CHEMICAL ENGINEERING TRANSACTIONS

VOL. 61, 2017

A publication of AIDIC

The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Petar S Varbanov, Rongxin Su, Hon Loong Lam, Xia Liu, Jiří J Klemeš

ISBN 978-88-95608-51-8; **ISSN** 2283-9216

DOI: 10.3303/CET1761291

Thermodynamic Mechanism of Self-Heat Recuperative and Self-heat Recovery Heat Circulation System for a Continuous Heating and Cooling Gas Cycle Process

Atsushi Tsutsumi*, Yasuki Kansha

Collaborative Research Center for Energy Engineering, Institute of Industrial Science, The University of Tokyo,
4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan
a-tsu2mi@iis.u-tokyo.ac.jp

The thermodynamic mechanism of self-heat recuperative and self-heat recovery heat circulation system for a continuous isobaric heating and cooling gas cycle process without chemical reaction has been studied in terms of the exergy analysis by using energy conversion and temperature-entropy diagrams. The modularization of the thermal gas cycle process which is decomposed into four thermodynamic elementary process modules, isobaric heating and cooling process modules (HR and HT) and adiabatic compression and expansion process modules (WR and WT), and a heat exchange process module (HX) indicates that in four thermodynamic elementary process modules (HR, HT, WR, and WT) both exergy and anergy are conserved except for HX in which the exergy is transformed into the anergy because of the exergy destruction due to the heat transfer. In the self-heat recuperative heat circulation system for the heating and cooling gas cycle process, providing the minimum work required for the heat circulation to compensate for the exergy destruction in HX the process heat is recuperated with increasing temperature of process fluid from T to $T+\Delta T$ and then recirculated through HX. The minimum work required for heat circulation, or work input, is converted to heat output, or the thermal energy of which anergy and exergy are the exergy destruction due to heat transfer in HX and the exergy to discard the anergy transformed by the exergy destruction, respectively. For the conventional self-heat recovery heat circulation system by providing heat instead of work the additional exergy to discard the anergy of heat input into the environment is needed with the minimum work required for heat circulation to compensate for the exergy destruction due to the heat transfer in HX, increasing the energy requirement for heat circulation by self-heat recovery.

1. Introduction

In the last several years an innovative energy-saving technology based on the self-heat recuperation for the heating and cooling thermal processes has been developed, in which the heat of an effluent stream is recuperated and recycled for feed stream heating by the adiabatic compression of gas and/or vapor (Kansha et al., 2009). The self-heat recuperation technology has been applied to various thermal processes such as distillation (Matsuda et al., 2011), drying (Liu et al., 2014), CO_2 chemical absorption (Kishimoto et al., 2012), cryogenic air separation (Fu et al., 2016), pressure swing adsorption (PSA) (Song et al., 2015), sea water desalination (Mizuno et al., 2015), chemical reaction processes (Kansha et al., 2015), etc. The amount of energy required for heat circulation of the proposed self-heat recuperative thermal process and the conventional self-heat recovery thermal process were calculated by using a process simulator. The simulation results showed that most of the energy consumption for the self-heat recuperative thermal processes was drastically reduced to 1/3-1/20 compared with that for the conventional self-heat recovery thermal processes.

In the present paper, the theoretical foundation for the heat circulation system of a continuous isobaric heating and cooling gas cycle process without chemical reaction by the self-heat recuperation and self-heat recovery was studied to understand the thermodynamic mechanism of self-heat recuperation in terms of the modularization of the heat circulation system and the exergy analysis by using energy conversion and temperature-entropy diagrams.

Please cite this article as: Tsutsumi A., Kansha Y., 2017, Thermodynamic mechanism of self-heat recuperative and self-heat recovery heat circulation system for a continuous heating and cooling gas cycle process, Chemical Engineering Transactions, 61, 1759-1764 DOI:10.3303/CET1761291

