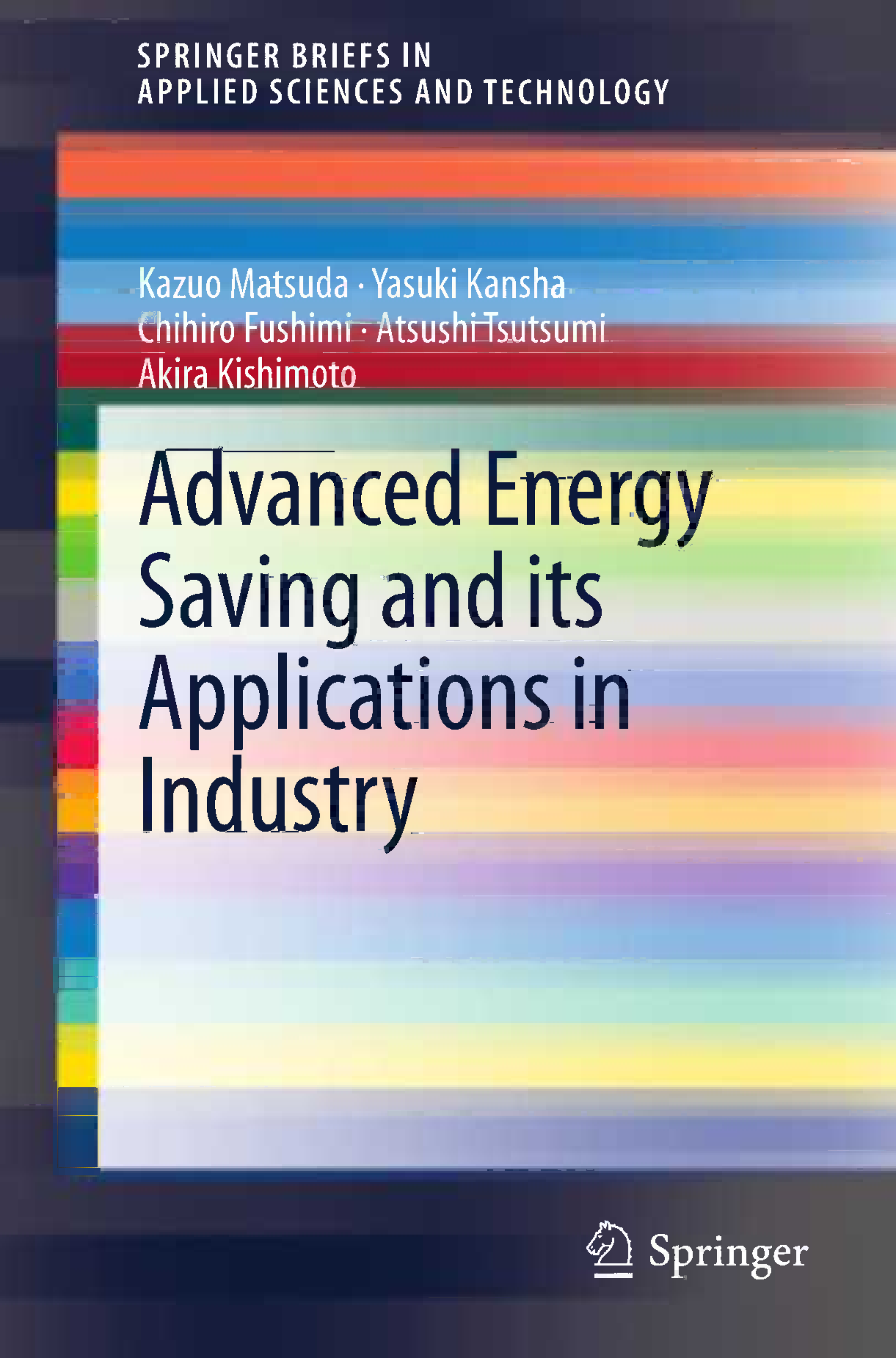

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Advanced Energy Saving and its Applications in Industry

