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Magnetocaloric heat circulator based on self-heat recuperation technology

Yui Kotani [a], Muhammad Aziz [b], Yasuki Kansha [a], Chihiro Fushimi [c], Atsushi Tsutsumi [a,*]

[a] Collaborative Research Center for Energy Engineering, Institute of Industrial Science, The University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan
[b] Solution Research Laboratory, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8550, Japan
[c] Department of Chemical Engineering, Tokyo University of Agriculture and Technology, 2-24-16 Nakacho, Koganei-shi, Tokyo 184-8588, Japan

HIGHLIGHTS

- Magnetocaloric heat circulator for thermal process based on self-heat recuperation is proposed.
- Magnetization of magnetic material instead of compression is used for process heat circulation.
- Magnetic heat circulation cycle has been described in terms of temperature–entropy diagram.
- The simulation results show potential for drastic energy saving in thermal processes.

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ABSTRACT

A concept of a novel magnetocaloric heat circulator based on self-heat recuperation technology for application in thermal processing is proposed. In the heat circulator, process heat is recirculated by using the magnetocaloric effect of ferromagnetic materials subjected to cyclic magnetization and demagnetization. The ferromagnetic material is magnetized or demagnetized adiabatically at the highest or lowest process temperature to create the temperature difference required for heat exchange so that all heat is recirculated inside the thermal process without heat addition. The magnetocaloric heat circulation cycle has been analyzed in terms of the temperature–entropy diagram to evaluate its energy consumption. Simulation has been conducted to clarify the theoretical potentials of applying magnetocaloric effect to self-heat recuperation. The simulation results show that the total energy consumption of the magnetocaloric heat circulator is reduced below 1/5 compared to conventional processes with heat recovery, thus showing its potential for energy saving in thermal processes.

1. Introduction

Over the last few decades, carbon dioxide (CO_2) reduction and fossil fuel consumption have been of global concern. In chemical processes that involve heating, the provision of heat by fossil fuel combustion or joule heating is associated with large exergy losses, leading to large amounts of CO_2 emissions. Thus far, heat recovery technologies represented by Pinch Technology based on the principle of heat cascading utilization have been applied to reduce energy consumption (Linnhoff and Hindmarsh, 1983; Linnhoff and Eastwood, 1997). However, because of the temperature difference required for heat exchange, not all of the heat can be recovered and addition of make-up heat is needed. Heat pump is a well-known technology to reduce the energy consumption and exergy loss of thermal processes compared to furnace heater. But the large temperature difference between the heat source and the heat sink reduces the coefficient of performance (COP) and increase the energy consumption and exergy loss.

Recently, self-heat recuperation technology based on the exergy recuperative heat utilization principle has been developed, which can recirculate all process heat providing temperature difference needed for self-heat exchange by compression (Kansha et al., 2009). The amount of energy required for the self-heat recuperative thermal process is much smaller than that for conventional thermal process with heat recovery because no make-up heat is added. A system based on the principle of self-heat recuperation is called a heat circulator. In heat circulator for gaseous materials, it is essential that self-heat recuperation gives the temperature difference for self-heat exchange of process material by adiabatic compression. In general, the temperature for self-heat exchange is smaller than that between external heat source and heat sink. Thus, larger energy saving could be expected for heat circulators in many processes. In the case of gas

* Corresponding author. Tel.: +81 3 5452 6727; fax: +81 3 5452 6728.
E-mail address: a-tsu2mi@iis.u-tokyo.ac.jp (A. Tsutsumi).

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systems, the compression energy can be recovered partially by the expander after heat exchange.

In the last few years, several applications of self-heat recuperation technology have been studied in various processes, such as distillation (Kansha et al., 2010), biomass drying (Fushimi et al., 2011; Aziz et al., 2011), cryogenic air separation (Kansha et al., 2011) and chemical absorption CO_2 separation (Kishimoto et al., 2011). From process simulation results, it was shown that energy consumption in these self-heat recuperative processes can be reduced to 1/5–1/20 compared to conventional processes with heat recovery.

In this paper, a novel magnetocaloric heat circulator for thermal processing based on the magnetocaloric effect (MCE) of ferromagnetic materials is proposed, where adiabatic magnetization instead of compression is applied to ferromagnetic materials to cause a reversible temperature change. The performance of magnetocaloric heat circulator was evaluated in terms of the temperature–entropy diagram and its theoretical energy saving potential has been clarified.

2. Magnetocaloric heat circulation

2.1. Magnetocaloric effect

The magnetocaloric effect is the heating or cooling of magnetic materials subjected to varying magnetic field (Tishin and Spichkin, 2003; Oliveira and Ranke, 2010). When the magnetic field is applied adiabatically to a magnetic material, its magnetic moments become ordered so that the magnetic part of the total entropy is reduced. In order to keep constant the total entropy in the adiabatic process, the crystalline lattice entropy increases, raising the temperature. The opposite effect occurs when the magnetic field is removed adiabatically, the temperature decreases. The variation in temperature owing to the magnetocaloric effect is called the adiabatic temperature change, ΔT_{ad}, and is a function of the initial magnetic flux density, B_1, final magnetic flux density, B_2, and its initial temperature, T. For paramagnetic materials in the temperature regions above 15–20 K, the entropy change from the ordering of the magnetic spins of paramagnetic materials is insufficient to cause any practical temperature change. On the other hand, in the case of ferromagnetic materials, it is possible to gain a practical temperature change where the maximum magnetocaloric effect occurs, near the magnetic ordering temperature, known as the Curie temperature, θ_c.

