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 factor 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 $\mathrm{Nu}/C_f^{1/3}$ is chosen as an indicator to evaluate the performance of the four fillers, and the potential of being a future regenerator filler is discussed.

Highlights

- A three-dimensional model of regenerator filled with powder sintered material is established
- The model is simulated with oscillating flow
- The relationship between Reynolds number and friction coefficient as well as Nusselt number is numerically solved
- A method to acquire the characteristics of flow resistance and heat transfer for specific configuration is provided

Governing equations

The pressure drop in the regenerator can be described as:

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

Ergun has determined the general form of the friction coefficient equation:

$$C_f = \frac{a_1}{Re} + a_2$$

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

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

The hydraulic diameter is converted into the expression related to the diameter of particles:

$$d_h = \frac{2d_p\varepsilon}{3(1-\varepsilon)}$$

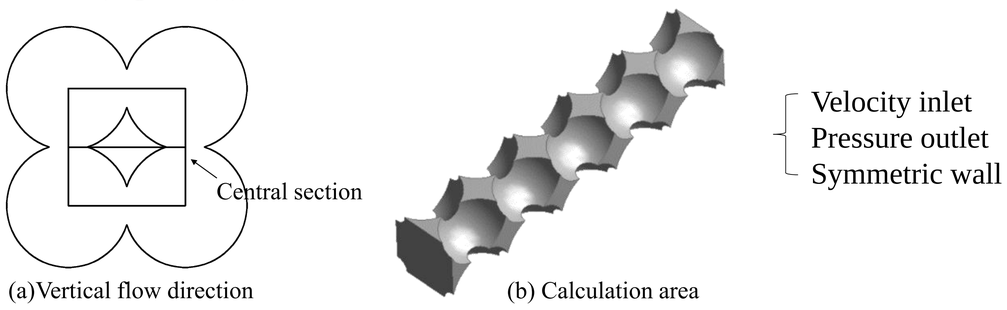
Therefore, the equation of pressure drop can be expressed as:

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

As long as the pressure drop and velocity are numerically calculated, the relationship between the friction coefficient and the Reynolds number can be fitted by the curve.

Establishment of numerical model

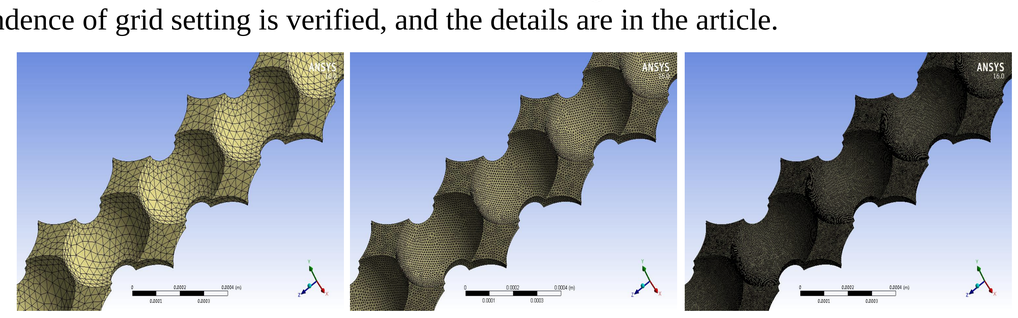
Due to the limited computational ability of the computer, it is difficult to establish a completed regenerator model, so a simplified model of five particles length is established along the flow direction (Figure 1(b)). There are four particles in each layer, each of which is cut along the center to form the central section (Figure 1(a)).



(a)Vertical flow direction (b) Calculation area

Figure 1. Establishment of model

Figure 2 shows three different maximum size of the grid, 10^{-4}mm, 10^{-5}mm and 5 X 10^{-6}mm. The independence of grid setting is verified, and the details are in the article.



(a)10^{-4}mm (b) 10^{-5} mm (c) 5×10^{-6} mm

Figure 2. Grid of model

The actual arrangement of the particles has great difference with which in figure 1, so a research on the influence of particle arrangement to the simulation result is needed. Three structures which have a particle diameter of 40 μm with 40% porosity are selected and the details are shown in figure 3. And the influence of particle arrangement is calculated.