2. Modularization of gas cycle process

In general, an energy and material production process is a cycle process that starts and ends at environmental condition, in which work and heat are exchanged between process or working fluid and other systems such as heat generation system, waste heat removal system, etc. Assuming no heat and mass leakage, input energy is equal to output energy in a continuous cycle process according to the first law of thermodynamics.
A continuous gas and/or vapor cycle process can be decomposed into four thermodynamic elementary process modules and a heat exchange module as the following
1) isobaric heating process module (heat receiver, HR)
2) adiabatic compression process module (work receiver, WR)
3) isobaric cooling process module (heat transmitter, HT)
4) adiabatic expansion process module (work transmitter, WT)
5) heat exchange process module (heat exchanger, HX).
Figure 1 shows the process module expression, the temperature *T*-entropy *S* diagram and the energy conversion diagram of (a) HR, (b) WR, (c) HT, (d) WT, and (e) HX, respectively. Energy consists of exergy and anergy. The exergy *Ex* is defined as the maximum work that can be extracted from the energy. The anergy *An* is unavailable energy that can be defined as the thermal energy at ambient temperature (25°C). In the the temperature *T*-entropy *S* diagram the amount of thermal energy *Q* can be obtained by

$$Q = \int_{S_1}^{S_2} T\, dS \tag{1}$$

The anergy of thermal energy is given by

$$An = T_0\left(S_2 - S_1\right) \tag{2}$$

Thus, *Q* can be expressed as

$$Q \equiv \left(Ex,\ An\right) = \left(Q - T_0\left(S_2 - S_1\right),\ T_0\left(S_2 - S_1\right)\right) \tag{3}$$

In HR and WR energies with high and low exergy rates are merged into energy with medium exergy rate. In HT and WT energy with medium exergy rate is split into energies with higher and lower exergy rates. It is noteworthy that both exergy and anergy are conserved without any exergy destruction in all four thermodynamic elementary process modules, HR, WR, HT and WT as shown in the energy conversion diagrams of Fig 1.
In the heat exchange process module (HX) thermal energy at higher temperature, or heat input, is converted to thermal energy at lower temperature, or heat output, leading to the exergy destruction associated with the irreversibility of heat transfer as shown in Fig.1(e). The amount of heat input Q_{in} and heat output Q_{out} in the heat exchange module are given by the area surrounding 4-3-7-6 and the area surrounding 1-2-7-5 in T-S diagram, respectively. Assuming no heat leakage, heat input Q_{in} is equal to heat output Q_{out}. The exergies of heat input and output are represented by the area surrounding 3-4-9-10 and 1-2-10-8, respectively. In addition, the anergies of heat input and output in the heat exchange module are represented by the area surrounding 9-10-7-6 and 8-10-7-5, respectively. Therefore, the exergy destruction due to heat transfer in HX represented with the area coloured in grey (8-9-6-5) Ex_{loss} is given by

$$Ex_{loss} = T_0 S_{gen} = \left(\Delta S_{cold} - \Delta S_{hot}\right) \tag{4}$$

where S_{gen} represents the entropy generation given by (ΔS_{cold}-ΔS_{hot}). Thus, a part of the exergy of heat input represented with the area surrounding 3-4-11-2 is considered to be a minimum work required for heat transfer, which is converted to a part of heat output represented with the area surrounding 1-5-6-11 which consists of exergy discard (exergy) (1-11-9-8) and exergy destruction (anergy) (8-9-6-5).

3. Heat circulation for heating and cooling gas cycle process

3.1 Heat circulation mechanism

Consider a continuous isobaric heating and cooling ideal gas cycle process. Figure 2 shows a simple heating and cooling gas cycle process with a heat generation and supply system and a waste heat removal system. Heat generated by combustion of fuel or heat pump is transferred to the heat receiver of the heating and cooling cycle process through a heat exchange process module. By receiving heat from heat generation and supply system temperature of the process fluid in heating and cooling cycle process rises from the environmental temperature T_0 to the processing temperature of unit operation *T* in the isobaric heating process module (HR). After processing same amount of heat is transferred to the waste heat removal system through the heat

