CFD ANALYSIS OF UNSTEADY FLOW IN THERMAL REGENERATOR

Kuldeep Panwar[1], D. S. Murthy [2]

[1,2] *Department of Mechanical Engineering, G.B.Pant University of Agriculture and Technology, Pantnagar, (India)*

ABSTRACT

This study aims to provide a computational fluid dynamics (CFD) analysis of Pebble bed regenerator for transient flow powered by solar air heater. Hot air at 100^{0}C enters at one end of the regenerator and the amount of heat absorbed by the pebbles are studied by the commercial Ansys Fluent software. A regenerator physical model is developed to estimate actual performance of regenerator under transient flow condition. The proposed model is used to simulate the behavior of regenerator working under different operating and design condition. The standard k-e turbulent model with standard wall function is used for modeling of gas flow.

Keywords*: *CFD, Regenerator, Transient Flow, Solar Air Heater, Ansys Fluent

I. INTRODUCTION

The major drawback of solar energy is that it is intermittent, the energy demand of various application is also time dependent but in different way and phase by solar energy supply. So there is a need to bring the demand and supply together in a time domain through integration of solar system. Thermal storage is major technical constraint that inhibits deployment of solar thermal systems due to intermittent nature. Solids can be effectively used as intermediary in transferring heat from one gas to another on their large volume basis. This transfer of heat from one gas to another through solids is done in two different steps namely charging and discharging. The first step hot gas give up heat to the solids and in second step the heat is transferred to the other gas. A review of various method for storage of thermal energy have been discussed by Pinel et al (2011)[1]. According to the study of Wei et al. (2014)[2], regenerator consists of heat storing matrix (pebble bed), which have high heat storage capacity, high temperature resistance and flow resistance. The complete working of regenerator consists of heating and cooling cycle. During the heating cycle, hot air from solar air heater passes through the regenerator and transfers the heat to the matrix. After a fixed time hot gases flow from solar air heater stops and cooling cycle starts with cool air passing through the regenerator in direction opposite to the direction of hot air and heat is transferred from matrix to cold air. Many paper are published to understand the regenerative process in regenerator. Yu et al. (2002)[3] provided one dimensional transient mathematical model to describe heat transfer in solid and liquid phase in regenerator. Park et al. (2003)[4] established one dimensional two phase fluid dynamics model to describe transient thermal flow through regenerator with spherical particles. Zong et al. (2004)[5] gave three dimensional transient mathematical model for heat transfer in regenerator matrix. 2-Dimensional for honeycomb regenerator was developed by Rafldi et al. (2005)[6]. Levenspiel (1983)[7] in his paper discussed the spreading of temperature front in fixed bed regenerator. When hot gas enters an initially cold bed of solids, temperature front of gas moves down the bed. Basically three phenomenon lads to this spreading of thee hot fronts, firstly deviation from plug flow of gas in packed bed, secondly fluid resistance to heat transfer between solid and gas and thirdly resistance to heat flow into particles. Liu et al. (2014)[8] in his paper has presented 3-dimentional analysis of gas flow and heat transfer in regenerator with aluminium balls.

Nomenclature

A area of heat exchange between soil and gas, m^2

c specific heat at constant pressure, J $kg^{-1}K^{-1}$

D diameter of solids, m

C_2 resistance factor. m^{-1}

h heat transfer coefficient by convection, w m^{-2} K^{-1}

k thermal conductivity, w m^{-1} K^{-1}

p pressure, Pa

t time, s

u velocity components, ms^{-1}

Subscript

s solid phase

f fluid phase

Greek Symbols

ρ density, kg m^{-3}

μ viscosity of gas, kg m^{-1} s^{-1}

μ_t turbulent viscosity, kg m^{-1} s^{-1}

ø porosity

ε solid emissivity

1.1. Physical Model

Considering the advancement in high performance computing machine and better analysis capability of commercial CFD software, the heat storage system (Regenerator) is simulated and results are evaluated.

