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Active Magnetic Regenerative Heat Circulator for Energy Saving in Thermal Process

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Recently, a conceptual design of an active magnetic regenerative (AMR) heat circulator that utilizes magnetocaloric effect to self-heat recuperation technology for energy saving in thermal process has been proposed. In an AMR heat circulator, the heat of the effluent process stream is given to the ferromagnetic working material, where it is recuperated through adiabatic magnetization. All of the recuperated process stream heat is given back to the feeding process stream so that it can be circulated. In this paper, the AMR heat circulator has been evaluated in two ways 1) through a mathematical model is constructed for understanding the temperature behaviour and the energy consumption of the process stream, and 2) through a temperature-entropy diagram for understanding the theoretical energy saving limit at given conditions. It was seen from the simulation results, that the AMR heat circulator is capable of circulating the process heat in the vicinity of the Curie temperature of a magnetocaloric material with small energy consumption.

1. Introduction

It has become one of our common concerns to suppress the emission of carbon dioxide and reduce the usage of fossil fuels. In order to minimize energy consumption in thermal processes, it is necessary to 1) avoid combustion, which is associated with large exergy loss, and 2) keep the temperature difference during heat exchange at its minimum value. Thus far, heat recovering technologies such as pinch technology (Linnhoff and Hindmarsh, 1983) are being applied to reduce the energy consumption in thermal processes. Recently, Kansha et al. (2009) proposed a self-heat recuperation technology that circulates all process stream heat without any heat addition. The heat of effluent process stream is recuperated by compression, so that it can be used for heating the feed process stream. In a self-heat recuperative process, no heat is added from outside the process, thus is free of combustion. Also, noting that the feed stream and the effluent stream are of the same mixture, the temperature difference during heat exchange is always kept at its minimum value leading to drastic reduction of exergy loss (Kansha et al. 2012).
Recuperation of the process stream heat by enforcing a change of state is essential for self-heat recuperation. In all of the conventional self-heat recuperative processes, compressors are applied to recuperate the process stream heat. However, method to recuperate heat exergy by enforcing a reversible temperature change is not only limited to pressure variation. When a magnetic material is subjected to a varying magnetic field, the entropy change of the magnetic moment inside the material enforces a reversible temperature change, which is known as the magnetocaloric effect (MCE) (Tishin and Spichkin, 2003; Oliveria and Ranke, 2010). Although above around 15 K, the entropy difference one can obtain from magnetization of paramagnetic materials is too small to enforce any practical temperature change, it is known that a large entropy change can be obtained through magnetization of ferromagnetic materials in the vicinity of its magnetic turning point where the material changes from ferromagnetic to paramagnetic, known as the Curie temperature (Tishin, 1990). In this research, to reduce the energy consumption in thermal processes, an active magnetic regenerative (AMR) heat circulator that utilizes MCE in self-heat recuperation is proposed and has been evaluated in terms of temperature-entropy diagram and one dimensional mathematical model.

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2. Conceptual design of active magnetic regenerative heat circulator

To realize the heat circulation using MCE, Kotani et al. (2012) introduced the concept of using an active magnetic regenerator (AMR) for self-heat recuperation. Employing a revolver type configuration proposed by Okamura et al. (2006) and Engelbrecht et al. (2012) for magnetic heat pumping, the device will look as shown in Figure 1. Two packed beds of magnetocaloric material is set. A temperature gradient is initially set so that the process fluid can be heated to its set temperature, T_{set}. The process stream enters the magnetized bed at environmental temperature, T_0, where it is heated to its set temperature, T_{set}. Via the next process, it is inserted to the demagnetized bed where it gives the heat to the magnetocaloric material and is cooled. After a certain period of time, the magnetized bed and the demagnetized bed will switch places, enabling a quasi-counter current heat exchange between the process fluid and the magnetocaloric material. Pulling the bed out of the magnetic field involves work, W_{demag}, while the magnet automatically pulls the demagnetized bed into the field so that work, W_{mag}, can be recovered. The net work can expressed as

$$W_{\text{net}} = W_{\text{demag}} - W_{\text{mag}} \tag{4}$$

which is equivalent to the heat discarded at the cooler, from the conservation law of energy. Unlike the heat pump, which is a mean to provide heat in to the system from outside, heat circulator is a mean to circulate the heat of the system internally. So it cannot be applied to system that needs heat provision, but can be a suitable option for chemical processes where the process fluid needs to be set to certain temperature condition and return to its original environmental temperature T_0. Thus, some of the suitable applications are separation, drying and ventilation.