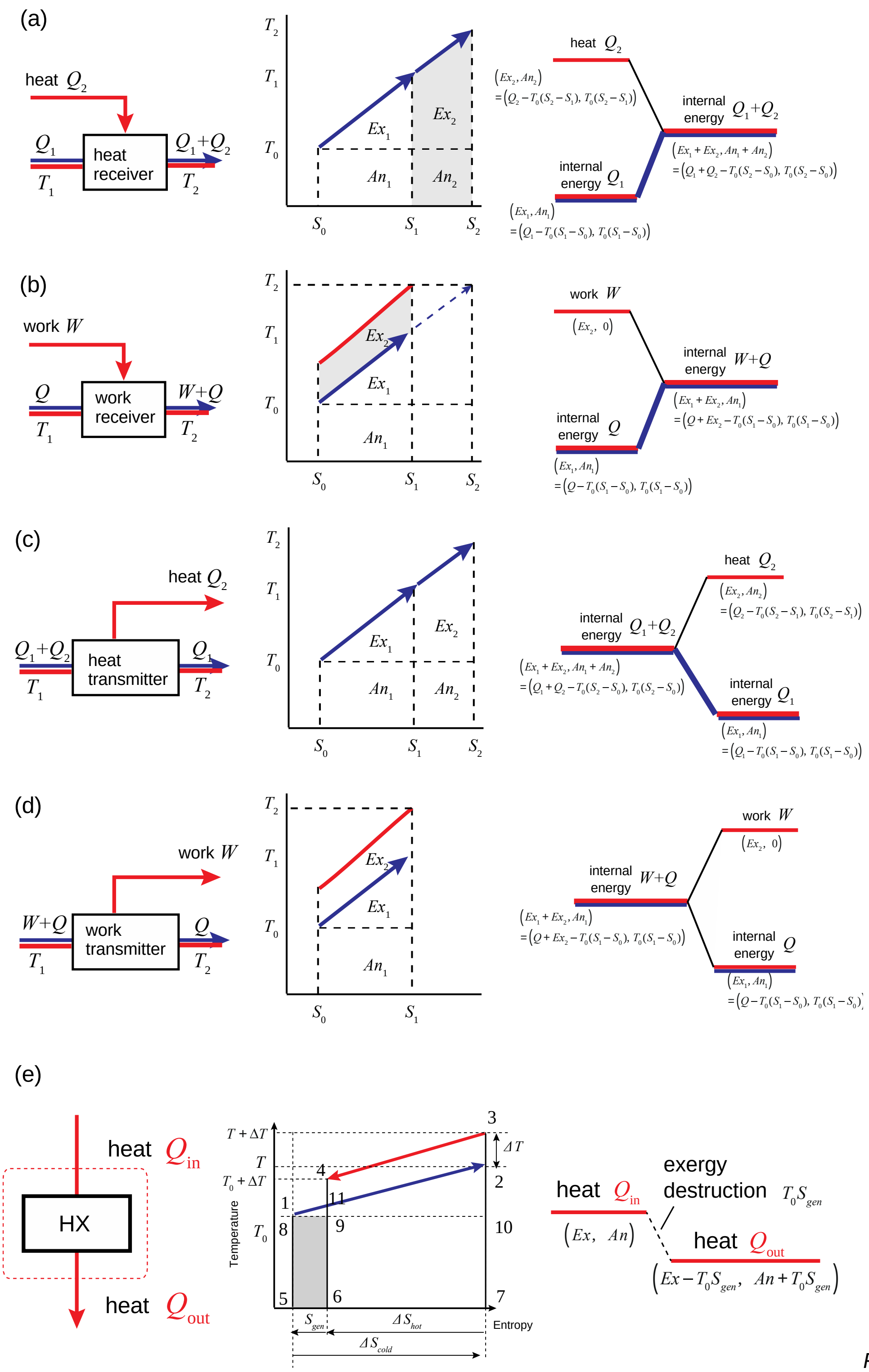

Figure 1: (a) isobaric heating process module (heat receiver, HR), (b) adiabatic compression process module (work receiver, WR), (c) isobaric cooling process module (heat transmitter, HT), (d) adiabatic expansion process module (work transmitter, WT), (e) heat exchange process module (heat exchanger, HX).

exchange process module, returning the temperature of process fluid to T_0 in the heating and cooling process module (HT). Note that no exergy destruction takes place in the heating and cooling cycle process. Exergy is destructed only in the heat generation and supply system including the heat exchange module mainly due to the irreversible energy conversion such as heat transfer and fuel combustion. In the heating and cooling process without the heat exchange process module the amount of heat input Q_{in} is balanced with heat output Q_{out}. Both exergy and anergy of heat input and output are conserved as follows

$$Q_{in} \circ Q_{out} \circ (Ex,\ An) \tag{5}$$

In the heating and cooling cycle process combined with the heat exchange process module, providing the minimum work required for heat transfer in the heat exchange process module to compensate for the exergy destruction the process heat can be recuperated with increasing the temperature of process fluid and then recirculated from self-heat transmitter (SHT) to self-heat receiver (SHR) through HX. There are two types of the heat circulation system for heating and cooling thermal process: a conventional self-heat recovery heat circulation system by providing heat and a self-heat recuperative heat circulation system by providing the compression work. For both heat circulation systems the exergy destruction takes place only in the heat exchange module.

