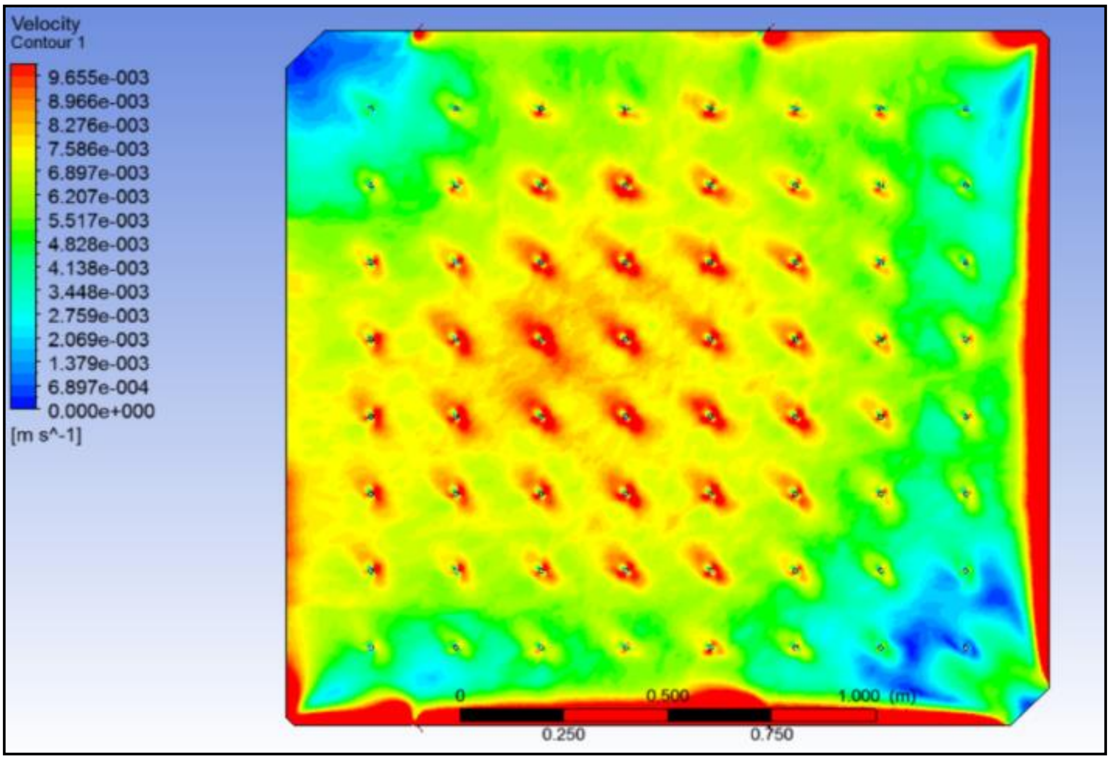

Figure 4.36: Velocity contour at 0.17 m/s

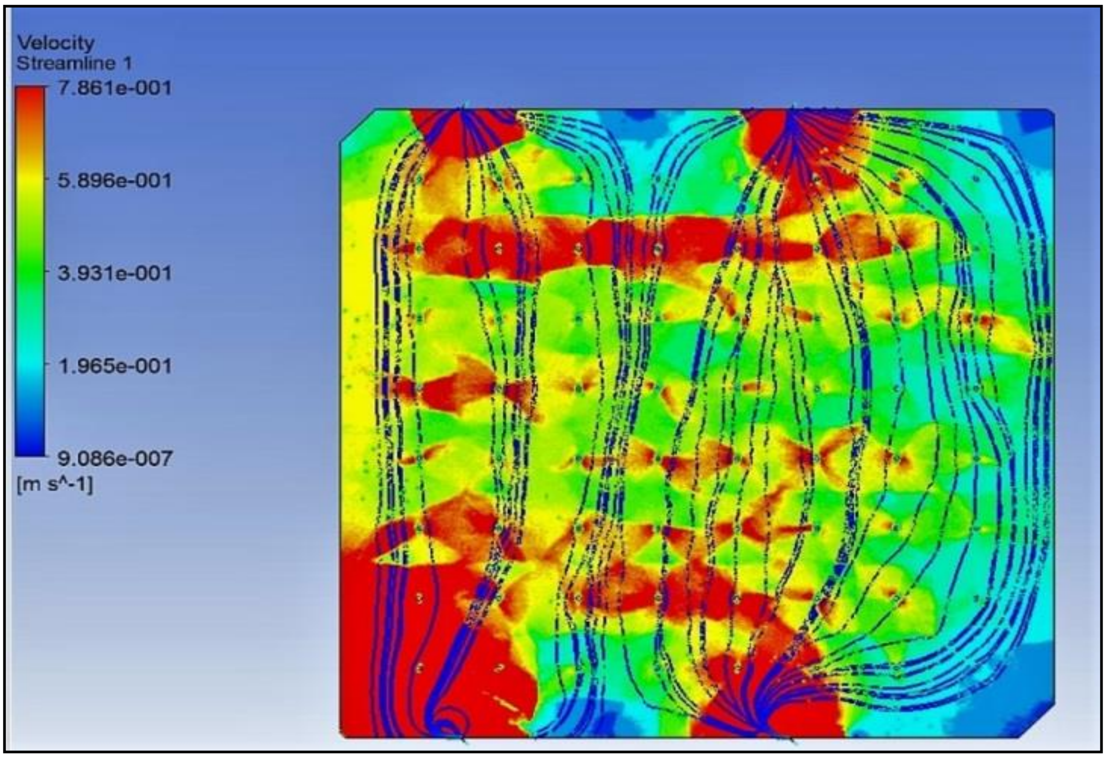

Figure 4.37: Velocity contour and streamlines at 0.17 m/s

As we can see for residual velocity of 10^{-4} and 10^{-6}, from the Figure 4.36 and Figure 4.37 , there is clearly a large difference between the two results. Therefore, these results are further confirmed by the transient flow simulation through RPC. In both cases the Dead Zones, which the gas flow is almost zero (blue-region). The Figure 4.36 shows positioning of the buttons place inside to hold the two glasses.

The Figure 4.38, Figure 4.39 and Figure 4.40 show the transient simulations for 0.17 m/s, 0.085 m/s and 0.85 m/s respective. The Dead Zones are visible in all the plots.

4.4.3.3 Transient simulation with the residual of 10^{-6}

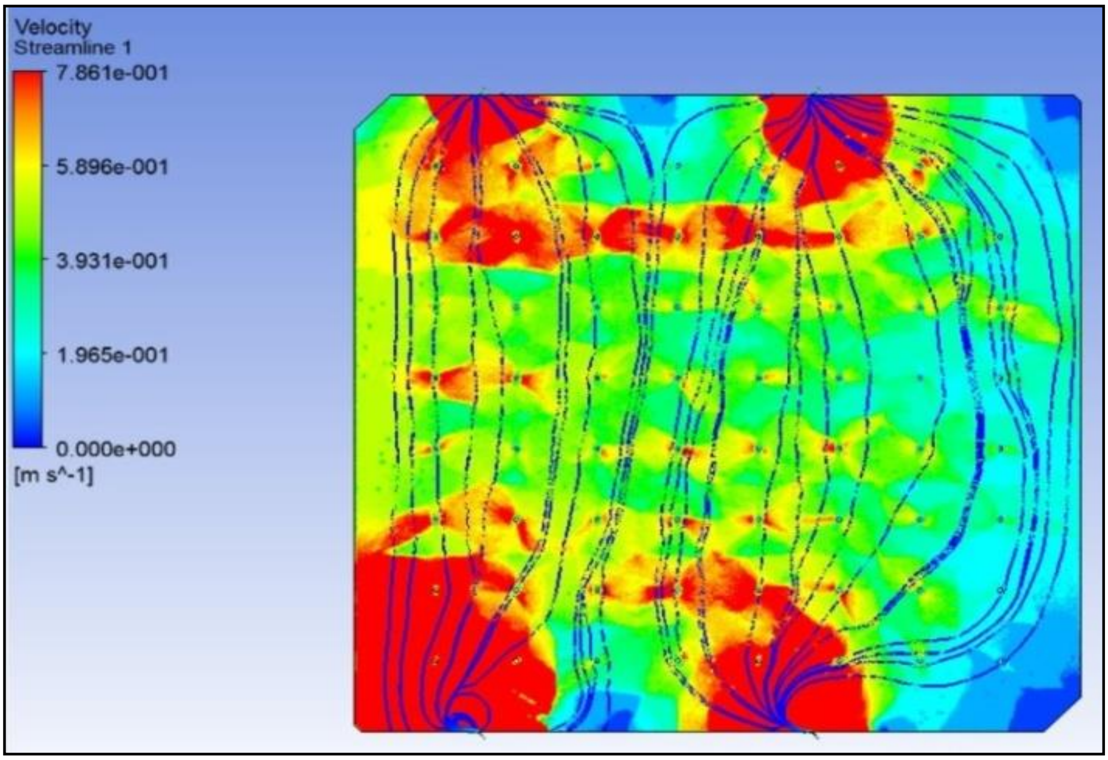

Figure 4.38: Transient simulations at 0.17 m/s

4.4.3.4 Inlet velocity of 0.085 m/s

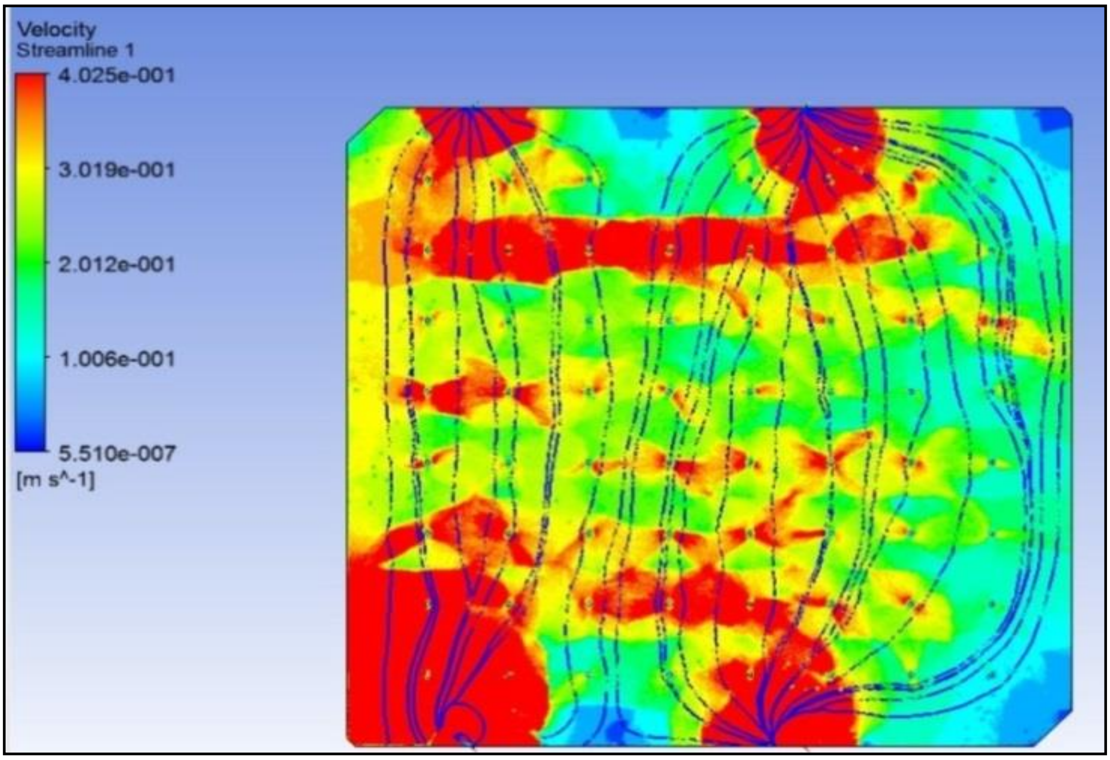

Figure 4.39: Transient simulations at 0.085 m/s

4.4.3.5 Inlet velocity of 0.85 m/s

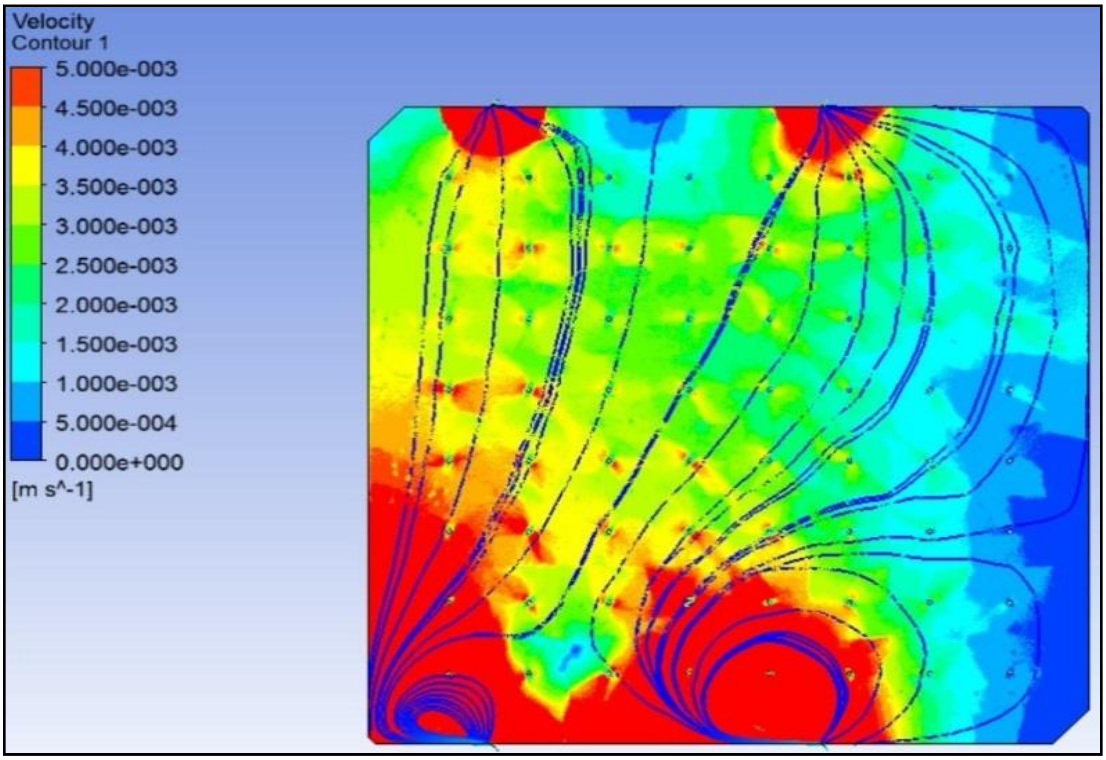

Figure 4.40: Transient simulations at 0.85 m/s

4.4.4 Interpretations of the velocities

In the RPC the volume fraction of all 3 gases are hardly changing. In the case of R34a the volume fraction is hardly varying between 94.5 to 95.5 per cent. The similar results can be observed for the SF_6 and I-butane. That's why assuming the gas as fixed composition mixture is a good approximation. The simulation has been also done by assuming the gas as the fixed composition mixture. The mass percentage of the respective gas was given to the solver and the values were interpolated.

