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3

Self-Heat Recuperation:
Theory and Applications

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1. Introduction

Since the 1970s, energy saving has contributed to various elements of societies around the world for economic reasons. Recently, energy saving technology has attracted increased interest in many countries as a means to suppress global warming and to reduce the use of fossil fuels. The combustion of fossil fuels for heating produces a large amount of carbon dioxide (CO_2), which is the main contributor to global greenhouse gas effects (Eastop & Croft 1990, Kemp 2007). Thus, the reduction of energy consumption for heating is a very important issue. To date, to reduce energy consumption, heat recovery technology such as pinch technology, which exchanges heat between the hot and cold streams in a process, has been applied to thermal processes (Linnhoff et al. 1979, Cerda et al. 1983, Linnhoff et al. 1983, Linnhoff 1993, Linnhoff & Eastwood 1997, Ebrahim & Kawari 2000). A simple example of this technology is the application of a feed-effluent heat exchanger in thermal processes, wherein heat is exchanged between feed (cold) and effluent (hot) streams to recirculate the self-heat of the stream (Seider et al. 2004). To exchange the heat, an additional heat source may be required, depending on the available temperature difference between two streams for heat exchange. The additional heat may be provided by the combustion of fossil fuels, leading to exergy destruction during heat production (Som & Datta 2008). In addition, many energy saving technologies recently developed are only considered on the basis of the first law of thermodynamics, i.e. energy conservation. Hence, process design methods based on these technologies are distinguished by cascading heat utilization.

Simultaneously, many researchers have paid attention to the analysis of process exergy and irreversibility through consideration of the second law of thermodynamics. However, many of these investigations show only the calculation results of exergy analysis and the possibility of the energy savings of some processes, and few clearly describe methods for reducing the energy consumption of processes (Lampinen & Heillinen 1995, Chengqin et al 2002, Grubbström 2007). To reduce exergy reduction, a heat pump has been applied to thermal processes, in which the ambient heat or the process waste heat is generally pumped to heat the process stream by using working fluid compression. Although it is well-known that a heat pump can reduce energy consumption and exergy destruction in a process, the

heat load and capacity of the process stream are often different from those of the pumped heat. Thus, a normal heat pump still possibly causes large exergy destruction during heating. In heat recovery technologies, vapor recompression has been applied to evaporation, distillation, and drying, in which the vapor evaporated from the process is compressed to a higher pressure and then condensed, providing a heating effect. The condensation heat of the stream is recirculated as the vaporization heat in the process by using vapor recompression. However, many investigators have only focused on latent heat and few have paid attention to sensible heat. As a result, the total process heat cannot be recovered, indicating the potential for further energy savings in many cases. Recently, an energy recuperative integrated gasification power generation system has been proposed and a design method for the system developed (Kuchonthara & Tsutsumi 2003, Kuchonthara et al. 2005, Kuchonthara & Tsutsumi 2006). Kansha et al. have developed self-heat recuperation technology based on exergy recuperation (2009). The most important characteristics of this technology are that the entire process stream heat can be recirculated into a process designed by this technology based on exergy recuperation, leading to marked energy savings for the process.

In this chapter, an innovative self-heat recuperation technology, in which not only the latent heat but also the sensible heat of the process stream can be circulated without heat addition, and the theoretical analysis of this technology are introduced. Then, several industrial application case studies of this technology are presented and compared with their conventional counterparts.

2. Self-heat recuperation technology

Self-heat recuperation technology (Kansha et al. 2009) facilitates recirculation of not only latent heat but also sensible heat in a process, and helps to reduce the energy consumption of the process by using compressors and self-heat exchangers based on exergy recuperation. In this technology, i) a process unit is divided on the basis of functions to balance the heating and cooling loads by performing enthalpy and exergy analysis and ii) the cooling load is recuperated by compressors and exchanged with the heating load. As a result, the heat of the process stream is perfectly circulated without heat addition, and thus the energy consumption for the process can be greatly reduced. In this section, first, the theory of the self-heat recuperation technology and the design methodology for self-heat recuperative processes are introduced for a basic thermal process, and then self-heat recuperative processes applied to separation processes are introduced.

2.1 Self-heat recuperative thermal process

Exergy loss in conventional thermal processes such as a fired heater normally occurs during heat transfer between the reaction heat produced by fuel combustion and the heat of the process stream, leading to large energy consumption in the process. To reduce the energy consumption in the process through heat recovery, heating and cooling functions are generally integrated for heat exchange between feed and effluent to introduce heat circulation. A system in which such integration is adopted is called a self-heat exchange system. To maximize the self-heat exchange load, a heat circulation module for the heating and cooling functions of the process unit has been proposed, as shown in Figure 1 (Kansha et al. 2009).

Figure 1 (a) shows a thermal process for gas streams with heat circulation using self-heat recuperation technology. In this process, the feed stream is heated with a heat exchanger (1→2) from a standard temperature, T_1, to a set temperature, T_2. The effluent stream from the following process is pressurized with a compressor to recuperate the heat of the effluent stream (3→4) and the temperature of the stream exiting the compressor is raised to T_2 through adiabatic compression. Stream 4 is cooled with a heat exchanger for self-heat exchange (4→5). The effluent stream is then decompressed with an expander to recover part of the work of the compressor. This leads to perfect internal heat circulation through self-heat recuperation. The effluent stream is finally cooled to T_1 with a cooler (6→7). Note that the total heating duty is equal to the internal self-heat exchange load without any external heating load, as shown in Fig. 1 (b). Thus, the net energy required of this process is equal to the cooling duty in the cooler (6→7). To be exact, the heat capacity of the feed stream is not equal to that of the effluent stream. However, the effect of pressure to the heat capacity is small. Thus, two composite curves in Fig. 1 (b) seem to be in parallel. In addition, the exergy destruction occurs only during the heat transfer in the heat exchanger. The amount of this exergy destruction is illustrated by the gray area in Fig. 1 (b).

In the case of ideal adiabatic compression and expansion, the input work provided to the compressor performs a heat pumping role in which the effluent temperature can achieve perfect internal heat circulation without exergy destruction. Therefore, self-heat recuperation can dramatically reduce energy consumption. Figure 1 (c) shows a thermal process for vapor/liquid streams with heat circulation using the self-heat recuperation technology. In this process, the feed stream is heated with a heat exchanger (1→2) from a standard temperature, T_1, to a set temperature, T_2. The effluent stream from the subsequent process is pressurized by a compressor (3→4). The latent heat can then be exchanged between feed and effluent streams because the boiling temperature of the effluent stream is raised to $T_{b'}$ by compression. Thus, the effluent stream is cooled through the heat exchanger for self-heat exchange (4→5) while recuperating its heat. The effluent stream is then depressurized by a valve (5→6) and finally cooled to T_1 with a cooler (6→7). This leads to perfect internal heat circulation by self-heat recuperation, similar to the above gas stream case. Note that the total heating duty is equal to the internal self-heat exchange load without an external heating load, as shown in Fig. 1 (d). It is clear that the vapor and liquid sensible heat of the feed stream can be exchanged with the sensible heat of the corresponding effluent stream and the vaporization heat of the feed stream is exchanged with the condensation heat of the effluent stream. Similar to the thermal process for gas streams with heat circulation using self-heat recuperation technology mentioned above, the net energy required of this process is equal to the cooling duty in the cooler (6→7) and the exergy destruction occurs only during heat transfer in the heat exchanger and the amount of this exergy destruction is indicated by the gray area in Fig. 1 (d). As well as the gas stream, the effect of pressure to the heat capacity is small. Thus, two composite curves in Fig. 1 (b) are closed to be in parallel. As a result, the energy required by the heat circulation module is reduced to 1/22–1/2 of the original by the self-heat exchange system in gas streams and/or vapor/liquid streams.