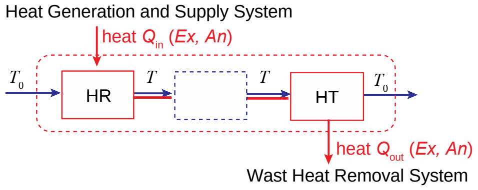

Figure 2: A continuous isobaric heating and cooling cycle process

3.2 Self-heat recuperative heat circulation system

Figures 3 (a)-(d) show the process module expression, the temperature T-entropy S diagram, the energy conversion diagram and the simplified energy conversion diagram for the heat circulation system by self-heat recuperation, respectively. Heat $Q_1(Ex,\ An)$ represented by the area surrounding 1-2-7-5 in Figure 3 (b) is recuperated by adding the compression work $W_{in}(Ex_1{+}Ex_6{,}0)$ to increase the temperature from T to $T{+}\Delta T$ and then heat Q_3 represented by the area surrounding 4-3-7-6 is transferred from SHT to SHR through HX. In the heat exchange module where heat Q_3 at $T{+}\Delta T$ is converted to heat Q_1 at T the exergy destruction $Ex_{loss}{=}T_0S_{gen}$ $= An_2$ takes place, transforming exergy $(Ex_1 - Ex_2)$ into anergy An_2.

$$Ex_1 = Ex_2 + An_2 \tag{6}$$

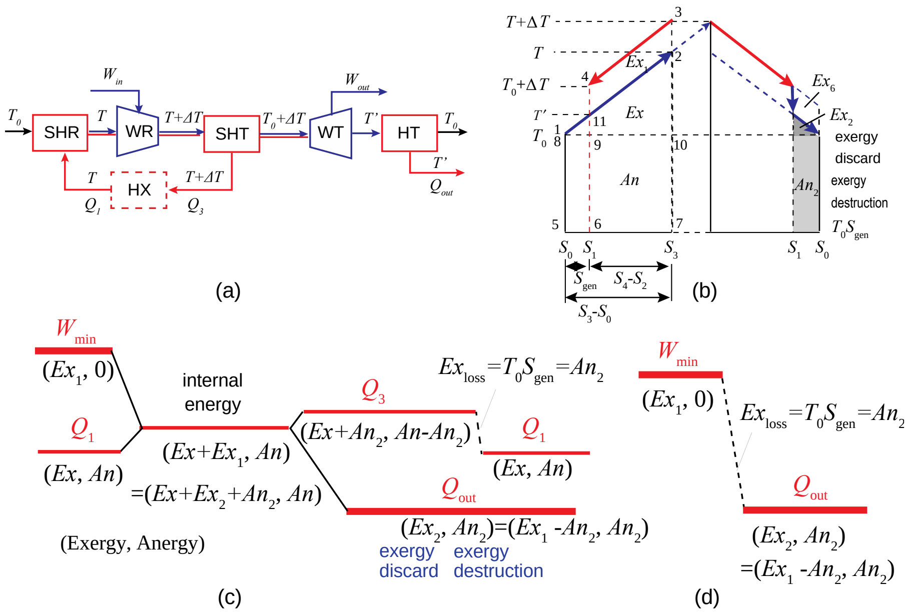

Figure 3: Heat circulation system by self-heat recuperation: (a) the process module expression, (b) the temperature T-entropy S diagram, (c) the energy conversion diagram and (d)the simplified energy conversion diagram

In the self-heat recuperative heat circulation system and net work input (W_{in}-W_{out}) (Ex_1, 0) is equal to the minimum work required for heat circulation to compensate for the exergy destruction due to heat transfer, which is converted to the waste heat Q_{out} (Ex_2, An_2) as shown in Fig. 3(d). To discard the waste heat into the environment the temperature of the waste heat must be higher than the ambient temperature. Hence Ex_2 is considered to be the exergy requirement to discard the anergy An_2 of the wast heat Q_{out} into the environment.

