23ME541 INTERNSHIP REPORT

Submitted by
HARISH V
2303717611421086

In partial fulfillment of the award of the degree

Of

BACHELOR OF ENGINEERING

IN

MECHANICAL ENGINEERING

COIMBATORE INSTITUTE OF TECHNOLOGY

(Govt. Aided Autonomous Institution Affiliated to Anna University, Chennai) COIMBATORE – 641014

SEPTEMBER– 2025

BONAFIDE CERTIFICATE

This is to certify that this **Internship Report** entitled **"Development of an analytical model for natural convection flow in Passive Autocatalytic Recombiner"** in partial fulfilment for the award of Bachelor of Mechanical Engineering submitted to Coimbatore Institute of Technology, Coimbatore, is a Bonafide record of work done by **V. HARISH (2303717611421086)** under my supervision from **22.05.2025** to **04.06.2025**.

Signature of the Supervisor
Name and Designation
Dr. Nilesh Agrawal,
SCIENTIFIC MANAGER (G),
SRI - AERB IGCAR,
Kalpakkam,
TamilNadu-603102.

Dr. C. Balaji Ayyanar, M.E., Ph.D.,
Assistant Professor,
Department of Mechanical Engineering,
Coimbatore Institute of Technology,
Coimbatore – 641014

Dr. RAJESH RANGANATHAN. M.E., Ph.D.
PROFESSOR, Head of Department,
Department of Mechanical Engineering,
Coimbatore Institute of Technology,
Coimbatore - 641 014.

CERTIFICATION OF EVALUATION

Name of the college : **Coimbatore Institute of Technology**

Branch and Semester : **Mechanical Engineering, V Semester**

Name of the Student	Name of the Internship Industry	Name of the Supervisor with Designation
V. Harish	**Safety Research Institute, Atomic Energy Regulatory Board, Government of India**	**Dr. Nilesh Agrawal, Scientific Officer (G), SRI**

The report of the internship submitted by the above students in partial fulfilment for the award of the degree of Bachelor of Engineering in the Department of Mechanical Engineering of Coimbatore Institute of Technology were evaluated and confirmed to be the report of the internship done by the above students.

Certified that the candidates were examined by us in the internship viva-voice examination held on ____________________.

INTERNSHIP CO-ORDINATOR

INTERNAL EXAMINER **EXTERNAL EXAMINER**

सत्यमेव जयते

GOVERNMENT OF INDIA
SAFETY RESEARCH INSTITUTE
ATOMIC ENERGY REGULATORY BOARD
KALPAKKAM 603102, TAMIL NADU

CERTIFICATE

This is to certify that Mr. Harish V., a student of B.E. in Mechanical Engineering in COIMBATORE INSTITUTE OF TECHNOLOGY, COIMBATORE, Tamil Nadu, 641 014 underwent summer internship at SRI, AERB from May 22 to June 04, 2025 and worked on the project titled:

Development of an Analytical Model for Natural Convection Flow in a Passive Autocatalytic Recombiner

He has completed the assigned work to our satisfaction and the project work is useful to the institute. We wish him success in all his future endeavors.

Place: Kalpakkam
Date: June 04, 2025

Dr. D.K. Mohapatra
Head, SRI
AERB

ACKNOWLEDGEMENT

This Internship report "Development of an analytical model for natural convection flow in Passive Autocatalytic Recombiner" has been prepared to fulfill the requirement of B.E degree. Sincere guidance, supervision, and cooperation were generously extended to me by various individuals, for which I feel truly fortunate.

A deep sense of gratitude is extended to all the respondents of my project for having provided the necessary data and information, and for their kind support in its completion. Special thanks are also expressed to **Dr. A. Rajeswari**, Principal, Coimbatore Institute of Technology, Coimbatore.

Gratitude is extended to our Head of the Department, **Dr. Rajesh Ranganathan**, M.E, Ph.D., Professor, for the support and encouragement that were provided in the completion of this project.

I would like to express my sincere gratitude to **Dr. D.K. Mohapatra,** Head SRI**, and Dr. Seik Mansoor Ali,** Head, Safety Research and Engineering section and for give me this opportunity to work in Safety Research Institute, Atomic Energy Regulatory Board as well as coordinating and overseeing this project.

I would also like to thank **Dr. Nilesh Agrawal**, Scientific Officer (G), SRI for his invaluable guidance, constant support, and insightful supervision throughout the course of this project. It has been a privilege to work under his mentorship, and I am truly grateful for the opportunity to learn from him. I also extend my gratitude to all staff of SRI for providing me with facilities and help whenever required.

Gratitude is sincerely extended to our internship coordinators, **Dr. C. Balaji Ayyanar**, M.E., Ph.D., Assistant Professor, for the support and encouragement provided throughout the completion of this internship.

V. HARISH

TABLE OF CONTENTS:

ABSTRACT

Hydrogen generation during severe accidents in water-cooled nuclear power plants poses a significant threat to containment integrity due to the potential for flammable or explosive mixtures. Passive Autocatalytic Recombiners (PARs) are critical safety devices installed in reactor containments to passively remove hydrogen by catalysing its reaction with oxygen to form steam. This reaction is exothermic and induces buoyancy-driven natural convection flow, which transports unreacted hydrogen into the PAR and removes the reaction products.

The present study focuses on the development of an analytical model to estimate the natural convection flow rate within a PAR based on its geometry, thermal boundary conditions, and fluid properties. The model incorporates the effects of heat release from catalytic surfaces and flow resistance due to narrow plate spacing. It is implemented in Microsoft Excel for ease of use in parametric studies and engineering calculations. Key parameters such as plate spacing, heat flux, and inlet gas temperature were varied to assess their impact on flow velocity, temperature rise, and hydrogen removal capacity.

The results provide insight into the sensitivity of PAR performance to design and operating conditions, supporting the optimization of PAR design for nuclear safety applications. The developed tool serves as a valuable aid for preliminary design, safety assessment, and experimental planning for hydrogen mitigation in nuclear reactor containments.

INTRODUCTION TO THE COMPANY

The AERB-Safety Research Institute (SRI) Kalpakkam was setup by the Atomic Energy Regulatory Board, Government of India within the Campus of Indira Gandhi Centre for Atomic Research, Kalpakkam in the year 1999. The activities of SRI are diverse in nature and are linked to various regulatory functions of AERB as depicted in Fig. 1

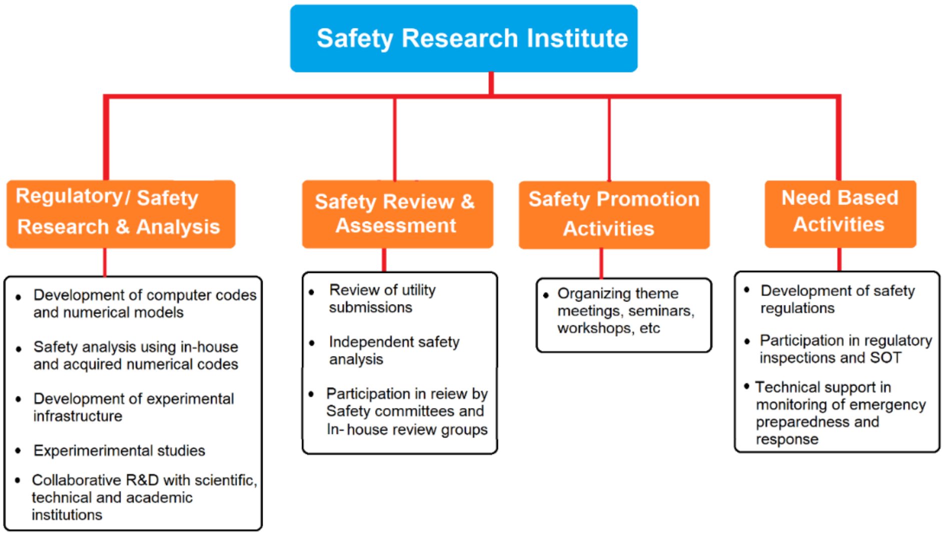

Fig. 1: Activities of SRI

The main focus of SRI is safety research and analysis. The areas of research undertaken in SRI are specifically chosen in a way to complement the ongoing R&D activities at other DAE units. The broad areas of research at SRI are given below.