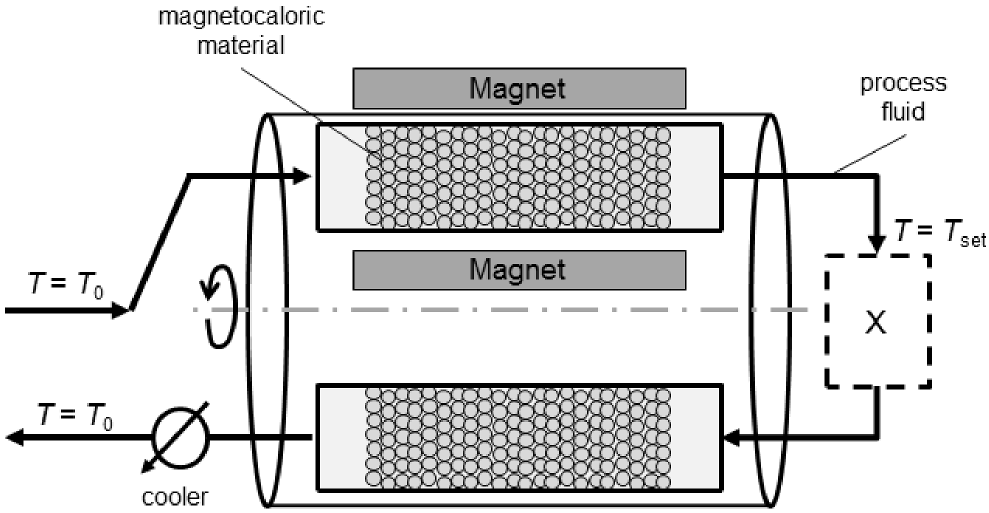

Figure 1: A schematic of active magnetic regenerative heat circulator. X is a process which does not involve exchange of reaction heat. T_0 and T_{set} denote the environmental temperature and the set temperature at process X respectively

3. Simulation with mathematical model

3.1 Mathematical model

To evaluate the temperature behaviour of the process fluid and the energy consumption, a mathematical model is built. Gadolinium was chosen as the magnetocaloric material for its magneto-thermal properties are well understood (Dan'kov et al., 1998) and water as the process fluid.

From the energy balance of the magnetocaloric material and the process fluid, the bed can be expressed by the following one dimensional model.

$$\rho_{\text{f}} c_{\text{f}} A_{\text{cs}} \varepsilon \frac{\partial T_{\text{f}}}{\partial t} + \dot{m}_{\text{f}} c_{\text{f}} \frac{\partial T_{\text{f}}}{\partial x} = A_{\text{cs}} \varepsilon k_{\text{f}} \frac{\partial^2 T_{\text{f}}}{\partial x^2} - h a_{\text{s}} \left(T_{\text{f}} - T_{\text{s}} \right) \tag{5}$$

$$\rho_s c_s(B,T_s)A_{cs}(1-\varepsilon)\frac{\partial T_s}{\partial t} = A_{cs}(1-\varepsilon)k_s\frac{\partial^2 T_s}{\partial x^2} + ha_s(T_f - T_s) + A_{cs}(1-\varepsilon)T_s\left(\frac{\partial M}{\partial T_s}\right)_B \frac{\partial B}{\partial t} \quad (6)$$

ρ, c, k, M and T denote the density, heat capacity, heat conductivity, strength of magnetization and temperature respectively, and the subscripts f and s denote the fluid (process fluid) and the solid (magnetocaloric material) respectively. A_{cs}, ε, m_f, a_s and B respectively denote the cross sectional area, porosity, flow rate, heat transfer surface and magnetic flux density. The solid–fluid heat transfer coefficient, *h,* for a packed bed of spherical solids is calculated using the equation by Wakao et al. (1979).

$$h = \frac{k_f}{d_p}\left[2.0 + 1.1\mathrm{Pr}_f^{1/3}\,\mathrm{Re}_f^{0.6}\right] \quad (7)$$

d_p, Pr_f and Re_f are the diameter of the spheres, Prandtl number and Reynolds number of the process fluid, respectively.
The magnetization, M, and the heat capacity of the magnetocaloric material, c_s, was calculated using the mean field approximation (Tishin and Spichkin, 2003). Figure 2 shows the heat capacity of Gadolinium calculated using the mean field approximation. It can be seen that the heat capacity changes drastically in the vicinity of its Curie temperature (= 293 K), thus must be considered during simulations.