4.4.5 Mixed Gas simulation and Nozzle position variation studies

In the previous simulations assumption made was that the physical properties of the gases are almost constant and the volume by volume percentages of the gases are not varying with time and it is independent of where it flows. So the composition of the gas at inlet was given. The inlet and out composition of the gas are assumed to be equal.

4.4.5.1 Boundary conditions

a) Gap Inlet

For a 6 cm^3 Volumetric flow of gas the inlet velocity will be 0.012 m^2.

Diameter of the inlet nozzle is 2.30 mm.

Therefore Area of the inlet is $\pi \times (1.15 \times 10^{-3})^2$ = 4.15475E-006

Volumetric flow is 6cm^3 per minute. Per nozzle the volume flow will be 3 SCCM.

So per second it is 0.1 cm^3 per minute $\left[\frac{6\ \mathrm{cm3}}{60\ sec}\right]$

Inlet velocity is ($\mathrm{cm3/sec})/(4.15475\mathrm{E} - 006\ \mathrm{m2})$ = 0.012034 m/s

b) Gap Outlet

The outlet of the nozzle is kept as atmospheric opening and the volume fraction of the gas components at the outlet are assumed to be same as inlet.

4.4.5.2 Material properties

a) R134a.

Molecular Weight - 102.03 gram /mole

Density - 4.25 kg/m^3

Dynamic viscosity - 11.6E-006 Pa.S

b) I-butane

Molecular Weight - 58.122 gram /mole

Density - 2.4397 kg/m^3

Dynamic viscosity - 7.4978E-006 Pa.S

c) Sulphur hexafluoride

Molecular Weight – 146 gram /mole

Density - 6.2563 kg/m^3

d) Dynamic viscosity and concentration of gases

The assumed viscosity is 1.5123E-005 Pa. S and the actual gas flowing through the RPC is the mixture of above three gases with fixed composition viz., R134a of 95 %, I-butane of 4.5 % and SF_6 of 0.5 % by volume.

4.4.5.3 RPC size of (1.850 × 1.738) m^2

The boundary conditions were same except the inlet velocity. The velocities are 0.01243 m/s (for 6 SCCM), 0.17m/s and 0.85m/s.

(a) For inlet velocity of 0.85

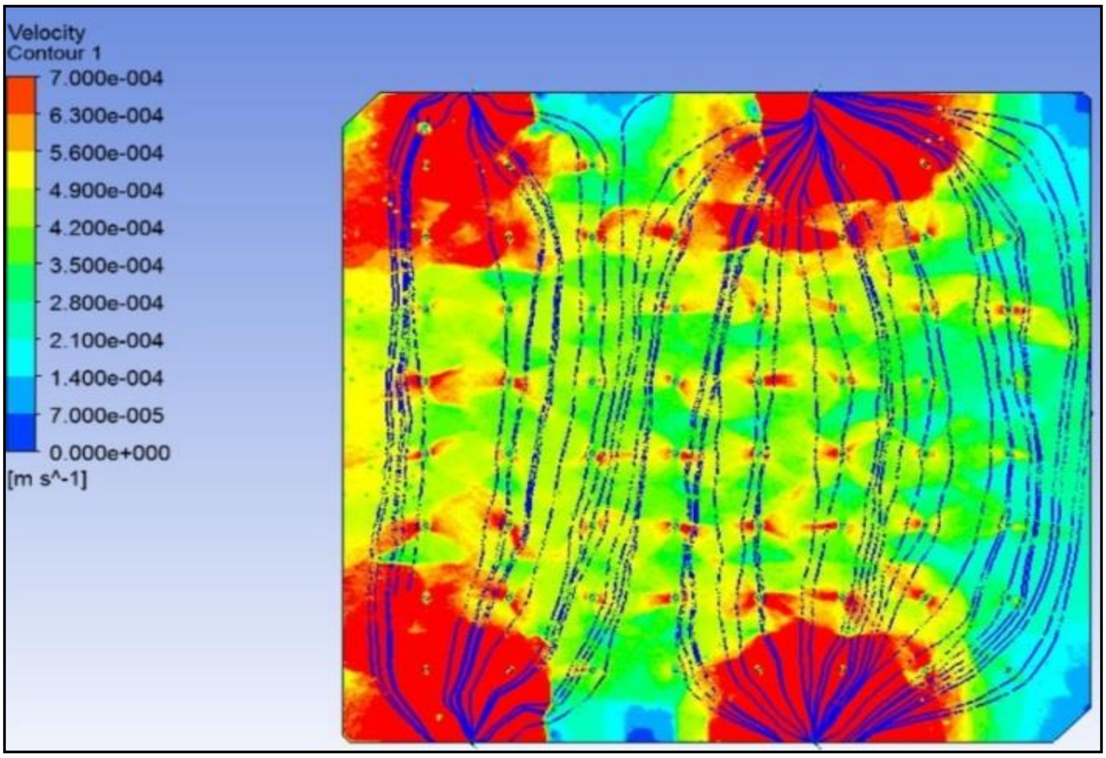

Figure 4.41: Transient simulations at 0.85 m/s for mixed gas

(b) inlet velocity of 0.17

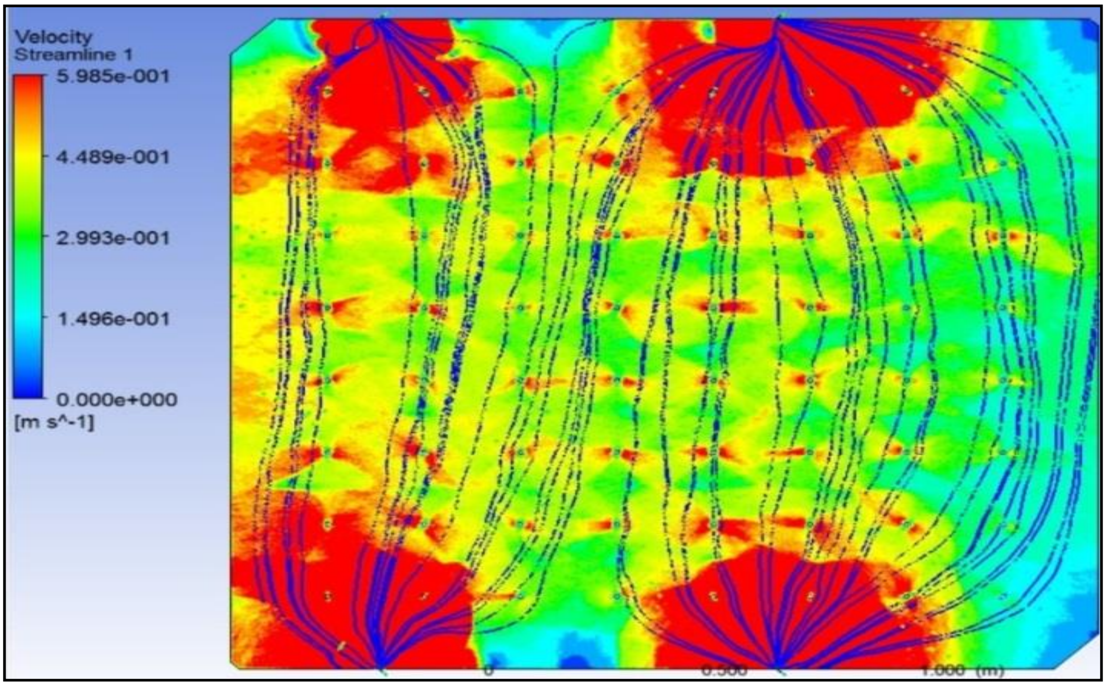

Figure 4.42: Transient simulations at 0.17 m/s for mixed gas

(c) inlet velocity 0.01234 m/s

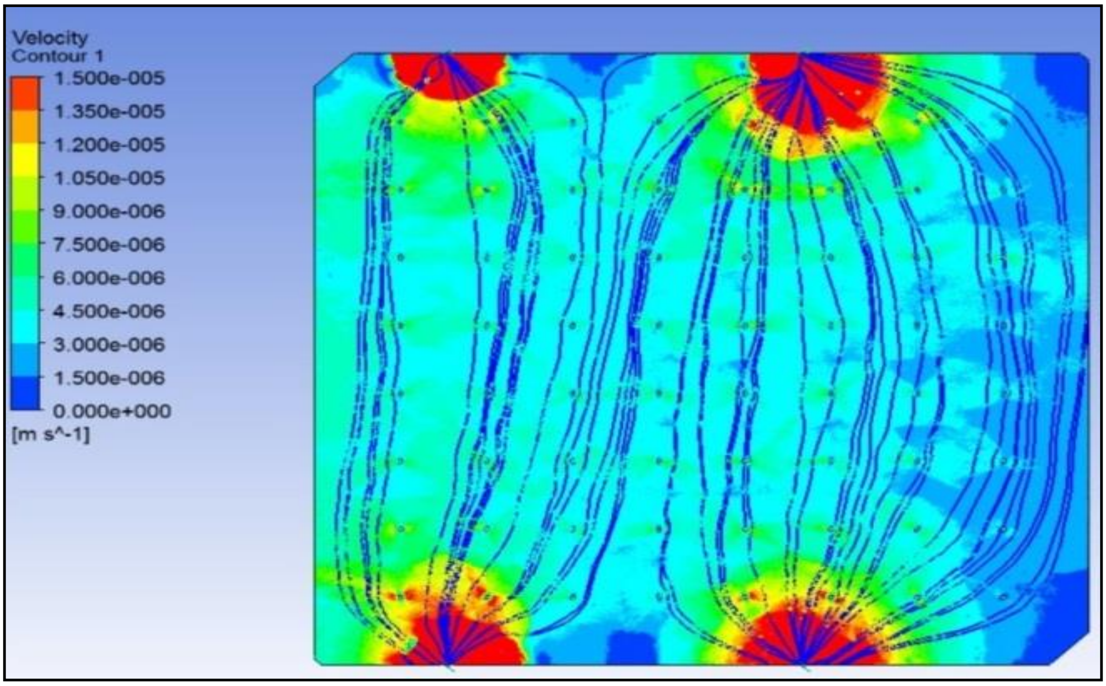

Figure 4.43: Transient simulations at 0.01234 m/s for mixed gas

The Figure 4.41, Figure 4.42 and Figure 4.43 show the transient flow simulation plots for various velocities. The dead zones are visible an all the plots.

4.4.5.4 Study of flow with nozzle position variations on the RPC

The latest or the final and modified design of nozzle positions of the RPC gap with an angle of 45° is considered and then changing the position of the input and output nozzles, some simulation studies are done. Firstly, the flow of R134a is done and then for the mixed gas.

The gas mixture flowing through the RPC gap is considered as a fixed component mixture. The transient simulation for the time of 60 sec has been performed. A laminar is assumed during the simulation because of very low velocity of gases, all the surfaces like polycarbonate buttons, glass sheets are assumed to be smooth. The gas leakages within an RPC is assumed to be zero.

