COMPUTATIONAL AND EXPERIMENTAL STUDY OF FLUID FLOW AND HEAT FLOW CHARACTERISTICS IN POROUS MEDIA

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Abstract. Shortage of energy is increasing day by day and we have to store energy for our future. Storage is a challenge in the current scenario and lot of research is being conducted to find an effective way to store energy. Packed beds are one of the promising and potential methods to store thermal energy. This paper describes an attempt that has been made to study the fluid flow and heat flow characteristics in porous media. CFD analysis and experiments have been carried out with air-alumina as the porous medium. Pressure drop, velocity distribution, temperature distribution and Effective thermal conductivity have been found out. Parametric studies have been done both in experimentation and in the CFD analysis. Both experimental and computational results seem to be in good agreement.

1. Introduction
In view of the growing energy demands and incrementing environmental concern, alternatives to the utilization of conventional and polluting fossil fuels have to be carried out. One such substitute is the utilization of renewable energy sources, which are considered to be capable of overcoming the energy crisis and environmental threat. Solar energy is the most important among renewable energy resources due to its large availability. Even though the solar energy is available everywhere but its availability is discontinuous. So, heat storage system with solar collectors is the possible solution to store energy and this energy can be harnessed to meet the demand during unavailability of solar radiation. Packed bed is generally recommended for heat storage.

A packed bed or porous bed is a hollow container packed with selectively small sized materials. Numerous studies related to packed beds performance analysis were reported in the literature, as it has been used in several important applications. Primarily heat transfer and pressure drop in the packed bed has been the consideration for analysis of several experimental and theoretical studies. Generally small size storage materials with low thermal diffusivity have been used to store thermal energy. The
advantage of using small sized storage material as packing material in packed bed would give a large surface area with high heat transfer rate but large pressure drop. A computational study and an extensive experimental investigation were planned to study the fluid flow and heat flow characteristics of the packed bed and also the effects of influencing parameters on fluid flow and heat transfer.

2. Objective
The first phase of this work is to simulate the fluid flow and heat flow in a packed bed of spheres using FLUENT and to report Pressure drop, Velocity distribution and Temperature distribution. The fluid is air and the packing material is alumina. The second phase of this work is to analyze a packed bed of same geometry through experimentation and to find Pressure drop across the porous zone, temperature distribution and effective thermal conductivity ($k_{eff}$). Then the simulated results of pressure drop and temperature distribution will be compared with the experimental results.

3. Problem Description
The problem is of interest with the packed bed generally used for storage of thermal energy. A Porous media is a hollow pipe, creates the outer shell of the bed, in which packing material (alumina balls) arranged or randomly dumped and packed within the tube. Hot air, which is the heat source, is sent to the porous media in the axial direction shown below in Figure 1.

![Figure 1: Porous media - problem](image)

It was planned to conduct a computational study and an experimental study to analyze the fluid flow and heat flow characteristics of the packed bed and also the effects of influencing parameters on fluid flow and heat transfer. Those investigations would be helpful in future to design packed beds in such a way the overall performance of the system will be better. The problem is considered as two dimensional, steady, incompressible, forced convection.

4. Simulations
In the present work of porous media solid material is the alumina balls which are in static condition inside the hollow pipe. The hot air introduced from the left of the tube, so that the fluidization starts. The entire outside surface of the hollow tube is insulated to minimize the heat loss. The basic governing equations are solved using the Computational fluid dynamics software package ANSYS FLUENT.

4.1 Geometry creation and mesh generation
The initial step is to create a computational domain representing porous media. Porous pipe geometry and the computational mesh for the same geometry was generated using GAMBIT tool. Then boundary zones were specified, so that FLUENT solver would determine the respective fluid flow domain to evaluate the solution.

The two dimensional axisymmetric model was created and meshed to form the grid. After meshing, the FLUENT 5/6 solver needs to be specified so that GAMBIT knows what types of boundary conditions are allowed. The boundary types such as walls, velocity-inlet, pressure outlet, and default interior have been set. Then the final two dimensional grid has been exported to ANSYS FLUENT as mesh file.
4.2 Boundary and Initial Conditions
In order to develop a definite mathematical system of equations, reasonable boundary and initial conditions for the computational domain have been selected. Inlet boundary condition is a uniform air velocity and outlet boundary condition is the pressure outlet boundary condition, which is set as atmospheric pressure of 1 bar. Wall boundary conditions have been set as no-slip conditions, assuming there is no relative velocity between solid and fluid boundary.

