The CFD study of three-dimensional model of porous medium regenerator with oscillating flow

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Abstract. The regenerator is the core heat exchange component of the Stirling engine. The performance of it is determined by the configurations and physical properties of the filling material. In this paper, a three-dimensional model of the regenerator filled with powder sintered material is established and simulated with the oscillating flow using ANSYS. After specific post-processing, the relationship between Reynolds number and specific friction coefficient as well as Nusselt number is numerically solved which provides a method to acquire characteristics of flow resistance and heat transfer for the specific configuration. Finally, the parameter of Nu/𝐶f¹/³ is chosen as an indicator to evaluate the performance of the four fillers, and the potential of being a future regenerator filler is discussed.

1. Introduction

The regenerator is the core heat exchange component of the engine, and plays the role of alternating heat absorption and heat release inside the engine, which has a great influence on performance of the whole machine. The filler is the most significant and complex part of the regenerator, and its heat transfer and flow characteristics are critical to the performance of the regenerator, so it is necessary to research the performance of regenerator filler. At present, numerical calculation methods are used to establish model for research because of its simplicity, short cycle and low expense.

Anderson used numerical methods to consider the temperature change of the regenerator matrix in one cycle under actual heat transfer process. It was found that the regenerator filler had temperature oscillation. The temperature distribution in the axial direction is nearly linear, but the curve bends downward at the end of the axial direction, which reduces the performance of the engine [1]. Kuralidhar used non-thermodynamic equilibrium model to study the heat transfer and flow characteristics in the wire mesh regenerator under oscillating flow, and the influence of Reynolds number and frequency on the performance of regenerator were discussed. It is proved that the ratio of length and diameter is an important factor affecting the regenerator [2]. Nair et al established a two-dimensional thermal equilibrium porous medium model to investigate the heat transfer characteristics in the wire mesh regenerator with different porosity [3]. Costa et al established a three-dimensional model by using finite volume method and derived the relationship between the Reynolds number and friction factor as well as the Nusselt number. Besides, they proved the wire mesh regenerator can be accurately modeled as a porous medium model [4]. PF Chen compared the friction coefficient and
At present, the research of regenerator fillers mainly focuses on the wire mesh type regenerator. And the porous medium model in CFD software is used to establish two-dimensional or three-dimensional model for calculation directly. There are few studies in other type of regenerator fillers, not to mention the establishment of three-dimensional numerical models.

In this paper, a three-dimensional model of regenerator of powder sintered stainless steel is established and the relationship between the Reynolds number with friction factor as well as the Nusselt number is numerically solved. It provides a method to get the inertial coefficient and the viscous coefficient of specific configuration which lays the foundation for the use of the porous medium model in the future. Finally, the parameter of \( \frac{Nu}{C_f^{1/3}} \) is chosen as an indicator to evaluate the performance of the four fillers which is wire mesh, foam metal, powder sintered material and random fiber, and their potential of being a future regenerator filler is discussed.

2. Governing equations

Sufficient flow of fluid in the porous medium can be described by Darcy's law:

\[
-\frac{dp}{dx} = \frac{\mu}{K} u
\]  

(1)

Forchheimer introduced the effects of inertial force to Darcy's law [4] and the formula changed as:

\[
-\frac{dp}{dx} = \frac{\mu}{K} u + a \rho u^2
\]  

(2)

According to the equation (2), Ergun conducted a large number of experiments and gave the expression of \( a \), and then the formula was corrected.

\[
a = \frac{F}{\sqrt{K}}
\]  

(3)

\[
-\frac{dp}{dx} = \frac{\mu}{K} u + \frac{F}{\sqrt{K}} \rho u^2
\]  

(4)

The Ergun coefficient is related to the flow state closely. For low-speed flows, the inertial effect is negligible, and the Darcy equation can be used directly. But as the velocity of flow increases, the inertial effect increases, and the Forchheimer's formula is more consistent with the fluid [4]. The inertial effect can be explained by the Ergun coefficient in the actual state. In addition, Ergun has determined the general form of the friction coefficient equation, which is of great value to the performance evaluation of the regenerator filling.

\[
C_f = \frac{a_1}{Re} + a_2
\]  

(5)

Then the pressure drop in the regenerator can be described as equation (6):

\[
\Delta p = C_f \frac{L \rho}{d_h^2} u^2
\]  

(6)

Considering the above equations, the pressure drop is expressed using two parameters of Ergun:

\[
\Delta p = \frac{\mu \cdot a_1 \cdot L}{2d_h^2} u + \frac{a_2 L}{2} \rho u^2
\]  

(7)
The hydraulic diameter is converted into the expression related to the diameter of particles [6]:

\[ d_h = \frac{2d_p \epsilon}{3(1-\epsilon)} \]  

(8)

The equivalent Reynolds number is defined as:

\[ Re = \frac{2\rho d_p u}{3\mu(1-\epsilon)} \]  

(9)

Therefore, the equation of pressure drop can be expressed as:

\[ \Delta p = \frac{1}{4}C_f \frac{3(1-\epsilon)L}{d_p} \rho u^2 \]  

(10)

It can be seen from the equation (10) that as long as the pressure drop and velocity are calculated by simulation, the relationship between friction factor and velocity can be obtained. As the Reynolds number is a function of velocity, the relationship between Reynolds number and friction factor can be obtained, and the viscous coefficient $1/K$ and the inertia coefficient $F$ can be deduced too.