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Preface

Refineries that occupy large sites in heavy chemical complexes and the petrochemical industry in general, have for long years been utilizing and consuming a huge amount of fossil fuel as an energy source for operation. “Energy saving”, in the way of reduction in the use of fossil fuel, has been under active consideration for many years as this leads to the strengthening of competitiveness by saving cost in operation. Moreover the industry in general fully recognizes that public opinion is less accepting of the combustion of fossil fuel that results in the generation and release of large amounts of the greenhouse gas CO_2 in to the atmosphere. Energy saving eventually leads to a significant reduction in the emission of greenhouse gases and is one of the most important measures that can be taken to mitigate the problem of global warming.

The sites in heavy chemical complexes have two systems in general; the process system and the utility system. The history of energy saving in the process system shows that its purpose was to improve and strengthen heat recovery. Pinch technology, a methodology of heat analysis based on thermodynamic principles, was developed in 1980s and applied for the study of heat recovery. Pinch technology is used to minimize the energy consumption of chemical processes by calculating thermodynamically feasible energy targets (or minimum energy consumption) and achieving them by optimizing heat recovery systems, energy supply methods and process operating conditions. Over the past 30 years, pinch technology has been applied on thousands of processes with a large amount of energy savings having been achieved.

However the general consensus in engineers was that almost all possible methods of heat recovery had already been investigated and that a new breakthrough was needed to be any further significant improvement in energy efficiency. That breakthrough was a new approach in the development of the process system, which would replace the conventional system.

The process system, in heavy chemical complexes, has a reaction section and a distillation section. In these sections, the amount of low-grade heat discarded as waste heat is about the same amount required to be supplied for the operation of the process. Conventionally heat recovery is maximized by using pinch

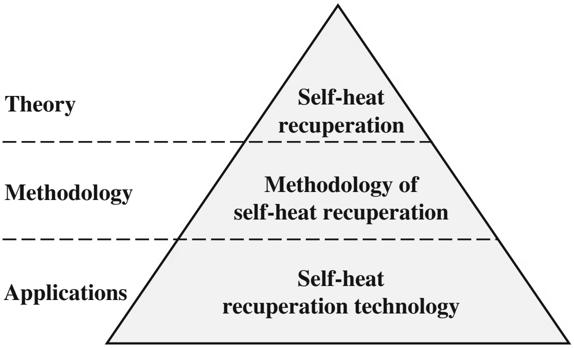

Fig. 1 From theory to applications about self-heat recuperation

technology, which means that the amount of heat input is minimized and the waste heat is reduced. It should be noted that with this methodology the process operating condition is not changed but maintained as it is.

To achieve further energy saving in the process system, “self-heat recuperation” (SHR) was developed. (see Fig. 1) SHR is able to be applied for both the reaction section and the distillation section. SHR has a novel approach in that the process operating condition is changed by using a compressor, but the process core condition, such as a reactor inlet condition, is still maintained. Self-heat recuperation technology (SHRT) was applied to the reaction section of the naphtha HDS process and the benzene distillation section in the refinery and it was found that the advanced process with SHRT was able to reduce the energy consumption significantly for both the reaction section and the distillation section. SHRT is able to be applied not only to the process systems in the heavy chemical complexes but also to the other processes which require heating and cooling, such as drying and gas separation processes. It was found that SHRT was effective to reduce energy consumption considerably in such processes.

The utility system has also been targeted to become more efficient in energy saving. Major items of equipment, such as boilers and turbines, are considered to have reached the limit for further improvement in efficiency and therefore the utility system must be optimized. However, when looking at heavy chemical complexes, it appeared that a refinery would discharge low-grade heat as waste heat whereas, at same time, an adjacent petrochemical plant could make use of such heat. There could, therefore, be a large energy saving potential by utilizing the surplus heat across the sites. The total site approach, based on pinch technology, was applied to the heavy chemical complexes and it became apparent that there was a huge amount of energy saving potential through energy sharing among various sites in the complexes, despite the very high efficiency of the individual sites in the complex.

