

Concentrating Volumetric Air Receiver Materials: Experimental Determination of Heat Transfer Coefficient

Rohit Polas¹, Nikhilesh Kamane², Dr. Pradyumna Dhamangaonkar³

PG Scholar, Department of Mechanical Engineering, College of Engineering Pune, India^{1,2}

Associate Professor, Department of Mechanical Engineering, College of Engineering Pune, India³

ABSTRACT: Solar concentrating collector of 10 m² area with the use of oxidized copper filament as a volumetric air receiver material which gets disintegrated when temperature reaches above 500 °C. Volumetric air receiver material is porous in nature through which air is sucked through other end so that air gets heated with a sufficient outlet temperature. Aim of this paper is to suggest best suitable packing material, it has been decided to design and fabricate an experimental test setup. Experiments have been conducted to estimate heat transfer performance of different packing materials. Setup is fabricated in three major parts i.e. inlet section, heater section in which material is being tested and outlet section with heat exchanger to reduce temperature of air for the safety of Blower operation. Experiments have been performed with Al₂O₃ (particle diameter 10 mm) and steel balls (particle diameter 4 mm) with various porosity values. Steady state and unsteady state analysis with total period of 15 minutes is performed. In case of unsteady state heat rate and heat gain by air for both materials with respect to time is calculated for period of 15 minutes. For steady state condition heat transfer coefficient has been evaluated for both the materials and compared. Based on the results one material is suggested as a volumetric air receiver material in concentrating collectors.

KEYWORDS: heat transfer coefficient, steady state, unsteady state, volumetric air receiver.

I. INTRODUCTION

Solar energy collectors are special kind of heat exchangers that transform solar radiation energy to internal energy of the transport medium. The major component of any solar system is the solar collector. This is a device which absorbs the incoming solar radiation, converts it into heat, and transfers this heat to a fluid (usually air, water, or oil) flowing through the collector. The solar energy thus collected is carried from the circulating fluid either directly to the hot water or space conditioning equipment or to a thermal energy storage tank from which can be drawn for use at night or cloudy days. In concentrating type a parabolic dish reflector the receiver absorbs the radiant solar energy, converting it into thermal energy in a circulating fluid. This thermal energy fluid can be used for domestic and industrial purpose. Parabolic dish systems can achieve temperatures in excess of 1500 °C. Because the receivers are distributed throughout a collector field, like parabolic troughs, parabolic dishes are often called distributed receiver systems.

The porous material inside this receiver absorbs the highly concentrated solar irradiation by radiation and then heat is transferred inside this material by conduction. Air is then passes through this receiver as the air gets enough time inside this receiver due to the resistance offered by the porous material against the air flow air gets heated. Heat is transferred from porous material to air by convection. The heated air which is coming out of this receiver is then passes through shell and tube type of heat exchanger. In this heat exchanger air passes through shell side and the cold fluid which is water in this case is passes through tubes. The tubes are arranged inside this heat exchanger in such a manner that water should remain inside this heat exchanger for longer duration for effective exchange of heat between air and water i.e. the number of passes of water through the tubes has been increased. The main purpose of this heat exchanger is to determine the quantity of heat given by air to water. A blower is attached at the outlet of this heat exchanger which sucks the air through the porous material and maintains the flow rate of air in the entire setup. The mass flow rate of air

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 5, May 2016

inside this setup is controlled by varying the speed of the blower thus the heat transfer performance can be checked with different mass flow rate of air.

II. LITERATURE SURVEY

Ja Hyun Cho *et al.* [1] has studied characteristics of heat transfer and pressure loss of fills for solar volumetric air receivers by experimental investigation. Volumetric air receiver considered which consists of a ceramic tube and fills inserted in the ceramic tube. Two materials, which are honeycomb (diameter: 100 mm, thickness: 300 mm) and laminated mesh (diameter: 100 mm, thickness: 1 mm), are considered as the fills. This receiver is heated by an electric heater. The inner air temperatures of the ceramic tube are measured by thermocouples, which are installed at each layer of the ceramic tube. After the experiments it has been found that the air outlet temperature increases to 190 °C to 340 °C while the surface temperature of the porous material increases to 320 °C to 370 °C. That is, the air temperature becomes closer to the porous material temperature as the Power on Aperture increases. The efficiency of the mesh is 3% to 4% higher than that of the honeycomb the pressure loss of the honeycomb is greater than that of the mesh. Also, the result shows that the pressure loss increases linearly as the Reynolds number and the fills thickness increases. Based on these results, the mesh is more suitable than the honeycomb as the fills of the volumetric air receiver because the mesh has the high efficiency and the low pressure loss.

G. shrinivasa rao *et al.* [2] has developed experimental test rig for packed bed to determine the heat transfer of a packed bed system with Schumann Model. It is assumed that the temperature of the bed is uniform. Variation of heat transfer coefficient with non dimensional axial distance along the bed length at 400 °C for minimum and maximum flow rates for water and nano fluid at two different concentrations for the two particles. The heat transfer coefficient increase with increasing flow rate and concentration of the nano fluid. Variation of heat transfer coefficient for 6mm, 14.56 mm particles for different operating conditions such as for flow rate of 150 litres per hour at 400 °C for water and nano fluids at different concentration, the heat transfer coefficient increased with decreasing particle diameter. At higher flow rates and temperatures, the heat transfer coefficient is greater, for 6mm compared to 14.56 mm particle size. The heat transfer coefficient is higher with 6mm particles due to larger surface area and the number of particles. Similarly, the heat transfer coefficient is greater at higher concentrations of the nano fluid. With an increase in volume concentration, the heat transfer is more and increases with the flow rate and inlet fluid temperature. The enhancement in heat transfer coefficient with nano fluids than base fluid lies between 10 to 15% due to higher values of thermal conductivity. The values from Schumann model agree with the experimental data for the two bead sizes of 6.0 and 14.56mm. The deviation between the two is less than 10%.

Pei Xue Jiang *et al.* [3] has developed experimental test setup to investigate the heat transfer between solid particles and the fluid in a mini porous media. The test section contained a sintered bronze porous media with an average particle diameter of 0.2 mm. The particle-to-fluid heat transfer coefficients were calculated from the experimental data using the lumped capacitance method and a one-dimensional numerical analysis of the experimental data. In the experiments, the mini porous media solid matrix experienced a sudden change in its thermal environment. The essence of the lumped capacitance method is the assumption that the temperature of the solid is spatially uniform at any instant during the transient process. This assumption implies that temperature gradients within the solid are negligible compared to the temperature gradients in the fluid. Since the particle diameter of the mini porous test section is very small and the conductivity of the bronze particle is quite large, the thermal resistance within the particle is small compared with the thermal resistance between the particle and its surroundings, therefore, the lumped capacitance method can be used to calculate the particle-to-fluid heat transfer coefficient. The transient temperature response was determined by formulating an overall energy balance on the solid. The test section thickness and the variation of solid temperature along the flow direction are very small. The experimental Biot number was 0.0001; therefore, the lumped capacitance method was appropriate. The final particle-to-fluid heat transfer coefficient calculated from above equation was $h = 12.16\text{W/m}^2\text{K}$.

