COMPARATIVE STUDY OF MATHEMATICAL MODEL AND CFD SIMULATION OF A PEBBLE BED HEAT REGENERATOR

Kuldeep Panwar, D. S. Murthy, Hitendra Pal Gangwar, R. Kumar

Abstract- This paper aims to provide the comparison between results obtained by the CFD simulation of a cylindrical pebble bed thermal regenerator and results obtained by a mathematical model to simulate the operational behaviour of a pebble bed thermal regenerator. A cylindrical regenerator model of 7ft length and 8 in diameter is used to simulate the behaviour of heat regenerator during both cooling and heating cycle. Hot flue gases are made to enter at 200 0C at an average flow rate of 365 l min-1. The mathematical model is developed by energy balance along a elemental volume and the results are compared with the results obtained by commercial Ansys fluent software. CFD simulation of the model shows the excellent accuracy and shows negligible deviation with the simulation results of mathematical model.

Index Terms- Ansys fluent, CFD, pebble bed, regenerator, transient, thermal storage, flue gases

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1 INTRODUCTION

According to fifth assessment (AR5) in 2014 of the Intergovernmental Panel Change (IPCC) the scientists are 95% certain that most of the global warming is caused due to increase in concentrations of greenhouse gases and other human activities. In today's scenario with increasing global warming, waste heat utilization is gaining its significance.

Thermal heat regenerator are an very essential heat storage system which nowadays have found wide range of applications in utilization of thermal waste heat. In thermal regenerators the waste heat from flue gases is stored by solids which in turn is transferred to other gas.

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. In first step hot gas give up heat to the solids (heating cycle) and in second step the heat is transferred to the other gas(cooling cycle). Choudhury and Hossain [1] has developed a mathematical model to simulate the actual working of a pebble bed regenerator.

The present study aim to compare the result provided by the mathematical model simulation with the result which are obtained by CFD simulation of the same model during heating and cooling cycles simultaneously.

A review of various method for storage of thermal energy have been discussed by Pinel, Cruickshank, Beausoleil-Morrison and Wills [2]. According to the study of Wei, Li, Xu and Tan [3], 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 same direction and heat is transferred from matrix to cold air. Many paper are published to understand the regenerative process in regenerator by Lorsch, Kauffman and Denton [4], Schmidt and Willmott [5], Schmidt [6]. Levenspiel [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, Tao, X. Liu and Wen [8] in his paper has presented 3-dimentional analysis of gas flow and heat transfer in regenerator with aluminium balls. Yu, Zhang, Fan, Zhou and Zhao [9] provided one dimensional transient mathematical model to describe heat transfer in solid and liquid phase in regenerator. Park, Cho and Shin

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- *Kuldeep Panwar is currently pursuing PhD degree program in Thermal engineering in G.B.pant University,India, PH-+919760305410. E-mail: kuldeeppanwar.kec@gmail.com*
- *D.S.Murthy is currently professor in Mechanical Engineering Deptt.atG.B.Pant University, India,.*
- *H.P.Gangwar is currently pursuing PhD degree program in Thermal engineering in G.B.pant University,India, PH-+919458960192. E-mail: hitendra.gangwar@gmail.com*
- *R. Kumar is currently guest faculty at MMM University,Gorakhpur, India E-mail: srameswar31@gmail.com@gmail.com*

[10] established one dimensional two phase fluid dynamics model to describe transient thermal flow through regenerator with spherical particles. Zhong, Liu and Wang [11] gave three dimensional transient mathematical model for heat transfer in regenerator matrix. 2- dimensional for honeycomb regenerator was developed by Rafidi and Blasiak [12].

