

SUPPRESSION OF THERMO-ACOUSTIC OSCILLATIONS USING POROUS MEDIA (PROOF OF CONCEPT FOR GAS TURBINE COMBUSTOR TECHNOLOGY) DEMONSTRATION USING RIJKE TUBE.

Submitted in partial fulfillment of the requirements for the award of
Bachelor of Engineering in Aeronautical Engineering

by

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SATHYABAMA

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

**Accredited with Grade "A" by NAAC | 12B Status by UGC | Approved by AICTE
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March - 2021



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BONAFIDE CERTIFICATE

This is to certify that this Project Report is the bonafide work of **SHLOK SRIVASTAVA (37260038)** and **DANIEL PARMAR (37260010)** who carried out the project entitled "**SUPPRESSION OF THERMO-ACOUSTIC OSCILLATIONS USING POROUS MEDIA (PROOF OF CONCEPT FOR GAS TURBINE COMBUSTOR TECHNOLOGY) DEMONSTRATION USING RIJKE TUBE.**" under our supervision from SEPTEMBER 2020 to MARCH 2021

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DECLARATION

I, **SHLOK SRIVASTAVA (37260038)** hereby declare that the Project Report entitled "**SUPPRESSION OF THERMO-ACOUSTIC OSCILLATIONS USING POROUS MEDIA (PROOF OF CONCEPT FOR GAS TURBINE COMBUSTOR TECHNOLOGY) DEMONSTRATION USING RIJKE TUBE**" done by me under the guidance of **Mr. R GOKULNATH** at Satyabama Institute of Science and Technology, Chennai is submitted in partial fulfilment of the requirements for the award of Bachelor of Engineering in Aeronautical.

DATE: 14-04-2021
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ACKNOWLEDGEMENT

I am pleased to acknowledge my sincere thanks to Board of Management of SATHYABAMA for their kind encouragement in doing this project and for completing it successfully. I am grateful to them.

I convey my thanks to Dr. S PRAKASH M.E PhD., Dean, School of Mechanical and Dr.P BOOMA DEVI M.E, PhD, Head of the Department, Dept. of Aeronautical for providing me necessary support and details at the right time during the progressive reviews.

I would like to express my sincere and deep sense of gratitude to my Project Guide Mr. R GOKULNATH for his valuable guidance, suggestions and constant encouragement paved way for the successful completion of my project work.

I wish to express my thanks to all Teaching and Non-teaching staff members of the Department of Aeronautical who were helpful in many ways for the completion of the project.

ABSTRACT

Pressure oscillations or thermoacoustic instabilities are few of the terms used by community of researchers which cause extensive damage to the gas turbine combustors. To analyse the concept of thermoacoustic instabilities and its methods of suppressions were studied by constructing a simple Rijke tube combustor. Ample amount of experimental and simulation data was empowering to understand the physics of mitigation of the thermoacoustic instabilities occurring inside the Rijke tube combustor. The instability was studied by Rayleigh's criterion. The main objective of the study was conducted by application of intermediate porous plug to suppress the acoustic oscillations inside the Rijke tube. The intermediate porous plug was kept at variable altitude and to study was conducted about the suppression of the oscillations. The heat provided to the porous plug and the formation of the pores played a vital role for the generation of the acoustic oscillations. Due to the reticulated and honeycomb formation of pores of porous media it affected the heat distribution along with the airflow inside the Rijke tube combustor. The experimental results in the research conducted are interlinked with each other and thus every parameter is important in order to model the estimation of the suppression of the thermoacoustic instabilities.

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LIST OF ABBREVIATIONS AND SYMBOLS

TA Thermoacoustic

f Frequency

a Speed of Sound

L Length

n Positive Integer

d Diameter

R Rayleigh's Index

Q Rate of Heat Release

P Acoustic Pressure

λ Wavelength

ω Frequency

t Time

Δp : Pressure Drop

M : Dynamic Viscosity of Fluid

L : Thickness of Perforated Plate

U : Velocity of Fluid

P : Density of Fluid

D : Darcy Coefficient

F : Forchheimer Coefficient

ϕ Porosity

d_h Hydraulic Diameter

d_m Mean Particle Diameter

Gr Grasof Number

Re Reynolds Number

Ra Rayleigh's Number

ν Kinematic Viscosity

β Thermal Expansion Coefficient

α Thermal Diffusivity

∂P Change in Pressure

∂T Change in Temperature

K= Thermal Conductivity

C_p = Specific Heat

G= Gravitational Acceleration

CHAPTER 1

INTRODUCTION

The most common approach to reduce the NO_x emissions Lean premixed combustion is preferred where the temperature of the flame is reduced in combustion chamber but this leads to the TA instabilities. One of the main reasons for the mitigation of the TA instabilities is Flame stabilization where the fuel mixes with the airflow and it goes into the flame region in the combustion chamber. This only happens when there is high velocity and the flame is not blown away. The flame cannot survive high velocity and there is pressure drop inside the combustion chamber. Failure occurs due to unwanted noise when TA instabilities occur close to the resonating frequencies in the combustion chambers. It was not a humongous issue for a long time because non-premixed flame was used with the supplementary air injected by the combustion chamber. Premixed air-fuel is used in existing gas turbines, removing the need for secondary air. Most of the holes in the combustor walls disappeared as a consequence of this operation, and the chamber effectively became a resonator with very little diminution. However, this has led to the turbulent flame with fluctuations which associates with the acoustics of the combustion chamber. Therefore, the researchers have shown a keen interest in the thermoacoustic instabilities that is defined as the association of the acoustic pressure and the rate of heat release. As the alleviation of the TA instabilities became trending the research has been categorised as active control and passive control. The active control can be defined as the alleviation of the TA instabilities with the help of the control system which detects the changes in the pressure and there by controlling the amount of fuel injection. Whereas, passive control is defined as the mitigation of the TA instability with the help of changing the design of the geometry of the combustor such as length, shape or by adding different injection tubes or resonators.

1.1 RAYLEIGH'S CRITERION

In 1877 Lord Rayleigh described the equilibrium between the acoustic excitation and acoustic depression caused by the unsteady heat transfer can lead to the self-excited, uneven acoustic response this is called as the Rayleigh's Criterion. This can be understood by concept of thermal expansion. Consider a small amount of gas which is adjoining to the heated wall. The heat is transferred to the gas near the wall and leads to expansion. This expansion of gases pushes the surrounding gases located in the middle. If the pressure pulse is reaching near to the layer of the wall while the expansion is taking place then the pulse is pushed away with a bigger amplitude and as result a bigger sound is heard. From this we can understand that the pressure and heat transfer oscillations are amplified.

1.2 CHANNEL OF HEAT PROPELLED OSCILLATIONS

1.2.1 Soundhauss Tube (Conduction propelled oscillations)

Soundhauss-Type phenomenon is actually an oscillation that is caused due to the variation in the wall temperature between the tube sections. This can be explained as the propelled contact of the acoustic wave and boundary layer. Here the boundary layer acts as the medium for driving or damping the oscillations to the core.

1.2.2 Rijke Tubes (Convection propelled oscillations)

Rijke tubes is an example of thermoacoustic instabilities. The mechanism consists of heated wire gauge which blows the air in upward direction caused by natural convection. The pressure nodes are damping present at the end of the tube and antinodes at the middle of the tube for an open-open Rijke tube. In the same way the node for the velocity is in the middle and antinode at the ends of the tubes. During one-fourth of the cycle and prior to the attainment of maximum pressure the velocities and acoustics from the lower and upper halves are directed inside of the tube. When the velocity and acoustics combine in the lower half of the tube the heat transfer takes place from the gauze. The heat transfer oscillation mainly depends on the pressure oscillations and drives the acoustics.

Prior to the maximum pressure the upper half of the tube the velocity and acoustic are opposed during the one-fourth cycle. In case of the hot medium in the upper half of the tube the velocity and heat transfer repel with each other. As a result, the pressure oscillation and the heat transfer oscillation repel and this results into the damping. Velocity and pressure oscillation are required for driving. This doesn't occur if the heat source is kept at velocity or pressure node. This is only possible at a point that is one-fourth to the length of the tube where the pressure and velocity of the acoustics is maximum. If more amount of heat energy is provided then there is possibility of multiple excitation due to the coincidence of different harmonics.

Rijke tube was an experimental setup constructed by Rijke in 1859 that is used to study the thermoacoustic instabilities. The Rijke tube has large length to diameter ratio and is representation of a full-scale combustor. The analysis of the acoustics is easier in Rijke tube because the large length to diameter ratio makes it one dimensional so that the sudden area changes and the flame vortices are reduced. Thus, one can specifically opt out several factors occurring inside a full-scale combustors. The flames inside the Rijke tube are flatter and simpler as compared to complex flames inside the full-scale combustors that leads to the less flame and acoustic interaction.

Specific phenomena have been studied in the area of the thermoacoustic instabilities in the past few decade by researchers. Some have studied the thermoacoustic instabilities in terms of the frequency and amplitude and other factors. Some have focused on the flame stability for thermoacoustic instabilities. In the thesis presented, efforts have been made to quantify the understanding of the thermoacoustic instabilities with the help of the temperature variation, frequency and amplitude along the length of the tube.

CHAPTER 2

LITERATURE SURVEY

This literature survey does not purport to be important in provision of the literature on Rijke tube combustors dynamics. The aim of this analysis is to provide context for this research as well as some insight into the work that has been done has been carried out in the following research areas.

2.1 RIJKE TYPE TUBE COMBUSTORS

The first experiment was performed in the Rijke tubes was by Rijke after whom it is name. He performed the experiment with the help of open tube having the length of open from both the sides and a copper wire gauze was used as local heat source and as a result the tube was able to perform sound.

This phenomenon was explained by Rayleigh (Rayleigh, 1878) where he states that “If heat be given to the air at the moment of greatest condensation, or taken from it at the moment of greatest rarefaction, the vibration is encouraged.” This statement in the domain of thermoacoustic is known as Rayleigh’s criterion.

(Putnam) studied three different types of systems for acoustics oscillations i.e., open-open type with premixed flame, closed-open type with premixed flame and closed-with non-premixed flame. From this we can conclude that different configurations lead to either mitigation or encouragement of the oscillations.

(Du, Li and Yang, 2019) conducted a study in thermoacoustic oscillations with the help of the Rijke tube and numerical simulation to model the airflow inside the heating coils in the Rijke tube and to calculate the temperature and flow field distribution. According to him Rijke tubes are related to uniform distribution of heat but tangential heat source also encountered which impacts the encountered thermoacoustic instability in actual situation. Later he concluded that the optimum spacing in the heating coils can minimise the TA acoustic oscillations under

various airflows. The increase in the different spacing lead to decrease in the oscillations and later increases slightly.

(Iannelli *et al.*, 2020) in his work considered a vertical Rijke tube with a heater inside and equipped with speaker and microphone where his motive was to characterise the non-linear closed loop in terms of the limiting cycle oscillations with respect to the heat parameter. Through his he found that the amount of heat exchanged on macroscopic level can be used to design active suppression controllers.

(Hernandez and Matveev, 2010) wanted to analyse TA instabilities inside the rocket motors thus they considered two tubes of different correctional areas and connected to form a single resonator a later concluded the reduction in the sound is twice lower with the supplied heat and range of the flow rate can be increased keeping in mind the increase of the sound generation.

(Matveev and Culick, 2003) considered a horizontal Rijke tube with pressure transducers, damper and a blower attached to obtain mean airflow for stable analysis of the TA oscillations and to study the linear behaviours of small amplitude oscillations.

(Paschereit, Gutmark and Weisenstein, 2000) concentrated on unstable TA modes and modification of the acoustic boundary condition to obtain combustion instability. This was performed by a plenum chamber consisting of perforated plates and combustion chamber with double walled quartz glass for full flame observation. He applied this to low emission swirl stabilizer to obtain unstable operating conditions.

By considering a horizontal Rijke tube with distributed heat source, (Yang, Turan and Lei, 2015) investigated TA dynamic behaviour patterns of Rijke and observed that multiple heat sources can possibly strengthen or weaken acoustic energy based on the specified distribution.

(Noble *et al.*, 2012) proposed a main tube having the ring stabilized jet burner supported with base in order to study data driven non linearity and the chaos theory of TA instabilities in Rijke tube.

(Epperlein, Bamieh and Åström, 2015) created a simple Rijke tube made up of glass and heating coil fitted, microphone and preamplifier. Their main motive was to study the empirical identification, verification and feedback control techniques of TA instabilities. Later, they conclude that limiting cycle produced by the TA instabilities can be used to convert some of the steady heater power into acoustic power.

(Li *et al.*, 2016) performed a theoretical and experimental demonstration to minimize self-excited TA instabilities where they considered a loud speaker of 100 W and resistance attached to bottom open end Rijke tube and a Bunsen burner to provide premixed laminar flame. Later, they observed that implementing the identification and optimization algorithms can successfully reduce the limiting cycle oscillation by 45 dB

(Moeck *et al.*, 2009) considered a hybrid method for the simulation of thermoacoustic instabilities in a Rijke tube with premixed burner stabilised flat flame, and found out that flame acoustic coupling is not more accurate as compared to the compressible equations.

In the same way (Zhao and Chow, 2013) estimated the frequency of the Rijke burner surrounding an oscillating gas and microphone where they observed that frequency is decreased and then increased and the flame is placed at different axial locations.

(Yang, Turan and Lei, 2015) wanted to explore the physiochemical foundations and wanted to clarify the analysis of TA instabilities inside the premixed flame combustors. They fabricated horizontal Rijke tube with distributed heat source. Later they concluded that it influences the stability of the system.

(Deshmukh and Sharma, 2017) were able to demonstrate the effectiveness of the control techniques and were able to achieve complete suppression by 30dB.

(Moeck, Paul and Paschereit, 2010) introduces surrogate system by considering 12 tubes connected to an annular duct and were able to suppress the unstable modes by the help of elementary feedback controller.

(Zhao *et al.*, 2015) applied two heat sources in a Rijke tube where the premixed flame was placed in the bottom and an electrical heater on the upper half of the tube. It was found that the heater acted as the sound absorber to mitigate combustion excited oscillations. The flame in the bottom half was able to generate self-sustained combustion oscillations.

(Mukutmoni, Powell and Mutnuri, 2014) conducted the study about vertical and hollow cylindrical tube open at both ends where the sound is generated by the buoyancy flow. The experiment was conducted on both numerical and experimental scale. They were later able to conclude that unsteady turbulence modelling with the help of Lattice-Boltzmann Method show to acquire very accurate data between the experiment and numerical simulation.

(Hantschk and Vortmeyer, 1999) was able to perform numerical simulation of a non-linear self-excited thermoacoustic oscillation inside the Rijke tube. They were able to model the development of oscillations at limiting cycles with the support of unsteady compressible Navier-Stokes' equations and conservation of mass and energy equations.

(Song, Lee and Shin, 2011) in his work combined Computational Fluid Dynamics (CFD) and Computational Aero Acoustics (CAA) to predict the phenomena of thermoacoustic instability. They were able to calculate the heat release response, distribution of density and speed of sound inside the tube. This data was later used to calculate the thermoacoustic instability in CAA simulation.

2.2 POROUS MEDIA BURNER

(Dunnmon *et al.*, 2017) studied porous media burners for noise reduction in reconstruction domain. They used X ray computed tomography in the combustible systems to get the three-dimensional temperature field at higher resolution. With the help of CT scan, they were able to observe recirculation, temporal irregularities in the reaction zone.

(Mohaddes, Chang and Ihme, 2020) studied the effects of matrix stabilized combustion on a gas turbine operating on the Bryton cycle. A stationary gas turbine engine was used which used fuel-lean premixed combustion and

considering the bypass ratio and liquid fuel operation. The porous media combustion was implemented as a means of preheating the fuel air mixture to achieve flammability and thereby extending lean flammability and to enable the cycle performance.

(Sobhani, Allan, *et al.*, 2020) as able to achieve a range of thermal conductivities for a single material which provided a thermal transport property of porous ceramic media. This was made possible by creating a digital rendering of the desired structure in a lithography based ceramic manufacturing.

Later (Sobhani, Muhunthan, *et al.*, 2020) studied the feasibility and the performance of additive manufactured ceramic structures in porous media burners and the trends to be observed in flame stability, pressure drop and the emissions that are associated with the design of the burners. This was made possible with help of X-ray Computed tomography in order to extract the geometric characteristics of the designed burners and the post-combustion material. Thus, they later conclude from the study that the highly regular structure of the burners leads to the build-up stress and they were prone to the cracks and less structural durability was observed.

In the same year (Sobhani, Legg, *et al.*, 2020) investigated the lean premixed porous media combustion at an elevated pressure which are mainly observed using gaseous fuels and are limited to the atmospheric conditions. This was made possible by considering the expected pressure and the temperature at the combustor inlet of high bypass ratio turbo fan engine at cruise and take-off conditions. This helped to measure combustion stability regimes, temperature, pressure drop after the normalization with the laminar burning and the larger stability was observed for the methane as compared to n-heptane.

(Sobhani *et al.*, 2017) performed a study to examine the effect of the material, geometric properties and the thermal properties on the flame stability and to determine the limits of the flame- blow-off and the flash back in an inter-stabilised burner with help of silicon carbide and Ytria stabilized zirconia. For this study they considered an inter stabilised burner where upstream matrix had high pore density that acts as flame arrestor and the lower part had low pore density that acted as combustion. As a result, it was analysed that proportions of NOx

increased at higher equivalence ratios and the CO emissions were higher at lower flow rate. The low temperature became an obstacle for complete burning of CO oxidation.

(Nozari *et al.*, 2017) understood flame characteristics, combustion characteristics, combustion quality with ammonia hydrogen flames. For this he developed a fully premixed atmospheric combustion test rig modified in order to conduct ammonia combustion. A CFD model was developed based on volumetric heat for examination of the combustion efficiency of the burners through flow field and the temperature distribution. Thus, he saw that there was 40% increase in the flame holding capacity for the porous media and high-power generation density is achieved.

2.3 THEORITICAL BACKGROUND

This topic relates with high-power the theoretical aspects of the high-power experiment. This includes the pressure oscillations of the open-open Rijke tube and the integral form of the Rayleigh's criterion.

2.3.1 Solution for pressure oscillation in an open-open Rijke tube

The tube is resonating and thus we get a standing wave inside the tube. The wavelength λ of the acoustic wave is twice the length of the tube. The frequency f and the relation with wave length is written as,

$$f = a/\lambda = na/2L$$

Here 'a' is the speed of sound. n is a positive integer (1, 2, 3...) representing the resonance node.

The more precise equation can be written as,

$$f = \frac{na}{2(L + 0.8d)}$$

For $n=1$ we get

$$f(2(L + 0.8d)) = a$$

$$f\lambda = a$$

$$\lambda = 2(L + 0.8d)$$

The maximum amplitude is observed at the centre of the tube, thus for open ended pipe the antinode is present at the ends and the node is observed at the centre of the pipe. It can be inferred that velocity-pressure amplitude in the

bottom half part lies on the same axis. In the top part of the pipe, they are on the opposite sites. Thus, we can say that if heat is applied to the middle-lower half part of the tube will pulse. This can be said to be cycle, so heat additions generate pressure oscillations and produces velocity oscillations.

2.3.2 The Rayleigh's criterion and Rijke's Standing Wave

If heat release and the acoustic pressure are combined with each other they result in thermoacoustic instabilities. This is called as Rayleigh's criterion and it is written in terms of Rayleigh Integral,

$$R = \frac{1}{T} \int P' Q' dt$$

Where R is the Rayleigh's Index, p' is the acoustic pressure and Q' is rate of heat release and T is time.

The Rayleigh criterion can only be applied to Time dependant component of heat transfer q' . According to this if heat is added ($q' > 0$) during the half cycle ($p' > 0$) or taken out ($q' < 0$) during half cycle ($p' < 0$), then acoustic waves are produced.

