Thermodynamic Mechanism of Self-Heat Recuperative Heat Circulation of Vapour System

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Self-Heat Recuperation Technology has recently been proved to be an effective method to cut the huge energy consumption in the chemical industry. In the present paper, the thermodynamic mechanism of the self-heat recuperative heat circulation of the vapour system without chemical reaction is studied in terms of exergy analysis using process module, temperature-entropy and energy conversion diagrams. The self-heat recuperative thermal vapour cycle process was modularized by combining four types of thermodynamic elementary process modules, namely isobaric heating and cooling process modules (heat receiver (HR) and heat transmitter (HT)) and isentropic compression and expansion process modules (work receiver (WR) and work transmitter (WT)), and a heat exchange process module (heat exchanger (HX)). In the four types of thermodynamic elementary process modules (HR, HT, WR, WT), both exergy and anergy are conserved. It is only in the heat exchange process module (HX) that exergy destruction takes place and the destructed exergy transforms into the same amount of anergy due to irreversibility of heat transfer. In the self-heat exchange process, the process fluid undergoes temperature change and phase transition. Therefore, the self-heat exchange process should be divided into three stages, namely the self-heat exchange of the liquid sensible heat, the self-heat exchange of the latent heat, the self-heat exchange of the vapour sensible heat. Correspondingly three HXs are necessary, and only in these three HXs do all the exergy destructions of the self-heat recuperative thermal vapour cycle process take place. The work provided as the minimum work required for the self-heat recuperative heat circulation of the vapour system by compressing the process fluid in the vapour phase through one WR, i.e. work input, equals the sum of the exergy required to compensate for the three exergy destructions of the three HXs and the exergy required to discard waste heat to the environment. The work input eventually converts to the waste heat, i.e. heat output, the exergy of which is the exergy required to discard the waste heat to the environment and the anergy of which results from the three exergy destructions of the three HXs.

1. Introduction

In the chemical industry, vapour generation accompanies various production processes, such as drying, desalination and distillation. Owning to high latent heat of vaporization and relatively low energy utilization efficiency of production systems, vapour generation consumes considerable energy. The conventional self-heat recovery thermal process uses an external heat source to raise the process fluid temperature and then recovers the sensible heat of the process fluid based on Pinch Technology. Its main problem is that the latent heat cannot be recovered due to the unchangeable boiling point (T_b) before and after heat provision. As a result, vast energy is required to compensate for the discarded unrecoverable latent heat.

During the last decade, Self-Heat Recuperation Technology (SHRT) was proposed as an innovative energy-saving technology, and the self-heat recuperative thermal process showed superior energy-saving performance compared to the conventional self-heat recovery thermal process (Kansha et al., 2009). In the former process, a relatively small amount of compression work is provided to the compressible process fluid (gas and/or vapour) to raise its temperature through a compressor, and then its self-heat is recuperated through heat exchangers. Particularly in the vapour process fluid's case, because the boiling point (T_b) is raised after vapour compression, the latent heat can be recuperated as well. The characteristic of SHRT is that all the self-heat of the compressible

process fluid, i.e. not only the sensible heat but also the latent heat, can be perfectly circulated within the system by providing just a relatively small amount of compression work instead of a large amount of heat. So far, SHRT has been applied to various thermal processes, such as cryogenic air separation (Fu et al., 2016), biodiesel production (Fu et al., 2015), biomass drying (Liu et al., 2015), pressure swing CO_2 adsorption (Song et al., 2015), methanol synthesis (Kansha et al., 2014), thermal seawater desalination (Mizuno et al., 2013) and crude oil distillation (Kansha et al., 2012). Their simulation results showed that the energy consumption of the self-heat recuperative thermal process can be drastically cut to 1/3-1/20 of that of the self-heat recovery thermal process. However, these researches are application-oriented, and have not sufficiently elucidated the thermodynamic mechanism of SHRT yet.

