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MODELLING AND COMPARISON STUDIES OF PACKED SCREEN REGENERATORS FOR ACTIVE MAGNETOCALORIC REFRIGERATION

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ABSTRACT — In active magnetic regeneration (AMR) systems, not only the magnetocaloric properties of materials, but also the regenerator geometry plays an important role in the system performance. Packed sphere regenerators are often employed in existing prototypes, however, the characteristics such as relatively large pressure drop and almost fixed porosity make loss reductions and further optimization challenging. This paper proposes and focuses on packed screen regenerators, which may exhibit lower pressure drop and equivalent heat transfer performance to packed sphere regenerators. A 1D AMR model is improved and applied to simulate the regenerators. The performance of the new regenerators is studied and compared with that of the packed sphere regenerators. Possible fabrication methods of the packed screen regenerators are also discussed.

1. INTRODUCTION

In recent years, magnetocaloric refrigeration based on the AMR cycle has attracted the interest of many researchers, as the AMR systems have high theoretical efficiency, and use environmentally friendly working fluids. Given the limited magnetic flux density and magnetized volume, efficient regenerator design is important for the overall performance of the AMR system. In most current prototypes, packed spheres and parallel plates are the most common regenerator geometries. The packed sphere regenerators are somewhat easy to construct and have demonstrated relatively high performance in AMR devices. However, they exhibit relatively large pressure drop, and a nearly fixed porosity around 0.36, which make loss reductions and further optimization challenging. Alternatively, parallel plate regenerators have much lower pressure drop, but the geometry requires very small plate thickness and plate spacing to behave as efficient regenerators. The small dimensions required make fabrication of high performance regenerators sensitive to manufacturing tolerances and difficult to fabricate [1]. In many research and industrial applications, wire screens have been applied in regenerative heat engines, catalytic reactors, etc. [2], as they have highly ordered structures, high heat transfer rates, and moderate flow resistance. Screens with different materials are commercially available and the mesh number (the number of wires per inch) ranges into hundreds, correspondingly the pore diameter ranges from several millimeters to dozens of microns. The porosity can be adjusted by varying the wire diameter, and the stacking technique can reduce axial conduction losses. These qualities give regenerator optimization more flexibility. In this paper, packed screen regenerators are simulated and researched by using a 1D numerical model.

2. SIMULATION MODEL

To simulate the packed screen regenerator, an existing 1D model [3] has been modified. In the model, the heat transfer fluid flows through 24 regenerator beds periodically, which is synchronized with the changing magnetic field. The regenerator material is gadolinium (Gd) and the heat transfer fluid is water mixed with 20% ethylene glycol by volume. By solving discretized energy equations of liquid and solid, the temperature profiles, cooling power, heat rejection, pressure drop and COP etc., can be calculated once the model has converged to cyclical steady state. A detailed model is described in Ref. [4]. To estimate the friction factor and heat transfer performance of packed screens, Armour and Park's correlations [2, 5], which cover the range of Reynolds number, Prandtl number, porosity and mesh number in this study, are used (see (1) and (2)).

$$\Delta P = (8.61/\mathrm{Re_{Armour}} + 0.52)\, L\, u_0^2 \rho_f\, / \,[\, \varepsilon^2\, (1/M_w\text{-}D_w)], \text{ where } \mathrm{Re_{Armour}} = \rho_f\, u_0/[\mu A_w^2(1/M_w\text{-}D_w)] \text{ and } 0.1<\mathrm{Re_{Armour}}<1000 \quad (1)$$

$$\mathrm{Nu} = 1.315\, \mathrm{Pr}^{0.33}\, \mathrm{Re_{Park}}^{0.35}\, [(1-\varepsilon)\,/\,\varepsilon]^{0.2}, \text{ where } \mathrm{Re_{Park}} = \rho_f\, u_0/\mu\, A_w, \text{ and } 30<\mathrm{Re_{Park}}<500 \quad (2)$$

In this study, each regenerator bed has a length of 150 mm and a cross sectional area of 250 mm². We consider six groups of screens with a mesh number range of 25 – 600 wires/inch and porosity ε from 0.36 to 0.71, which are adjusted by changing wire diameter for a given mesh number. The screens are stacked with random orientation and are close packed. For comparison, a group of packed sphere regenerators with sphere diameter ranging from 0.7 to 0.2 mm, which means the flow channel is smaller, is simulated. A typical 75 wires/inch screen has on average 2.95 pores in 1 mm distance, and wire diameter can vary from 0.118 mm to 0.229 mm. This means the porosity changes from 0.71 to 0.36 and specific surface area from 9824 to 11193 m^{-1}. Comparatively the packed sphere bed has a fixed porosity of 0.36 and a specific surface area of 9600 m^{-1} when the sphere diameter is 0.4 mm. The temperature span is fixed from 275 to 305 K.