If $I < 0$, Acoustic oscillation will damp out

If $I > 0$, Acoustic oscillation will grow

If $I = 0$, Acoustic oscillations neither damp or grow

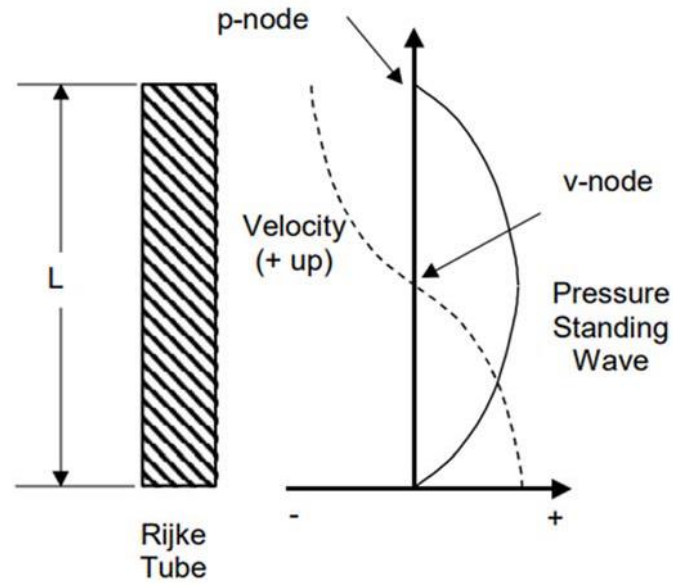


Fig 2.1 Schematic Rijke Tube Standing wave (Wavelength=2L)

For Rijke's standing wave,

Consider right moving wave as,

$$P'_{\text{R}} = P_{\text{max}} \sin \left(\frac{2\pi x}{\lambda} - \omega t \right)$$

For Left moving wave,

$$P'_{\text{L}} = P_{\text{max}} \sin \left(\frac{2\pi x}{\lambda} + \omega t \right)$$

Adding both above equations

$$P' = P'_R + P'_L = 2P_{\max} \sin\left(\frac{2\pi x}{\lambda}\right) \cos(\omega t)$$

With the help of wave equation velocity fluctuation can be calculated,

$$\rho \frac{\partial u'}{\partial t} + \frac{\partial p'}{\partial x} = 0$$

$$\therefore \rho \frac{\partial u'}{\partial t} = - \frac{\partial P'}{\partial x}$$

$$\frac{\partial u'}{\partial t} = 2P_{\max} \cos\left(\frac{2\pi x}{\lambda}\right) \left(\frac{2\pi}{\lambda}\right) \cos(\omega t)$$

$$\therefore \dot{U} = -\frac{2}{\rho} P_{\max} \left(\frac{2\pi}{\lambda}\right) \cos\left(\frac{2\pi x}{\lambda}\right) \frac{\sin(\omega t)}{\omega}$$

Now using Rayleigh's Criterion,

Resonance waves for maximum value is

$$R = \int P' Q' dt$$

If, $Q \propto U'$

$$\therefore R = \int P' U' dt$$

Now,

$$P'U' = -2 \frac{P_{\max}}{\rho} \left(\frac{2\pi}{\lambda}\right) \cos\left(\frac{2\pi x}{\lambda}\right) \frac{\sin \omega t}{\omega} \times 2P_{\max} \sin\left(\frac{2\pi x}{\lambda}\right) \cos(\omega t)$$

The space dependant term from the above equation is,

$$\sin\left(\frac{2\pi x}{\lambda}\right) \cos\left(\frac{2\pi x}{\lambda}\right)$$

$$\therefore 2\sin\left(\frac{4\pi x}{\lambda}\right)$$

Above equation is max at,

$$\frac{4\pi x}{\lambda} = \frac{\pi}{2}$$

$$\therefore x = \frac{\lambda}{8}$$

$$\lambda = 2Ln, \text{ for } n = 1$$

$$x = \frac{L}{4}$$

CHAPTER 3

AIM AND SCOPE

The entire objective of this conducted research is to amplify the knowledge of the thermoacoustic instabilities in order to be eligible for the prediction of the active control and passive control of the thermoacoustic instabilities in a full-scale combustor. This thesis will help in analysis of the burner performance, pressure drop, stability of the flame and its operating range and durability. To achieve this computational fluid dynamics, dynamics of flame, structure and properties of porous media. Flame and porous media interactions have to be developed.

The project presented in this thesis involves study of a simple tube combustor. The research shown here will, with help of wide spread data reinforces the suggested theories proposed. The experiment will serve as a data for the researchers those are associated with the domain of thermoacoustics.

This will also help in reducing the thermoacoustic workload by developing simple and precise prediction schemes for the thermoacoustic instabilities.

This thesis has included both experimental and computer simulation in order to illustrate the Rijke type combustor in terms of acoustic frequency, temperature distribution, various porous media burner specimen.

CHAPTER 4

EXPERIMENTAL METHODS AND ALGORITHMS

4.1 SYNOPSIS OF EXPERIMENTAL SETUP

A vertical open-open type Rijke tube type combustor was used for the investigation of the study as shown in the below figure.

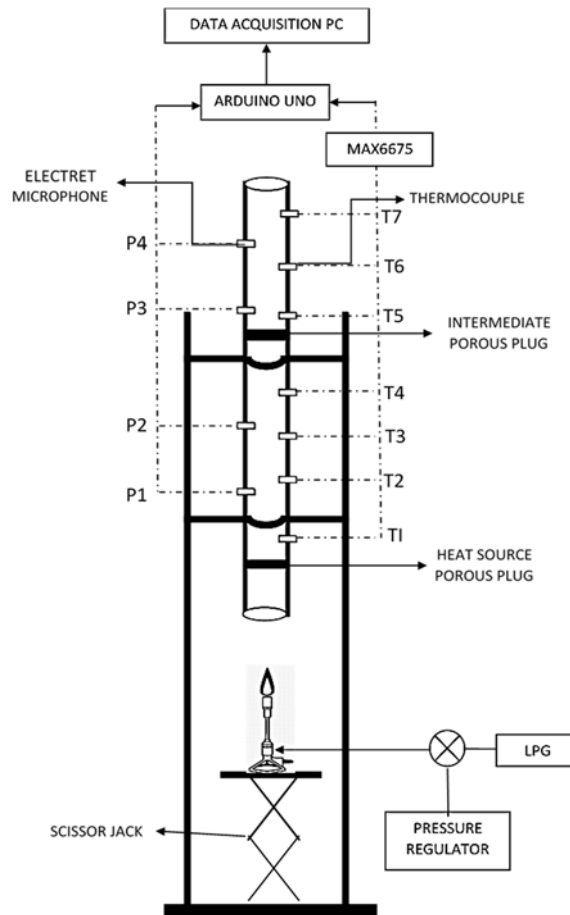


Fig 4.1 Overall experimental setup of Rijke tube combustor

Premixed unreduced liquefied petroleum gas coming from the cylinder was fed into the bottom part of the tube combustor with the help of customised blow-torch. The flame was stabilised with two different materials i.e., steel mesh and ceramic honeycomb, positioned at one-fourth span of the tube. For investigation of temperature seven K type thermocouple were introduced on the combustor wall and inside combustor tube with a bush located on the centreline of the tube combustor to keep them intact. The data acquisition and analysis were done

through the PC. For study of suppression of sound, electret microphone with adjustable gain were affixed on the opposite direction of the tube combustor. Later the data was analysed with the help of Arduino boards.

4.2 TUBE COMBUSTOR

The tube combustor was comprised of 1000mm long SAE 304 Stainless steel tube with inner diameter of 52mm supported on the steel rack with the help of two bore clamps, as shown in the figures 4.3. Seven holes were drilled for insertion of seven different thermocouples. On the opposite side five holes were drilled for microphones. Furthermore, a scissor jack capable of reciprocating motion was fitted in the bottom of the tube combustor which supported the blow torch igniting the premixed LPG-air to the flame holder. The hole in the bottom for the microphone helped in measuring the frequency of the flame. The rack of the tube combustor also consisted of a small stand to support the data acquisition board

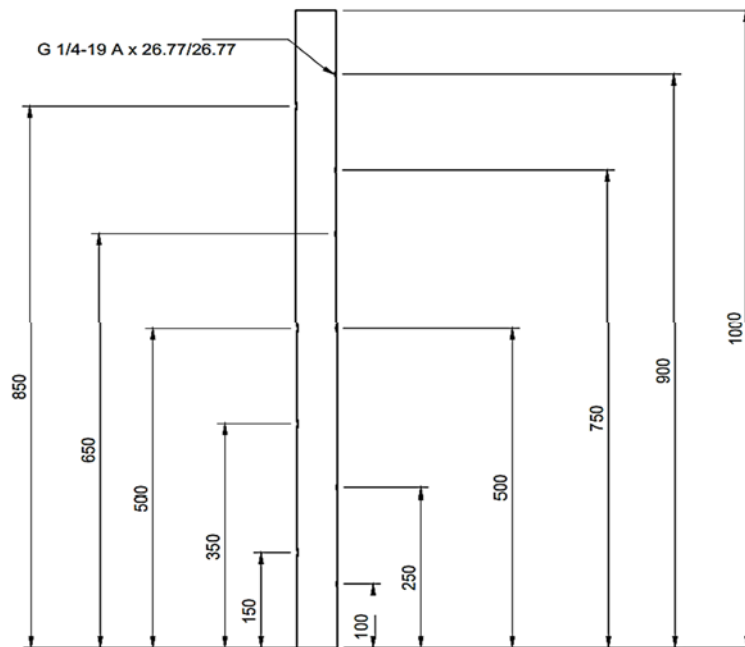


Fig 4.2 Rijke tube dimensions



Fig 4.3 Rijke tube combustor containing electret microphones and thermocouples

4.3 IGNITOR and FLAME HOLDER:

The ignitor consisted a set of an extended Bunsen burner and a customised blow torch as shown in the figure 4.4. Both were connected to the liquified petroleum gas cylinder with the help of regulators. The motive of the using two different ignitors was to study the power produced by them is whether capable of generating the sound inside the tube. Both the ignitors were supported on the help of scissor jack that made the reciprocating motion.



Fig 4.4 Customised blowtorch

4.4 MICROPHONE AMPLIFIERS

The microphone amplifiers, MAX4466 Electret Microphone Amplifier with Adjustable Gain Modules were used as shown in the figure 4.5. The module consisted of 20-20KHz electret microphone with an operational amplifier MAX4466 with a variable gain from 25x-125x. The operational supply voltage was +2.4V to +5.5V. These microphones were inserted inside a T-Joint. One of the connections of the T-Joint was connected to tube combustor via Teflon tape to avoid any leakage. The opposite connection was connection to a plastic tube to reduce the reflective pressure waves coming back to a T tube combustor and a T affecting the sound sensor. The third connection was used for the microphone. The signals from all the five microphones were sent to the Arduino Uno board connected to the PC for data acquisition.



Fig 4.5 MAX4466 Electret Microphone Amplifier

4.5 THERMOCOUPLES

The temperature measurements were conducted by seven K type thermocouples of two different types named as washer type thermocouple and Mineral insulated thermocouple. They are shown in figure 4.6. The type K washer thermocouple consisted of 5mm diameter hole with the length of the wire 2000mm, with capability of measuring temperature up to 600°C. These thermocouples were utilised for the measurement of the wall temperature on the tube combustor at different height in order to study the heat distribution. In order to read the temperature a cold-junction compensated K-Thermocouple to digital converter (MAX6675) was used. The MAX6675 outputs the data in a 12-bit resolution. The temperature resolution was approximately 0.25°C and is capable to read the readings up to 1024°C. The temperature error was $\pm 2^\circ\text{C}$ for the range of 0-700°C. Since the module prone to the electric noise the sheath provided nearly accurate results. The remaining three thermocouples were mineral insulated to measure the flame temperature and gas temperature at variable heights. The probe length as 30mm with probe diameter 3mm with the length of wire 2000mm. The thermocouple wires were surrounded by magnesium oxide inside thin-walled sheath. The probe was made of Inconel 600 inside which was the measuring wire of 2 NiCr-Ni capable of measuring temperature from -200 to 1200°C. These thermocouples were connected to Cold-Junction Compensated Thermocouple-to-Digital Converter (MAX31855) to read the data. The data output is in the format of 14-bits SPI compatible read only format. This sensor was capable of resolving the temperatures to 0.25°C which allowed the readings as high as 1800°C and as low as -200°C with accuracy of $\pm 2^\circ\text{C}$.



Fig 4.6 K-type Thermocouple

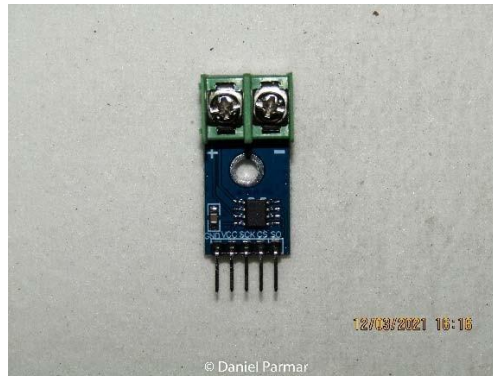


Fig 4.7 Max6675 K-Type Thermocouple Temperature Sensor Module

4.6 POROUS PLUG SPECIMENS

The porous plug heat source was kept at 250mm i.e., is one-fourth of the total length of the tube. The specimens used for the heat source were steel mesh and cordierite honey comb ($\text{Mg}_2\text{Al}_4\text{Si}_5\text{O}_{18}$). Another specimen that that was kept at variable height to suppression of thermoacoustic instability were Silicon Carbide (SiC) and Zirconia (ZrO_2). The thermal properties of all the materials are discussed in the table 4.1.

Table 4.1 Thermal properties of porous plugs

Material	Specific Heat	Thermal Conductivity	Density	Max Temperature
	J/g-°C	W/m-K	g/cc	°C
Cordierite	0.900	2.50	2.30	1100
Silicon Carbide	0.670	77.5	3.10	2797
Zirconia	0.270	1.675	5.68	2681
Steel	0.500	16.2	8.00	1400



Fig 4.8 Steel mesh

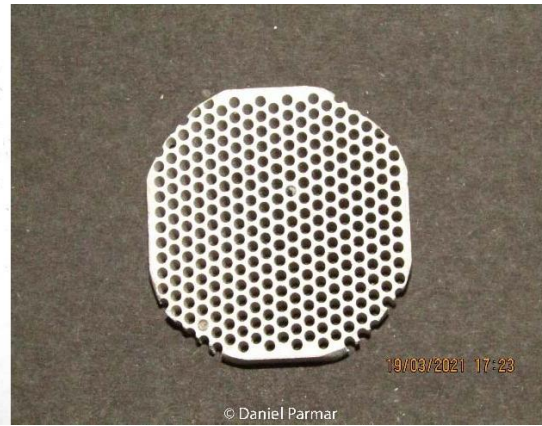


Fig 4.9 Cordierite honeycomb

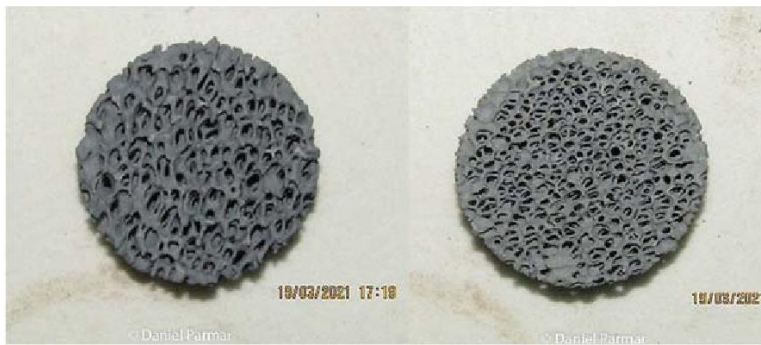


Fig 4.10 SiC 10PPI



Fig 4.11 SiC 20PPI



Fig 4.12 ZrO2 10PPI

4.7 DATA ACQUISITION EQUIPMENT

The thermocouple module (MAX6675 and MAX 31855) and microphone amplifiers (MAX4466) were connected to two Arduino UNO boards which were used for the purpose of data acquisition which were connected to a PC of intel core i7 to acquire the temperature, frequency and digital signals. The Arduino UNO is a microcontroller board based on ATMEGA382P. The board contains 14 I/O digital pins, 6 analogue input with a 16MHz resonator. The interface used for the data acquisition was Arduino IDE where writing the code for specific operation was found to be effortless. The figure 4.13 shows the circuit of the two Arduino UNO boards connected to the system.

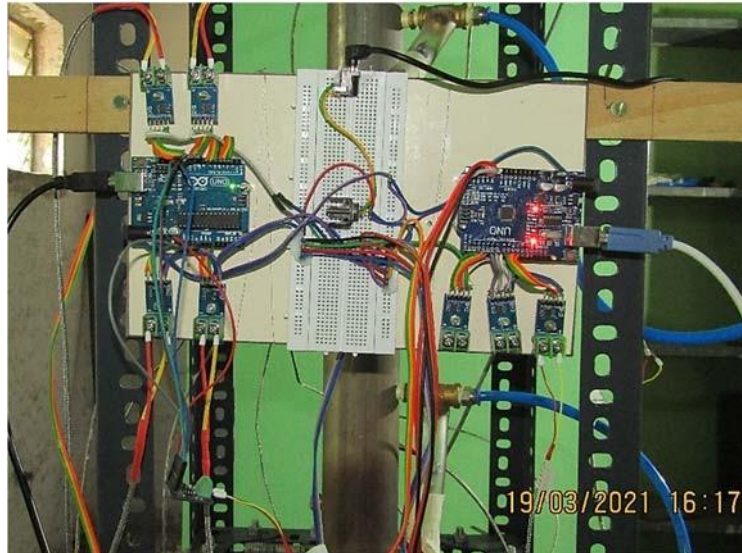


Fig 4.13 Data Acquisition Board

4.7.1 Fast Fourier Transform:

The frequency data for different specimens were acquired with the help of fast Fourier transform (FFT) code. FFT is an algorithm which makes the computation of Direct Fourier Transform (DFT) faster. The calculation considers the sine and cosine values for several times. The results discussed in the next section will show that the difference between the readings is little higher. This is because the function of Arduino is not fast to cope up and requires more amount of time to print the data. FFT has to be performed with the samples having the size of 2,4,6,8, 2^n .

Below code has helped to determine and compare the numerical calculation of frequency and identify the peaks of frequencies at various spots and print the peak values.

```
#include "arduinoFFT.h"
```

```
#define SAMPLES 128          //SAMPLES-pt FFT. Must be a base 2 number.  
Max 128 for Arduino Uno.
```

```
#define SAMPLING_FREQUENCY 2048 //Ts = Based on Nyquist, must be 2  
times the highest expected frequency.
```

```

arduinoFFT FFT = arduinoFFT ();

unsigned int samplingPeriod;

unsigned long microSeconds;

double vReal[SAMPLES]; //create vector of size SAMPLES to hold real values

double vImag[SAMPLES]; //create vector of size SAMPLES to hold imaginary
values

double peakout = 0;

double peakout1 = 0;

double peakout2 = 0;

double peakout3 = 0;

void setup()

{

Serial.begin(9600); //Baud rate for the Serial Monitor

samplingPeriod = round(1000000 * (1.0 / SAMPLING_FREQUENCY)); //Period
in microseconds

}

void loop()

{

float t1 = millis();

float r = t1/1000;

Serial.print(r);

for (int j = 0; j < 4; j++)

{

/*Sample SAMPLES times*/

for (int i = 0; i < SAMPLES; i++)

```

```

{
microSeconds = micros();

//Returns the number of microseconds since the Arduino board began running
the current script.

if (j == 0)
{
vReal[i] = analogRead(0);

//Reads the value from analog pin 0 (A0), quantize it and save it as a real term.

}

if (j == 1)
{
vReal[i] = analogRead(1);

//Reads the value from analog pin 0 (A0), quantize it and save it as a real term.

}

if (j == 2)
{
vReal[i] = analogRead(2);

//Reads the value from analog pin 0 (A0), quantize it and save it as a real term.

}

if (j == 3)
{
vReal[i] = analogRead(3);

//Reads the value from analog pin 0 (A0), quantize it and save it as a real term.

}

vImag[i] = 0; //Makes imaginary term 0 always

```

```

/*remaining wait time between samples if necessary*/
while (micros() < (microSeconds + samplingPeriod))
{
    //do nothing
}
}

/*Perform FFT on samples*/

FFT.Windowing(vReal, SAMPLES, FFT_WIN_TYP_HAMMING,
FFT_FORWARD);

FFT.Compute(vReal, vImag, SAMPLES, FFT_FORWARD);

FFT.ComplexToMagnitude(vReal, vImag, SAMPLES);

/*Find peak frequency and print peak*/

double peak = FFT.MajorPeak(vReal, SAMPLES, SAMPLING_FREQUENCY);

// Serial.print(peak);    //Print out the most dominant frequency.

//Serial.print(",");    //Print out the most dominant frequency.

if (j == 0)
{
    peakout = peak;

    Serial.print(" , ");

    Serial.print(peakout);    //Print out the most dominant frequency.

    Serial.print(" , ");    //Print out the most dominant frequency.

}

if (j == 1)
{

```

```

peakout1 = peak;

//Serial.print(" P2 - ");

Serial.print(peakout1);    //Print out the most dominant frequency.

Serial.print(" , ");    //Print out the most dominant frequency.

}

if (j == 2)

{

peakout2 = peak;

//Serial.print(" P3 - ");

Serial.print(peakout2);    //Print out the most dominant frequency.

Serial.print(" , ");    //Print out the most dominant frequency.

}

if (j == 3)

{

peakout3 = peak;

//Serial.print(" , ");

Serial.println(peakout3);    //Print out the most dominant frequency.

}

}

/*Script stops here. Hardware reset required.*/

}

```

4.8 NUMERICAL SIMULATION

This numerical study focuses on the required. * study of the heat transfer occurring through the Rijke tube combustor. The work has been moulded to capture the physics and the mechanism of the coupling of heat transfer and the porous media. The Navier-Stroke's equations were solved using commercially available software FLUENT. It was used to create a three-dimensional structure of the same dimensions as of the experimental Rijke tube to precisely capture the data from the calculation. The honeycomb structure was fitted inside the tube and a heat source was defined by coupling to the wall of the tube.

