



A novel method based on entransy theory for setting energy targets of heat exchanger network☆



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ABSTRACT

A T-Q diagram based on entransy theory is applied to graphically and quantitatively describe the irreversibility of the heat transfer processes. The hot and cold composite curves can be obtained in the T-Q diagram. The entransy recovery and entransy dissipation that are affected by temperature differences can be obtained through the shaded area under the composite curves. The method for setting the energy target of the HENs in T-Q diagram based on entransy theory is proposed. A case study of the diesel oil hydrogenation unit is used to illustrate the application of the method. The results show that three different heat transfer temperature differences is 10 K, 15 K and 20 K, and the entransy recovery is $5.498 \times 10^7 \text{ kW} \cdot \text{K}$, $5.377 \times 10^7 \text{ kW} \cdot \text{K}$, $5.257 \times 10^7 \text{ kW} \cdot \text{K}$, respectively. And the entransy transfer efficiency is 92.29%, 91.63%, 90.99%. Thus, the energy-saving potential of the HENs is obtained by setting the energy target based on the entransy transfer efficiency.

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1. Introduction

Energy is the driving force for economic growth and sustainable development of a country. Simultaneously, a series of environmental and health problems have been caused by energy production and consumption. Currently China has become the first energy producer and the second largest energy consumer in the world. With the rapid economic development and improved standards of living, energy demand in China is continually rising and resource constraints are becoming more seriously [1].

Heat exchanger networks are widely used in oil refining, chemical, metallurgy, pharmaceutical and other large industrial enterprises. Its significance can be attributed to its role in reducing energy consumption and increasing energy utilization ratio [2]. Nowadays, three kinds of heat exchanger network synthesis methods have been established: the pinch design method (PDM), the mathematical programming approach, and the artificial intelligence approach. PDM is the most mature and successful method in the heat exchange network design. Besides, PDM is applied to analyze the distribution of energy flow along the temperature gradient in the heat transfer process. The maximum energy recovery (MER) network can be obtained by PDM, but the heat transfer efficiency cannot be calculated. With the heat recovery processes becoming more complex, the PDM has some shortcomings. For example, the operating and investment costs are not considered in this method.

Heat transfer was widely thought to originate in 19th century, which had gradually matured in theory and engineering application [3]. The various quantity methods have been used to describe the heat transfer rate, but there is no concept of efficiency for transfer processes. Guo *et al.* [4] introduced a new physical quantity, entransy, based on the analogy between heat and electrical conduction. The entransy of an object describes its heat transfer ability and “thermal potential energy”. The concept of entransy dissipation was introduced to analyze an irreversible heating transfer process. Moreover, Chen *et al.* [5,6] derived the extremum principle of entransy dissipation to optimize the processes of the heat conduction. This attracts many scholars to carry out a series of in-depth related research in various directions, such as heat conduction [7–9], heat convection [10], the optimal design of heat exchangers [11,12], mass transfer [13,14], heat radiation [15–17], and multiple transfer process [18].

In order to analyze the performance of heat transfer processes, Chen *et al.* [19] introduced a two-dimension property diagram, temperature-heat flow diagram (T-q' diagram). The area between the process curves of the hot and cold streams represented the total entransy dissipation rate in the whole heat exchanger. The diagram can be used to analyze the irreversibility of heat transfer processes. Wu *et al.* [20] compared the entransy dissipation rates of three simple chemical processes in the temperature-heat flow rate diagram (T-Q' diagram). This approach was applied to evaluate the performance of self-heat recuperation technology (SHRT).

The theoretical basis for simplifying the complex chemical process was only provided in the previous work, but was not applied to the optimal design of HENs [29].

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This article will propose an energy target approach of HENs based on the concept of entransy and entransy dissipation. In comparison with the PDM, the entransy method of HENs has some obvious advantages, such as accurate calculation of entransy transfer efficiency, minimizing the entransy dissipation and maximizing the entransy recovery. A real case study is used to show the application of the novel method. Thus, the energy-saving potential of the HENs can be obtained based on the entransy transfer efficiency analysis.