3. RESULTS AND DISCUSSION

Figs. 1 - 3 show the cooling power, pressure drop and COP of packed screen regenerators with variable mesh numbers (bottom axis), compared to packed sphere regenerators with different sphere diameters (top axis). The flow rate is 800 liters/hr. With increasing mesh number, both cooling power and COP reach a peak (see Figs. 1 and 3) and consequently reduce, whereas the pressure drop (shown in Fig. 2) increases continuously. It can be seen that there is an optimal mesh number between 75 - 100 wires/inch for all groups of packed screen regenerators. The heat transfer performance is enhanced by increasing the mesh number, because the channel size becomes smaller and the heat transfer area increases. This effect increases the enthalpy flow in the cold blow period, i.e. cooling power, at the cold end of regenerator. However, the rising viscous dissipation, represented by the pressure drop, will degrade the performance considerably. Therefore, packed screen regenerators with an approximate mesh number between 75 - 100 wires/inch, providing sufficient heat transfer and moderate pressure drop, gives the best performance. The COP can be increased by reducing the porosity, however cooling power behaves oppositely, which may be due to a reduction in Gd mass and larger utilization of the regenerator. The maximum cooling power is 471.5 W when the porosity is 0.36, while the maximum COP is 5.2 when the porosity is 0.71. The results of packed sphere regenerators with different sphere diameters from 0.7 - 0.2 mm are also shown in Figs. 1 - 3. The optimal sphere diameter is between 0.3 to 0.4 mm and the maximum cooling power and COP are 291.9 W and 0.9, respectively. Compared to packed sphere regenerators, packed screen regenerators with mesh numbers between 50 and 250 wires/inch can achieve larger cooling power and COP, as well as lower pressure drop. Even with a porosity larger than 0.50, meaning that less Gd is used, better performance can be observed in the packed screen regenerators.
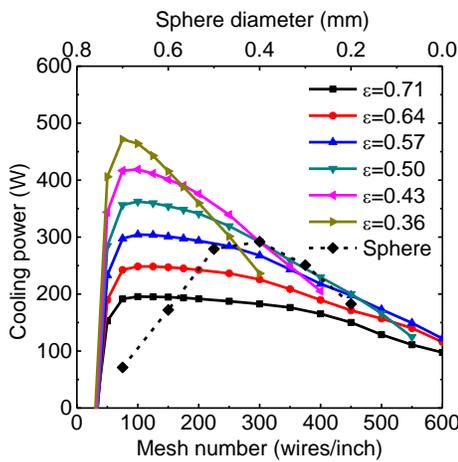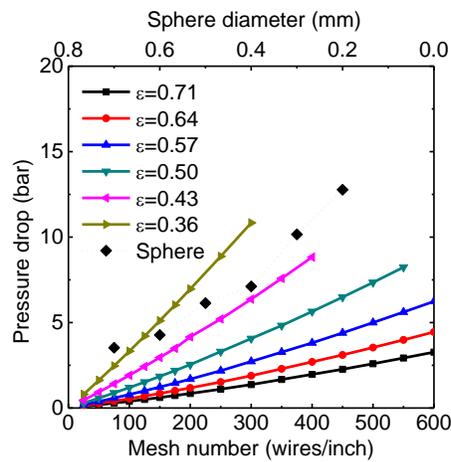

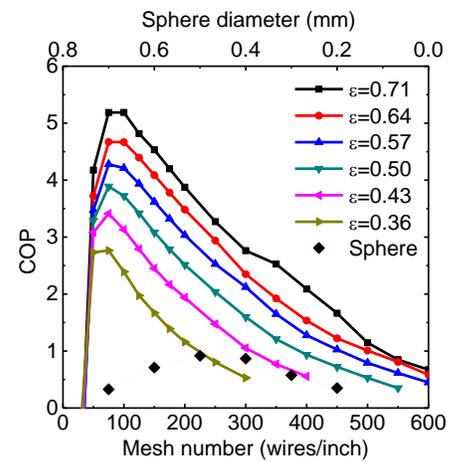Fig.1 The cooling power   Fig.2 The pressure drop   Fig.3 The COP

4. POSSIBLE FABRICATION METHODS

Although the performance of the AMR system may be increased by utilizing a packed screen regenerator compared with a packed sphere regenerator, it is difficult to manufacture screens from many magnetocaloric materials. Therefore, in this study we present some alternative methods for fabricating regenerators with a similar structure as the packed screen regenerator. The first method is electro-spinning processing, in which ceramic fine fibers (typically on the micro or nano-scale) can be drawn out from the solution, and deposited as porous media on a collector by using high electrical charge. It is possible to fabricate such a porous ceramic regenerator, with the same structure of randomly packed wires as packed screen bed. Another choice is co-extrusion fabrication, which can also be used to fabricate ceramic fibers on the micro scale. A proper wire diameter may be achieved after extruding repeatedly, and a packed bed with a porous structure can be realized by depositing the fibers randomly.

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