4.8.1 Geometry and 3-D grid generation

As mentioned earlier the fitted Rijke tube was modelled with the length of 1000mm, inner diameter of 52mm and thickness of 4mm was considered. The porous media was kept at one-fourth (250mm) from the bottom of the tube. In order to accurately capture the data at the heat source the mesh was kept fine at the edges. Coarse mesh was kept at the centre part of the geometry.

Poly-hexacore mesh was created with the help of the FLUENT MESHING (formerly T-Grid). Two different local sizing were added to the geometry for preparation of the surface mesh. The body sizing was added to the porous media of size 0.5mm with a growth rate of 1.2, similarly a face sizing of 0.9mm with growth rate of 1.2 was added to the tube wall. Since, this is an assembly of porous media and the tube shared topology was implemented. The boundary layers were created in the fluid section of the geometry in order to calculate the heat transfer at thee walls accurately. Five layers were added with a smooth transition ratio of 0.272 on all the fluid regions. As a result, the geometry contained 2134952 cells. The figure 4.14 shows the geometry and the boundary conditions. Figure 4.15 shows the mesh structure of the geometry.

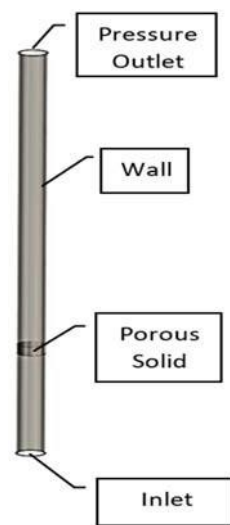


Fig 4.14 Geometry and Boundary walls

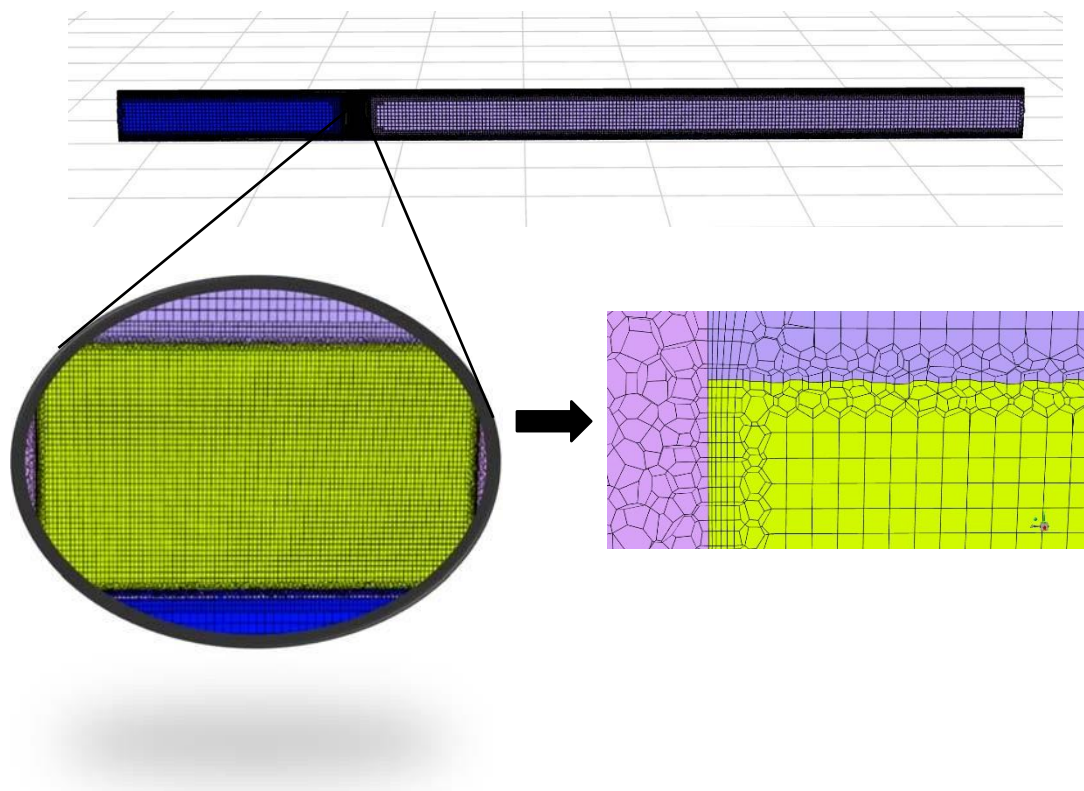


Fig 4.15 Mesh structure of Rijke tube geometry

4.8.2 Flow and Heat Transfer modelling

4.8.2.1 Darcy–Forchheimer analytical approach.

In order to define the parameters of the porous medium Darcy–Forchheimer coefficients plays an important role. This equation defines the pressure loss caused by the friction along the porous medium, with respect to the velocity of the flow inside the medium. The equation is as follows,

$$\Delta P = \mu \cdot d \cdot L \cdot u + \frac{\rho}{2} \cdot f \cdot L \cdot u^2$$

ΔP : Pressure drop [Pa]

μ : Dynamic viscosity of fluid [kg/ms]

L : Thickness of perforated plate [m]

u : Velocity of fluid [m/s]

ρ : Density of fluid [kgm³]

d : Darcy coefficient

f : Forchheimer coefficient

The above equation denotes the pressure loss inside a medium caused by the friction which is in terms of shear forces and pressure forces. The shear forces are signified by Darcy equation; therefore, it is also called as linear resistance coefficient 'd'. The Pressure forces are defined by the Forchheimer equation and 'f' in the above equation is the quadratic resistance coefficient.

4.8.2.2 Porosity:

Porosity is defined as the percentage of empty space in a porous material. For a perforated material with a certain thickness, it can be defined by equation below,

$$\phi = \frac{\text{Open area of porous material}}{\text{Total area of porous material}}$$

For circular holes the hydraulic diameter is calculated by equation,

$$d_h = \frac{4 \cdot \text{Open Volume}}{\text{Wet surface area}}$$

From above equations we can calculate the mean particle diameter which is equated as,

$$d_m = \frac{3 \cdot (1 - \phi) \cdot d_h}{2 \cdot \phi}$$

d_h = Hydraulic Diametre, ϕ = Porosity

Thus, we can write the Darcy and Forchheimer coefficients as below,

$$d = 150 \cdot \frac{(1 - \phi)^2}{(\phi^3 \cdot d_m^2)}$$

$$f = 3.5 \cdot \frac{(1 - \phi)}{(\phi^3 \cdot d_m)}$$

4.8.2.3 Association of Buoyancy driven flows and Natural Convection

We know that when heat is added to any fluid the density changes with respect to the change in temperature. The flow is encouraged due to the gravitational force acting on the change in the density.

The buoyancy flows are measured by the ratio of Grashof and Reynolds number:

$$\frac{Gr}{Re^2} = \frac{g\beta\Delta TL}{\nu^2}$$

In case of Natural convection, the buoyancy is measured with non-dimensional parameter called as Rayleigh's number,

$$Ra = \frac{g\beta\Delta TL^3\rho}{\mu\alpha}$$

Here β is thermal expansion coefficient, expressed as

$$\beta = -\frac{1}{\rho} \left(\frac{\partial \rho}{\partial T} \right)_p$$

And α is the thermal diffusivity (m^2/s), expressed as

$$\alpha = \frac{k}{\rho c_p}$$

g = gravitational acceleration (m/s^2)

ΔT = Change in temperature (K)

L = Length (m)

V = velocity of fluid (m/s)

μ = dynamic viscosity ($\text{kg/m}\cdot\text{s}$)

ν = kinematic viscosity (m^2/s)

ρ =density (kg/m^3)

∂P = Change in pressure (Pa)

∂T = Change in temperature

K = thermal conductivity ($\text{W}/(\text{m}\cdot\text{K})$)

C_p = Specific Heat ($\text{J}\cdot\text{kg}^{-1}\cdot\text{K}$)

4.8.3 Boundary Conditions:

Since the Rayleigh number is below 10^8 , the flow is laminar. Initially the Boussinesq model was implied keeping the density constant in order to speed up the convergence. Since, the temperature difference is very high it was not useful. Thus, steady-state solution was achieved by initially decreasing the magnitude of the velocity and running the solution on first-order scheme till the convergence is reached. Using the current data, the solution the calculation was run again with

higher order scheme till the convergence is reached. The boundary conditions are discussed in table 4.2 and material properties in table 4.3.

Table 4.2 Boundary conditions

Boundary	Boundary Condition
Inlet- Capped Wall	Velocity Inlet, 0.056 (m/s)
Outlet	Pressure Outlet, 0 Pa
Tube wall	Convective heat loss from outer wall
Porous Wall	Coupled to tube solid and fluid regions

Table 4.3 Material Properties

Tube Properties	
Material	STEEL
Height	1 m
Diameter	0.052 m
Wall Thickness	0.004 m
Thermal Conductivity	16.27 W/mK
Specific Heat (Cp)	502.48 J/kgK
Density	8030.0 kg/m ³
Convective Heat Transfer Coefficient	20.0 W/m ² K
Porous Media Properties	
Material	CORDIERITE
Height	0.022 m
Diameter	0.052 m
Thermal Conductivity	2.5 W/mK
Specific Heat (Cp)	900 J/kgK
Density	2300.0 kg/m ³

CHAPTER 5

RESULTS AND CHARACTERISATION OF RIJKE TUBE COMBUSTOR

5.1 EXPERIMENTAL RESULTS

The results described in this thesis correlate with the theories connected to the occurrences inside the tube combustor. This research with the support of lots of data, experimental and computational empowers the suggested theories. Thus, this will help to implement the concept of porous media inside jet combustors. The experimental investigation included capturing of tube combustor data in terms of frequency, analysis of digital data, gas temperature and surface temperature.

For production of thermoacoustic oscillations two different sources of power were supplied. Initially the flame was generated with the help Bunsen burner, but it was found due to less amount of power the oscillations were damping and enough number of oscillations was not produced. Later, with help of unreduced pressure regulator and blowtorch a high-pressure wide jet flame was produced which was able to supply enough power to the porous media to generate oscillations. The figures 5.1-5.3 shows the types of flames and the heated area of the porous media by the two heat sources.

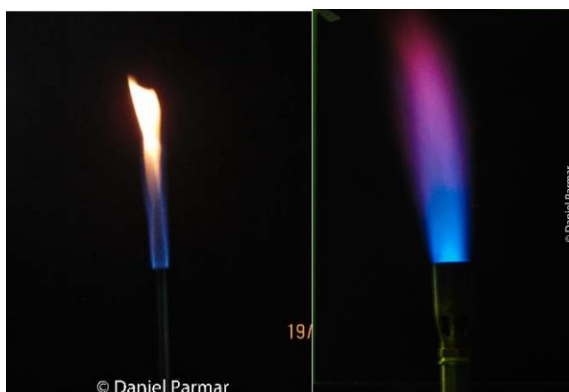


Fig 5.1 Bunsen ***Fig 5.2 Blowtorch***
Burner flame ***flame***

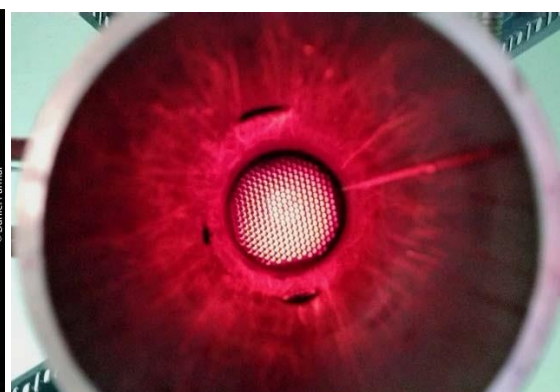


Fig 5.3 Flame distribution

Different specimens were tested for the analysis out of which the oscillations were produced only by single steel mesh and single piece of Cordierite honeycomb. Later an intermediate porous media was kept at varying heights. The specimen details are mentioned in the below table.

Table 5.1 Tested specimen details

Main Porous Burner	Intermediate Porous Burner	Height (From bottom)
Metal Mesh Steel EN304	Silicon Carbide Reticulated (10PPI)	500mm, 850mm
	Silicon Carbide Reticulated (20PPI)	500mm, 850mm
	Zirconia Reticulated (10PPI)	500mm, 850mm
Cordierite (Hoffman Filter)	Silicon Carbide Reticulated (10PPI)	500mm, 850mm
	Silicon Carbide Reticulated (20PPI)	500mm, 850mm
	Zirconia Reticulated (10PPI)	500mm, 850mm
	Cordierite-Hoffman (20PPI)	Combined
Cordierite (Hoffman Filter)	—	
Metal Mesh-Steel EN304		
Silicon Carbide Reticulated (10PPI)		

5.1.1 Characterisation of Acoustic response

In this section the characteristics of sound oscillation are discussed. The data acquisition happened to be at four different locations P1, P2, P3, P4, which are located at distance of 150mm, 350mm, 500mm, 850mm from bottom.

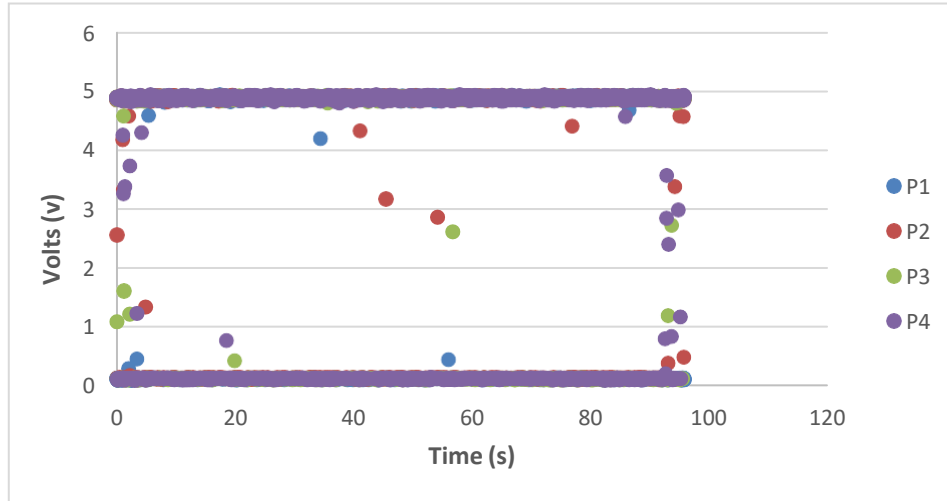


Fig 5.4 Time vs Volt graph of only steel mesh

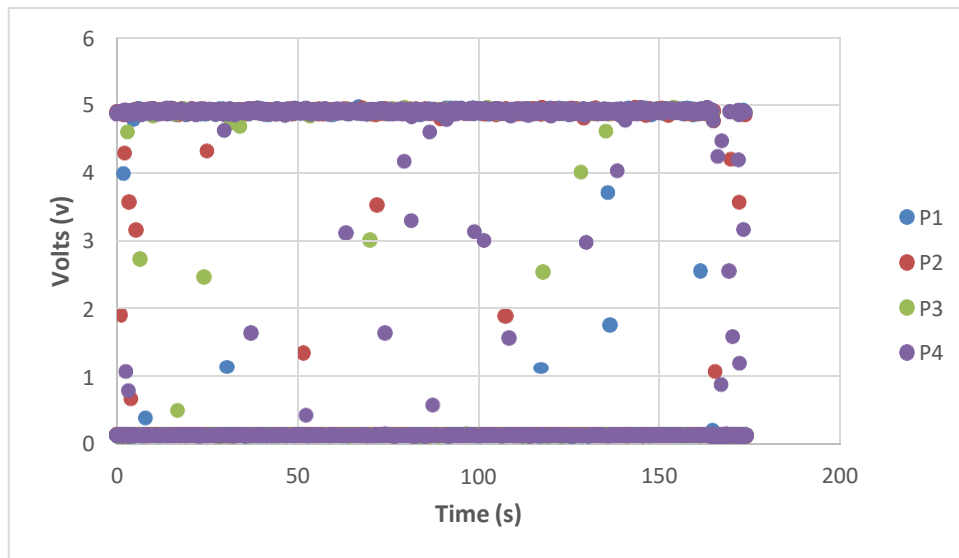


Fig 5.5 Time vs Volt graph of only Cordierite honeycomb

The above graphs 5.4 and 5.5 denote the time vs voltage curve where it can be seen that during certain amount of time when sound oscillations were produced then the upper curve was generated.

The data acquisition for frequency happened by the FFT code that is discussed in section 4.7.1 at four different locations F1, F2, F3, F4, which are located at distance of 150mm, 350mm, 500mm, 850mm from bottom. Frequency vs time it can be seen that of the specimens produce a single frequency of 200dB after flame is removed from the heat source. Initially when heat was provided to the specimens the sound that produced was of 900dB.