- Reactor and Radiation Physics Studies
- Reactor Safety and Engineering Studies
- Fuel Cycle Chemistry and remediation related safety studies
- Radiological Impact Assessment and RS-GIS applications

Over the last two decades, SRI has established Physics laboratory, Environment Chemistry Laboratory and RS-GIS Laboratory, Engineering Hall and computational facilities for confirmatory and anticipatory research in support of regulation and for collaboration with Technical Support Organizations (BARC and IGCAR) and academic institutions. The institute located within IGCAR campus possess an added advantage with access to various state-of-art laboratories, library facilities, interaction with large pool of scientists & engineers etc.

SRI also makes significant contributions to safety review and assessment of nuclear and radiation facilities through independent safety analyses and participation in AERB safety committees and in-house review groups. SRI organizes theme meetings, seminars and workshops in the areas of interest to the regulatory body and participates in various safety promotion activities. SRI also participates in the process of development of safety regulations, monitoring of emergency preparedness and similar activities to support the regulatory functions of AERB

CHAPTER 1

INTRODUCTION

1.1. Background

The present summer internship work was carried out at the AERB–Safety Research Institute (SRI), Kalpakkam, during May and June 2025. As a research wing of the regulatory body, SRI is engaged in safety-related research in nuclear engineering and reactor safety.

Passive Autocatalytic Recombiners (PARs) play a critical role in reducing the risk of hydrogen deflagration or detonation following an extremely unlikely situation arising out of multiple failures in process and safety systems. One such event in a pressurized heavy water reactor (PHWR) based nuclear power plant (NPP) is Loss of Coolant Accident (LOCA) along with failure of emergency core cooling system (ECCS) and moderator cooling system.

The present project is part of hydrogen mitigation studies being undertaken in SRI. The overall objective is to obtain the reaction rate and other important parameters for a PAR using controlled experiments. For this, the velocity in the PAR under natural circulation condition has to be estimated. The project aimed at studying buoyancy-driven flow behavior due to hydrogen recombination in PARs. The flow rate obtained will be used to design experiments for hydrogen mitigation studies.

The internship involved detailed understanding of the PHWR based NPP, familiarization of the context of the problem, understanding hydrogen behavior and mitigation strategies during postulated accident scenarios in nuclear reactor containments, development of an analytical model, theoretical analysis, derivation of flow characteristics, and investigation of thermal–hydraulic parameters associated with PAR operation.

1.2. Containment Accident and Hydrogen Generation

During a severe nuclear reactor accident, such as a Loss of Coolant Accident (LOCA), high-temperature conditions in the reactor core can lead to the oxidation of zirconium cladding, which reacts exothermically with steam as given in Eq. (1). This reaction is the primary source of hydrogen generation in the containment. This reaction releases a significant amount of hydrogen gas and heat. Other sources include radiolysis, corrosion of paints etc.

$$Zr + 2H_2O \rightarrow ZrO_2 + 2H_2 + \underset{Heat}{\Delta} \tag{1}$$

The containment is meant to prevent release of radioactivity to the environment during normal operation and accident conditions. Hence, the hydrogen accumulated cannot be vented out. Accumulation of hydrogen in the containment can pose a serious risk of deflagration or detonation. Hence, hydrogen mitigation systems are essential for efficient and safe removal of hydrogen from the containment and maintaining containment integrity. This is achieved using passive autocatalytic recombiners.

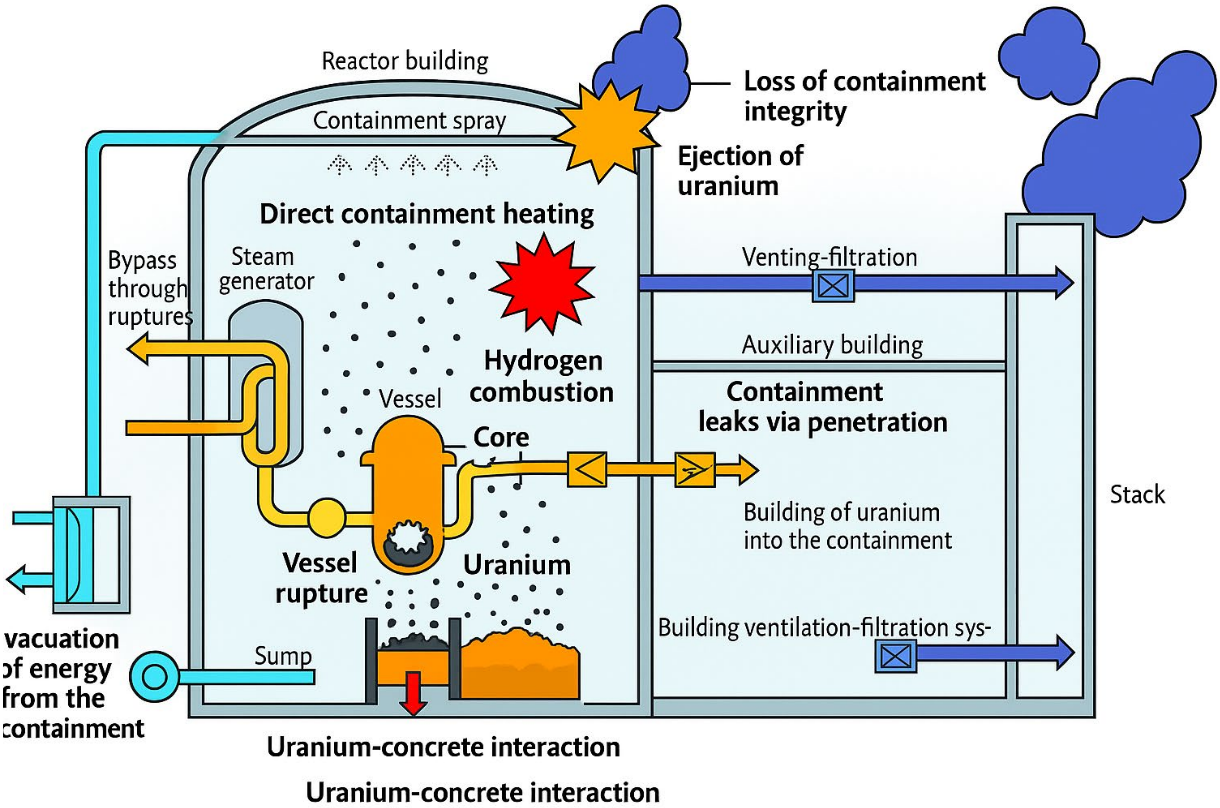

Figure 1.1 Loss of coolant accident in nuclear reactor

1.3. Passive Autocatalytic Recombiners (PARs)

PARs are safety systems installed in reactor containments to passively remove hydrogen from the atmosphere. These devices function without external power or human intervention. Inside the PAR, hydrogen and oxygen react catalytically on metal surfaces (usually platinum or palladium-coated), forming water vapor and releasing heat. This is given in Eq. (2).

$$2H_2 + O_2 \xrightarrow{Pt} 2H_2O + \underset{Heat}{\Delta} \tag{2}$$

This reaction is exothermic and results in heating of the surrounding gas, causing buoyant forces that drive natural convection. Fresh hydrogen-air mixture enters the PAR due to buoyancy-driven flow, enabling continuous hydrogen removal. This is illustrated in Fig. 2.2.