2 CFD SIMULATION

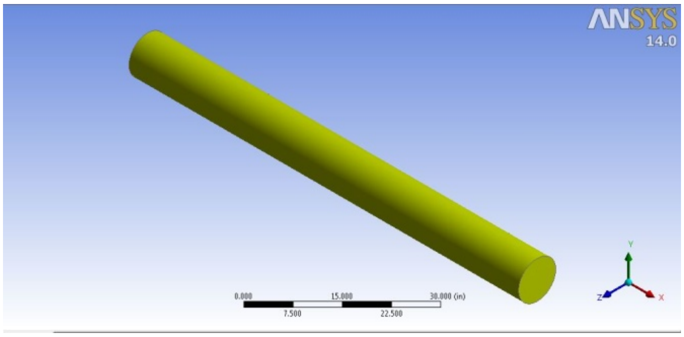

Fig. 1 Physical model of regenerator

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. The entire region of the regenerator is considered as a single fluid zone, instead of the three different zones. "Fig.1" shows physical model of regenerator of length 7 ft and diameter 8 in. The operation involves heating the pebble bed using waste heat in one cycle, and recovering the stored heat using clean air in another cycle. "Fig.3" shows the arrangement of 6 thermocouples at equal distance are fixed to obtain the temperature at the specific points throughout the regenerator. "Fig.2" shows computational grid using ICME Fluent 14 with hexahedral cell in all zones.

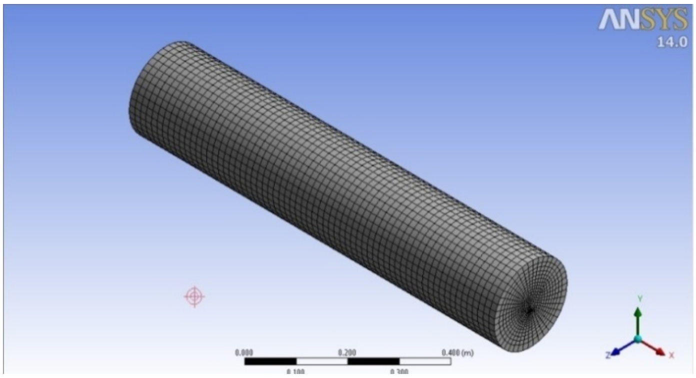

Fig. 2 Computational model of regenerator

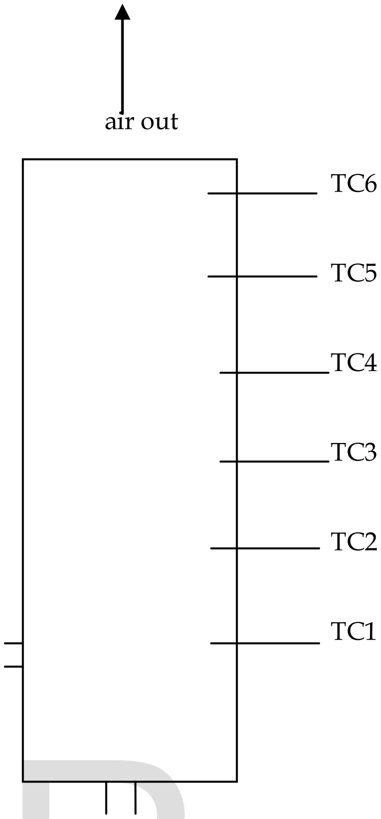

Fig. 3 Physical model of regenerator with thermocouple positions

Assumptions for mathematical modelling of regenerator are as follows:

Temperature gradient within pebbles is neglected, Thermo physical properties of gas and solids are only dependent on temperature. No heat loss from column wall.

3 GOVERNING EQUATIONS

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

A. Continuity equation:

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

B. 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, Si 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 [13].

The equation for permeability and inertial resistance factor for gas flow in axial direction are given by Huang [14] in his paper where he simulated heat transfer in regenerator. Those equations are as follows:

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

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

C. Energy Balance Equation:

$$u_f \rho_f c_f \frac{\partial t}{\partial x} + \rho_s c_s (1-\varepsilon) \frac{\partial t}{\partial \tau} = k_s \frac{\partial^2 t}{\partial x^2} \tag{5}$$

Heat carried by fluid Heat stored in solid Heat transfered by solid

D. Boundary Condition:

at x=0

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

at τ=0

t=tamb (7)

E. 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

F. Initial and boundary conditions:

at τ=0

t=ts=t0 (7)

at τ**>0** x=0 tf=tfi

$$t_s = (t_0 - t_{fi}) \exp\left(\frac{\tau h A}{S_s \rho_s c_s} \right) + t_{fi} \tag{8}$$

Table 1 Boundary Conditions

S.No.	zone	Flow rate	Flow	Temperature
1	Inlet	365 l min-1 for hot gas	K=constant ε=constant	200 0C for hot gas
		360 l min-1 for air		27 0C for air
2	Outlet	Outflow	Extrapolate from interior of domain wall functions	Extrapolate from interior of domain q= constant
3	Porous (ø = 0.415)	No slip		

4 MATHEMATICAL MODEL

Mathematical model used to compare the results of CFD simulation is developed by Choudhury [2] in his paper. In his paper he has considered an elemental section of Δz as shown in "Fig. 4".