2. Model and Theoretical Analysis

2.1. Model of a two-stream heat transfer process with entransy theory

Guo *et al.* [4] proposed a new physical quantity, entransy, which correspond to electrical potential energy in a capacitor based on the analogy between electrical and thermal systems. The entransy of an object is,

$$E_{vh} = \frac{1}{2} Q_{vh} U_h = \frac{1}{2} Q_{vh} T = \frac{1}{2} m c_v T \quad (1)$$

where Q_{vh} is thermal capacity of an object with constant volume, c_v is specific heat capacity at constant volume, U_h or T represents the thermal potential.

For a two-stream heat exchanger, which is operated in steady state, when the temperature drop of the stream is dT , heat flow generating is dQ , and the output entransy is [21]:

$$dE_{vh} = T dQ_{vh} \quad (2)$$

It is assumed that there is no heat exchanging with environment, the change of kinetic and potential energy, the effects of conduction and mixing in the direction of stream can be ignored [22]. The heat capacities and heat transfer coefficients are defined as constant.

With these assumptions, specific heat capacity at constant volume and specific heat capacity at constant pressure are approximately equal, which can be written as

$$c_v \approx c_p \quad (3)$$

The heat transfer between the hot and cold streams is

$$dQ_{vh} = -m_h c_{p,h} dT_h = m_c c_{p,c} dT_c \quad (4)$$

where m is the mass flow, the subscript h refers to the hot stream, and the subscript c refers to the cold stream.

The entransy change between the hot and cold streams is

$$dE_h = -T_h dQ, dE_c = T_c dQ \quad (5)$$

The entransy balance equation of hot and cold streams in heat transfer can be defined as.

$$E_{h,in} + \int_0^{Q_t} -T_h dQ = E_{h,out} \quad (6a)$$

$$E_{c,in} + \int_0^{Q_t} T_c dQ = E_{c,out} \quad (6b)$$

where the subscripts in and out denote the inlet and outlet states, respectively.

The entransy dissipation in the whole heat exchange network can be obtained by summing Eqs. (6a) and (6b)

$$\begin{aligned} \Delta E = E_{in} - E_{out} &= \left(\frac{1}{2} m_h c_{p,h} T_{h,in}^2 + \frac{1}{2} m_c c_{p,c} T_{c,in}^2 \right) - \left(\frac{1}{2} m_h c_{p,h} T_{h,out}^2 + \frac{1}{2} m_c c_{p,c} T_{c,out}^2 \right) \\ &= \int_0^{Q_t} (T_h - T_c) dQ \end{aligned} \quad (7)$$

In Eq. (7), we can see that entransy is not completely conserved due to dissipation, which means the entransy dissipation is a measurement of the irreversibility of heat transfer processes. If the quantity of entransy that the hot streams release is absorbed by the cold streams, the entransy dissipation is reduced. So the effective energy utilization is achieved.

The entransy transfer efficiency can be used to evaluate the heat transfer performance of HENs, expressed as.

$$\eta = \frac{\text{output entransy flux}}{\text{input entransy flux}} = \frac{E_c}{E_h} \quad (8)$$

where E_h , E_c represent the quantity of entransy that the hot streams release and the cold streams absorb, respectively. The more entransy that cold streams absorb and the less entransy that hot streams dissipate, the higher entransy transfer efficiency can be obtained.

2.2. Available entransy and the physical meaning of T-Q diagram

Entransy possesses both the nature of “energy” and the heat transfer ability. The temperature represents the potential of the heat because the heat differs at different temperatures. Hence the entransy of hot streams, which means “potential energy” of heat, can be used effectively by cold streams.

When two objects at different temperatures are in thermal contact, the total quantity of “potential energy” of heat can be transferred, which represent the entransy transfer associated with the heat transfer. Guo *et al.* [23] considered the entransy as the heat transport potential capacity in an earlier paper. Cheng *et al.* [24] found that entransy changes in heat transfer process of an isolated system and a closed system. This principle was called entransy decrease, based on the first and second laws of thermodynamics. That can be written as $dG \leq 0$ (the equal sign is tenable for an ideal heat transfer process, while the sign of “less than” is tenable for natural heat transfer process), which can be described as the irreversibility of heat transfer process due to entransy loss or heat transfer ability.