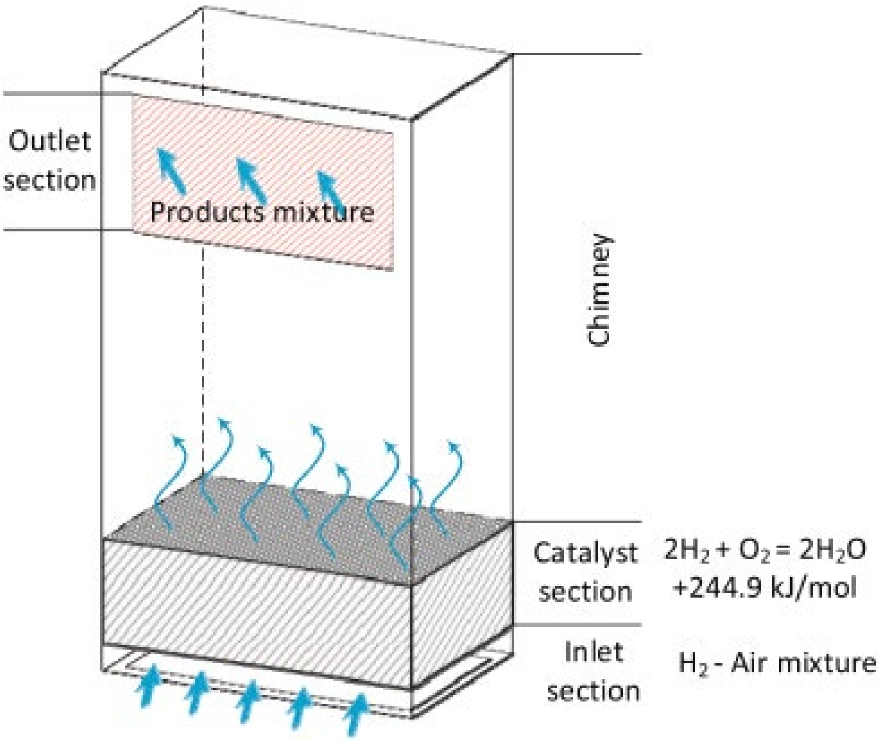

Figure 1.2 Schematic diagram of a Passive Autocatalytic Recombiners (PARs)

1.4. Objectives and scope

The key objectives of the internship were:

1) Understand the phenomena associated with gas flow in a PAR and H_2 removal.

2) Develop an analytical model for buoyancy induced flow in the PAR.

3) Incorporate the analytical model in MS excel sheet and calculate the expected flow rate in the PAR for given condition.

4) Carry out parametric studies to determine the range of flow velocity and temperature on the PAR

1.5. Outline of the Report

The report is organized into five chapters as follows:

- **Chapter 1** introduces the background, objectives, and scope of the work carried out during the internship programme.
- **Chapter 2** presents the Literature review about the Passive Autocatalytic Recombiners(PARs).
- **Chapter 3** provides the derivation of buoyancy-driven flow rates, including both small and large temperature difference cases.
- **Chapter 4** covers the parametric study of flow velocity, temperature distribution, and hydrogen concentration in the PAR.
- **Chapter 5** concludes the report with key findings and suggestions for future work.
- **Chapter 6** provides the reference for this project.

CHAPTER 2
Literature review

The techniques for hydrogen mitigation for water cooled nuclear power plants are outlined by IAEA in Tecdocs 1196 and 1661 [1-2]. These include: (a) pre-inerting of the containment during normal operation or post-accident inerting at selected regions of the containment; (b) mixing of gases from various regions of the containment to reduce hydrogen concentration below the lower flammability limit (LFL) everywhere; (c) deliberate ignition at hydrogen concentration just above LFL; (d) catalytic oxidation preferably below the LFL; and (e) venting of containment gases under suitable conditions.

Passive catalytic oxidation (or recombination) is a promising method for hydrogen mitigation because it is passive and can oxidize hydrogen even below LFL (nearly 4% H2 in dry air.), thus delaying the build-up of hydrogen in the containment and mitigating the consequence of hydrogen released during design extension conditions. The device used is called passive auto-catalytic recombiner (PAR). Appropriate number of PARs, estimated through safety analyses, are placed in various compartments of the containment. It is a metallic box open at top and bottom and has an array of platinum or palladium (catalyst) coated plates near the bottom end. The spontaneous exothermic reactions heat up the catalyst plates and gas mixture in their vicinity, setting up buoyancy driven flow within the PAR. This ensures continuous supply of reactants at the reaction sites and removal of hydrogen in a passive manner. The chimney region above the catalyst plates provides buoyancy for drawing fresh hydrogen rich mixture into the PAR from below.

Different types of catalytic recombiners have been supplied by PAR manufacturers such as AREVA [3], NIS [4], AECL [5], etc. AREVA and AECL have utilized vertical catalyst plates coated with a catalyst material while NUKEM invented a specialized cartridge containing alumina pellets coated with palladium. Park et al. [6] have used honey comb catalyst chamber and have presented reaction rate model for the same. Indigenous PAR systems with catalyst plates prepared by depositing platinum and palladium on cordierite plates and stainless-steel mesh plates have been developed by Bhabha Atomic Research Centre (BARC) and Nuclear Power Corporation of India (NPCIL) [7].

