Analysis of Thermal & Resistance Characteristics of Aluminium refractories-bed Regenerator

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Abstract. The paper presents the (3D) CFD modelling and analysis of unsteady flow through an Aluminium refractories-bed regenerator. Aluminium refractories-bed regenerator having particle to diameter ratio (D/d_p) 3, 8, 12 were used to analyse the flow complexities and thermal characteristics of the regenerator. Due to low D/d_p the void ratio near the regenerator wall is greater than in bulk region due to which there are large flow complexities in these beds. To study the detailed flow complexities within these vicinities commercial fluent software is used. The predicted results of pressure drop and wall effect were compared with the previous experimental results and a good agreement was found between them.

1. Introduction
To utilize the waste heat from flue gases various units are being used today namely Heat exchangers, Recuperators, Regenerators, Heat pipe exchangers, Rotary heat exchangers, Economizers and Heat pumps etc. In the present study Regenerators is studied as an effective heat recovery system being used in industries to recover heat from flue gases. A heat regenerator is an insulated container filled with metals or ceramics of different shapes that can absorb and store relatively large amounts of thermal energy.

2. Literature Review
The pressure drop inside the regenerator in case of a fully developed flow is given by Ergun’s equation given by [1]. The limitation of this equation is that it holds good for large D/d_p ratio (>15), where condition of uniformity in void fraction prevails. The Ergun’s equation is:

\[
\frac{\Delta p}{H} = 150 \left( \frac{1-\varepsilon}{\varepsilon^3} \right) \frac{\mu U}{d_p^2} + 1.75 \left( \frac{1-\varepsilon}{\varepsilon^3} \right) \frac{\rho U^2}{d_p} \tag{1}
\]

The coefficients of Ergun’s equation in Eq. 1 (150 and 1.75) are universally disputed and controversial. Another study by [2] has also given an equation for pressure drop in Aluminium refractories bed regenerator with spherical particle but the coefficients in his equation are not constant but are the function of Reynolds number. In another research conducted by [3] it was found that Ergun’s equation was unable to predict the pressure in irregular packed bed regenerator. Another equation for pressure drop in Aluminium refractories bed regenerator is given by [4] as given in Eq. 2:
\[
\Delta p = 180 \left( 1 - \varepsilon \right)^2 \frac{\mu U}{d_p^2} + 1.8 \frac{1 - \varepsilon}{\varepsilon^3} \frac{\rho U^2}{d_p}
\]  

(2)

All the above mentioned pressure equations are for Aluminium refractories bed regenerator with \(D/d_p\) greater than 15. Since the regenerators with \(D/d_p > 15\) are considered having uniformity in void fraction in the bed, the flow complexities is very low in these cases. In Aluminium refractories bed having low \(D/d_p < 10\) the void ratio near the regenerator wall is greater than in bulk region due to which there are large flow complexities in these beds. The detailed understanding of flow structure in spaces near the particles in these beds can only be gathered by highly sophisticated flow analysis tool like Ansys Fluent. The complete review of wall effects in regenerator done by [5] concluded that correlation for pressure drop by [6] is most promising one. One of the major objectives of the present study is focused on calculating the pressure drop and drag coefficients for Aluminium refractories bed with \(D/d_p\) less than 10 with the help of CFD simulations and comparison of the simulated results with [6].

2.1. A Flow regimes in Aluminium refractories bed regenerator

The performance of regenerator depends on the resistance and thermal characteristics and these characteristics are majorly affected by the flow regimes with in the regenerator. Ergun’s equation holds good only for fully developed flows, and various other researchers has studied the effect of wall on pressure drop in regenerator for different flow regimes. [7] and [8] has predicted the wall effects for creeping flow regimes. Similarly [9] have predicted the pressure drop for the case of \(D/d_p\) 4 and Reynolds number 100-1000. The present paper predicts the wall effects with in the regenerator, for low \(D/d_p < 12\) and for all flow regimes (creeping, transition and turbulent flow) i.e. \(Re = 0.1 – 10000\).

For the study of temperature variation throughout the regenerator bed length, the regenerator is modeled in the Ansys design modular and after proper meshing of the model in GAMBIT it is imported in Ansys Fluent [10], where the transient simulation with time step of \(10^{-3}\) and switching time or cycle time of 1 minute is carried out for regenerator with \(D/d_p\) 3, 8, 12. This transient CFD simulation of flue gases in heating cycle and ambient air in cooling cycle is continued till the steady state in temperature flow is reached.