To use the proposed self-heat recuperative thermal process in the reaction section of hydro-desulfurization in the petrochemical industry as an industrial application, Matsuda et al. (2010) reported that the advanced process requires 1/5 of the energy required of the

conventional process on the basis of enthalpy and examined the considerable reduction of the exergy destructions in this process. The other related industrial applications of the proposed self-heat recuperative thermal process are the preheating sections of the feed streams for reaction to satisfy the required physical conditions.
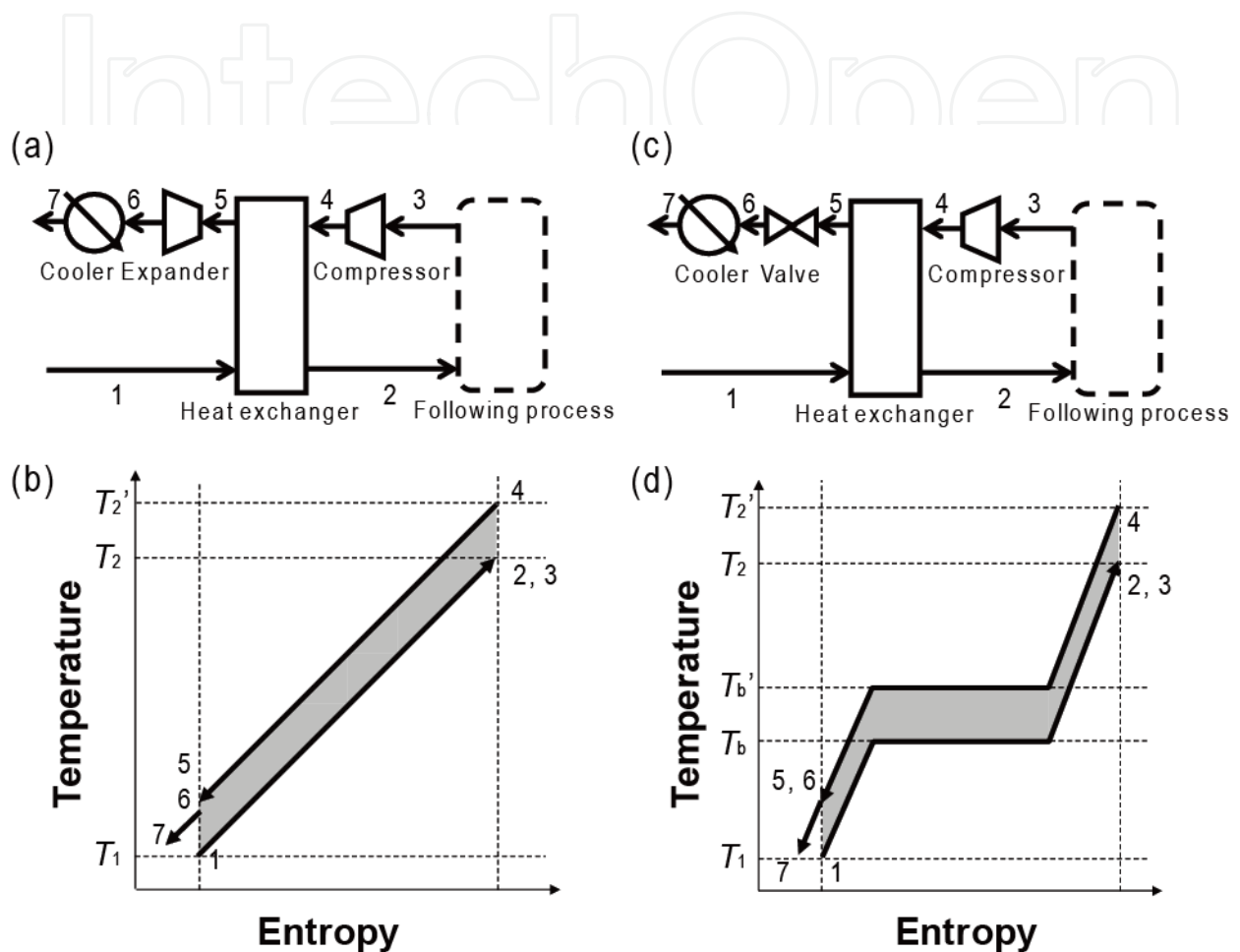

Fig. 1. Self-heat recuperative thermal process a) process flow of gas streams, b) temperature-entropy diagram of gas streams, c) process flow of vapor/liquid streams, d) temperature-entropy diagram of vapor/liquid streams.

2.2 Self-heat recuperative separation processes

Expanding the self-heat recuperative thermal process to separation processes (Kansha et al. 2010a), a system including not only the separation process itself but also the preheating/cooling section, can be divided on the basis of functions, namely the separation module and the heat circulation module, in which the heating and cooling loads are balanced, as shown in Fig. 2. To simplify the process for explanation, Fig. 2 shows a case that has one feed and two effluents. In this figure, the enthalpy of inlet stream (feed) is equal to the sum of the outlet streams (effluents) enthalpies in each module, giving an enthalpy

difference between inlet and outlet streams of zero. The cooling load in each module is then recuperated by compressors and exchanged with the heating load using self-heat recuperation technology. As a result, the heat of the process stream (self-heat) is perfectly circulated without heat addition in each module, resulting in perfect internal heat circulation over the entire separation process.
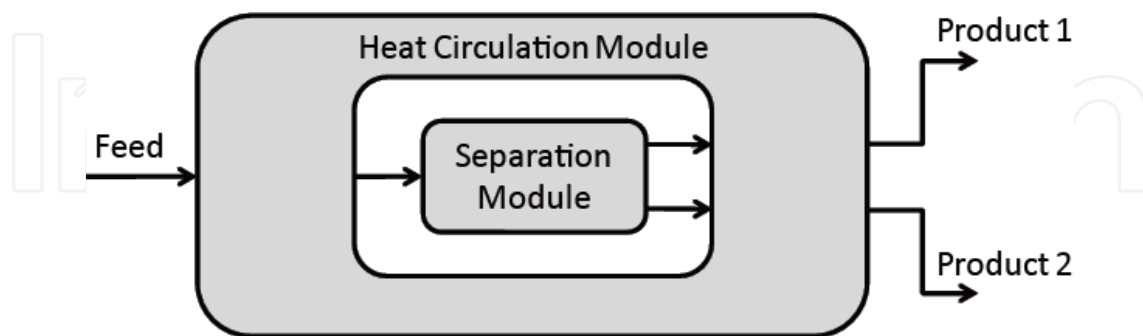

Fig. 2. Conceptual figure for self-heat recuperative separation processes.