Figure 2.1 NIS

Figure 2.2 AECL

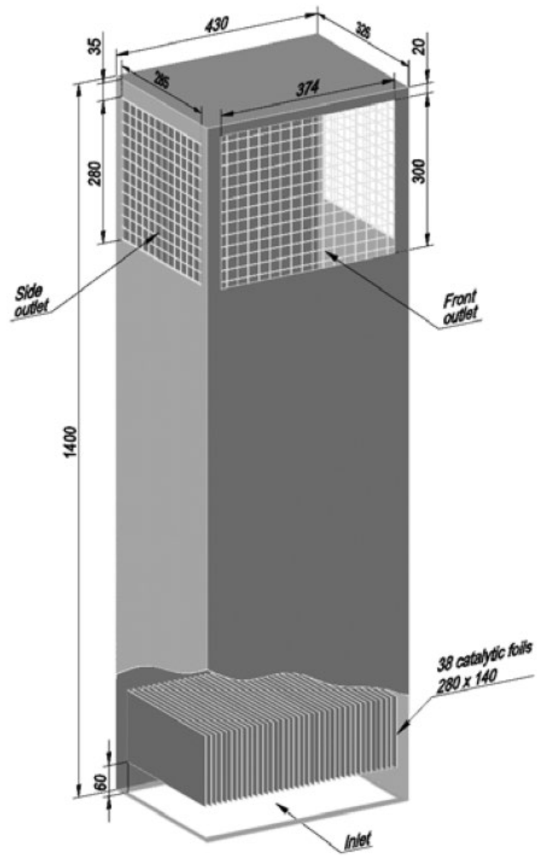

Figure 2.1 AREVA

CHAPTER 3
Analytic model for natural convection flow in the PAR

3.1. Geometrical details

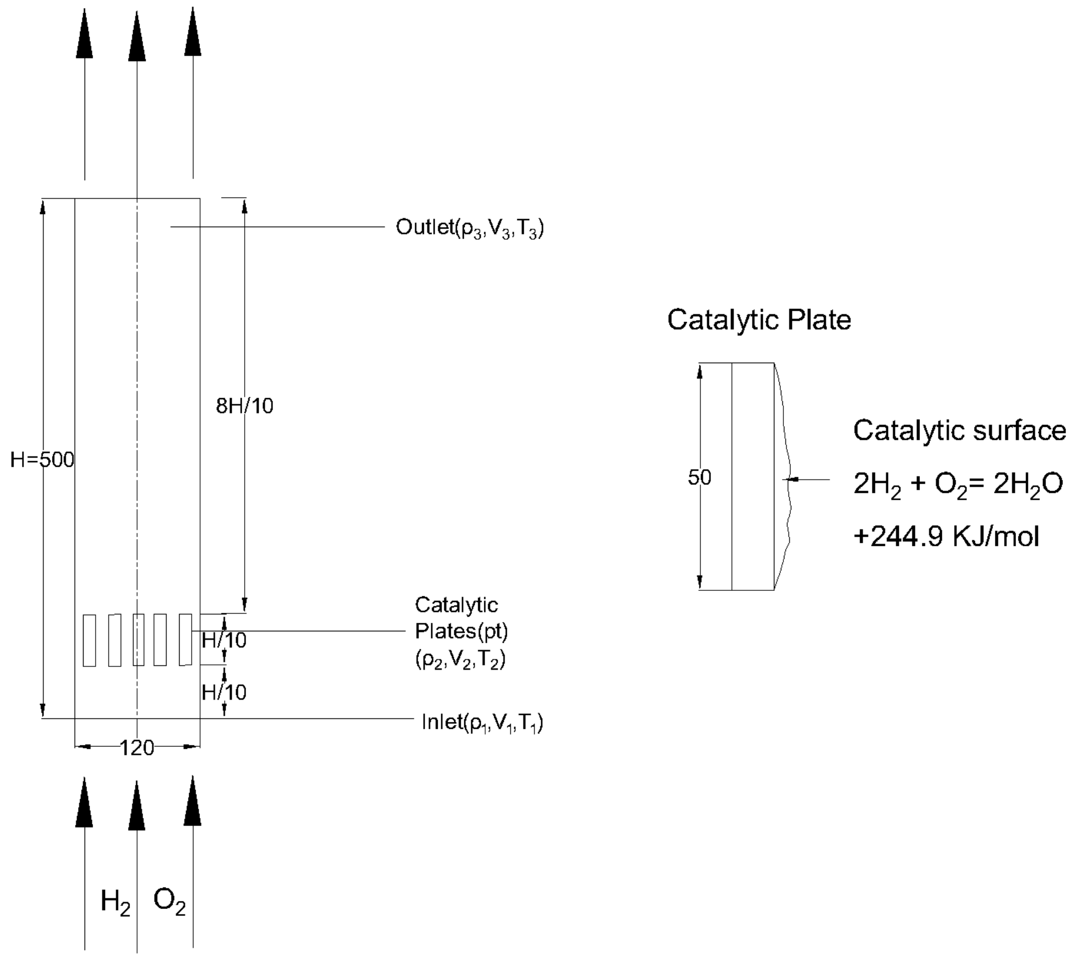

Figure 3.1 Schematic of the PAR geometry showing catalyst plates and enclosure dimensions.

Hydrogen mole fraction (X_{H2})	:	1% – 6 %
Temperature	:	25°C -70°C
Pressure	:	~1.0 bar
Number of Catalytic Plates	:	4-6
Plate Spacing	:	10mm -20mm
Recombination Heat Release	:	244.9kJ/mol

Table 3.1 Test Parameters for PAR Natural Convection Model

The physical configuration of the Passive Autocatalytic Recombiner (PAR) investigated in this study is shown in Figure 3.1. The system is modeled as a vertically oriented rectangular channel that is open at both the bottom and top ends. This geometry promotes natural convection flow, driven entirely by buoyancy forces arising from temperature gradients due to the exothermic recombination of hydrogen and oxygen.

3.2. Catalytic Plate Configuration

- Arrangement: Vertically mounted plates positioned in the catalytic zone, equally spaced.
- Coating: Platinum or palladium catalysts enhance hydrogen-oxygen recombination.
- Plate Height: 50 mm (matching the catalytic zone height)
- Spacing Between Plates: 10 mm to 20 mm
- Number of Plates: 4 to 6, depending on configuration

The catalytic reaction follows:

$$2H_2 + O_2 \xrightarrow{Pt} 2H_2O + \underset{Heat}{\Delta}$$

This exothermic process significantly raises the local temperature (T_2), reducing the density of the gas and increasing its velocity due to buoyancy.

3.3. Flow and Thermal Behavior

- Inlet (p_1, V_1, T_1): Hydrogen-air mixture enters at ambient conditions. Driven by a density difference, it begins to rise naturally.
- Catalytic Zone (p_2, V_2, T_2): Combustion occurs over catalyst surfaces, sharply increasing temperature and accelerating the gas flow.
- Outlet (p_3, V_3, T_3): Hot product gases (mainly water vapor and residual air) exit at reduced density and elevated velocity**.**

3.4. Assumptions

The following assumptions are made in the derivation:

1. The flow inside the PAR is steady and one-dimensional.
2. Ideal Gas Behavior: The gas mixture behaves as an ideal gas for large ΔT case.
3. Negligible Radiation Losses: Heat loss due to radiation is neglected.
4. Fully Developed Flow: Frictional losses are estimated using the Darcy-Weisbach equation for fully developed flow.
5. No External Power: The flow is purely driven by buoyancy (natural convection).

6. Isobaric Conditions: Pressure remains constant across the PAR except for buoyancy and friction effects.
7. Vertical Flow Path: The primary direction of flow and buoyancy is vertical.

3.5. Buoyancy-Induced Flow Theory

The performance of PARs is significantly influenced by the natural convection of gas through the device. As hydrogen reacts inside the PAR, the temperature of the gas mixture rises. This creates a density difference between the hot gas at the outlet and the cooler gas at the inlet, generating buoyancy forces that drive the flow.

