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Research Paper

Passive characterization and active testing of epoxy bonded regenerators for room temperature magnetic refrigeration

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HIGHLIGHTS

- Two epoxy bonded regenerators are characterized in an oscillating flow test.
- The friction factor and overall Nusselt number are presented and compared.
- A five-layer AMR achieves a no-load temperature span of 16.8 °C.
- A series of active tests with cooling loads is done and analyzed.
- 1D AMR model is validated against the test results, exhibiting a good prediction.

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ABSTRACT

Epoxy bonded regenerators of both spherical and irregular $La(Fe,Mn,Si)_{13}H_y$ particles have been developed aiming at increasing the mechanical strength of active magnetic regenerators (AMR) loaded with brittle magnetocaloric materials and improving the flexibility of shaping the regenerator geometry. Although the magnetocaloric properties of these materials are well studied, the flow and heat transfer characteristics of the epoxy bonded regenerators have seldom been investigated. This paper presents a test apparatus that passively characterizes regenerators using a liquid heat transfer fluid with an oscillating flow at low Reynolds numbers, simulating the hydraulic working conditions in AMRs. Dimensionless parameters, including friction factor, effectiveness and overall Nusselt number, are presented for the epoxy bonded $La(Fe,Mn,Si)_{13}H_y$ regenerators and reference packed particle beds. Moreover, a five-layer AMR based on spherical particles is tested actively in a small reciprocating magnetic refrigerator, achieving a no-load temperature span of 16.8 °C using about 143 g of epoxy-bonded $La(Fe,Mn,Si)_{13}H_y$ materials. Simulations based on a one-dimensional (1D) AMR model are also implemented to validate and analyze the results from the active test.

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1. Introduction

Magnetic refrigeration, which exhibits advantages such as the avoidance of volatile, harmful gases and potentially high efficiency [1], is an alternative to the traditional vapor compression technology. Recently, emerging prototypes that approach the performance of vapor-compression based systems have been reported and they presented high cooling capacity on the order of kilowatts [2,3] and improved efficiency up to 18% of the Carnot efficiency [4]. An active magnetic regenerator (AMR) is a porous matrix consisting of magnetocaloric materials (MCMs), in which the fluid exchanges heat with the solid matrix during a periodical reciprocating flow coupled to a varying magnetic field. The refrigeration cycle of an AMR consists of four steps [5,6]: the magnetization process associated with the temperature increase in the MCM; the cold-to-hot blow that cools the porous matrix by rejecting heat to the ambient; the demagnetization process resulting in a further temperature decrease; the hot-to-cold blow where the fluid absorbs a cooling load and the MCM returns to its original temperature. During the two blows, the inlet fluid temperatures at the hot and cold ends are kept constant as T_h and T_c, the hot and cold reservoir temperatures, respectively. After several cycles, a temperature span $\Delta T = T_h - T_c$ is built up along the regenerator and the system reaches a periodic steady state. The enthalpy differences at the cold and hot ends are the cooling capacity and the heat dissipation,

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respectively. The concept of heat regeneration allows materials arranged along the temperature gradient to operate at their own thermodynamic cycles, which realizes a temperature span several times larger than the adiabatic temperature change, ΔT_{ad}, of the MCMs.

In order to improve the cooling performance, much effort has been devoted to developing magnetocaloric materials and shaping these into regenerators with suitable porous geometries. The derivatives of $La(Fe,Si)_{13}$ [7], including LaFeCoSi [8] and $La(Fe,Mn,Si)_{13}H_y$ [9,10], are promising MCMs with a first order phase transition (FOPT), which exhibit a large peak in isothermal entropy change, moderate adiabatic temperature change and tunable Curie temperatures. Both experimental and theoretical studies [3,11] show that proper layering of $La(Fe,Si)_{13}$ materials in AMRs could realize an outstanding cooling performance. However, many of these materials are brittle and can break during the cycling of the magnetic field, which may lead to problems such as mechanical instability and possible degradation of the magnetocaloric effect [12]. The possible reason of the cracking lies in the significant volume change up to 1% associated with the phase transition [13] and the magneto-structural transitions. Therefore, epoxy bonded regenerators have been developed to increase the overall mechanical strength of the porous media [3,14,15] and to facilitate building a monolithic MCM regenerator [16].