2.2.1 Self-heat recuperative distillation process

Although distillation columns have been widely used in separation processes based on vapor/liquid equilibria in petroleum refineries and chemical plants, the distillation process consumes a massive amount of energy required for the latent heat of the phase change, resulting in the emission of a large amount of CO_2. To prevent the emission of CO_2 through use of self-heat recuperation technology (Kansha et al. 2010b), a distillation process can be divided into two sections, namely the preheating and distillation sections, on the basis of functions that balance the heating and cooling load by performing enthalpy and exergy analysis, and the self-heat recuperation technology is applied to these two sections. In the preheating section, one of the streams from the distillation section is a vapor stream and the stream to the distillation section has a vapor–liquid phase that balances the enthalpy of the feed streams and that of the effluent streams in the section. In balancing the enthalpy of the feed and effluent streams in the heat circulation module, the enthalpy of the streams in the distillation module is automatically balanced. Thus, the reboiler duty is equal to the condenser duty of the distillation column. Therefore, the vapor and liquid sensible heat of the feed streams can be exchanged with the sensible heat of the corresponding effluent streams, and the vaporization heat can be exchanged with the condensation heat in each module.

Figure 3 (a) shows the structure of a self-heat recuperative distillation process consisting of two standardized modules, namely, the heat circulation module and the distillation module. Note that in each module, the sum of the enthalpy of the feed streams and that of the effluent streams are equal. The feed stream in this integrated process module is represented by stream 1. This stream is heated to its boiling point by the two streams independently recuperating heat from the distillate (12) and bottoms (13) by the heat exchanger (1→2). A distillation column separates the distillate (3) and bottoms (9) from stream 2. The distillate (3) is divided into two streams (4, 12). Stream 4 is compressed adiabatically by a compressor and cooled down by the heat exchanger (2). The pressure and temperature of stream 6 are adjusted by a valve and a cooler (6→7→8), and stream 8 is then fed into the distillation

column as a reflux stream. Simultaneously, the bottoms (9) is divided into two streams (10, 13). Stream 10 is heated by the heat exchanger and fed to the distillation column (10→11). Streams 12 and 13 are the effluent streams from the distillation module and return to the heat circulation module. In addition, the cooling duty of the cooler in the distillation module is equal to the compression work of the compressor in the distillation module because of the enthalpy balance in the distillation module.

The effluent stream (12) from the distillation module is compressed adiabatically by a compressor (12→14). Streams 13 and 14 are successively cooled by a heat exchanger. The pressure of stream 17 is adjusted to standard pressure by a valve (17→18), and the effluents are finally cooled to standard temperature by coolers (15→16, 18→19). The sum of the cooling duties of the coolers is equal to the compression work of the compressor in the heat circulation module. Streams 16 and 19 are the products.

Figure 3 (b) shows the temperature and heat diagram for the self-heat recuperative distillation process. In this figure, each number corresponds to the stream numbers in Fig. 3 (a), and T_{std} and T_b are the standard temperature and the boiling temperature of the feed stream, respectively. Both the sensible heat and the latent heat of the feed stream are subsequently exchanged with the sensible and latent heat of effluents in heat exchanger 1. The vaporization heat of the bottoms from the distillation column is exchanged with the condensation heat of the distillate from the distillation column in the distillation module. The heat of streams 4 and 12 is recuperated by the compressors and exchanged with the heat in the module. It can be seen that all the self-heat is exchanged. As a result, the exergy loss of the heat exchangers can be minimized and the energy required by the distillation process is reduced to 1/6–1/8 of that required by the conventional, heat-exchanged distillation process. To examine the energy required, the temperature difference of heat exchangers between cold and hot streams is an important parameter. In fact, to increase this, the heat transfer surface area can be decreased. To achieve industrial self-heat recuperative distillation processes, further investigation of the minimum temperature difference in the heat exchangers is required, especially the difference of the heat types of the streams in the heat exchanger (e.g. sensible heat and latent heat).

As industrial applications of this self-heat recuperative distillation processes, Kansha et al. (2010c) examined the energy saving efficiency of an integrated bioethanol distillation process using an azeotropic distillation method as compared with the conventional azeotropic distillation processes. In this paper, the energy required for the proposed integrated processes using self-heat recuperative distillation was only 1/8 of the conventional process, leading to a dramatic reduction in the production cost of bioethanol. They also applied it to the cryogenic air separation process and examined the energy required compared with the conventional cryogenic air separation for an industrial feasibility study (Kansha et al. 2011a). In that paper, the conventional cryogenic air separation was well integrated on the basis of the heat required to decrease the temperature to near -200 °C, especially, and they pointed out that a cryogenic air separation is a kind of multi-effect distillation column. However, there was potential for a 40% energy reduction by using self-heat recuperative distillation. Furthermore, the authors applied it to a well-known and recently developed energy saving distillation process, an internally heat integrated distillation column (HIDiC). In HIDiC, the distillation column can be divided into two sections (the rectification section and the stripping section) and the condensation heat is exchanged with the vaporization heat between these two sections using

the pressure difference. Designing this based on self-heat recuperation technology shows further energy saving (Kansha et al. 2011b). From these three industrial case studies, self-heat recuperation technology can be applied to recently developed heat recovery distillation processes such as heat integrated distillation processes, multi-effect distillation processes and HIDiC processes. Finally, to examine the feasibility of self-heat recuperation for industrial processes in the petrochemical industry, Matsuda et al. (2011) applied it using practical industrial data and modified the stream lines to enable practical processes and examined the energy required, exergy destruction and economical efficiency. From these studies, it can be concluded that the self-heat recuperative distillation process is very promising for saving energy.
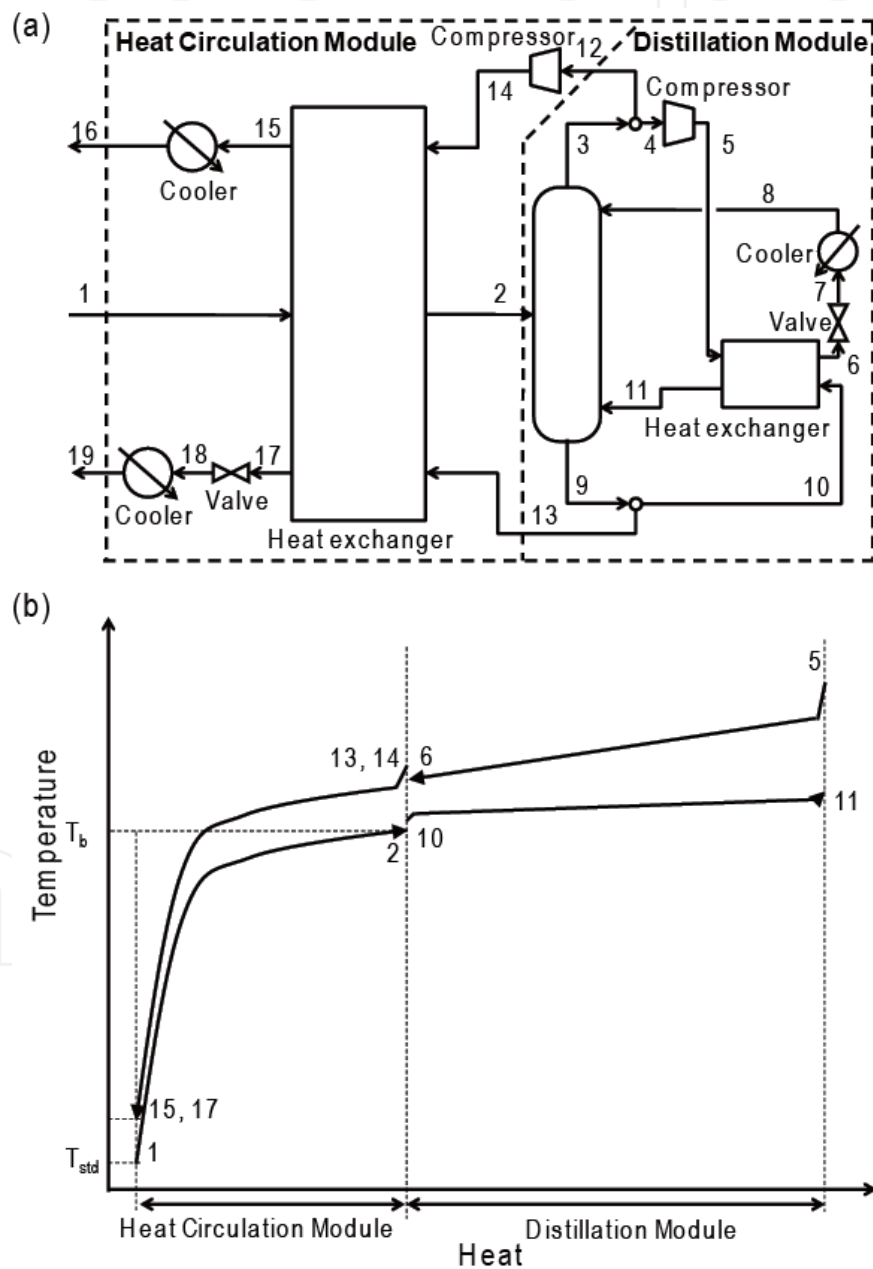
Fig. 3. Self-heat recuperative distillation process a) process flow diagram, b) temperature-heat diagram.

