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Theoretical and Experimental Investigation on the Energy Consumption of Self-Heat Recuperation using Magnetocaloric Effect

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The minimum energy consumption needed for heat circulation is derived from the exergy destruction due to heat exchange in terms of temperature-entropy diagram. The obtained value is compared with the numerical energy consumption when magnetocaloric effect is applied to self-heat recuperation technology. Furthermore, a magnetocaloric heat circulator has newly been constructed and its energy consumption has been measured. It is explained by the temperature-entropy diagram, that the minimum energy consumption needed for heat circulation is proportional to the minimum temperature difference needed for heat exchange. In a magnetocaloric heat circulator, the heat transfer between the process fluid and the working material is direct, thus leading to small temperature difference during heat exchange and small input work required for heat circulation.

1. Introduction

Magnetocaloric effect is characterized by a reversible temperature change of magnetic materials that can be detected when it is subjected to a varying magnetic field (Tishin and Spichkin, 2003). The first practical use of the magnetocaloric effect was the attempt to reach extreme cold temperatures through adiabatic demagnetization by Giauque (1927). After Brown (1976) introduced the concept of magnetic heat pumping at room temperature using an active magnetic regenerative heat pump, considerable number of works has been performed aiming to replace the conventional heat pumps using vapour (Sari and Bali, 2014). The adiabatic temperature change, ΔT_{ad}, which can be gained through adiabatic magnetization of a magnetocaloric material is usually merely few K/T. Although active magnetic regeneration can enlarge the temperature difference in which the heat can be pumped, 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. Recently, the authors proposed the concept of applying magnetocaloric effect to self-heat recuperation technology, where only temperature difference needed for heat exchange between the process fluid and the magnetocaloric working material is required for heat circulation (Kotani et al., 2013a).

In a self-heat recuperative process, all of the effluent process stream heat is recuperated by work provision and reused to heat the feed process stream (Kansha et al., 2009). No makeup heat but only work is added to circulate the process stream heat. In a conventional self-heat recuperative process, work was provided through compressors and has been applied to various processes including sea water desalination (Mizuno et al., 2012), distillation (Matsuda et al., 2011), and biomass drying (Liu et al., 2012) showing potential of drastic energy savings.

The authors proposed the concept of using the active magnetic regeneration used in magnetic heat pumping in self-heat recuperation, and its energy saving potential has been presented through a one-dimensional mathematical model (Kotani et al., 2013b). In this paper, the minimum energy consumption needed for heat circulation is derived from exergy destruction in terms of temperature-entropy diagram.

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The obtained value is compared with the numerical energy consumption when magnetocaloric effect is applied to self-heat recuperation technology. A magnetocaloric heat circulator for self-heat recuperation has been constructed and its energy consumption has been measured. Potential of further reduction of energy consumption has been discussed through comparison of the numerically and experimentally obtained value.

2. Energy consumption needed for heat circulation derived in terms of exergy destruction

In order to raise the temperature of a cold process fluid from a certain temperature, T_0, to a set temperature, T_{set}, heat needs to be transferred from a hot process stream. When heat is transferred between process fluids of different temperatures, exergy destruction will occur. If we consider a minimum temperature difference needed for heat exchange, ΔT_{min}, the exergy destruction during heat exchange is the smallest when the temperature difference during heat exchange is ΔT_{min} from start to end, thus the composite curve of the hot and the cold stream is parallel (Figure 1a). Figure 1b shows the temperature-entropy diagram during heat exchange between the hot and the cold stream when the temperature difference during heat exchange is kept constant at ΔT_{min}. The heat that is transferred, $Q_{transfer}$, is represent by area A-B-III-I for the cold stream and area a-b-II-III in Figure 1b and are of the same size. The minimum exergy destruction for heat exchange when the minimum temperature difference can be written as,