Generally, the compressible process fluid of SHRT can be categorized into two groups: gas and vapour. Tsutsumi and Kansha (2017) studied the thermodynamic mechanisms of the self-heat recuperative and the self-heat recovery heat circulations in the gaseous process fluid's case. They concluded that part of the work provided as the minimum work required for the self-heat recuperative heat circulation of the gas system is used as the exergy required to compensate for the exergy destruction of the heat exchanger and transforms into the same amount of anergy of waste heat due to irreversibility of heat transfer, and the remaining provided work is used as the exergy required to discard the waste heat to the environment. On the other hand, for the self-heat recovery heat circulation of the gas system, where heat is provided instead of work, additional exergy is required to discard additional waste heat, arising from a larger amount of energy input, to the environment. In contrast, the theoretical foundation of the self-heat recuperative heat circulation in the vapour process fluid's case was not discussed in their paper, and thus needs exploring. The present paper aims to explicate the thermodynamic mechanism of the self-heat recuperative heat circulation of the vapour system without chemical reaction in terms of exergy analysis using process module, temperature-entropy and energy conversion diagrams. The modularization of the self-heat recuperative thermal vapour cycle process was performed. The essence of the energy conversion from work input to heat output was illustrated.

2. Modularization of vapour cycle process

2.1 Basic concepts on modularization of vapour cycle process

To clarify the thermodynamic mechanism of the self-heat recuperative heat circulation, this section briefly cites the basic concepts proposed by Tsutsumi and Kansha (2017) on the modularization of a gas and/or vapour cycle process without chemical reaction. Detailed explanations can be found in their original paper.

A material and/or energy production process is usually a continuous process which starts and ends under environmental conditions and in which process materials exchange heat and/or work with heat and/or work provision system(s) and/or heat and/or work removal system(s). A continuous gas and/or vapour cycle process without chemical reaction can be decomposed into four types of thermodynamic elementary process modules, namely isobaric heating and cooling process modules (heat receiver (HR) and heat transmitter (HT)) and isentropic compression and expansion process modules (work receiver (WR) and work transmitter (WT)), and a heat exchange process module (heat exchanger (HX)). In such a gas and/or vapour cycle process, energy input equals energy output on the premise of no heat or mass leakage.

Energy consists of exergy and anergy. The exergy (*Ex*) is the part of energy that theoretically can be extracted in the form of work. The anergy (*An*) is the part of energy that theoretically cannot be extracted in the form of work. In a temperature (*T*)-entropy (*S*) diagram, heat (*Q*) can be calculated by Eq(1).

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

Anergy (*An*) of heat (*Q*) can be calculated by Eq(2).

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

where T_0 stands for environmental temperature, say, 25 °C.
Hence, heat (*Q*) can be expressed as Eq(3).

$$Q(Ex, An) = Q\big(Q - T_0 * (S_2 - S_1), T_0 * (S_2 - S_1)\big) \tag{3}$$

In the four types of thermodynamic elementary process modules (HR, HT, WR, WT), both exergy and anergy are conserved. It is only in the heat exchange process module (HX) that exergy destruction takes place and the destructed exergy transforms into the same amount of anergy due to irreversibility of heat transfer. Exergy destruction (*Ex*loss) can be calculated by Eq(4).

$$Ex_{\text{loss}} = T_0 * S_{\text{gen}} = T_0 * (\Delta S_{\text{cold}} + \Delta S_{\text{hot}}) \tag{4}$$

where S_{gen} calculated by $\Delta S_{cold}+\Delta S_{hot}$ stands for entropy generation of heat exchange, ΔS_{cold} (positive number) and ΔS_{hot} (negative number) stand for entropy changes of cold feed and hot effluent of heat exchange.