(a) Simple cubes (b) Body cubes (c) Face cubes

Figure 3. Arrangement of particles

Simulation results

Figure 4 shows the pressure drop as a function of velocity. Considering Forchheimer's law, the curve is approximated as a second-order polynomial and can be fitted to calculate the inertial drag coefficient and the viscous drag coefficient in the porous medium model in CFD software. Figure 5 shows the relationship between the friction coefficient and the Reynolds number. According to the curve, the relationship can be fitted as:

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

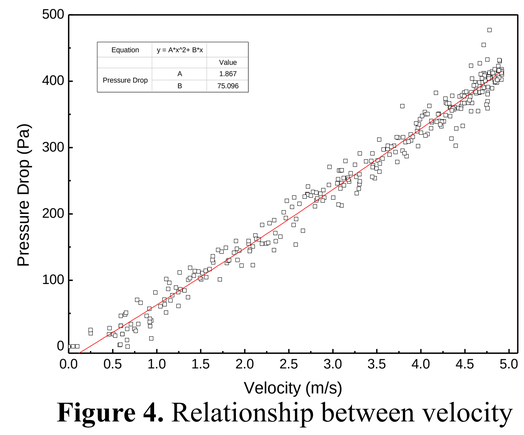


Figure 4. Relationship between velocity and pressure drop

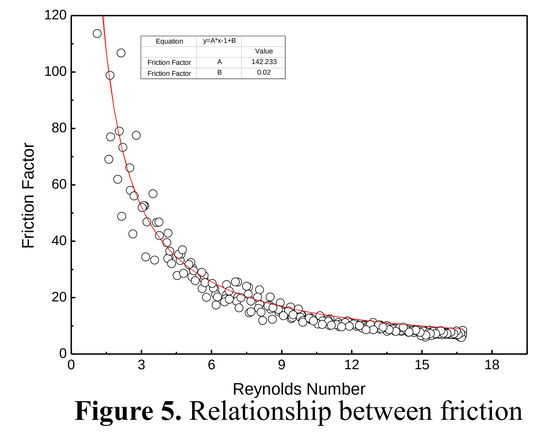


Figure 5. Relationship between friction factor and Reynolds number

Figure 6 shows the friction factor with time calculated from v and v_z. The trends of the two curves are basically similar, but there exists difference. The friction faction calculated by v_z becomes infinite every half cycle since v_z becomes zero when fluid turns. But the other curve maintains at an order of magnitude because of the existing of eddy current.

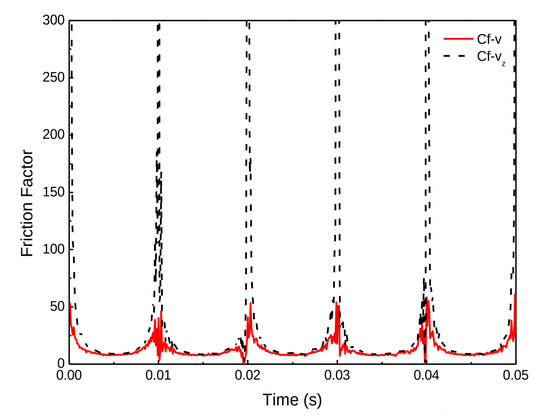


Figure 6. Relationship between friction factor and time

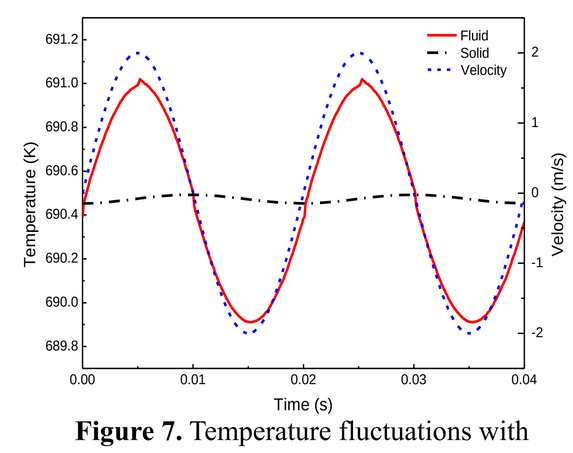


Figure 7. Temperature fluctuations with time

Figure 8 shows the relationship between the Nusselt number and the Reynolds number, and the Nusselt number equation is as follows. Based on the numerical results obtained for different solid and working medium properties, a specific surface Nusselt number correlation is obtained.