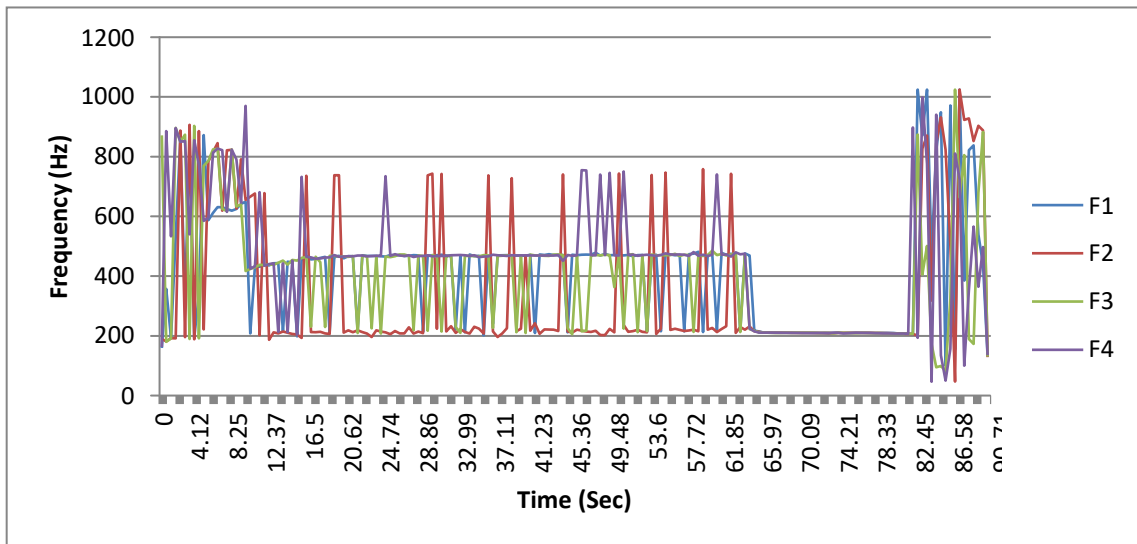


Fig 5.6 Frequency vs Time plot of only steel mesh

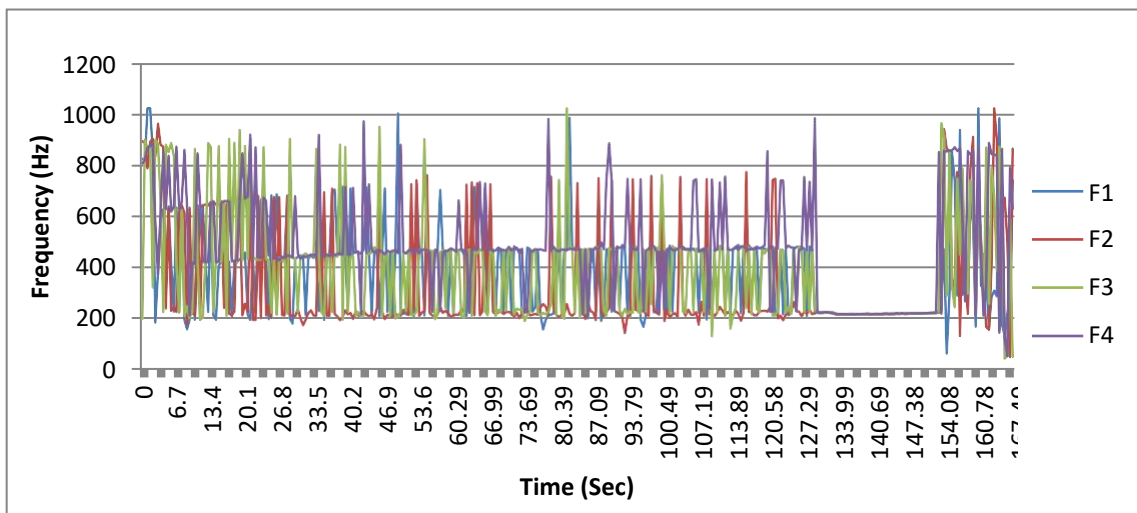


Fig 5.7 Frequency vs Time plot of only Cordierite honeycomb

After the intermediate porous plug was inserted the variation in the oscillation of sound can be seen from the data presented below. The below data presented is for silicon carbide of 20ppi kept at 500mm as an intermediate porous plug keeping steel mesh and cordierite as heat source.

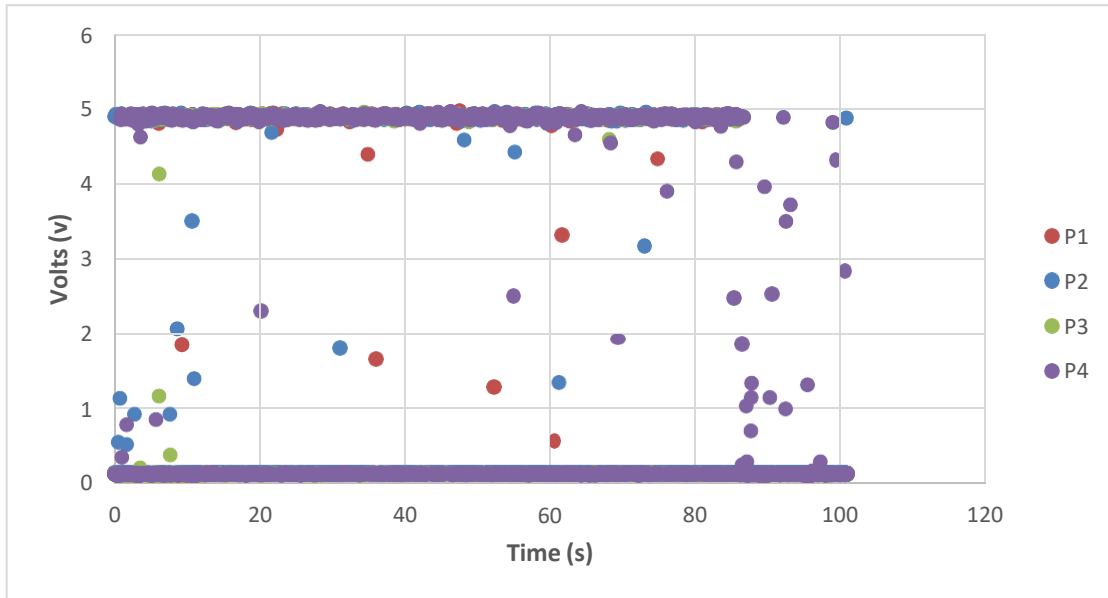


Fig 5.8 Volt vs Time plot of Steel Mesh-SiC 20PPI at 500mm

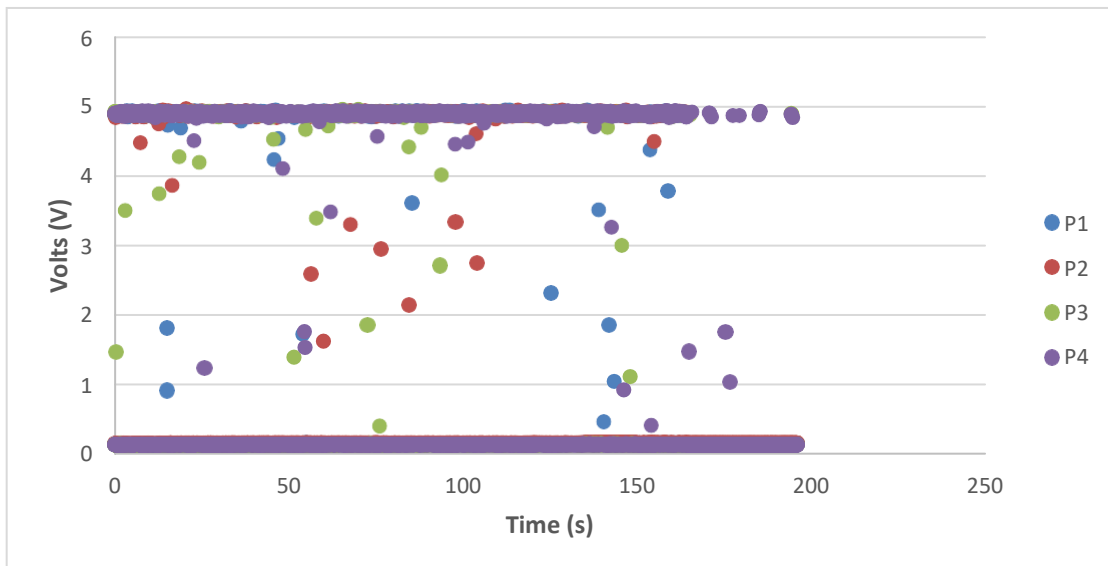


Fig 5.9 Volt vs Time plot of Cordierite-SiC 20PPI at 500mm

5.1.2 Temperature Distribution

5.1.2.1 Gas Temperature

The temperature data was used to study the temperature distribution of the gas inside tube combustor. This is data boosts the concept of the thermoacoustics instabilities and adding to this it was found to be helpful for the verification of the computational simulation of the tube combustor. Data was taken at two location namely GT1 and GT2 located at 500mm and 750mm. From the figure 5.10, 5.11 it can be seen that the gas temperature is high at location GT1 because of the distance from the heat source and the GT2 shows significantly less temperature due increase in the distance.

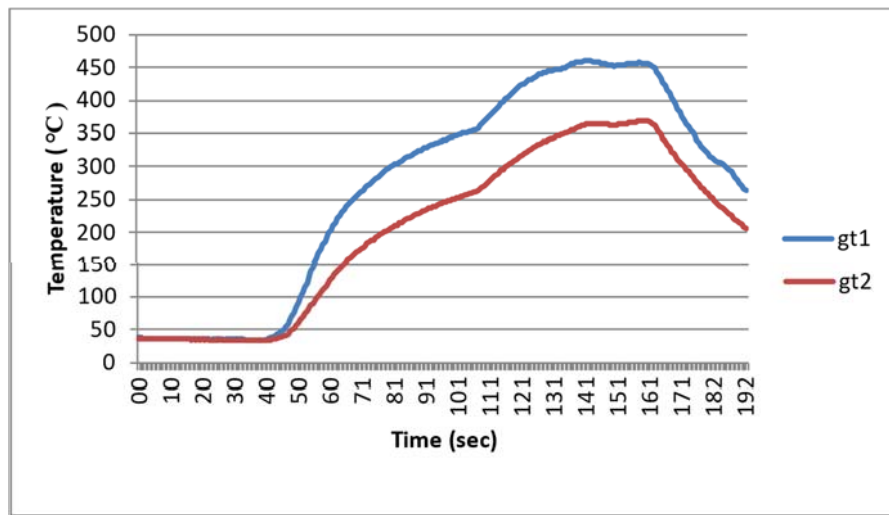


Fig 5.10 Gas temperature plot of only Steel mesh

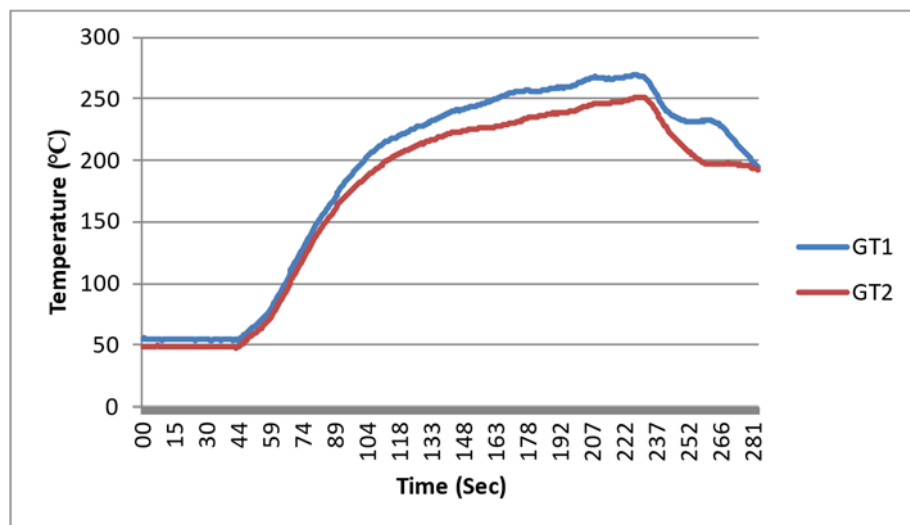


Fig 5.11 Gas temperature plot of only Cordierite Honeycomb

The first graph shows the distribution of the temperature for only steel mesh kept as heat source and it is evident that steel has more thermal conduction as compared to cordierite shown in the second graph. Thus, the maximum temperature that was observed 250C for cordierite where as for steel it was above 450C.

The below data is for the intermediate silicon carbide 20PPI porous plug kept at the height of 500mm from the bottom and keeping the steel mesh and cordierite as the heat source. It is evident that due to the reticulated structure of silicon carbide there is drop in temperature distribution after the 500mm, as the porous plug acts as hinderance for the airflow.

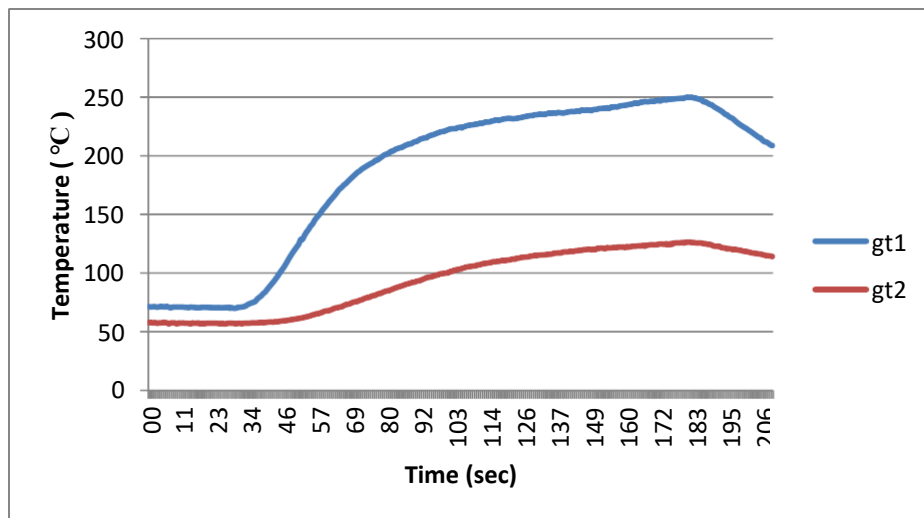


Fig 5.12 Gas temperature plot of Steel mesh-SiC20 PPI

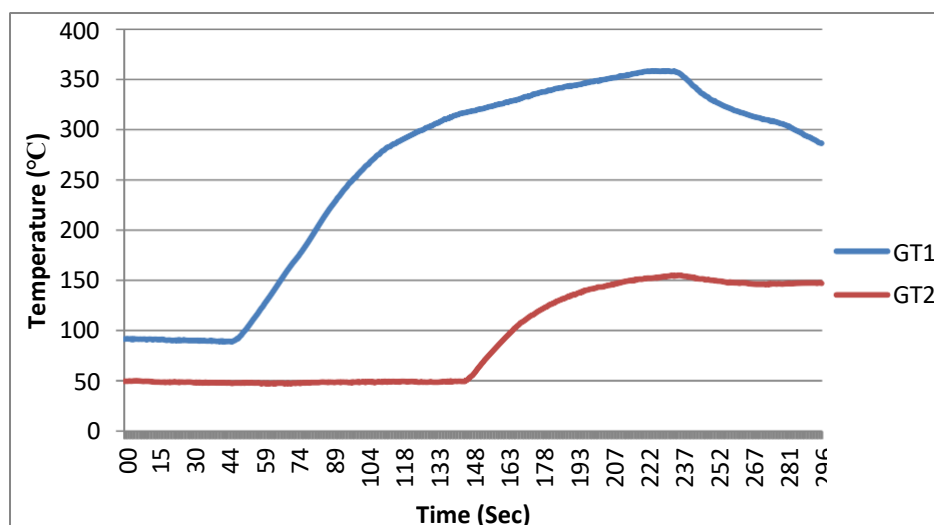


Fig 5.13 Gas temperature plot of Cordierite-SiC20 PPI

5.1.2.2 Wall Temperature:

The temperature variation caused by the porous media outside of the tube can only be investigated by surface wall temperature. Another factor of analysing the wall temperature is to verify whether the temperature has reached steady state. The below data for the steel mesh and cordierite demonstrate that the experiment has reached the steady state. For the following application four washer thermocouples were fastened namely ST1, ST2, ST3, ST4, at height of 100mm, 500mm, 750mm, 900mm.

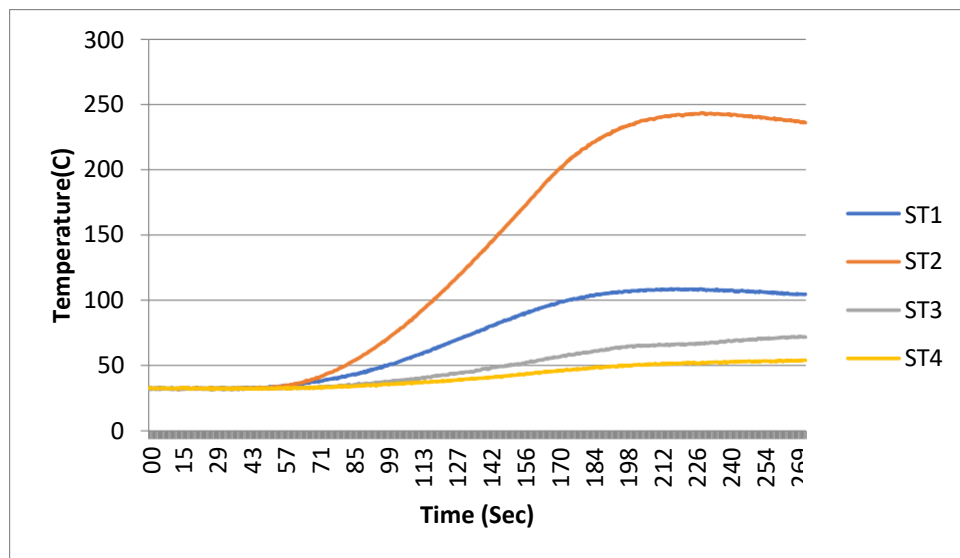


Fig 5.14 Gas temperature plot of only Steel mesh

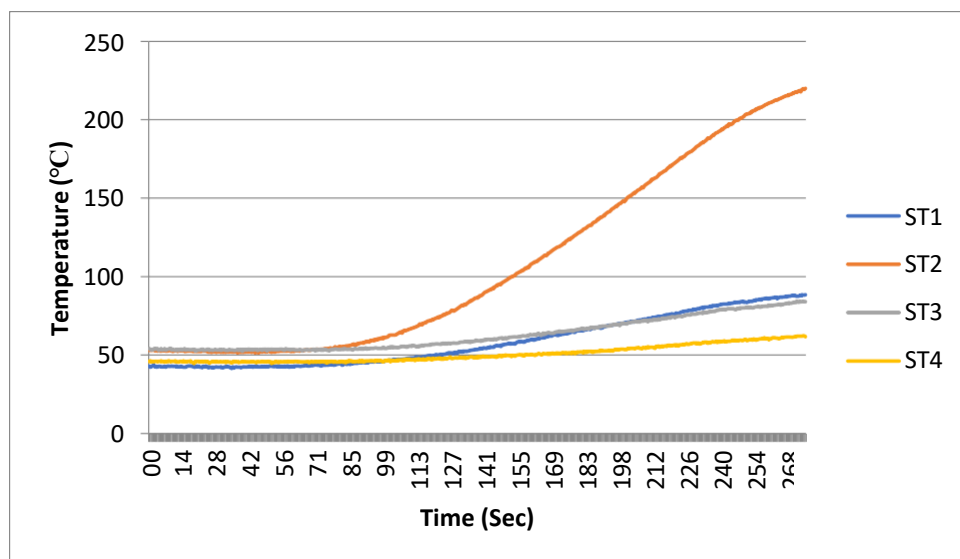


Fig 5.15 Gas temperature plot of only Cordierite Honeycomb

5.2 FLOW AND HEAT TRANSFER PERFORMANCE ANALYSIS

As mentioned earlier the simulation was run with lower order scheme and later with higher order scheme in order to achieve good convergence. The convergence criteria were kept 10^{-6} for all the equations. As shown in the figure below it can be seen the convergence was achieved after 190 iterations even though it was kept for 500 iterations for total duration of calculation.

Two main parameters were analysed from the simulation, that is velocity and temperature distribution of the modelled geometry. From the figure 5.17 velocity distribution is uniform due to change in the density of air inside the tube combustor and the buoyancy force. From the figure 5.18 it can be seen that the temperature is higher at the centre of the heat source. Though flame temperature was not captured during the experiment but from the contour presented below it the temperature distribution can be clearly observed.

The maximum velocity that as observed was 0.1 m/s at the centre of the cross section of the tube and the further decreases at the walls due to friction and wall shear. The flow was observed to be laminar which can be observed from the contours of the velocity vectors and the Reynolds number.