The volume changes are not usually considered in heat transfer. As T is a state quantity and δQ is a process quantity, entransy $T \cdot \delta Q$ is obviously a process quantity. Hu *et al.* [25] derived that the entransy flow of a system, which was called the system entransy G , corresponded to a state quantity in a reversible process with constant volume.

Based on the first law of thermodynamics, the energy balance equation can be expressed as.

$$(T \delta Q)_{\text{rev}} = T dU + T \delta W \quad (9)$$

Eq. (9) points out that in entransy transfer, a portion of the entransy flow will be converted into work entransy, $T \cdot \delta W$, which makes no contribution to the heating or cooling of an object. $T \cdot dU$ is the available portion of the entransy flow, which is called the available entransy.

As mentioned above, the heat transfer process of streams can be shown in the T - Q diagram. It is clear that the heat transfer capability should be enhanced in the HENs. The available entransy, which makes contribution to the heating or cooling streams, needs to be maximized. Thus, the heat transfer performance is improved, and the effective utilization of energy is realized.

3. Novel Method to Setting the Energy Targets

The tasks of HENs synthesis are minimizing capital and operating costs, achieving the initial temperature to the target temperature. The feed, which starts cold and needs to be heated up, is called as a cold stream; conversely which starts hot and needs to be cooled down, is called as a hot stream [26].

In the proposed method, the available entransy of the HENs can be maximized, which means the entransy of all hot streams can maximum

possible absorbed by the cold streams. Taking the temperature T and the heat flow rate Q as the horizontal and vertical coordinates, respectively, a T - Q diagram to express the heat flow processes of streams can be constructed, as shown in Fig. 1 [19]. The green shade area under the composite curve stands for the entransy flow when the stream temperature from T_{in} to T_{out} , as shown in Eq. (2), which means the available entransy of the system.

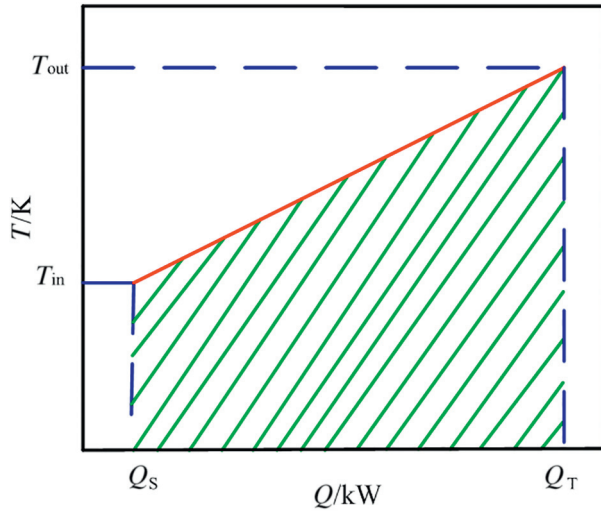


Fig. 1. The property diagram in heat transfer processes of streams.

During the heat transfer processes, the change of heat is equal to the enthalpy change of each stream. In Fig. 2, the T -axis is a continuous change and the Q -axis is a relative change. If process curve is shifted along the Q -axis, the change of temperature, heat and entransy will not affect the property of stream. Thus, to handle multiple streams, it is convenient to combine the lines of multiple streams into a single curve.

Fig. 2 shows a formation of the hot composite curve. It is formed by three hot streams, whose heat capacity flow rates are named as A, B, C. The enthalpy change can be calculated in a series of every interval temperatures. If there is only one line in an interval, the slope cannot be changed. If multiple lines exit in an interval, the temperature of vertical coordinates in this interval remains unchanged, the enthalpy change of horizontal coordinates added together, which means the vector sum of these lines in this interval can be got. Finally, the line segments are connected end-to-end to form a single curve, shown in Fig. 2(b).