3. Numerical modelling study

In this chapter, the stainless steel powder sintered material with a particle diameter of 40 μm and a porosity of about 40% is selected to model the flow and heat transfer. Although there are empirically correlation equations which are reported in NASA Contractor Report [7], but the test material was 173 μm particle and it couldn’t be used to explain the flow and heat transfer characteristics of different particle diameters. Using the method in this research, the characteristic of flow and heat transfer of the porous medium with specific configuration under oscillating flow can be obtained.

3.1. Establishment of numerical model

Because of the limited computational ability of the computer, the entire regenerator model cannot be simulated, so a simplified model whose length is five times the diameter of the particle is established along the flow direction. There are four particles in each layer, each of which is cut along the center to form the central section (Figure 1(a)), and the computational domain can be obtained, figure 1(b) shows the fluid calculation area. The equations of velocity and pressure of the oscillating flow are written by UDF, and velocity inlet and pressure outlet boundary conditions are adopted. And the walls of central section are set to symmetric boundary conditions. The standard SIMPLE method is used to solve the problem and the governing equations are discrete with second order upwind scheme.

![Central section](image1.png)

(a) Vertical flow direction

![Fluid calculation area](image2.png)

(b) Fluid calculation area

**Figure 1.** Establishment of model

3.1.1. Grid-independent verification. Three different maximum sizes of the grid are selected to verify the independence of grid, which are $10^{-4}$, $10^{-5}$ and $5 \times 10^{-6}$ respectively. The numerical results of pressure drop are shown in figure 2. The pressure drop curve of the first setting has a certain angle difference with the latter two, and the maximum difference is 50 Pa which means that the setting is unreasonable. The results of latter two are roughly coincident, indicating the reasonability of the second setting. Therefore, the second setting is used in the later simulation with the considering of calculation time.
3.1.2. Particle arrangement independence verification. The actual arrangement of the metal particles has great difference with which in figure 1 and it is difficult to establish a model which is the same with the actual. Therefore, it seems to be a good way to establish different particle distribution models to examine the influence of permutations. The following three crystal-like arrangements are selected. The name of them are simple cubic structure, body-central cubic structure and face-central cubic structure respectively. These three structures have a particle size of 40 μm with the porosity of about 40% and the specific distribution is shown in figure 3.

RN Xu has ever established the above three models and verified the independence of arrangement in steady flow. The results show that the three structures can be well matched to the empirical equation and the results deviate from experimental correlation are 6.7%, 6.6%, and 5.9% respectively [6]. Due to limited time, it will be verified under oscillating flow in the future. And this paper uses a simple cube structure for subsequent simulations.

Figure 3. Arrangement of particles

3.2. Flow characteristics

The period is divided into eight equal parts to observe the flow characteristics of the calculation domain of each time period. In figure 4, it can be clearly observed that the maximum velocity of the flow field occurs substantially at the central of the calculation domain, and the streamlines are evenly distributed. The velocity steering of the oscillating flow is clearly observed in figure 4, eddy currents are generated in the flow path especially when the steering occurs. This characteristic is most evident in the last graph of figure 4.

In order to investigate the rationality of the setting and the influence of the oscillating flow on the pressure drop, the pressure outlet was set to a constant value, and the inlet velocity was changed to examine the pressure drop change, the result is shown in figure 5. Dividing the inlet velocity in figure 5 by the porosity is the velocity in figure 6, it is found that the corresponding pressure drops of figure 5 and 6 are substantially the same which confirms the pressure drop have no relation with the flow state in porous medium. It is worth noting that the pressure drops on the curve in figure 6 refers to a fitted value rather than a fixed value, because the same speed value under oscillating flow does not mean the same velocity, so it is possible to bring different pressure drops.
Figure 4. Variation of the streamline at the central section

Figure 5. Relationship between inlet velocity and pressure drop;

Figure 6. Relationship between fluid average velocity and pressure drop

Figure 7 shows that the pressure drop is a function of fluid average velocity. Considering Forchheimer's law, the curve is approximated as a second-order polynomial, and the equation can be fitted by the curve. Besides, the inertial coefficient $F$ and the viscous coefficient $1/K$ can be calculated which are important parameters in the porous medium model in CFD software. It is worth noting that this simulation ignores changes in fluid density and viscosity. Figure 7 shows the relationship between the friction coefficient and the Reynolds number. According to the above numerical calculation, the relationship of the curve can be fitted. The friction equation for the filler is given by equation (11):

$$C_f = \frac{142.233}{Re} + 0.02$$  

(11)