2.2 Self-heat exchange process module in vapour process fluid's case

In the gas cycle process discussed by Tsutsumi and Kansha (2017), the process fluid remains in the gaseous phase constantly without undergoing phase transition, and one HX is enough for the self-heat exchange process. While in the vapour cycle process discussed in the present paper, the process fluid undergoes temperature change and phase transition; therefore the self-heat exchange process should be divided into three stages, namely the self-heat exchange of the liquid sensible heat, the self-heat exchange of the latent heat, the self-heat exchange of the vapour sensible heat, and correspondingly three HXs are necessary. In other words, the self-heat exchange process module in the vapour process fluid's case can be viewed as the extension of that in the gaseous process fluid's case proposed by Tsutsumi and Kansha (2017) from the single-phase process fluid and single-stage heat exchange process to double-phase and triple-stage, and hence two more HXs are needed.

Figure 1, 2 show the process module diagram and the temperature (T)-entropy (S) diagram of the self-heat exchange process module in the vapour process fluid's case, respectively. In Figure 1, 2, the blue line stands for the feed of self-heat exchange at lower temperature and pressure, and the red line stands for the effluent of that at higher temperature and pressure; $Q_{in1}(Ex_1,An_1)$ and Q_{out1}, $Q_{in2}(Ex_2,An_2)$ and Q_{out2}, $Q_{in3}(Ex_3,An_3)$ and Q_{out3} stand for the heat inputs and heat outputs of HX_1, HX_2, HX_3, which correspond to the three stages of the self-heat exchange process. The purple, orange, brown lines in Figure 1 stand for the energy flows corresponding to the three stages of the self-heat exchange process. The purple, orange, brown areas in Figure 2 stand for exergy destruction Ex_{loss1}, Ex_{loss2}, Ex_{loss3} of HX_1, HX_2, HX_3. The energy conversion from heat $Q_{in1}+Q_{in2}+Q_{in3}$ to heat $Q_{out1}+Q_{out2}+Q_{out3}$ through HX_1, HX_2, HX_3 was formulated as Eq(5).

$$\sum_{i=1}^{3} Q_{\text{in}i}\left(\sum_{i=1}^{3} Ex_i, \sum_{i=1}^{3} An_i\right) \rhd \sum_{i=1}^{3} Q_{\text{out}i}\left(\sum_{i=1}^{3}\left(Ex_i - T_0 * S_{\text{gen}i}\right), \sum_{i=1}^{3}\left(An_i + T_0 * S_{\text{gen}i}\right)\right) \tag{5}$$
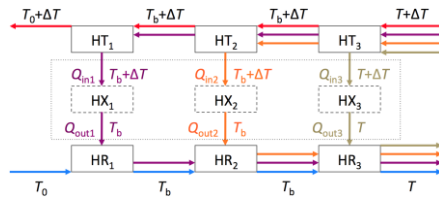

Figure 1: Process module diagram of self-heat exchange process module in vapour process fluid's case
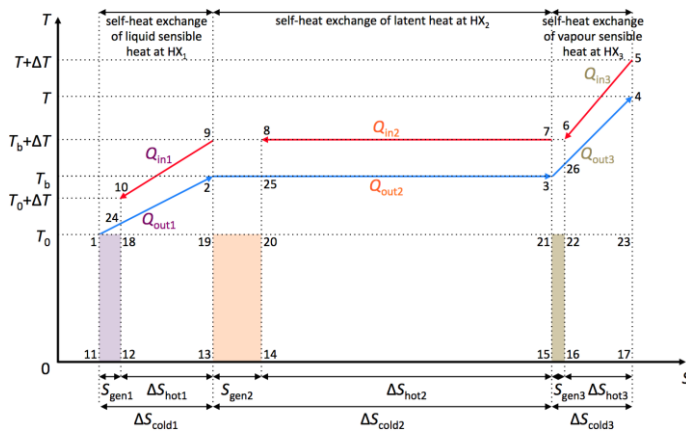

Figure 2: Temperature-entropy diagram of self-heat exchange process module in vapour process fluid's case