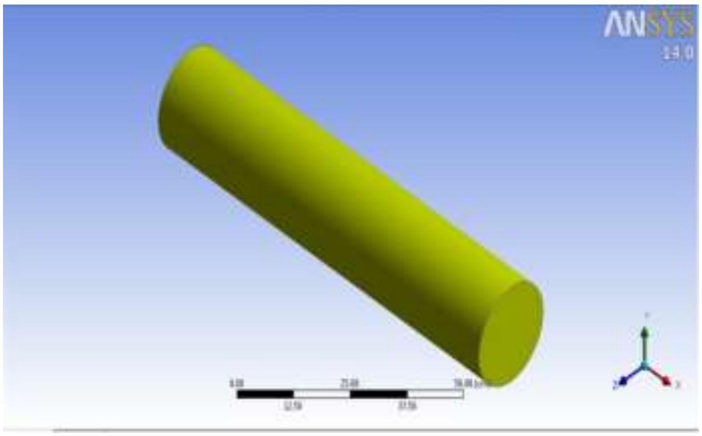


Fig. 1 Physical Model of Regenerator

The entire region of the storage tank is considered as a single fluid zone, instead of the three different zones. Fig 1. shows physical model of regenerator of length 100 cm and diameter 20 cm. Fig 2. shows computational grid using ICME Fluent 14 with hexahedral cell in all zone. Assumptions for mathematical modeling of regenerator are as follows:

1.1.1 Gas flowing through pebble bed of regenerator is assumed to be flowing n porous medium and the flow is laminar.

1.1.2 Gas in regenerator is assumed to be incompressible.

1.1.3 Thermo physical properties of gas and solids are only dependent on temperature.

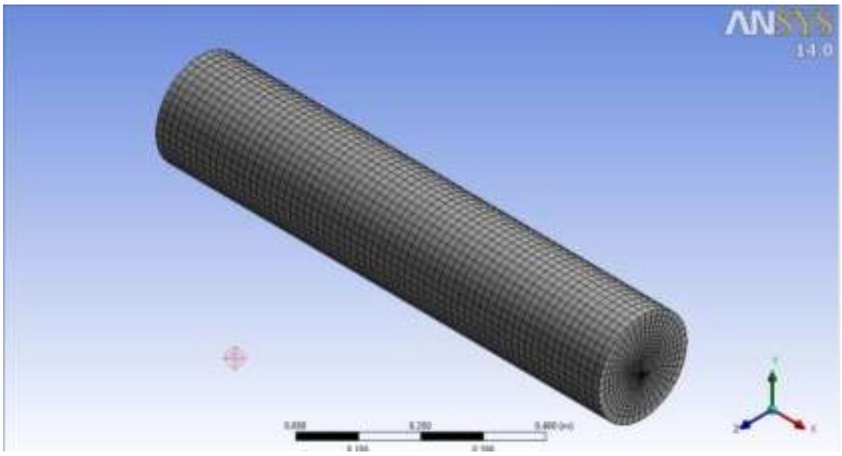


Fig.2. Computational Model of Regenerator

1.2 Governing Equations

As discussed earlier standard k-ε turbulence model is used to calculate the turbulent flow field in regenerator.

1.2.1 Continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \qquad (1)$$

1.2.2 Momentum Equation:

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial}{\partial x_i}\left(p + \frac{2}{3}\rho k\right) + \frac{\partial}{\partial x_j}\left((\mu + \mu_t)\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_l}{\partial x_l}\right)\right) + S_i \qquad (2)$$

where, S_i is the source term for ith moment equation. Pressure drop and drag coefficient in fixed bed regenerator using CFD has been discussed by Reddy and Joshi (2006)[9].