$$Ex = T_0\left(\Delta S_{\text{cold}} - \Delta S_{\text{hot}}\right) \tag{1}$$

where ΔS_{hot} and ΔS_{cold} is the entropy difference after heat exchange for the hot stream and the cold stream. The exergy destruction, Ex, is represented by the shaded area in Figure 1b. It can be seen that the exergy destruction due to heat exchange is proportional to the temperature difference during heat exchange. The heat capacity of the hot and the cold stream must match for the minimum temperature difference during heat exchange to be constant. In self-heat recuperation, the heat exergy of the effluent process stream is recuperated by compression so that it can be used to heat the feed process stream. Thus, assuming the effect of pressure to heat capacity is small the heat capacity of the hot and cold stream matches, so that the exergy destruction due to heat exchange is kept minimum. The exergy destruction, Ex, is equal to the minimum shaft work needed for heat circulation (Kansha et al., 2013).

In self-heat recuperation when the process stream is composed of gaseous materials, compression can be applied to recuperate the heat exergy of the effluent stream. However, in the case when the process stream is composed of liquid, it cannot be compressed. In the case when the process stream is incompressible, heat of the effluent process stream can be transferred to a working material where it is recuperated and used to heat the feed process stream. The exergy destruction is minimum when the temperature difference during heat exchange between the working material and the process stream is constant at ΔT_{min} (Figure 2a). The heat that is transferred, $Q_{transfer}$, is represent by the area A-B-IV-I for the

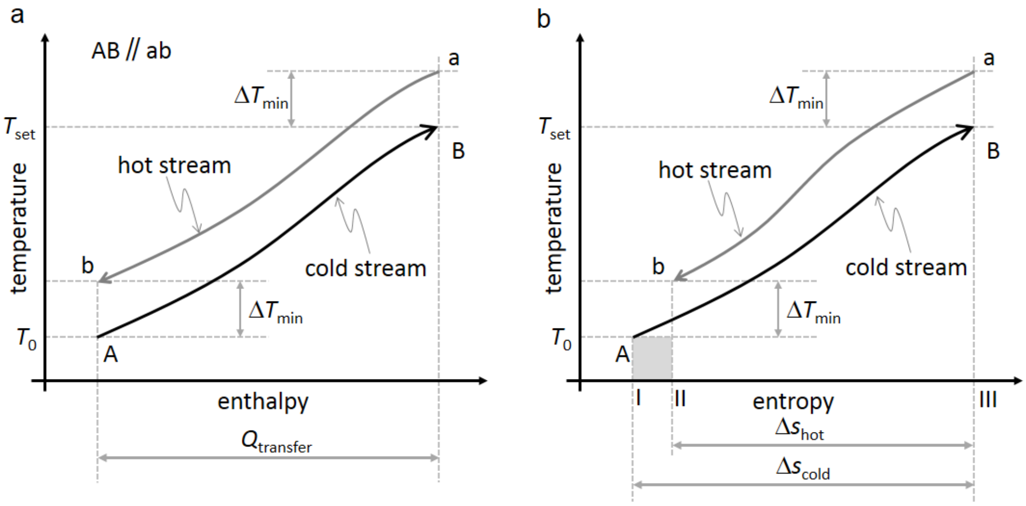

Figure 1: (a) Temperature-enthalpy diagram and (b) temperature-entropy diagram, when heat is transferred between hot and cold stream at constant temperature ΔT_{min}