2.2.2 Self-heat recuperative drying process

Drying is usually conducted to reduce transportation costs by decreasing product weight and size, giving long-term storage stability and increasing the thermal efficiency in thermochemical conversion processes. Unfortunately, drying is one of the most energy intensive processes owing to the high latent heat of water evaporation. Theoretically, assuming an ambient temperature of 15 °C, the energy required for water evaporation ranges from 2.5 to 2.6 MJ per kg evaporated water, depending on the wet bulb temperature (Brammer & Bridgwater 1999). There are two important points regarding reduction of energy consumption during drying: (i) intensification of heat and mass transfer inside the dryer and (ii) efficient heat recovery and energy utilization (Strumillo et al. 2006). Concerning the latter, several methods have been developed to improve energy saving during drying, including heat recovery with and without flue gas recirculation, heat pumps, and pinch technology. However, these systems cannot effectively recover all the heat of the drying medium, the evaporated water, and the dried products.

To improve the energy efficiency in drying, Aziz et al. (2011a, 2011b) have recently developed a drying process based on self-heat recuperation technology. In this technology, the hot stream is heated by compression to provide a minimum temperature difference required for heat pairing and exchange with the cold stream and all of the self-heat of the process stream is recirculated based on exergy recuperation. As a result, all of the heat involved in drying can be recuperated and reused as a heat source for the subsequent drying process. This includes recuperation of sensible heat from the gas serving as the drying medium, both sensible and latent heat of the evaporated water and the sensible heat of the dried products. A process diagram for brown coal drying based on self-heat recuperation technology is shown in Fig. 4 (a). A fluidized bed dryer with an immersed heat exchanger is selected as the evaporator owing to its high heat transfer coefficient, excellent solid mixing, and uniform temperature distribution (Wan Daud, 2008, Law & Mujumdar 2009). Wet brown coal is fed and heated through a pre-heater (dryer 1a) to a given temperature. Subsequently, the main drying stage (water evaporation) is performed inside the fluidized bed dryer (dryer 2), where evaporation occurs. The immersed heat exchangers, which are filled by a compressed mixture of air and steam, are immersed inside the fluidized bed, providing the heat required for water removal. The exhausted mixture of air and steam is then compressed to achieve a higher exergy rate before it is circulated back and utilized as the heat source for evaporation (dryer 2) and pre-heating (dryer 1a, dryer 1b), in that order. In addition, the sensible heat of the hot, dried brown coal is recovered by the drying medium, to further reduce drying energy consumption (dryer 1c).

The heat exchange inside the fluidized bed dryer is considered to be co-current because the bed is well mixed and the minimum temperature approach depends on the outlet temperature of the hot streams (compressed air-steam mixture) and the temperature of the bed.

Figure 4 (b) shows a temperature-enthalpy diagram for the self-heat recuperative brown coal drying. Almost all of the heat is recovered, leading to a significant reduction in the total energy consumption. The largest amount of heat recuperation occurs in dryer 2, which involves the heat exchange between the condensation heat of the compressed air-steam mixture and the evaporation heat of the water in the brown coal. The heat curves of the hot

and cold streams, especially in dryer 2, are almost parallel owing to the efficient heat pairing within the dryer.
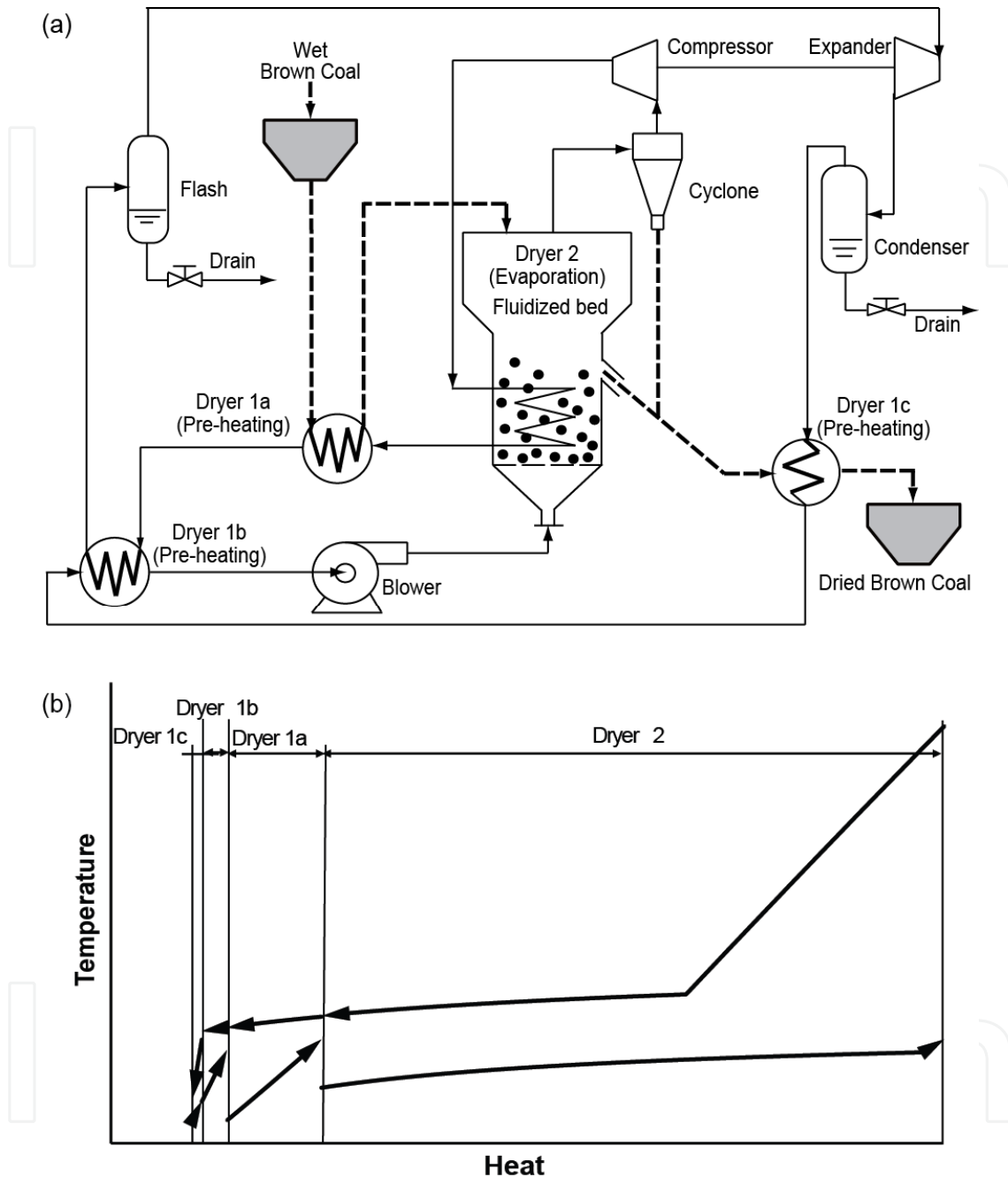