Energy balance equation in the elemental section for air:

Heat of air in at z = heat exchange between pebble and air + Heat out at (z + Δz)

$$M_{m,n} c_A T_{m,n} = h(S \Delta z A)\left(T_{m+\frac{1}{2},n} - \theta_{m+\frac{1}{2},n} \right) + M_{m+1,n} c_A T_{m+1,n}$$

$$T_{m+1,n} = \frac{2M-1}{2M+1} T_{m,n} + \frac{2}{2M+1} \theta_{m+\frac{1}{2},n} \tag{9}$$

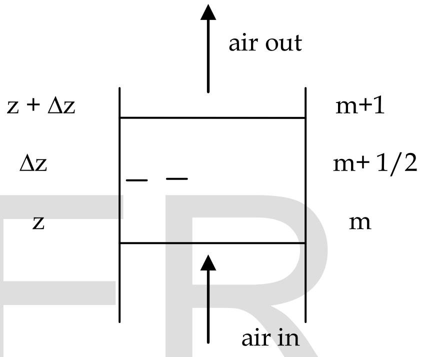

Fig. 4 Energy balance for elemental volume

Energy balance equation for air and pebbles in the elemental section:

Heat gain/lost by air in Δt time = Heat gain/lost by pebbles in Δt time

$$M_A c_A (T_{m,n} - T_{m+1,n}) \Delta t = W_s c_s \left(\theta_{m+\frac{1}{2},n+1} - \theta_{m+\frac{1}{2},n} \right)$$

$$\theta_{m+\frac{1}{2},n+1} = \frac{N(2M+1)-2}{N(2M+1)} \theta_{m+\frac{1}{2},n} + \frac{2}{N(2M+1)} T_{m,n} \tag{10}$$

Equation (9) & (10) gives the curve s of temperature versus time at different bed positions. The values of Δz and Δt were taken 4 in and 10 min respectively.

5 RESULT AND DISCUSSIONS

The calculation starts with heating cycle, The initial temperature of hot air from air heater is 200 0C and the regenerator is maintained at 27 0C. Boundary condition are shown in Table I. CFD software Ansys Fluent is used to solve the mathematical modelling 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 120 min and results are studied at the interval of 10 min at different thermocouple positions. "Fig.5" shows the curve between temperature and time at different position of bed for heating cycle. The position in the bed are designated by number 1 to 6. 1 being closest to the distributor and 6 being farthest from it. Curve T1 shows the modelled result at position 1 of the bed and TS1 shows the results obtained by the Fluent. As it could be seen from the curve the top portion of bed is slightly heated after the entire 2 hrs cycle. The temperature obtained by the topmost portion is 64 0C. Curve shows a very close variation between simulated and modelled results and verifies the modelled results.

After the completion of heating cycle, cooling cycle starts with introduction of air at ambient temperature 27 0C in the regenerator. The cooling cycle continue for 2 hrs. "Fig.6" shows the curve between temperature and time at different position of bed for cooling cycle. The position in the bed are designated by number 1 to 6. 1 being closest to the distributor and 6 being farthest from it. Curve T1 shows the modelled result at position 1 of the bed and TS1 shows the results obtained by the fluent software.

It could be seen from the curve that during the starting of cycle the regenerator seems to be heating instead of cooling this phenomenon is due to the fact that the length of the regenerator is unduly long due to which the during the cooling cycle the air will move the heat from lower section of bed to top section. The CFD simulation is fully predicting this phenomenon which means it is a excellent simulation.