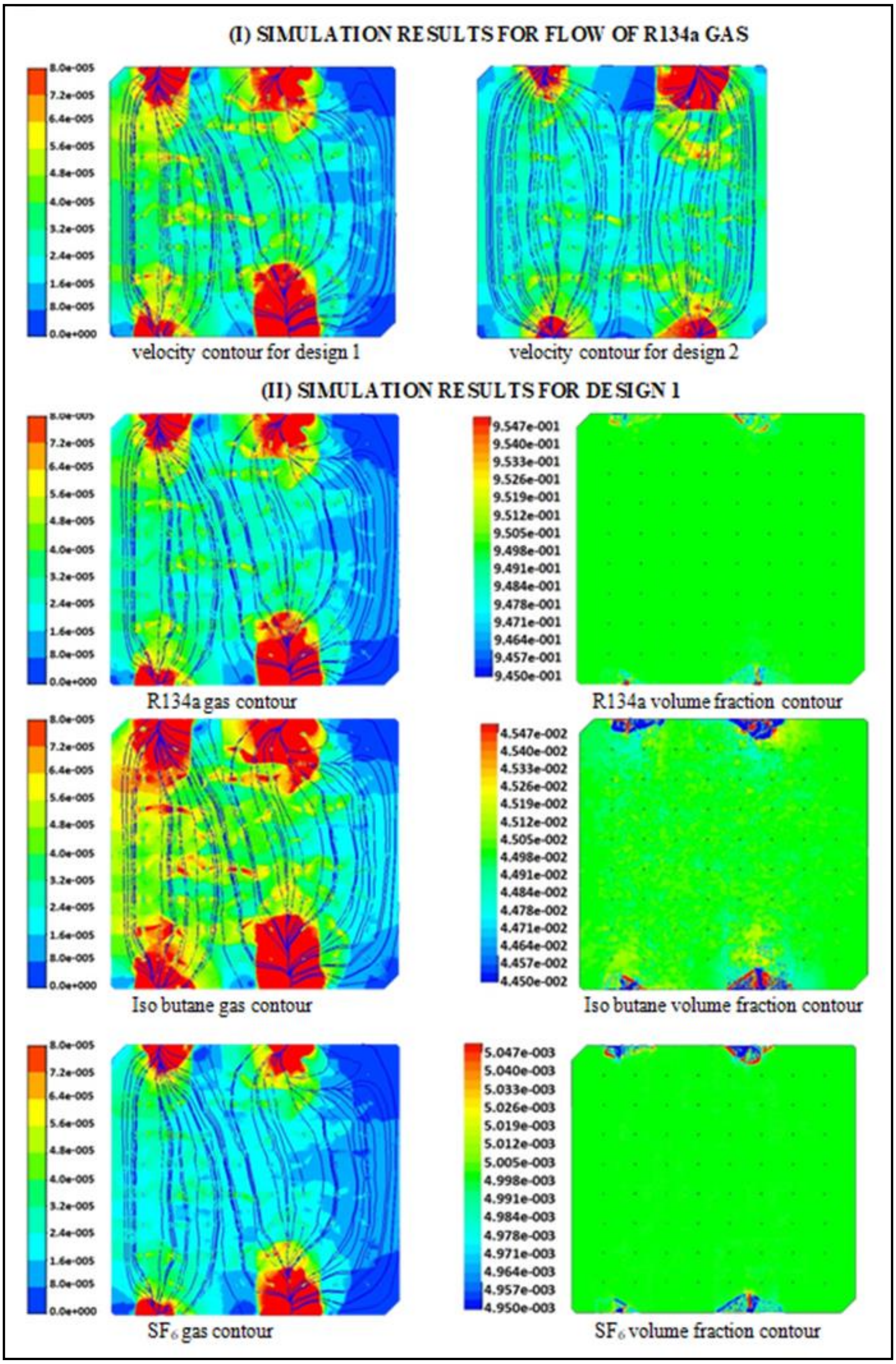

Figure 4.44: Simulation results Nozzle Position Design 1

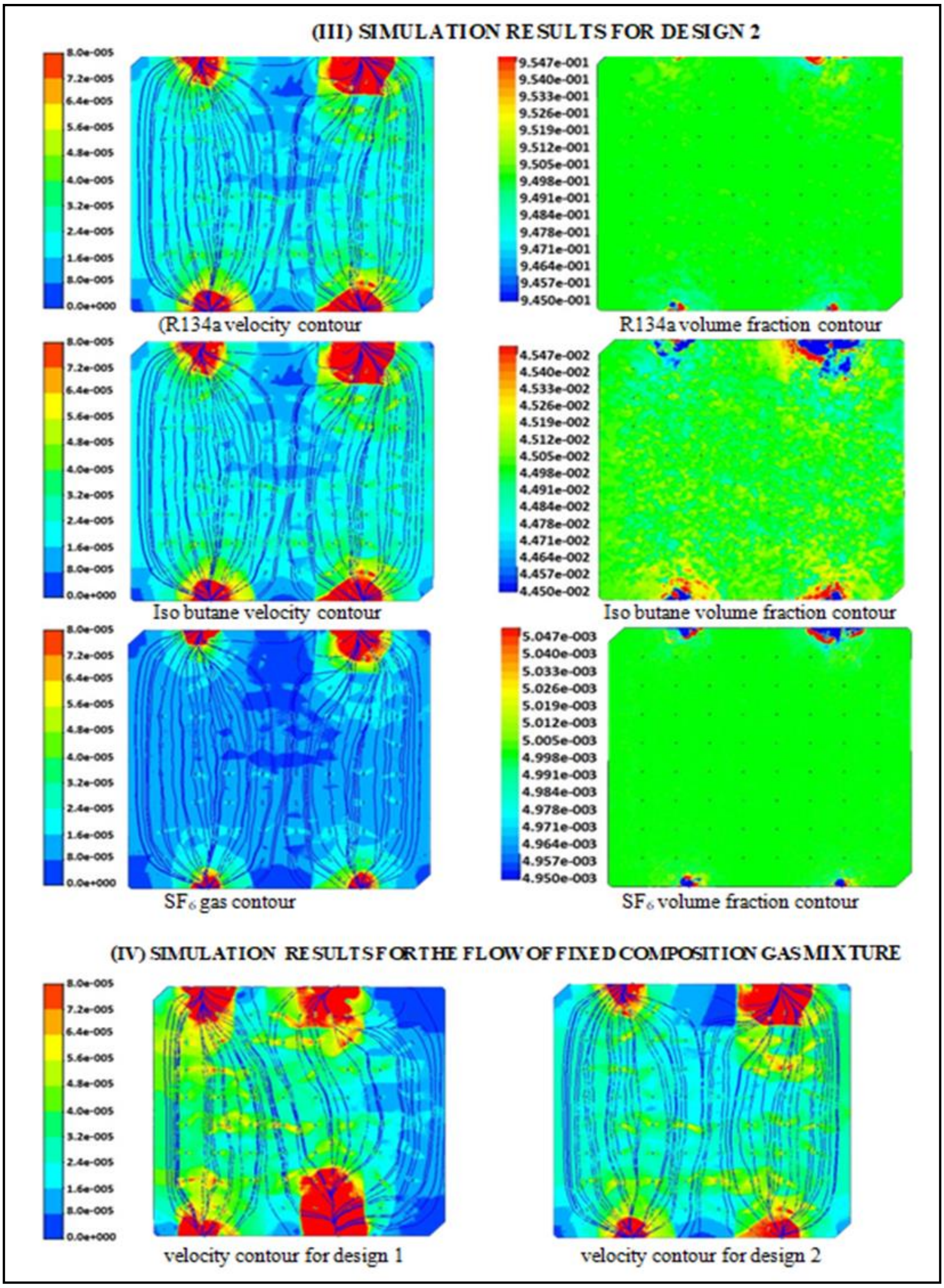

Figure 4.45: Simulation results Nozzle Position Design 2

4.4.6 Results and interpretation

In the design 1, the distance between the left wall and left inlet is less compared to the distance between right nozzle and right wall. The direction of the velocity vector of the gas at the inlet is 45° in the direction of the left wall. Due to this particular configuration, gas entering the setup from the left nozzle has little space to flow compared to the gas entering from the right nozzle. As a result, velocity of the gas in the left side of the RPC is greater than the velocity of the gas from the right nozzle. The flow rate remains constant throughout the RPC and hence the velocity of the gas decreases after entering the RPC, reaches a minimum and then increases as the gas approaches the outlet.

The stream lines and the velocity contour are symmetric in all simulations for the design 2. But in this case flow rate in the right outlet nozzle is more to that of the left outlet nozzle. The volume fraction for all the 3 gases is hardly changing for both configurations. The results for both the cases (parameters) are compared in the Table 4.1

In the Figure 4.44 and Figure 4.45 we can see that in the green area the volume fraction of the SF6 is varying from the values 4.998e-003 to 5.012e-003. This is ±2.4 % change with respect to the assumed value. Similar results have been observed for the R134a and I-butane.

Table 4.1: Parameters for Design 1 and Design 2 for nozzle positions

Parameter	R134a		Mixed Gas		Fixed composition mixture	
	Current design	Design 2	Current design	Design 2	Current design	Design 2
Inlet mass flow (Kg/s)	4.21E-07	4.21E-07	4.14E-07	4.14E-07	4.14E-07	4.14E-07
Outlet left nozzle (Kg/s)	2.14E-07	2.09E-07	2.10E-07	2.06E-07	2.11E-07	2.05E-07
Outlet right nozzle (Kg/s)	2.07E-07	2.12E-07	2.04E-07	2.08E-07	2.04E-07	2.09E-07
Inlet pressure (Pa)	0.145123	0.134771	0.141226	0.13171	0.143007	0.133737

For the given set of boundary conditions, the flow pattern in the RPC design is almost same for the R134a gas, mixed gas and fixed composition mixture.

4.4.7 Conclusion on simulations

The main concern during the study was the change in the concentration in the SF_6. The studies have shown that a small change in the concentration of SF_6 will affect the performance of RPC drastically. The results show that for the flow of 6 SCCM, change in the volume concentration is very small for the SF_6 in all cases. For the case of 6 SCCM flow, for both designs, the volume concentration of all gases are not changing significantly. So the overall performance of the RPC will not be affected.

Some dead places for the gas flows are also observed in both designs. In the design 1, at the right side of the RPC the velocity of the gases is very low. As a result in the practical arrangement, gas may stagnate. Consequently, the formation of radicals at these spots will affect the performance the RPC.

In the design 2, dead zones are comparatively less. The previous design of the RPC seems to be a better design as flow lines are spread out and pressure drop across it compared to the design 1 is less. *As previously mentioned due to some physical constraints nozzle positions are changed. So to improve the flow of gases, more optimization needs to be done.*

The "dead zones" are observed in the simulation results, but the performance of the RPCs for long run under cosmic rays muon studies show that the position efficiency is more than 95%, so this could be because of diffusion (not drift) of the gas in the entire volume of the RPC chamber and also the air leakages into the RPCs help in reducing these dead zones.

Chapter 5

Validation and results related to flow and control of gas mixture for RPC performance.

The Proto-type CLS designed for a stack of 12 RPCs is functioning as per the design specification and being used. The system is tested thoroughly for 6 RPCs at a given time and some of their performance parameters are described below. The designed numbers of 12 RPCs were not integrating in the CLS due to time constrains and other research activities.

The applied high voltage, the current drawn, noise rate, ambient parameters etc., play a vital role in the performance on an RPC. The following are some of the studies and results obtained by us when RPC's are operated in both OES and CLS.

5.1 Long term study stability

a) The Figure 5.1 and Figure 5.2 are the ***noise rate*** for L2, X-side and for strip number 14 and L2, Y-side strip number 12, of an (1.85 × 1.73) m^2 size RPC, over a period of one year in an OES gas system with a flow rate of (3 to 6) SCCM per RPC. The expected noise rate is about 100 hertz and some fluctuation seen in the plots is due to ambient environment. The Figure 5.3 shows the error bar in the noise rate data which is within ± 1 %.