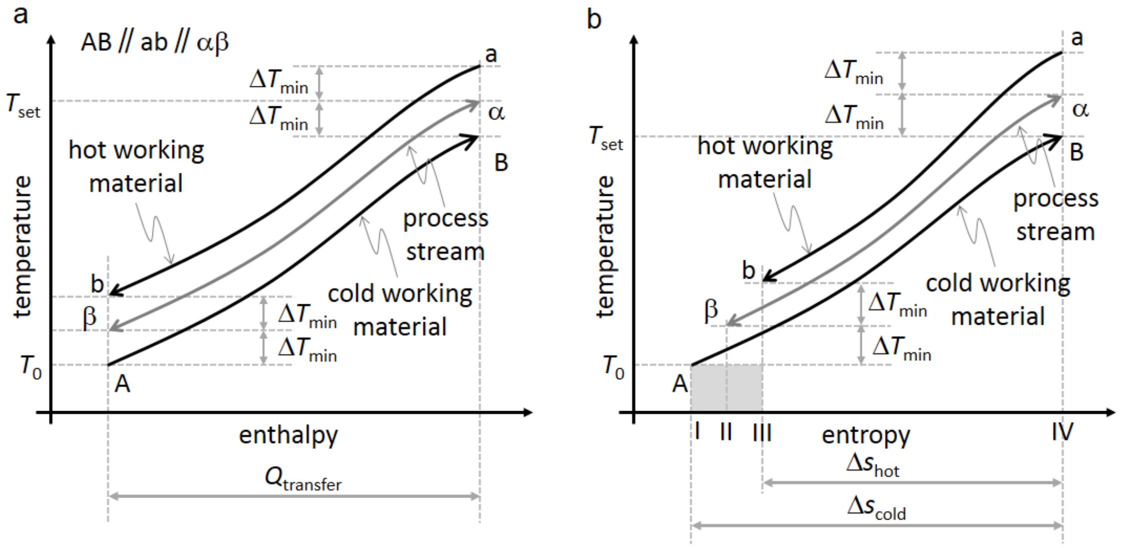

Figure 2: (a) Temperature-enthalpy diagram and (b) temperature-entropy diagram, when heat is transferred to working material at constant temperature ΔT_{min} for heat exergy recuperation

cold working material, area β-α-IV-II for the process stream and area a-b-III-IV in Figure 2b for the hot working material and are of the same size. The exergy destruction, *Ex*, is represented by the shaded area in Figure 2b, which is equal to the minimum shaft work needed for heat circulation.

It can be seen that the input work needed for heat circulation in a self-heat recuperative process is proportional to the minimum temperature difference needed for heat exchange. In a case where magnetocaloric effect is applied to self-heat recuperation, the heat transfer between the working magnetocaloric material and the process fluid is direct. Thus, the minimum temperature difference needed for heat exchange can be made small leading to small input work needed for heat circulation. However, magnetocaloric effect only shows large temperature difference in the vicinity of the Curie temperature of the magnetocaloric material, so that the magnetic field has larger effect to the heat capacity than the pressure did to gaseous materials. It can be seen from the temperature-entropy diagram of gadolinium (Gd), the heat capacity of the hot and cold working material may differ quite largely depending on the magnetic field, leading to extra exergy destruction during heat exchange and extra input work.

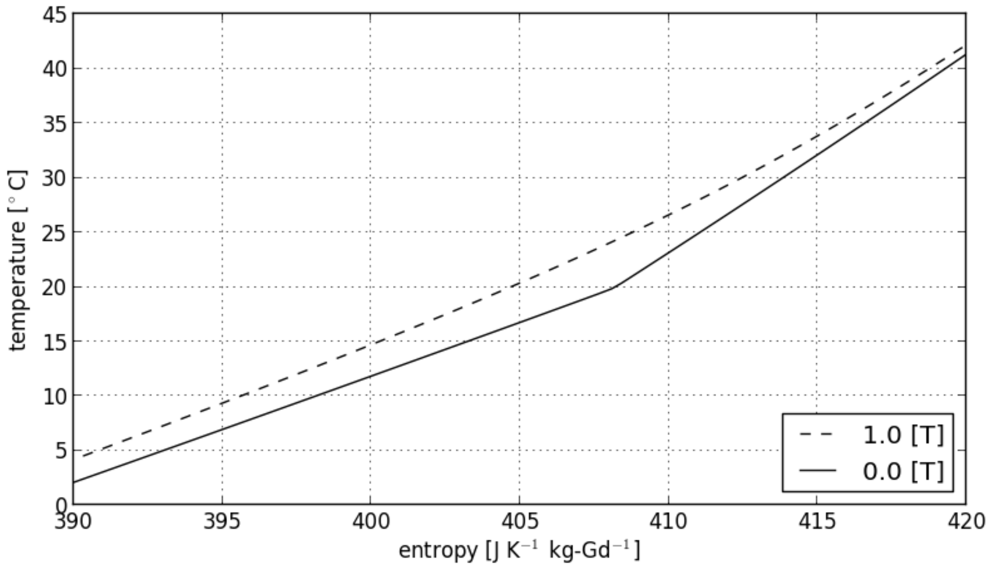

Figure 3: Temperature-entropy diagram of Gd at 0 and 1.0 [T] in the vicinity of its Curie temperature, calculated using the Mean Field Theory (Tishin and Spichkin, 2003)