3.3 Conventional self-heat recovery heat circulation system

For the heat circulation system by conventional self-heat recovery the process module expression, the temperature-entropy diagram, the energy conversion diagram and the simplified energy conversion diagram are shown in Figures 4 (a), (b), (c) and (d), respectively. Heat input Q_{in} (Ex_4, An_4) represented by the area surrounding 2-12-14-7 in Fig. 4(b) is supplied to increase the temperature of process fluid from T to T+ΔT. In the heat exchange module in which heat recuperated Q_3 (Ex- An_2, An+ An_2) at T+ΔT is converted to heat Q_1(Ex, An) at T the same amount of exergy destruction An_2 due to the heat transfer takes place as that of the self-heat recuperative heat circulation system as shown in Fig. 4(c). The waste heat Q_{out} (Ex_2+ Ex_5, An_2+ An_5) represented by the area surrounding 1-15-17-5 in Fig. 4(b) is discarded. Using eq.(6) the waste heat Q_{out} is given by

$$Q_{out} \equiv \left(Ex_2 + Ex_5,\ An_2 + An_5\right) \equiv \left(Ex_1 - An_2 + Ex_5,\ An_2 + An_5\right) \tag{7}$$

Since the exergy destruction due to heat transfer is An_2, heat input Q_{in} is obtained as

$$Q_{in} \equiv \left(Ex_4,\ An_4\right) = \left(Ex_1 + Ex_5,\ An_5\right) \tag{8}$$

Thus, in the heat circulation system by self-heat recovery heat input Q_{in} is converted to the waste heat Q_{out} by using exergy Ex_1 of Q_{in} to recuperate the recycling heat Q_1 and then the waste heat Q_{out} is discarded. Hence, the minimum heat required for heat circulation by self-heat recovery can be decomposed into the minimum work required for heat circulation W_{min} and heat discarded $Q_{discard}$ as following

$$Q_{\min} = W_{\min} + Q_{discard} \equiv \left(Ex_1,\ 0\right) + \left(Ex_5,\ An_5\right) \tag{9}$$

where Ex_5 is the exergy requirement to discard the anergy An_5 of the heat discarded $Q_{discard}$ (Ex_5, An_5). Thus, in spite of the same minimum work W_{min} (Ex_1,0) required for heat circulation to compensate for the exergy destruction An_2 due to the heat transfer in HX the additional exergy Ex_5 is required to discard heat $Q_{discard}$ (Ex_5,

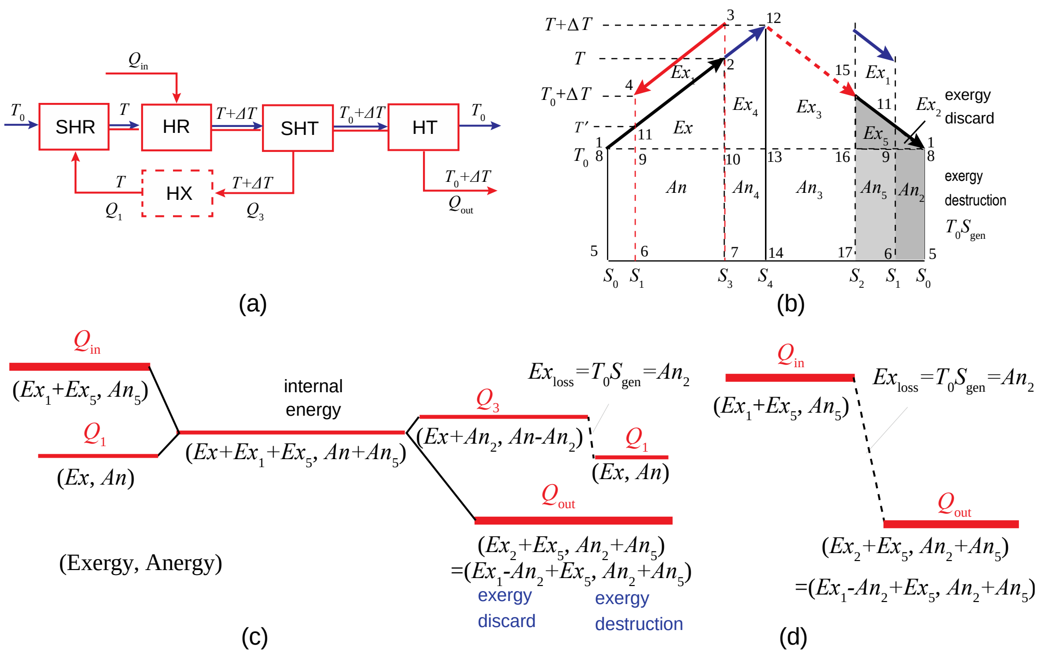

Figure 4: Heat circulation system by self-heat recovery: (a) the process module expression, (b) the temperature T-entropy S diagram, (c) the energy conversion diagram and (d) the simplified energy conversion diagram

An_5) into the environment for the self-heat recovery heat circulation system. It can be, therefore, concluded that for the conventional self-heat recovery heat circulation system by providing heat the additional exergy to discard the anergy of heat input into the environment is needed with the minimum work required for heat circulation to compensate for the exergy destruction due to the heat transfer in HX, increasing the energy requirement for heat circulation in comparison with the self-heat recuperative heat circulation system of heating and cooling gas cycle process.