Richard et al. [16] bonded Gd and GdTb flakes with a thin coating of epoxy to form monolithic layers in an AMR, which realized a no-load temperature span near to 20 °C. Jacobs et al. [3] introduced the epoxy-connection process to fabricate six-layer LaFeSiH regenerators and tested them in a rotary magnetic refrigeration device. This refrigerator realized a cooling power of around 2500 W over a span of 11 °C with a coefficient of performance (COP) of approximately 2. Pulko et al. [14] constructed epoxy-bonded LaFeCoSi plates, which maintained the mechanical integrity after 90,000 cycles of applying magnetic field. A no-load temperature span of about 10 °C was achieved in a magnetic refrigerator using these plates. Neves Bez et al. [15] tested epoxy bonded AMRs using 1 and 2 layers of $La(Fe,Mn,Si)_{13}H_y$, which achieved a maximum no-load temperature span of 13 °C. Note that a technique of compositing magnetocaloric and metal by hot pressing also has the function of increasing the mechanical stability potentially [17]. However, most of the studies focus on active testing of the epoxy bonded regenerators, and the investigation of the flow and heat transfer characteristics of such regenerators is seldom done. Besides, the particles used in these epoxy bonded regenerators were usually irregular and testing of spherical particles has not yet been reported. Therefore, a passive characterization of the epoxy bonded regenerators is presented in the first part of this article, followed by an active test of a five-layer AMR using spherical particles as the second part. Herein, "passive" means that no magnetic field is applied and in contrast "active" represents testing the cooling performance of AMRs with the magnet assembly.

A quantitative study based on the technique of entropy production minimization [18] has shown that viscous dissipation and imperfect heat transfer are the two mechanisms that present the largest irreversibility inside AMRs. The viscous dissipation is associated with the large pump power and high pressure drop, which reduce efficiency and require thicker housing walls, wasting more magnetized volume. In addition, perfect heat transfer is impossible and there is always a certain temperature difference between the fluid and the solid bed. Enhancing the heat transfer and decreasing the flow resistance simultaneously is always challenging. Therefore, the dimensionless parameters such as the friction factor f_F and the Nusselt number Nu are of essential interest, as they are tightly connected to both irreversible effects. In the passive test, the friction factor could be calculated from the measured pressure drop over the regenerator in either unidirectional or oscillating flow. Moreover, the heat transfer coefficient h_f and Nu in the convective flow through the porous regenerator could be estimated using different methods, including the unidirectional flow test with constant wall temperature/heat flux, single blow test [19], and the oscillating flow test [20,21]. In the single blow test, a fluid with constant temperature is blown through the regenerator that starts at a uniform temperature different from the inlet fluid and the response of the outflow temperature is recorded for deducing the heat transfer coefficient. Engelbrecht [22] and Frischmann et al. [23] presented experimental results for packed sphere beds in the single blow test. Under oscillating flow condition, Schopfer [20] studied the thermal-hydraulic properties of the liquid-saturated regenerators. The friction factor and the Nusselt number in the regenerators with microchannels and packed beds were estimated in experiments based on a harmonic approximation technique. Trevizoli et al. [21] constructed a laboratory apparatus and presented the pressure drop, the pumping power and the effectiveness of passive regenerators. The effectiveness is the heat transfer efficiency of a regenerator and is defined as the ratio of the amount of heat that transferred during a blow process to the maximum possible amount of heat transfer.

In this study, two groups of regenerators, including epoxy bonded regenerators using irregular or spherical $La(Fe,Mn,Si)_{13}H_y$ particles, as well as reference regenerators packed with stainless steel (SS) particles, are characterized in a passive test apparatus. The experiments are run with an oscillating flow in the low Reynolds number region. The dimensionless group consisting of the friction factor f_F, the effectiveness η, and the overall Nusselt number Nu_o is deduced and presented, based on the measured pressure drop and the temperature profiles. Furthermore, an AMR using five layers of spherical $La(Fe,Mn,Si)_{13}H_y$ particles is tested actively and the experimental results are validated with the simulations based on an established 1D AMR model.

2. Passive characterization of epoxy bonded regenerators

2.1. Test apparatus and methodology

The passive regenerator test apparatus is composed of four main sections: the regenerator test section, the oscillating flow generator, the cold heat exchanger with a cold reservoir and the hot heat exchanger with an electric heater. The schematic diagram and a photograph of the test apparatus are shown in Fig. 1 (a) and (b), respectively. In detail, the regenerator test section includes a porous regenerator bed (REG), four check valves (CV), thermocouples (T) and two piezoelectric pressure gauges (P). The oscillating flow generator is a motor-crank system (MT) connected to two cylinders (CYL 1 and 2). The displacement of the cylinders is measured by a linear encoder. The cold heat exchanger (CHX) is a double-pipe type. The cold water with a constant temperature is circulating from the cold reservoir to cool down the thermal liquid in the inner tube. The hot heat exchanger (HHX) for heating up the fluid is made by inserting and sealing an electrical cartridge heater in a small insulated chamber.

The reciprocating movement of the two cylinders generates the oscillating flow through the porous regenerator. During the cold-to-hot blow, the fluid is pushed from CYL1, cooled down by CHX, blown through CV1-REG-CV4, and then stored in CYL2. A similar flow pattern is seen in the hot-to-cold blow, and the fluid is heated up by the electric heater in the HHX. On each side of the regenerator, two check valves are set to separate the inflow and outflow, ensuring unidirectional flows in both heat exchangers. By using the check valve system, the dead volume is reduced to 4% of the

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