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Part II Application of Self-Heat Recuperation Technology

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Part I
Process System

Chapter 1
Energy Saving Technology

Abstract This chapter introduces the conventional and latest energy saving technologies for process systems, especially for use in oil refineries and petrochemical plants. One of the most famous energy saving technologies for these processes is a well-known heat recovery technology that uses pinch technology. The hot and cold stream lines can be moved horizontally within the temperature limits in the temperature-heat diagram. Process systems are designed based on this graphical analysis. In contrast, in the latest energy saving technology termed self-heat recuperation technology, the hot stream line is shifted vertically by using the adiabatic compression of the hot stream in the temperature-heat diagram. Thus, the whole process heat can be recirculated into the process without any heat addition, leading to further energy saving in the process systems. In addition, process design methodology based on self-heat recuperation and the overall energy efficiency of the designed process are illustrated using simple thermal and distillation process examples.

Keywords Energy saving · Pinch technology · Self-heat recuperation technology · Process design · Process system · Exergy

1.1 Pinch Technology

Energy saving has, over several years, been attracting ever-increasing interest in many countries, as it would greatly assist in minimizing global warming caused mainly by the consumption of fossil fuels. Although many heat integration techniques for process energy saving have been applied to oil refineries since the 1970s' energy crisis, oil refineries, and petrochemical plants still consume large amounts of energy compared to the required values based on an exergy analysis. It

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is commonly known that about 5 % of the amount of crude oil throughput in an oil refinery is used as fuel. In particular, about half of the total amount of fuel in an oil refinery is consumed in the crude oil distillation unit (CDU; atmospheric distillation). The CDU has one of largest fired heaters on the site, which consumes a huge amount of fuel oil and gas. In order to reduce the fuel consumption, CDUs had been equipped with a heat recovery system, which consists of approximately 10–20 heat exchangers, a so-called heat exchanger network system (HEN), leading to energy saving. However, it was very complicated to manage many hot and cold streams simultaneously in HEN. Thus, HEN was considered to be a prime candidate for implementation of a new methodology for optimization of its fuel consumption.

From 1980s, pinch technology has been applied to heavy chemical industries to determine suitable HENs based on a thermodynamic approach for energy saving. The concept of "target before design" was introduced by Linnhoff et al. (1982) using pinch technology for the design of individual processes. Pinch technology for HEN design was developed by Linnhoff and Hindmarsh (1983). Linnhoff and Ahmad (1990) and Ahmad et al. (1990) further evolved the methodologies to incorporate total cost targeting and block-decomposition based HEN synthesis. Later a HEN retrofit framework, based on the "process pinch" (Tjoe and Linnhoff 1986) and "network pinch" (Asante and Zhu 1996) concepts was established. Over time pinch technology has been applied to increasingly large and complex sites. To facilitate this, a variety of tools and techniques have been developed to enhance the methodology and simplify the analysis.

Figure 1.1 shows a conceptual temperature-heat diagram of heat integration systems by using conventional pinch technology (Eastop and Croft 1990; Kemp 2007). The lines which represent the cold and hot streams are plotted in the temperature-heat diagram. To handle multiple streams, the heat loads of all streams are added and a single composite of all hot streams and a single composite of all cold streams can be produced. They are called "Composite Curves." The cold stream means the process stream, in which the temperature is increasing, and the hot stream means the process stream, in which the temperature is decreasing. If ΔT_{min} is negligible, the hot and cold stream lines overlap perfectly. In conventional pinch technology, these lines can be moved horizontally within the temperature limits until the nearest points (pinch points) are separated by the minimum temperature difference. From these plots, the lines can identify the region in which the heat is exchanged between the hot and the cold streams for heat recovery. Beyond the area of overlap, the curves identify the need for an additional heat source and sink. Pinch technology is based on a concept of energy cascading utilization, in which the heat energy is used from high grade heat to low grade heat and low grade waste heat is discarded from the process. Thus, pinch technology enables energy targets to be set without actual complete design and provides a consistent methodology for energy saving from the basic heat and material balance to the total site utility system.