3. Thermodynamic mechanism of self-heat recuperative heat circulation of vapour system

Figure 3, 4, 5 show the process module diagram, the temperature (T)-entropy (S) diagram, the energy conversion diagram and the simplified energy conversion diagram of the self-heat recuperative thermal vapour cycle process, respectively. In Figure 3, SHR and SHT are the abbreviations of self-heat receiver and self-heat

transmitter; HX_1, HX_2, HX_3, where exergy destruction Ex_{loss1}, Ex_{loss2}, Ex_{loss3} take place, are depicted by the dashed lines; incidentally, WT is optional and not taken into consideration temporarily, and will be explained afterwards in Section 3.5. In Figure 4, the areas enclosed by the green dashed lines stand for the exergies (Exs) and anergies (Ans) of heat Q_1, Q_2, Q_3, Q_4, Q_5, Q_6, Q_{out}. In Figure 5, the black solid lines stand for the energy conversions belonging to one of the four types of thermodynamic elementary process modules (HR, HT, WR, WT), where no exergy destruction takes place; the black dashed lines stand for the energy conversions belonging to the heat exchange process module (HX), where exergy destruction takes place.

The thermodynamic mechanism can be explained by combining Figure 3, 4, 5 as follows.

3.1 Self-heat exchange of liquid sensible heat

The feed is heated from the subcooled liquid state (at environmental temperature T_0) to the saturated liquid state (at boiling point T_b) without undergoing phase transition. Heat $Q_1(Ex_1,An_1)$ (represented by area 1-2-13-11 in Figure 4) is recuperated by first providing compression work $W_{in}(Ex_{Win},0)$ (represented by area 4-5-29-30-26-27-28) to the superheated vapour to raise the saturated liquid temperature from T_b to $T_b+\Delta T_1$ through WR and then transferring heat $Q_4(Ex_4,An_4)$ (represented by area 9-10-12-13) from SHT_1 to SHR_1 through HX_1. In HX_1, where heat Q_4 (at $T_b+\Delta T_1$) converts to heat Q_1 (at T_b), exergy destruction $Ex_{loss1}(=T_0{}^*S_{gen1})$ takes place, and the destructed exergy transforms into the same amount of anergy $An_1'(=An_1-An_4)$ (represented by purple area 1-18-12-11). The energy conversion from heat Q_4 to heat Q_1 through HX_1 was formulated as Eq(6).

$$Q_4(Ex_4, An_4) \rhd Q_1\left(Ex_4 - T_0 * S_{gen1}, An_4 + T_0 * S_{gen1}\right) \equiv Q_1(Ex_1, An_1) \tag{6}$$

3.2 Self-heat exchange of latent heat

The feed is heated from the saturated liquid state (at boiling point T_b) to the saturated vapour state (at boiling point T_b) with undergoing phase transition. Heat $Q_2(Ex_2,An_2)$ (represented by area 2-3-15-13 in Figure 4) is recuperated by first providing compression work $W_{in}(Ex_{Win},0)$ (represented by area 4-5-29-30-26-27-28) to the superheated vapour to raise the saturated vapour temperature from T_b to $T_b+\Delta T_1$ through WR and then transferring heat $Q_5(Ex_5,An_5)$ (represented by area 7-8-14-15) from SHT_2 to SHR_2 through HX_2. In HX_2, where heat Q_5 (at $T_b+\Delta T_1$) converts to heat Q_2 (at T_b), exergy destruction $Ex_{loss2}(=T_0{}^*S_{gen2})$ takes place, and the destructed exergy transforms into the same amount of anergy $An_2'(=An_2-An_5)$ (represented by orange area 19-20-14-13). The energy conversion from heat Q_5 to heat Q_2 through HX_2 was formulated as Eq(7).

$$Q_5(Ex_5, An_5) \rhd Q_2\left(Ex_5 - T_0 * S_{gen2}, An_5 + T_0 * S_{gen2}\right) \equiv Q_2(Ex_2, An_2) \tag{7}$$