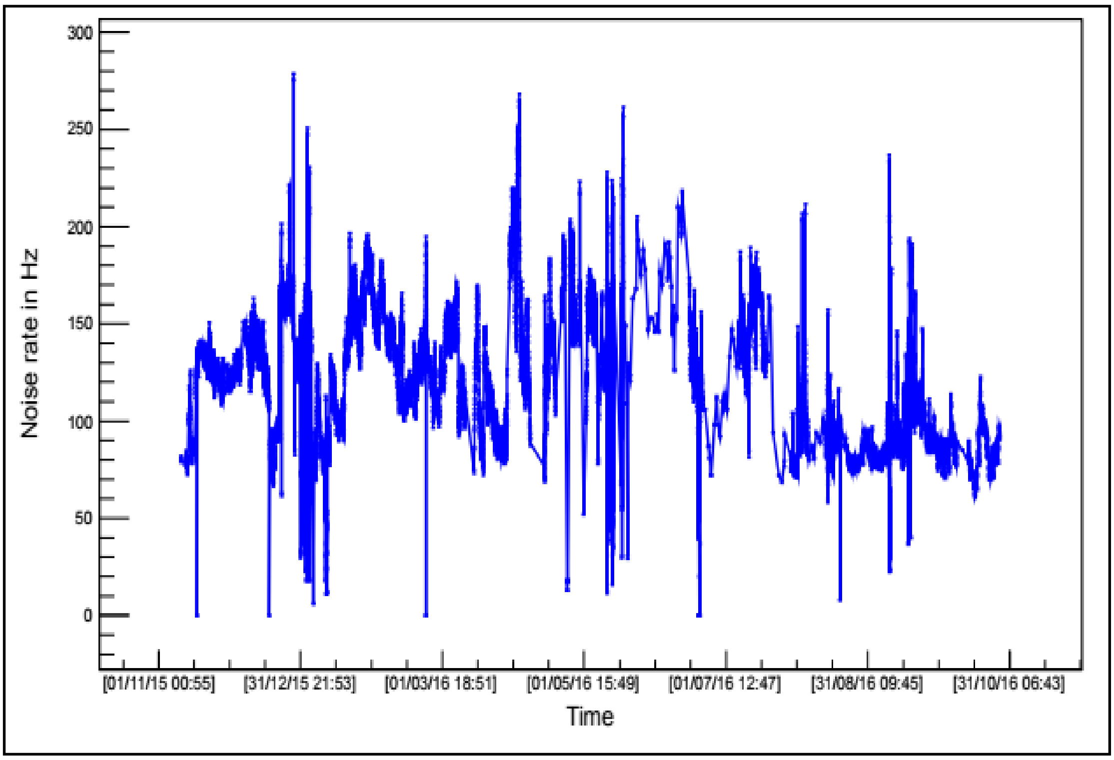

Figure 5.1: Noise rate for Layer-2 X-side for strip # 14

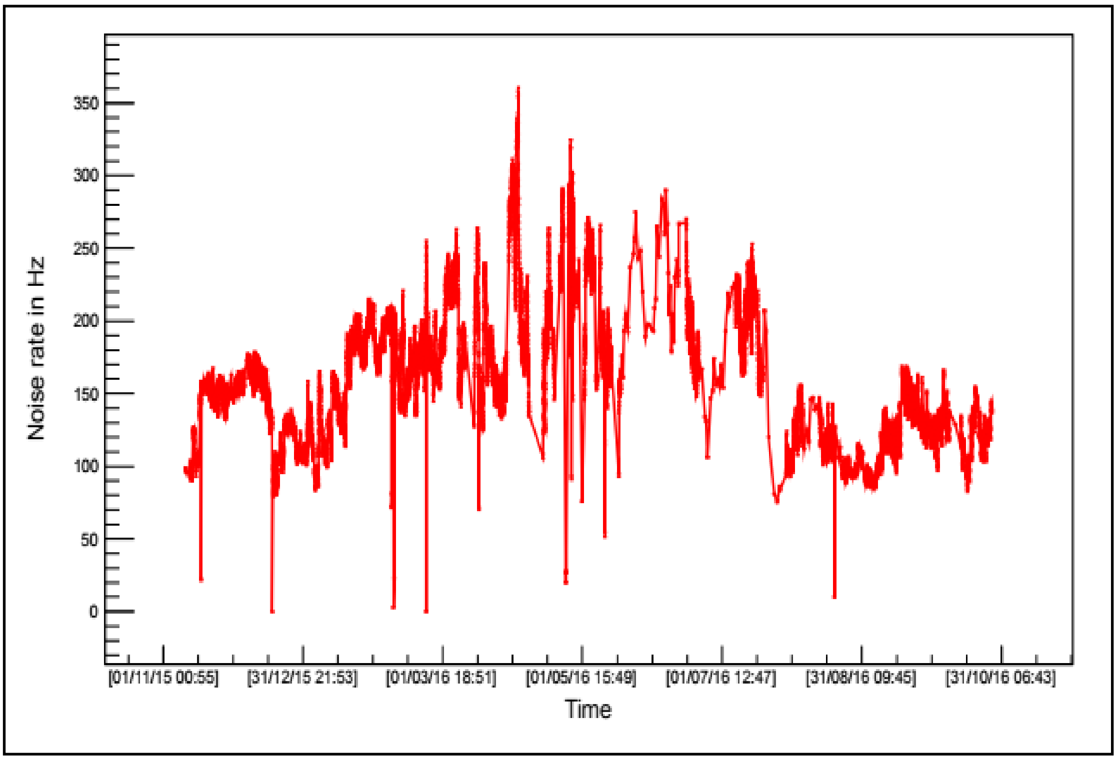

Figure 5.2: Noise rate for Layer-2 Y-side for strip # 12

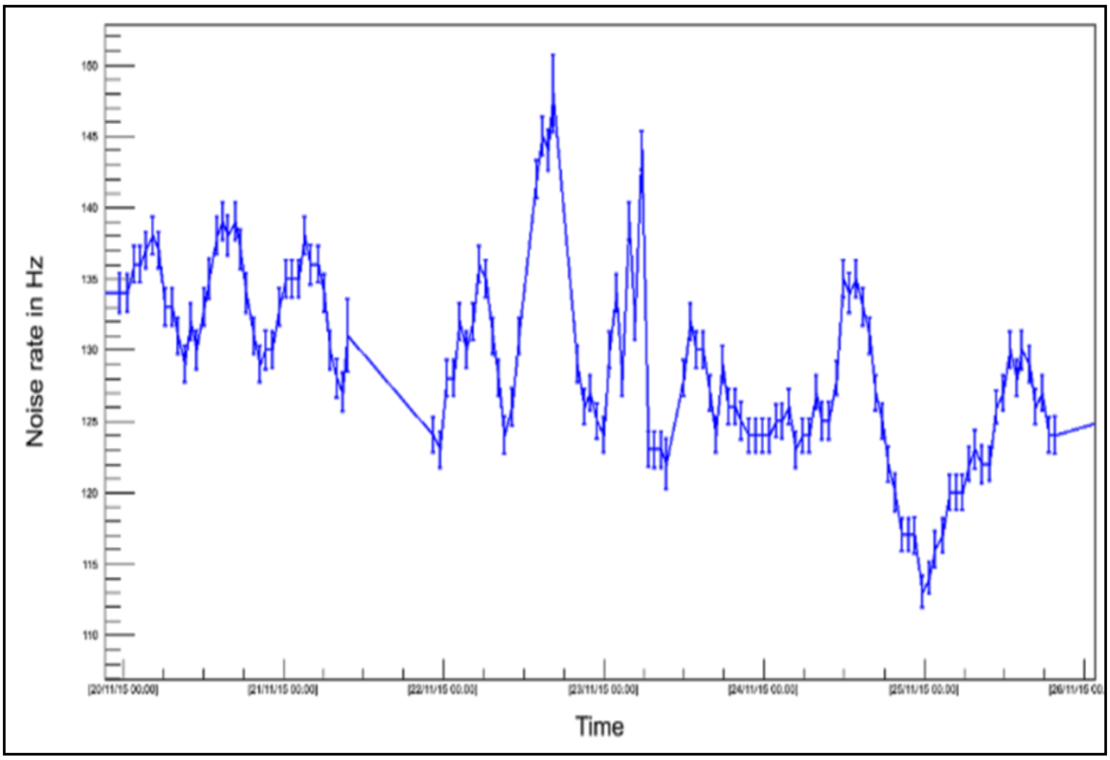

Figure 5.3: Noise rate with error bar

b) The Figure 5.4 is the V-I (voltage-current) characteristics of an RPC and it is seen to be stable over a period of a year. The average current drawn is within the expected range of ~250 n A. The operating voltage is at 10 KV and is quite stable.

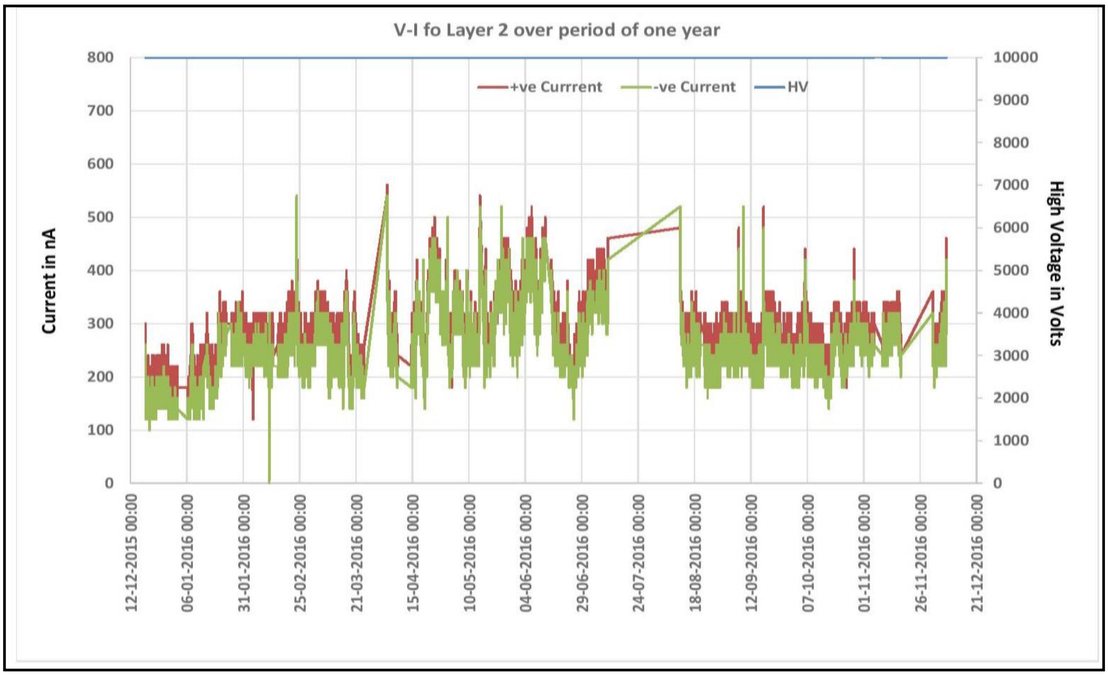

Figure 5.4: V-I stability for a period of one year

c) The temperature and humidity monitoring for a two RPC connected in series in CLS, namely RPC- AL 01 and RPC- AL 03 (2nd in series) over a period of 6 months is shown in the Figure 5.5 and Figure 5.6. As seen in these figures there is correlation between temperature, humidity and the current drawn by the RPCs. The missing data is due to power failure. The laboratory temperature maintained is about 22 ^{0} C and humidity of (40-45) %.

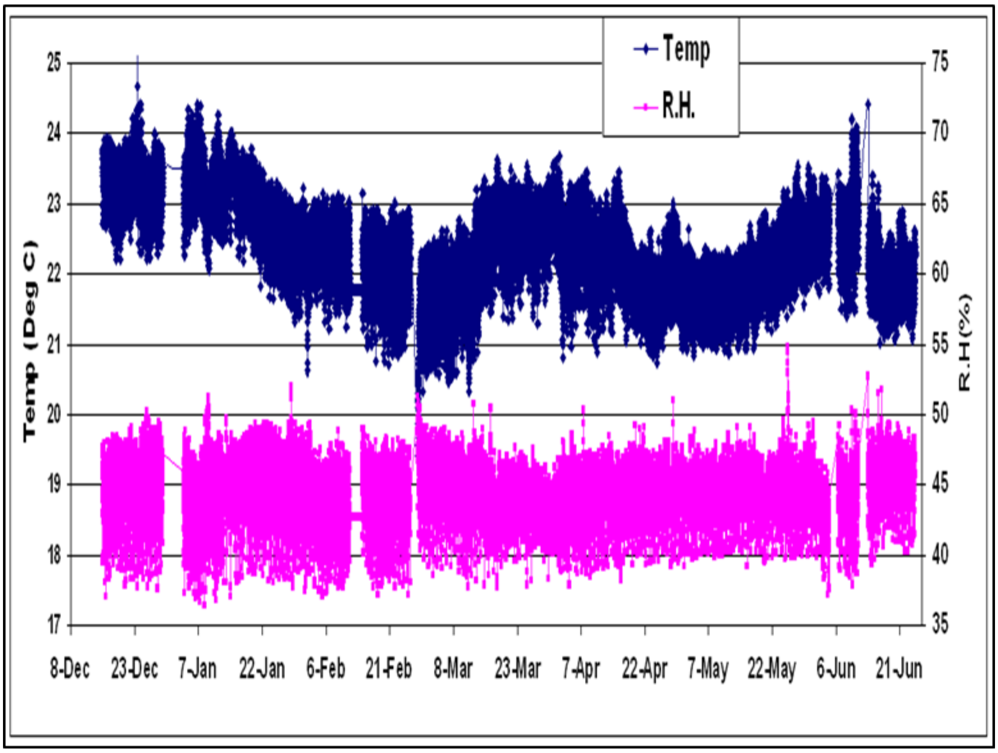

Figure 5.5: Ambient parameters temperature and humidity over a period of 6 months

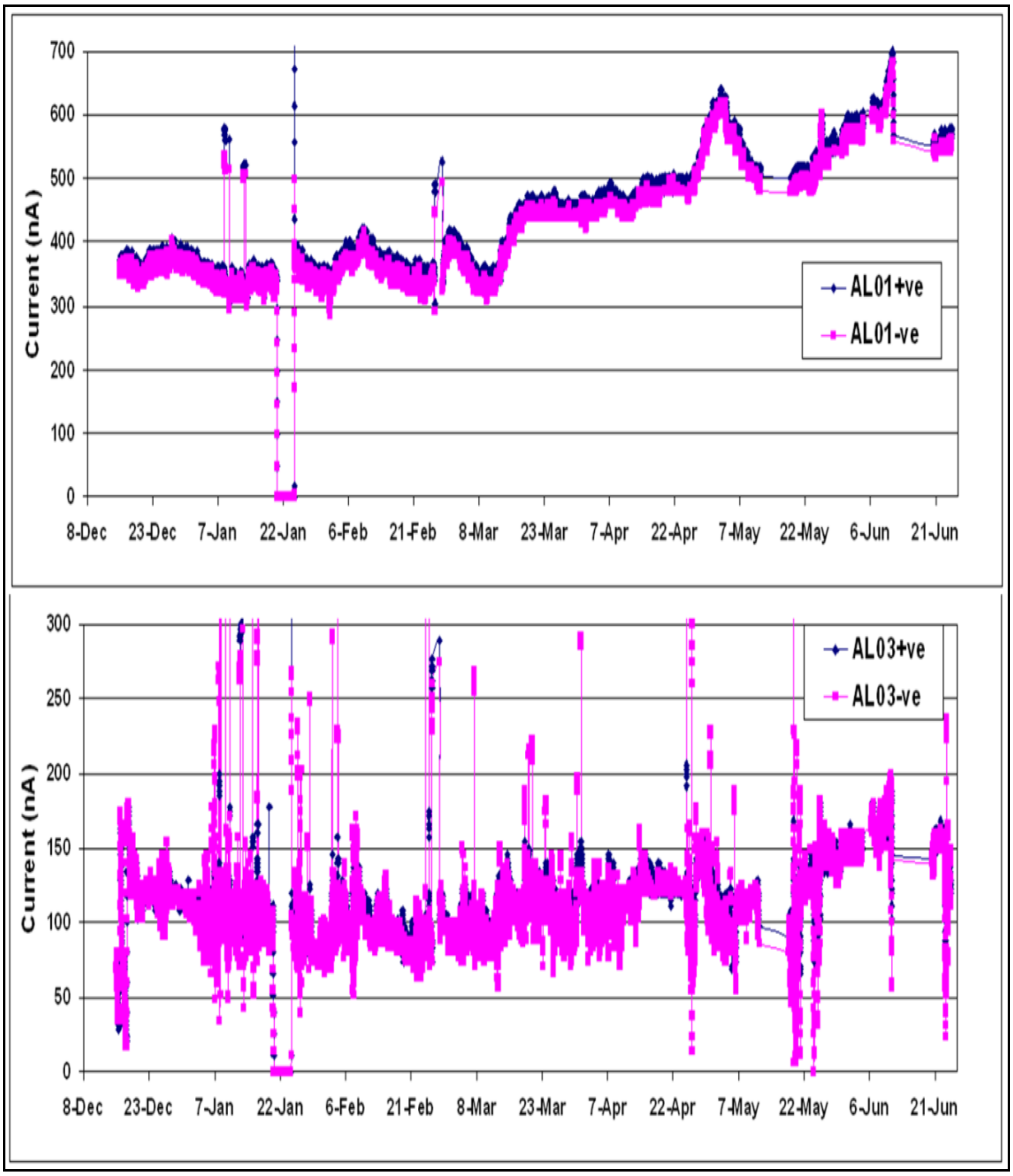

Figure 5.6: current monitoring (RPCs in series for gas flow)