Laith Jaafer Habeeb *et al.* [4] presents an experimental study of free and forced convection heat transfer for three dimensional laminar steady flows in a cubic space manufactured from glass with dimensions (30cm×30cm×30cm)

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 5, May 2016

filled with saturated porous medium. Plastic balls porous media is used with homogeneous in diameter (11.7mm). The lower wall is heated by an electrical heater; the other walls are thermally isolated. Two vents were made at the two vertical opposite walls, one for inlet and the other for outlet of air with equal dimensions (6cm×6cm). Also a square section cavity was manufactured with dimensions (6cm×6cm) and (70 cm) length made of transparent plastic for air entering. The experimental work is included the study of porous medium effect on forced convection heat transfer with selected values of heat flux and for Reynolds number ranges $17.45 \leq Re \leq 22.13$ for every heat flux (q_w) with $41.52 \leq Nu \leq 82.85$. The results show that the average Nusselt number increases with the increase of Reynolds Number and decreases with the high increase of heat flux.

III. OBJECTIVE OF WORK

Currently packing material in the existing setup is oxidized copper filament which gets disintegrated at 500°C, so the main objective of this work is to suggest best suitable material which can be used at higher temperatures. It must also be equipped with high heat transfer performance which indirectly depends upon heat transfer coefficient, surface area of material in contact with air, packing density of material, thermo-physical properties of material with more importance to heat transfer coefficient. It has been decided to design and fabricate an experimental test setup with a proper arrangement for filling of material inside test section. Test section is heated to desired temperature and air will be flown through test section filled with material. Heat performance of different packing materials in spherical form such as Al_2O_3 and steel balls for steady state condition is evaluated based on heat transfer coefficient, outlet fluid temperature, pressure drop of air across material. In unsteady state condition variation of heat gain by air, heat rate of material with respect to time has been studied and comparative analysis is performed. Based on results obtained one material is suggested which can be used as volumetric receiver material in concentrating type of collectors.

IV. DESIGN OF TEST SETUP

To estimate heat performance of different packing materials it is necessary to design setup as per our application need, setup has been divided in three sections such as inlet section, heater section and outlet section in the form of circular pipe. These sections are interconnected to each other with the help of flange and bolt arrangement. Centrifugal bower is fitted at the end of outlet section which is creating suction to establish flow. Purpose of inlet section is to establish flow which can be passed through each pores of packing material, and to reduce heat loss from heater test section. Heater section is provided with proper insulation material in order to reduce heat transfer to atmosphere. Coils are wounded on ceramic tube with equal spacing so that heat distribution per unit length of the heater section is equal, also packing material will also get uniform heating. Outlet section with blower is for measurement of temperature fluid coming out of heater. Proper length has been taken for the safety operation of blower as it won't operate at higher temperatures. Suction pressure created by blower must be more than that of pressure drop across packing material then only flow establishment takes place.

Ergun has proposed equation for calculating pressure drop per unit length across porous receiver material which is as follows [5]

$$\frac{\Delta P}{L} = \frac{150\mu(1-\varepsilon)V}{D^2\varepsilon^3} + \frac{1.75\rho(1-\varepsilon)V^2}{D\varepsilon^3} \quad (1)$$

Where

- μ = Dynamic viscosity of air
- ε = Porosity of material
- V = Inlet velocity of air
- ρ = Density of air
- D = Diameter of pore

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 5, May 2016

At this stage we can predict inlet velocity to the heater section in the range of 1-3 m/s. Porosity of material can be varied between 0.4 - 0.8, diameter of pore will generally in the range of 3 -7 mm .With trial and error method by varying inlet velocity and porosity of 0.4, 0.6 and 0.8 maximum value of pressure drop found to be 2044.41 Pascal. So Blower must create at least 2045 Pascal of suction pressure so as to overcome pressure drop across material and to establish flow through packing material.

Volume of the packing material calculated value is 6848 cm³, so it has been decided to design heater test section with equivalent diameter of 17cm. Length of heater section is fixed to 300 mm so that three thermocouples can be placed in three different planes. Due to manufacturing difficulties, the diameter available for ceramic tube over which coils are wounded was available 15cm and 20 cm. So finally 20 cm diameter is selected for all the three sections. By taking inlet velocity of 1 to 3 m/s, CFM is calculated which is found to be 200 CFM.

Maximum pressure drop occurred is 2044 Pa and maximum flow rate 0.094 m³/s. Power required for running blower can be given as follows:

$$P = \rho g Q h$$

Where

P = Power (W)

ρ = Density of Air (Kg/m³)

g = Acceleration due gravity (m/s²)

Q = Air flow rate (m³/s)

h = head in meters of air column (m)

As maximum pressure drop occurred is 2044 Pa (200 mm water column with 0.094 m³/s as flow rate and head developed of 173.63 m, so power can be calculated from above mentioned formula which is **0.25 hp**.

V. CONCEPTUAL 3D MODEL OF TEST SETUP

With design calculation of each section conceptual 3D model created in CATIA as show in figure 5.1. It consists of inlet section, ceramic band heater section and outlet section with centrifugal blower attached at the end. Thermocouples are placed in different planes of heater section to monitor average material zone temperature. Pressure gauges shown will be of vacuum type which must sustain at higher temperatures, digital temperature indicator is to show temperature recorded by thermocouples at various sections.

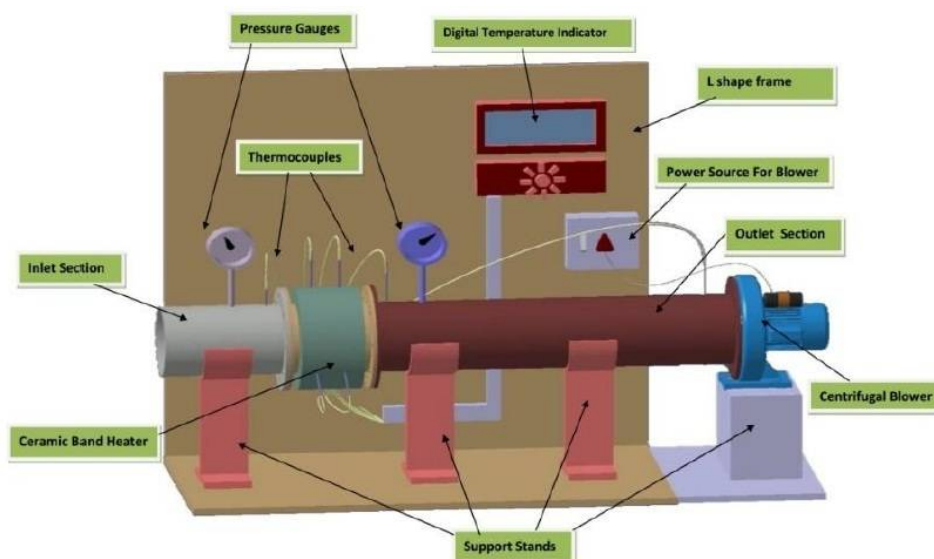


Fig 5.1 Conceptual 3D Model of Test setup

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 5, May 2016

Experimental procedure for this setup is to switch on heater section which is filled with packing material, set heater at desired temperature. After getting desired temperature, blower is switched on and air velocity at the inlet is measured with the help of digital hot wire anemometer. Each thermocouple readings have been note down for thermal analysis of packing material. Blower is provided with regulator to vary the speed of impeller so that mass flow rate can also be changed.

