

論文の内容の要旨

論文題目 Development of a Magnetocaloric Heat Circulator based
on Self-heat Recuperation Technology
(自己熱再生技術に基づいた磁気熱循環システムの開発)

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Global warming and resource depletion has grown to become one of humanity's greatest challenges. Needless to say, the emission of carbon-dioxide is rising at rapid rate and is assumed to grow at a faster rate. Although development to use renewable energy sources are being pursued, a fundamental shift in the ways we use energy is needed.

In this research, a magnetocaloric heat circulator based on self-heat recuperation technology for energy saving in thermal processes is introduced. Self-heat recuperation technology was first introduced by Kansha et al. in 2009 (Kansha et al., 2009. Ind. Eng. Chem. Res., 48(16), 7682–7686.). In a self-heat recuperative process, the exergy of the effluent process stream heat is recuperated so that it can be used to heat the feed process stream and thus circulate all process stream heat, leading to drastic reduction in energy consumption. In the conventional self-heat recuperative processes, compressors were used to recuperate the heat exergy of the process stream. However, compressors can only be applied to gaseous process streams and the adiabatic efficiency can become quite low when implemented to small size applications. In this research, a self-heat recuperative process, which utilizes magnetocaloric effect instead of compression, has been proposed. First, in order to properly evaluate thermal processes and a reference factor which accounts for the minimum exergy destruction, for heat exchange has been set. Then, the magnetocaloric heat circulator has theoretically been evaluated. Active magnetic regenerative heat circulator has been presented to actualize self-heat recuperation using magnetocaloric effect. The AMR heat circulator has been analyzed by a one-dimensional model and experimentally to verify its heat circulating and energy saving potentials.

In Chapter 2, thermal processes were analyzed in terms of irreversibility and exergy. In order to

maintain steady state in chemical process and keep the process running, all of the exergy lost during the process must constantly be provided. Thus, it is important to minimize the exergy lost in the process. It was explained that exergy destruction in thermal process is mainly caused by creation of low temperature heat and heat transfer between two process streams. The two cause of exergy destruction were graphically presented in temperature-entropy diagram. Also, a method to obtain the minimum exergy destruction for a thermal process when the minimum temperature difference during heat exchange has been presented. It is explained that the exergy destruction for thermal process is minimum when the temperature difference during heat exchange is at the minimum temperature difference required for heat exchange throughout the heat exchange. The value can be used as a reference factor when evaluating different thermal processes. The exergy destruction of a simple thermal process, thermal process with feed-effluent heat exchanger, and self-heat recuperative thermal process were compared with the minimum exergy destruction during heat exchange. The results showed that the self-heat recuperative process has the least exergy destruction because, 1) exergy is not destroyed in the process of creating heat for provision, and 2) since the heat source and the heat sink is the process stream itself, the amount of heat and the heat capacity matches, leading to small exergy destruction during heat exchange. The total exergy destruction in a self-heat recuperative process is quite close to the minimum exergy destruction in heat transfer.

In Chapter 3, amongst the several methods to recuperate the heat exergy of the process stream, magnetocaloric effect was chosen and applied to self-heat recuperation and a magnetocaloric heat circulator based on self-heat recuperation technology is presented. The basic concept and the energy saving potential of a magnetocaloric heat circulator. When magnetocaloric material is subjected to field variation, a reversible temperature change can be obtained, thus recuperating the heat carried by the magnetocaloric material. All process stream heat is recirculated inside the system without heat addition. The magnetocaloric heat circulator when magnetocaloric material is the process material is evaluated in terms of temperature-entropy diagram. Also, a method to apply a magnetocaloric heat circulator to non-magnetocaloric process material is presented and evaluated. From the evaluation, the theoretical limit of energy reduction by applying a magnetocaloric heat circulator was derived. The results obtained were compared with a benchmark process with heat recovery. It was made clear that the total energy consumption can be reduced to 4.8–18.2% by applying the magnetocaloric heat circulator. Also, the energy consumption of a magnetocaloric heat circulator has been compared with the theoretical minimum exergy destruction during heat exchange when the minimum temperature difference during heat exchange is fixed. It was seen that exergy destruction in a magnetocaloric heat circulator is quite close to the theoretical minimum exergy destruction for heat exchange.

The difference was due to the fact that magnetic field variation is subjected in the vicinity of the Curie temperature, of the magnetocaloric material where specific large entropy change of magnetic spins can be observed. It was seen that the magnetocaloric heat circulator has great potential of drastic energy reduction by circulating the process stream heat in the vicinity of the Curie temperature of the magnetocaloric working material. Furthermore, the energy consumption of heat circulator using magnetocaloric effect and compressors were compared. It was seen that the effect of adiabatic efficiency is large when the temperature range in which the heat is circulated is small. Indicating the potential of magnetocaloric heat circulators for small size applications due to its high adiabatic efficiency.

Chapter 4 explains the conceptual design of an Active Regenerative Magnetic (AMR) heat circulator to actualize self-heat recuperation using magnetocaloric effect for non-magnetocaloric process material presented in Chapter 3. The basic concept of AMR is that the magnetocaloric material works as a regenerator as well as a heat exergy recuperator. AMR heat circulator adopts a quasi-counterflow heat exchange between the process stream and the magnetocaloric working material. In an AMR heat circulator, the minimum temperature difference needed for heat exchange between the process stream and the magnetocaloric working material can be made small due to heat exchange in packed bed form. A basic one-dimensional mathematical model is constructed based on the energy balance of the AMR bed. Through thermal simulation using the constructed mathematical model, the heat circulating capability and energy saving potential of an AMR heat circulator is discussed. The required work needed for heat circulation was reasonably close to the minimum exergy destruction during heat exchange, derived from the temperature-entropy diagram. The difference in the energy consumption of AMR heat circulator simulation and the temperature-entropy diagram was due to the temperature change of the magnetocaloric working material during the hot and cold blow step. Nevertheless, the results showed that the AMR heat circulator has great potential to reduce energy consumption in thermal processes in the vicinity of Curie temperatures, of the magnetocaloric working material.

Chapter 5 verifies the mathematical model of an AMR heat circulator presented in Chapter 4 by a newly constructed AMR heat circulator. The AMR heat circulator circulates the heat carried by the process stream. Heat of the process stream is recuperated by magnetic field variation. In the newly constructed AMR heat circulator, Gd particles under 850 [μm] were used as the working magnetocaloric material. Water was used as the process fluid. The AMR bed underwent the AMR cycle in between 0 [T] and 1.07 [T] and was able to circulate heat of 8.70 [J]

cycle⁻¹] in between 289.5 and 297.0 [K] with mere 0.16 [J cycle⁻¹], which accounts for only 1.8 % of the amount of heat circulated. The work obtained experimentally was compared with the theoretical minimum exergy due to heat exchange. The obtained result was reasonably in good agreement, indicating that the high energy saving potential of AMR heat circulator. Furthermore, the time evolution of the temperature gradient inside the magnetocaloric bed was measured along with the magnetic work needed for heat circulation. The result showed similar behavior to the behavior anticipated by the mathematical model. The ability to circulate the heat of a liquid process stream in the vicinity of the Curie temperature of the magnetocaloric working material with small work input has been verified.

In this research, magnetocaloric effect was implemented to self-heat recuperation technology. In order to properly evaluate the energy saving potential of heat circulators, an evaluation factor was set based on exergy and irreversibility. The basic concept of applying magnetocaloric effect for heat exergy recuperation is explained and actual method to circulate the process stream heat is presented. The concept was evaluated by simulation of a mathematical model and experiment, where the results showed potential of great energy saving in thermal processes.