The equation for permeability and inertial resistance factor for gas flow in axial direction are given by Huang (2008)[10] in his paper where he simulated heat transfer in regenerator. Those equations are as follows:

$$\alpha = \frac{D^2}{203}\frac{\phi^3}{(1-\phi)^2} \qquad (3)$$

$$C_2 = \frac{3.9}{D}\frac{(1-\phi)}{\phi^3} \qquad (4)$$

1.2.3 Energy Balance Equation:

$$u_f \rho_f c_f \frac{\partial t}{\partial x} + \rho_s c_s (1-\varepsilon) \frac{\partial t}{\partial \tau} = k_s \frac{\partial^2 t}{\partial x^2}$$

Heat carried by fluid | Heat stored in solid | Heat transfered by solid (5)

1.2.4Boundary Condition:

at x=0

$$v_F \rho_f c_f (t_{fi} - t) = -k_s \frac{\partial^2 t}{\partial x^2} \quad (6)$$

atτ=0

$$t=t_{amb} \quad (7)$$

1.2.5 Energy Balance for Solid:

$$S_{fr}(1-\varepsilon)\rho_s c_s \frac{\partial t_s}{\partial \tau} = hA(t_f - t_s)$$

Heat stored in solids | Heat transfered by Fluid to Solids

1.2.6Initial and boundary conditions:

atτ=0

$$t=t_s=t_0 \quad (7)$$

atτ>0 x=0 $t_f=t_{fi}$

$$x=0 \quad t_s = (t_0 - t_{fi})\exp\left(\frac{\tau hA}{S_s \rho_s c_s}\right) + t_{fi} \quad (8)$$

TABLE 1 Boundary Conditions

S.No	Modeled Equation	Velocity	Flow	Temperature
1	Inlet	5 m/s	K=constant ε=constant	373K
2	Outlet	Outflow	Extrapolate from interior of domain wall functions	Extrapolate from interior of domain q= constant
3	Porous (ø = 0.6)	No slip		

II. RESULTS & DISCUSSIONS

The calculation starts with heating cycle, The initial temperature of hot air from air heater is 373K and the regenerator is maintained at 300K. Initial pressure in the regenerator is 0. Boundary condition are shown in TABLE 1.CFD software Ansys Fluent is used to solve the mathematical modeling of thermal regenerator. Density based transient solver is used to solve the domain. Governing equations are discretized in implicit form using control volume method and solved using COUPLE- based approaches. Heating cycle is continued for 60sec and results are studied.

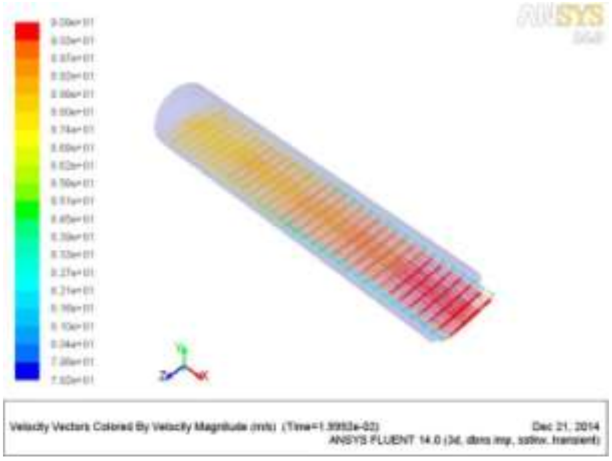


Fig.3 Velocity Variation Along Regenerator During Heating Cycle.

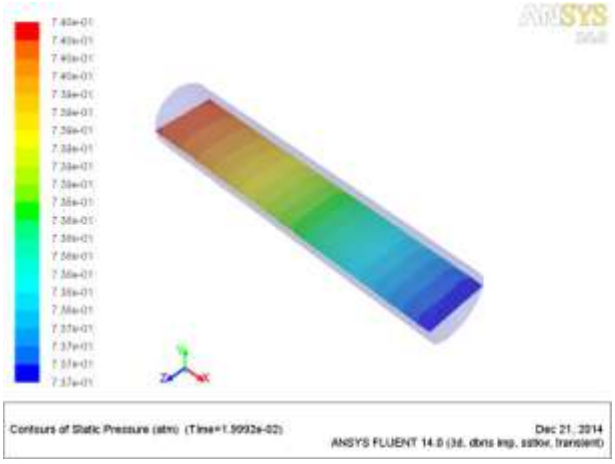


Fig.4 Pressure Variation Along Regenerator During Heating Cycle.