VI. EXPERIMENTATION

At the time of testing of Al_2O_3 test section is provided with stainless tube of inner diameter 180 mm & outer diameter 186 mm. It was introduced between actual ceramic tube over which coil is wound and test sample material in order to keep coil safe otherwise material may get adhered to in case of metals to coil which may lead to coil damage. Location of thermocouple is given as follows:

T1 = Ambient Temperature of Inlet Air

T2 = Temperature of porous zone at $x = 50$ mm along axial direction

T3 = Temperature of porous zone at $x = 150$ mm along axial direction

T4 = Temperature of porous zone at $x = 250$ mm along axial direction

T5 = Temperature of porous zone at 45° CW from vertical axis between T2 and T3

Heater = Temperature of porous zone at 45° CCW from vertical axis between T3 and T4

T6 = Temperature of Air coming out from porous zone

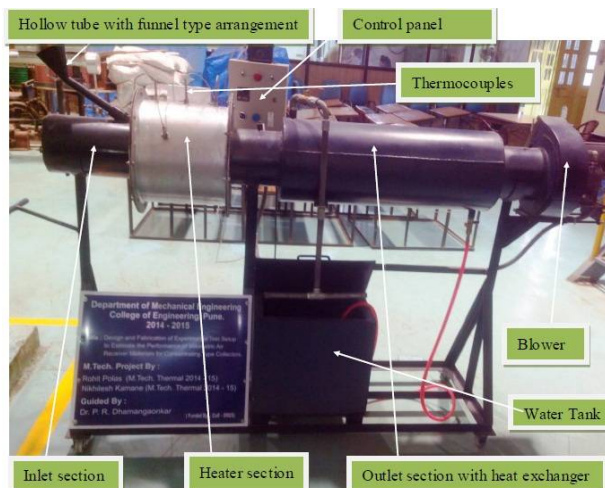


Fig 6.1 Complete setup with all sections

Complete experimental setup with all instruments is shown in fig 6.1. Inlet section is provided with funnel arrangement for filling material. With its help material can directly loaded into heater section. Control panel is provided to maintain heater temperature within limits and blower and water pump on/off operation. Two different material has been tested detailed experimental observations are provided as follows

1. Al_2O_3

Initially Al_2O_3 in the form of spheres has been tested with particle diameter of 10 mm. Setup is developed in such a way that, there is an arrangement is made hollow tube and funnel arrangement for inserting these testing materials in to the porous zone heating chamber. Heater portion is having flanges on the both side out of which one connected to heat exchanger part while other is to inlet portion. Once the temperature inside the chamber reached to desired temperature,

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 5, May 2016

and then blower is switched on so that air starts flowing in the porous zone thereby heated by convection & then goes through tube in tube heat exchanger followed by blower at the end. Steady as well as unsteady behaviour has been tested and experimental data are reported as follows:

Amount of Al_2O_3 filled inside test section = 15.4 kg

Al_2O_3 Thermo-physical Properties:

$K = 46 \text{ W/m}^2\text{K}$

$C = 765 \text{ J/kg K}$

Porosity can be calculated with density based approach [4]:

$$\varepsilon = 1 - \frac{\rho_b}{\rho_s} \quad (2)$$

Where

ρ_b = Bulk density of material inside test section

ρ_s = Standard density of material = 3400 kg/m^3

ρ_b = (Amount of material filled inside test section / Volume of Test section) / Standard density of material

$\rho_b = (15.4) / (\pi/4 * 0.18^2 * 0.3) / 3400$

$\rho_b = 2017.27 \text{ Kg/m}^3$

Therefore equation (2) becomes

$\varepsilon = 1 - (2017.27 / 3400)$

$\varepsilon = 0.41$

Porosity by density approach is:

$\varepsilon = (\text{Total Volume} - \text{Material Volume}) / (\text{Total Volume})$

$\varepsilon = \text{Void Volume} / \text{Total Volume}$

$0.41 = \text{Void Volume} / \text{Total Volume}$

$\text{Void Volume} = 3.12 \times 10^{-3} \text{ m}^3$

$\text{Annular space volume} = \pi/4 * (0.2^2 - 0.18^2)$
 $= 1.79 \times 10^{-3} \text{ m}^3$

$\varepsilon = (\text{Total Volume} - \text{Material Volume}) / (\text{Total Volume})$

$= 1 - (\text{Material Volume} / \text{Total Volume})$

$\text{New Void Volume} = \text{Void Volume} + \text{Annular space volume}$

$= 4.91 \times 10^{-3} \text{ m}^3$

$\text{Total volume of test section} = \pi/4 * 0.18^2 * 0.3$

$= 9.42 \times 10^{-3} \text{ m}^3$

New Porosity including annular space can be found as follows:

$\varepsilon = \text{New Void Volume} / \text{Total Volume}$

$\varepsilon = 0.52$

1.1 Pressure Measurement

Pressure is measured with tapping provided after porous test section with U tube manometer with water as fluid.

$\Delta h = (22.5 - 20.5) = 2 \text{ cm}$

$\Delta p = \rho g h$

$\Delta p = 1000 * 9.81 * 0.02$

$\Delta p = 196.20 \text{ Pa}$

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 5, May 2016

1.2 Steady State Condition

For achieving steady state condition heater and blower simultaneously switched on, with material filled inside test section with inlet diameter of 200 mm diameter and whole test section made run for around 3 hours. Following parameters are measured:

$$\begin{aligned} \text{Inlet velocity} &= 1.2 \text{ m/s} \\ \text{Average Material zone} &= 71 \text{ }^\circ\text{C} \\ \text{temperature} & \\ \text{Inlet Air Temperature} &= 35 \text{ }^\circ\text{C} \\ \text{Outlet Air Temperature} &= 66 \text{ }^\circ\text{C} \\ C_p = \text{specific heat of air} &= 1005 \text{ J/kg K} \\ \text{Mass flow rate} &= \rho A V = 0.045 \text{ kg/s} \end{aligned}$$

1.2.1 Estimation of Heat transfer Coefficient:

Heat transfer coefficient is calculated based on assumption of heat convected by material is equal to heat gain by air.

Heat transfer Coefficient can be calculated as follows:

$$\begin{aligned} \text{Heat gain by Air} &= m C_p \Delta T \\ &= 0.045 * 1005 * (66-35) \\ &= 1401.97 \text{ W} \\ \text{Heat Gain by Air} &= \text{Heat convected to fluid by material} \\ 1401.97 &= h A_s (T_s - T_{fm}) \end{aligned}$$

Where

$$\begin{aligned} T_s &= \text{Material Temperature} = 71 \text{ }^\circ\text{C} \\ T_{fm} &= \frac{T_{fi} + T_{fo}}{2} = \frac{35 + 66}{2} \\ &= 50.5 \text{ }^\circ\text{C} \end{aligned}$$

$$\begin{aligned} A_s &= 1.15 \text{ m}^2 \\ h &= \frac{1401.97}{1.15 * (71 - 50.5)} \end{aligned}$$

$$h = 59.46 \text{ W/m}^2\text{K}$$

1.3 Unsteady State Condition

Unsteady means when properties of the system are not fluctuating with respect to time.