5.1.1 Efficiency of the CLS

The efficiency of CLS is defined by measurement of its leak rate and in the ideal case it should be Zero. There is top-up of fresh gas every 12 days in the CLS operation as seen in the Figure 5.7 . This leakage is from the contribution of the leak in the CLS itself; leak(s) in the RPCs and from the various joint in the gas path. As per the accepted criteria for RPC at CERN, the leak rate should be $10E^{-4}$ SCCM (1 cc in 33 hours). But for the Glass based ICAL RPCs, the test criteria for the accepted leak is 2 cc per day at 3 mbar pressure (taking into consideration the variation in temperature in room, the atmospheric periodic pressure variations etc.).

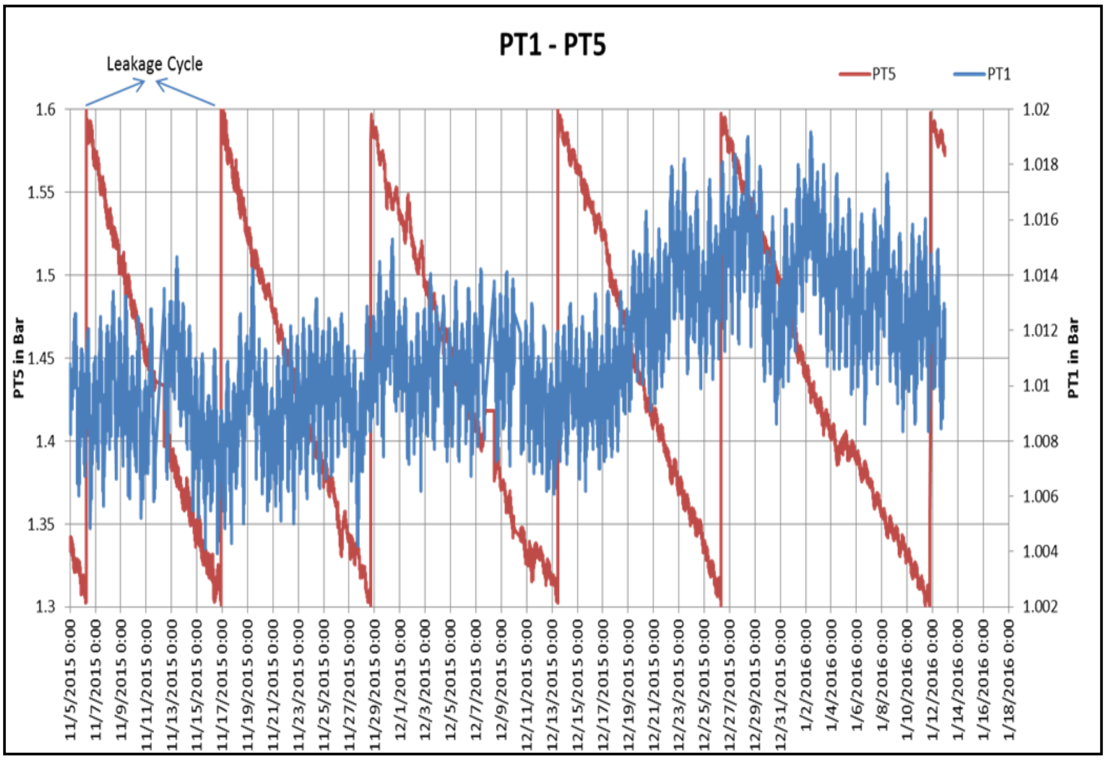

Figure 5.7: Fresh gas top-up every 12 days in CLS

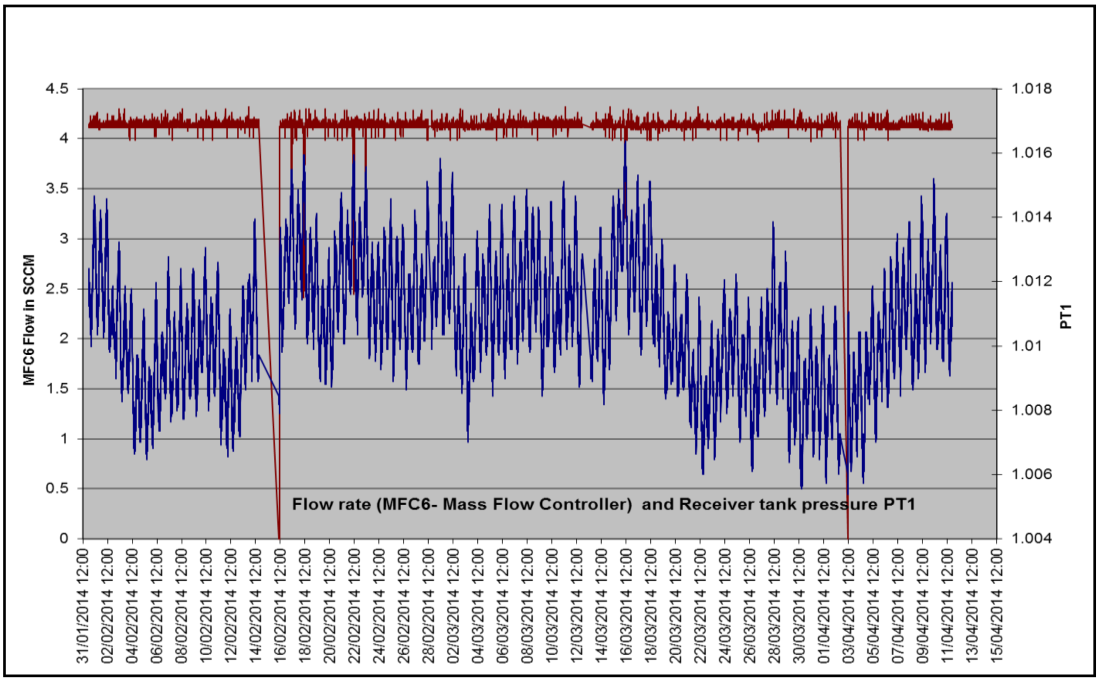

Figure 5.8: RPC set flow using MFC-6 in CLS

The performance or the stability of the set flow rate of the MFC-6 in the CLS is shown in Figure 5.8. It is observed that irrespective of variation in pressure (PT1 sensor) in the receiver tank the set flow of 4.5 SCCM for an RPC remain uniform throughout the period of operation of few months. The glitches seen may be due to system parameter, which was eventually corrected by tracking the ambient lab pressure.

In lieu of an RPC of (1.85 × 1.73) m^2 size, an equivalent RPC of (2 × 2) m^2 is formed using four RPCs of (1 × 1) m^2 and connecting two in series (the output gas line of the first is connected to the input of the second) as shown in Figure 5.9. These were made for ease of handling and testing in the initial stages of testing RPCs.

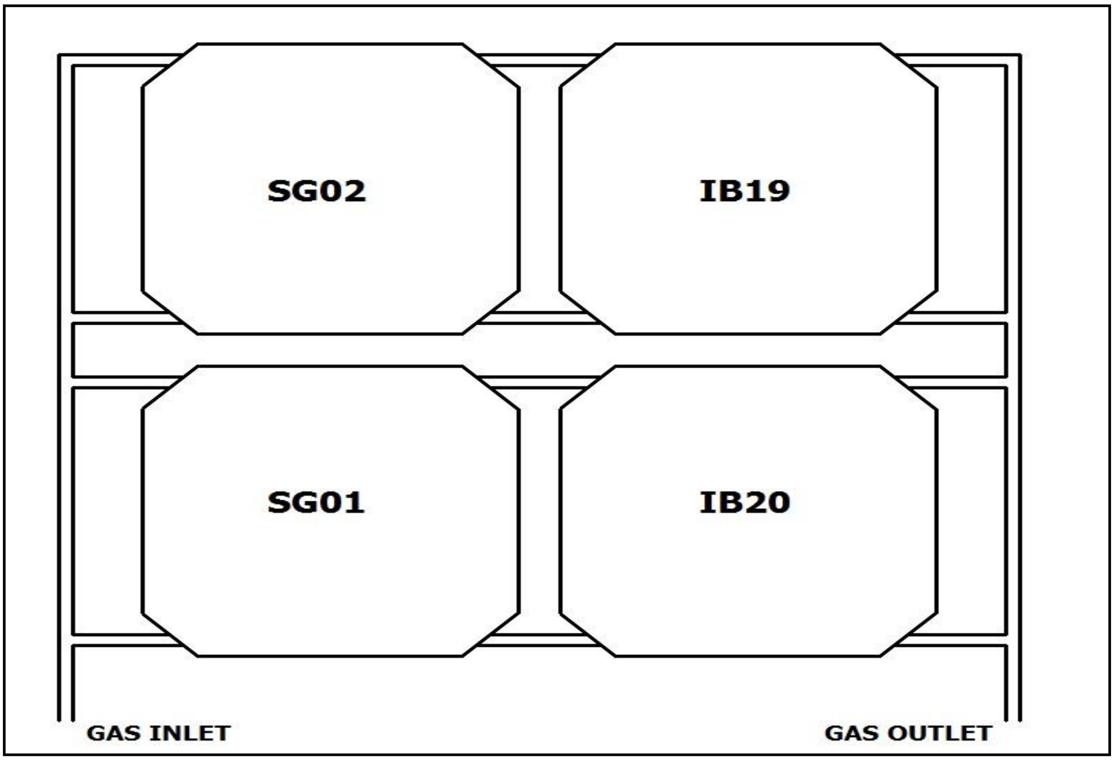

Figure 5.9: Cascading of four number of (1 × 1) m^2 RPCs

This RPC is in operation in one of the channels of the CLS for more than a year. But when each of these four were tested in the OES (Open Ended gas System), an interesting result was observed by us. The efficiency of the RPC (IB-20) one of the (1 ×

1) m ^{2} when observed in CLS and the same gap operated in OLE gas system, was found to be as close as that of an RPC in an OES as seen in the Figure 5.10. While the expected efficiency would have been lower, because the efficiency of the RPC would have deteriorated with time due to leakages of air and moisture inside the RPC gap when it was operated in the CLS system for a long period, while that when connected in the OES, a fresh gas flows in to the RPC every time. Hence the performance of an RPC has not deteriorated with time in the CLS.