![Figure 3: Boundary conditions](image)

In order to develop a porous media model, it is necessary to specify a cell zone where the porous media model is to be applied. Regarding representing the heat flow inside the porous media, it has been assumed as thermally equilibrium between the solid medium and the fluid flow. The porous media modelled here is integrated with an experimentally determined flow resistance in a porous region. To model a porous zone, the necessary input conditions provided are specifying the fluid material flowing through the porous media, assigning the porosity of the porous media and finally specifying the solid material packed in the porous medium in case of heat flow.

5. Experimentation

5.1 Setup
Components of experimental setup comprises of Blower, Flow control valve, Orifice meter, Orifice manometer, Heater, thermocouple, porous media holder, Porous zone manometer.

![Figure 4: Schematic diagram of Experimental setup](image)

In this experiment, refractory alumina balls and air together makes up the Porous medium. Alumina balls of diameters 5mm, 6mm, 7mm and 8mm are used in the experiment independently.
5.2 Heater
Nichrome wire is used as a heating element in experimental setup, as it has relatively highest resistance. The Nichrome heating coil was wound over an insulator in such a way that the inlet air attains a highest turbulence flow, so as to have a better heating of the air.

5.3 Thermocouples
Eight k-type thermocouples were fixed along the length of the porous media holder to measure temperature. The thermocouples location is shown in the figure.

![Thermocouple Location](image)

**Figure 5:** Thermocouple locations

5.4 Orifice meter and its design
An orifice meter (placed next to the flow control value) is used to determine the mass flow rate and so velocity of the air.

![Orifice design](image)

**Figure 6:** Orifice design

The Discharge co-efficient is determined using the formula,

\[
C_d = 0.5959 + 0.0312 \beta^{2.1} - 0.1840 \beta^{9} + 0.0029 \beta^{2.5} \left(10^6/Re\right)^{0.75} + 0.0900(L_2/D) \left[\frac{\beta^{2/3}}{(1 - \beta^{4})}\right] - 0.0337(L_1/D)\beta^{3/2}.
\]

The above one is an iterative calculation. A reasonable value for the Reynolds number is assumed and the iteration is started. The value of Re and \(C_d\) at after the convergence point is used for the further calculation. The volumetric flow rate of the fluid is given by

\[
Q_1 = C_d A_2 \sqrt{2 \frac{ZRT_1}{M} \left(\frac{k}{k-1}\right) \left[(P_2/P_1)^{2/k} - (P_2/P_1)^{(k+1)/k}\right]}.
\]

Since the velocity is significantly very low, the above equation is reduced to,

\[
Q = C_d A_2 \sqrt{\frac{1}{1 - \beta^4} \sqrt{2 \left(P_1 - P_2\right)/\rho}}.
\]

Where,

\[
\beta = \frac{D_o}{D_{inlet}}
\]

The orifice diameter is 18 mm and pipe diameter is 43 mm and so the value of \(\beta\) is 0.4186.

By continuity equation:

\[
Q = A_1 \cdot V_1 = A_2 \cdot V_2 \text{ or } V_1 = Q/A_1; \ V_2 = Q/A_2
\]
The Velocity of the fluid can be found from the above equation. And the mass flow rate is given by, 
\[ \dot{m} = \frac{Q}{A_1} \].
The pressure tapings are connected to a differential Electronic pressure sensor. MPX12DF Specifications:
- Pressure range: 0-10KPa
- Sensitivity= 0.5 mV/P

5.5 Experimental procedure
The experimentation was carried out two stages: Experiment preparation and execution. The pipe is packed with the alumina balls of required diameter, by removing the tail race of the porous zone. The balls are hand dropped. No agitation or ramming is done. The porosity is obtained in the order of 0.37 to 0.40. Quantity of alumina balls that are dropped into the porous zone are measured in order to ensure the porosity of the medium. After filling the tube, the end is sealed using the wire mesh and the flanges are fastened together. The Pressure drop across the porous media is measured using a manometer.