4. Conclusions

The thermodynamic mechanism of heat circulation system for a continuous isobaric heating and cooling gas cycle process without chemical reaction by self-heat recuperation and self-heat recovery was studied in terms of the exergy analysis by using energy conversion and temperature-entropy diagrams and the modularization of cycle process. A continuous gas cycle process without chemical energy conversion is decomposed into four thermodynamic elementary process modules: an isobaric heating process module (heat receiver, HR), an adiabatic compression process module (work receiver, WR), an isobaric cooling process module (heat transmitter, HT), an adiabatic expansion process module (work transmitter, WT) and a heat exchange process module (HX). The modularization of the thermal cycle process shows that the exergy destruction takes place only in the heat exchange process module due to the heat transfer. The exergy analysis for the heat circulation system of the heating and cooling gas cycle process by self-heat recuperation and self-heat recovery was conducted by using energy conversion and temperature-entropy diagrams. The minimum exergy required for heat circulation of the heating and cooling cycle process is given by the sum of the exergy to compensate for the exergy destruction due to heat transfer and the exergy required to discard the waste heat that is converted from the energy input. In the self-heat recuperative heat circulation system by providing the work as the minimum work required for heat circulation the process heat is recuperated with increasing the temperature of process fluid from T to $T+\Delta T$ and then recirculated through HX process module. Work input is converted to the waste heat of which anergy is the exergy distruction due to heat transfer and exergy is the exergy discard. On the other hand, in the case of the self-heat recovery heat circulation system by providing heat instead of work, the additional exergy to discard the anergy of heat input into the environment is needed with the minimum work required for heat circulation to compensate for the exergy destruction due to heat transfer. Hence the energy requirement for the self-heat recovery heat circulation is larger than that for the self-heat recuperative heat circulation by the additional exergy to discard the anergy of heat input into the environment.

Acknowledgments

This research was supported by a CREST grant from Japan Science and Technology Agency (JST). The authors appreciate this financial support.

References

Fu Q., Kansha Y., Song C., Liu Y., Ishizuka M., Tsutsumi A., 2016, An elevated-pressure cryogenic air separation unit based on self-heat recuperation technology for integrated gasification combined cycle systems, Energy, 103, 440–446.

Kansha Y., Tsuru N., Sato K., Fushimi C., Tsutsumi A., 2009, Self-heat recuperation technology for energy saving in chemical processes, Industrial and Engineering Chemistry Research, 48, 7682–7686.

Kansha Y., Ishizuka M., Song C., Tsutsumi A., 2014, Process intensification for dimethyl ether production by self-heat recuperation, Energy, 90, 122–127.

Kishimoto A., Kansha Y., Fushimi C., Tsutsumi A., 2012, Exergy recuperative CO_2 gas separation in pre-combustion capture, Clean Technologies and Environmental Policy, 14, 465–474.

Liu Y., Aziz M., Kansha Y., Bhattacharya S., Tsutsumi A., 2014, Application of the self-heat recuperation technology for energy saving in biomass drying system, Fuel Processing Technology, 117, 66–74.

Matsuda K., Kawazuishi K., Kansha Y., Fushimi C., Nagao M., Kunikiyo H., Masuda F., Tsutsumi A., 2011, Advanced energy saving in distillation process with self-heat recuperation technology, Energy, 36, 4640–4645.

Mizuno H., Kansha Y., Ishizuka M., Tsutsumi A., 2015, Agglomeration behavior in fluidized-bed evaporator for thermal seawater desalination, Applied Thermal Engineering, 89, 1096–1103.

Song C., Kansha Y., Ishizuka M., Fu Q., Tsutsumi A., 2015, Conceptual design of a novel pressure swing CO_2 adsorption process based on self-heat recuperation technology, Chemical Engineering and Processing, 94, 20–28.