Pressure variation along the plane y=o is shown in Fig. 4 is an important parameter to evaluate regenerator performance. As it is very clear from the figure pressure gradually decreases in the direction of gas flow. The out pressure of gas at the end of heating cycle is 7469 pa. with decreases in pressure in the regenerator velocity along the flow direction increases as shown in Fig.3.

Temperature variation of porous medium at plane x=0, x=0.5 and x=1m are shown in Fig.5, Fig.6, Fig.7, Fig.8. at different time steps during heating cycle. Hot gas enters at 373K through inlet in regenerator, porous medium is initially maintained at 300K. Temperature increases along Y axis. The average inlet and outlet temperature at t= $1.02X10^{-1}$ are 370K and 300K, which goes on increasing as time steps increases.

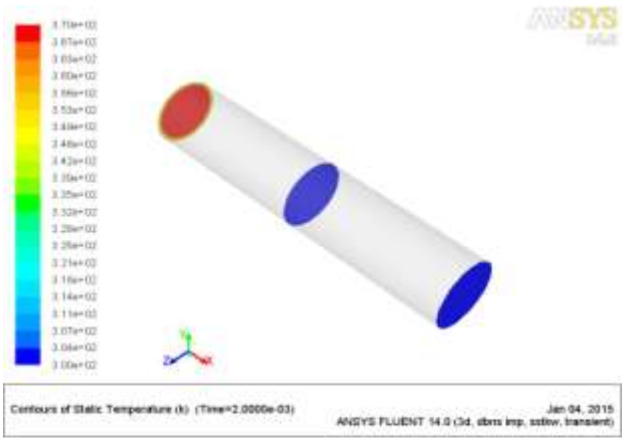


Fig. 5 Gas Temperature Variation Along X=0, X=0.5 And X=1m Plane At T=$2X10^{-3}$

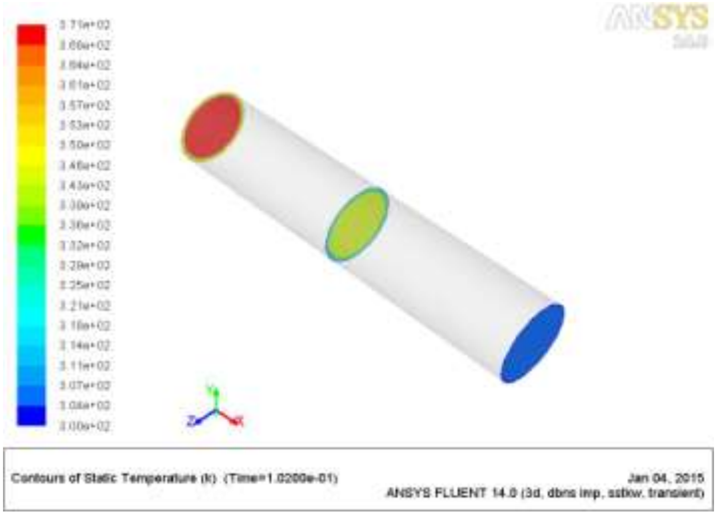


Fig. 6 Gas Temperature Variation Along X=0, X=0.5 And X=1m Plane At T=1.02X10^{-3}

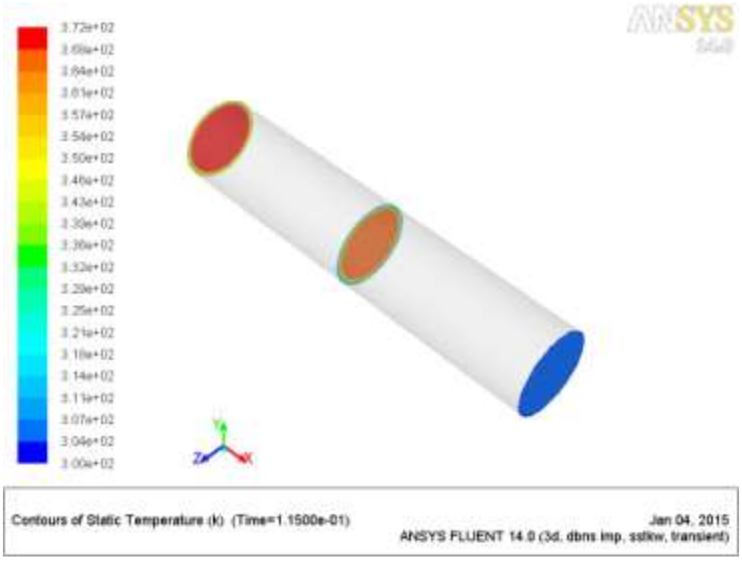


Fig. 7 Gas Temperature Variation Along X=0, X=0.5 And X=1m Plane At T=1.15X 10^{-1}

