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Self-Heat Recuperation Using Magnetocaloric Effect

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Recently, self-heat recuperation using a magnetic heat circulator for thermal processes that uses liquids as their process stream has been proposed. In the heat circulator, the heat exergy of the process stream is recuperated by magnetocaloric effect of ferromagnetic material so that it can be recirculated. All heat is recirculated inside the system without heat addition, leading to drastic energy saving. A numerical one-dimensional time-dependant model has also been presented to study the transient and steady behaviour of the magnetic heat circulator. Gadolinium was chosen as the magnetocaloric material while the process fluid is represented by liquid water. With this model it is possible to define the temperature where the heat conduction balances with the heat from the magnetocaloric effect and to make a quick comparison of parameters such as the maximum magnetic flux density, bed length and diameter, magnetocaloric material and fluids.

1. Introduction

Over the last few decades, carbon dioxide (CO_2) reduction and fossil fuel consumption has 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 (Linnhoff and Hindmarsh, 1983) based on the principle of heat cascading utilization have been applied to reduce energy consumption. However, because of the temperature difference required for heat exchange, not all of the heat can be recovered and extra heating by a furnace heater is required.
To reduce the energy consumption of thermal processes, self-heat recuperation technology based on the exergy recuperative heat utilization has been proposed (Kansha et al., 2009). In the self-heat recuperation technology, all process stream heat is recirculated by providing work to recuperate the heat exergy. The total energy consumption in the self-heat recuperative thermal process is much smaller than that for conventional heat recovery on enthalpy basis (Kansha et al., 2010). A system that is constructed upon the principle of self-heat recuperation is called a heat circulator.
In a case of gas and vapour heat circulator systems, the process stream can be adiabatically compressed to raise its temperature. But adiabatic compression cannot be applied to processes that treat liquids or solids as their process stream. To apply self-heat recuperation to incompressible fluids, a magnetic heat circulator that utilizes the magnetocaloric effect (MCE) of ferromagnetic material has been presented by Kotani et al. (2011). The process stream heat is recirculated by cyclic magnetization and demagnetization, no heat is added from outside the process leading to large energy savings.
Magnetocaloric effect is the heating or cooling of magnetic material subjected to varying magnetic field (Pecharsky and Gschneidner Jr, 1999; Oliveria and Ranke, 2010). Brown (1976) introduced the concept of using an active magnetic regenerator (AMR) using gadolinium to utilize magnetocaloric effect for heat pumping at room temperature regions. Some numerical models has been studied to

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evaluate its performances (Aprea and Maioriono, 2010; Sarlah and Poredos, 2010). These studies showed the potential of magnetic heat pumps as an energy saving alternative.
In the heat pump system, environmental or process waste heat is pumped to heat the process stream. However, the heat load and capacity of the process stream are often different from those of the pumped heat, thus excess heating is needed leading to an increase of energy consumption. On the other hand, in the case of heat circulators, the effluent stream temperature is raised by providing work so that its heat can be reused for heating the feed stream. Thus, no excess heating is needed leading to large energy saving. Figure 1 shows the process image and the cycle of magnetic heat in terms of temperature-entropy diagram. The total energy consumption is equal to the heat that is discarded at the cooling water Q_{discard}.
It is essential for the magnetic heat circulator that the heat of the magnetocaloric material transfers to the fluid at the two heat exchangers (HEXs) so that it can be circulated. The temperature elevation by the magnetocaloric effect itself is usually merely a few K/T, thus slow heat transfer due to small temperature difference in exchanging heat is expected. To overcome this issue, heat is exchanged in a packed bed with the spherical magnetocaloric material. Numerical modelling techniques are used to allow design and optimization of heat exchange in the magnetic heat circulator. In this paper, a numerical one-dimensional time-dependant model of the magnetic heat circulator has been proposed. The model can be used to predict the transient and steady behaviour of the heat circulator.

