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Research Paper

Improving magnetic refrigerator performances by enhancing convection heat transfer with staggered twin-wedged elements

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HIGHLIGHTS

- Twin-wedged plates are proposed to enhance convection heat transfer in AMR.
- Refrigeration performances are notably increased by adopting twin-wedge Gd plates.
- Effects of pitch (s), fluid displacement (φ) and cycling period (τ) are studied.
- Smallest s and τ combined with medium φ generate the maximal $q_{V,ref}$ of 284.9 kW/m^3.

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ABSTRACT

The room-temperature magnetic refrigerator with the magneto-caloric materials of long Gd plates was simulated in our previous investigation. In the present work, the Gd materials are processed into the twin-wedged shape to improve refrigerator performances. The numerical simulation with the Fluent is performed for the novel refrigerator and the performance comparison between the refrigerators with long Gd plates and twin-wedged elements is conducted. Besides, the influences of longitudinal element pitch (s), cycling period (τ) and relative fluid displacement (φ) on refrigerator behaviors are studied. Moreover, the velocity vector and temperature contours are presented to understand the operation principle of refrigerator. In addition, the thermo-hydraulic performances of twin-wedged elements are predicted for discussing the enhancement of refrigeration performances. The numerical results indicate that the proposed elements could effectively enhance the convective heat transfer rate under weak laminar flow conditions and thus notably improve the specific refrigeration capacity ($q_{V,ref}$), maximal refrigeration temperature span and Coefficient of Performance of refrigerators. Besides, the above three performances are found to vary convexly with the increment of τ or φ and the maximal $q_{V,ref}$ of 284.9 kW/m^3 is obtained at the condition of smallest s(=1 mm) and τ(=0.25 s) together with moderate φ(=0.2) for all present cases.

1. Introductions

The magneto-caloric effects (MCEs) of solid magneto-caloric materials (MCMs) under alternate high and low magnetic fields can be exploited for the refrigeration near room temperature. The magnetic refrigeration has the advantages of high energy efficiency and environmental protection, etc., and could be the promising alternative to the traditional vapor compression counterpart [1–3]. The performances of magnetic refrigerators are greatly dependent on the MCE magnitude of solid MCMs, and the advanced MCMs [4–6] and high-efficient magnets [7,8] are always the hot research points of magnetic refrigeration. Besides, the active magnetic regenerator (AMR) is the key component of advanced magnetic refrigerator, and the heat transfer in AMR plays an important role on refrigerator performances as it determines whether the MCE could be fully taken out in an efficient way. From the available literatures, the AMRs are usually manufactured into porous structure by thin MCM plates or small MCM particles, etc., so that the working fluid can flow through and conduct the heat transfer efficiently [9–14]. Aprea et al. [15] conducted a research to compare the performances of magnetic refrigerators with the AMRs of packed bed or parallel plates of MCMs, and found

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Nomenclature

A	area of cooler in 2D model (mm^2)
AMR	active magnetic regenerator
c	specific heat capacity (J/kg·K)
H	magnetic field (T)
k	thermal conductivity (W/m·K)
L	longitudinal length of AMR (mm)
MCE	magneto-caloric effect
MCM	magneto-caloric material
p	pressure (Pa)
$q_{V,MCE}$	specific magneto-caloric energy source (W/m^3)
$q_{V,HX}$	specific energy source of heat radiator or cooler (W/m^3)
$q_{V,ref}$	specific refrigeration capacity (W/m^3)
Rt	thermal resistance (K/W)
s	longitudinal pitch (mm)
t	time (s)
T	temperature (K)
u	fluid velocity vector (m/s)
u_p	magnitude of piston velocity during shot (m/s)

Greek

Δ	difference
δ	a small variation
δp	twin-wedged plate thickness (mm)
δf	channel width (mm)
τ	cycling period (s)
ρ	density (kg/m^3)
θ	attack angle (°)
μ	dynamic viscosity (kg/m·s)
φ	relative fluid displacement

Superscript and subscript

a	ambient cooling or cooled fluid
ad	adiabatic
f	fluid
H	constant field
max	maximal
s	solid
T	matrix transposition

that the large flowrate could facilitate the plate-type refrigerator to generate a good behavior. As for the current magnetic refrigerator with heat transfer enhanced in AMR, where the MCE can be smoothly transferred from the MCMs to working fluid and a great fluid flowrate is required to carry out all the MCE, the plate-type AMR could be the optimal choice.