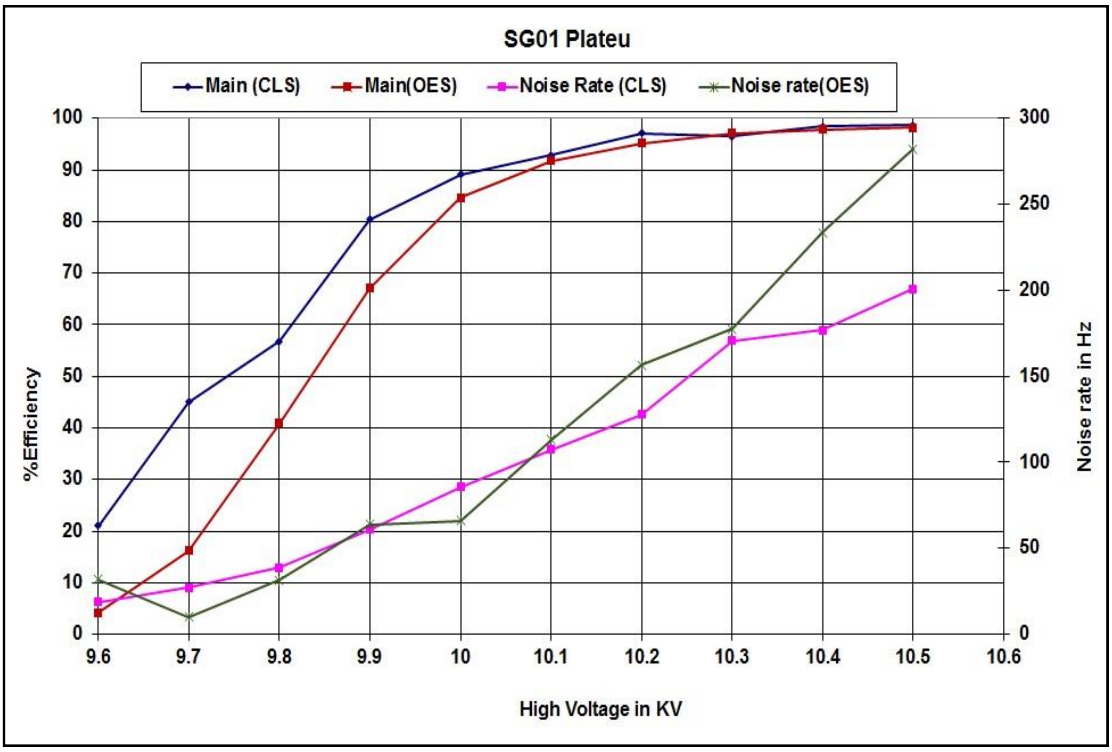

Figure 5.10: Performance of an RPC in a CLS and Open Ended System

5.1.2 Ageing effect and recovery of RPCs

A long-term (~3 years) aging test of a Resistive Plate Chamber (RPC) was carried out with an intense gamma ^{137}Cs source [82], [83] and [84] at the GIF facility at CERN. The detectors used were operated in avalanche mode and had the Bakelite surface treated with linseed oil. After the irradiation the estimated dose, charge and fluency were approximately equal to the expected values after 10 years of operation in the CMS experiment. The increase in the current and noise rates were observed under radiation but the increase was irreversible. When the radiation was withdrawn within a few months the rates decreased. The localized accumulated charge for strip was also studied and no significant variation of strip profile or dead strips were observed. The only ageing effect observed was due to the water vapor contamination. However, by flushing ammonia for a short period, the chambers were full recovered.

In the case of glass RPCs the resistivity is found to be stable with the integrated charge. No ageing effect has been observed on glass RPCs which are operated in avalanche mode at high temperature (55 ^{0}C for few months), because glass electrodes do not need a surface treatment as that required in an Bakelite RPC with linseed oil. As expected, the rate capability of glass RPCs improve with temperature, due to the lowering of glass resistivity.

In the long term operation of the glass RPC in CLS the decomposition of the gases used under electrical discharge produce a significant concentration of fluorine ionic at the RPC output or exhaust gas. The F^- radicals may produce HF which possibly interact with the inner surface of the RPC electrode due to chemical reactivity and may be removed by the gas flow with high rate or may damage the glass surface and hence deteriorate the efficiency of RPCs.

The RGA analysis does not shown any HF radicles for the ICAL RPCs for the last several years of operations.

5.1.3 CLS Validation

The above results of RPC performance with a flow rate of about 6 SCCM per RPC indicate that the CLS is functioning as expected and following are some of conclusions and precautions to be taken care.

a) RPCs should not be operated under negative differential pressure with respect to atmospheric pressure, one volume change/day flow rate (~ 6 SCCM) is sufficient to cope up with regular changes in atmospheric pressure but a provision for 5 volume changes/day flow rate must be made for emergency atmospheric pressure transients.

b) Actual position of an RPC in the stack must be considered to calculate effective pressure inside.

c) A differential pressure of (2 to 4) mbar is safe for an ICAL RPC.

d) Mass flow controllers should be vented before and after back fill cycle. The MFC control valve should be electrically grounded when not in use and the valves must be normally closed.

e) Flow division through calibrated capillaries is adequate, no actual measurement is required.

f) Under cosmic conditions radicals are not produced or observed by us from the SF_6 gas inside RPC for the last 5 years.

Chapter 6

Summary, Conclusions and Remarks

The INO project is awaiting for the clearance from the respective government agencies and is non-technical in nature. This chapter is dedicated to conclusion of the research work done and with some important remarks. Some of the CLS validation results are covered in the previous chapter.

The ICAL will have a magnetic field of ~1.5 tesla around each RPC and a substantial research and development is done including testing and simulation of the fields for a proto-type system by all the collaborating groups. The readout electronics plays an important role in building large experiments like INO and will help to improve the detector performance.

The INO electronics team has developed a low noise and fast electronics in the form of miniature DAQ board sitting on the 100 square centimeter chamfered triangular area on one of corner of each RPC and it is working as per the specifications. The data from the DAQ board is being transferred by packet switching at a rate of few megahertz. More the space occupied by the FEB (Front End Board) , more will be the inefficiency of the system and hence miniaturization is a must to achieve the physics goals.The RPCs provide excellent timings, spatial precision and homogeneity.

6.1 RPC Performance

The performance of the active RPCs dependence on many factors like

a) Making a gas gap of uniform thickness (2 mm) throughout the large area and especially at the edges, so that the applied high voltage provides uniform potential throughput the active area.

b) Air tight or leak proof gas gap and the ideal expected leak rate is **8.33 × 10^{-4} SCCM** (equivalent to a pressure drop of less than 1.75 mm WC in about 33 hours) is an important parameter which decides the performance and hence for ICAL RPCs the leak test is a mandatory, before accepting it for operation. The observed leak rate using an automated microcontroller based system developed by the INO students has shown to be is 1.5 ml / hour (manometer cannot detect this kind of leak rate) [80].

c) Uniform resistance coating: Our studies have shown that 1M Ω to about 5M Ω are ideal for proper pulse formation for the ICAL glass RPCs.

d) Purity of gases used should have not have oxygen and moisture level more than 2 ppm for long term stable operations of the gaps, while our observation for RPC under tests have shown that, the moisture level using RGA in an CLS was found to be about 46 % (Base Pressure =1.6×10^{-7}, Water = 46% = $1.6 \times 10^{-7} \times 0.46$) which corresponds to 0.06 ppm) and hence has not affected the performance in spite of the leakages at the various joints.

e) Proper composition of the gas mixture as per the required ratio (higher value of any one of the gases in the mixture say by more than a percentage, the gap may start discharge into the streamer mode of operation or vice versa) is necessary and need to be monitored on line.

f) The optimum flow rate parameter of gas mixture into the RPCs operated in the CLS is very crucial parameter, the leakage of air from the atmosphere into the RPC or / and leakage of the gas from the system into the atmosphere (higher the flow rate may lead into leakage of gas into the atmosphere and lower may cause moisture and air to enter into detector) in the loop is to be kept under control.

The efficiency of the CLS depends on maintaining pressure balance, flow rate, efficiency of purification process and very much on leak integrity of the RPCs.

6.2 Not in the scope of the research work

Some of the following parameters are mandatory as of now and most of these are defined taking into consideration the physics goals and the large scale volume of the INO- ICAL experiment by the collaboration team.

a) Based on the initial studies done, the type of electrode to be used for making the RPC gas gap is the float glass of 3 mm thick and of about (2 × 2) m^2 size. This parameter is decided based on the availability, cost and design constrains of the ICAL having a magnetic field of about1.5 mega tesla. The dimensions of the RPCs (except for the nozzle positions) cannot be optimized based on the study results, but efficiency, handling and operation can be optimised.

b) Underground environment, which has the advantage of filtering the high energy cosmic rays.

c) Safety accepts to be considered in design about rapid drop or rise in the differential pressure at the chosen working place.

d) The flammable gas namely, I-butane being used cannot be exceeding 12 % in composition of the mixed gas. The SF_6 gas cannot be more than 1 %, as the INO RPCs are to be operated in avalanche mode as of now.

6.3 Summary of various Gas Systems

The proposed INO-ICAL detector will be instrumented with 28,800 RPCs (Resistive Plate Chamber). These RPCs are of (1.85 × 1.78) m^2 size will be made of glass as electrode with 2 mm. gas gap and will be operated in avalanche mode. The gas mixture used for operating these detectors is R134a ($C_2H_2F_4$) of about 95 %, I-butane (iC_4H_{10}) of 4.5% and 0.5 % of Sulphur hexafluoride (SF_6). Several types of Gas mixing system were evolved with time so that the gas mixture is equally distributed into each RPC under tests. The total internal volume of gas mixture is huge about 200 m^3 in the ICAL detectors. The two main gas recirculation systems for which elaborate and research work is done by us is summarised.

6.3.1 Open Ended gas System (OES)

The most commonly used gas mixing and distributing systems for small detector setups is Open Ended gas System (OES), which vents the gas mixture into atmosphere after only one passage through the RPC detector. However OES is not suitable for large area experiments as the gases are too expensive and hazardous (due to high global warming potential) and hence gas cannot be let out into atmosphere in large volumes after single use.

A Closed Loop System (CLS) capable of purifying and recirculating gas mixture in a loop is more suitable. The efficiency of CLS is defined as ratio of difference between total gas mixture volume and gas volume lost as leakage and formation of radicals, to total gas mixture volume. Typical efficiency of a closed loop system is in range of 85 % to 95 %. However for setups with small number of detectors working under cosmic luminosity this value is found to be near 97 % by us.

Another type of gas recirculation system namely the Open Loop Recirculation System (OLS) has been implemented as an alternative to CLS. The basic difference between these gas systems is that in OLS major gas component (R134a) is extracted from the gas stream and reused while the remaining small quantity of gas mixture is chemically treated into safer compounds and disposed. In case of CLS, the gas breakdown impurities and radicals are trapped through several filters and removed from gas stream while remaining major part of gas mixture is re-circulated. In the OLS, the R134a gas contained in the gas mixture flowing out of RPC outlet is converted into liquefied state and separated from gas mixture. Selective condensation and separation of R134a is achieved by maintaining gas mixture under specific combination of pressure and temperature. Liquefied R134a at -10°C is filled in container and sent back to inlet of gas mixing system. Cold liquefied gas in the container is heated to room temperature, develops pressure due to heating and reused. In this way R134a gas is being recalculated, not in a direct loop but by batch type transfer, hence the name "Open Loop". This type of system does not require the filters /adsorbents for individual impurities, delicate loop pressure control or any precision chemical analysis to decide the top-up gas quantities. A moisture sensor placed at the outlet of RPC is sufficient to indicate amount of moisture which serves as indicator to ingress of air into gas mixture by leakages.

It is observed that the efficiency of the OLS built earlier was around 75.0 % only. This poor efficiency was due to loss of I-butane (4.5 %) and sulphur hexafluoride (0.5 %) and additional loss of about 10.0 % R134a which must have remain uncondensed to avoid co-condensation of I-butane towards the end of batch cycle. To enhance the efficiency of the open loop process to greater than 95.0 %, it is necessary to extract maximum I-butane before R134a extraction. Recovery of I-butane will increase OLS efficiency. It will also help in more extraction of R134a and thereby increasing OLS efficiency further. I-butane and R134a can be separated by using a centrifuge technique because of the large difference in the molecular weights.

The feasibility study of centrifugal separation of R134a and I-butane from the gas mixture was explored by us. The open loop recirculation system has advantage that it can remove nitrogen impurity and does not need filters / adsorbents for each type of impurity. Yet, it is neither economical nor necessary to separate the R134a and I-butane for every volume change cycle of gas mixture. Instead, the gases could be separated only after a predetermined number of volume changes till impurity concentration builds up as indicated by the moisture sensor. Such combination of closed loop and open loop recirculation will be quite effective and efficient. The feasibility study of centrifugal separation of R134a and I-butane from the gas mixture was explored.

The efficiency of Open Loop Gas recirculation can be increased from 75 to 90 % by extraction of I-butane before liquefaction and recovery of R134a. RGA and Gas chromatograph results show that I-butane is pumped faster than R134a by turbo-molecular pump of RGA. I-butane concentration is seen to drop from 4.5 to under 2 %. Hence separation of R134a and I-butane is possible by centrifugal process. Contaminants will also get separated and removed due to their lower molecular weight. SF_6 will not interfere with extraction process as its concentration is too low to alter and affect partial pressures of I-butane or R134a. The efficiency of open loop system can be enhanced with centrifugal concentrator and this could address problems of removal of contaminant. *The OLS has advantage that the nitrogen impurity gets removed automatically without using filters/adsorbents. There is no need to use a filter for each type of impurity.*

It is not necessary to separate the R134a and I-butane for every volume change of gas mixture. Instead, the gases could be separated only after a predetermined number of volume changes. This combination of closed loop and open loop recirculation would be very effective.

The Centrifuge being very expensive equipment and it has not been procured yet. A Varian V70 turbo pump was used to simulate the centrifuge to study dynamic drag *due to RPC gases*. Therefore the design and testing of the OLS is still at a conceptual or a proto-typing and testing level. The detailed reported by us is given in [107].

6.3.2 Closed loop system

The basic principle of design of the INO-ICAL proto-type CLS is based on the LHC-CERN gas systems used at CERN; these systems are operated for a flow rate of few liters per minute, as they use Bakelite electrodes for the RPCs in their experiments and are operated at high luminosity, where in the background rate is high due to their operation of particle collusion environment. The INO ICAL will uses glass RPC and are operated underground which has a low background.

The proto-type CLS designed for a stack of 12 RPCs of size (1.85 × 1.73) m^2 is an automated system developed using the SEIMENS make PLCs. During the testing and integrating this system, in the initial stage of design, a diaphragm based High Pressure to Low Pressure (HPLP) regulator was used by us at the input of the supply gas cylinder and the output of this HPLP was connected to the RPCs. This regulator being a mechanical device, the response was slow to the variation in the periodic atmospheric and seasonal changes in pressure (not expected by us). This problem was overcome by using a capillary in lieu of the HPLP regulator at the input of the RPC.