1.3.1 Lumped heat capacity system:

In this model, when a mass, which can be well-conducting solid or a well-mixed fluid, is subjected to heating or cooling by exposure to an environment with which it exchanges heat, one assumes that temperature variations within the mass can be neglected in comparison with the temperature difference between the mass and the surrounding fluid. Another way of stating this idea is that the resistance to heat transfer within the mass is negligible when compared with the resistance to heat transfer with the surroundings.

The convection heat loss from the body is evidenced as a decrease in the internal energy of the body

$$q = hA(T - T_\infty) = -c_p \frac{dT}{d\tau} \quad (3)$$

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 5, May 2016

Where

A - Surface area for convection

The initial condition is

$$T = T_0 \text{ at } \tau = 0$$

So that the solution to Equation is

$$\frac{T - T_\infty}{T_0 - T_\infty} = e^{-\frac{hA\tau}{\rho Vc}t} \quad (4)$$

Where

- T = Temperature of material at instant t
- T_∞ = Surrounding fluid temperature
- T_0 = Initial temperature of material
- h = Heat transfer coefficient ($\text{W/m}^2\text{K}$)
- V/A = $d_p/6$ (for sphere particles)
- C = specific heat of material (J/kg K)
- t = time instant in seconds

From above equation heat transfer coefficient is estimated for the period of 15 min time interval.

Heat Rate of Material per square meter is given by:

$$q = -h(T_0 - T_\infty)e^{-\frac{hA\tau}{\rho Vc}t} \quad (5)$$

Where

q = heat rate of material in W/m^2

Lumped heat analysis method is applicable only when $Bi \leq 0.1$. Tests have been conducted on various mass flow rates with adjusting inlet diameter plates 80, 60, 40 mm with heating at different Average zone temperatures such as 300°C , 400°C , 500°C , 600°C . While carrying out experiments inlet velocity has been measured for different diameter plates, as well as thermocouple readings in the porous zone at different planes and outlet fluid temperature has been note down. Inlet portion is insulated with 1 cm thickness to reduce heat loss, so actual inlet diameter becomes 190 mm. Due to space constraint, only observations with 300°C average zone temperature are provided.

Following parameters are measured experimentally:

- Inlet Velocity = 1.2 m/s
- Mass of Al_2O_3 filled in test section = 15.4 kg
- Number of Al_2O_3 spheres in 1 kg = 495

In order to change mass flow rate various diameter plates are attached at inlet section

(a) 200 mm Diameter:

- Inlet Velocity = 1.2 m/s
- Mass flow rate = $\rho A V = 0.045 \text{ kg/s}$

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 5, May 2016

Table 6.1 300 °C Zone Temperature

Δt	Tzone	Air Heat Gain (W)	h (W/m ² K)	Heat Rate (W/m ²)
0	300.60			
130	185.40	3690	18.96	2852.14
300	115.80	3280	8.98	725.43
300	88.00	2829	6.09	322.9
300	70.80	2419	5.67	202.96

Table 6.1 shows observations for 200 mm diameter plate, 300 °C zone temperature with time interval of 300 seconds. As air starts flowing through porous material, it releases heat to air through convection media. As time passes air gains heat and material loses heat. Air heat gain decreases with time because of average zone temperature dropping down as continuously fresh air is introduced. Heat transfer coefficient decreases with reduction in average zone temperature. Let us check whether lumped heat capacity is valid or not by calculating Biot number:

$$Bi = \frac{hL_c}{K} = \frac{18.96 * 0.01}{46 * 6} = 6.86 * 10^{-4} \tag{6}$$

So our assumption was correct as Biot number is less than 0.1.

(b) 80 mm Diameter:

Inlet Velocity = 6.2 m/s
Mass flow rate = $\rho A V = 0.0371$ kg/s

Table 6.2 300 °C Zone Temperature

Δt	Tzone	Air Heat Gain (W)	h (W/m ² K)	Heat Rate (W/m ²)
0	306.6	1519.56		
133	211.2	5036.66	14.10	2485.08
300	138	3758.70	7.76	799.08
300	99.2	3270.07	6.83	438.54
300	80.4	2894.20	5.01	227.30

With 80 mm diameter plate, mass flow rate is decreased and average zone temperature is higher i.e. 211.2 °C than that of 185.40 °C in case of 200 mm plate condition.

(c) 60 mm Diameter:

Inlet Velocity = 7.5 m/s
Mass flow rate = $\rho A V = 0.0254$ kg/s

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 5, May 2016

Table 6.3 300 °C Zone Temperature

Δt	Tzone	Air Heat Gain (W)	h (W/m ² K)	Heat Rate (W/m ²)
0	386.6	1778.85		
136	291	4033	10.11	2589.30
300	183.4	3319	7.88	1169.26
300	138.2	3114	5.25	541.68
300	118	3012	3.15	261.25

(d) 40 mm Diameter:

Inlet Velocity = 9.6 m/s

Mass flow rate = $\rho A V = 0.0145$ kg/s

Table 6.4 300 °C Zone Temperature

Δt	Tzone	Air Heat Gain (W)	h (W/m ² K)	Heat Rate (W/m ²)
0	298.8	912.0375		
129	247.6	2769	7.25	1541.60
300	191.8	2448	4.40	689.79
300	160.6	2200	3.21	402.67
300	142.6	2084	2.24	240.50

As inlet section diameter decreases, mass flow rate also decreases and it directly affects Tzone temperature which is inversely proportional to mass flow rate. In this work 4 to 5 observations are taken, so that relationship between Δt , Air Heat Gain and Heat Rate can be developed. With these observations we can predict behavior of Al₂O₃ in unsteady state condition for the cumulative period of around 1000 seconds.

2. Steel Balls

While conducting experiments heating coil failure observed due to it was unable heat the test section so new size of test section developed in square shape of side 150 mm with ceramic wall having thickness of around 15 mm.

Surface Area $A = 0.15 \times 0.15 = 0.0225$ m²

Amount of Steel Balls filled inside test section = 30.34 Kg

2.1 Steady State Condition:

For achieving steady state condition Heater & Blower simultaneously switched on with material filled inside test section with inlet square section of 150 mm and whole test section made run for around 2 hours.