3. CFD modelling

The importance of new methodology to solve the complex problems in fluid mechanics and heat transfer has become known as Computational Fluid Dynamics (CFD). Recently to predict the flow and temperature distribution for complex geometries CFD have been proved to be a very handy, useful and efficient. The capability of CFD has helped the researchers a lot to conduct simulations or analysis by changing material properties, geometries, and studying their effects on the performance. The present work is based on one of the most respected CFD code “FLUENT”. Ansys Fluent is a state of art computer software which is used to model the heat transfer and fluid flow process in complex engineering situations.

3.1. Problem formulation of CFD simulation

In the present work the Aluminium refractories bed regenerator having \(D/d_p< 12\) are analysed with Fluent. Due to the non-uniformity in the voidage between the area near the regenerator wall and the bulk region of the regenerator the mathematical model and other simulating codes are not capable of analysing such flow complexities, but with the help of Fluent this analysis can be done accurately.
3.2. Physical model, Computational geometry & Meshing

The physical model considered in the present analysis model was used to analyse the transient flow and temperature pattern throughout the regenerator bed for \( D/d_p = 3, 8, 12 \) is shown in Fig.1. The geometrical details of physical mode are given in Table 1.

![Figure 1. Schematic of physical models of different bed heights and D/d_p ratio](image)

The computational model was made in Gambit which is a pre-processor of Fluent. It is used to create the geometries and generate the meshes.

| Parameters                      | Physical Model |
|--------------------------------|----------------|
|                                | \( D/d_p = 3 \) | \( D/d_p = 8 \) | \( D/d_p = 12 \) |
| Average voidage/ porosity      | 0.439          | 0.439          | 0.439          |
| Regenerator Diameter, mm       | 76.3           | 201.2          | 301.8          |
| Regenerator height/ Bed height, mm | 179.2           | 250            | 350            |
| Particle/Solid Diameter, mm    | 25.15          | 25.15          | 25.15          |
| Max. Skewness                  | 0.55           | 0.54           | 0.54           |
| Average aspect ratio           | 1.62           | 1.55           | 1.73           |
| Particle material              | Aluminium refractories |

The meshing of the regenerator model developed in design modeler was done in Ansys ICEM. 101332 hexahedral cells comprising 102445 nodes were used for meshing to capture the effect of stratification accurately with in the regenerator.

The quality of mesh is very important in the CFD for getting the accurate results in minimum simulation time. To measure the quality of the mesh skewness is one of the important factors. Skewness of a grid is an indicator of quality and suitability. Range of skewness is from 0 to 1. For hexahedral cells, skewness should not exceed 0.85. The worst value of skewness factor in the present geometrical model was 0.54 and the average skewness of the geometric model was 0.10. The details of skewness factors for both computational models are given in Table 1.
Another factor to measure the quality of meshing is aspect ratio. Aspect ratio is defined as the ratio of longest to shortest side in a cell. Ideally it should 1. The details of aspect ratio for computational models are also given in Table 1.

Effective conductivity of the porous medium is computed by Fluent as the volume average of fluid conductivity and solid conductivity. The appropriate boundary conditions for the simulations were defined as follows [11]:

- Inlet velocity (Re = 0.1 to 10000) and inlet flue gas (1473K) and air temperature (300K) were specified at the inlet zone.
- Zero gauge pressure was given at the outlet boundary.
- Material type was specified for the corresponding zones which were defined as fluid type in design modeler.
- For porous media model, in cell zone condition dialog box, porous zone option was set on.
- Fluid porosity was kept 0.439.
- For regenerator wall surface was considered insulated.

Once the meshing of computational model was done in Ansys ICEM the mesh file is imported in Ansys Fluent. Grid check was done for domain extant, volume statistics, and face area and the geometry was scaled in cm. Velocity formulation was absolute, space was 3D and for unsteady simulations transient option was selected. Option of energy equation was chosen to get temperature field and porous formulation was chosen in cell zone condition. In materials option, thermal and physical properties for solids were specified. Second order upwind scheme was used for momentum equation. Pressure was solved using simple pressure interpolation. First order implicit scheme was used for transient formulation. Residuals for the continuity, velocity were set $10^{-3}$, Residual for the energy were set to convergence up to $10^{-6}$.

4. Results & Discussion

Pressure drop within the regenerator is defined as difference in pressure between the top and bottom of the regenerator bed. The simulation for pressure drop in present study is conducted for creeping, transition and turbulent flow regimes i.e. over a range of Re from 0.1 to 10000 for D/dp 3, 8, 12. The details of geometrical model are given in the Table 2.