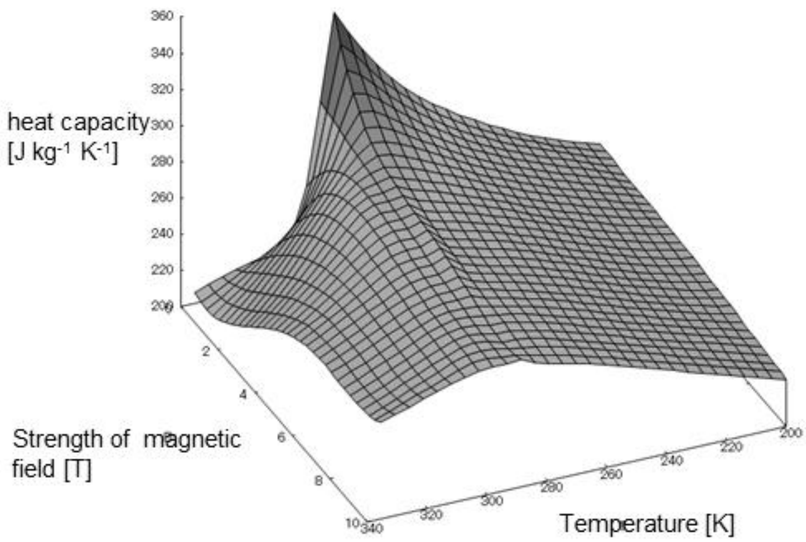

Figure 2: Heat capacity of Gadolinium in the vicinity of its Curie temperature under various magnetic fields

The AMR heat circulator cycle can be realized through the following four steps

1. Magnetization: by increasing the magnetic field applied to the bed, the temperature of the magnetocaloric material is increased.
2. Isomagnetic cooling: the magnetocaloric material is cooled by the process fluid which enters the bed at environmental temperature T_0. The process fluid temperature is raised to T_{set}.
3. Demagnetization: by reducing the magnetic field applied to the bed, the temperature of the magnetocaloric material is decreased.
4. Isomagnetic heating: the magnetocaloric material is heated by the process fluid which enters the bed at set temperature T_{set}. The process fluid temperature is cooled to T_0.

Initially, the temperature of the bed is set to environmental temperature. The bed temperature of the hot end gradually increases as the cycle is repeated and will saturate at a certain temperature where the heat discarded balances with the work input. The temperature in which it saturates is the set temperature, T_{set}.
Table 1 shows the conditions in which the simulation was performed. The cycle of the pitch is set to 3.0 seconds, where time for magnetization and demagnetization is set to 0.5 seconds and time for isomagnetic heating and cooling is set to 1.0 second.

.*Table 1: AMR heat circulator simulation conditions*

environmental temp. T_0	293.15 [K]	porosity ε	0.55 [-]
bed diameter d_b	7.7 [mm]	pitch $1/f$	3.0 [s]
bed length l_b	60 [mm]	magnetic field B	0.9 [T]
sphere diameter d_p	0.8 [mm]	mass flow rate m	0.45×10^{-3} [kg s^{-1}]

3.2 Temperature profile and energy consumption

Figure 3 shows the temperature evolution of the process fluid at the hot end of the bed. It can be seen that after 266 cycles, the set temperature, T_{set}, reached 317.4 K. The Temperature of the hot end saturates when the heat that has been discarded matches the work provided. The amount of heat discarded increases as the temperature gradient inside the bed becomes larger and the amount of work provided decreases as the bed temperature furthers from the Curie temperature of the magnetocaloric material, until they finally meet at the same value.