Hence, pinch technology is well-known and has significant role of process design and optimization. In fact, it has now been applied to several heat exchanger networks.

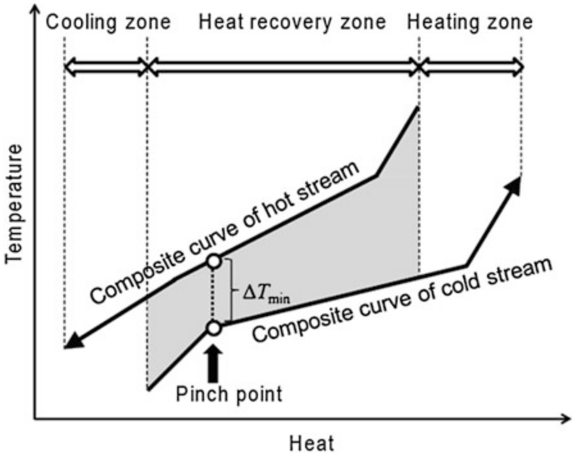


Fig. 1.1 Temperature-heat diagram of heat integration

1.2 Self-Heat Recuperation Technology

The combustion of fossil fuels for heating produces a large amount of carbon dioxide (CO_2), which is the main contributor to the global greenhouse gas effect. Hence, the reduction of carbon dioxide (CO_2) emission and the reduction of energy consumption for heating has currently become a very important issue in the efforts to suppress global warming. Heat recovery technology such as pinch technology (Eastop and Croft 1990; Kemp 2007), which exchanges heat between the hot and cold streams in a process, has been applied to thermal processes to reduce energy consumption. A simple example of this technology is the application of a feed-effluent heat exchanger in thermal processes. In this heat exchanger, heat is exchanged between feed and effluent streams to recirculate the self heat of the stream (Seider et al. 2004). To exchange the heat, an additional heat source is required to provide temperature difference between two streams for heat exchange due to the second law of thermodynamics. These conventional heat recovery technologies are distinguished by cascading heat utilization, by which the required additional heat is provided by the exhausted heat from the other process or by the combustion of fuels. Although the net energy input seems to be reduced by using exhausted heat as the additional heat, the heat is also provided by the combustion of fossil fuels, leading to exergy destruction during energy conversion from chemical energy to heat (Som and Datta 2008).

Recently, attention has been paid to the analysis of process exergy and its irreversibility through consideration of the second law of thermodynamics. In many of these investigations, the calculation results of only exergy analysis and the possibility of the energy savings of some processes are only shown (Lampinen and Heillinen 1995; Chengqin et al. 2002; Aspelund et al. 2007; Grubbström 2007). From the process design point of view, a heat pump has been applied to thermal processes to reduce exergy destruction, in which the ambient heat or the process waste heat is generally pumped to heat the process stream by using working fluid compression (Fonyo and Benko 1996; Wu et al. 1998; Hou et al. 2007; Tarnawski 2009). 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. As well as heat pumps for energy saving, vapor recompression in heat recovery technologies for the process has been applied to evaporation (Ettouney 2006; Nafey et al. 2008), distillation (Brousse et al. 1985; Annakou and Mizsey 1995; Haelssig 2008), and drying (Fehlau and Specht 2000), 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.