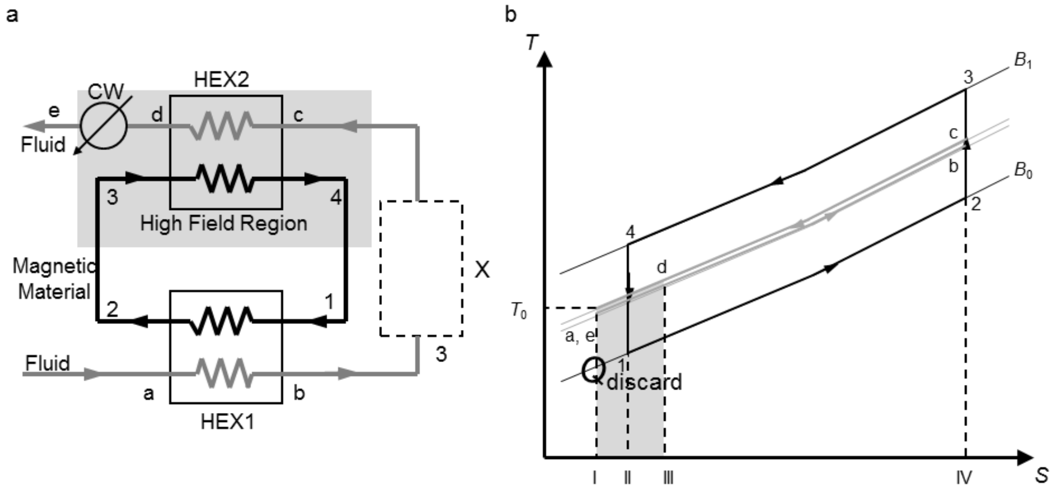

Figure 1: Schematic image of magnetic heat circulator a) process image b) cycle in terms of temperature-entropy diagram. T_0 denotes the ambient temperature, B_0 and B_1 denotes the initial and high field region magnetic flux density respectively

2. Numerical one-dimensional model

2.1 Magnetic heat circulator

The configuration of the magnetic heat circulator for effective heat exchange between the magnetocaloric material and the fluid is shown in Figure 2. The spherical magnetocaloric material is configured as a packed bed. It is essential for self-heat recuperation to exchange heat in counter flow to minimize the exergy loss due to heat exchange. Thus, temperature gradient is created inside the packed bed for a quasi-counter current heat exchange with the fluid. The cycle of magnetic heat circulator consists of 4 steps.

1) both valves are closed, adiabatic magnetization of magnetocaloric material
2) valve 1 is opened, fluid at ambient temperature T_0 flows through the material packed bed from cold to the hot end (cold fluid blow)
3) both valves are closed, adiabatic demagnetization of magnetocaloric material

4) valve 2 is opened, fluid temperature at T_h flows through the material packed bed from hot to the cold end (hot fluid blow)

The temperature at the hot end (X in Figure 2) is determined by the balance between the amount of heat induced by the magnetocaloric effect and the rate in which the amount of heat conducted through the bed.

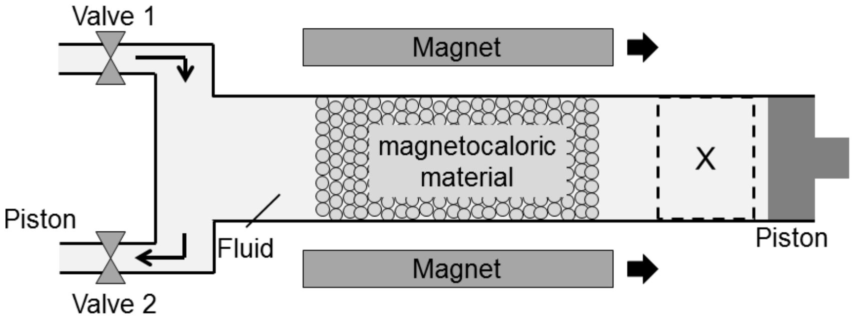

Figure 2: Configuration of magnetic heat circulator using packed bed with temperature gradient to obtain a quasi-counter flow heat exchange

2.2 Description of the model

In order to predict the temperature at the hot end, a numerical one dimensional model is constructed. Gadolinium was chosen as the reference magnetocaloric material for its physical properties are well known (Dan'kov et al. 1998) and water as the reference fluid.

To simplify the equation, the temperature of the magnetocaloric particle and the fluid are considered the same at each location inside the bed. Heat losses and effect of viscous dissipation has been neglected, the fluid water is considered incompressible and hysteresis and electro-induction of gadolinium is neglected. The heat capacity, head conductivity and the density of the fluid and the magnetocaloric material has been considered as a constant except the heat capacity of the magnetocaloric particle, c_s, which is a function of temperature and the magnetic flux density. The energy balance of the bed can be described in one equation as

$$\rho_b c_b \frac{\partial T_b}{\partial t} + \rho_f c_f u_f \frac{\partial T_b}{\partial x} = \frac{\partial}{\partial x}\left(k_{eff} \frac{\partial T_b}{\partial x}\right) - (1-\varepsilon) T_b \left(\frac{\partial M}{\partial T_b}\right)_B \frac{\partial B}{\partial t} \tag{1}$$