3. Comparison of experimental and numerical energy consumption

A magnetocaloric heat circulator has been constructed to obtain its energy consumption. The schematic of experimental setup configuration is shown in Figure 4. Crushed Gd, after passage through an 850 μm sieve was packed in an acrylic tube as the magnetocaloric working material, and water was used as the process fluid. The temperature and the pressure of the inlet and the outlet of the magnetocaloric material packed bed was measured using T type thermocouples and pressure sensors. An actuator was used to control the magnetization and the demagnetization of the bed by pushing and pulling the magnetocaloric bed in and out of the magnetic field created by a permanent magnet. The permanent magnet was created by TOWA Industrial Co, Ltd., and could provide a magnetic field over 0.9 T within 25 mm radius from the point at which the field was at a maximum. A tubing pump was used to control the flow rate and the direction of the process fluid synchronized with the magnetization and the demagnetization of the bed. The bed is magnetized whilst the process fluid flows in one direction, then the bed is demagnetized whilst the process fluid flows in the other direction so that a temperature gradient can be created in between the two ends of the bed. Cooling water is used to ensure that the process fluid enters the magnetocaloric bed at constant temperature T_0. A force sensor was inserted in between the actuator and the magnetocaloric packed bed so that the input work needed for magnetization and demagnetization can be calculated. The net work input is the work that is needed for magnetization minus the work needed for demagnetization, regarding that the forces can be compensated (Balli et al., 2011). The bed length was 50 mm and the void ratio was 0.65. The fluid flow rate was set to 0.16 mL s^{-1}. The frequency of the AMR cycle was set at 0.25 Hz. From the experimental investigation, it was seen that net work input of 0.16 J $cycle^{-1}$ is needed to circulate heat of 8.70 J $cycle^{-1}$ between 17.5 and 24.0 °C. Assuming that the magnetic field was at constant 0.9 T throughout the magnetocaloric bed, the minimum temperature difference during heat exchange, ΔT_{min}, can be calculated as 1.7 K, which is half of the adiabatic temperature change, ΔT_{ad}, of Gd when it is magnetized from 0 to 0.9 T at 22.3 °C, calculated using the mean field theory (Tishin and Spichkin, 2003). Table 2 compares the net work input, W_{net}, and the heat circulated, Q_{cir}, for (case 1) the minimum energy consumption derived from exergy destruction, when heat is transferred to working material at constant temperature ΔT_{min}, (case 2) the energy consumption when magnetocaloric effect is applied to self-heat recuperation assuming the cold working material to be Gd at 0 T and hot working material to be Gd at 0.9 T, and (case 3) the energy consumption derived from experimental measurements. Table 1 shows the parameters in which the experiment was performed.