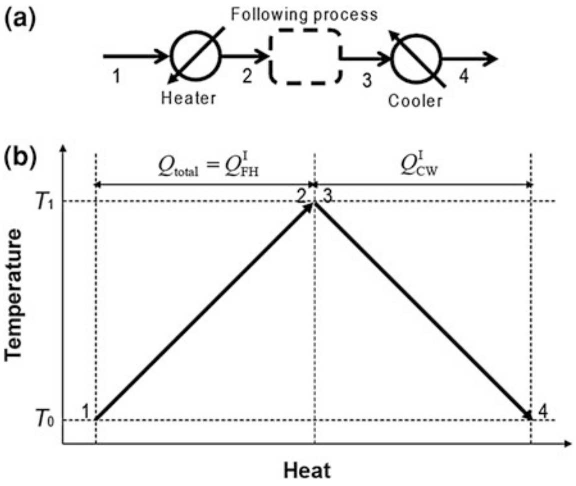
Recently, an energy and exergy recuperative integrated gasification power generation system has been proposed and a design method for the system developed (Kuchonthara and Tsutsumi 2003; Kuchonthara et al. 2005; Kuchonthara and Tsutsumi 2006). Kansha et al. (2009) following on this concept developed self-heat recuperation technology (SHRT) based on exergy recuperation. The most important characteristic of this technology is that the entire process stream heat can be recirculated into a process without any heat addition, leading to marked reduction of exergy and energy savings for the process.

Self-heat recuperation (SHR; Kansha et al. 2009) facilitates recirculation, not only of the latent heat but also the 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 theory, (1) a process unit is divided on the basis of functions to balance the heating and cooling loads by performing enthalpy and exergy analysis and (2) 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. Next, the process design methodology based on SHR is illustrated by using the simple thermal processes of the gas stream.

1.2.1 Process Design Methodology

Generally, separate process units each have functions such as heating, cooling, reaction, and separation. Figure 1.2 shows a thermal process without any heat recovery [I] in which a gas stream is heated from the standard temperature T_0 to a certain operating temperature T_1 of the following process by a heater (1→2) and cooled to the standard temperature by cooler (3→4). Note that, the following process is assumed not to affect the enthalpy of the process stream. The

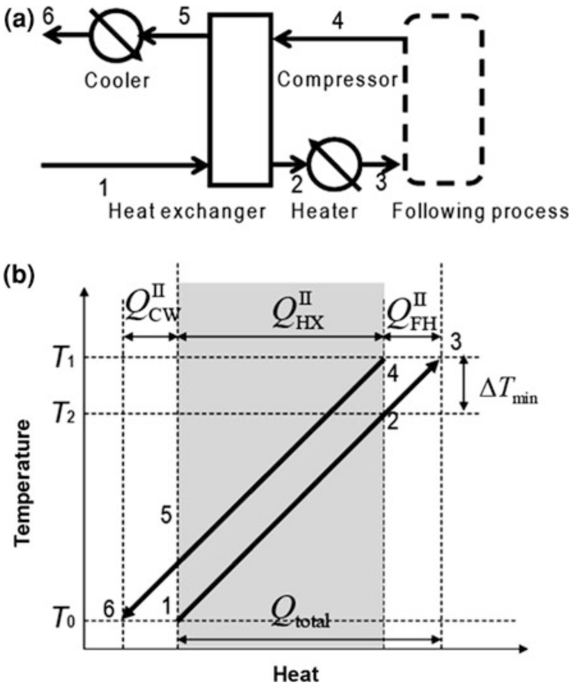
Fig. 1.2 Simple thermal process [I] (for the gas stream): **a** flow diagram, **b** temperature-heat diagram



temperature-heat diagram of the thermal process [I] is shown in Fig. 1.2b. The total heating duty, Q_{total}, is provided by the heater. If the temperatures of the streams 2 and 3 are the same, the external heating load, ${Q_{\text{FH}}}^{\text{I}}$, is always equal to the external cooling load ${Q_{\text{CW}}}^{\text{I}}$.