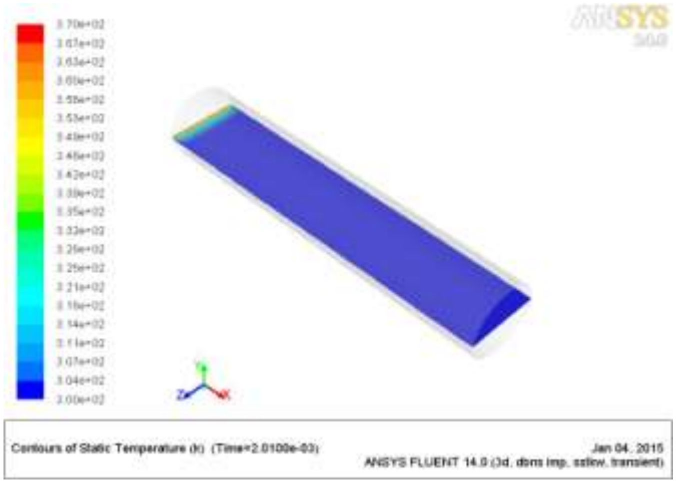


Fig. 8 Gas Temperature Variation Along X=0, X=0.5 And X=1m Plane At T=2.04X 10^{-1}

Temperature variation along Y=0 plane also varies in same pattern as discuss for x plane, Fig. 9, Fig.10, Fig.11, Fig.12 shows the transient temperature variation of regenerator bed (pebble bed) for heating cycle at different time step values. It is observed that the heat is taken by regenerator from hot air during heating cycle which is seen by increase in temperature of regenerator bed.