There are two main cases depending on the temperature difference:

Case 1 : *For Small Temperature Difference*

Buoyancy – induced pressure difference :

$$\Delta P_{buyancy} = \int_0^H \left(\rho_1 - \rho_2\right) g \, dy$$

$$= \left(\rho_1 - \rho_2\right) gH \rightarrow (1)$$

Boussinesq approximation

$$\rho_1 = \rho_{ref}\left(1 - \beta\left(T_1 - T_{ref}\right)\right) \rightarrow (2)$$

$$\rho_2 = \rho_{ref}\left(1 - \beta\left(T_2 - T_{ref}\right)\right) \rightarrow (3)$$

Sub eqn (2) *and* (3) *in eqn* (1) *we get*

$$\Delta P_{buyancy} = \rho_{ref} \beta \Delta TgH \rightarrow (4)$$

Frictional pressure drop :

From Darcy – Weisbach equation

$$\Delta P_{frictional} = f\left(\frac{L}{D_h}\right)\left(\frac{\rho_2 V^2{}_2}{2}\right) \rightarrow (5)$$

$Using\ continuity\ equation$

$$\rho_1 V_1 = \rho_2 V_2$$

$$V_2 = \frac{\rho_1 V_1}{\rho_2}$$

$$V_2 = \frac{V_1}{(1-\beta \Delta T)} \rightarrow (6)$$

$Sub\ eqn\ (6)\ in\ (5)\ we\ get$

$$\Delta P_{frictional} = f\left(\frac{L}{D_h}\right)\left(\frac{\rho_2 V_1^{\ 2}}{2(1-\beta \Delta T)^2}\right) \longrightarrow (8)$$

$$\Delta P_{buyancy} = \Delta P_{frictional}$$

$$\rho_{ref} \beta \Delta TgH = f\left(\frac{L}{D_h}\right)\left(\frac{\rho_2 V_1^{\ 2}}{2(1-\beta \Delta T)^2}\right) \rightarrow (9)$$

$Sub\ eqn\ (3)\ in\ (9)\ we\ get$

$$\beta \Delta TgH = f\left(\frac{L}{D_h}\right)\left(\frac{V_1^{\ 2}}{2(1-\beta \Delta T)}\right)$$

$Buoyancy\ induced\ flow\ rate$

$$V_1 = \sqrt{\frac{(2\beta \Delta TgH)}{f\left(\frac{L}{D_h}\right)}} \rightarrow (10)$$

$Where:$

β : $Thermal\ expansion\ coefficient$

g : $Gravitational\ acceleration$

H : $Height\ of\ the\ PAR$

f : $Friction\ factor$

L : $Flow\ path\ length$

D_h : $Hydraulic\ diameter$

$Heat\ absorbed\ by\ the\ gas\ mixture = Heat\ released\ by\ PAR$

$$\dot{m}_{in} C_p \Delta T = \dot{m}_{in}\left(Y_{H_2,in} - Y_{H_2,out}\right) \times \Delta H_r$$

$$\Delta T = \frac{\left(Y_{H_2,in} - Y_{H_2,out}\right) \times \Delta H_r}{C_p}$$

Case 2 : *For Large Temperature Difference Buoyancy* − *induced pressure difference* :

$$\Delta P_{buyancy} = \int_0^H \left(\rho_1 - \rho_2\right) g\,\mathrm{d}y$$

$$= \left(\rho_1 - \rho_2\right) gH \rightarrow (1)$$

$$\rho_1 = \rho_{ref} \qquad T_1 = T_{ref}$$

$$\frac{\rho_2}{\rho_{ref}} = \frac{P}{RT_2} \times \frac{RT_{ref}}{P}$$

$$\rho_2 = \frac{\rho_{ref} T_{ref}}{T_2}$$

Sub ρ_1 & ρ_2 *in eqn*(1)

$$\Delta P_{buyancy} = \left(\rho_{ref} - \frac{\rho_{ref} T_{ref}}{T_2}\right) gH$$

$$= \left(1 - \frac{T_{ref}}{T_2}\right) \rho_{ref}\, gH$$

$$\Delta P_{buyancy} = \frac{\Delta T \rho_{ref}\, gH}{T_2} \rightarrow (2)$$

Frictional pressure drop :

From Darcy − *Weisbach equation*

$$\Delta P_{frictional} = f\left(\frac{L}{D_h}\right)\left(\frac{\rho_2 V^2{}_2}{2}\right) \rightarrow (3)$$

*U*sing *continuity equation*

$$\rho_1 V_1 = \rho_2 V_2$$

$$V_2 = \frac{\rho_1 V_1}{\rho_2} \rightarrow (4)$$

$Sub\ \rho_1\ \&\ \rho_2\ in\ eqn\ (4)$

$$V_2 = \frac{V_1 T_2}{T_{ref}} \rightarrow (5)$$

$Sub\ V_2\ in\ eqn(3)\ we\ get$

$$\Delta P_{frictional} = f\left(\frac{L}{D_h}\right)\left(\frac{\rho_2 V_1{}^2 T_2{}^2}{2 \times T_{ref}{}^2}\right) \longrightarrow (6)$$

$Sub\ \rho_2\ in\ eqn\ (6)\ we\ get$

$$\Delta P_{frictional} = f\left(\frac{L}{D_h}\right)\left(\frac{\rho_{ref} V_1{}^2 T_2}{2 \times T_{ref}}\right) \rightarrow (7)$$

$$\Delta P_{buyancy} = \Delta P_{frictional}$$

$$\frac{\Delta T \rho_{ref} gH}{T_2} = f\left(\frac{L}{D_h}\right)\left(\frac{\rho_{ref} V_1{}^2 T_2}{2 \times T_{ref}}\right) \rightarrow (8)$$

$$\frac{\Delta TgH}{T_2} = f\left(\frac{L}{D_h}\right)\left(\frac{V_1{}^2 T_2}{2 \times T_{ref}}\right)$$

$Buoyancy\ induced\ flow\ rate$

$$V_1 = \sqrt{\frac{2\Delta TgHT_{ref}}{f \times \left(\frac{L}{D_h}\right) \times T_2{}^2}} \rightarrow (9)$$

Chapter 4
Parametric Studies of Flow Velocity and Temperature

This chapter presents a detailed parametric investigation into the behavior of flow velocity and gas temperature within a Passive Autocatalytic Recombiner (PAR). The study focuses on how these parameters vary with changes in inlet hydrogen concentration and temperature rise, using data obtained from experimental or simulation-based results.

4.1. **Parameters Used in the Study**

Parameter	Value	Unit	Description
Acceleration due to gravity	9.81	m/s^2	Standard gravitational constant
Hydraulic diameter of PAR box	0.08	m	Governs bulk flow in the PAR enclosure
Hydraulic diameter of catalyst plates	0.02	m	Governs channel flow between plates
Height of PAR	0.5	m	Total height of the PAR box
Height of PAR plate	0.05	m	Individual plate height
Number of PAR plates	4	–	Parallel catalyst racks
$(L/D)_1$	0.625	–	Length-to-diameter ratio at inlet section
$(L/D)_2$	10	–	Length-to-diameter ratio across catalyst region
$(L/D)_3$	5	–	Length-to-diameter ratio at outlet section
Area of Section 1	0.1984	m^2	Inlet flow area
Area of Section 2	0.01	m^2	Flow area between catalyst plates
Dynamic viscosity	3.00×10^{-5}	Ns/m^2	Viscosity of the gas mixture
Reference temperature	323.15	K	Ambient temperature for calculations
Thermal expansion coefficient (β)	0.0030945	K^{-1}	Inverse of reference temperature for ideal gas
Inlet pressure	1.00×10^{5}	Pa	Atmospheric pressure
Molecular weight of H_2	2.016	kg/kmol	Lightest component of the mixture
Molecular weight of steam	18	kg/kmol	Product of hydrogen recombination
Molecular weight of air	28.97	kg/kmol	Background gas in containment
Enthalpy of reaction ($H_2 + ½O_2 \rightarrow H_2O$)	241.8	kJ/mol	Heat released during recombination