3.3 Self-heat exchange of vapour sensible heat

The feed is heated from the saturated vapour state (at boiling point T_b) to the superheated vapour state (at high temperature T) without undergoing phase transition. Heat $Q_3(Ex_3,An_3)$ (represented by area 3-4-17-15 in Figure 4) is recuperated by first providing compression work $W_{in}(Ex_{Win},0)$ (represented by area 4-5-29-30-26-27-28) to the superheated vapour to raise the superheated vapour temperature from T to $T+\Delta T_1$ through WR and then transferring heat $Q_6(Ex_6,An_6)$ (represented by area 5-6-16-17) from SHT_3 to SHR_3 through HX_3. In HX_3, where heat Q_6 (at $T+\Delta T_1$) converts to heat Q_3 (at T), exergy destruction $Ex_{loss3}(=T_0{}^*S_{gen3})$ takes place, and the destructed exergy transforms into the same amount of anergy $An_3'(=An_3-An_6)$ (represented by brown area 21-22-16-15). The energy conversion from heat Q_6 to heat Q_3 through HX_3 was formulated as Eq(8).

$$Q_6(Ex_6, An_6) \rhd Q_3\left(Ex_6 - T_0 * S_{gen3}, An_6 + T_0 * S_{gen3}\right) \equiv Q_3(Ex_3, An_3) \tag{8}$$

3.4 Energy conversion from work input to heat output

Compression work $W_{in}(Ex_{Win},0)$ (represented by area 4-5-29-30-26-27-28 in Figure 4) provided to the superheated vapour as the minimum work required for the self-heat recuperative heat circulation of the vapour system through WR, i.e. work input, equals the sum of the exergy required to compensate for exergy destruction Ex_{loss1}, Ex_{loss2}, Ex_{loss3} of HX_1, HX_2, HX_3 and the exergy required to discard waste heat $Q_{out}(Ex_{Qout},An_{Qout})$ (represented by area 34-26-31-32) to the environment. The work input eventually converts to the waste heat, i.e. heat output, exergy Ex_{Qout} (represented by area 33-26-34) of which is the exergy required to discard the waste heat to the environment and anergy An_{Qout} (represented by area 33-26-31-32) of which results from the three exergy destructions of the three HXs. The energy conversion from work input W_{in} to heat output Q_{out} was formulated as Eq(9).

