Thermal Performance Analysis of a Honeycomb Regenerator

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Abstract-Thermal regenerators are heat exchangers in which heat is absorbed and released using high heat capacity materials. In fixed bed regenerators the bed absorbing and releasing thermal energy is fixed and the hot and cold fluid streams are alternatively passed through the bed. Honeycomb regenerators find their wide applications in regenerative burners in large number of industries to preheat combustion air with exhausted flue gases and their unsteady conjugated heat transfer was investigated by two-dimensional numerical simulations in the literatures. In the present work two dimensional simulation has been carried out for predicting temperature profiles andthree-dimensional simulation has been carried for predicting thermal efficiency and the same has been validated with the available literature.

Index Terms- Fixed bed , Honeycomb structure,Ceramic, Unsteady,Conjugated heat transfer, Temperature profile, Thermal efficiency.

1 INTRODUCTION

With the ever increasing demand of fossil fuels and their faster depleting rates and global warming,there is a consistent demand to increase the efficiency of industrial systems and waste heat recovery systems have become increasingly more important. One such system for the recovery of waste heat is thermal regenerator. A regenerator is a type of heat exchanger which operates in a cyclic mode, in which the hot fluid and the cold fluid enter alternatively and exchange heat with a solid acting as a storage medium for the thermal energy.By using this principle, thermal energy is indirectly transferred from the hot fluid to the cold fluid through the solid matrix.Thermal regenerators find their applications in metallurgical industries, glass industries and various other fields for utilization of waste heat. In glass and steel industries, power plants fixed bed regenerators are used for producing high are used for preheating the inlet air to the furnace by recovering thermal energy from waste flue gases resulting in significantly increased thermal efficiency. The operating temperatures and operating conditions require the regenerator packing to be made from the low thermal conductivity materials such as ceramics. Compared with the metallic heat exchangers used traditionally[1], regenerators manufactured by ceramic materials can withstandhigher temperature and larger thermal stresses, and thus they are widely used in advanced regenerative burners to preheat the combustion air with the flue gas [2],[3],[4]. Scholars and engineers investigated the time-dependent heat transfer in the regenerators and obtained analytical solutions based on various assumptions [5],[6]. Muralikrishna [7] obtained the analytical solutions for the governing equations with and without axial conduction terms and validated them by comparing with experimental data. Monte [8] considered the effect of flushing phase, i.e. removing the remaining fluid from previous period, and obtained a solution for counterflow regenerators running in cyclic states. The above solutions are obtained by assuming constant properties and uniform lateral temperatures, and could result in considerable errors for the regenerators of regenerative burners with large temperature variations. Thus, scholars and engineers resorted to experiments [9],[10], which are expensive and time-consuming. With the development of numerical heat transfer technology and performance of computers, numerical simulations extensively used in the research of regenerators [22][24]. Compared with the packed particle regenerators, honeycomb structure regenerators have straight openings and larger specific surface areas, which are capable of obtaining greater heat transfer rates and reduced flow resistances [9]. Rafidi and Blasiak [12] conducted numerical and experimental investigations for the ceramic honeycomb structure regenerator with square openings. With the assumption that fluid streamwise velocities always take the fully-developed parabolic profiles, they constructed the 2D numerical model of unit cell and obtained the temperature profiles, regenerator effectiveness and energy recovery ratio, etc.

In the present work, the 3D numerical study has been conducted with the commercial package of ANSYS Fluent for the ceramic honeycomb structure regenerator. The Navier - Stokes equations have been solved for the fluid velocities and thecomputation of conjugated heat transfer between fluids and solidhas been performed. The numerical model is validated by comparing the results obtained with experimental and numerical results available in the literature. With the present 3D numerical simulation, the mechanism of heat transfer inside the regenerator has also been analyzed.

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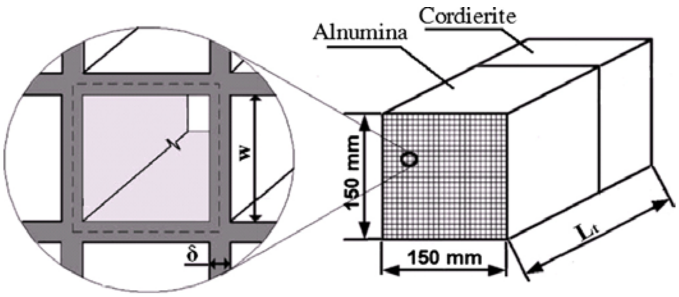
2PHYSICAL MODEL

The ceramic honeycomb structure regenerator in [12], having length (L_t= 300 mm) , and having square openings is depicted in Fig. 1(b) and 1(a), respectively. To reduce the cost of the regenerator, the regenerator was divided into two portions. The portion with combustion air inlet, having length $L_t/3$, was manufactured with the cheap cordierite. The dimensions of the square opening i.e. side length and thickness of the wall arew(=2.07 mm) and δ(=0.43 mm), respectively. During the operation of the regenerator, the flue gas and combustion air flowed alternatively through the honeycomb openings in opposite directions, and the switching time is τ.