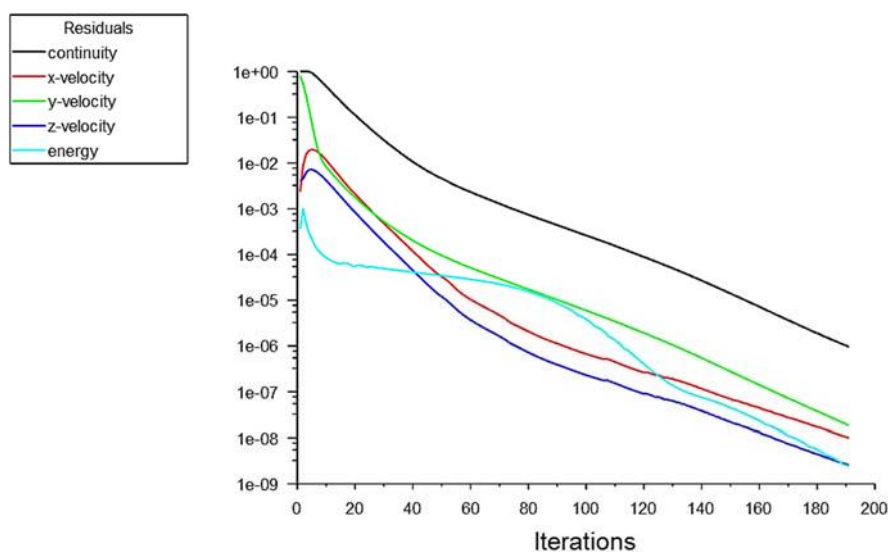


Fig 5.16 Convergence Plot

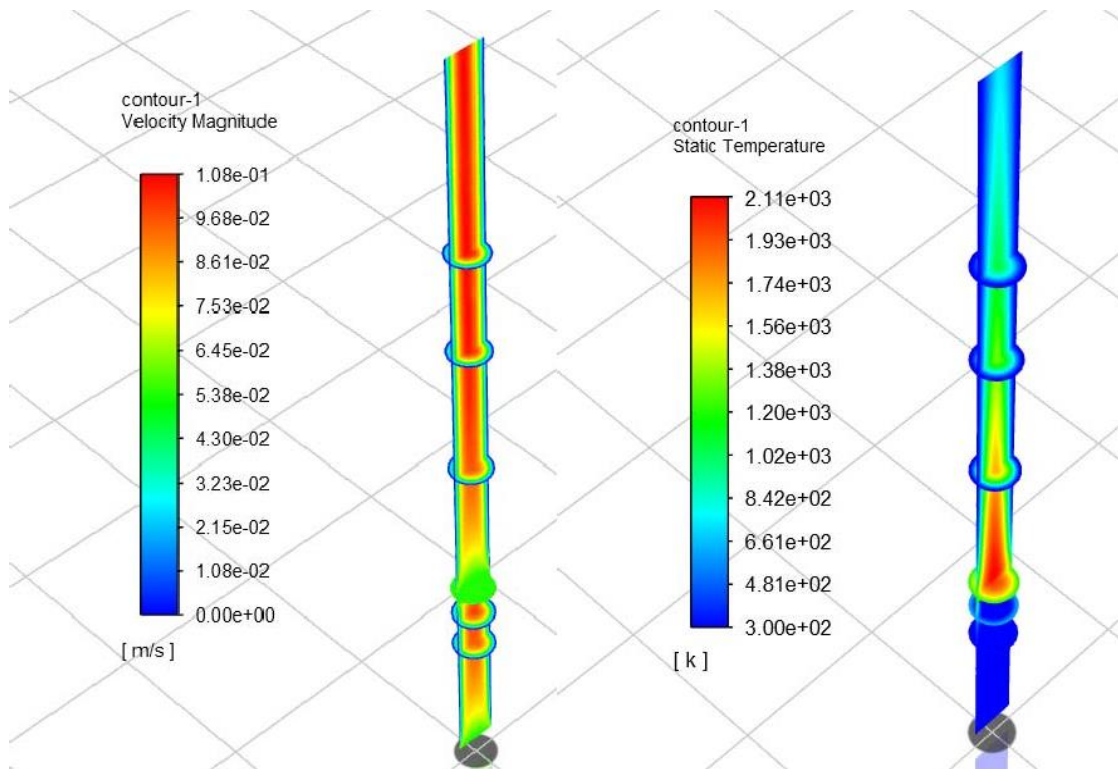


Fig 5.17 Velocity contour

Fig 5.18 Temperature contour

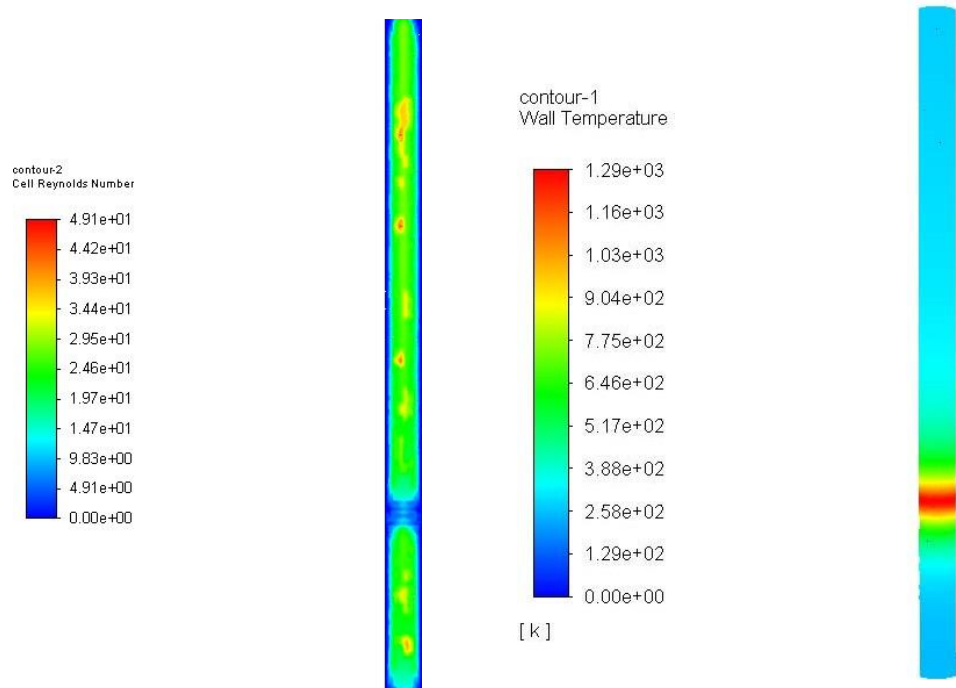


Fig 5.19 Reynolds number contour

Fig 5.20 Wall Temperature contour

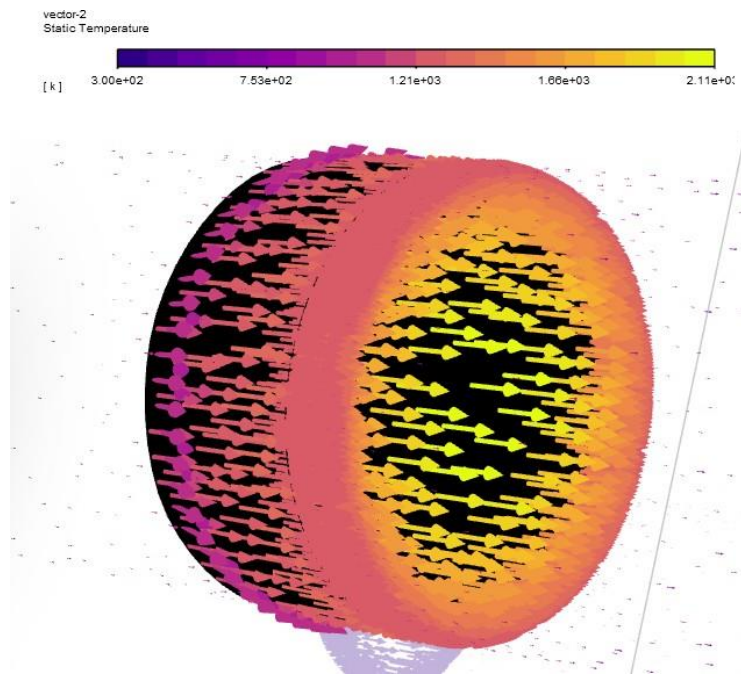


Fig 5.21 Velocity vector w.r.t Temperature gradient at Porous media

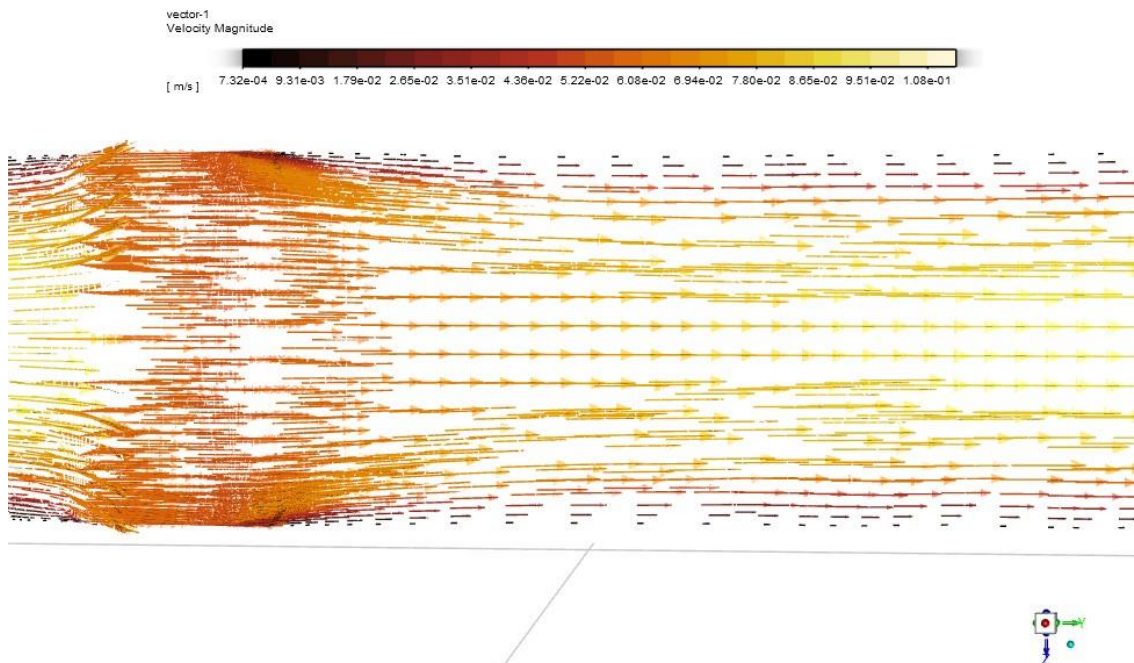


Fig 5.22 Velocity vectors along tube walls

CHAPTER 6

CONCLUSIONS AND FUTURE WORK

From the experiment and the simulation conducted, all the factors that affect the thermoacoustic instability of the Rijke tube combustor was investigated in this thesis. From this we can say that to understand thermoacoustics, Rayleigh's criteria are the firm foundation of this concept. From the study of extensive data of the experimental and computer simulation the suppression of instabilities with the intermediate porous plug was observed.

All the experimental data that was gathered during the work support that porous media can suppress and mitigate the thermoacoustic instabilities inside a jet combustor. It was observed that for oscillation of sound inside the tube combustor enough amount of heat has to be provided to a heat source. Once this was achieved, the next factor to be considered was the material that is used for the heat source. The steel mesh has more conductivity as compared to the Cordierite; thus, the amplitude was higher for a shorter duration of time. In case of Cordierite the thermal conductivity is low thus amplitude is significantly lower as compared steel mesh but the oscillation was produced for longer duration of time. From fixing the intermediate porous plug there was decrease in the flow of air and thus it led to damping of the oscillation. We can further say that the altitude of the intermediate porous plug from the heat source plays a vital role in the suppression of the acoustics. Even further the temperature distribution can be controlled with the help of porous media which adds benefit to the application in jet combustors.

This work has comprised of many factors associated with the thermoacoustic instabilities. This will help other to compare the experiment data with the theoretical calculations. In order to understand the concept of the thermoacoustic instabilities in full scale combustor a thorough understanding is important. We can say that further research can be carried out for mitigation the NO_x and CO_x emissions from jet combustors using porous plugs. Thus, concluding we can say that implementation of the porous media inside combustors can lead to reduction in NO_x and CO_x , low noise emissions, fuel efficiency and increase in structural durability against thermoacoustic instabilities.

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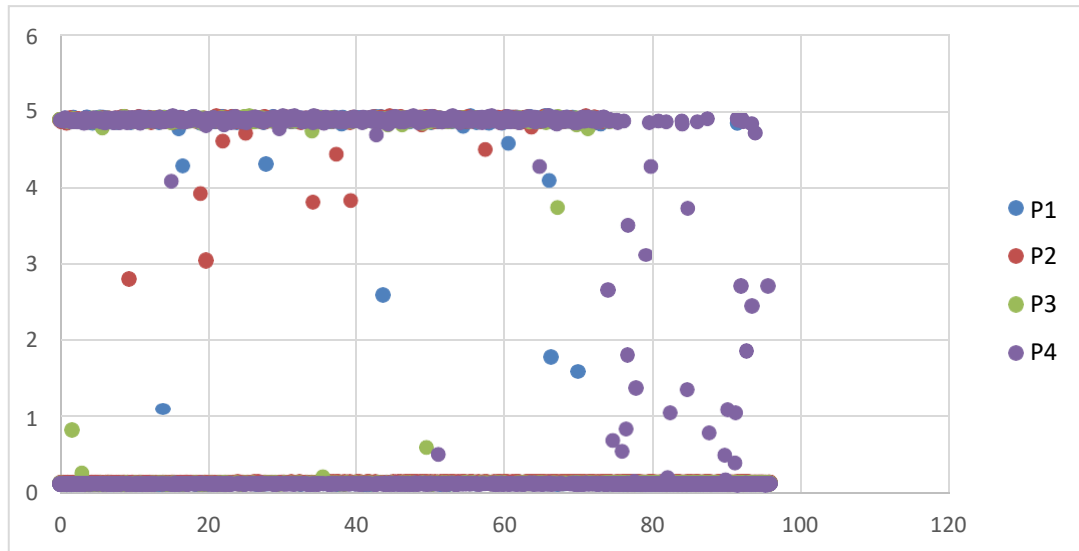
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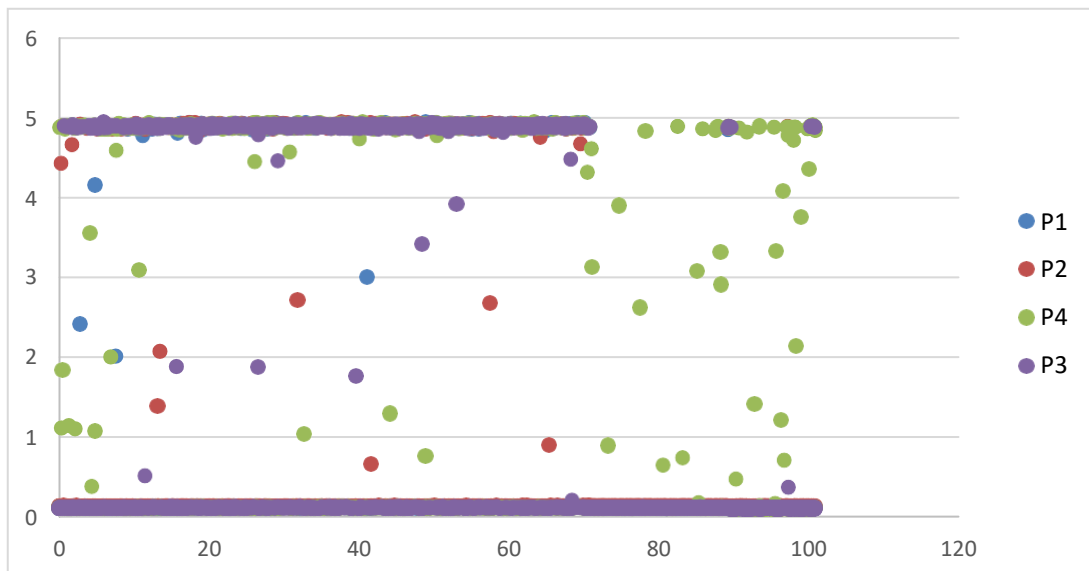
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APPENDIX 1

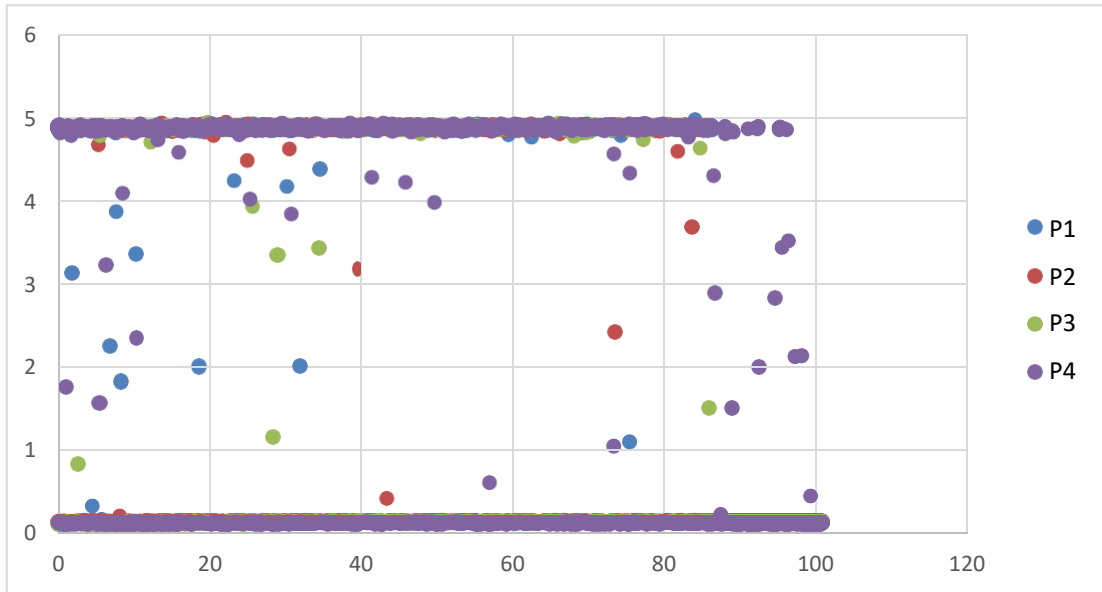
ACOUSTIC RESPONSE



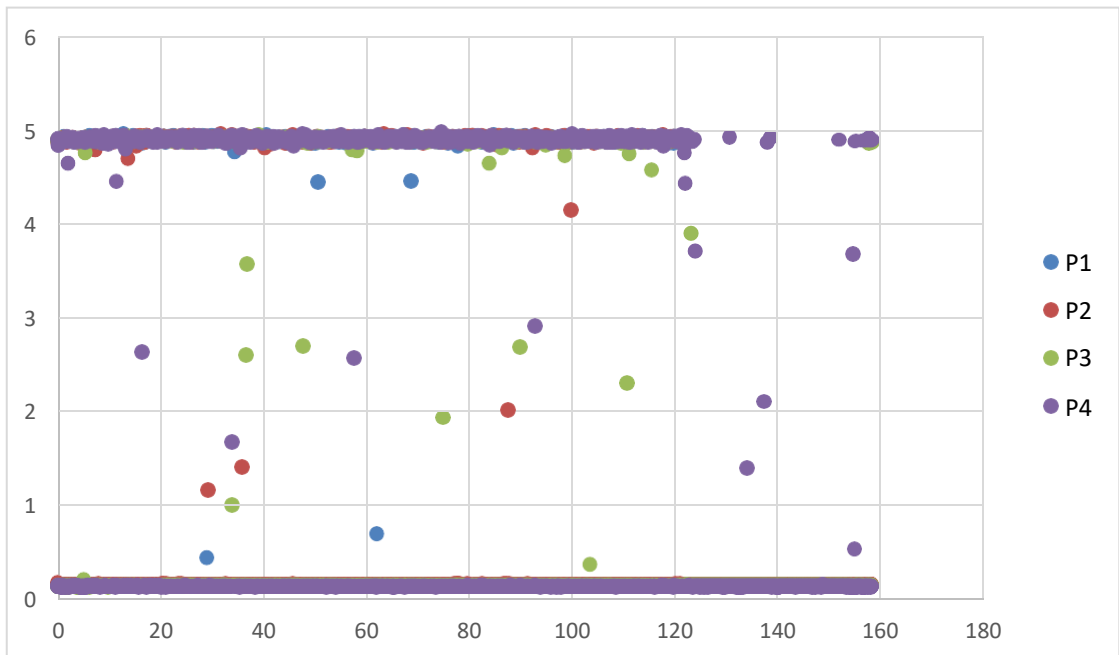
Steel mesh with Sic.20 at 850mm – (Volts vs. Time)



