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Experimental investigation of an active magnetic regenerative heat circulator applied to self-heat recuperation technology

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HIGHLIGHTS

- AMR heat circulator has newly been constructed for experimental evaluation.
- Heat circulation in the vicinity of Curie temperature was observed.
- Energy consumption of an AMR heat circulator has been measured.
- Energy saving for processes near Curie temperature of working material was seen.

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ABSTRACT

An experimental investigation into an active magnetic regenerative (AMR) heat circulator based on self-heat recuperation technology, was conducted to evaluate its energy saving potential in heat circulation. In an AMR heat circulator, magnetocaloric effect is applied to recuperate the heat exergy of the process fluid. The recuperated heat can be reused to heat the feed process fluid and realize self-heat recuperation. In this paper, AMR heat circulator has newly been constructed to determine the amount of heat circulated when applied to self-heat recuperation and the energy consumption of the heat circulator. Gadolinium and water was used as the magnetocaloric working material and the process fluid, respectively. The heat circulated amount was determined by measuring the temperature of the process fluid and gadolinium. The net work input for heat circulation was obtained from the magnetizing and demagnetizing forces and the distance travelled by the magnetocaloric bed. The results were compared with the minimum work input needed for heat circulation derived from exergy loss during heat exchange. It was seen that the experimentally obtained value was close to the minimum work input needed for heat circulation.

1. Introduction

Chemical processes often comprise a combination of several heating and cooling processes. In order to reduce the energy consumption in these chemical processes, methods focused on heat recovering technologies represented by pinch analysis has been applied [1]. However, since the pinch analysis only considers the temperature as the quality parameter of the process stream, Aspelund et al. extended the pinch analysis to include exergy calculation so that pressure and composition of the process stream can be included in the calculation [2]. The main factors that cause exergy destruction in thermal processes are (1) combustion of fossil fuels and (2) heat transfer between process streams at different temperatures. To minimize the exergy destruction involved in thermal processes and gain a dramatic reduction in energy consumption, Kansha et al. proposed self-heat recuperation technology [3]. In the proposed technology, the exergy of the effluent process stream heat is recuperated through pressure variation enforced by compressors. The recuperated heat can be reused to heat the feed process stream. Unlike conventional systems that require heat input from external sources, in self-heat recuperation work is provided to recirculate the process stream heat. By applying self-heat recuperation technology to thermal processes, it has been seen that the energy consumption can be significantly reduced compared with conventional heat processes with heat recovery systems [4].

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Instead of using compression, the authors proposed the concept of applying the magnetocaloric effect (MCE) in self-heat recuperation technology to recuperate the heat exergy of the process stream [5]. MCE enforces a reversible temperature change that can be obtained by subjecting a magnetic material into a varying magnetic field [6]. In a self-heat recuperative process where MCE is applied, the heat of the effluent process stream is passed to the magnetocaloric working material, recuperated through magnetization before being reutilized to heat the feed process stream.

An active magnetic regenerative (AMR) heat circulator that realizes self-heat recuperation employing MCE has newly been constructed. This paper examines the measurement of the temperature evolution of the magnetocaloric bed and the work needed to circulate the heat using gadolinium and water as magnetocaloric working material and process fluid, respectively. The heat circulation and the energy saving potential of an active magnetic regenerative heat circulator that uses MCE in a process based on self-heat recuperation technology is evaluated.

2. Experimental investigation of active magnetic regenerative heat circulator

2.1. Basic concept of active magnetic regenerative heat circulator

Active magnetic regeneration is a method where magnetocaloric material is utilized as a working material providing temperature change as a result of magnetization or demagnetization, and also as a regenerator for the heat transfer fluids [7]. Active magnetic regeneration has been studied for heat pumping applications aiming for the replacement of conventional heat pumps using compressors. By applying an active magnetic regenerative heat pump, the use of greenhouse gases as working fluids are avoided, and in some cases a higher efficiency is obtained [8]. Various researches has been performed in order to bring the magnetic heat pump to use, including the work by Tušek et al. who compared different geometries of the active magnetic regenerator beds [9]. The temperature change, ΔT_{ad}, which can be induced by adiabatic magnetization or demagnetization of a magnetocaloric material, is only few Kelvin/Tesla in most cases. Active magnetic regeneration can enlarge the temperature difference in which the heat can be pumped. However, the amount of heat that can be pumped is still rather small because only small temperature difference can be gained between the heat sink or the heat source and the magnetocaloric material [10].