$$W_{in}(Ex_{Win}, 0) \rhd Q_{out}\left(Ex_{Qout}, An_{Qout}\right) \equiv Q_{out}\left(Ex_{Qout}, T_0 * \left(S_{gen1} + S_{gen2} + S_{gen3}\right)\right) \tag{9}$$
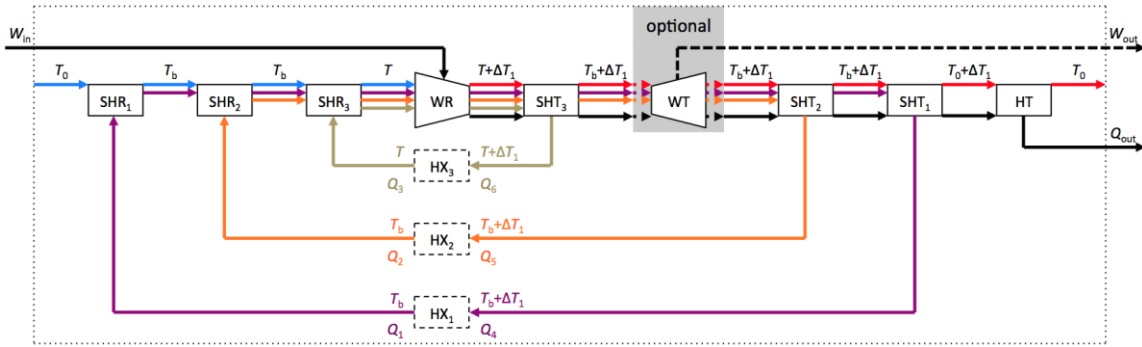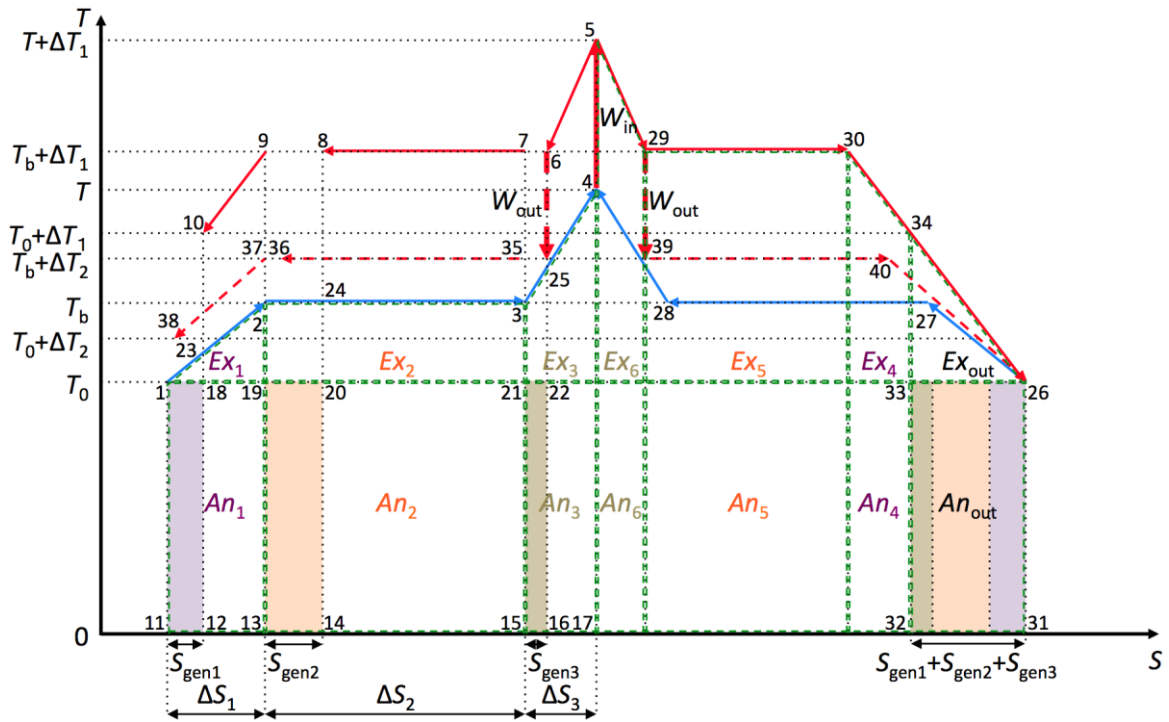
Figure 3: Process module diagram
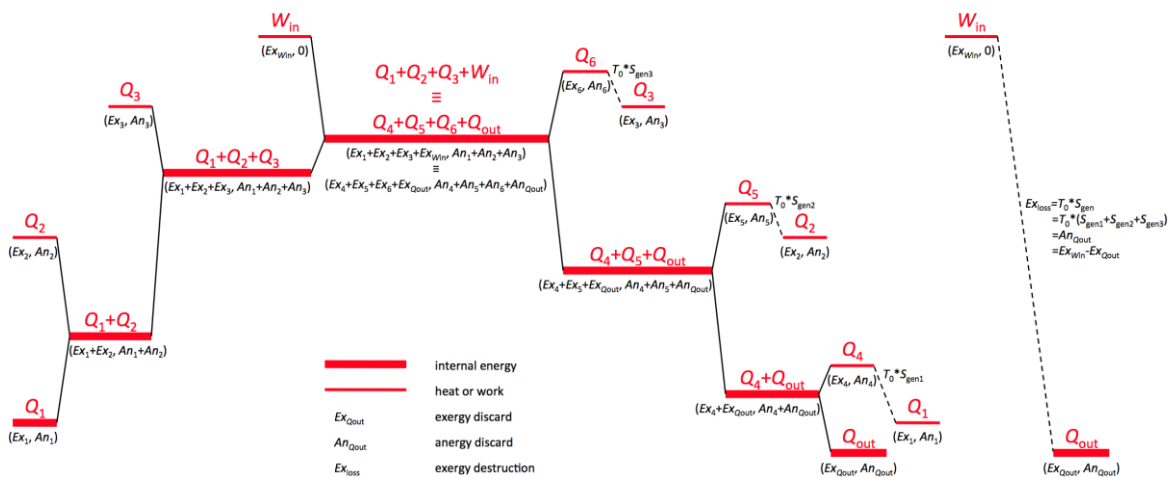