(a) Cell structure (b) Honeycomb regenerator

Fig.1. Schematics of ceramic honeycomb structure regenerator [12]. (a) Cell structure; (b) honeycomb structure regenerator.

The above-mentioned composite ceramic honeycomb regenerator is used in the present investigation. The switching time for both flue gas and combustion air is taken to be the same, τ =30 s. The inlet temperatures of the flue gas and combustion air taken to be 1373K and 380K respectively. Air inlet velocity of (u_{ai} =) 2.6 m/s is considered for the present study.

3 NUMERICAL MODEL

3.1 Governing Equations

The flow and heat transfer in the regenerator is essentially unsteady. With the assumption that fluid flows are laminarand ignoring heat transferdue to radiation because of the small characteristic length of regenerator opening, the energy conservation equations of fluid and solid are expressed by"(1)" and "(2)", respectively.

$$\rho_f Cp_f \frac{\partial T_f}{\partial t} + \rho_f Cp_f (u.\nabla)T_f = \nabla.(k_f \nabla T_f) \qquad (1)$$

$$\frac{\partial(\rho_s Cp_s T_s)}{\partial t} = \nabla.(k_s \nabla T_s) \qquad (2)$$

where$T_f$andT_s are coupled with the heat flux conservation through the interfaces of fluid and solid, and the fluid velocity (u) is determined by solving the continuity equation"(3)" and Navier-Stokes equations "(4)".

$$\frac{\partial \rho_f}{\partial t} + \nabla.(\rho_f \mathrm{u}) = 0 \qquad (3)$$

$$\rho_f \frac{\partial u}{\partial t} + \rho_f (u.\nabla)u = -\nabla p + \nabla.[\mu_f \left(\nabla u + \nabla u^T - \frac{2}{3}\nabla.uI\right)] \qquad (4)$$

The buoyancy effect does not play a significant role because of the small characteristic length of the honeycomb structure and hence the gravity terms are omitted in the N-S equations.

3.2 Computational region, mesh and boundary conditions

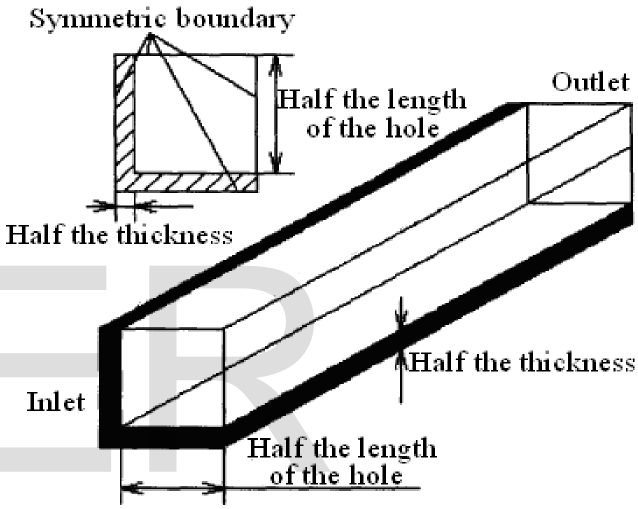


Fig. 2.Computational Region

Computational Region: As regenerators are usually installed near furnaces, the impact of tubes on flue gas temperatures is limited. Therefore the inlet temperature of flue gas is assumed to be uniform. The three-dimensional region in the simulation includes the solid material and flow path (the gas phase). The honeycomb cell is square-axisymmetric, the velocity, temperature and pressure distribution are all symmetric. So half the wall thickness, 1/4 flow path and the whole length of the cell is taken as the computational region as shown in Fig.2.

Boundary conditions: There is symmetry of the flow and heat transfer in the three-dimensional flow zone of the honeycomb structure used for simulation and therefore the four exterior sides along the direction of the gas flow are defined as symmetric boundary condition. The solid surfaces at both the ends of the honeycomb structure are defined as adiabatic boundaryconditions. The contact surfaces cannot be used as pre-specified boundary conditions as these are dynamically determined by the thermal transformation process, which cannot be predetermined and is known as conjugate heat transfer.

The coupled boundary conditions at the interfaces of fluid and solid can be listed by the following expressions:

$T_w|_{honeycomb} = T_w|_{gas}$ (Continuous Temperature)

$q_w|_{honeycomb} = q_w|_{gas}$ (Continuous heat flux)

where, the subscript-honeycomb and gas mean the simulation regions respectively, w means the interface between the two regions. The gas mass flow rates of the two heat-exchange stages in one working cycle should be the same. However, the inlet temperature of flue gas is 1373 K and that of air is 380 K. The density of cold air is about four times larger than that of flue gas. So the inlet velocities of the two flows differ widely because of the differences of the temperatures of flue gas and cold air.