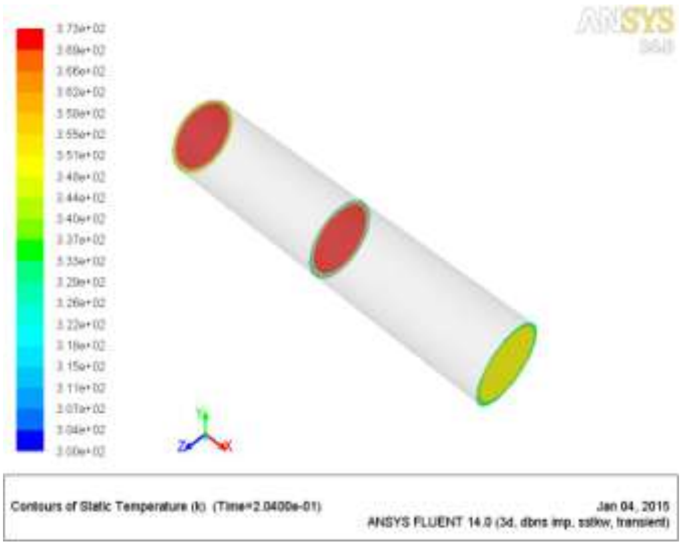


Fig. 9 Pebble Bed Temperature Variation Along Y=0 Plane At (A) T=2X10^{-3}

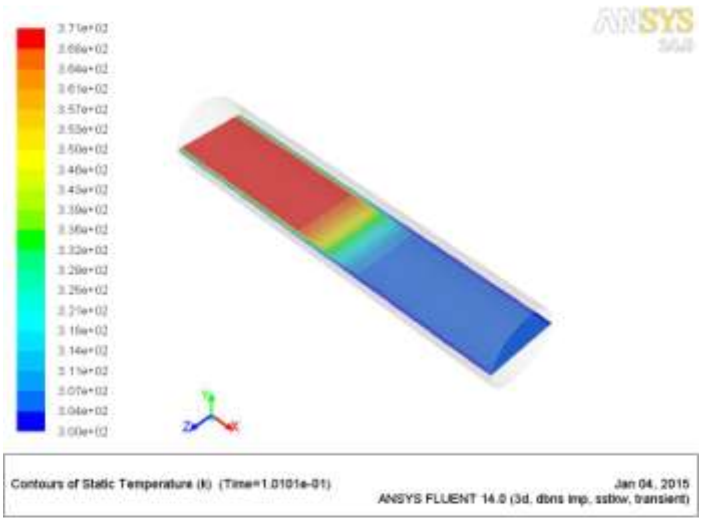


Fig. 10 Pebble Bed Temperature Variation Along Y=0 Plane At (A) T=2X10^{-3}

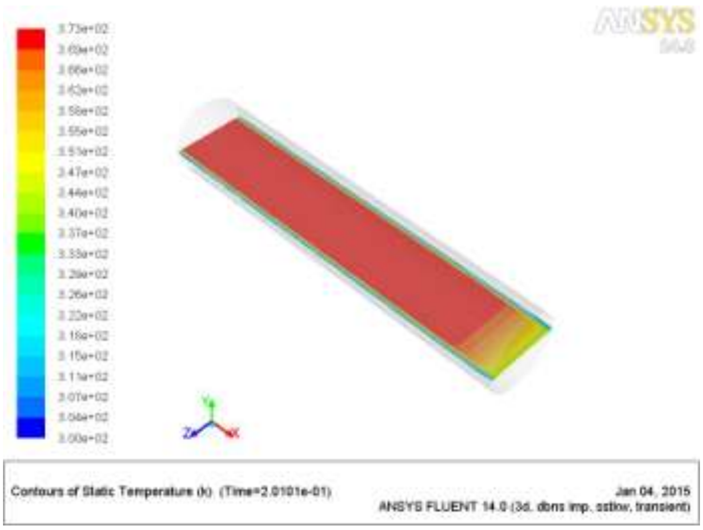


Fig. 11 Pebble Bed Temperature Variation Along Y=0 Plane At (A) T=2X10^{-3}

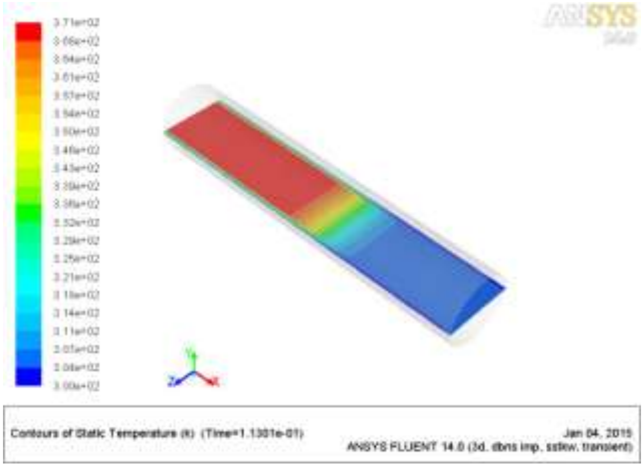
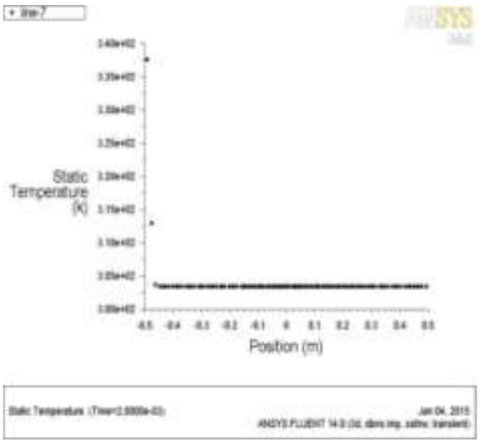
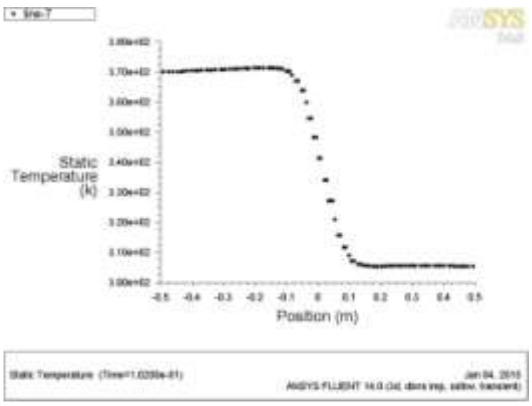