$$\mathrm{Nu} = 0.82 + 0.96Re^{0.92}$$

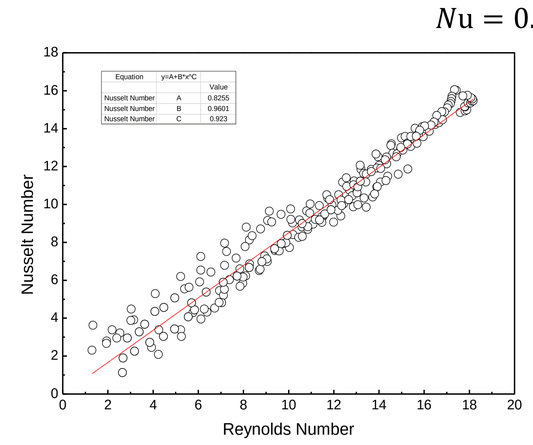


Figure 8. Relationship between Nusselt number and Reynolds number

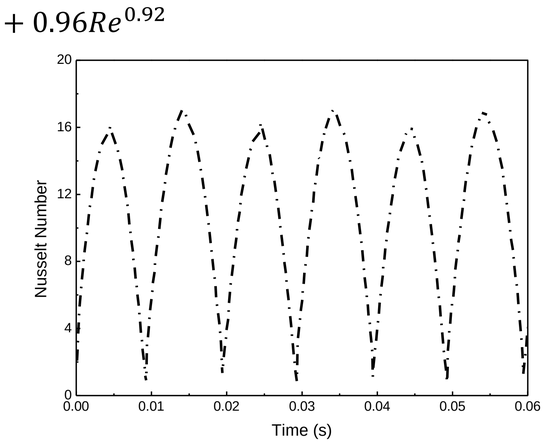


Figure 9. Relationship between Nusselt number and time

Both the temperature of fluid and solid exhibit a periodic change, and the former varies significantly more than the latter because of a lower specific heat capacity. Figure 9 represents the Nusselt number variation with respect to the time. The Nusselt number peaks due to a small temperature difference between the solid and fluid and the direction change of fluid under oscillating flow.

Assuming the material is stainless steel and the porosity is 40%, the correlation between Reynolds number and the $\mathrm{Nu}/C_f^{1/3}$ of four fillers is compared as shown in figure 10. However, the conclusion is limited to the case where the porosity is 40%, 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 the future regenerator filler.

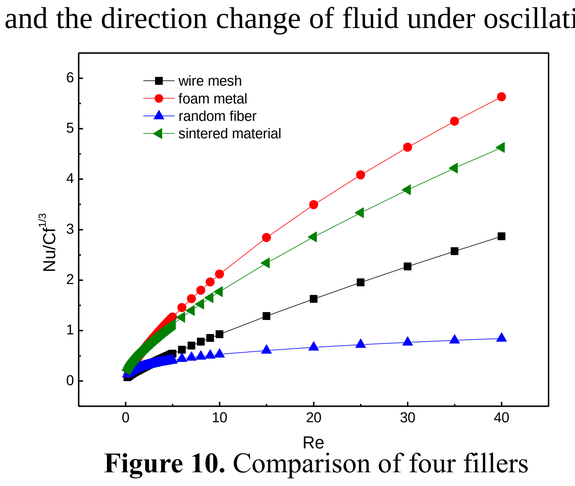


Figure 10. Comparison of four fillers

Conclusion

In this study, a three-dimensional model of sintered material type regenerator with oscillating flow is established. The flow resistance coefficient and heat transfer coefficient of the porous medium are derived by simulation calculation. 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 $\mathrm{Nu}/C_f^{1/3}$ is used as an indicator to measure the performance of four kinds of common fillers, more detailed comparison of performance needs further analysis, but the sintered material has the potential to become a future regenerator filler.