During the periodwhen honeycomb structure is heated, the honeycomb regenerator end where the hot flue gas enters is defined as the inlet boundary condition, where the velocity of the incoming hot flue gas is taken as 10 m/s and the pressure is taken as 0Pa respectively. While the other end of the honeycomb regenerator where the hot flue gas leaves the honeycomb regenerator isset as pressure outlet.

During the period, whenthe honeycomb structure is cooled, the end where the cold combustion air enters is defined as the inlet boundary condition, where the velocity of the incoming combustion air is taken as 2.6 m/s and pressure is taken as 0Pa, while the other end is set as the pressure outlet. Besides, with the adoption of symmetric boundary conditions, the computation domain is reduced to one quarter of cell structure. The structural hexahedral elements are adopted for the mesh generation.

Physical property parameters of gas and honeycomb structure: Alumina (ρ= 2800 kg/m3, k = 2.2 W/m-K, c_p = 1005 J/kg -K) and cordierite (ρ = 1700 kg/m3, k = 2.15 W/m-K, c_p = 920 J/kg-K) were used for making walls of the honeycomb structure. The flue-gas and the preheated air flow through the honeycomb alternately. There is a small influence of the difference in physical properties of the flue gas and air on the heat transfer performance of the honeycomb structure regenerator, the physical properties of the air is used instead of the flue gas in the numerical simulation for convenience.

3.3. Computational scheme

ANSYS Fluent is employed for the current numerical study of regenerators with unsteady conjugated heat transfer. The implicitpressure-based solver is adopted and pressure and velocity are coupled with the 'SIMPLE' algorithm. The unsteady terms take the two-orderimplicit formulation, while the momentum terms and energy terms are discretized with second-order upwind scheme. The switches between air and flue gas are assumed to take place instantly. All equations take the convergent criterions of relative residual of 1E -3 except energy taking 1E-7.

The assumption of negligible heat transfer due to radiation is validated by comparing the CFD results obtained with and without activating the radiation model. The difference is very small compared to the outlet temperature of the combustion air and therefore heat transfer due to radiation can be neglected. The assumption of small buoyancy effect is validated by obtaining the results with and without activating the gravity term. The difference in the temperature of preheated air is small and hence the simulation can be carried out without considering gravity and radiant heat transfer.

The solution independence ontime step is checked with the time step of 1 s, and the grid system with about 160 k cells is adopted in the final computation after the balance of computation load and prediction precision.

4 Results and Discussion

Rafidi and Blasiak[12] obtained the temperature profiles of honeycomb regenerator with their 2D numerical model. The 2D simulation with current numerical method is performed on the same regenerator(L_t = 300mm) and switching time (τ = 30s). The comparisons of fluid temperatures on the two regenerator ends between the two simulations are depicted in Fig.3.(a). In the two simulations, the inlet temperatures of the flue gas and combustion air are 1373 K and 380 K respectively, while their inlet velocities are 10 m/s and 2.6 m/s, respectively. It is clear from the Fig. 3.(a) that the fluid temperatures obtained by current 2D model oscillate with the period of two times switching time, and the fluctuations become periodic steady after running for 600s, which match the numerical counterparts in Ref. [12]well, with the maximum relative error below 6.0% in the periodic steady state.

The errors arise because constant properties have been considered for both the working fluids under operating conditions which involve large temperature difference between the working fluids as shown in Fig. 4.

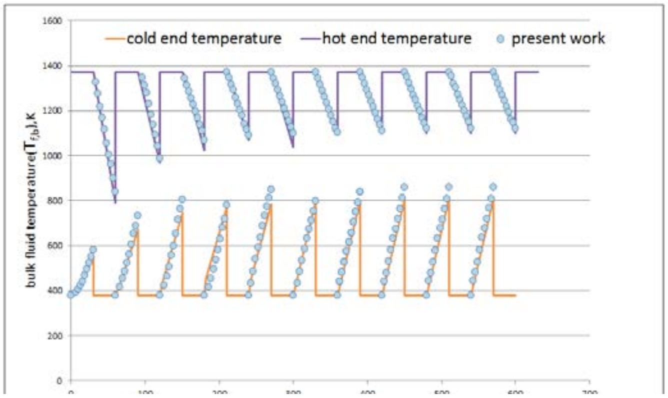


Fig. 3. Comparison of present work gas temperatures with 2D simulation in [12]