Figure 4: Temperature-entropy diagram

Figure 5: Energy conversion diagram (left) and simplified energy conversion diagram (right)

3.5 Energy-saving performance

In Figure 4, the energy consumptions of the vapour generations from environmental temperature T_0 to high temperature T using an external heat source without recovering self-heat (by providing heat) and using SHRT (by providing work) can be represented by area 26-27-28-4-17-31 and 4-5-29-30-26-27-28, respectively. The latter area is far smaller than the former one, indicating the outstanding energy-saving performance of SHRT. Given that in chemical production processes the typical Overall Heat Transfer Coefficient corresponding to the stage of the self-heat exchange of the vapour sensible heat is two orders of magnitude smaller than those corresponding to the other two stages (Engineering ToolBox, 2003), the minimum temperature difference of heat exchange corresponding to this stage is usually set far larger than those corresponding to the other two stages. Thus, WT can be utilized, as shown in Figure 3, to reduce the temperature differences of the self-heat exchanges of the other two stages and simultaneously recover part of compression work $W_{in}(Ex_{Win},0)$ (represented by area 4-5-29-30-26-27-28 in Figure 4) from the effluent in the vapour phase. In Figure 4, the red dashed lines stand for the effluent of the time when WT is utilized, and recovered work $W_{out}(Ex_{Wout},0)$ can be represented by area 29-30-26-40-39. Consequently, the energy consumption of the vapour generation can be further cut to some extent using SHRT with work recovery and represented by area 4-5-29-39-40-26-27-28. The energy conversion from network input $W_{in,net}(=W_{in}-W_{out})$ to heat output Q_{out}' was formulated as Eq(10).

$$W_{in,net}(Ex_{Win} - Ex_{Wout}, 0) \rhd Q_{out}'(Ex_{Qout}', An_{Qout}') \equiv Q_{out}'\left(Ex_{Qout}', T_0 * \left(S_{gen1}' + S_{gen2}' + S_{gen3}'\right)\right) \qquad (10)$$

4. Conclusions

The thermodynamic mechanism of the self-heat recuperative heat circulation of the vapour system without chemical reaction was studied in terms of exergy analysis using process module, temperature-entropy and energy conversion diagrams. The self-heat exchange process should be divided into three stages, and therefore three HXs are necessary correspondingly, and only in these three HXs do all the exergy destructions of the self-heat recuperative thermal vapour cycle process take place. The work provided as the minimum work required for the self-heat recuperative heat circulation of the vapour system by compressing the process fluid in the vapour phase through one WR, i.e. work input, equals the sum of the exergy required to compensate for the three exergy destructions of the three HXs and the exergy required to discard waste heat to the environment. The work input eventually converts to the waste heat, i.e. heat output, the exergy of which is the exergy required to discard the waste heat to the environment and the anergy of which results from the three exergy destructions of the three HXs.

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