Figure 8 shows the relationship between velocity and pressure drop versus time. As can be seen from figure 8, the velocity along the z-direction is approximately equal to the total velocity, indicating that the flow in the non-mainstream direction has little effect on the overall. The phenomenon confirms that the sintered powder type regenerator can be calculated in the porous medium model. Although the porous medium model ignores the flow in the non-main flow direction which is inconsistent with the actual situation. In view of the above conclusions, readers can use the method of this paper to calculate the values of inertial coefficient and the viscous coefficient under different configurations, then set the porous media model and perform calculations. In this way, the same simulation results may be obtained, while saving a lot of time.

The two curves in figure 9 are the coefficients of friction calculated from the fluid velocity and the velocity component in the main flow direction as a function of time. It can be seen that the trends of the two curves are basically similar, but the friction coefficient which calculated by the velocity
always maintains at an order of magnitude, and the friction coefficient calculated by velocity component is infinitely large at every half cycle. Since the fluid turns in the z direction, \( v_z \) becomes zero, so the frictional resistance is infinite. The value of the velocity is always not zero, because there is still local eddy current, so there is always velocity in the x and y directions. Details can be seen on the above graphs.

Figure 7. Relationship between friction factor and Reynolds number;

Figure 8. Relationship between velocity and pressure drop and time;

Figure 9. Relationship between friction factor and time

3.3. Heat transfer characteristics

Figure 10 shows the relationship between the Nusselt number and the Reynolds number of the simulation. Based on the numerical results obtained for different solid and working medium properties, a specific surface Nusselt number correlation is obtained for each filler configuration. Specific Nusselt correlation equation is as follows:

\[
Nu = 0.82 + Pr^{0.25}Re^{0.92}
\]  

(12)

Figure 11 illustrates the temperature fluctuations over time during flow. It is apparent that both the temperature of the fluid and solid exhibit a periodic change, and the temperature of the fluid varies significantly more than the solid because of a lower specific heat capacity than which of solid. The change of the average temperature and velocity of the fluid is roughly the same, and the former lags behind the latter slightly. When the fluid velocity is zero, the ability of heat exchange is the worst. And the flow turns at next moment, so the average solid temperature remains at the highest or lowest. Figure 12 represents the Nusselt number variation with respect to the time. The Nusselt number peaks are due to a small temperature difference between the solid and fluid and the fluid during direction change under oscillating flow.
4. **Comparison of four regenerator fillers**

For a regenerator, the enhancement of heat transfer ability and the reduction of the resistance loss are contradictory. Therefore, it is necessary to make a trade-off between the two aspects. In order to evaluate the performance of these fillers comprehensively, \( \frac{\text{Nu}}{C_f^{1/3}} \) is used as an evaluation index [8].

According to the survey, the equations of friction coefficient and the Nusselt number are shown in the table 1.

| Friction coefficient | Nusselt number |
|----------------------|---------------|
| Wire mesh \( C_f = \frac{129}{Re} + 2.91Re^{-0.103} \) | \( Nu = [1 + 0.99(RePr)^{0.66}]e^{1.79} \) |
| Metal foam \( C_f = 22 \frac{1 - e}{Re} + 0.22 \) | \( Nu = 1.2Re^{0.43}Pr^{0.33} \) |
| Random fibre \( \frac{C_f}{Re} = \frac{25.7e + 79.8}{Re} + 3.76Re^{0.00283e-0.0748} \) | \( Nu = 1 + 0.186e(PrRe)^{0.55} \) |

Assuming the material is stainless steel and the porosity of porous medium is 40%, the correlation between Reynolds number and the index of four fillers is compared as shown in figure 13. It is apparent that foam metal has the optimal performance in this situation. And the performance of the sintered material is superior to that of the wire mesh. However, the conclusion is limited to the case
where the porosity is 40%. The porosity of wire mesh, metal foam and random fibre have many specifications, so the more detailed comparison of performance needs further analysis. But there is no doubt that the sintered material has the potential to be used as future regenerator filler.

5. Conclusion
In this study, a three-dimensional model of sintered material type regenerator is established directly. The flow resistance coefficient and thermal non-equilibrium heat transfer coefficient of the porous media are derived by simulation calculation under oscillating flow. The successful application of this method provides a way for the future to study the characteristic changes of the regenerator with different specific configuration. The parameter of \(\frac{\text{Nu}}{\text{C}_f^{1/3}}\) is used as an indicator to measure the performance of four kinds of common fillers. Comparing the comprehensive performance of four fillers results that the sintered material may become a future regenerator filler.

6. References
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