Conventionally, active magnetic regeneration has only been applied for heat pumping uses [11]. The basic concept of using active magnetic regeneration in self-heat recuperation technology (AMR heat circulator) was presented by the authors [12] and has been evaluated through mathematical modelling [13]. In an active magnetic regenerative (AMR) heat circulator, only temperature difference needed for heat exchange between the process fluid and the magnetocaloric working material is required for heat circulation. In order to realize self-heat recuperation, the heat of the effluent process fluid is transferred to the magnetocaloric working material. The heat is then recuperated through magnetization and returned to the feed process fluid so to realize self-heat recuperation. Fig. 1 shows the schematic of an AMR heat circulator. A bed constructed of magnetocaloric material is set with a temperature gradient so that it is cold on one end and hot on the other. The feed process fluid at initial temperature, T_0, is heated in the magnetized magnetocaloric bed (Fig. 1a) by receiving heat from the magnetocaloric working material to the set temperature, T_{set}, for a certain application at X. Via the next process, X, the direction of the process fluid flow is reversed whilst the bed is demagnetized. The heat of the effluent process fluid is transferred to the demagnetized magnetocaloric bed and the remaining heat is discarded at the cooler (Fig. 1b). The cycle can be repeated to obtain continuous heat circulation. If the magnetocaloric bed is arranged so that the forces during magnetization and demagnetization can be compensated [14], the net work input, W_{net}, is defined as the work needed for demagnetization, W_{demag}, less the work that can be recovered during magnetization, W_{mag}. From the conservation of energy, this work is equal to the quantity of heat discarded at the cooler, $Q_{discard}$.

$$Q_{discard} = W_{net} = \left|W_{demag} - W_{mag}\right|. \quad (1)$$

2.2. Experimental

An experimental setup of the AMR heat circulator has been newly constructed to examine its heat circulation potential and its energy consumption. The schematic of experimental setup configuration is shown in Fig. 2. In this study, gadolinium (Gd), often chosen as a benchmark material for room temperature MCE, was used as the magnetocaloric working material. Its magneto-thermal properties are well studied by Dan'kov et al. [15] and by Benford and Brown [16]. Water was used as the process fluid. The temperatures of the two ends and middle of the bed were measured using T type thermocouples to monitor the change of the temperature gradient in the bed of magnetocaloric material. The actuator controls the magnetization and demagnetization of the bed by pushing and pulling the magnetocaloric bed in and out of the magnetic field. Synchronized with the control of magnetization and demagnetization, a tubing pump was used to control the flow rate and the flow direction of the process fluid. The magnetic field was provided by a permanent magnet manufactured by TOWA Industrial Co, Ltd., and could provide a maximum magnetic field of 1.07 T and over 0.7 T within 30 mm radius from the point at which the field was at a maximum. The process fluid exchanged heat with the cooling water before entering the cold end of the bed to ensure that the initial temperature, T_0, was kept constant. Thermocouples were used to measure the temperature of the cooling water. A piezoelectric sensor was inserted between the actuator and the bed of magnetocaloric material so that the magnetizing and demagnetizing work can be calculated from the output force and the distance that the bed was moved. The experimental apparatus is depicted in Fig. 3.

Crushed Gd, passed through an 850 μm sieve, was packed inside an acrylic tube with an inner diameter of 8.0 mm. The bed length, l_b,

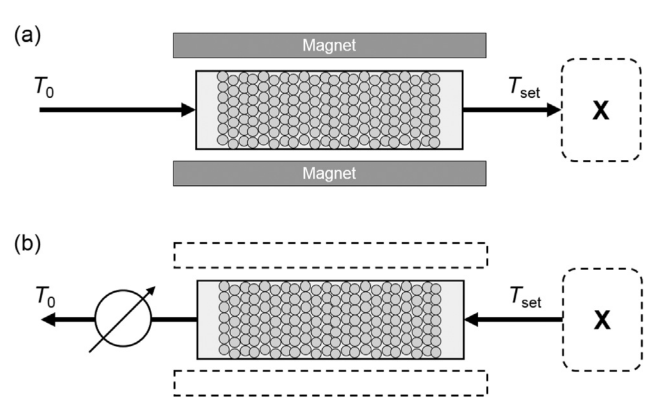

Fig. 1. Schematic diagram of the active magnetic regenerative heat circulator for self-heat recuperation technology. After a certain period of time, the direction of the process fluid is reversed and the magnetocaloric bed is demagnetized (a → b).