Using the same method, the cold composite curve can be obtained. Therefore, the green shade area between the hot and cold streams in Fig. 3 is the total entransy dissipation, ΔE , as shown in Eq. (7). The

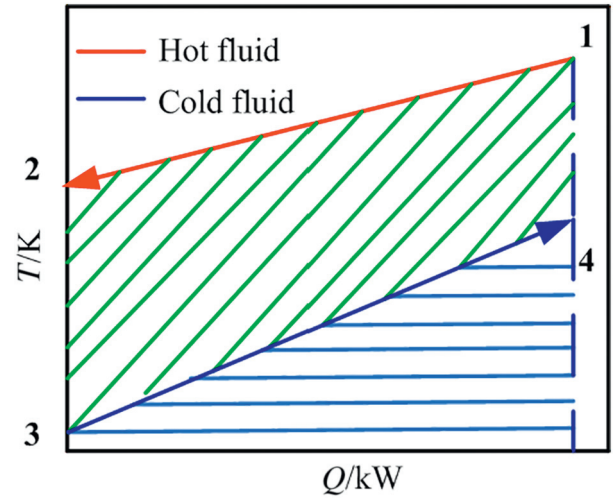


Fig. 3. The property diagram in heat transfer processes between hot and cold streams. Meanwhile, the amount of entransy dissipation and entransy recovery are shown in this diagram.

blue shaded area under the cold composite curve, which is identified as the entransy recovery of the system, indicates that the cold streams effectively utilize the entransy transferred from the hot streams.

For a heat exchanger network, in order to meet the actual industrial production needs, the quantity of entransy that the hot stream releases is not completely absorbed by the cold stream. The entransy required for the cold stream to be heated to the target temperature cannot be provided entirely by the hot stream. Generally we need additional hot and cold utilities in the system.

The maximum energy recovery and the minimum utility requirements can be achieved by the HENs synthesis method, which means that the entransy of all hot streams can possibly be absorbed in maximum by the cold streams. Meanwhile for the maximum entransy recovery, the minimum entransy dissipation and the minimum utility requirements are represented in the optimization of heat exchanger network, shown in Fig. 4.

For the design of heat exchangers, considering exchanger area, utility requirements and capital cost with minimum approach temperature ΔT_{min} changes. There is an optimum value for ΔT_{min} , which is usually 10–20 K.

In Fig. 4, the hot and cold composite curves are shifted on the Q -axis and close to each other. Until the two composite curves reach to the predetermined target position (ΔT_{min}) in a vertical direction, the lower right corner area indicates the minimum entransy of hot utility requirements ($E_{h,min}$), which means the cold streams can be entirely heated to target temperature. The lower left corner area indicates the minimum entransy of cold utility requirements ($E_{c,min}$), which means

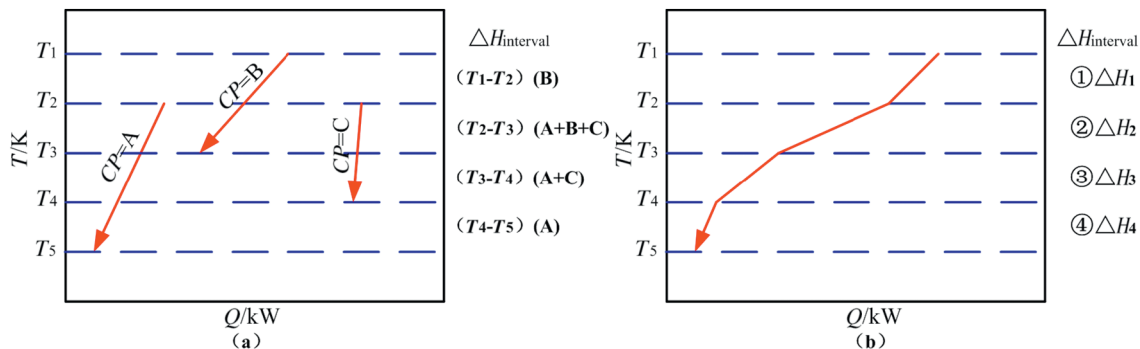


Fig. 2. Example of formation of the hot composite curve: (a) A T - Q diagram of three hot streams; (b) The process of forming a hot composite curve through three hot streams.