Giauque and MacDougall first realized the use of the magnetocaloric effect to reach extremely low temperatures (<1 K) by the adiabatic demagnetization of paramagnetic salts (Giauque and MacDougall, 1933). Brown introduced the concept of magnetic heat pumping using a regenerative cycle of a ferromagnetic material and extended the temperature range of magnetocaloric effect applications to room temperature (Brown, 1976). After this work by Brown, Barclay introduced the concept of active magnetic regenerator (Barclay, 1982) and substantial research has been conducted into magnetic heat pumping at room temperature regions, using superconducting (Zimm et al., 1998; Hirano et al., 2002; Blumenfeld et al., 2002) and permanent magnets (Bohigas et al., 2000; Okamura et al., 2006; Zimm et al., 2006; Engelbrecht et al., 2012) to create a magnetic field. These studies show that magnetic heat pumps are energy efficient and fully compatible with conventional compression heat pumps. Much effort is being put into modeling the active magnetic regenerative heat pumps to optimize their parameters and the geometry of the regenerators to gain further efficiency (Nielsen et al., 2011; Tura et al., 2012).

Although by applying heat pumps, it is often possible to reduce the energy consumption of a thermal process, the heat load and

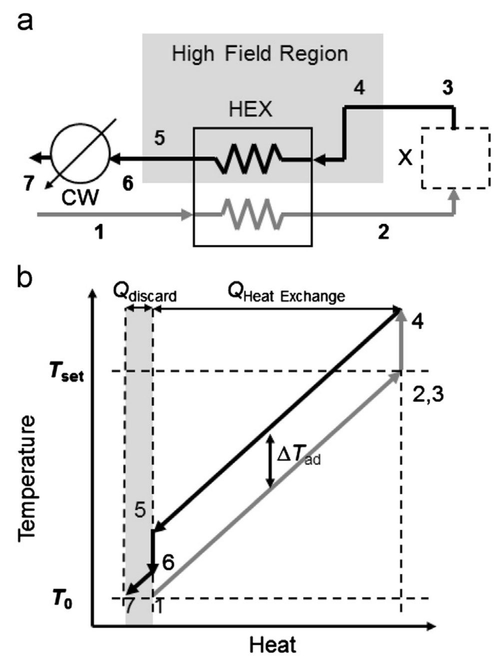

Fig. 1. (a) Schematic and (b) its temperature–heat diagram of the magnetocaloric heat circulator when the set temperature, T_{set}, is above environmental temperature, T_0, and the process material is ferromagnetic.

capacity of the process stream are often different from those of the pumped heat. In heat circulators the feed process stream is heated by the recuperated effluent process stream, thus the exergy destruction due to heat transfer is minimized.

2.2. Magnetocaloric heat circulator

In the magnetocaloric heat circulator, the adiabatic magnetization is applied to ferromagnetic materials to cause a reversible temperature change. The process heat is recirculated by the magnetocaloric effect of magnetic material subjected to cyclic magnetization and demagnetization. Fig. 1 shows a schematic of the magnetocaloric heat circulator when the process material is ferromagnetic. It consists of a feed effluent counter-flow heat exchanger and a high field region. The temperature of the process material is raised from the environmental temperature, T_0, to its set temperature, T_{set}, in the counter-flow heat exchanger (HEX) ($1\rightarrow2$) receiving the heat from effluent process material ($4\rightarrow5$). The temperature difference needed for heat exchange is provided by adiabatic magnetization ($3\rightarrow4$). Part of the magnetizing work is recovered when demagnetizing ($5\rightarrow6$), and rest of the heat is discarded at the cooling water (CW) ($6\rightarrow7$). Thus, all of the heat is circulated without heat addition. Note that there is a temperature gradient within the heat exchanger for it is a counter-flow heat exchanger.

Fig. 2 shows a schematic of the magnetocaloric heat circulator when the process material is non-magnetic. The magnetocaloric heat circulator consists of two heat exchangers, a closed cycle with ferromagnetic working material, and a high field region. The ferromagnetic material circulates in and out of the magnetic field. The temperature of the working material rises when it is magnetized ($2\rightarrow3$), and decreases when it is demagnetized ($4\rightarrow1$). The process material is inserted at environmental temperature, T_0, and is heated in HEX1 ($a\rightarrow b$) to its set temperature, T_{set}. The process material is then cooled in HEX2 ($c\rightarrow d$) and the remaining heat is discarded at the cooling water ($d\rightarrow e$). The remaining heat is discarded from the fluid, thus point 1 is shifted to point 1' in the temperature–heat diagram but both points are of the same state.