In the case of a thermal process [II] using a feed-effluent heat exchanger as a representative example of conventional heat recovery with a minimum temperature difference $\Delta T_{\min}$ (self-heat exchange thermal process), the heat of the effluent stream can be reused to preheat the feed stream up to T_2, reducing overall energy consumption, as shown in Fig. 1.3. In this process, the process stream is preheated from T_0 to T_2 with a heat exchanger (1→2) and heated with a heater from T_2 to T_1 (2→3). The effluent stream from the following process is cooled with the heat exchanger for self-heat exchange (4→5) and finally cooled to T_0 by a cooler (5→6). In Fig. 1.3b, the overlapping interval corresponds to the heat transfer duty from the hot effluent stream to the cold feed stream (the self-heat exchange load: ${Q_{\text{HX}}}^{\text{II}}$). Thus, heat recovery by means of self-heat exchange can reduce the external heating load (${Q_{\text{FH}}}^{\text{II}}$). Note that ${Q_{\text{CW}}}^{\text{II}}$ represents the external cooling load (5→6 in Fig. 1.3). Even with a self-heat exchange process, the heater is still required because the effluent stream should be heated to provide $\Delta T_{\min}$ for heat exchange. Moreover, the heat generated by the heater should be dispersed in the cooler. The proposed thermal process of the gas streams for heat circulation based on SHR is shown in Fig. 1.4a. In this process, the feed stream is heated up with a heat exchanger (1→2) from a standard temperature T_0 to a set temperature T_1. The effluent stream from the following process is compressed with a compressor to recuperate the heat of the effluent stream (3→4) and the temperature at the exit of the compressor rises up to $T_{1'}$ because of the adiabatic compression. Stream 4 is cooled with the 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. The effluent stream is finally cooled to T_0 with a cooler (6→7). Thus, SHR

Fig. 1.3 Thermal process with a feed-effluent heat exchanger [II] (for the gas stream): **a** flow diagram, **b** temperature-heat diagram



leads to perfect internal heat circulation. Note that the total heating duty, $Q_{\rm total}$, is equal to the internal self-heat exchange load, $Q_{\rm HX}{}^{\rm III}$, without any external heating load as shown in Fig. 1.4b. 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, SHR can dramatically reduce energy consumption. When designing the thermal process based on SHR, the enthalpy of inlet and outlet streams to the system must be equal. In this case, the enthalpy of stream 1 and 7, stream 2 and 3 must be equal. Otherwise, the energy saving efficiency of SHR is reduced.

As well as a gas stream case, a thermal process based on SHR in vapor/liquid stream case can be developed as shown in Fig. 1.5. Figure 1.5a shows a thermal process for vapor/liquid streams with heat circulation based on SHR. 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 $T_{\rm b}$, 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 based on SHR, similar to the above gas stream

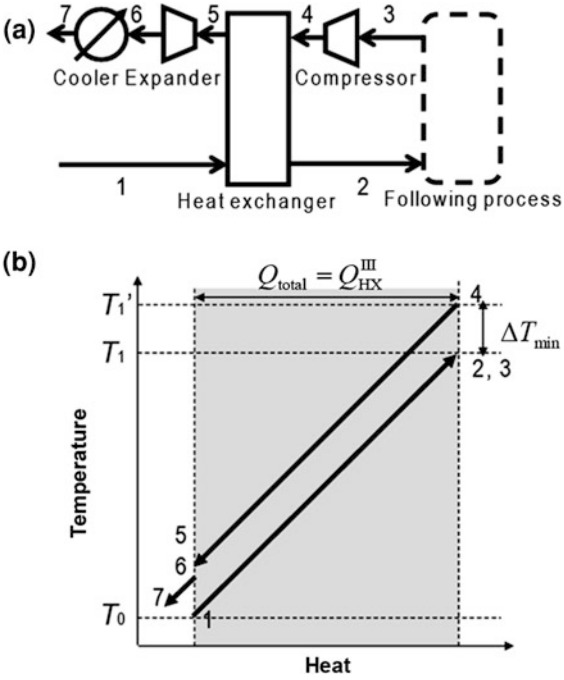
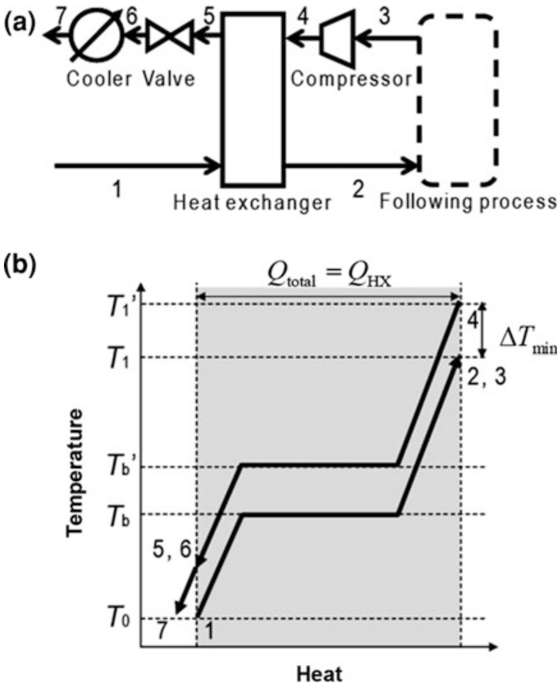