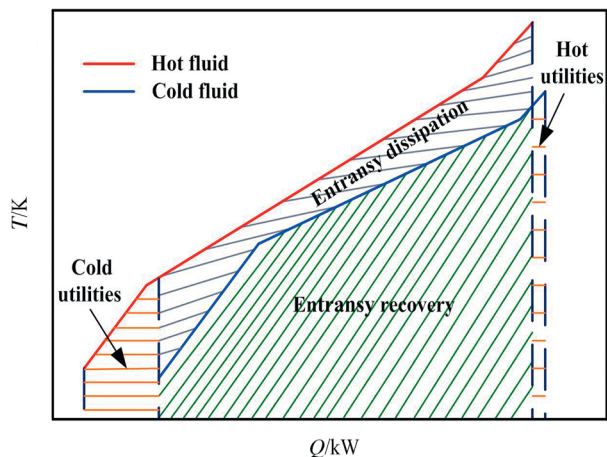


Fig. 4. The property diagram in heat transfer processes of all hot and cold streams in the HENs.

the hot streams can be entirely cooled to target temperature. And the overlapped area between the composite curves represents the maximum entransy recovery and the minimum entransy dissipation.

Entropy, which is another kind of physical quantity in thermodynamics, is a measure of the irreversibility of a process and the randomness of a system. The entropy theory is mainly applied to the heat-work conversion optimization in reversible process, but there is an “entropy paradox” [27]. That is with the increase of heat exchanger effectiveness, the entropy generation number is also increased. In addition, entropy cannot be used to describe energy quality. However, entransy is developed to describe heat transfer ability of a real system. The entransy dissipation number, which is introduced by the theory of entransy dissipation, can resolve entropy generation paradox. The entransy dissipation number can correctly describe the global performance of the heat exchangers with three different flow arrangements simultaneously [28]. Compared with the entropy analysis, the entransy analysis has obvious advantages.

4. Case Study

The diesel oil hydrogenation unit of one petrochemical company includes reaction, fractionation, acid gas desulfurization, and the design scale is 3.4 million tons per year. According to limits and measurement methods for emission from light-duty vehicles (China 5), part of the transformation of the unit is to meet the requirements of the production of diesel oil. To reduce the external hot utility usage, the optimization of heat exchanger network has a practical significance. The data of hot and cold streams are shown in Tables 1, 2. The process flow diagram of the

Table 1
The data of hot streams

	Flow	Initial temperature /K	Final temperature /K	CP /kW·K ⁻¹
1	Oil mixed with hydrogen	655.9	504.8	418.1
2	High pressure segregator gas	396.0	321.0	206.4
3	Thermal low pressure separator gas	505.0	307.0	1.5
4	Overhead recycle oil	418.5	303.1	30.7
5	Overhead recycle oil	428.7	319.2	17.2
6	Naphtha	320.0	310.8	1.9
7	Diesel oil	542.5	325.7	244.9
8	Lean amine	325.1	316.0	67.5
9	Lean amine	325.0	316.8	17.7
10	Acid gas	313.0	307.0	1.5

Table 2
The data of cold streams

	Flow	Initial temperature /K	Final temperature /K	CP /kW·K ⁻¹
1	Raw oil inlet	334.2	413.5	228.0
2	Mixed hydrogen	356.5	448.8	75.3
3	Oil mixed with hydrogen	423.4	618.9	401.3
4	Bottom oil	494.8	518.8	303.2
5	Fractionation column bottom oil	541.7	553.6	600.4
6	Steam	368.0	474.6	112.7
7	Steam	462.9	539.1	10.8

units is shown in Fig. 5 and the hot and cold streams are simultaneously represented (red represents hot stream and blue represents cold stream).

4.1. Before setting the energy target of diesel oil hydrogenation unit

According to Table 1, the hot and cold composite curves are shown in Fig. 6. As a result, the entransy of hot streams is 6.762×10^7 kW·K while the entransy of cold streams is 6.352×10^7 kW·K. There is no overlapped area between the composite curves, which means the quantity of entransy that the hot streams release is not absorbed by the cold streams. Hence, there are no entransy recovery, the minimum entransy dissipation is 1.311×10^8 kW·K.