Thermo-physical Properties of Steel Balls:

Density = 7820 Kg/m³
 Specific heat = 468 J/Kg K
 Thermal Conductivity = 57.9 W/m K
 Coefficient of Thermal Expansion = $11.8 \times 10^{-6} / ^\circ\text{C}$

Following parameters are measured:

Inlet velocity = 0.9 m/s
 Average Material zone temperature = 198 °C
 Inlet Air Temperature = 35 °C
 Outlet Air Temperature = 166 °C

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 5, May 2016

$$C_p = \text{specific heat of air} = 1005 \text{ J/kg K}$$

$$\text{Mass flow rate} = \rho A V = 0.0243 \text{ kg/s}$$

Porosity is calculated in the similar way as that of Al₂O₃ section
 $\epsilon = 0.42$

2.2 Pressure Measurement:

Pressure calculations are as follows

$$\Delta h = (22.4 - 19.8) = 2.6 \text{ cm}$$

$$\Delta p = \rho g h$$

$$\Delta p = 1000 * 9.81 * 0.026$$

$$\Delta p = 255.06 \text{ Pa}$$

2.3 Estimation of Heat transfer Coefficient:

Heat transfer coefficient can be calculated as follows:

$$\begin{aligned} \text{Heat gain by Air} &= m C_p \Delta T \\ &= 0.045 * 1005 * (166-35) \\ &= 3199.21 \text{ W} \end{aligned}$$

$$\begin{aligned} \text{Heat Gain by Air} &= \text{Heat convected to fluid by material} \\ 3199.21 &= h A (T_s - T_{fm}) \end{aligned}$$

Where

$$T_s = \text{Material Temperature} = 198 \text{ }^\circ\text{C}$$

$$T_{fm} = \frac{T_{fi} + T_{fo}}{2} = \frac{35 + 166}{2}$$

$$= 100.5 \text{ }^\circ\text{C}$$

$$A_s = 4\pi^2 N(1-\epsilon)$$

$$= 4\pi * (0.002)^2 * 90000 * (1-0.42)$$

$$= 2.62 \text{ m}^2$$

$$h = \frac{3199.21}{2.62 * (198 - 100.5)}$$

$$h = 12.52 \text{ W/m}^2\text{K}$$

2.4 Unsteady State Condition:

(a) 150 mm Diameter:

Table 6.5 300 °C Zone Temperature

Δt	Tzone	Air Heat Gain (W)	h	Heat Rate (W/m ²)
0	261.20			
164	236.20	2783	1.74	350.57
300	220.80	2764	0.65	120.32
300	216.00	2707	0.21	38.53
300	209.40	2630	0.30	52.69

Similar experimental procedure is adopted for steel balls. Initially steel balls are heated to 300 °C Zone Temperature and blower is switched on. Fresh air is taken in through porous material, which brings down material temperature to

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 5, May 2016

236.20 °C after 164 seconds. As time passes, all the quantities such as Air heat gain, h and Heat rate decreases with reduction in Tzone temperature.

(b) 80 mm Diameter:

Table 6.6 300 °C Zone Temperature

Δt	Tzone	Air Heat Gain (W)	h	Heat Rate (W/m ²)
0	288.60			
135	256.00	1511	2.49	549.57
300	231.20	1447	0.97	189.93
300	223.60	1366	0.32	60.60
300	219.20	1266	0.19	35.36

(c) 60 mm Diameter:

Table 6.7 300 °C Zone Temperature

Δt	Tzone	Air Heat Gain (W)	h	Heat Rate (W/m ²)
0	316.00			
120	291.40	1190	1.86	477.61
300	250.80	1171	1.40	302.55
300	223.80	1126	1.09	205.24
300	207.80	1081	0.72	124.45

(d) 40mm Diameter:

Table 6.8 300 °C Zone Temperature

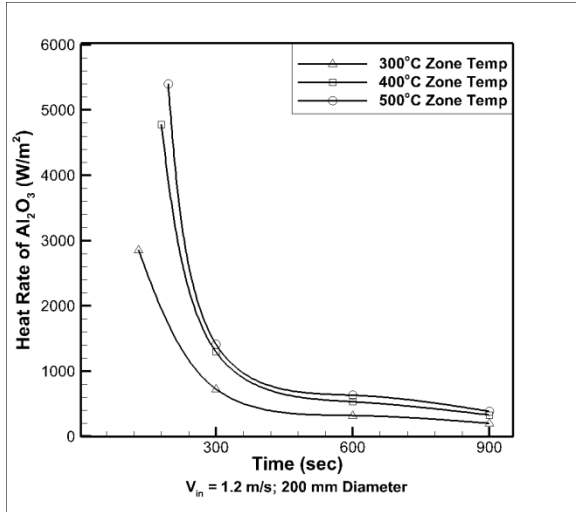
Δt	Tzone	Air Heat Gain (W)	h	Heat Rate (W/m ²)
0	319.40			
120	303.20	724	1.19	319.81
300	269.20	713	1.10	258.20
300	244.40	695	0.91	190.62
300	222.80	673	0.89	166.28

As we can observe from table 6.5 to table 6.8, Tzone increases from 236.20 °C to 303.20 °C with decrease in mass flow rate. Air heat gain decreases from 2783 W to 724 W whereas heat rate found to be fluctuating. All the observations are taken for total time period of 15 to 20 minutes.

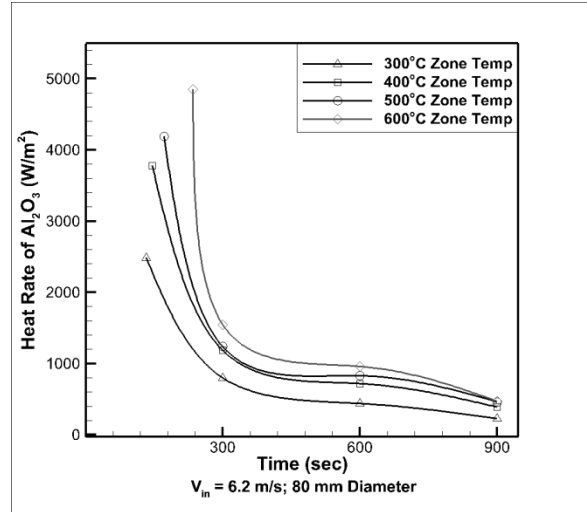
VII. RESULTS AND DISCUSSIONS

1. Al₂O₃

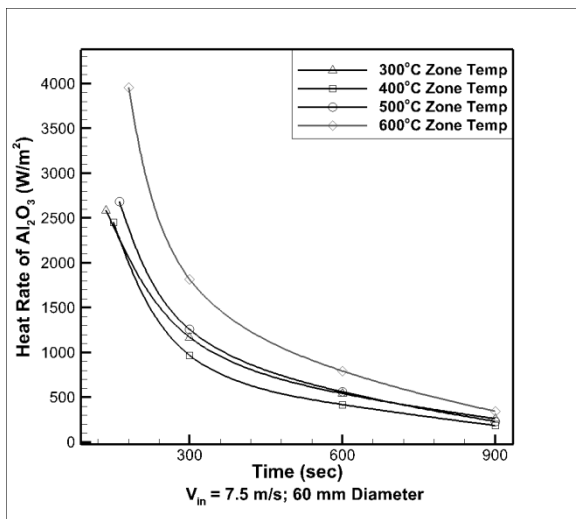
Heat rate of Al₂O₃ (W/m²) and Air heat gain with respect to time for different diameter plates such as 200mm, 80mm, 60mm, 40mm with porosity of 0.52 for different Average zone temperatures such as 300 °C, 400 °C, and 500 °C have been compared and plotted with respect to time over which experiments carried out for around 15 to 20 minutes.