4.2. Effect of Hydrogen Concentration on Velocity

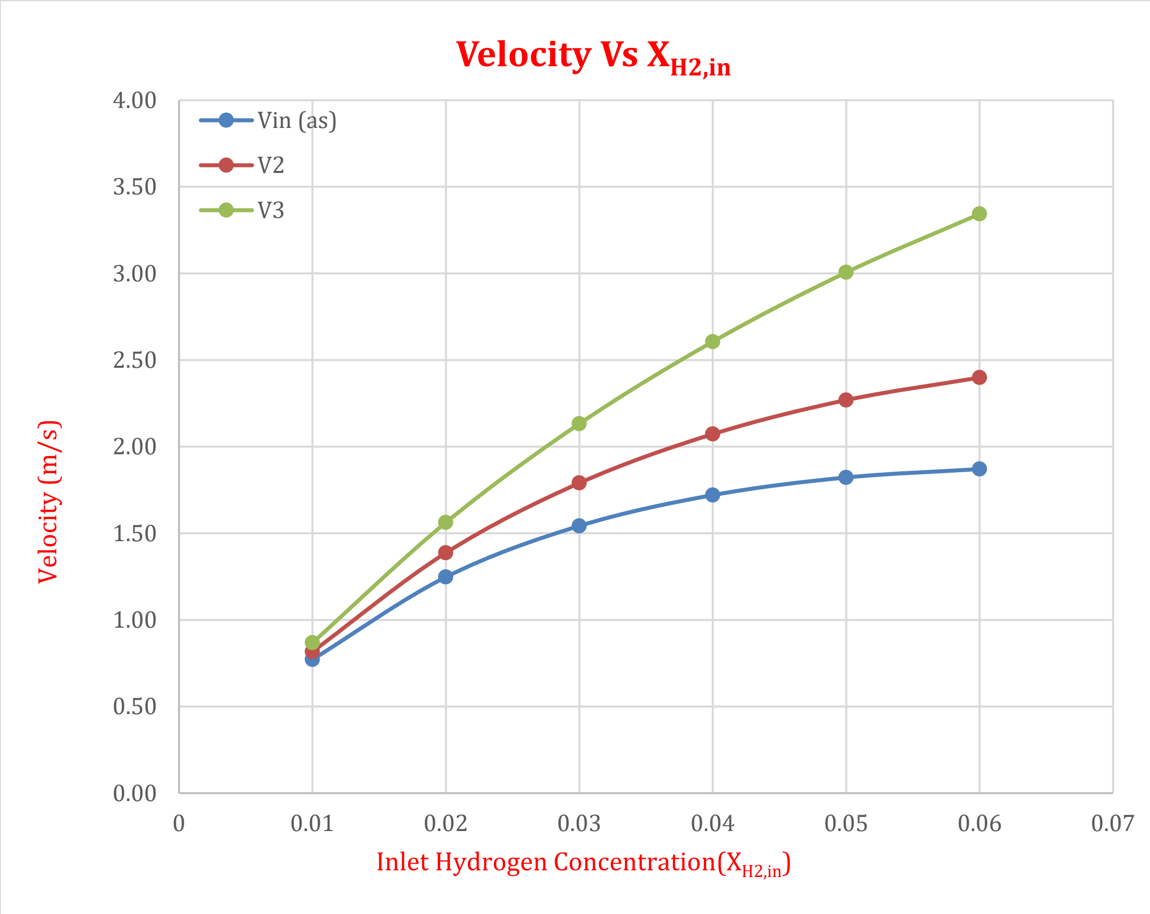

Figure 4.1 Velocity Vs Inlet Hydrogen Concentration

As shown in **Figure 4.1**, the flow velocity at different sections of the PAR increases noticeably with a rise in the inlet hydrogen mole fraction ($X_{H2,in}$). The inlet velocity (V_1), mid-point velocity (V_2), and outlet velocity (V_3) all follow this trend.

The observed increase is attributed to the intensified exothermic recombination reaction between hydrogen and oxygen. This reaction releases heat, which increases the buoyancy of the gas mixture, thereby accelerating the flow through the PAR. Notably, V_3 remains the highest among the three velocities, showing that flow accelerates progressively along the length of the recombiner.

4.3. Effect of Hydrogen Concentration on Temperature

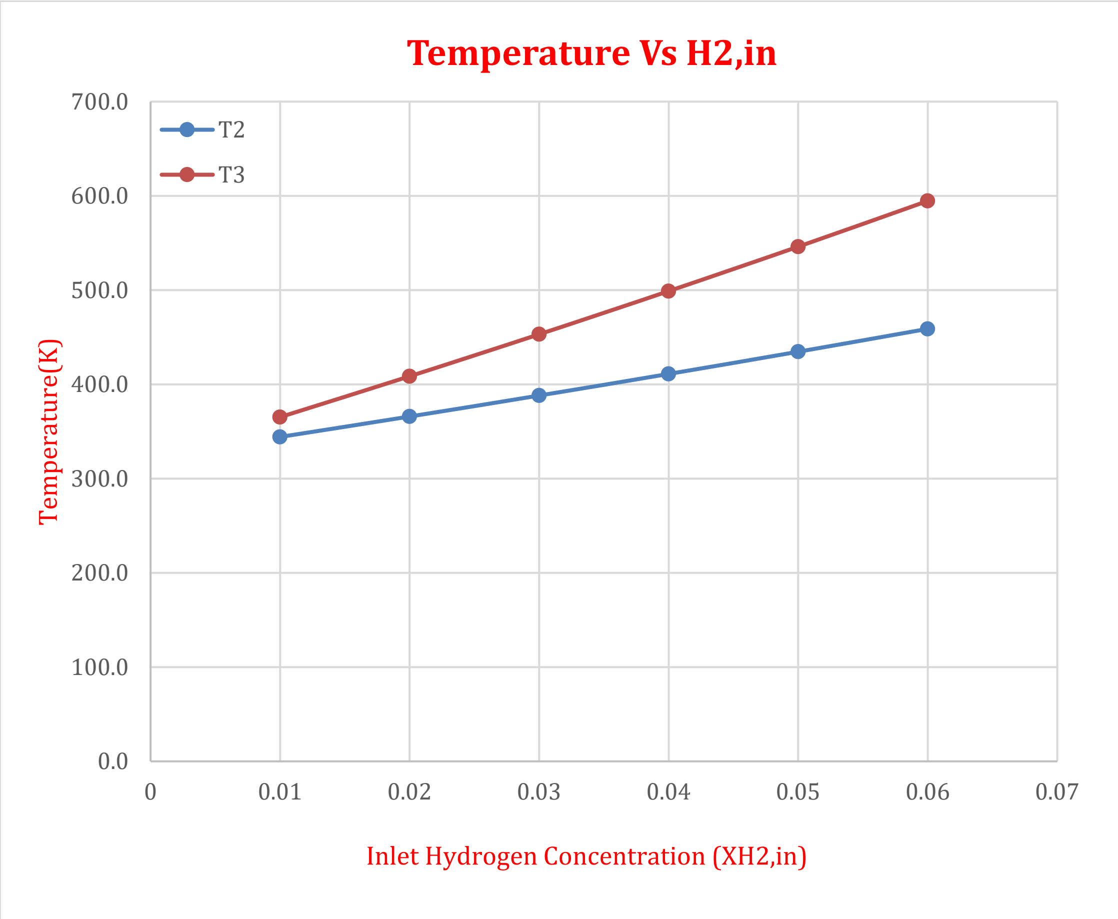

Figure 4.2 Temperature Vs Inlet Hydrogen Concentration

As shown in **Figure 4.2** presents the temperature variation with respect to $X_{H2,in}$. As the hydrogen mole fraction increases, both the intermediate temperature (T_2) and outlet temperature (T_3) show a significant rise.