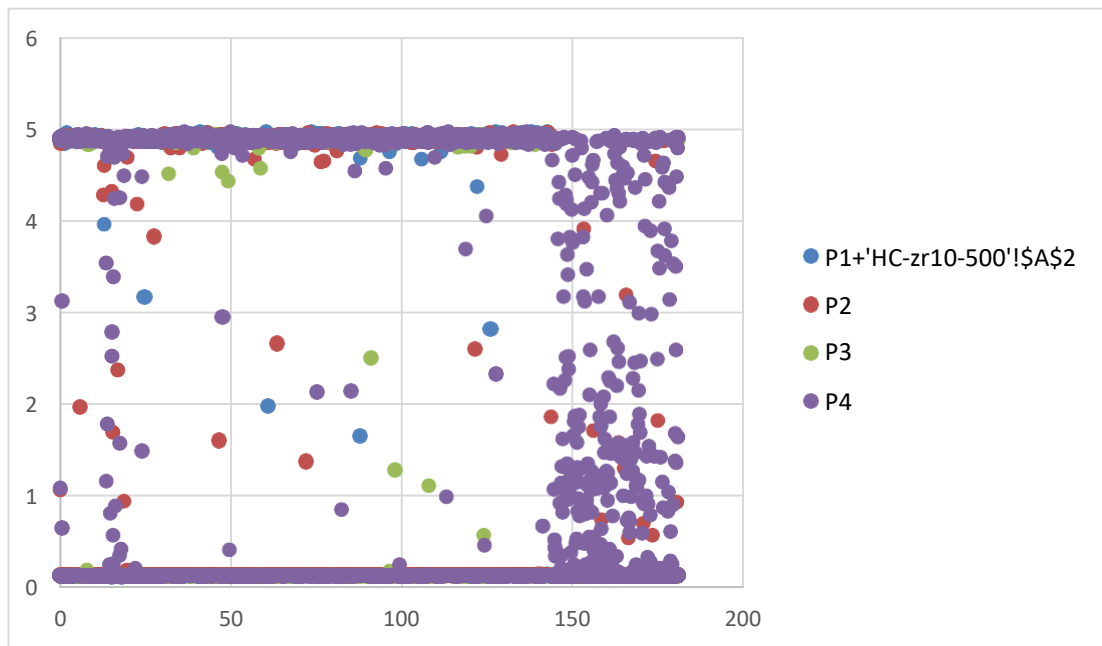
Steel mesh with Zr.10 at 500mm – (Volts vs. Time)



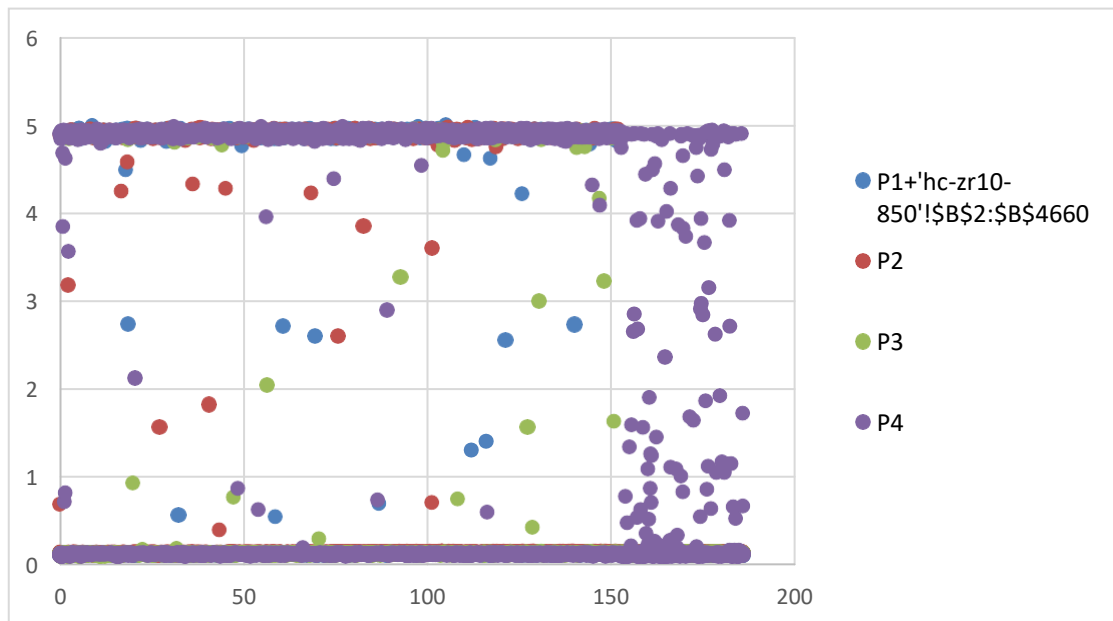
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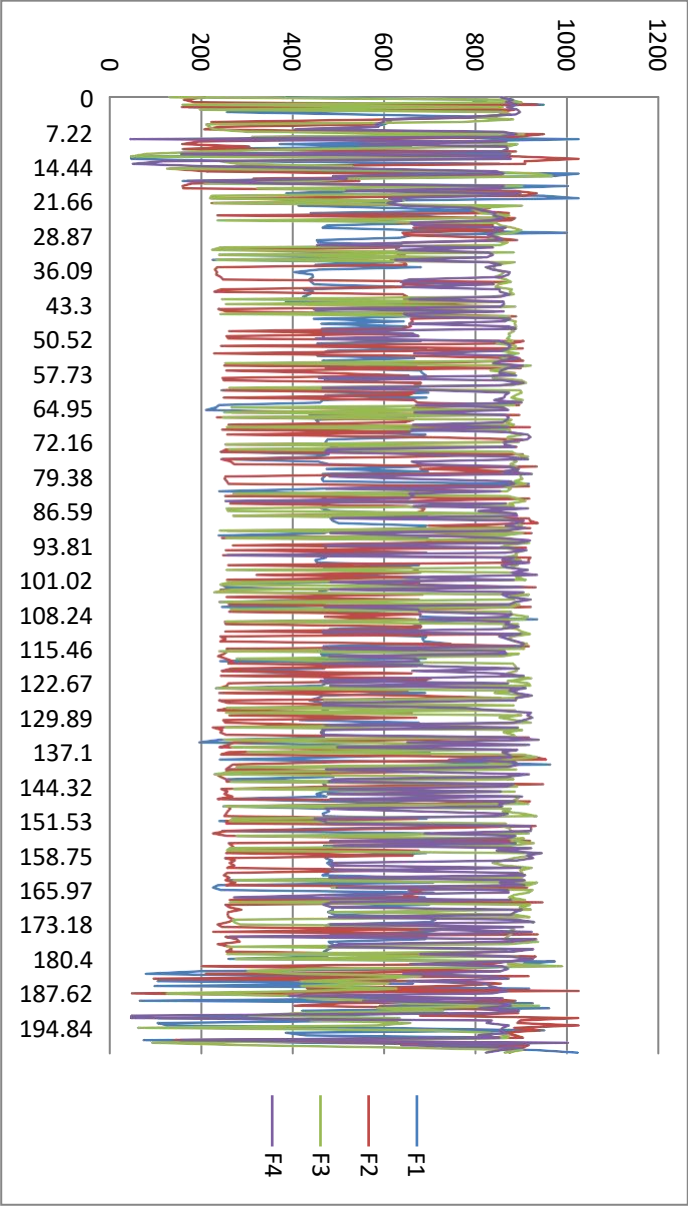
Cordierite Honeycomb with Sic20. at 850mm – (Volts vs. Time)



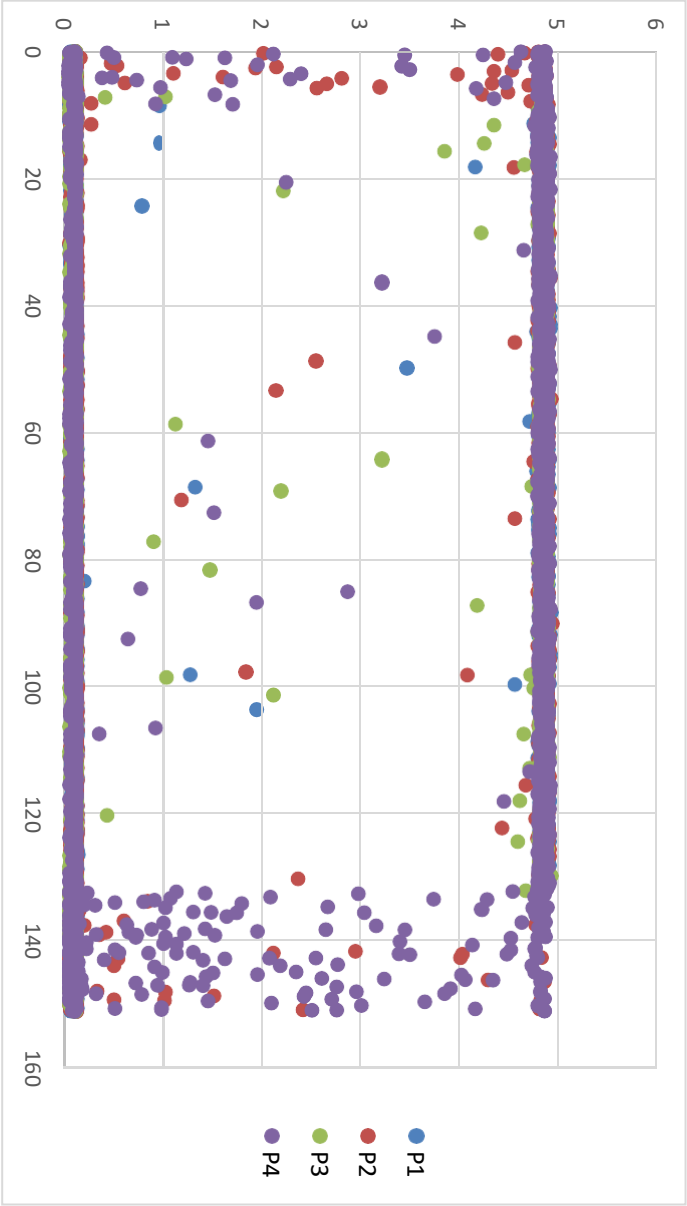
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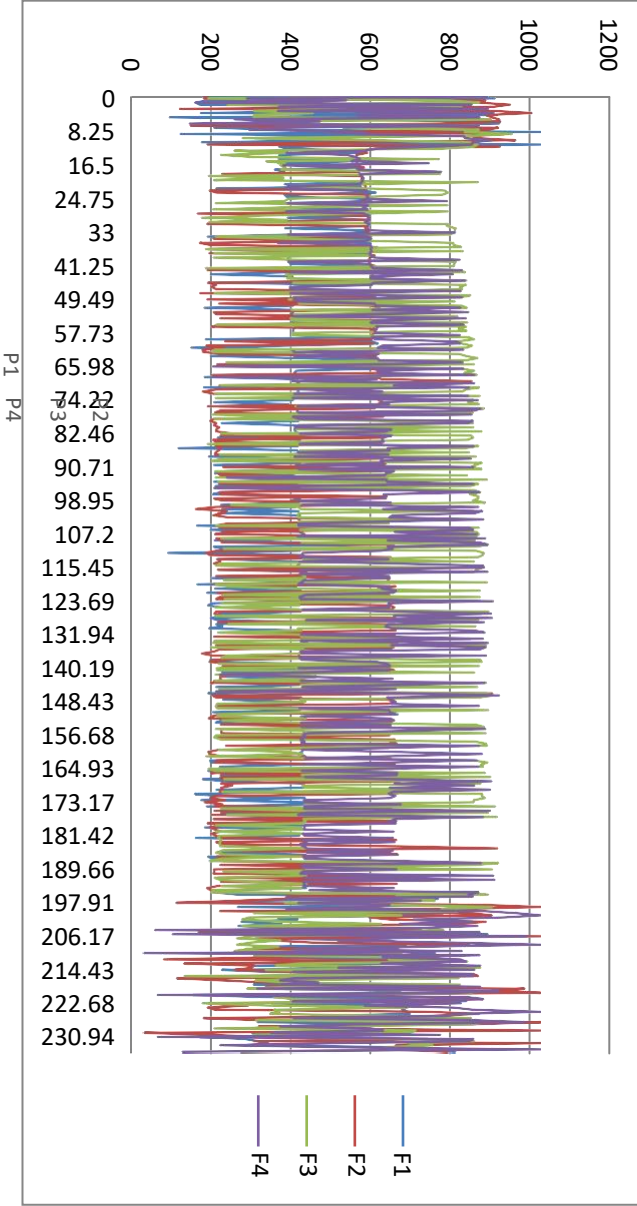
Cordierite Honeycomb with Zr.10 at 850mm – (Volts vs. Time)



Sic.10 – (Frequency vs. Time)

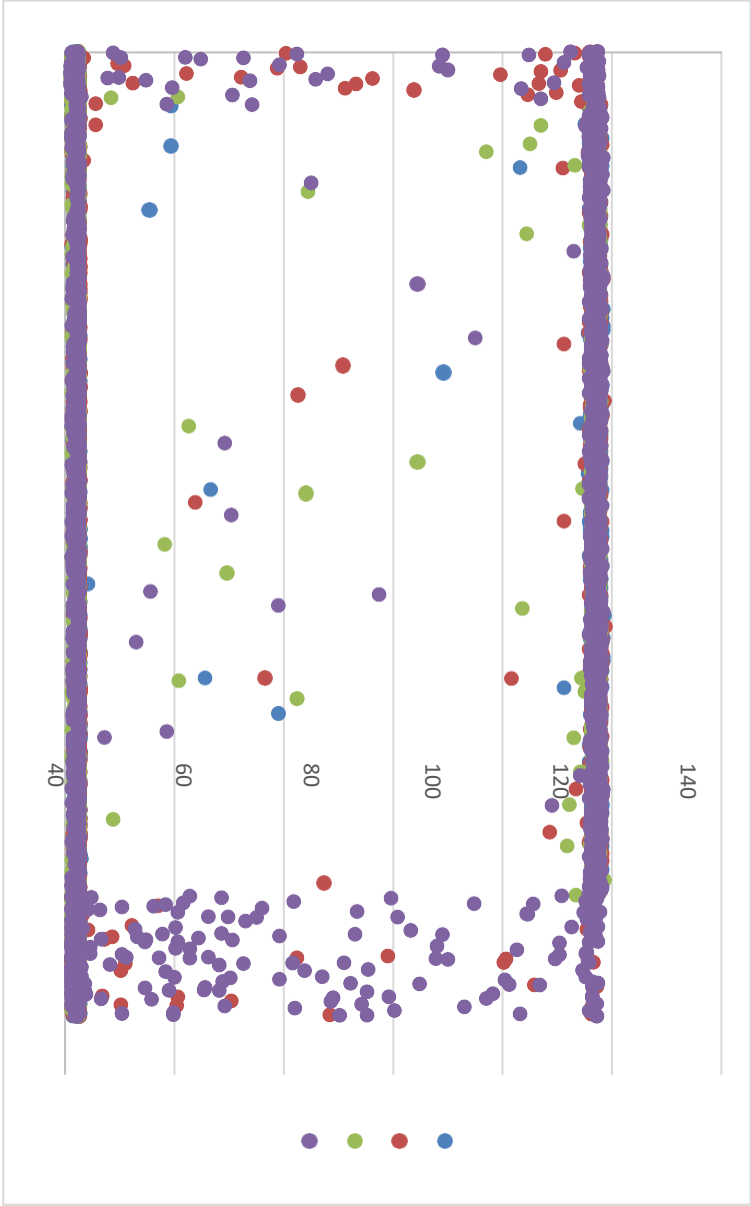


Sic.10 – (Volts vs. Time)



Two Cordierite Honeycomb combined – (Frequency vs. Time)

160

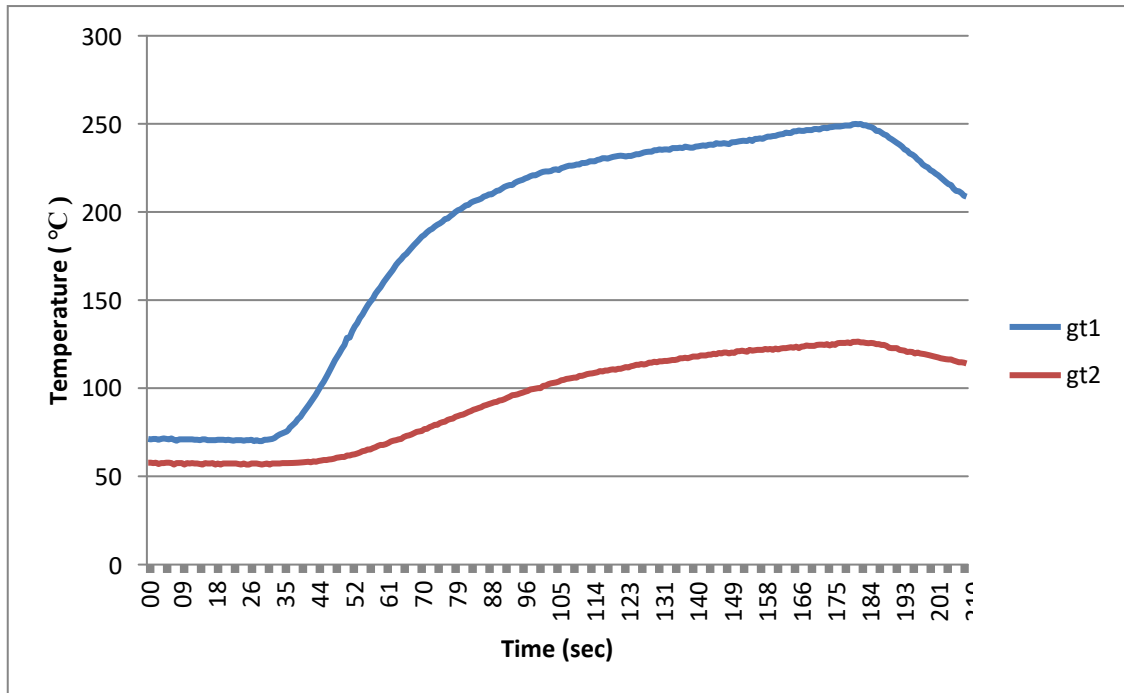


Two Cordierite Honeycomb combined – (Volts vs. Time)

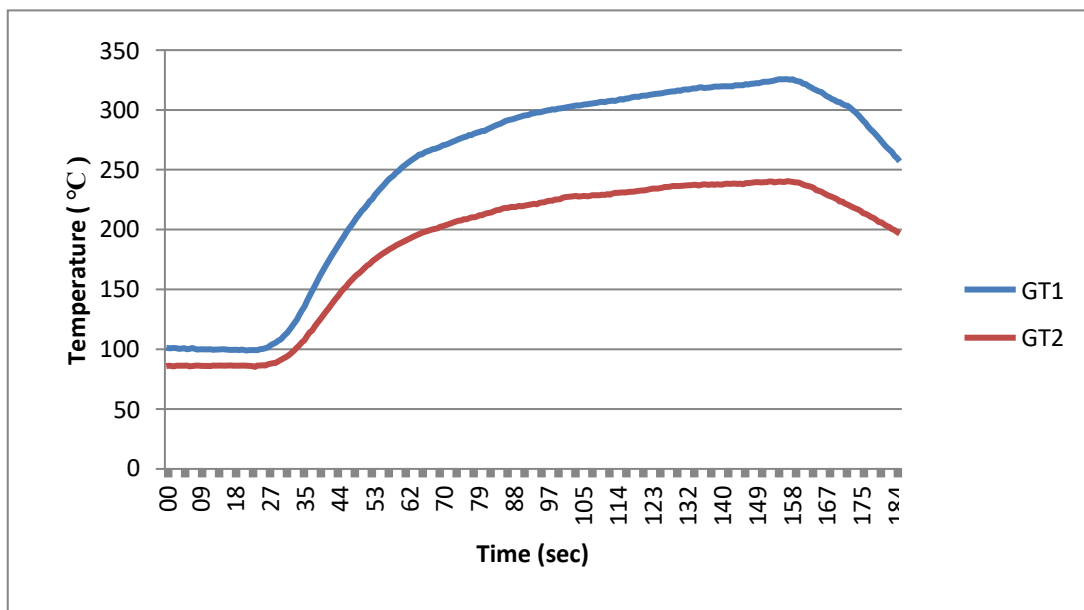
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APPENDIX 2