Fig. 4. Self-heat recuperative brown coal drying (a) process flow diagram, (b) temperature-heat diagram.

This drying process can reduce the total energy consumption to about 75% of that required for hot air drying using conventional heat recovery. Furthermore, as the heat required for water evaporation is provided by the condensation of the compressed air-steam mixture, the inlet air temperature is considerably lower, leading to safer operation due to reduced risk of fire or explosion.

In addition, the thermodynamic model of heat exchange inside the fluidized bed is shown in Fig. 5. The compressed air-steam mixture flows inside a heat transfer tube immersed in the fluidized bed dryer. Thus, in-tube condensation occurs and heat is transferred to the bed via the tube wall and is finally transferred from the bed to the brown coal particles.
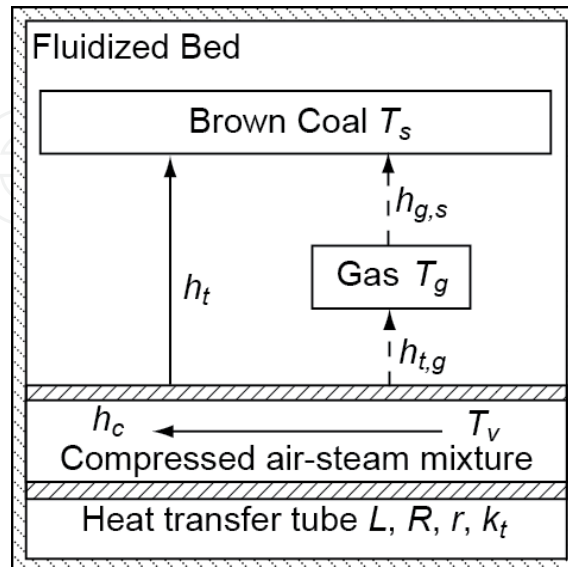

Fig. 5. Model of heat transfer inside the fluidized bed dryer.

The heat transfer rate from the compressed vapor inside the heat transfer tube to the drying sample in FBD, q_s, can be approximated as:

$$q_s = UA(T_v - T_s) \tag{1}$$

Also, because the heat exchange inside the fluidized bed dryer involves convection and conduction, the product of the overall heat transfer coefficient, U, and surface area, A, may be approximated by equation (2).

$$\frac{1}{UA} = \frac{1}{A_c \alpha_c} + \frac{\ln\left(R/r\right)}{2\pi L \lambda_t} + \frac{1}{\alpha_t A_t} \tag{2}$$

The first term of the right side of equation (2) represents the heat transfer resistance of vapor condensation inside the tube. A_c and α_c are the inner surface area of the tube and the heat transfer coefficient, respectively. The second term corresponds to the conductive heat transfer through the tube wall having the thermal conductivity, inner radius and outer radius of λ_t, r and R, respectively. Convective heat transfer from the outer tube surface to the brown coal particles inside the bed is expressed by the third term, in which the convective heat transfer coefficient and the outer surface area of the tube are α_t and A_t, respectively.

The heat transfer coefficient on a horizontal tube immersed inside the fluidized bed has been reported by Borodulya (1989, 1991):

$$Nu_t = 0.74\, Ar^{0.1} \left(\frac{\rho_s}{\rho_g}\right)^{0.14} \left(\frac{C_s}{C_g}\right)^{0.24} (1-\varepsilon)^{2/3} + 0.46\, Re\, Pr\frac{(1-\varepsilon)^{2/3}}{\varepsilon} \tag{3}$$

$$Nu_t = \frac{\alpha_t \, d_s}{\lambda_g} \qquad (4)$$

The heat transfer coefficient of the condensing vapor is calculated using a general correlation proposed by Shah (1979):

$$\alpha_c = \frac{0.023 \, Re_l^{0.8} \, Pr_l^{0.4} \, \lambda_l}{2r}\left[(1-x)^{0.8} + \frac{3.8 x^{0.76}(1-x)^{0.04}}{(p/p_{crit})^{0.38}} \right] \qquad (5)$$

2.2.3 Self-heat recuperative CO_2 absorption process

Carbon capture and storage (CCS) has attracted significant attention in the past two decades to reduce greenhouse gas emissions and mitigate global warming. CCS consists of the separation of CO_2 from industrial and energy-related sources, transportation of CO_2 to a storage location and long-term isolation of CO_2 from the atmosphere (Rubin et al. 2005).

It is reported that the most significant stationary point sources of CO_2 are power generation processes. In fact, the amount of CO_2 emission from power generation processes comprises 40% of global CO_2 emissions (Rubin et al. 2005, Toftegaard, 2010). For power generation, there are three different types for CO_2 capture processes: post-combustion, pre-combustion and oxy-fuel combustion (Rubin et al. 2005). In this section, the CO_2 absorption process for post-combustion is used as a case study (Fig. 6).

Post-combustion capture in power plants is generally used for pulverized-coal-fired power plants. The CO_2 concentration in post-combustion is low compared with the other two CO_2 capture processes: around 10% (wet base). The CO_2 capture is generally performed through chemical absorption with monoethanolamine (MEA).
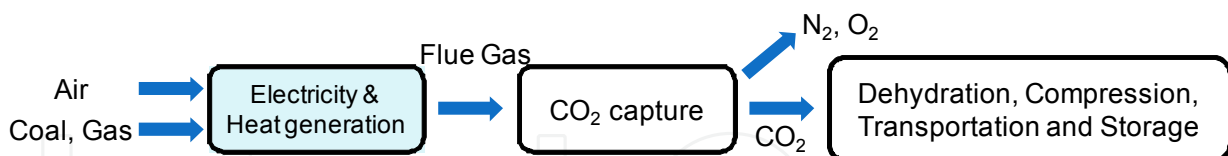

Fig. 6. Post-combustion capture.