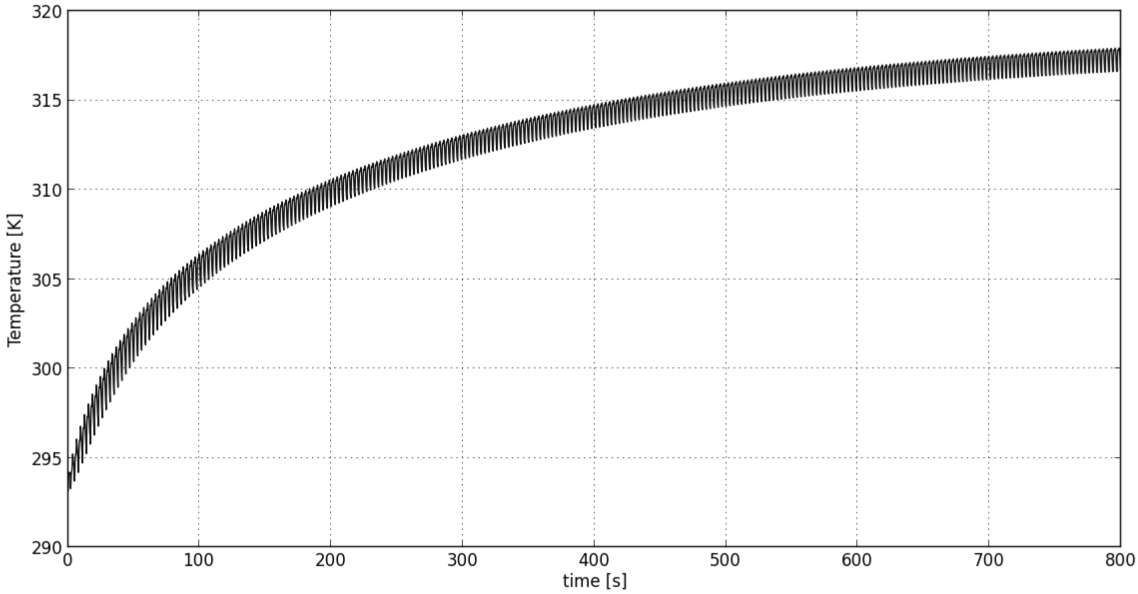

Figure 3: Temperature evolution of the process fluid at the hot end of the active regenerative bed

The energy consumption, W_{net}; of the AMR heat circulator was determined from the heat discarded by the process fluid, $Q_{discard}$. The total energy consumption, W_{net}; is 126.1 x 10^{-3} J cycle^{-1}. The circulated heat, Q_{cir}, is 42.70 J cycle^{-1}. If this heat is provided with a heat pump, the energy consumption is equivalent to a heat pump with coefficient of performance (COP) of 338.7. Therefore, it can be seen that although limited to temperature regions in the vicinity of the Curie temperature of the magnetocaloric material, AMR heat circulator is capable of circulating heat with drastically small energy consumption.

4. Theoretical energy saving limit in terms of temperature-entropy diagram

In order to obtain the theoretical energy saving limits of the AMR heat circulator, a process as shown in Figure 4a is considered. To recuperate the heat exergy of the process stream, the heat is passed to the magnetocaloric material at HEX2. The passed heat is recuperated through magnetization and given back to the process stream at HEX1. The process fluid at environmental temperature, T_0, is heated (a → b) to its set temperature, T_{set}, while the magnetized magnetic material is cooled (3 → 4) in HEX1. The process material is then cooled (c →d) while the demagnetized magnetic material is heated (1 → 2) in HEX2. The remaining heat is finally discarded at the cooler (d → e). The following equations may be realized through the energy balance:

$$Q_{\mathrm{ab}} = Q_{34} = Q_{\mathrm{cd}} + Q_{\mathrm{discaard}} = Q_{12} + Q_{\mathrm{discard}} \quad (1)$$

$$Q_{\mathrm{discard}} = W_{\mathrm{theo}} \tag{2}$$

where Q_{ab} (a - b - IV - I) and Q_{12} (1 - 2 - IV - II) are the heat exchanged in HEX2, Q_{cd} (c - d - III - IV) and Q_{34} (3 - 4 - II - IV) are the heat exchanged in HEX1 and Q_{discard} (d - e - I - III) is the heat discarded at the cooler. The theoretical energy consumption, W_{theo}; is equal to the heat discarded at the cooler, Q_{discard}. Exergy loss, *Ex,* can be derived from

$$Ex = \Delta H - T_0 \Delta S \tag{3}$$

where ΔH and ΔS denote the overall enthalpy and entropy variation respectively. The overall enthalpy variation, ΔH, is zero because the process stream and magnetocaloric material goes back to its original state after each cycle. Thus, the exergy loss is equal to $-T_0\Delta S$ (e - I - III – III') and is kept small. The temperature of the process fluid at T_0 = 293.15 K was raised to 317.4 K to match the former simulation using the mathematical model, and returned to its original temperature. The strength of the magnetic field, B_2, is set to 0.9 T. The temperature-entropy diagram was obtained by mean field approximation (Tishin and Spichkin, 2003).