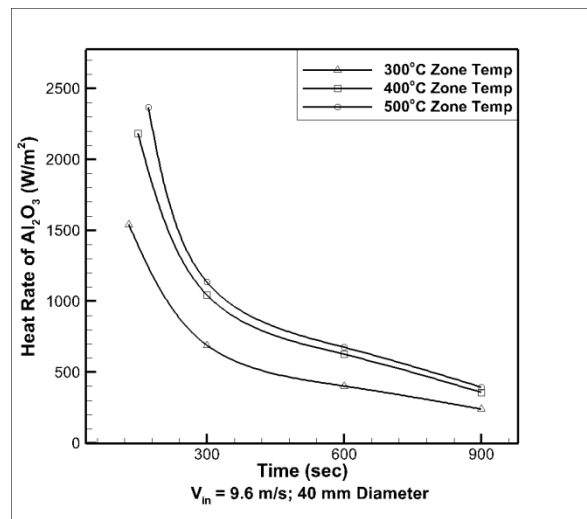
(a)



(b)



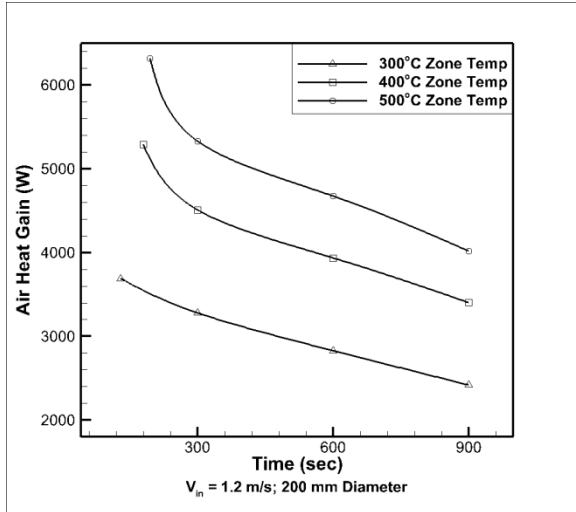
(c)



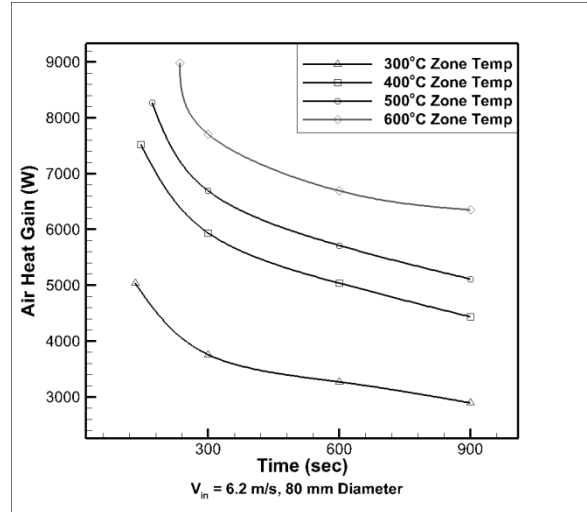
(d)

Fig 7.1 Heat Rate of Al_2O_3 (W/m^2) Vs Time (sec) for 200,80,60,40 mm diameter plates

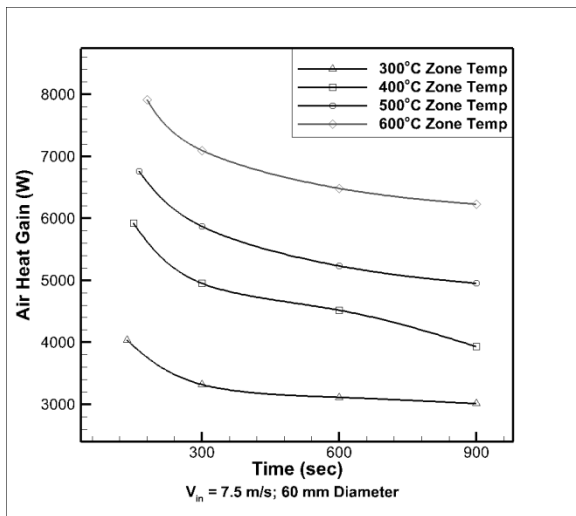
As we can see from figure 7.1 in (a) part, highest value of heat rate of Al_2O_3 is around $5500 W/m^2$ ($500^\circ C$, 200 mm) which goes on decreasing with decrease in diameter. In fig 7.1 (d) the value goes down to around $2500 W/m^2$ ($500^\circ C$, 80 mm) with 54.54% decrease. Also Heat release rate of Al_2O_3 decreases drastically in time zone ranges from 150 to 300 seconds. Slope of the curve is more in (a) and (b) as compared to (c) and (d) in time zone ranges from 150 to 300 seconds as compared to 300 to 900 seconds. This means that when material reaches at required zone temperature with ambient air introduced in the porous zone, material starts releasing heat very fast then get stable after period of 300 seconds. Heat rate is decreasing exponentially with respect to time with the lowest value in the case of 200 mm plate diameter is near around $500 W/m^2$ as that of $250 W/m^2$ with 50% reduction which lead us to with reduction of mass flow rate heat rate of material also decreases.



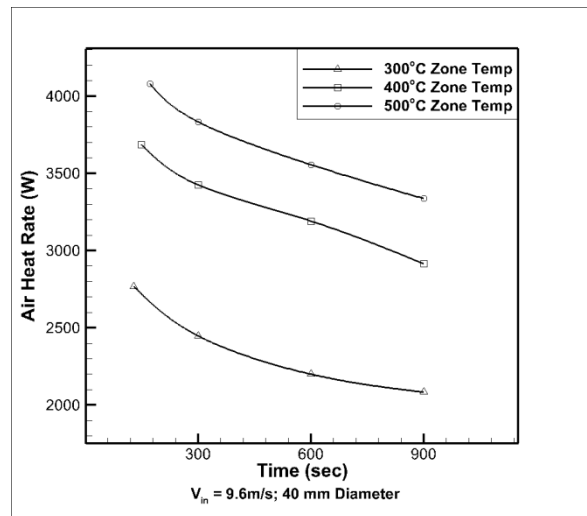
(a)



(b)



(c)



(d)

Fig 7.2 Air Heat Gain (W) from Al_2O_3 Vs Time (sec) for 200, 80, 60 and 40 mm diameter plates

From figure 7.2 in part (a) Heat gain by air is around 6500 W (500 °C, 200 mm) which is reduced up to 4200 W with 40 mm diameter plate with 35 % reduction. Heat gain by the air goes on reducing with respect to time as mass flow rate also goes on reducing.