where ρ, c, u, T, k, ε, M, B, t denote the density, specific heat capacity, flow rate, temperature, heat conductivity, porosity, strength of magnetization, magnetic flux density, time respectively and the subscripts *b*, *f*, *s* denote the bed, fluid and solid respectively. The strength of magnetization and the heat capacity of the magnetocaloric material have been determined by the mean field theory (Tishin 1990). The flow rate of the fluid has been set so that the heat capacity of the fluid will match the heat capacity of the magnetocaloric particles inside the bed. The thermal conductivity of the packed bed has been determined by the equations by Krunpichzka (1967) and Yagi and Kunii (1960).

$$\frac{k_{eff}}{k_f} = \left(\frac{k_s}{k_f}\right)^n + 0.75 \,\mathrm{Re}\,\mathrm{Pt} \tag{3}$$

$$n = 0.280 - 0.757 \log_{10} \varepsilon - 0.057 \log_{10} \frac{k_s}{k_f} \tag{4}$$

The input data to the magnetic heat circulator model is shown in Table 1. Three conditions were set to compare the effect of bed length and maximum magnetic flux density to the temperature in which the amount of heat induced by the magnetocaloric effect and the rate in which the amount of heat conducted through the bed balances. Condition 2 has larger bed length compared to condition 1; condition 3 has larger magnetic flux density. The bed was assumed to be at 293 K initially.

Table 1: Input data to the magnetic heat circulator model l_b, B_{max}, d_p, D, u_{max} denotes the bed length, maximum magnetic flux density, particle diameter, bed diameter, maximum flow rate

Characteristics	condition 1	condition 2	condition 3	dimension
l_b	60	<u>200</u>	60	mm
B_{max}	1.0	1.0	<u>2.0</u>	T
d_p	600	600	600	μm
D	8	8	8	mm
u_{max}	17	17	17	mm s^{-1}
T_0	293	293	293	K

3. Results and Discussion

Figure 3 shows the simulated time evolution of the hot and cold end of the packed bed calculated in condition 1. The temperature of the bed rises as it is magnetized, the hot end temperature decreases in cold fluid blow, then its temperature decreases further in demagnetization, then the cold end temperature rises in hot blow. The temperature difference that can be gained by magnetization of gadolinium to 1 T field is around 1.4 K and about the same for demagnetization. The cold end goes through practically the same cycle for fluid at 293 K is always inserted at the cold fluid blow, but the temperature of the hot end gradually increases. It can be seen that after about 5 cycles, the temperature of the hot end saturates at around 295.4 K which is about 2.4 K higher than the initial temperature T_0 293 K.

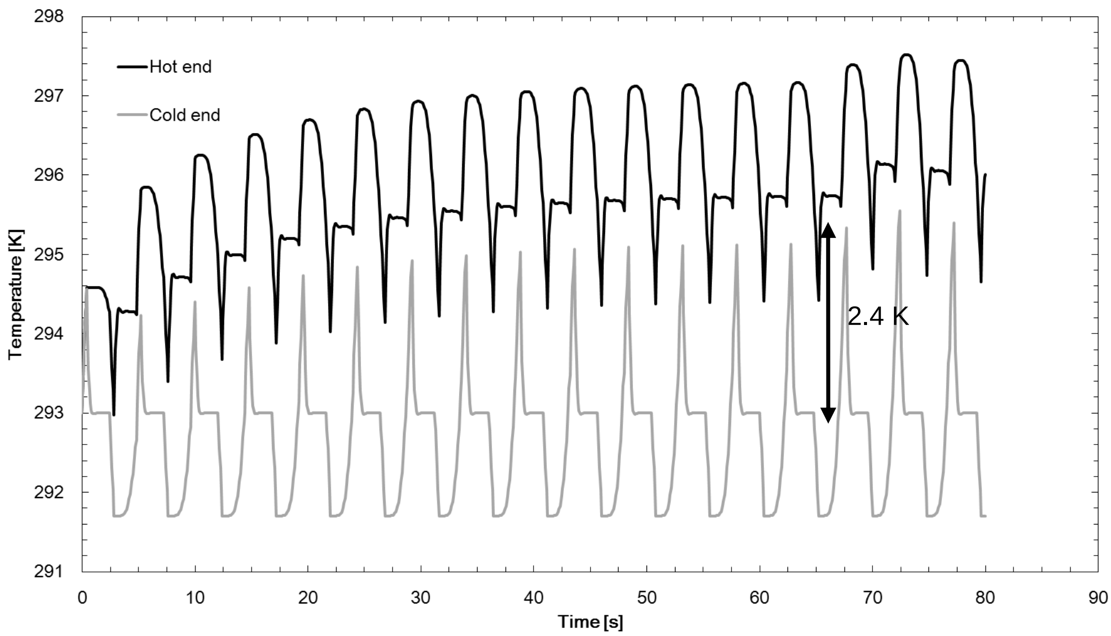

Figure 3: time evolution of hot and cold end of the packed bed calculated in condition 1