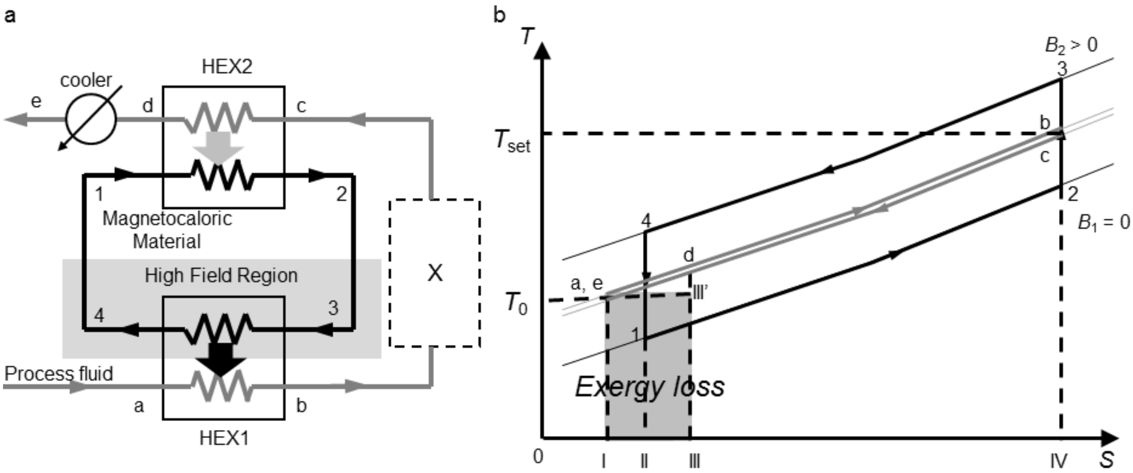

Figure 4: A schematic of heat circulator where magnetocaloric effect is applied, a) process image b) cycle in terms of temperature-entropy diagram

Table 2 shows the energy consumption obtained from the temperature-entropy diagram using Gadolinium. The circulated heat, Q_{cir}: is set so as to match the circulated heat amount in the former simulation. The theoretical work needed, W_{theo}; to circulate Q_{cir} is 110.6 x 10^{-3} J. Comparing the theoretical work W_{theo} with the work obtained from the mathematical model, W_{net}; the theoretical energy saving limit in a certain condition can be obtained. The difference in the value of energy consumption is caused by the method in which heat is exchanged. In the process shown in Figure 4 a, the heat is exchanged in counter current method, where as in the AMR heat circulator, the heat is exchanged in quasi-counter current method. Through optimization of parameters, such as the flow rate, bed length, and cycle pitch, it can be assumed that the energy consumption value, W_{net}; will get closer to the theoretical value, W_{theo}.

Table 2: Magnetic flux density, B; heat circulated, Q_{cir}; theoretical work required, W_{theo}; per unit mass of Gadolinium, Gd; when heat is circulated from T_0 = 293 K to T_{set}

ΔT_{set} [K]	B_2 [T]	Q_{cir} [J]	W_{theo} [J]	W_{net} / W_{theo} [-]
317.4	0.90	42.70	110.6 x 10^{-3}	0.88

5. Conclusions

An active magnetic regenerative (AMR) heat circulator for energy saving in thermal processes is proposed. The AMR heat circulator employs magnetocaloric effect (MCE) to self-heat recuperation. The heat exchanged between the process fluid and the magnetocaloric material in a quasi-counter current method. From the simulation, it was found that when the process stream heat of 42.70 J cycle^{-1} was circulated in between temperatures between 293.15 K and 317.4 K, 126.1 x 10^{-3} J cycle^{-1} of work is needed, which is equivalent to heat pump with COP 338.7. From the temperature-entropy diagram, the theoretical energy consumption at a given condition was obtained. By comparing the value obtained from the mathematical model and the value obtained from the temperature-entropy diagram, the limit of further energy saving through optimization of parameters such as flow rate, bed length and cycle pitch was clarified. The results showed that AMR heat circulator is capable of circulating the process heat in the vicinity of the Curie temperature of a magnetocaloric material, and has the potential of becoming an energy saving alternative for applications in which compressors cannot be applied.

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