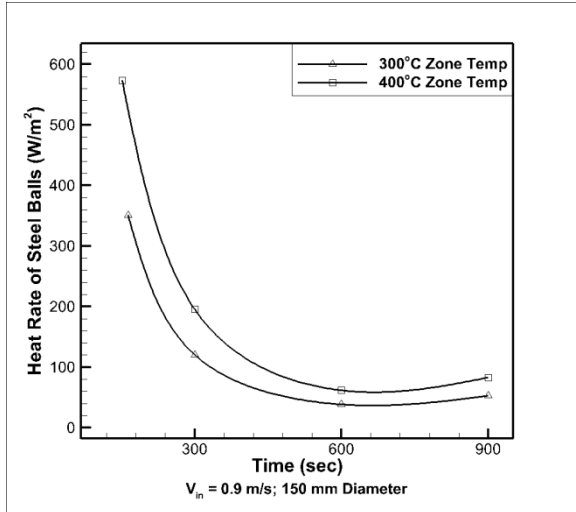
2. Steel Balls

Heat rate of steel balls (W/m^2) and Air heat gain with respect to time for different diameter plates such as 150mm, 80mm, 60mm, 40mm with porosity of 0.42 for different Average zone temperatures such as 300°C, 400°C, 500°C have been compared and plotted with respect to time over which experiments carried out i.e. of 15 minutes.

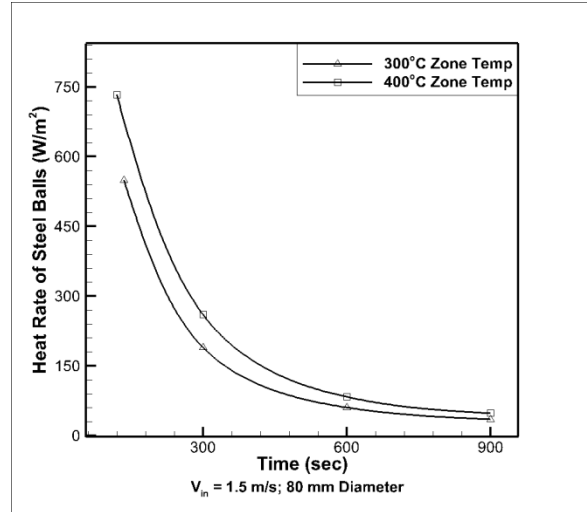
International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

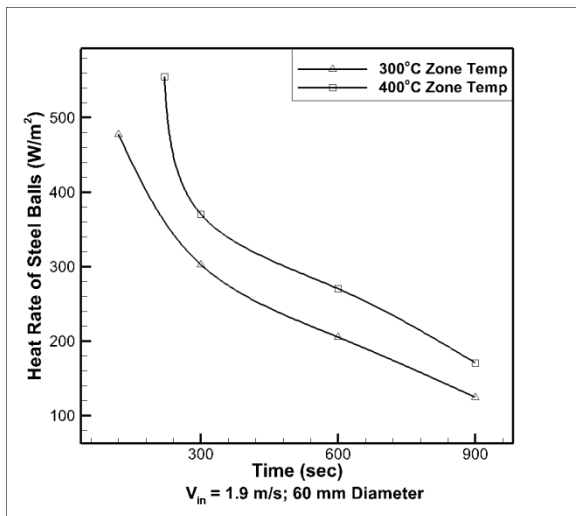
Vol. 5, Issue 5, May 2016



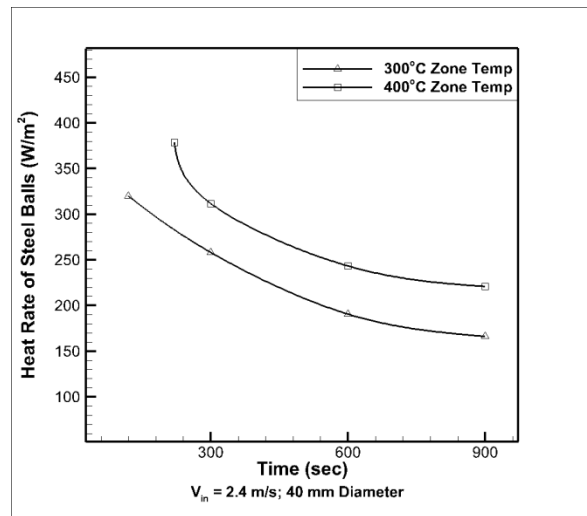
(a)



(b)



(c)



(d)

Fig 7.3 Heat Rate of Steel Balls (W) Vs Time (sec) for 150, 80, 60 and 40 mm diameter plates

From figure 7.3 (a) maximum heat rate of steel balls is around 580 W/m^2 with 150 mm diameter at 400°C zone temperature reduces to around 380 W/m^2 with 40 mm diameter by 34.48 % reduction. Slope of the curve is more in 7.3 (a) and 7.3 (b) than that of 7.3(c) and 7.3(d) within time range of 150 to 300 seconds.