The flow rate assumed was a few LPM (Liters Per Minute) in each RPC, which we found that it was very high for the glass RPCs and several RPC gaps were damaged. Our studies after long run tests proved that, the low flow rate of a few SCCM is ideal.

An additional pressure sensor had to be integrated to the system to monitor and correct the atmosphere periodic variation in the room as the RPC testing laboratory is temperature and humidity controlled and not pressure controlled.

6.4 Observation and conclusions of flow and control of gas in CLS

The RPC performance studies (noise rate, current, efficiency etc. under controlled temperature and humidity) for several years of operation in the CLS (also that in the OES) show that the safe operating pressure that is needed at the input of INO glass RPCs is (2 to 4) mbar. While the breakdown tests conducted by us show that the glass RPCs can sustain a few tens of mbar's of pressure.

a) In the process of testing the RPCs in the CLS for few years the flow rate could be optimized for the ICAL RPCs (1.85 × 1.9) m^2 with a gas gap of 2 mm, to be 6 SCCM (but as low 3 SCCM and high of 9 SCCM) which corresponds to about one volume change of gas per day. Some excess flow may be required to maintain a concentration gradient. The low flow rate of 3 SCCM has also yielded good results.

b) The pilot CLS has achieved leak rate of 0.09 SCCM when connected to 4 RPCs for 12 days (auto refill).

c) RPCs should be operated under negative differential pressure with respect to atmospheric pressure in a CLS is not tried out by us.

d) About One volume change/day flow rate is sufficient to cope up with regular changes in atmospheric pressure but a provision for 5 volume changes/day flow rate must be made for emergency atmospheric pressure transients.

e) Actual position of an RPC in the stack must be considered to calculate effective pressure inside.

f) At high temperature the two stage regulator on the supply cylinder of I-butane were found to be mall functioning and frequently we had to replace them and hence the cylinders need to be stored in a temperate controlled room.

The proto-type CLS developed, tested and validated has a simple purification unit containing molecular sieves and copper catalyst which are useful for removal of moisture and simple break down radicals. In the operation of the CLS for the last few years, using the simple RGA gas analyzer system no major breakdown radicals were observed by us. The only issue related to increase in the moisture level in the loop was observed and could be due to air leaks at the joints of the plumbing system. However, the performance of the RPCs like the current, nose rate and efficiency were studied in detail.

The flow resistors namely the capillary studies have shown that if 4 RPCs are connected in series (road in the final ICAL) a capillary of length 250 cm and diameter of 300 micron is ideally suitable, but if one needs to optimise the space then a capillary of few centimetres in length and of 300 micron diameter would also function suitably. The design of the nozzles used in the RPCs gap at the input and output is such that it has some capillary effect due to its small bore of (1.84 × 0.74) mm of length 3 mm (refer Figure 4.14) and may be in principal no capillary may be needed at the input. But, from safety point of view if the link is broken the complete pressure is exerted on the previous RPC, which would be equivalent to a no capillary at all. Therefore, some capillary is needed at the input of each RPC. As of now the flow of gas into the RPC is considered to in parallel that is each RPC will have a flow resistor at its input.

A Capillary is prone to choke as the diameter is 300 micron (dust particles etc.) and hence cause change of impendence. If the outlet blocks then the capillary will be unable to control and the pressure may rise to the dangerous level inside of RPC and may be damaged.

In view of the above a servo based motor controlled valve to produce a safety range of low pressure flow is designed (conceptual) and is given in the appendix.

The studies done us by sealing of an RPCs, where the gas is filled inside an RPC under safe pressure and sealed and operated for about 6 months show that the performance of the RPCs is stable for few months, which is a good indication that the glass RPCs can be used in CLS system without replacing the entire gas in the system for at least over a period of about a month or so.

The long studies using RGA (Residual Gas Analyzer), a small scale mass spectrometer hooked in the CLS loop has NOT shown any breakdown radicle of the mixed gases for the period of operation from 2013 onwards. The disadvantage of RGA is that, the gas under test is broken down into gas radicals for analysis. So one has to study and analyses in detail to understand if the gas breakdown takes place in the RGA or the radical is broken inside the RPC itself. If breakdown of SF_6 gas takes place then the fluorine would etch the glass electrode and which in turn would deteriorate the performance of the RPC.

6.5 Conclusions of Simulation Studies

The simulation studies are done to understand the gas flow rate, its distribution inside an RPC and the effect of gas distribution due to the position variation of the nozzles. The simulation studies are performed on the 3 platforms namely Solid works, COMSOL and CDF (CFX) with different goals. As a beginner started with available Solid works, then COMSOL was used and then finally CDF collaborative studies were done. The results in solid works and the CFX are more fruitful.

The conclusive results are summarized.

a) The preliminary results show that, there are “Dead Pockets” (where the drift velocity of gas is zero) in the RPC detector. The Dead zones can be smaller at high flow velocities of gas, but cannot be Zero. The same can be used for validating the large scale models. The Dead zones are observed near the mid-section of inlet wall and outlet walls if the nozzle position are at the four corners of the RPCs.

b) The calculations show that, the Reynolds Number for all gases for the flow rates between 0.3 SCCM to 30 SCCM is less than 2500 and hence the flow patter is considered is LAMINAR and NOT Transient (2500 to 3000) or Turbulent (above 3500*)*.

c) The flow through the both outlet nozzle is not equal. This can be a problem if RPCs are connected in the series because, for the next RPC the inlet flows will not be equal.

d) The SF_6 is the heaviest of the 3 gases and I-butane is the lightest. The density of the SF_6 is almost double of the I-butane and hence the velocity of the SF_6 and Freon is less compared to the velocity of I-butane.

e) In the RPC, the volume fractions of all 3 gases are hardly changing. In the case of R134a the volume fraction is hardly varying between 94.5 to 95.5 per cent. Similar results have been observed for the SF_6 and I-butane. That’s why assuming the gas as fixed composition mixture is a good approximation for simulation.

f) The average residence time in chamber from inlet to outlet is in range of 8×10^5 seconds (i.e. ~ 10 days). The residence (replacement) times are different for each gas and hence one need to optimise time and flow to fill the RPC with gas. A detailed study is required as the number of RPCs gap are huge in the final ICAL.

g) The flow rates of (3 to 10) SCCM is adequate to initiate the RPC in reasonable time and sufficient to operate it under cosmic radiation conditions. The objects in the path of the gas flow such as nozzles, buttons do not cause turbulent conditions at flow rates near 3 SCCM.

h) The Separation of gases does not take place even in the dead zones at flow rates of 3 SCCM or more.

i) There are four nozzles in an RPC of which two are for the flow of input gas and the other two for the output flow of gas. Simulation studies indicate that some dead zones are present, irrespective of the position of nozzles placed. The oldest design (nozzles at 4 corners) seems to be a better design both as flow lines are spread out and pressure drop across it compared to the design 1 which has less compared to design 2.

Simulation results play an important role in improving the performance of an RPC. A lot of work still needs to be done, to further improve on the study of distribution of gas inside an RPC. The dead zone pockets are still to be studied and understood in detail. The presented results are just the initial bench marks.

6.6 Some Remarks

In the existing CLS, the removal of water is by combination of $3A^0$ and $5A^0$ molecular sieves which are continuous duty purifier and the removal of radicals is by disposable activated alumina and the removal of oxygen is by Cu Zn and Ni-NiO on activated alumina by continuous duty purifier**.**

The above purification processes do not fully address the breakdown radicals of SF_6 in the CLS. The tests and analysis that have been done so far by us are for a smaller number of RPCs with minimum purifier stages therefore a detailed work has to be carried out.

A better gas analysis and monitoring system like the **Gas** Chromatograph, pH sensors contaminants detectors are needed for detailed studies of gases in the CLS loop.

6.6.1 Leak test and flow control in CLS.

One the major issues observed all around the globe where RPCs or any gas detectors, that are used in large scale experiment is the gas leak control which is observed either in the detector itself (smaller / marginal) and or in the complete chain of connection(s) in the overall system.

Some leakages in the detector(s) need to accepted, but more attention in integrating the gas systems with detectors has to be done in methodological way (like sealing of each joints, use of un hydrophobic tubes , standard fitting etc.). But when a huge number (like few thousands) of chambers are to be manufacture and assembled in an industry a more reliable test procedure need to be developed to qualify RPCs.

The most common leak tests are by pressure drop, bubble test (inaccurate for detecting $10E^{-4}$SCCM leak rate), sniffer (Hydrogen used as target gas and all joints scanned for leak using a sniffer, high sensitivity but laborious and unreliable due to large number of measurement points) and mass spectrometry etc.

6.7 Some new features for upgrading the CLS

a) A multi stage displacement pump with adjustable compression ratio in the CLS, which can mechanically adjust stroke and compression ratio (minimum and maximum pressure electronic valves for pressure and flow rate control)

b) Safety devices with full redundancy and safe parking in event of any failure.

c) A possible servo controlled electronic pressure regulator for safe flow and control of pressure at RPC input (a conceptual design for future upgrading the CLS) is given at the end in the annexure chapter.

The studies done on the flow rate, for the glass RPCs so far show that a flow rate of 6 SCCM to 10 SCCM is ideal. A more precise study to optimize the usage of expensive gases taking into the leak issues and keeping the performance of an RPC to a high level with the desired physics goals is to be further fine-tuned when the number of RPCs will be huge in the final ICAL.

6.7.1 Alternate gas mixture studies etc.

In a long run for RPCs, an alternative gas mixture is a must, though $C_2H_2F_4$ and SF_6 are the result of a long search to optimize the RPC gas. The gases need to eco-friendly and need to work towards it.

There is a need to fully exploit the RPC potential both in basic research and in industrial applications such as imaging, PET, Muon tomography etc.

Appendix A

Possible up-gradation / modification of the existing CLS for flow control

A1: Limitation in the present CLS

In the initial design of CLS, a HPLP mechanical regulator (which was to regulate the high pressure gas ~1.6 bar abs., flow from the storage tank connecting to the RPCs outlet pressure (15 to 50) mm WC. This control worked very well when the room pressure was steady. But due to periodic changes in the atmospheric pressure (this was not known at the design stage of CLS) the mechanical pressure regulator was unable to cope up with the changes seen daily and the seasonal atmospheric pressure variations due to mechanical hysteresis and inertia of control components. So the glass RPCs could be subjected to higher than specified pressure differences for short periods causing stress on glass. The HPLP regulator was removed and replaced with set of capillary elements to act as flow resistors and maintain the pressure inside RPC to a safe level. However there is an safety issue in this technique that if RPC outlet gets blocked due to some reason (pinching of Tygon tube used on the nozzle of the RPC, dust particle in the detector etc.), Then RPC can go to dangerous pressures, when using two or three RPCs care can be taken to maintain safe outlet condition. But the risk and extent of possible damage considerably increase when the number of RPC increases.

In view of the above a modified conceptual design of a servo motor controlled based electronic valve to replace HPLP valve is shown in Figure A -1 and Figure A -2.

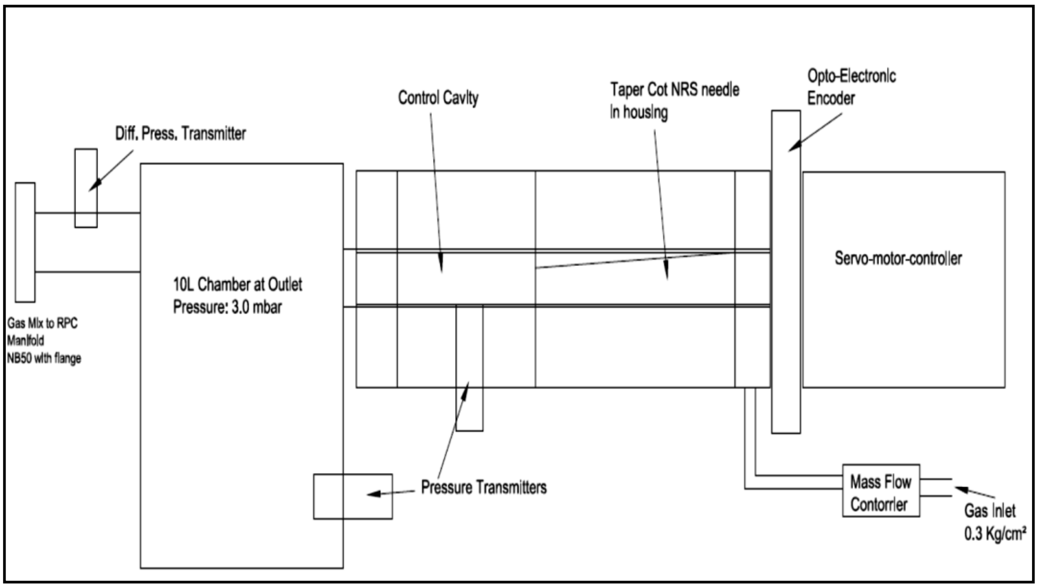

Figure A -1: HP-LP Servo controller based regulator (0.3 Kg/cm^2 to 3 mbar)