Figure 4 shows the simulated time evolution of the hot end at different conditions. It can be seen that the temperature at which the hot end saturates is larger in both cases; around 300.5 K for condition 2 and around 297.3 K for condition 3. The temperature difference that can be gained by magnetization of gadolinium to 2 T field is around 3 K and about the same for demagnetization. The temperature was higher in condition 2 which is a preferred result, for it is often difficult and consumes a lot of magnet to create small area with large magnetic flux density than large area with small magnetic flux density. It is also noted that large magnetic flux density will create a large adiabatic temperature change, thus a large temperature difference between the magnetocaloric material and the fluid resulting in larger exergy loss.

By using the described numerical model, it will become possible to make a quick comparison of parameters such as the maximum magnetic flux density, bed length and diameter, magnetocaloric material and fluids. The proposed model can be of great value when developing new heat transferring geometries.

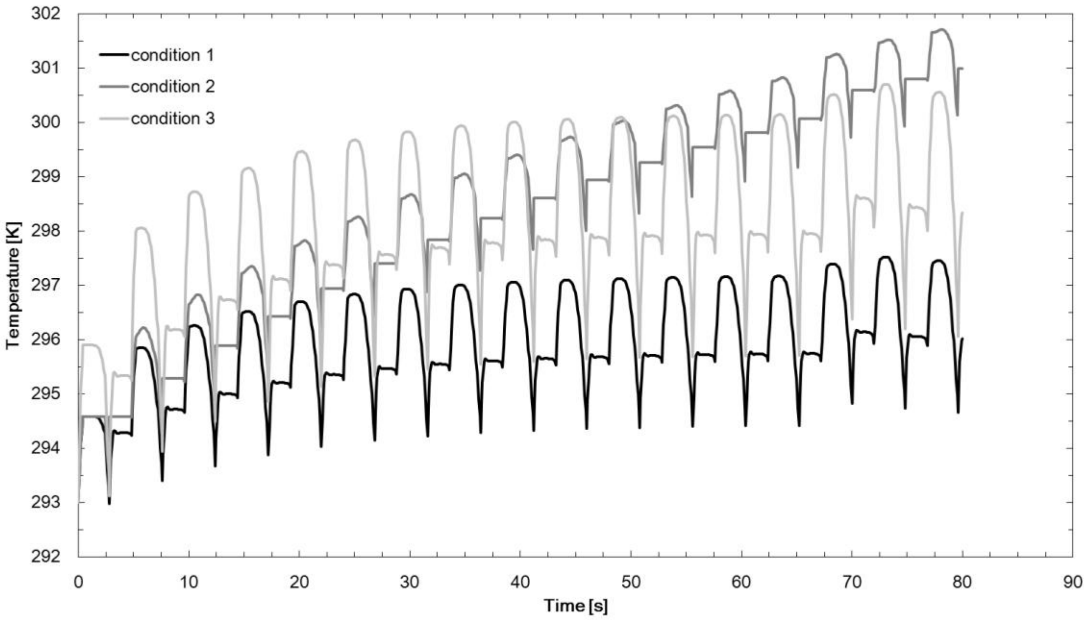

Figure 4: comparison of time evolution of particle bed hot end with reference (condition 1), larger bed length (condition 2), and large magnetic flux density (condition 3)

4. Conclusion

A numerical one-dimensional time-dependant model has also been presented to study the transient and steady behaviour of the magnetic heat circulator. To simplify the equation, the temperature of the magnetocaloric material and the fluid are considered same at each location inside the bed. Gadolinium and water was chosen as the reference material and simulation according to the model has been performed. From the simulation, the temperature in which the amount of heat induced by the magnetocaloric effect and the rate in which the amount of heat conducted through the bed balances was gained. The model can be used to make a quick comparison of parameters such as the maximum magnetic flux density, bed length and diameter, magnetocaloric material and fluids. The proposed model can be of great value when developing new geometries for the magnetic heat circulator.

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