The data logger is switched on to start logging the data once the booting and the initializations are finished. On an average it takes 1.5 seconds to finish this operation. Then, the blower is turned on. Using the flow control valve mass flow rate is adjusted. Orifice setup is used to measure the flow rate indirectly. So, electronic differential pressure sensor is used to measure the differential pressure head across the orifice setup. The heater is turned ON; following that using the autotransformer, input power for the heater is controlled. The thermocouple readings are logged every 5 seconds. Simultaneously the temperature values were displayed in the LCD display.

6. Results and discussion

6.1 Pressure Drop
The pressure difference across the porous media is the function of various parameters like superficial velocity, porosity, mean particle diameter, dynamic viscosity, and density of fluid. In this work comparative study was conducted to investigate the influence of variables like inlet velocity (U), porosity (\( \varepsilon \)) and Particle diameter (\( D_p \)) on pressure drop variation of packed bed
\[ \Delta p = f(U, \varepsilon, D_p) \]

With initialization of velocity 2.534m/s, a simulation was carried out and post processing of the results was done. The pressure drop contour fig 9 and the plot of the same along the axial length is shown above in fig10. The pressure distribution of the porous zone with the change in velocity was also simulated. Under similar conditions, the experimentation was also done and the obtained results are compared as provided below. Also by varying the mean particle size and porosity simulation was done and the pressure drop characteristics is tabulated and plotted below.
Table 1: Pressure drop obtained from CFD and Experimentation

| Inlet fluid velocity (m/s) | Pressure drop (Pa) | CFD      | Experimentation |
|----------------------------|--------------------|----------|-----------------|
| 2.53                       | 5363               | 5603     |
| 2.06                       | 3637               | 3824     |
| 1.79                       | 2816               | 3012     |
| 1.40                       | 1826               | 2012     |
| 1.23                       | 1445               | 1578     |
| 1.03                       | 1063               | 1123     |

Figure 8: Contours of static pressure

Figure 9: Pressure drop Vs Inlet Fluid Velocity
Table 2: Pressure drop obtained in CFD for various Particle size

| Alumina Particle size (m) | Pressure drop (Pa) | CFD   | Experimentation |
|---------------------------|--------------------|-------|-----------------|
| 0.0062                    | 5329               | 5689  |
| 0.0080                    | 4101               | 4456  |
| 0.010                     | 3281               | 3435  |
| 0.012                     | 2734               | 2890  |
| 0.014                     | 2343               | 2456  |
| 0.016                     | 2050               | 2126  |

Figure 10: Pressure drop Vs Mean Particle Diameter

6.2 Velocity distribution

Figure 11: contours of velocity magnitude
The presence of the alumina balls within the bed will reduce the fluid flow area available; i.e. to preserve the continuity of fluid, the fluid velocity within the porous zone has been increased comparing to the inlet velocity 2.534 m/s

### 6.3 Temperature Distribution

The temperature contour for the porous zone is shown below.

![Figure 13: Contours of static temperature](image)

From the above contour we can clearly see that the temperature drop is 25 K. From the literature study it was already known that the temperature drop for the same boundary conditions in an ordinary pipe is 3 K. From this we can clearly conclude that some of the thermal energy has been stored inside the porous zone which can be harnessed.

![Figure 14: Plot - Static Temperature Vs axial length (CFD)](image)
The heat flow characteristics are studied through simulation by changing the inlet velocity to the porous zone. The results showed that there was high heat transfer rate for high velocity which is furnished below in figure 16.

Figure 15: Plot - Temperature Vs Length of the porous media.

Figure 16: Temperature plot for various velocities

7. Conclusions
A computational and an experimental study of fluid flow and heat flow within the porous media have been presented. The temperature distribution, velocity distribution and pressure distribution is reported using the CFD analysis. The post processed results for different operating and physical conditions are compared with the results of the experimentation. The following conclusions can be made out of the above analysis. The pressure drop across the packed bed determined through CFD is found to be in agreement with that of the experimental results with few deviations. In both simulation and experimentation, it was observed that the pressure drop is directly proportional to inlet velocity and inversely proportional to particle diameter and porosity. The temperature distribution inside the porous medium is with same trend but with some deviation due to uncertainty in experiments. Further, the work can be extended for an extensive parametric study on the above aspects with an objective of optimizing them, so as to obtain a better functionality. This analysis should serve as a useful starting point for developing models for packed bed.
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