4.2. After setting the energy target of diesel oil hydrogenation unit

It is assumed that the minimum approach temperature $\Delta T_{\min}$ is 10 K. The cold and hot stream composite curves are shown in Fig. 7.

As a result, the entransy of hot streams is 6.762×10^7 kW·K, the entransy of cold streams is 6.352×10^7 kW·K, the entransy of hot utility is 8.543×10^6 kW·K, the entransy of cold utility is 7.428×10^6 kW·K, so the entransy recovery is 5.498×10^7 kW·K, the entransy dissipation is 5.212×10^6 kW·K, and the entransy transfer efficiency is 92.29%.

Using the similar methods mentioned, one can obtain the optimization results of three different minimum approach temperatures: 10 K, 15 K, and 20 K. The results of comparing three different energy targets are listed in Table 3.

From the results of calculation, we can see that the quantity of entransy is influenced by the variation of temperature difference. Corresponding to the minimum temperature difference, $\Delta T_{\min}$ is given as 10 K, 15 K, and 20 K while the entransy recovery is 5.498×10^7 kW·K, 5.377×10^7 kW·K, and 5.257×10^7 kW·K, respectively. The entransy dissipation is 5.212×10^6 kW·K, 5.661×10^6 kW·K, and 6.093×10^6 kW·K. Therefore, the entransy transfer efficiency is 92.29%, 91.63%, and 90.99%. It is obvious that the larger the temperature difference, the more hot and cold the utility requirements, the less the entransy recovery, the more the entransy dissipation, and the lower the entransy transfer efficiency.

The heat transfer rate equation could be expressed as.

$$Q = UA\Delta T_{LM} \quad (10)$$

where A is the heat transfer area, U is heat transfer coefficient. ΔT_{LM} is the log mean temperature difference, which expression is

$$\Delta T_{LM} = \frac{\Delta T_h - \Delta T_c}{\ln(\Delta T_h / \Delta T_c)} = \frac{T_{h,in} - T_{c,out} - T_{h,out} + T_{c,in}}{\ln(T_{h,in} - T_{c,out} / T_{h,out} - T_{c,in})} \quad (11)$$

It is found that the heat exchanger area is inversely proportional to the temperature difference. For an actual heat exchanger, the lower values of $\Delta T_{\min}$ can lead to larger area and more capital cost. Therefore, in the design of heat exchanger network, we need a comprehensive