The second cause of heating of regenerator during initial phase of cooling cycle is high inlet temperature of air which means that the air has very little capacity to absorb heat and then after moving a short distance in bed quickly attains the temperature higher than the considerable portion of the top section of the bed, due to which the bed starts absorbing the heat instead of giving heat.

From "Fig.5" & "Fig.6" gives the comparison of mathematical modelled and results from Ansys Fluent simulation and it is clear from the results that Fluent Simulation is very well able to predict the modelled results.

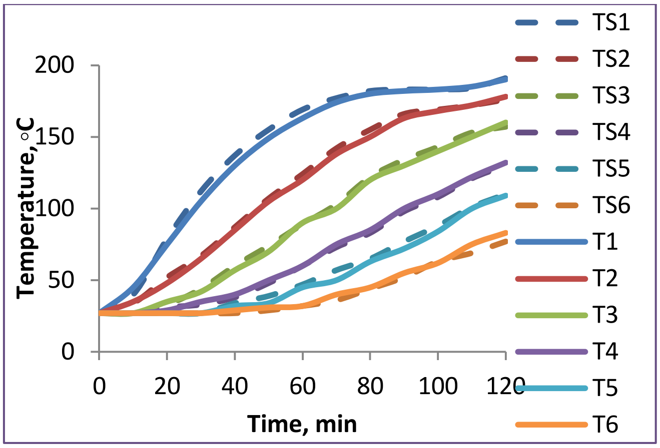

Fig. 5 Temperature against time at different bed position during heating cycle

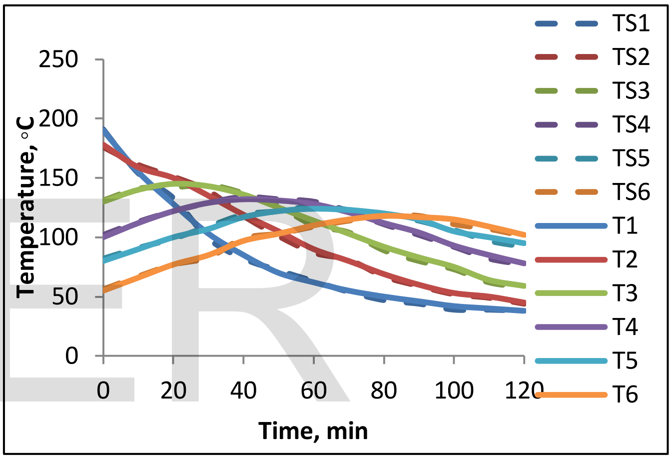

Fig. 6 Temperature against time at different bed position during cooling cycle

"Fig. 7" shows the pressure variation along the plane y=0 of the regenerator. The pressure difference within the regenerator is due to the porosity within the regenerator. It 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, with decreases in pressure in the regenerator velocity of air along the flow direction increases. The calculation starts with heating cycle, The initial temperature of hot air from air heater is 200 0C and the regenerator is maintained at 27 0C. Heating cycle is continued for 120 min and results are studied at different thermocouple positions. "Fig. 8" shows the temperature variation at different position of bed for heating cycle. As it could be seen from the curve the top portion of bed is slightly heated after the entire 2 hrs cycle. The temperature obtained by the topmost portion (x=72) is 64 0C.

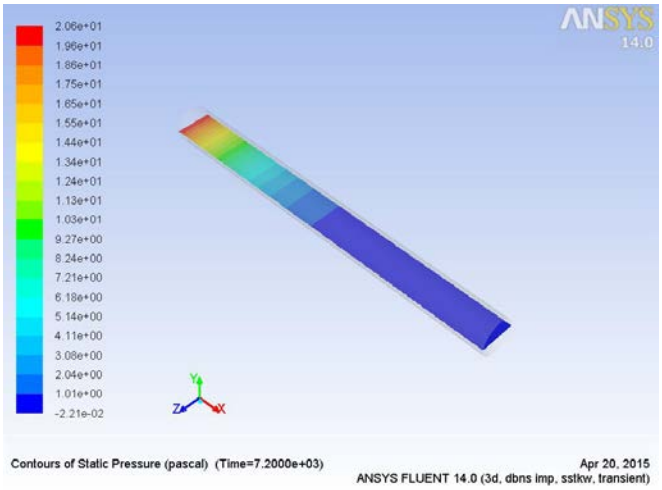

Fig. 7 Pressure variation along the regenerator during heating cycle

For cooling cycle air at 27 0C enters the pebble bed for 120 min. "Fig.9". shows the variation of temperature at different positions along the length of regenerator.