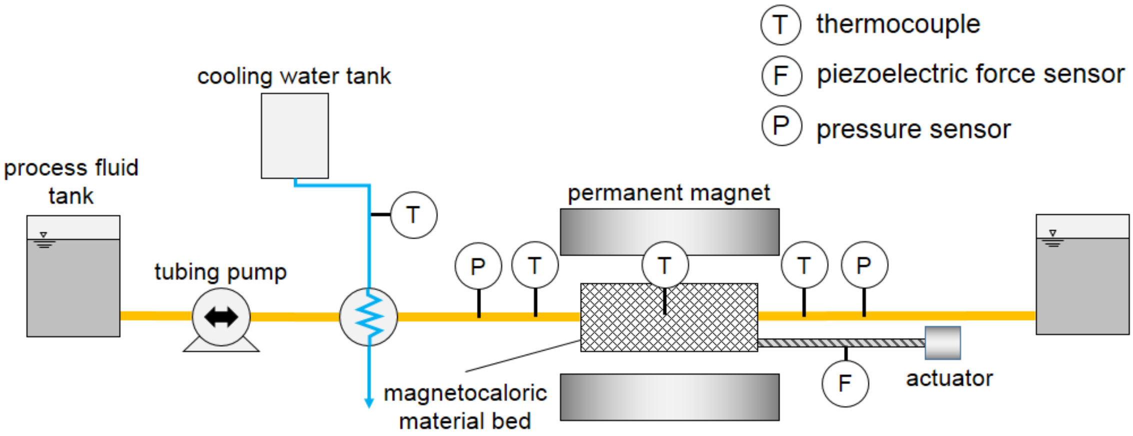

Figure 4: Schematic of the experimental setup configuration of a magnetocaloric heat circulator

Table 1: AMR heat circulator simulation conditions

environmental temp. T_0	290.65 [K]	void ratio ε	0.65 [-]
bed diameter d_b	8.0 [mm]	pitch $1/f$	4.0 [s]
bed length l_b	50 [mm]	magnetic field B	> 0.9 [T]
sphere diameter d_p	< 0.85 [mm]	mass flow rate m	0.16 [mL s^{-1}]

Table 2: Comparison of minimum (case 1), numerically derived (case 2), and experimentally derived (case 3) net work input, W_{net}, and the heat circulated, Q_{cir}

case	Q_{cir}	W_{net}	$W_{\mathrm{net}} / W_{\mathrm{theo}}$
1	1.66 [kJ kg-Gd^{-1}]	19.3 [J kg-Gd^{-1}]	1.1 %
2	1.66 [kJ kg-Gd^{-1}]	20.9 [J kg-Gd^{-1}]	1.3 %
3	8.70 [J cycle^{-1}]	0.16 [J cycle^{-1}]	1.8 %

It can be seen that if the temperature difference during heat exchange was fixed to 1.7 K, the minimum work input needed for heat circulation, which is the exergy destruction due to heat exchange is 1.1 % of the heat that is circulated. If self-heat recuperation with magnetocaloric effect is applied with Gd as the working material, the calculated net work input increases by 8 %. This is due to the effect of magnetic field on the heat capacity of Gd in the vicinity of its Curie temperature. In the case of experimental measurement, the input work was 1.8 % of the heat that was circulated, which is about 38 % larger than the input work calculated from the temperature-entropy diagram for Gd. The largest reason for the difference between the experimentally measured value and the value calculated from the temperature-entropy diagram is assumed to be caused by the low operation frequency because the magnetocaloric heat circulator applies a quasi-counter current heat exchange (Kotani et al., 2013b).

The reason for the low energy consumption required for heat circulation is caused by the small temperature difference during heat exchange made possible by employing a packed bed heat exchanger. The pump work due to pressure loss at the bed was merely 2.88 mJ cycle^{-1} and does not have a large effect in the net work input. This is because the flow rate is low and the viscosity of water is small. However in cases where the flow rate is high and the viscosity is large, pressure loss may become a trade-off to the large heat transfer area and coefficient gained by employing a packed bed heat exchanger. In a case where the flow rate is low and the viscosity of the process fluid is small, further energy reduction maybe possible if the heat transfer area and the coefficient can be made larger with smaller particles or with larger bed.

4. Conclusions

In this paper, the minimum energy consumption needed for heat circulation is derived from the exergy destruction due to heat exchange in terms of a temperature-entropy diagram. The obtained value is compared with the numerical energy consumption when magnetocaloric effect is applied to self-heat recuperation technology. It was seen that the effect of magnetic field on the heat capacity of the working magnetocaloric material results in extra energy consumption. Furthermore, a magnetocaloric heat circulator for self-heat recuperation has been constructed and its energy consumption has been measured. It was seen from the temperature-entropy diagram that the minimum energy consumption needed for heat circulation is proportional to the minimum temperature difference needed for heat exchange. In a magnetocaloric heat circulator, the heat transfer between the process fluid and the working material is direct, thus leading to small temperature difference during heat exchange and small input work for heat circulation.

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