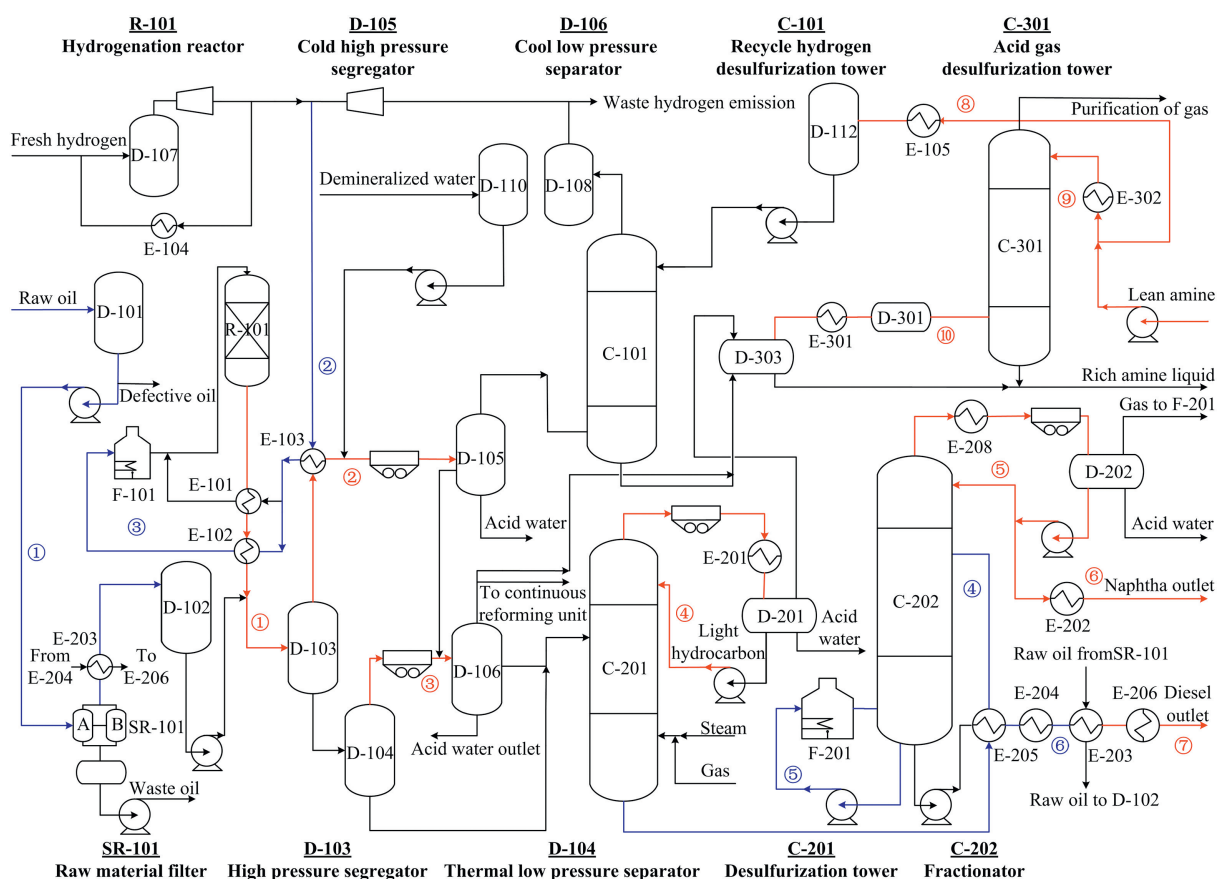


Fig. 5. The process flow diagram of diesel oil hydrogenation unit. In the diagram, red represents hot streams and blue represents cold streams.

consideration of operating and capital costs, heat exchanger surface area, process conditions, etc. Finally, the optimal minimum approach temperature, $\Delta T_{\min}$ and the effective energy utilization can be obtained.

5. Conclusions

This paper has presented a novel method based on entransy theory for setting energy targets of HENs in T - Q diagram. The hot and cold composite curves can be obtained in the T - Q diagram.

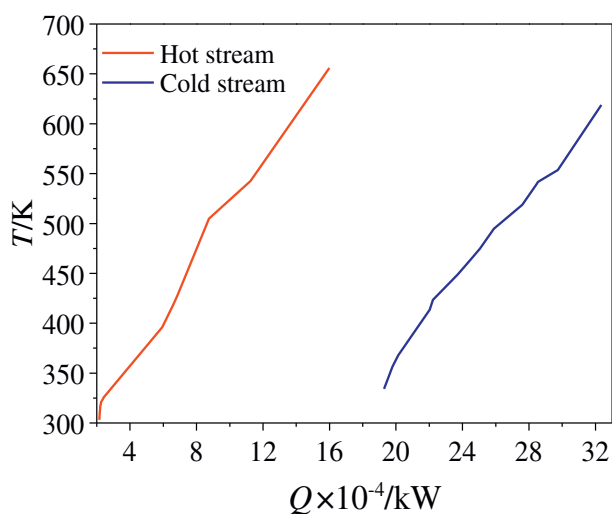


Fig. 6. The heat transfer property diagram of the diesel oil hydrogenation unit before setting the energy target.