Figure 7 shows a diagram of the conventional CO_2 absorption process, which consists of an absorber, a heat exchanger (HX) for heat recovery and a stripper (regenerator) with a reboiler. The flue gas and a 'lean CO_2 concentration' amine solution (lean amine) are fed into the absorber, and CO_2 gas is absorbed into the lean amine. This amine solution containing absorbed CO_2 is called the 'rich CO_2 concentration' amine solution (rich amine). Exhaust gases are discharged from the top of the absorber. The rich amine is fed into the stripper through the HX and then lean amine is regenerated and the CO_2 gas is stripped by heating in the reboiler of the stripper. In the conventional absorption process using MEA, the heat (4.1 GJ/t-CO_2) is supplied by the reboiler in the stripper. The ratio of this heat for regeneration and vaporization is 1:1. From Fig. 7, it can be understood that a part of sensible heat is recovered from lean amine using the HX. However, the heat of vaporization cannot be recovered from heat of steam condensation for stripping in the reboiler because of the

temperature difference between the condenser and the reboiler. Thus, CO_2 capture is the most costly and high energy consumption process of power generation, leading to higher CO_2 emissions. In fact, it is reported that this process drops the net efficiency of the power plant by about 10% (Damen 2006, Davison 2007).
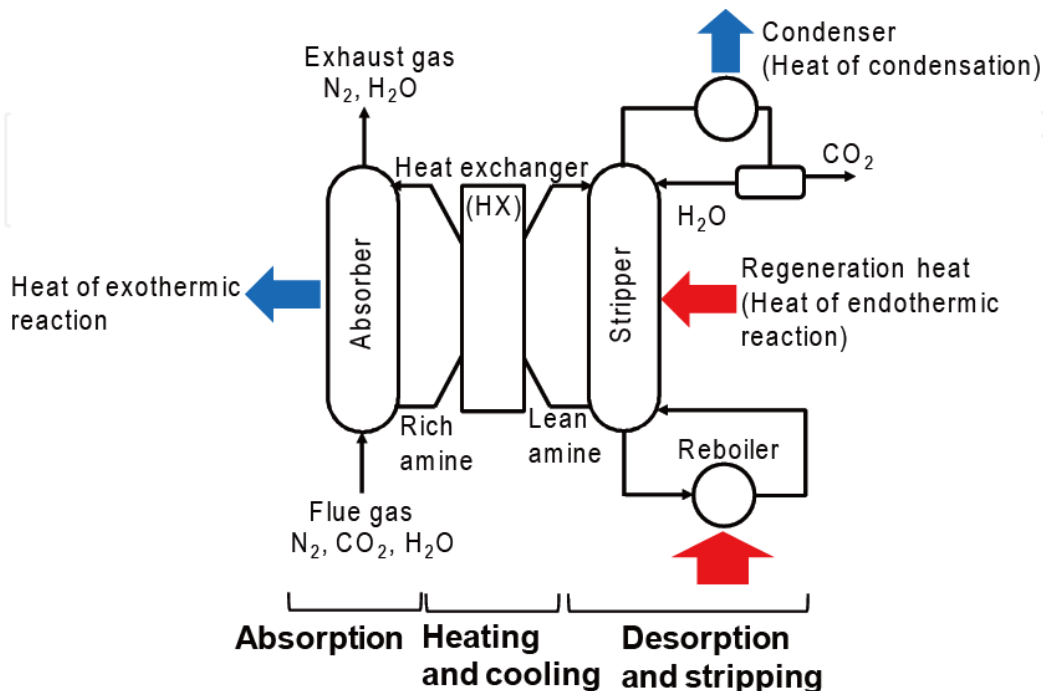

Fig. 7. Conventional CO_2 absorption process.

If all process heat (sensible heat, latent and reaction heat) can be recirculated into the process, the energy required for CO_2 capture can be greatly reduced. To achieve perfect internal heat circulation, a self-heat recuperation technology was applied to the CO_2 absorption process and a self-heat recuperative CO_2 absorption process was proposed, as shown in Fig. 8 (a) (Kishimoto et al. 2011). In this process, the aforementioned self-heat recuperative distillation module in 2.2.1 can be applied to the stripping section (A) in Fig. 8 (a). A mixture of CO_2 and steam is discharged from the top of stripper and compressed adiabatically by a compressor to recuperate the steam condensation heat. This recuperated heat is exchanged with the heat of vaporization for stripping in the reboiler, leading to a reduction in the energy consumption for stripping.

In the section B in Fig. 8 (a), the aforementioned heat circulation module in 2.2.1 can be applied, and furthermore the heat of the exothermic reaction generated at low temperature in the absorber is transported and reused as reaction heat for solution regeneration at high temperature using a reaction heat transformer (RHT). This RHT is a type of closed-cycle compression system with a volatile fluid as the working fluid and consists of an evaporator to receive heat from the heat of exothermic reaction in the absorber, a compressor with driving energy, a condenser to supply heat to the stripper as heat of the endothermic reaction, and an expansion valve. The heat of the exothermic absorption reaction at the evaporator in the absorber is transported to the endothermic desorption reaction in the condenser of the stripper by the RHT. Therefore, both the heat of the exothermic absorption reaction in the absorber and the heat of steam condensation from the condenser in the

stripper are recuperated and reused as the reaction heat for solution regeneration and the vaporization heat for CO_2 stripping in the reboiler of the stripper.

As a result, the proposed self-heat recuperative CO_2 absorption process can recirculate the entire process heat into the process and reduce the total energy consumption to about 1/3 of the conventional process.
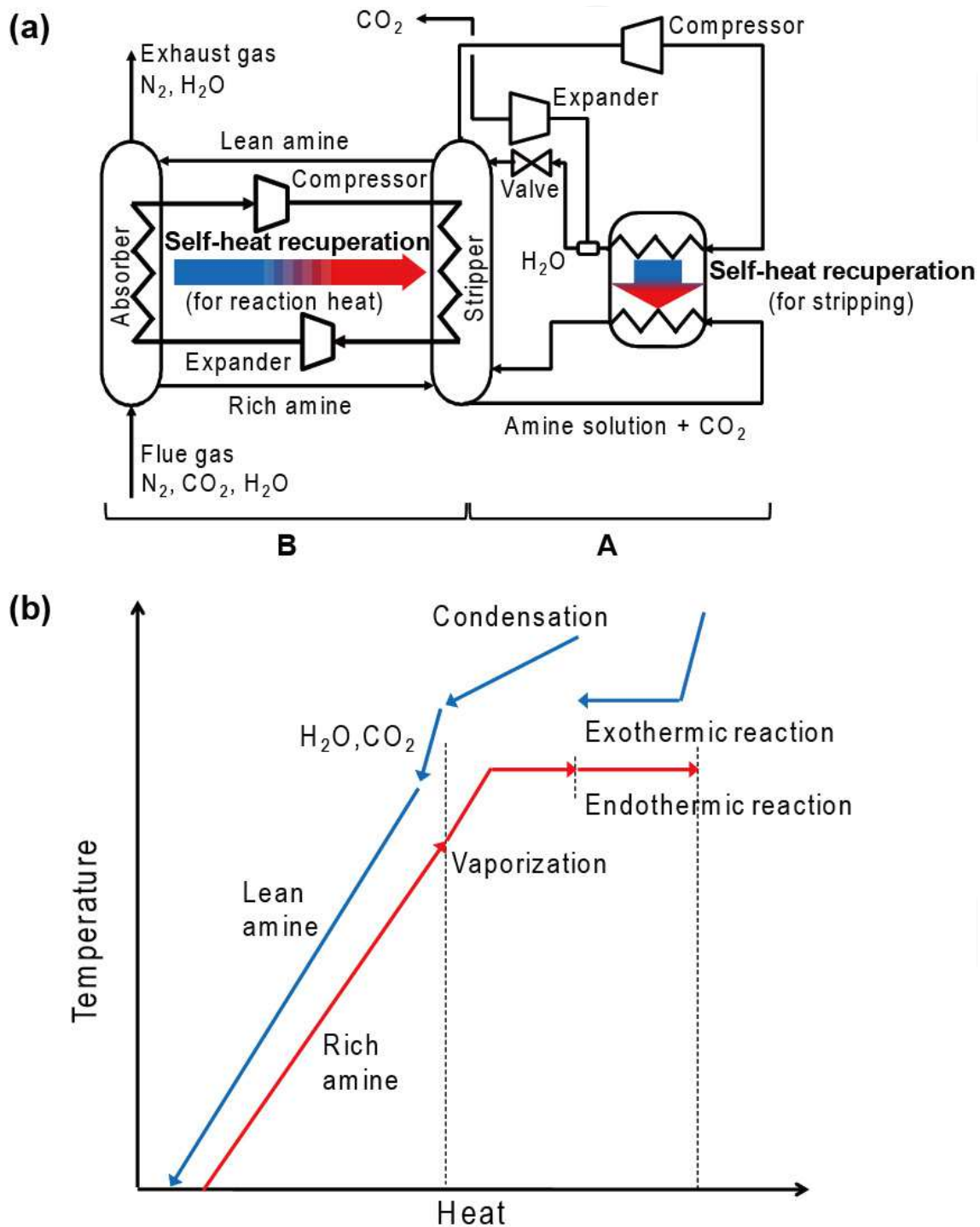