This increase is a direct consequence of greater heat release from the recombination process. The growing difference between T_3 and T_2 at higher hydrogen levels implies that thermal stratification becomes more prominent toward the outlet, indicating intensified heat generation and energy accumulation in that region.

4.4. Effect of Temperature Rise on Flow Velocity

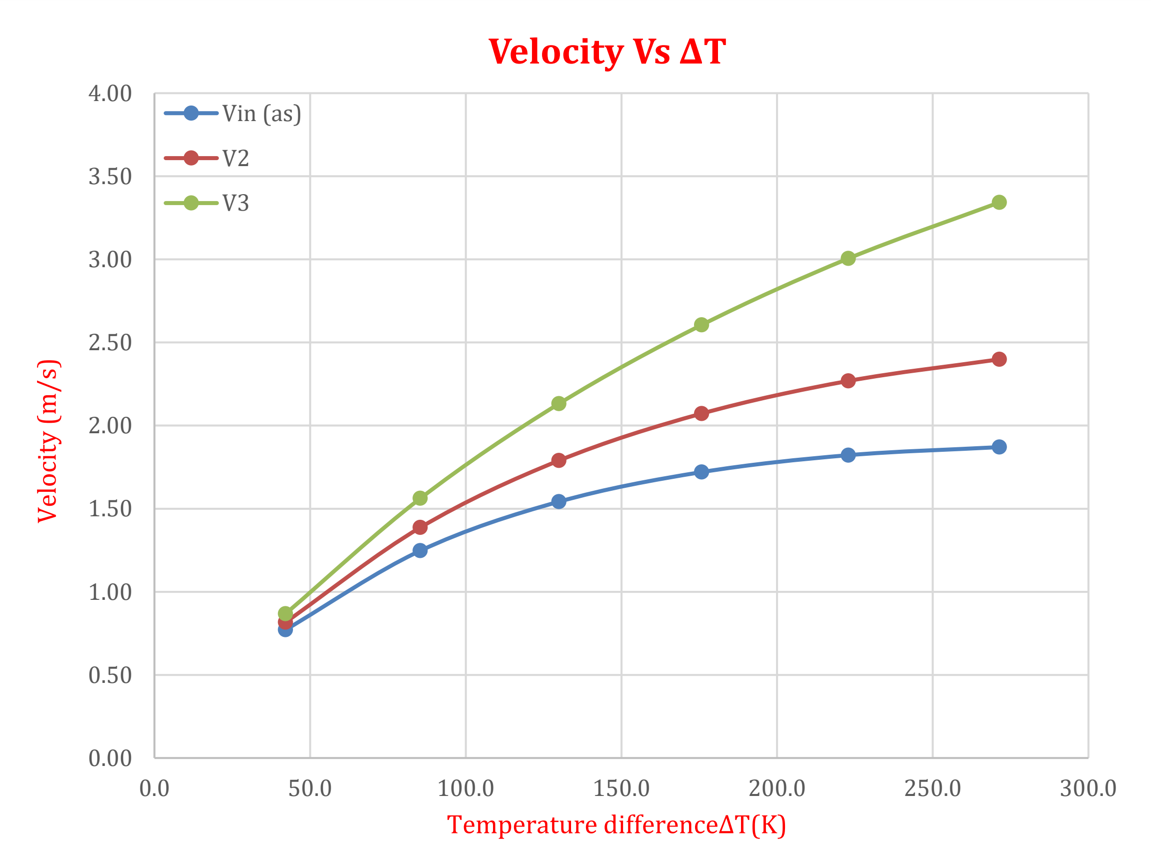

Figure 4.3 Velocity Vs Temperature Difference

In **Figure 4.3** examines the relationship between the overall temperature rise ($\Delta T = T_3 - T_{in}$) and the corresponding flow velocities. It demonstrates a clear positive correlation: as the temperature rise increases, so does the velocity at all three measured points.

The response is nonlinear velocity increases steeply at lower ΔT values and then grows more gradually. This behavior confirms that the thermal gradient is the primary driving force behind buoyant flow in the PAR, and its effect is most pronounced downstream, as shown by the highest growth in V3.

- At low ΔT:

  - Even a small temperature difference causes a **significant density gradient**.
  - This leads to a rapid **increase in buoyancy force**, hence a **steep rise in velocity**.
  - Flow is transitioning from stagnant to active — a regime change.

❖ At higher ΔT:

➢ The flow has already been established; further increases in ΔT **do increase buoyancy**, but not proportionally.

➢ **Viscous and inertial resistances** in the system become more significant.

➢ Hence, the **velocity grows more slowly**.