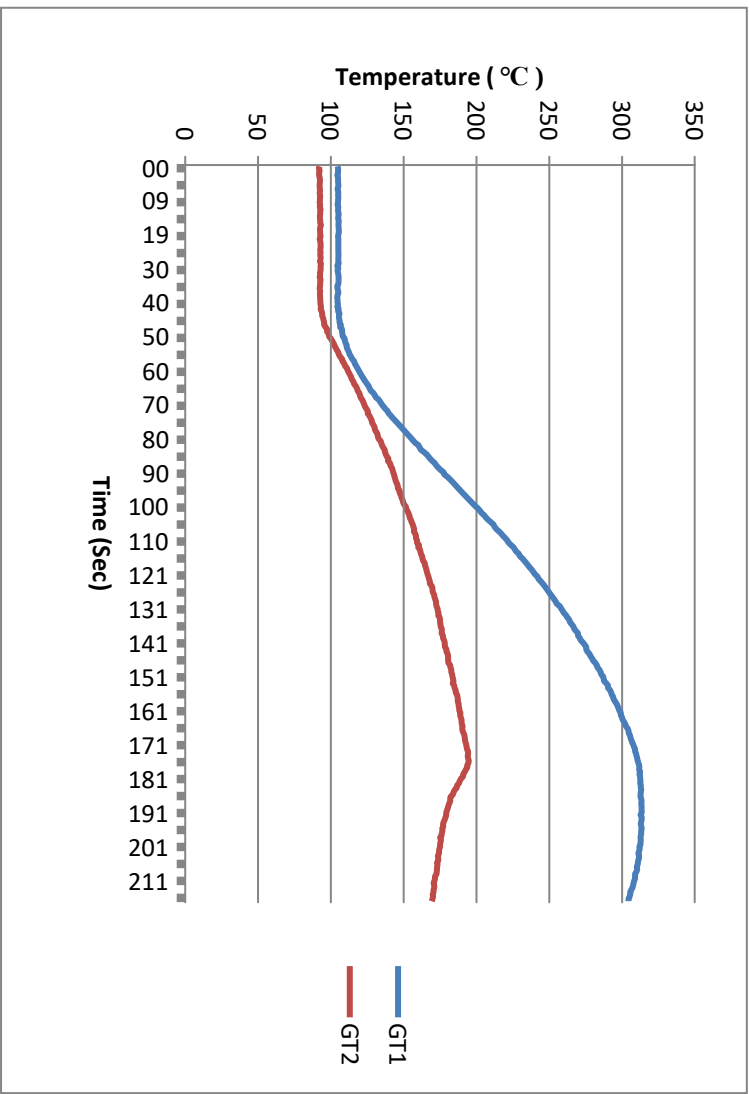
GAS TEMPERATURE DATA



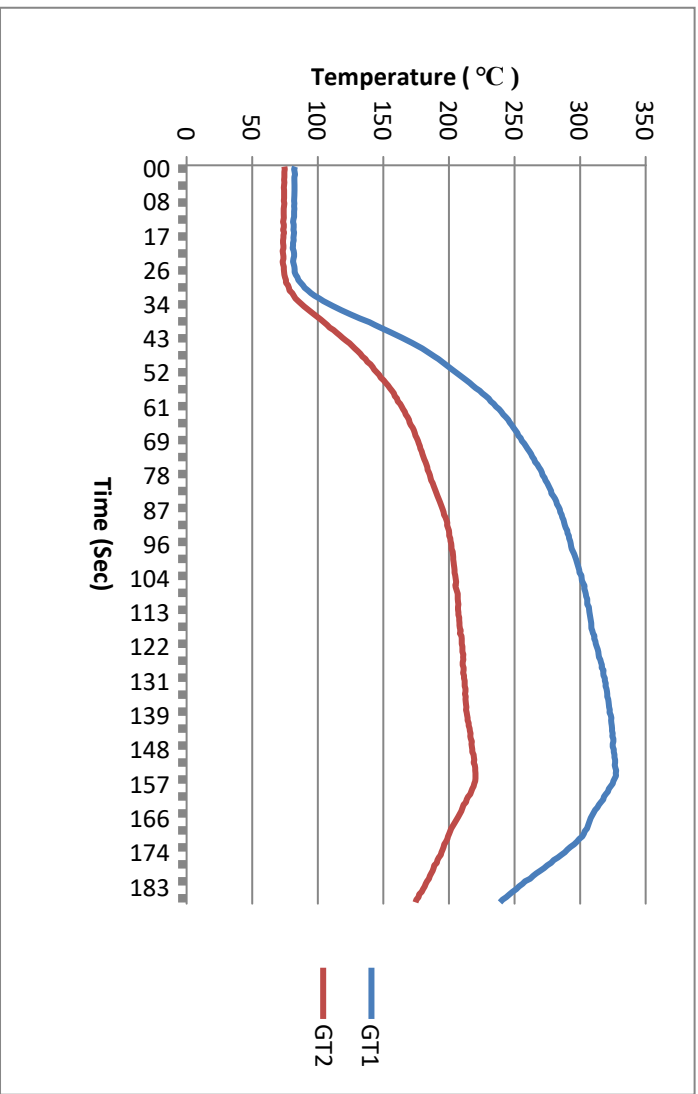
Steel mesh with Sic.20 at 500mm – (Temperature vs. Time)



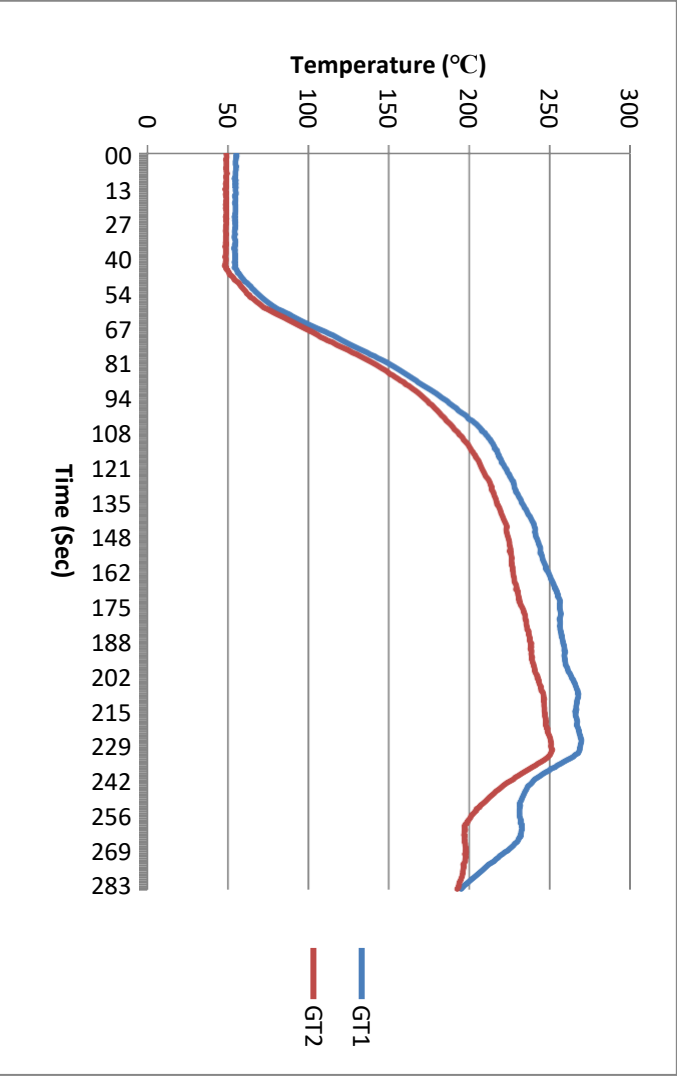
Steel mesh with Sic.20 at 850mm – (Temperature vs. Time)



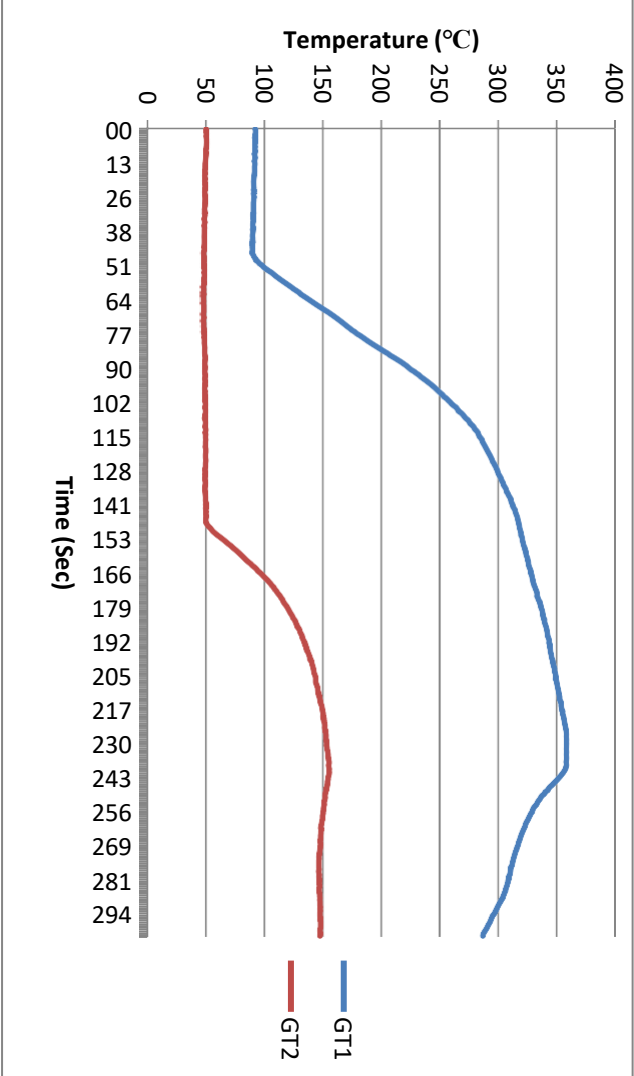
Steel mesh with Zr.10 at 500mm – (Temperature vs. Time)



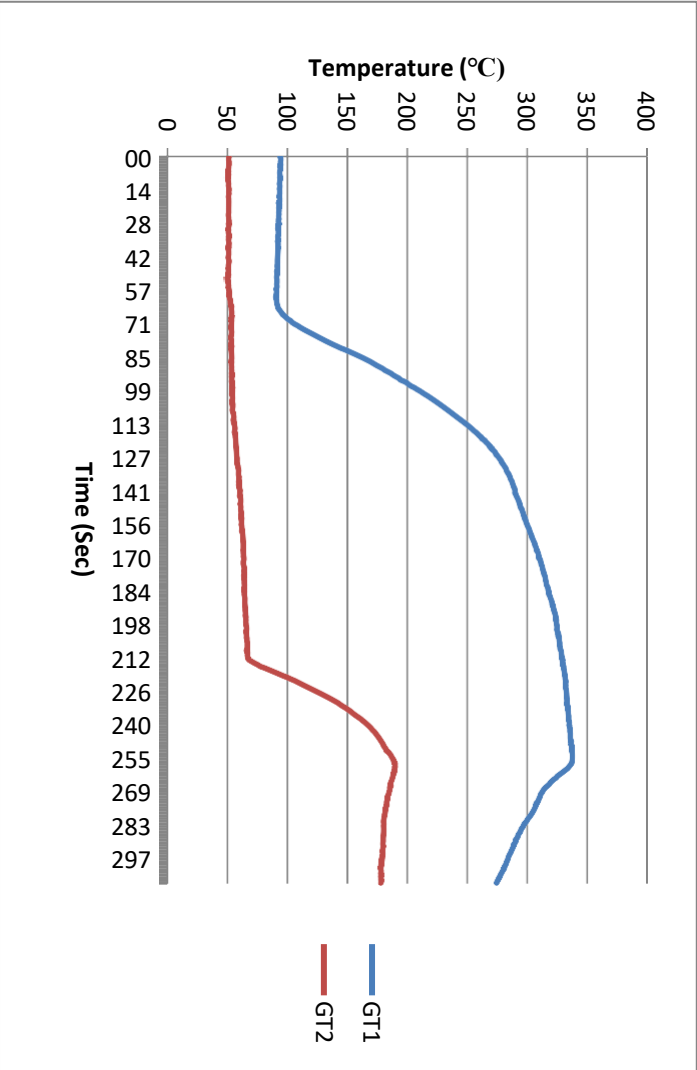
Steel mesh with Zr.10 at 850mm – (Temperature vs. Time)



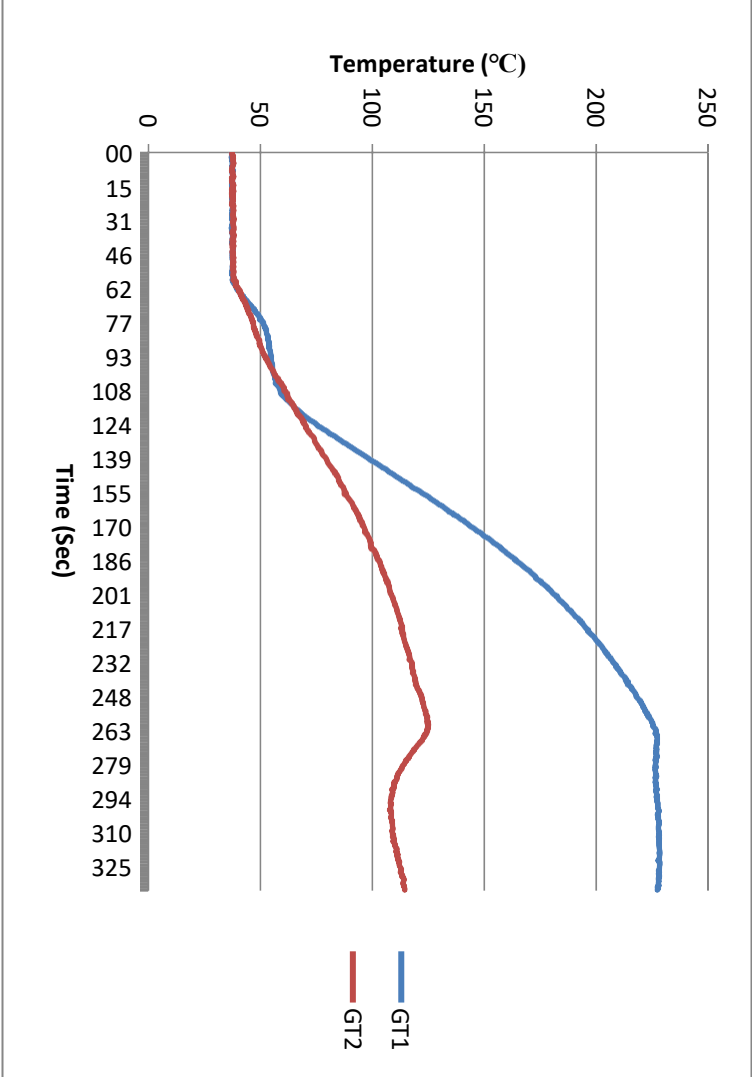
Cordierite Honeycomb – (Temperature vs. Time)



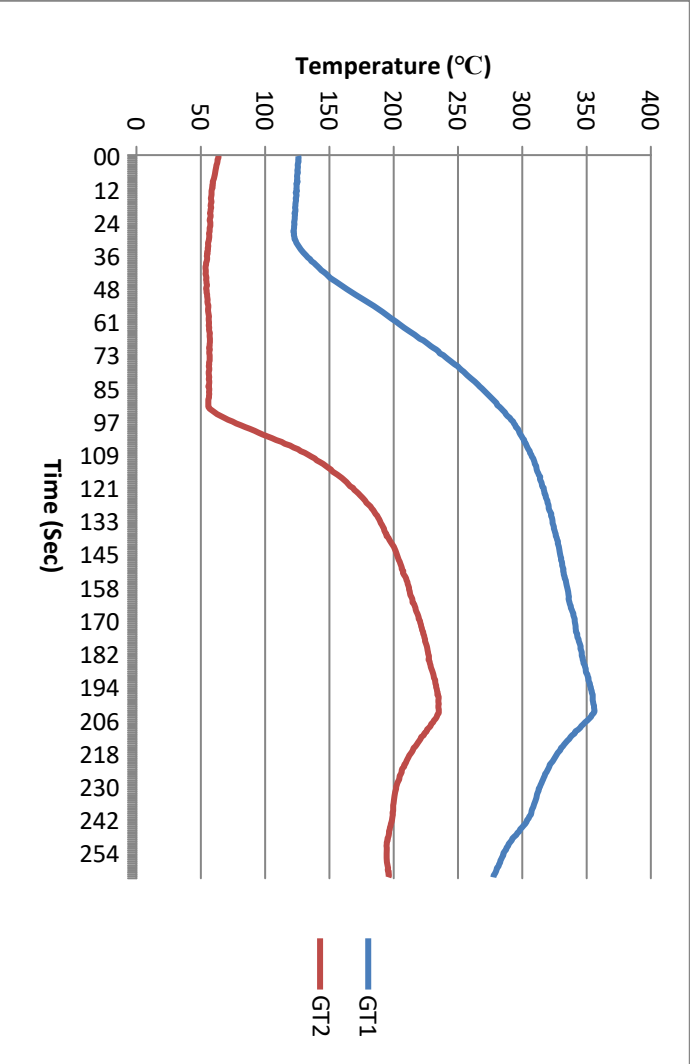
Cordierite Honeycomb with Sic.20 at 500mm – (Temperature vs. Time)



Cordierite Honeycomb with Sic.20 at 850mm – (Temperature vs. Time)



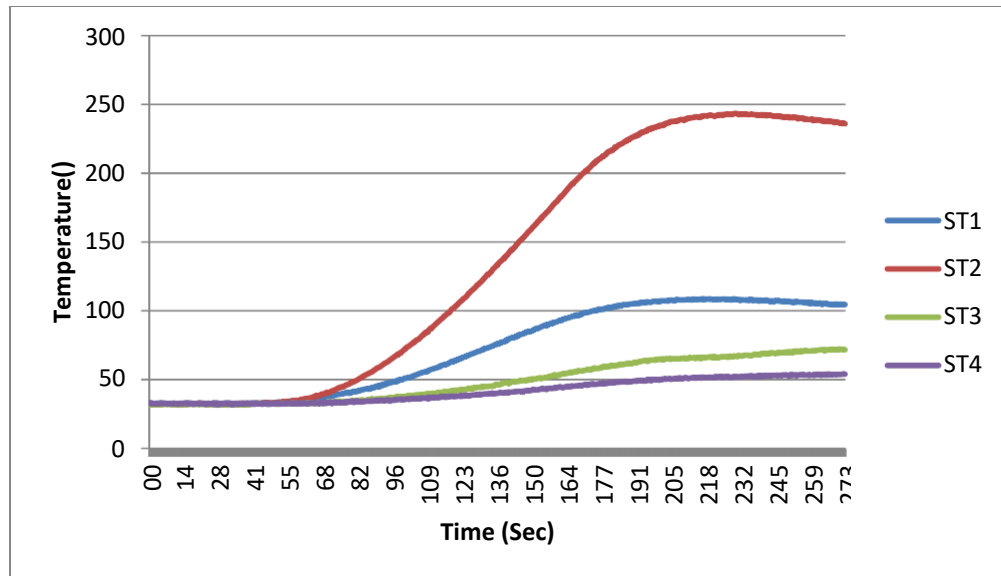
Cordierite Honeycomb with Zr.10 at 500mm – (Temperature vs. Time)