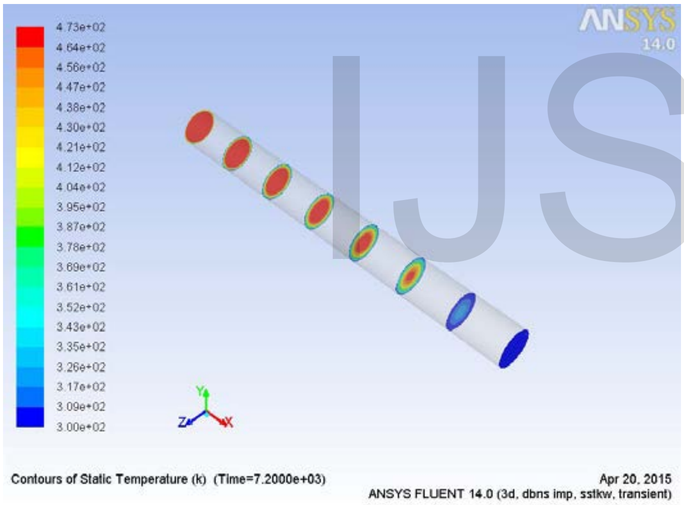

Fig. 8 Temperature variation at x=0, 12, 24, 36, 48, 60, 72, 84 at t = 120 min for heating cycle

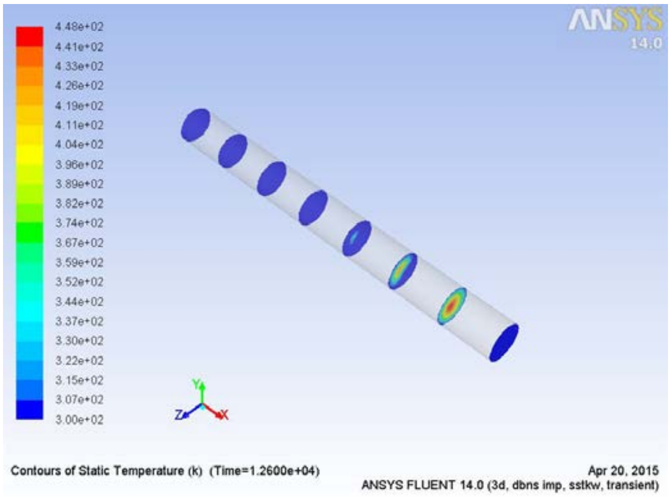

Fig. 9 Temperature variation at x=0, 12, 24, 36, 48, 60, 72, 84 for cooling cycle

The initial stage of cooling cycle shows the heating of regenerator due the high temperature of air then the bed and the length of the pebble bed.

5 CONCLUSION

The commercial Ansys Fluent software accurately predicts the mathematical modelled results. A good agreement was found between the modelled and CFD simulated results with maximum deviation of 7 ^{0}C during heating cycle and 5 ^{0}C during cooling cycle which is negligible. The slight deviation can be explained by the fact that the regenerator wall during the simulation was fixed at ambient temperature 27 ^{0}C. It is concluded that the modelled results that has been verified by the simulation model can be used by the designer to reliably design a thermal heat regenerator system for waste heat recovery from flue gases.

NOMENCLATURE

A = area of heat exchange between soil and gas, m2
c = specific heat at constant pressure, J kg-1K-1
D = diameter of solids, m
C2 = 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
T = temperature of air, 0C
M = mass flow rate of air, kgs-1

Subscript
s = solid phase
f = fluid phase
m = distance increment
n = time increment
a = air

Greek Symbols
ρ = density, kg m-3
μ = viscosity of gas, kg m-1 s-1
μt = turbulent viscosity, kg m-1 s-1
ø = porosity
ε = solid emissivity

θ = temperature of pebbles, 0C

Δt = time interval, s

Δz = height of volume element, m

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