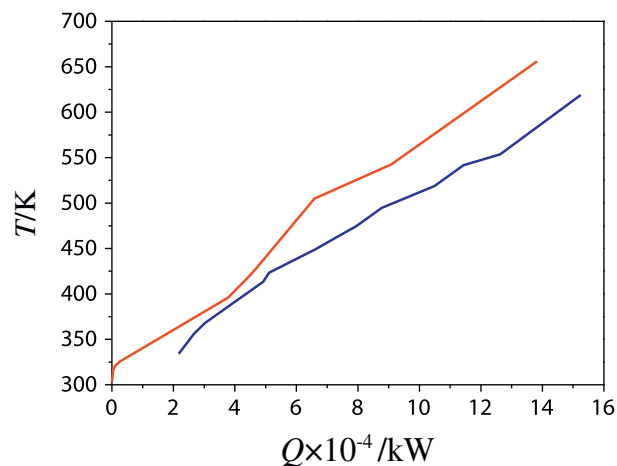


Fig. 7. The heat transfer property diagram of the diesel oil hydrogenation unit after setting the energy target.

Table 3

The results of setting different energy targets, $\Delta T_{\min} = 10$ K, 15 K, 20 K

The entransy of HEN	$\Delta T_{\min} = 10$ K	$\Delta T_{\min} = 15$ K	$\Delta T_{\min} = 20$ K
The entransy of hot streams/kW·K	6.762×10^7	6.762×10^7	6.762×10^7
The entransy of cold streams/kW·K	6.352×10^7	6.352×10^7	6.352×10^7
The entransy of hot utility/kW·K	8.543×10^6	9.751×10^6	1.095×10^7
The entransy of cold utility/kW·K	7.428×10^6	8.190×10^6	8.960×10^6
The entransy recovery/kW·K	5.498×10^7	5.377×10^7	5.257×10^7
The entransy dissipation/kW·K	5.212×10^6	5.661×10^6	6.093×10^6
The entransy transfer efficiency/%	92.29	91.63	90.99

Therefore, the shaded area between the hot and cold composite curves stood for the entransy dissipation. The effect of different temperature differences on entransy recovery was researched. It was found that the higher values of $\Delta T_{\min}$ can lead to more hot and cold utility requirements, the more entransy dissipation, the less entransy recovery and the lower entransy transfer efficiency. Steps to set the optimal energy target of heat exchange network in T - Q diagram based on entransy theory were determined.

The diesel oil hydrogenation unit of the industrial case study was shown in this paper. Comparing the three different temperature difference results, the optimal energy target was obtained. The entransy recovery was $5.498 \times 10^7 \text{ kW} \cdot \text{K}$, $5.377 \times 10^7 \text{ kW} \cdot \text{K}$, and $5.257 \times 10^7 \text{ kW} \cdot \text{K}$, and the entransy transfer efficiency was 92.29%, 91.63%, and 90.99% in 10 K, 15 K, and 20 K, respectively. The higher values of $\Delta T_{\min}$ can lead to less entransy recovery, and the entransy transfer efficiency was obviously reduced. Therefore, the entransy theory is more suitable for the analysis of HENs energy efficient use.

This method can be used as a criterion for the maximum entransy recovery of HENs. This paper has an important guideline value for setting the optimal minimum approach temperature of a heat exchanger network. It is worth making a further study on the synthesis of HENs of entransy theory. The principle and strategy of the synthesis of HENs can be proposed in the future.

Nomenclature

A	heat transfer area, m^2
CP	heat capacity flowrate, $\text{kW} \cdot \text{K}^{-1}$
c_v	specific heat at constant volume, $\text{kJ} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$
c_p	specific heat at constant pressure, $\text{kJ} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$
E_{vh}	entransy, $\text{kW} \cdot \text{K}$
G	system entransy, $\text{kW} \cdot \text{K}$
m	mass, $\text{kg} \cdot \text{s}^{-1}$
$\dot{Q}$	heat flow rate, W
Q_t	the total heat transfer, W
Q_{vh}	thermal capacity of an object, J
$\dot{q}$	heat flux, $\text{W} \cdot \text{m}^{-2}$
T	temperature, K
U	heat transfer coefficient, $\text{kW} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$
U_h	thermal potential, K
W	work, J
η	entransy transfer efficiency, %
ΔT_{LM}	the log mean temperature difference, K
$\Delta T_{\min}$	minimum approach temperature, K

Subscripts

c	cold stream
h	hot stream
in	inlet state
outlet	outlet state
rev	reversible condition

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