Fig. 8. Self-heat recuperative CO_2 absorption process, (a) process flow diagram, (b) temperature-heat diagram.

3. Conclusion

In this chapter, a newly developed self-heat recuperation technology, in which not only the latent heat but also the sensible heat of the process stream can be circulated without heat addition, and the theoretical analysis of this technology were introduced. Several industrial application case studies of the technology were then presented and compared with their conventional counterparts. Although these processes require the power to circulate the process self heat instead of fuel for the furnace heater, a large amount of the energy required can be eliminated. Furthermore, to integrate the proposed self-heat recuperative processes with power generation plants, some amount of the power required can be generated from surplus fuel and energy, leading to achievement to co-production of products and power. Finally, this self-heat recuperation technology is a very promising technology for suppressing global warming and reducing the use of fossil fuels.

4. Nomenclature

A   Surface area (m^2)
Ar   Archimedes number (dimensionless)
C   specific heat capacity (J kg^{-1} K^{-1})
d   diameter (m)
h   heat transfer coefficient (W m^{-2} K^{-1})
k   thermal conductivity (W m^{-1} K^{-1})
L   tube length (m)
Nu   Nusselt number (dimensionless)
p   pressure (kPa)
Pr   Prandtl number (dimensionless)
R   outer diameter (m)
Re   Reynolds number (dimensionless)
r   inner diameter (m)
q   heat transfer rate (W)
T   temperature (K)
U   overall heat transfer (W m^{-2} K^{-1})
x   vapor quality (dimensionless)

Greek letters

α heat transfer coefficient (W m^{-2} K^{-1})
ε void fraction (dimensionless)
λ thermal conductivity (W m^{-1} K^{-1})
ρ density (kg m^{-3})

Subscripts

b   boiling point
c   condensation
crit   critical
g   gas

l   liquid
s   particle sample
std   standard condition
t   heat transfer tube
v   vapor

5. References

Aziz, M.; Fushimi, C.; Kansha, Y.; Mochidzuki, K.; Kaneko, S.; Tsutsumi, A.; Matsumoto, K.; Hashimoto, T.; Kawamoto, N.; Oura, K.; Yokohama, K.; Yamaguchi, Y. & Kinoshita, M. (2011). Innovative Energy-Efficient Biomass Drying Based on Self-Heat Recuperation Technology. *Chemical Engineering and Technology*, Vol.34, No.7, pp. 1095-1103, ISSN 1521-4125

Aziz, M.; Kansha, Y. & Tsutsumi, A. (2011). Self Heat Recuperative Fluidized Bed Drying of Brown Coal. *Chemical Engineering and Processing: Process Intensification*, Vol.50, No.9, pp. 944-951, ISSN 0255-2701

Borodulya, V.A.; Teplitsky, Y.S.; Sorokin, A.P.; Matsnev, V.V.; Markevich, I.I. & Kovenskii, V.I. (1989). External Heat Transfer in Polydispersed Fluidized Beds at Elevated Temperatures. *Journal of Engineering Physics and Thermophysics*, Vol.56, No.5, (May 1989), pp. 541-546, ISSN 1062-0125

Borodulya, V.A.; Teplitsky, Y.S.; Sorokin, A.P.; Markevich, I.I.; Hassan, A.F. & Yeryomenko, T.P. (1991). Heat Transfer between a Surface and a Fluidized Bed: Consideration of Pressure and Temperature Effects. International Journal of Heat and Mass Transfer, Vol.34, No.1, pp. 47-53, ISSN 0017-9310

Brammer, J.G. & Bridgwater, A.D. (1999). Drying Technologies for an Integrated Gasification Bio-Energy Plant. *Renewable and Sustainable Energy Reviews*, Vol.3, No.4, pp. 243-289, ISSN 1364-0321

Eastop, T.D. & Croft, D.R. (1990). *Energy Efficiency for Engineers and Technologists*, Longman Scientific & Technical, ISBN 0-582-03184-2, London, UK

Ebrahim, M. & Kawari, A. (2000). Pinch Technology: An Efficient Tool for Chemical-Plant and Capital-Cost Saving, *Applied Energy*, Vol. 65, No. 1-4, pp. 45–49 ISSN 0306-2619

Cerda, J.; Westerberg, A. W.; Mason, D. & Linnhoff, B. (1983) Minimum Utility Usage in Heat Exchanger Network Synthesis, *Chemical Engineering Science*, Vol. 38, No. 3, pp. 371–387, ISSN 0009-2509

Chengqin, R.; Nianping, L. & Guangfa, T. (2002). Principle of Exergy Analysis in HVAC and Evaluation of Evaporative Cooling Schemes, *Building and Environment*, No. 37, No. 11, pp. 1045-1055, ISSN 0360-1323

Damen, K.; Troost, V.M.; Faaij, A. & Turkenburg, W. (2006). A Comparison of Electricity and Hydrogen Production Systems with CO2 Capture and Storage. Part A: Review and Selection of Promising Conversion and Capture Technologies, Progress in Energy and Combustion Science, Vol. 32, No. 6, pp. 215-246, ISSN 0360-1285

Davison, J. (2007) Performance and Costs of Power Plants with Capture and Storage of CO2. Energy, Vol. 32, No. 7, pp.1163-1176, ISSN 0360-5442.