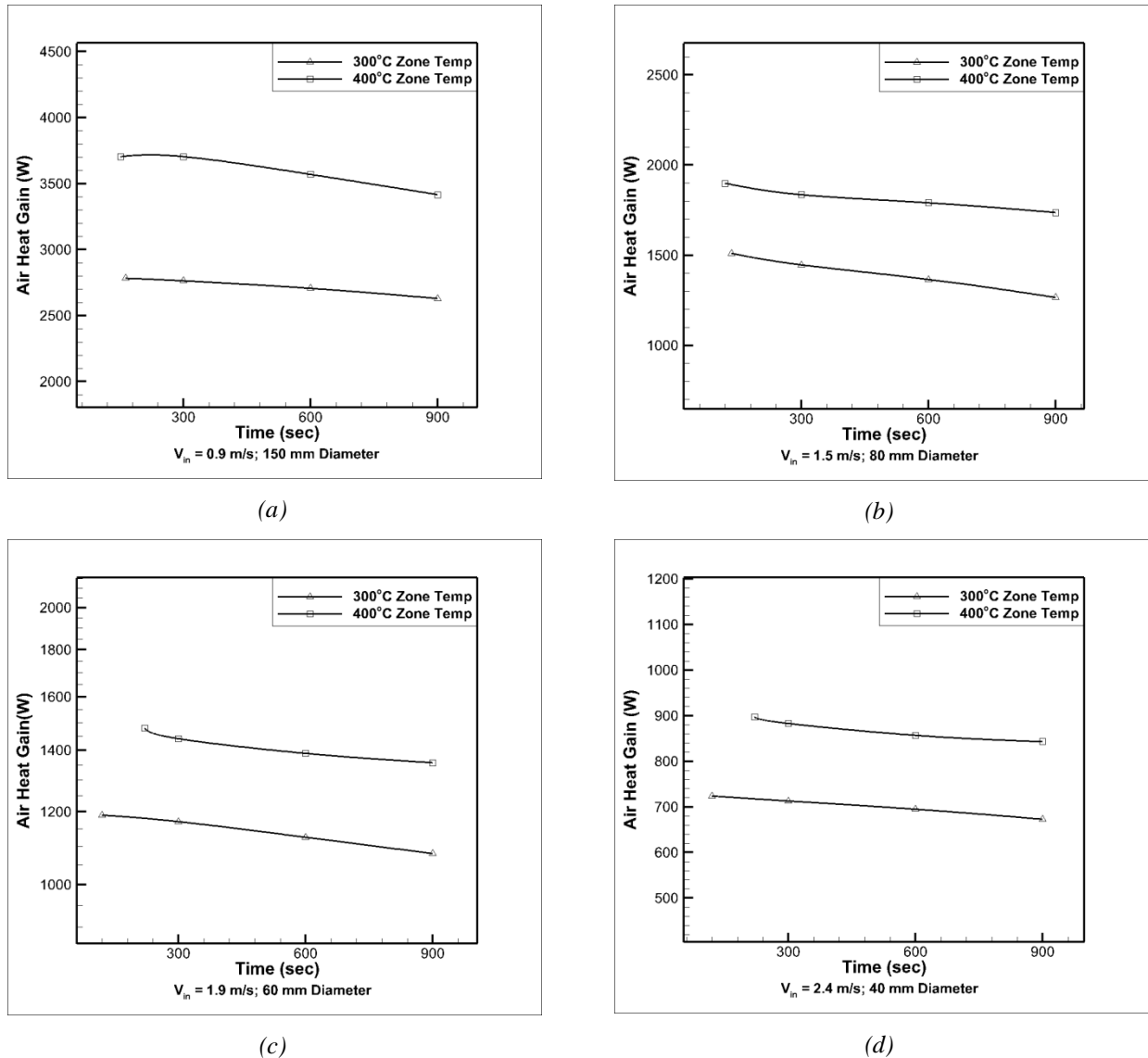


Fig 7.4 Air Heat Gain (W) from steel balls Vs Time (sec) for 150, 80, 60 and 40 mm diameter plates

From figure 7.4 Heat gain by air is more with 150 mm plate diameter at 400 °C zone temperature i.e. around 3750 W which goes on reducing to 900 W with 76% reduction as mass flow rate is also decreasing. In all parts heat gain by air reduced within range of around 300 Watts. Slope of the curve is also near about constant with less variation in all the cases. This means air takes heat at constant rate which is equal to heat absorbing capacity of steel balls.

VIII. COMPARATIVE ANALYSIS OF Al_2O_3 AND STEEL BALLS

From figure 7.1 (b) (80 mm diameter, $\epsilon = 0.52$, $T_{zone} = 400 \text{ }^\circ\text{C}$) the maximum value of heat rate of Al_2O_3 is around 3800 W/m^2 and in case of steel balls shown in figure 7.3 (b) (80 mm diameter, $\epsilon = 0.42$, $T_{zone} = 400 \text{ }^\circ\text{C}$) value is 745 W/m^2 with 80.52 % reduction. From figure 7.2 (b) with (80 mm diameter, $\epsilon = 0.52$, $T_{zone} = 400 \text{ }^\circ\text{C}$) maximum value of heat gain by air of Al_2O_3 is around 7500 W and in case of steel balls shown in figure 7.4 (b) (80 mm diameter, $\epsilon = 0.42$, $T_{zone} = 400 \text{ }^\circ\text{C}$) is around 1950 W with 74 % reduction.

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 5, May 2016

This is because of thermo physical properties of Al_2O_3 are good as compared to steel balls with specific heat of Al_2O_3 more than steel balls also from lumped heat capacity analysis heat transfer coefficient calculated over period of 15 minutes is more in case of Al_2O_3 than that of steel balls. We can observe that heat transfer coefficient in case of Al_2O_3 with 10 mm particle diameter is more even at high porosity than that of steel balls with 4 mm particle diameter. Heat transfer coefficient reduced up to 78.92 % in case of steel balls as compared to Al_2O_3 .

IX. CONCLUSION

In steady state condition heat transfer coefficient for Al_2O_3 with 10 mm particle diameter, 0.045 kg/s mass flow rate and 0.52 porosity is found to be $59.42 \text{ W/m}^2 \text{ K}$ and in steel balls with 4 mm particle diameter, 0.0243 kg/s and 0.42 porosity is $12.52 \text{ W/m}^2 \text{ K}$. Thermo physical property of Al_2O_3 is good as compared to steel balls also it is inert at high temperature and in steady state condition heat transfer coefficient in case of Al_2O_3 is more than that of steel balls.

In case of unsteady state condition with 80 mm diameter (0.0374 kg/s) and 0.52 porosity at 400°C zone temperature maximum value of heat rate of Al_2O_3 is around 3800 W/m^2 that of steel balls is $740 \text{ W/m}^2 \text{ K}$ at 0.42 porosity (0.0753 kg/s) with 80.52 % reduction and maximum value of heat gain by air of Al_2O_3 is around 7500 W that of steel balls is around 1950 W at 0.42 porosity with 74 % reduction.

So we can conclude that from above results Al_2O_3 is looking best promising material as a volumetric air receiver even it will sustain at higher temperature and will provide good heat transfer to air under proper packing density. In the future scope different materials with same or different diameter can be compared with the help of steady state analysis based on heat transfer coefficient, air heat gain, heat rate etc. Comparative analysis can be done and based on which material can be suggested.

ACKNOWLEDGMENT

I am grateful to Mr. Anil Newale (Proprietor) and Mr. B. L. More (Engineer) of Kalyani Enterprises, Bhosari, Maharashtra, India for accepting this project's fabrication part, without their guidance and support it would not been possible for us to complete this project within time. Grand thanks to Dr. S. B. Banerjee for giving us proper technical guidance each and every time.

REFERENCES

- [1] Ja Hyun Cho, Ju Han Lee, Yong Kim, Tae Beom Seo, Yong Heack Kang, "Characteristics of heat transfer and pressure loss of the porous materials for a solar volumetric air receiver", Proceedings of ISES World Congress 2007, Vol. V, pp.1889-1893, 2009.
- [2] G. Srinivasa Rao, K.V. Sharma, S.P. Chary, R.A. Bakar, M. M. Rahman, K. Kadirgama And M.M. Noor "Experimental Study On Heat Transfer Coefficient And Friction Factor Of Al_2O_3 Nano fluid In A Packed Bed Column", Journal of Mechanical Engineering and Sciences (JMES), Vol. I, pp. 1-15, December 2011.
- [3] Pei Xue Jiang, Rui Na Xu, Wei Gong, "Particle to fluid heat transfer coefficients in mini porous media", Chemical Engineering Science, Vol. 61, pp. 7213 – 7222, 2006.
- [4] Laith Jafer Habeeb, Mahmoud A. Mashkour and Hazim Jassim Jaber, " Experimental Study of Forced Convection Heat Transfer in a Partially Opened Box Filled With Porous Medium", Proceedings of International Conference on Engineering and Information Technology (ICEIT) pp. 92-103, September 2012.
- [5] C. Albanakis, D. Missrilis, N. Michalidis, K. Yakinthos, " Experimental analysis of the pressure drop and heat transfer through metal foams used as volumetric receivers under concentrated solar radiation", Journal of Experimental Thermal and Fluid science, Vol .33, pp. 246 – 252, 2009.