Table 2. Details of Geometrical models of Regenerator for CFD Analysis

| Parameters          | D/d = 3 | D/d = 8 | D/d = 12 |
|---------------------|---------|---------|----------|
| Porosity            | 0.439   | 0.439   | 0.439    |
| Regenerator Dia. (mm)| 76.3    | 201.2   | 301.8    |
| Particle Dia. (mm)  | 25.15   | 25.15   | 25.15    |
| Regenerator length, (mm) | 179.2   | 250    | 350      |
| Mesh                | Hexahedral | Hexahedral | Hexahedral |
| Mesh size, (mm)     | 1       | 1       | 1        |
4.1. Variation of Pressure Drop with Reynolds number for Regenerator with $D/d_p$ 3, 8, 12 and comparison with Reichelt et al. [1972]

The variation in pressure drop along the regenerator bed with Reynolds number for $D/d_p$ 3 and 8 is shown in Figure 2. The predicted pressure drop is compared with the Reichelt et al. [1972] correlation which is found most accurate for pressure drop calculations in a regenerator for all flow regimes in the previous literature review.

Figure 2. Comparison of simulated pressure drop with Reichelt correlation: (a) Re from 0.1 to 100; (b) Re from 100 to 10000.

It is seen from the Figure 2 (a) that for creeping flow, the simulated pressure drop within the regenerator is in good agreement with the Reichelt correlation. Whereas Fig.2 (b) shows that for turbulent flow, the simulated pressure drop within the regenerator is showing a deviation of 9-19% with the Reichelt correlation. The cause of this variation between the simulated results and experimental results are the gaps between solid within the regenerator bed and wall, where the fluid velocity is very high and the meshing is unstructured. Further, it is observed pressure drop increases with increases in $D/d_p$ ratio of the regenerator. This increase in the pressure drop can be understood as, with increase in $D/d_p$ ratio the number of Aluminium refractoriess within the regenerator increases which in turn increases the pressure drop.

4.2. CFD Pressure drop correlation for regenerator with $D/d_p < 15$ and for all flow regimes

The pressure drop calculated from the CFD simulation is used to evaluate the friction factor $f_v$. Figure 3 shows the variation of friction factor with modified Reynolds’s number for Ergun, Reichlet and CFD model. It is evident from the figure that the predicted friction factor by Fluent is in very good agreement with friction factor calculated by Reichelt’s correlation. Reichelt’s correlation holds good for all flow regimes while the Ergun’s correlation is used only for creeping flows and regenerators with $D/d_p>15$. Since the CFD results are in good agreement with Reichelt’s results, pressure drop correlation predicted by CFD can be used for regenerator with $D/d_p < 15$ and for all flow regimes.
A novel CFD pressure drop correlation developed with the help of friction factor and modified Reynolds number which holds good for all $\frac{D}{d_p} < 15$ and for all flow regimes is given below:

$$\frac{\Delta p}{H} = 294 \frac{(1-\varepsilon)^2}{\varepsilon^3} \frac{\mu U}{d_p^2} + 0.72 \frac{(1-\varepsilon)}{\varepsilon^3} \frac{\rho \mu v^2}{d_p} \quad (3)$$

$$f_v = 294 + 0.72 \frac{Re}{1-\varepsilon} \quad (4)$$

where,
- $H$ is the regenerator height
- $d_p$ is particle diameter
- $U$ is flow velocity
- $\varepsilon$ is porosity
- $Re$ is Reynolds number
- $Re/(1-\varepsilon)$ is Modified Reynolds number

5. Conclusions
The Aluminium refractories-bed regenerators having small $D/d_p<15$ have non-uniform porosity within the regenerator which increases the flow complexities in these beds. Fluent was used to develop and solve the computational model to analyse the fluid flow temperature distribution within the regenerator. The predicted thermal and resistance characteristics were compared with the previous experimental findings. The results were comparable in the creeping and transition flow regimes and a maximum deviation of 10 % was observed in the case of turbulent flow regimes due to the high velocities in the gaps between the solid particles and unstructured hexahedral meshing in these regions. At last the transient CFD model of regenerator with $D/d_p$ 3, 8, 12 was modelled and solved in Fluent.

The simulation results of each time cycle (heating and cooling cycle) were analysed and efficiency for each regenerator was calculated. This transient model of regenerator can be used for other applications of thermal regenerators. The thermal and resistance analysis of regenerators having smaller $D/d_p$ ratio was done in the present work. In comparison to Ergun’s correlation which can be used for regenerator with $D/d_p$ ratio higher than 15 and for the creeping flow regimes the predicted CFD correlation can be used efficiently for designing a regenerator with $D/d_p$ ratio less than 15 and for all flow regimes.
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