Grubbström, R. W. (2007). An Attempt to Introduce Dynamics into Generalized Exergy Consideration, *Applied Energy*, Vol. 84, No. 7-8, pp. 701-718, ISSN 0306-2619

Rubin, E.; Myer, L. & de Coninck, H., (2005). Technical Summary, In Carbon Dioxide Capture And Storage:, Metz, B., Davidson, O.; de Coninck, H.; Loos, M. & Meyer, L., (Ed.), 17-50, Cambridge University Press, ISBN 13 978-0-521-68551-1, New York, USA

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*, Vol. 48, No. 16, pp.7682-7686, ISSN 0888-5885

Kansha, Y.; Tsuru, N.; Fushimi, C.; Shimogawara, K. & Tsutsumi, A. (2010a). An Innovative Modularity of Heat Circulation for Fractional Distillation, *Chemical Engineering Science*, Vol. 65, No.1, pp.330-334, ISSN 0009-2509

Kansha, Y.; Tsuru, N.; Fushimi, C. & Tsutsumi, A. (2010b). Integrated Process Module for Distillation Processes Based on Self-Heat Recuperation Technology, *Journal of Chemical Engineering of Japan*, Vol. 43, No. 6, pp. 502-507, ISSN 0021-9592

Kansha, Y.; Tsuru, N.; Fushimi, C. & Tsutsumi, A. (2010c). New Design Methodology Based on Self-Heat Recuperation for Production by Azeotropic Distillation, *Energy & Fuels*, Vol. 24, No. 11, pp. 6099-6102, ISSN 0887-0624

Kansha, Y.; Kishimoto, A.; Nakagawa, T. & Tsutsumi, A (2011a). A Novel Cryogenic Air Separation Process Based on Self-Heat Recuperation, *Separation and Purification Technology*, Vol. 77, No. 3, pp. 389-396, ISSN 1383-5866

Kansha, Y.; Kishimoto, A. & Tsutsumi, A (2011b). Process Design Methodology for High-Energy Saving HIDiC Based on Self-Heat Recuperation, *Asia-Pacific Journal of Chemical Engineering*, Vol. 6, No. 3, pp. 320-326, ISSN 1932-2143

Kemp, I.C. (2007). *Pinch Analysis and Process Integration A User Guide on Process Integration for the Efficient Use of Energy 2nd Ed.*, Elsevier, ISBN 13 978-0-75068-260-2, Oxford, UK

Kishimoto, A.; Kansha, Y.; Fushimi, C. & Tsutsumi, A. (2011). Exergy Recuperative CO_2 Gas Separation in Post-Combustion Capture, *Industrial and Engineering Chemistry Research*, Vol. 50, No. 17, pp. 10128–10135, ISSN 0888-5885

Kuchonthara, P. & Tsutsumi, A. (2003). Energy-Recuperative Biomass Integrated Gasification Power Generation System, Journal of Chemical Engineering, Japan, Vol. 36, No. 7, pp. 846-851, ISSN 0021-9592

Kuchonthara, P.; Bhattacharya, S. & Tsutsumi, A. (2005). Combination of Thermochemical Recuperative Coal Gasification Cycle and Fuel Cell for Power Generation, Fuel, Vol. 84, No. 7-8, pp. 1019-1021, ISSN 0016-2361

Kuchonthara, P. & Tsutsumi, A. (2006). Energy-Recuperative Coal-Integrated Gasification/Gas Turbine Power Generation System, Journal of Chemical Engineering, Japan, Vol. 39, No. 5, pp. 545-552. ISSN 0021-9592

Lampinen, M. J.& Heillinen, M. A. (1995). Exergy Analysis for Stationary Flow Systems with Several Heat Exchange Temperatures, *International Journal of Energy Research*, Vol. 19, No. 5, pp. 407-418, ISSN 1099-114X

Law, C. & Mujumdar, A.S. (2009). Fluidize Bed Dryers, In: *Handbook of Industrial Drying*, A.S. Mujumdar, (Ed.), 173-202, CRC Press, ISBN 978-157-4446-68-5, Florida, USA

Linnhoff, B.; Mason, D.R. & Wardle, I. (1979). Understanding Heat Exchanger Networks, *Computers & Chemical Engineering*, Vol. 3, No. 1-4, pp. 295–302, ISSN 0098-1354

Linnhoff, B. & Hindmarsh, E. (1983). The Pinch Design Method for Heat Exchanger Networks, *Chemical Engineering Science*, Vol. 38, No. 5, pp. 745–763. ISSN 0009-2509

Linnhoff, B. (1993) Pinch Analysis-A State-of-the-Art Overview, *Chemical Engineering Research & Design*, Vol. 71, No. A5, pp. 503–522, ISSN 0263-8762

Linnhoff, B. & Eastwood, A.R. (1997). Overall Site Optimization by Pinch Technology. *Chemical Engineering Research & Design*, Vol. 75, pp. S138-S144, ISSN 0263-8762

Matsuda, K.; Kawazuishi, K.; Hirochi, Y.; Sato, R.; Kansha, Y.; Fushimi, C.; Shikatani, Y.; Kunikiyo, H. & Tsutsumi, A. (2010). Advanced Energy Saving in the Reaction Section of the Hydro-Desulfurization Process with Self-Heat Recuperation Technology, *Applied Thermal Engineering*, Vol. 30, No. 16, pp. 2300-2305, ISSN 1359-4311

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*, Vol. 36, No. 8, pp. 4640-4645, ISSN 0360-5442

Riemer, P. W. F. & Ormerod, W.G. (1995). International Perspectives and the Results of Carbon Dioxide Capture Disposal and Utilization Studies, *Energy Conversion and Management*, Vol. 36, No. 6-9, pp. 813-818, ISSN 0196-8904

Seider, W.D.; Seader, J.D. & Lewin D.R. (2004). *Product & Process Design Principles Synthesis, Analysis, and Evaluation 2nd Ed.*, John Wiley & Sons, ISBN 0-471-45247-5, New York, USA

Shah, M.M. (1979). A General Correlation for Heat Transfer during Film Condensation inside Pipes. *International Journal of Heat and Mass Transfer*, Vol.22, No.4, pp. 547-556, ISSN 0017-9310

Som, S. K. & Datta, A. (2008). Thermodynamic Irreversibilities and Exergy Balance in Combustion Processes, *Progress in Energy Combustion Science*, Vol. 34, No. 3, pp. 351-376, ISSN 0360-1285

Strumillo, C.; Jones, P.L. & Zylla, R. (2009). Energy Aspects in Drying, In: *Handbook of Industrial Drying*, A.S. Mujumdar, (Ed.), 1075-1101, CRC Press, ISBN 978-157-4446-68-5, Florida, USA

Toftegaard, MB.; Brix, J.; Jensen, P.A.; Glarborg, P. & Jensen, A.D. (2010). Oxy-Fuel Combustion of Solid Fuels, *Progress in Energy and Combustion Science*, Vol. 36, No. 5, pp. 581-625, ISSN 0360-1285

Wan Daud, W.R. (2008). Fluidized Bed Dryers-Recent Advances. *Advanced Powder Technology*, Vol.19, No.5, pp. 403-418, ISSN 0921-8831

Heat Exchangers - Basics Design Applications

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Selecting and bringing together matter provided by specialists, this project offers comprehensive information on particular cases of heat exchangers. The selection was guided by actual and future demands of applied research and industry, mainly focusing on the efficient use and conversion energy in changing environment. Beside the questions of thermodynamic basics, the book addresses several important issues, such as conceptions, design, operations, fouling and cleaning of heat exchangers. It includes also storage of thermal energy and geothermal energy use, directly or by application of heat pumps. The contributions are thematically grouped in sections and the content of each section is introduced by summarising the main objectives of the encompassed chapters. The book is not necessarily intended to be an elementary source of the knowledge in the area it covers, but rather a mentor while pursuing detailed solutions of specific technical problems which face engineers and technicians engaged in research and development in the fields of heat transfer and heat exchangers.

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