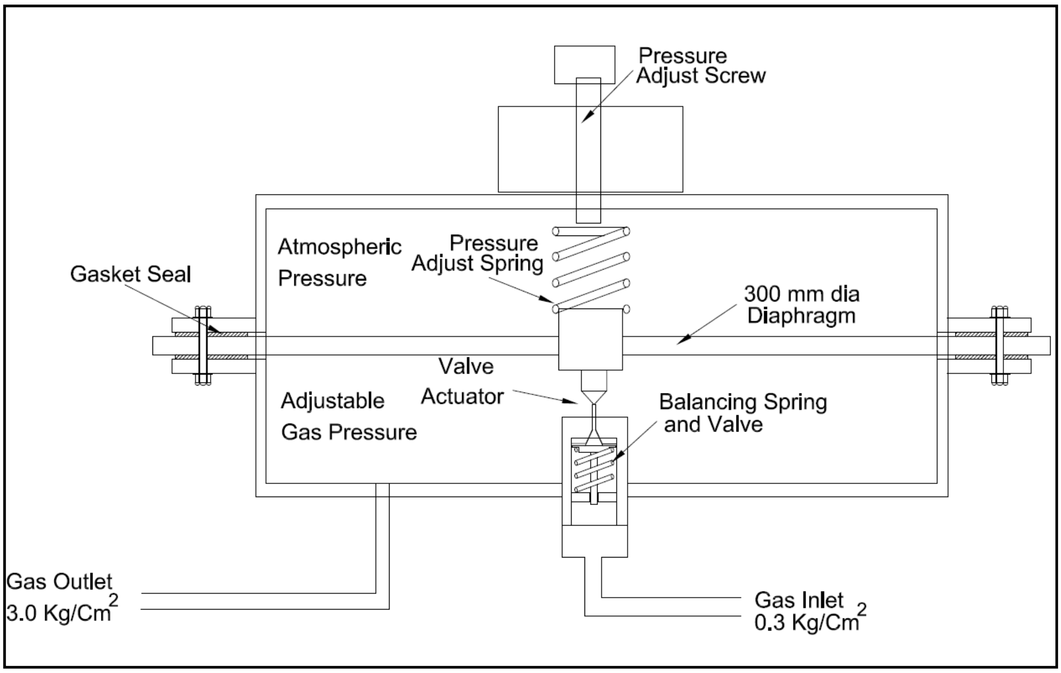

Figure A -2: Details of the valve

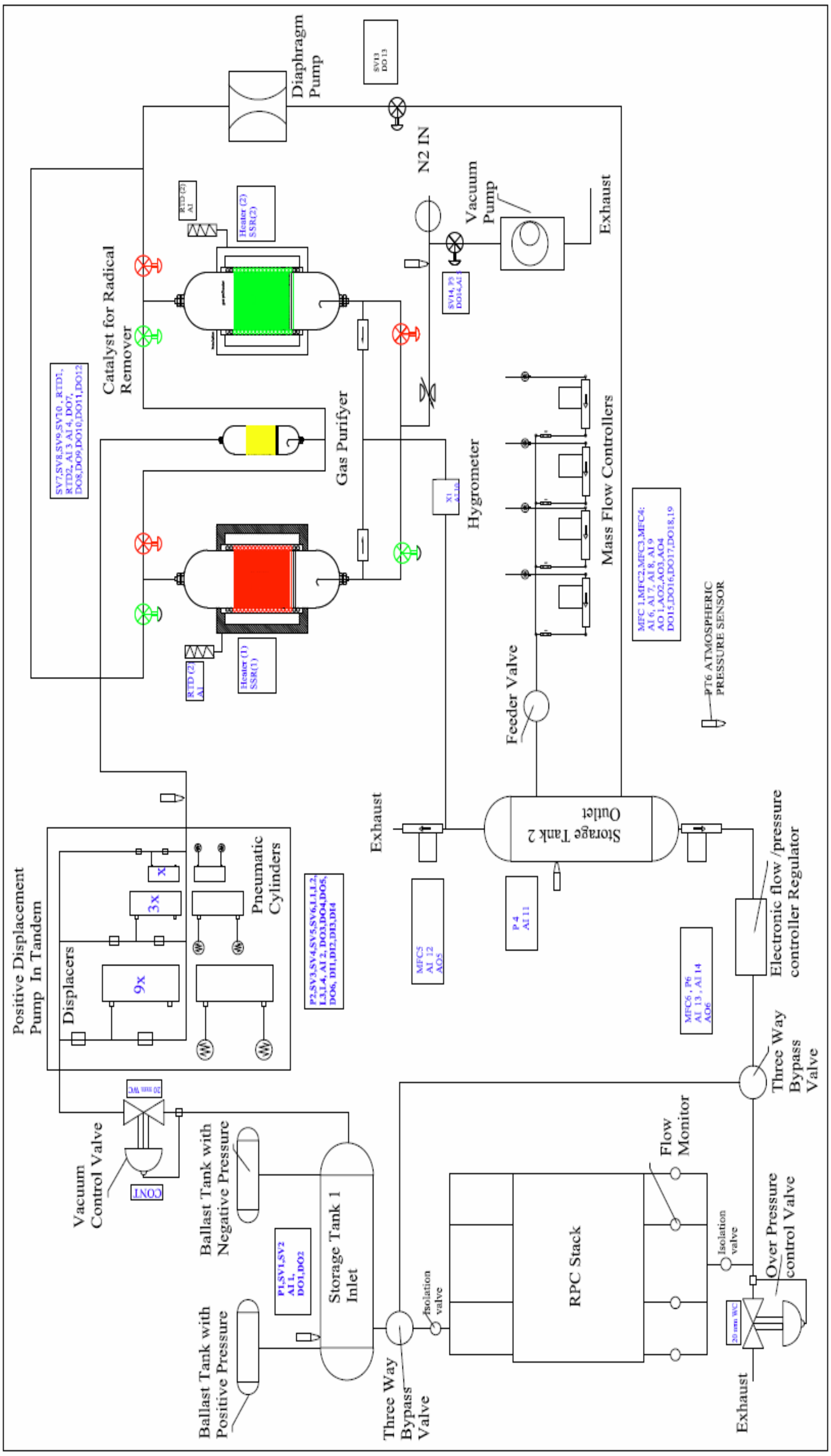

Figure A -3 : Up gradation of CLS in the displacement pump section

The Figure A -3 shows upgrade version of CLS with electronic control regulator (described in the earlier) and having multi-displacement pumps for different suction volume of gas so as to suck the gas from the storage tank (i.e. more efficiently from the RPC stack into the CLS).

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Publications of the author

National and International Journals:

1. S. D. Kalmani, P. Verma, P.V. Hunagund.,"Preliminary Simulation results on Optimisation of flow of mixed gas in Resistive Plate Chamber", *International Journal of Computer Science & Communication*, Volume 5. Number 2, July-Sept 2014. PP.124-133 ISSN-0973-7391.
2. S. D. Kalmani, P. Verma, P.V. Hunagund.,"Simulation: study of flow of gas in a resistive plate chamber", *International Journal of Research in Engineering and Technology* eISSN: 2319-1163 | pISSN: 2321-7308
3. Suresh Kalmani, Avinash Joshi, S. Bhattacharya and P. V. Hunagund., "Performance Enhancement of Open Loop Gas Recovery Process by Centrifugal Separation of Gases", *Journal of Instrumentation* (*JINST* -an IOP and SSISA Journal-Italy), JINST_101P_ 0516_ open_ loop.pdf., ISSN 1748-0221.
4. S. D. Kalmani, A.V. Joshi , R.R. Shinde and P. V. Hunagund,"PLC Based Instrumentation of Closed Loop Gas System for RPC Detectors", *IOSR (International Journal of Scientific Research) - Journal of Applied Physics (IOSR-JAP)* e-ISSN: 2278-4861, Volume 9, Issue 1 Ver. I Jan. – Feb. 2017, PP 74-77.
5. S. D. Kalmani, Mondal.S, Shinde R.R and Hunagund P.V., "Effect of capillary as a dynamic impedance element on the differential pressure across RPC detector in a closed loop gas system", *International Journal of Development Research*. Vol. 07, Issue, 07, pp.13710-13713, July 2017.
6. S. D. Kalmani, P.V. Verma, R. P. SHINDE and P. V. Hunagund "Study of Mixed Gas Flow Pattern Inside RPC" *International Journal of Applied Engineering Research*, Volume 12, Number 9 (2017) pp. 1094-1099. ISSN 0973-4562
7. S. D. Kalmani, Surya Mondal, R. R. Shinde and P. V. Hunagund, "Some studies using capillary for flow control in a closed loop gas recirculation system", https://link.springer.com/chapter/10.1007/978-3-319-73171-1_223-- XXII DAE High Energy Physics Symposium pp 913-915|

Photo-sheet of Closed Loop System (Front View)

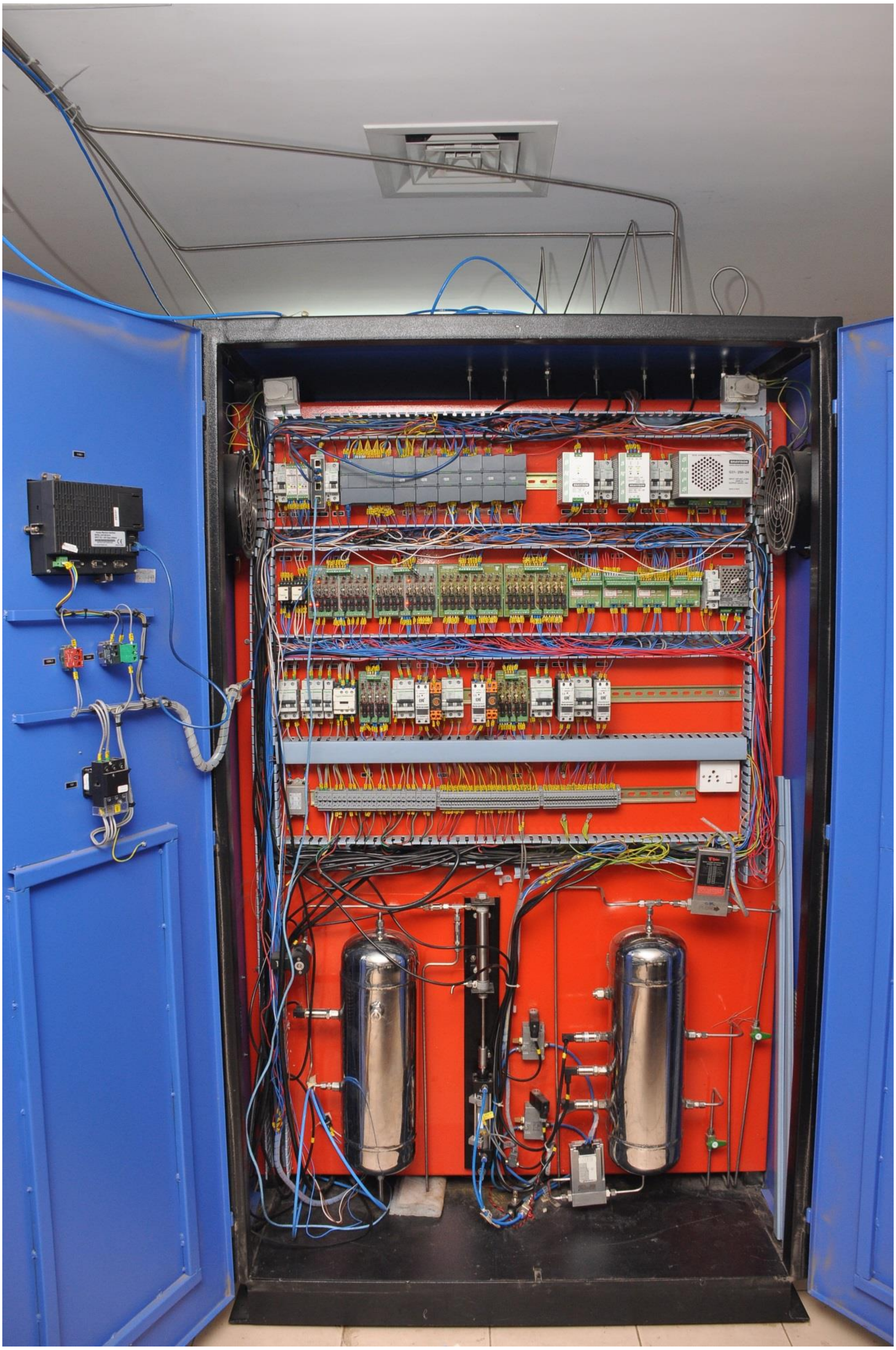

Photo-sheet of Closed Loop System (Rear View)

Back Page of the Thesis

STUDY OF FLOW AND CONTROL OF GAS MIXTURE FOR THE RESISTIVE PLATE CHAMBER PERFORMANCE IN CLOSED LOOP SYSTEM

Ph.D. Thesis

By

Kalmani Suresh Devendrappa

The upcoming INO-ICAL experiment will be instrumented with 28,800 of RPCs (glass based electrode) of size (1.85× 1.74) m2, which are the active elements and the key goal of ICAL is to precisely measure the neutrino(s) mass. The mixed gas used for RPCs is R134a (94.6%), I-Butane (4.5%) and SF6 (< 1%). As the number of RPCs are large with volume of ~ 200 m3, a Closed Loop gas mixing System (CLS) is mandatory.

A CLS is designed, developed and tested for 12 RPCs. The issues related to periodic atmospheric pressure variation are addressed, the flow resistors (capillaries) to be used at the input of the RPC(s) are designed and the flow rate of gas mixture to be injected into the RPCs connected in the CLS is optimised to (6 to 10) SCCM, depending on the leak rates. The input tested value for safe operating pressure for an RPC is (2 to 3) mbar. The Gas analysis studies in the CLS loop by using a RGA (a small scale mass spectrometer) to identify for gas breakdown radicles inside an RPC are studied and no break down radicals are observed by us, moisture is under control and except N_2 ,as of now no known technique to remove it. The simulation results; for the flow distribution of gas mixture inside an RPC show some "Dead zone" pockets and the position of the nozzle (polycarbonate) at the input and output of an RPC plays a significant role for different flow rates.