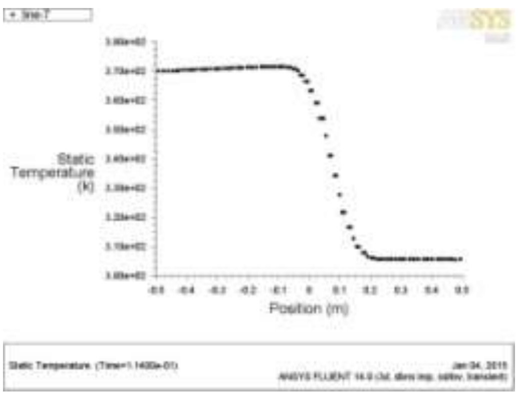
Fig. 12 Pebble Bed Temperature Variation Along Y=0 Plane At (A) T=2X10^{-3}

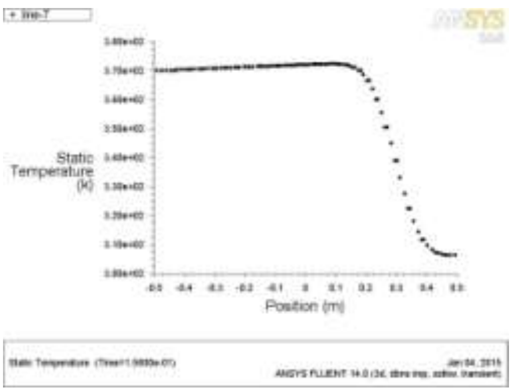
Fig. 13(a), (b), (c), (d) shows graphical representation of temperature variation of pebble bed regenerator along its axis.Fig. 13(b), 13(c) and 13(d) shows spreading of temperature front in regenerator, this is caused due to three factors (i) deviation from plug flow of hot gas in porous medium, some fluid particle moves faster some moves slower which disturbs the plug flow. (ii) fluid offers resistance to heat transfer between gas and solid. Due to large size of solid particles the product of area and heat transfer coefficient can be very much lower than for beds of fine solids. (iii) resistance to heat flow into particle, with large solid particles heating time is also large.





(a) **(b)**





(c) **(d)**

Fig. 13Regenerator Temperature Variation Along Y=0 Plane At (A) T=2X10^{-3}, (B) T=1.02X 10^{-1}, (C) T=1.15X 10^{-1}, (D) T=2.04X 10^{-1}

III. CONCLUSION

The greatest disadvantage of solar energy of being intermittent is neutralized by thermal storage systems. Regenerator provides high temperature which can be widely used in local and commercial purposes. To study the performance of regenerator a 3D transient(unsteady) mathematical model was developed and was solved using Fluent. Temperature, velocity and pressure variation were studied and presented. The following conclusion were made:

(i) Pressure gradually decreases in the direction of gas flow. The out pressure of gas at the end of heating cycle is 7469 pa. with decreases in pressure in the regenerator velocity along the flow direction increases up to 9 m/s at the outlet of regenerator from 5 m/s at the inlet of regenerator.

(ii) Hot gas enters at 373K through inlet in regenerator, porous medium is initially maintained at 300K. Temperature increases along Y axis. The average inlet and outlet temperature at t= $1.02X10^{-1}$ are 370K and 300K, which goes on increasing as time steps increases.

(iv) It is observed that the heat is taken by regenerator from hot air during heating cycle which is seen by increase in temperature of regenerator bed.

(v) Spreading of temperature front in regenerator is observed, this is caused due to three factors such as deviation from plug flow of hot gas in porous medium, fluid offering resistance to heat transfer between gas and solid and resistance to heat flow into particle.

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