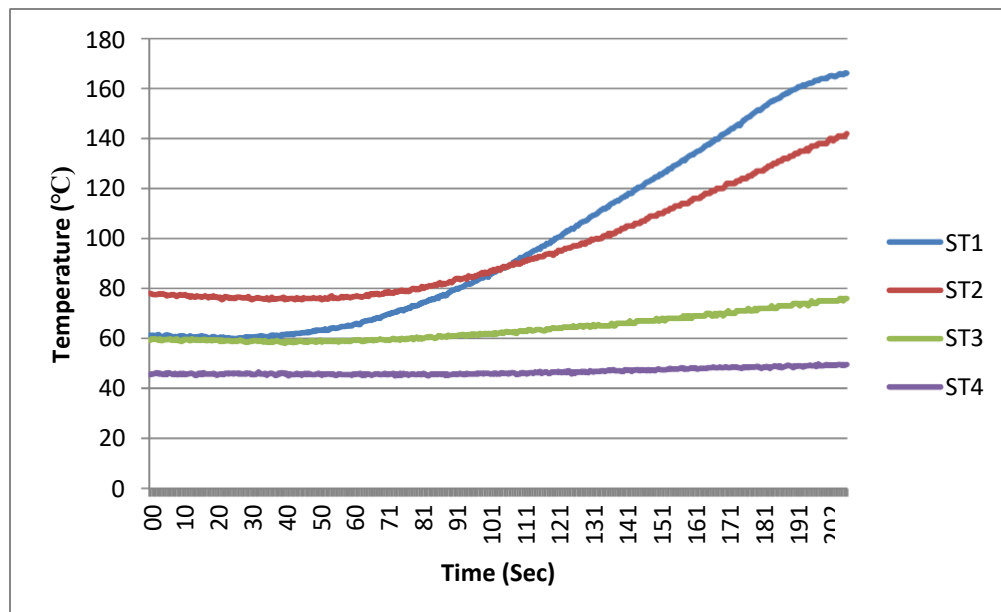
Cordierite Honeycomb with Zr.10 at 850mm – (Temperature vs. Time)

APPENDIX 3

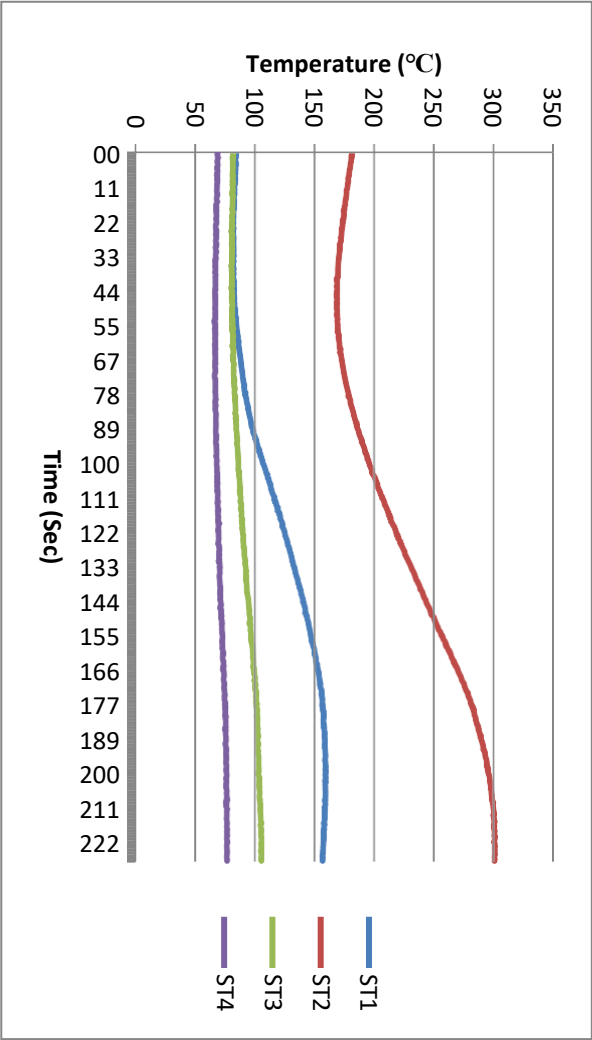
WALL TEMPERATURE DATA



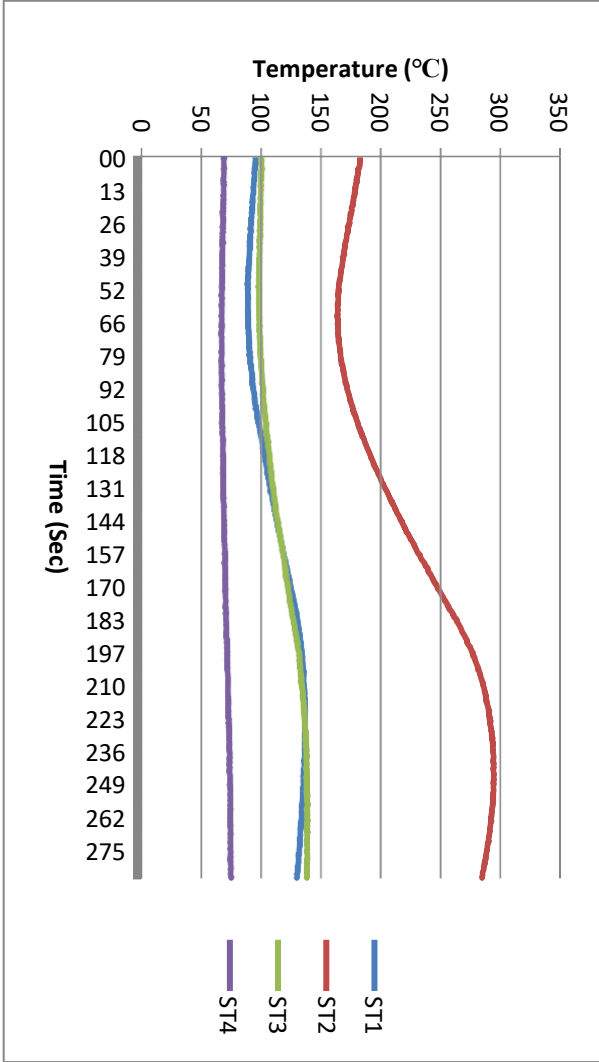
Steel mesh – (Temperature vs. Time)



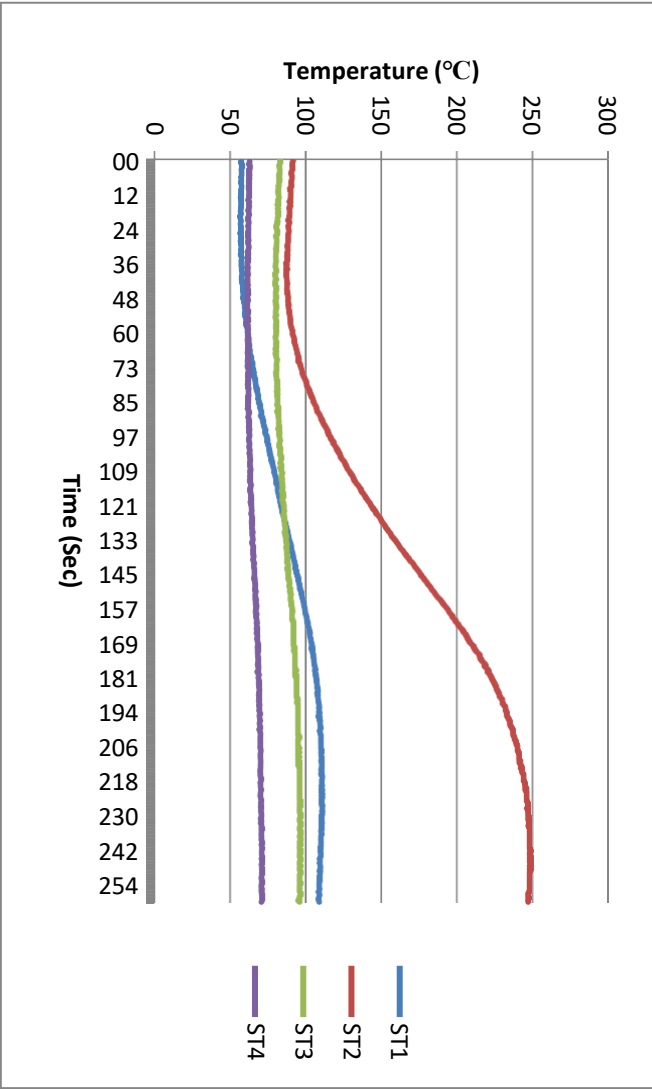
Steel mesh with Sic.20 at 500mm – (Temperature vs. Time)



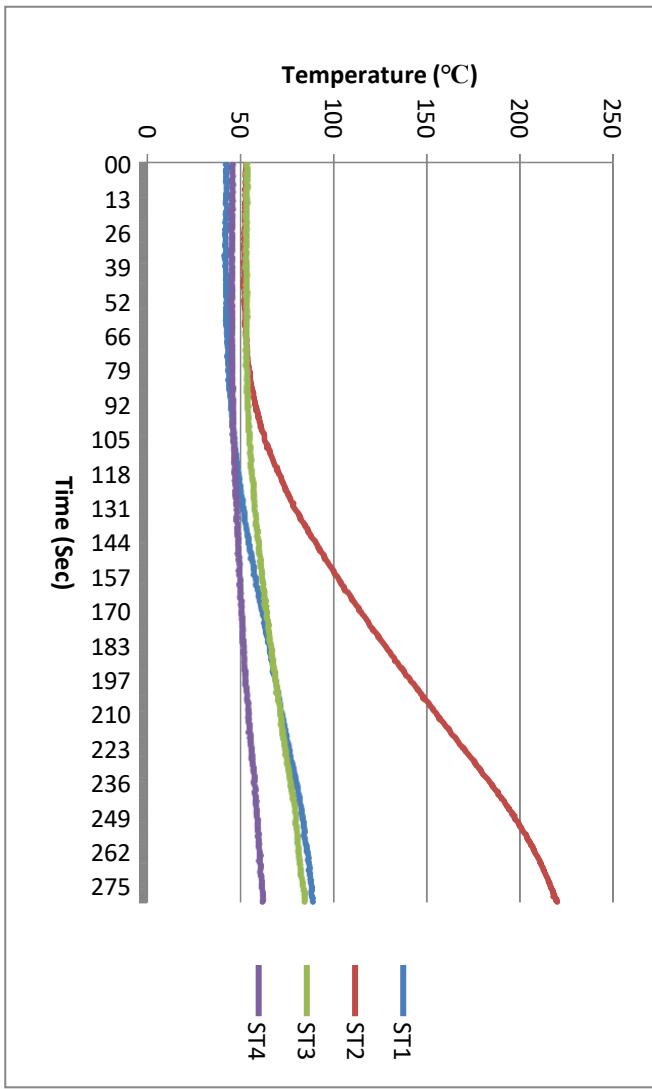
Steel mesh with Sic.20 at 850mm – (Temperature vs. Time)



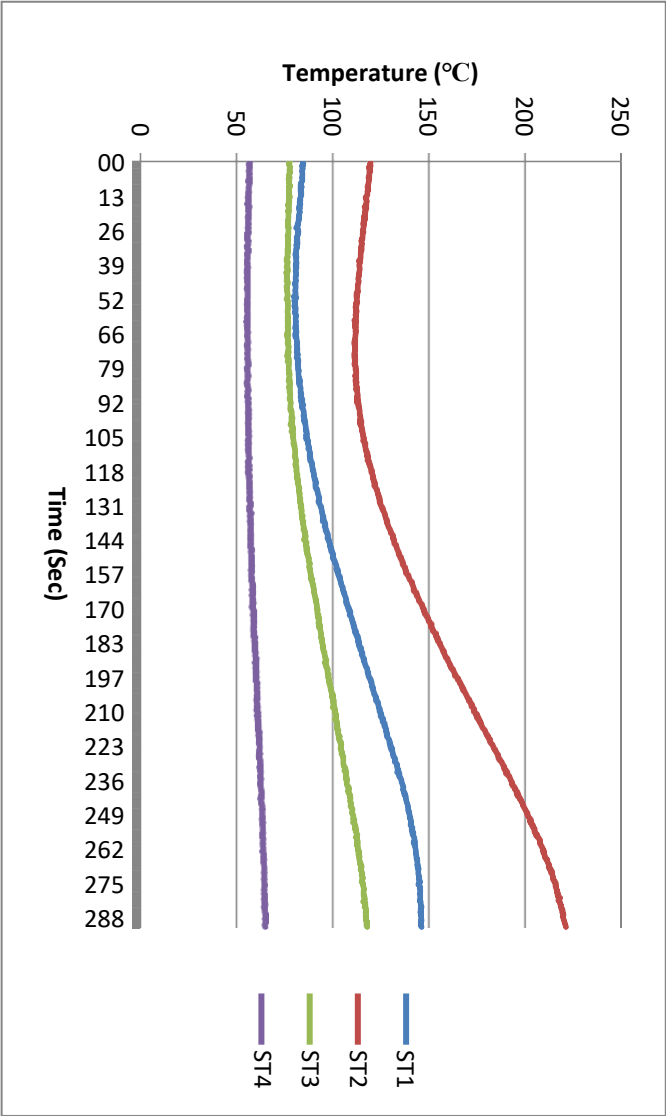
Steel mesh with Zr.10 at 500mm – (Temperature vs. Time)



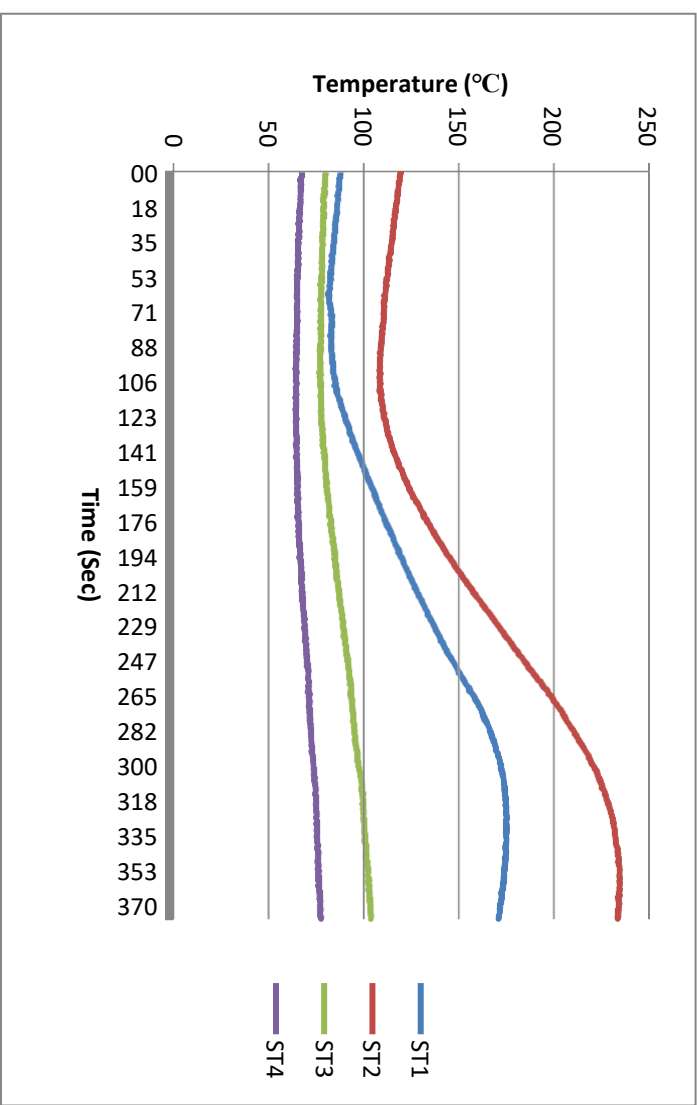
Steel mesh with Zr.10 at 850mm – (Temperature vs. Time)



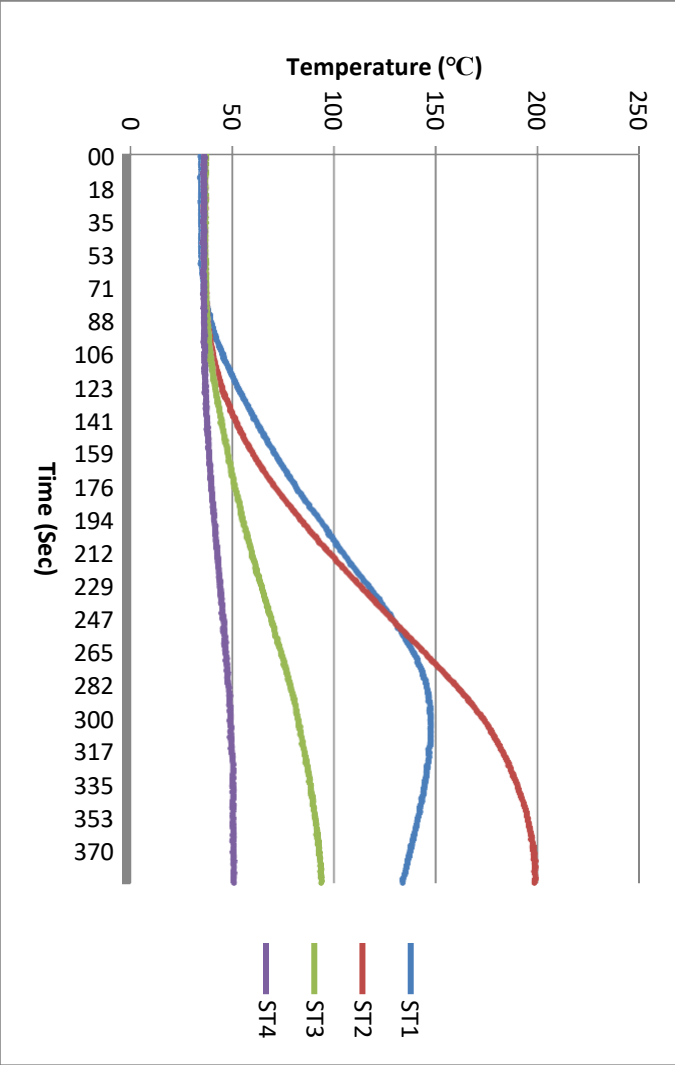
Cordierite Honeycomb – (Temperature vs. Time)



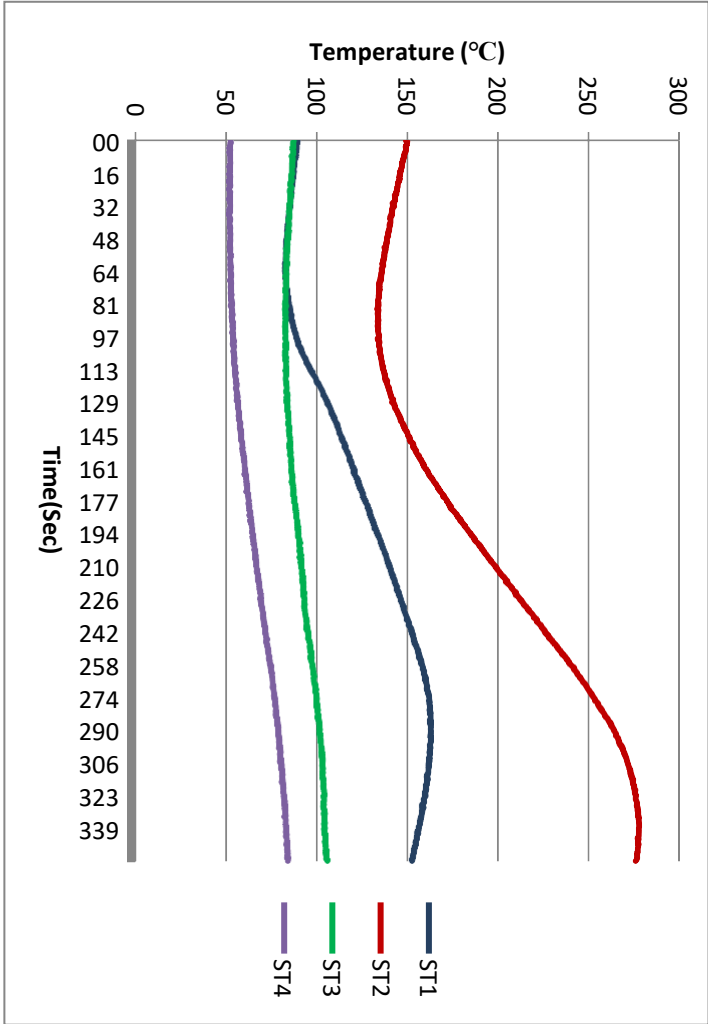
Cordierite Honeycomb with Sic.20 at 500mm – (Temperature vs. Time)



Cordierite Honeycomb with Sic.20 at 850mm – (Temperature vs. Time)



Cordierite Honeycomb with Zr.10 at 500mm – (Temperature vs. Time)



Cordierite Honeycomb with Zr.10 at 850mm – (Temperature vs. Time)