Nowadays, numerical simulation has become one of the routine methods for the researches on the flow and heat transfer processes. Different numerical models were presented for the unsteady heat transfer coupled with periodic MCE in the magnetic refrigerators [16,17]. Besides, several researchers adopted commercial CFD softwares to simulate the operation of magnetic refrigerators. For instances, with the Fluent software, Bouchard et al. [18] conducted the three-dimensional numerical study for the AMR with packed particles and the preliminary numerical results were reported. Ezan et al. [19] built the two-dimensional (2D) CFD model for the magnetic refrigerator with Gd plates. It is noted that its plate thickness and channel width were large (both 1 mm), thus a limited refrigeration performance was obtained. Recently, the present authors constructed the comprehensive 2D numerical model with the Fluent for the plate-type magnetic refrigerators [20], with which it was found that the maximal temperature span could be notably increased by decreasing the plate thickness or pitch. However, the decrement of plate pitch could be subjected to the constraint of allowable flow resistance. Besides, as the fluid flow in plate-type AMR was fully developed, the Nu number was limited and should be enhanced.

For the past decades, a variety of conventional scale heat transfer enhancement techniques, such as rib-roughen tubes [21], twisted tapes [22], coil wires and turbulators [23–25], etc., have been widely studied and applied in the industries. The flow channels in AMR fall into the mini or micro-channel category and many researches on the heat transfer in mini or micro-channels have been conducted [26–28]. However, these researches are insufficient and the heat transfer enhancement on those channels needs further studied. Besides, according to previous investigations [17,20], the flow Re numbers in the AMRs are usually small (<100) and the common thermal augmentation techniques such as rib-roughen plates could be unsatisfactory. Fortunately, Xu et al. extended the thermal boundary layer redeveloping concept to the micro-scale field in Ref. [29]. They constructed the micro-channel heat sink and good effect was demonstrated with this technique. Recently, Yu et al. [30] studied the heat transfer enhancement in the micro-channel with the Piranha Pin Fins, which have the wedge-type profile on the upwind side.

Inspired by the above researches, together with the consideration of the reciprocating flow in AMR, the twin-wedged Gd elements are proposed in the current work to fabricate the AMR of magnetic refrigerator, so that good refrigeration performances could be obtained with the heat transfer enhancement of redeveloping the boundary layer periodically. The numerical simulation with the Fluent will be performed for the novel magnetic refrigerator and the comparison of its refrigeration performances against the counterparts of traditional long Gd plates be conducted. Besides, the influences of structural and operational parameters on refrigerator performances will be studied. To facilitate the discussions on the refrigeration performance improvement, the thermo-hydraulic performances of the micro-channel formed by twin-wedged elements will be predicted.

2. Physical model

The present authors performed the numerical simulation on the reciprocating magnetic refrigerator with an AMR of long Gd plates, whose schematic can be referred to Ref. [20]. In the current work, the long Gd plates in that refrigerator are replaced by the twin-wedged Gd elements, so that the refrigerator performances could be improved be enhancing the convection heat transfer in the AMR. The twin-wedged elements are arranged regularly, and Fig. 1 presents the unit structure of current refrigerator, which consists of twin-wedged elements, a heat radiator, a cooler and two pistons, together with the fluid of 20% glycol aqueous solution.

The whole region with the twin-wedged Gd elements is the AMR. The length of AMR, expressed by L in Fig. 1(a), is equal to 60 mm. The twin-wedged elements have the thickness of δp and the attack angle of θ (=30°), while their lengths are such set that the fluid channel always has the same width. They are arranged staggered with the longitudinal and transversal pitches of s and (δp + δf)/2 respectively, as are depicted in Fig. 1(b). The δp and δf are kept constant of 0.3 and 0.2 mm, respectively, while the s takes the values of 1, 2 and 4 mm.

The current refrigerators work approximately with the AMR Brayton cycle. In more details, a typical cycle consists of a hot-