Fig. 1.4 Thermal process based on self-heat recuperation [III] (for the gas stream): **a** flow diagram, **b** temperature-heat diagram

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. 1.5b. 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 based on SHR, as 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. In SHR, the hot stream line of heat exchange is shifted vertically by using the adiabatic compression for the hot stream. The shaft work of the compression is required to circulate the internal heat in the process and exhausted with the process stream. If the heat capacity is independent from the pressure, the hot and cold stream lines are almost in parallel and are always separated by the minimum temperature difference. As a result, the energy required by the heat circulation module is reduced to 1/22–1/2 of the original by the feed-effluent heat exchange system in gas streams and/or vapor/liquid streams.

Fig. 1.5 Thermal process based on self-heat recuperation (for the vapor/liquid phase change stream): **a** flow diagram, **b** temperature-heat diagram



1.2.2 Design Methodology for Separation Process

Expanding the design methodology of the thermal process based on SHR to separation processes (Kansha et al. 2010a, b), 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. 1.6. To simplify the process for explanation, Fig. 1.6 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 based on SHR. As a result, the heat of the process stream (self heat) is perfectly circulated without the addition of heat in each module, resulting in perfect internal heat circulation over the entire separation process.

To understand this design methodology clearly, a binary distillation process is used as an example of separation process for single feed dual effluents. By following the above-mentioned design methodology, 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 both two sections are designed based on SHR. In the

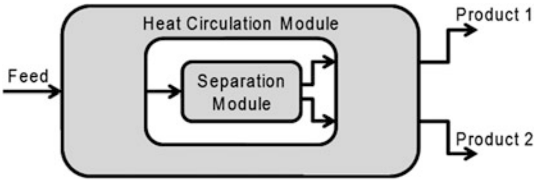


Fig. 1.6 Conceptual figure of separation processes based on self-heat recuperation

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 balance 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. The vapor stream from the distillation section is compressed by a compressor. The preheating duty is supplied to the feed of the distillation system by the effluents of the distillation section via self-heat exchange. This preheating section is referred to as a heat circulation module for single feed and dual effluent streams. In the distillation section, the distillate is extracted as vapor from the distillation column and compressed by a compressor. The reboiler duty is supplied to the bottoms by the distillate via heat exchange. This distillation section is called a distillation module.

Figure 1.7a shows the structure of a distillation process based on SHR. This process consists of two standardized modules, the heat circulation module and the distillation module. Note that, the summation of the enthalpy of the feed streams and that of the effluent streams are equal in each module. The feed stream in this integrated process module is represented as stream 1. This stream is heated to its boiling point by the two streams recuperating heat of 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 (5→6). 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 bottom (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. Furthermore, q value of column feed stream 2 ($q = \{\text{heat needed to vaporize one mole of feed}\}/\{\text{molar latent heat of feed}\}$) strictly depends on flow rate of distillate vapor and bottoms because of the enthalpy balance of distillation module.