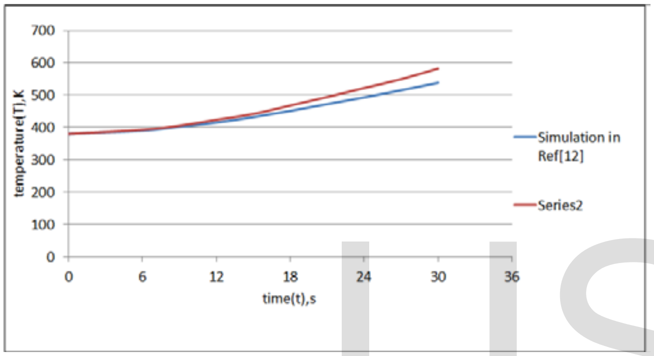


Fig. 4.-Error in temperature at cold end for switching time(τ = 30 s)

3.4.2. Comparison of temperature efficiencies

As the flow and heat transfer in honeycomb regenerator is three-dimensional, the above honeycomb regenerator, along with its working conditions, is simulated with the 3D numerical model in the present study and the computed temperature efficiencies of four different switching times are compared with experimental efficiencies in[12]. Temperature efficiencies are computed using the formula as shown below

$$\eta_T = \frac{(T_{mao} - T_{ai})}{(T_{gi} - T_{ai})}$$

From Fig. 5. it can be observed that the computed temperature efficiencies of current 3D model matches well with the experimental results[12], with the maximum relative error 5%. The error occurs because of the constant properties considered.

It is observed that with an increase in the switching time the temperature efficiency decreases both for the experimental results in [12] as well as for the current 3 dimensional simulation . So switching time should be too long.

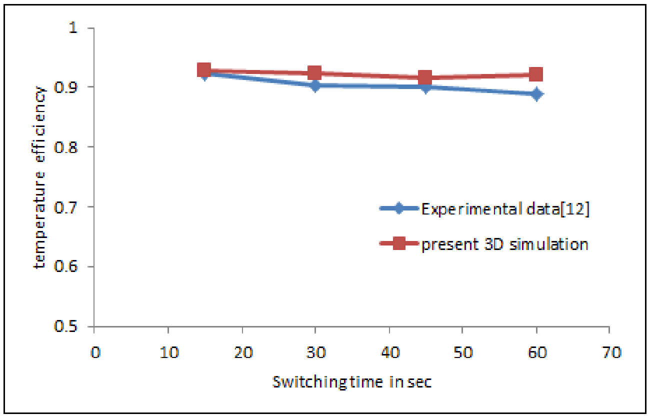


Fig. 5. Comparison of present temperature efficiencies with experimental counterparts

Theamount of thermal energy transferred from the flue gas to solid structureincreases with the increase in switching time of the flue gas shot. This is observed as the flue gas shot proceedsthe mean temperature of the solid honeycomb structure increases. As the solid temperature increases, the heat transferrate between gas and solid decreases, due to lowered temperature difference between the honeycomb structure and the flue gas and hence the temperature of the flue gasin the regenerator increases. The temperatures of the combustion air and soliddecreasewith combustion air shot in progress, and the combustion air temperaturesare always lower than those of surrounding solid honeycomb structure. Thisphenomenon indicates that with the advancement of air shot, theamount of thermal energy transferred from the honeycomb to the combustion air increases because the temperature of combustion air increases.As the honeycomb structure's temperature decreases as it loses its energy to the combustion air, heat transfer rate decreases, and the temperature of combustion airdrops.

5 Conclusions

In the present work, three-dimensional numerical simulation isconducted on the honeycomb structure regenerator with small square openings.
Some conclusions are obtained as below:
(1) The current three-dimensional numerical results match reasonably with the experimental data. The mean relative deviation of temperatureefficiency equals 7 % which is due to constant properties taken for the gases under operating conditions involving large temperature difference.
(2) As the flue gas and the combustion air shots are in progress, the amount of thermal energy transferred between fluids andsolid increases with time but the heat transfer rates decrease.

(3)The switching time is an important parameter which influences the temperature efficiency of thehoneycombregenerator.

(4)The switching time during the operation of the regenerator should not be too long as with longer switching times the temperature efficiency decreases .

Nomenclature

c_p specific heat capacity (J/(kg K))

p pressure (Pa)

L_t length of regenerator (m)

$T_m$mean temperature (K)

u_{ai} velocity at the inlet (m/s)

x, y Cartesian coordinates perpendicular to the flow direction.

Δ gradient operator difference

μ viscosity (kg/m-s)

C capacity rate (W/K)

I identity matrix

k thermal conductivity (W/(m K))

t time (s)

T temperature (K)

u velocity vector (m/s)

w side length of square opening (m)

z Cartesian coordinate parallel to the flow direction, z = 0

δ skeleton wall thickness (m)

η_T temperature efficiency

ρ density (kg/m3)

τ switching time (s)

Subscripts and superscripts

a combustion air

f working fluid

o flue gas outlet

g flue gas

z parallel to the flow direction

s solid

0 ambient, reference

i inlet

b bulk

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