4.5. Effect of reducing the inlet Hydrogen Concentration on Flow Velocity

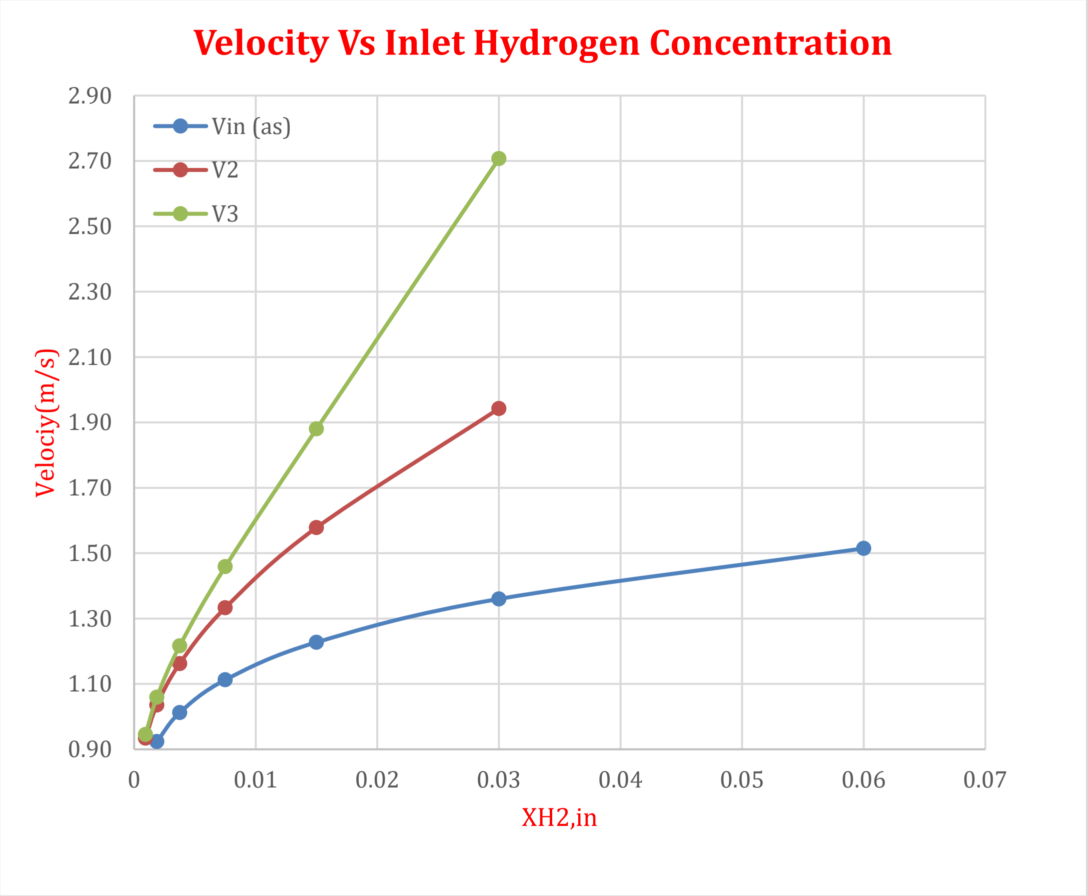

Figure 4.5 Velocity Vs Inlet Hydrogen Concentration

As shown in **Figure 4.5**, the flow velocity at different sections of the PAR decreases noticeably with reduing the inlet hydrogen mole fraction ($X_{H2,in}$). The inlet velocity (V_1), mid-point velocity (V_2), and outlet velocity (V_3) all follow this trend.

The observed the decrease in inlet hydrogen concentration in the containment reduce the reaction rate in the surface of the PAR plate. This reduce the temperature in the outlet section as shown in **Figure 4.6**. The decrease in temperature affect the natural convection flow and finally it reduce the buoyancy velocity.

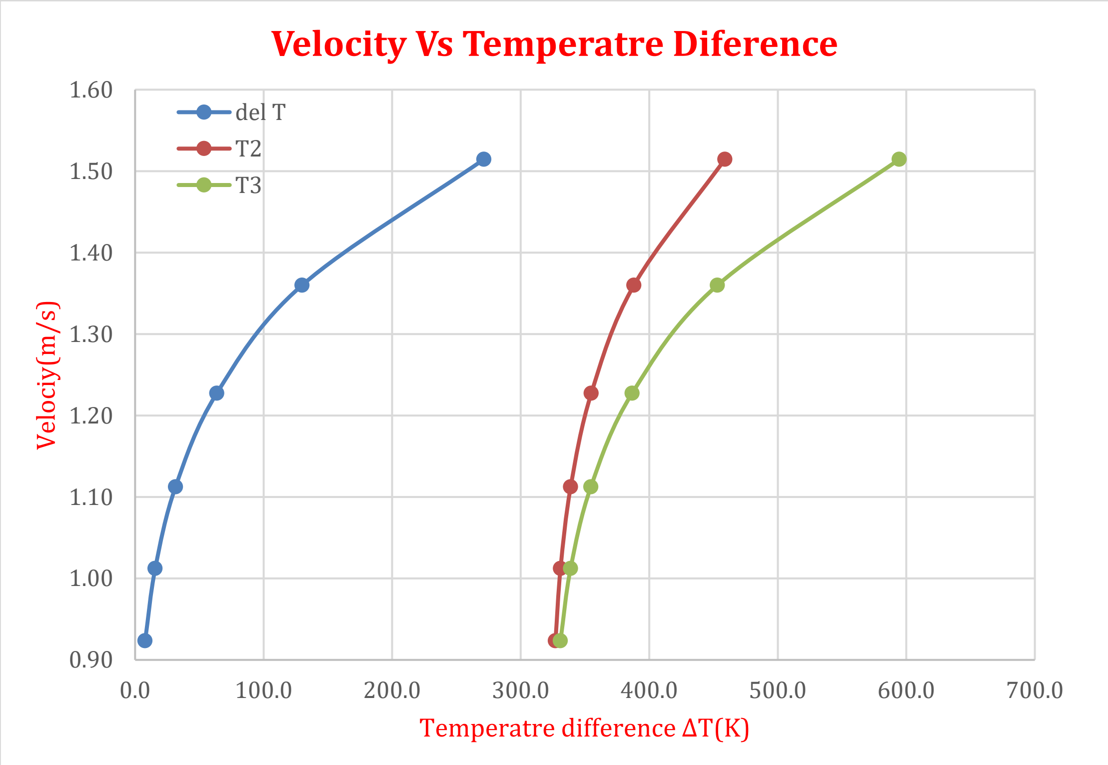

Figure 4.5 Velocity Vs Temperature Difference

4.6. Summary

The results of the parametric studies highlight the interconnected behavior of hydrogen concentration, temperature rise, and flow velocity in PARs:

- Increasing hydrogen concentration enhances recombination rates.
- Enhanced recombination leads to greater heat release, causing a stronger buoyant force.
- The buoyant force accelerates the flow through the PAR, with velocity increasing along the path.

These insights are critical for optimizing PAR design and performance, ensuring reliable hydrogen mitigation under varying containment conditions.

Chapter 5

Closure

5.1. Conclusions

This report summarizes the summer internship at Safety Research Institute (SRI), Kalpakkam (May–June 2025), focused on hydrogen mitigation in nuclear containments, especially flow inside Passive Autocatalytic Recombiners (PARs).

Main activities included:

- Studying how flow velocity and temperature inside a PAR change with hydrogen levels and heat.
- Understanding how heat from hydrogen recombination affects buoyancy-driven flow.
- Analyzing pressure losses to learn about flow resistance and system behavior.

The study showed clear links between hydrogen concentration, heat generation, flow patterns, and temperature layering in PARs. These results can help improve PAR designs for better safety during accidents.

5.2. Future Work

Recommended next steps:

1. Create detailed CFD models to confirm these results.
2. Conduct experiments with scaled models or existing data to measure flow and temperature.
3. Include pressure drop and recombination efficiency in performance evaluations.
4. Use these findings in broader safety simulations and risk assessments.

This internship provides a strong base for further research on hydrogen safety in nuclear reactors.

Reference

[1] International Atomic Energy Agency (IAEA), Mitigation of Hydrogen Hazards in Water Cooled Power Plants, IAEA-TECDOC-1196, IAEA, Vienna, Austria (2001)

[2] International Atomic Energy Agency (IAEA), International Atomic Energy Agency, 2011. Mitigation of Hydrogen Hazards in Severe Accidents in Nuclear Power Plants, IAEA-TECDOC-1661.

[3] Ro˙ze´n A, 2018. Simulation of start-up behaviour of a passive autocatalytic hydrogen recombiner. NUKLEONIKA 2018;63(2):27-41.

[4] Calic V., 1999. Passive Autocatalytic Recombiners Periodic Testing Issues. Journal of energy, VOLUME 68-61-68.

[5] Dewit W.A., Koroll G.W.,Sitar J.L., 1996. Hydrogen Recombiner Development at AECL. Workshop on the Implementation of Hydrogen Mitigation Techniques, Winnipeg, Canada, May 13-15, 1996.

[6] Jae-Won Park, Byung-Ryung Koh, Kune Y. Suh, (2011). Demonstrative testing of honeycomb passive autocatalytic recombiner for nuclear power plant, Nuclear Engineering and Design, V-241, pp 4280-4288.

[7] Sanap K.K., Varma S., Waghmode S.B., Bharadwaj S.R., (2015). Wire gauze and cordierite supported noble metal catalysts for passive autocatalytic recombiner. Nuclear Engineering and Design, Volume 294, Pages 226-232.