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Comparative Study of Adaptability for S-zorb Unit Based on Exergy Analysis and Entransy Analysis

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The mathematical models for calculating the energy utilization efficiency of heat exchanger networks (HENs) based on exergy analysis method and entransy analysis method are built, respectively. With the goal of maximum energy recovery, the HENs of the gasoline adsorption desulfurization (S-zorb) unit are analysed by these two models. The exergy loss is accurately calculated using subsection integral by temperature-enthalpy (T-H) diagram. The entransy dissipation is calculated by the integration of the cold and hot composite curves in the temperature-heat flow rate (T-Q) diagram. The results are obtained in three different ΔT_{min}15 K, 20 K and 25 K. Then, the adaptability of the two methods to the HENs of the S-zorb unit was further compared. For the S-zorb unit, the exergy efficiency decreases, respectively 89.89 %, 88.21 %, 86.49 %, and save utility about 82.90 %, 72.13 %, 67.46 %. The entransy transfer efficiency also decreases 92.41 %, 91.07 %, 89.73 %, and save utility about 80.03 %, 72.33 %, 64.63 %. Compared with exergy analysis method, the calculation process of entransy dissipation is simpler, and the results are closer to reality. The entransy analysis method is more suitable for the analysis of energy utilization efficiency of the HENs of S-zorb unit.

1. Introduction

The first law of thermodynamics only reflects the quantitative relationship of energy, but does not reflect the quality of energy. Aiming at this problem, Rant (1956) introduced a new thermodynamic parameter which was called “exergy”. Ahern (1980) proposed exergy analysis method which can effectively analyse the value, cause and location of the exergy loss. At present, exergy analysis method has been widely studied in many fields, such as petroleum and chemical industry (Ghannadzadeh and Sadeqzadeh, 2016), blast furnace smelting (Liu et al., 2015), pneumatic pulsator system (Wolosz and Wernik, 2016), environmental resource (Park et al., 2014), ecosystem (Mabrouka et al., 2016).

Scholars have been looking for ways to improve the energy utilization efficiency in petrochemical industry (Oravec et al., 2015). In the study of HENs synthesis, Linnhoff (1990) has introduced the concept of exergy loss into the design of HENs. After a great deal of research, the exergy analysis method used for HENs synthesis is divided into graphic method (Stijepovic et al., 2014) and formula method (İpeka et al., 2017), objective function method (Miladi et al., 2016) etc. However, due to the complexity of the calculation process of the exergy, the use of exergy analysis method for HENs in petrochemical industry is limited.

Based on the nature of heat transfer phenomena, Guo et al. (2007) introduced a new physical quantity, entransy. In recent years, some scholars have introduced the idea of entransy into HENs synthesis (Li et al., 2016), such as heat exchanger design, graphical method. But no research has been done on using entransy dissipation for computing the entransy transfer efficiency of a petrochemical unit.

The exergy analysis method and entransy analysis method are based on the second law of thermodynamics, but they have their own characteristics. For the HENs synthesis of petrochemical unit, which method is better? In this work, with the goal of maximum energy recovery, the HENs of the S-zorb unit are analysed by these two methods. The energy utilization efficiency of the HENs for the S-zorb unit is respectively calculated using the exergy analysis method and entransy analysis method. Then, the adaptability of the two methods to the HENs of the S-zorb unit was further compared.

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2. Exergy analysis method and entransy analysis method of HENs

2.1 Exergy analysis method of HENs

Exergy analysis method of HENs is based on the first and second laws of thermodynamics. Its aim is to study the effective use of energy in the process. Through the calculation of the exergy efficiency of HENs, energy analysis method can evaluate energy use efficiency of HENs.
Based on the T-H diagram, the balanced composite curves of hot and cold streams (including utilities) can be made. The exergy loss of the HENs is calculated by using the integral method (Jin et al., 2008).

$$\Delta E_L = \int_0^{Q_1} \frac{T_0}{T_H \cdot T_C}(T_H - T_C)\delta Q + \int_{Q_1}^{Q_2} \frac{T_0}{T_H \cdot T_C}(T_H - T_C)\delta Q + \cdots + \int_{Q_{n-1}}^{Q_n} \frac{T_0}{T_H \cdot T_C}(T_H - T_C)\delta Q \quad (1)$$

where ΔE_L denotes the exergy loss, T_H and T_C are changed continuously with the line relations between temperature and enthalpy, T_0 denotes ambient temperature.
According to Eq(1), the exergy efficiency of stream is:

$$\eta_{e,o} = 1 - \frac{\Delta E_L}{\Delta E_H} = \frac{\sum_{i=1}^{n} \int_0^{Q_n} \frac{T_0}{T_H \cdot T_C}(T_H - T_C)\delta Q}{\sum_{i=1}^{n} Q_{h,i}(1 - T_0 / T_{m,h,i})} \quad (2)$$

where the subscripts i denotes the stream numbers; $T_{m,h,i}$ denote the log mean temperature difference.
In order to determine the weak links in the process, exergy loss rate $e_{L,i}$ is the ratio of the exergy loss of each part to the exergy loss of all equipment:

$$e_{L,i} = \frac{\Delta E_{L,\mathrm{i}}}{\sum_{i=1}^{n} E_{L,\mathrm{i}}} = \frac{\sum_{i=1}^{n} \int_o^{Q_n} \frac{T_0}{T_H \cdot T_C}(T_H - T_C)\delta Q}{\sum_{i=1}^{n} Q_{h,i}(1 - T_0 / T_{m,h,i}) - \sum_{i=1}^{n} Q_{c,i}(1 - T_0 / T_{m,c,i})} \quad (3)$$

According to the different heat transfer temperature differences, the calculation exergy efficiency using the Eq (2) is $\eta_{e,1}$, $\eta_{e,2}$.... The result of exergy loss rate by Eq(3) reveals that there exist larger energy consumption of the equipment, such as heat exchanger, cooler, air cooler, steam generator, etc.

2.2 Entransy analysis method of HENs

The quantity of entransy (absolute zero is taken as the zero temperature potential) can be written as

$$E_H = \sum_{\mathrm{i=1}}^{\mathrm{h_n}} E_{h,i}\ , E_C = \sum_{\mathrm{i=1}}^{\mathrm{c_n}} E_{c,i}\ ,\ E_{h,i} = \frac{1}{2} CP_{h,i}(T_{h,i,in}^2 - T_{h,i,\mathrm{out}}^2)\ ,\ E_{c,i} = \frac{1}{2} CP_{\mathrm{c},i}(T_{\mathrm{c},i,\mathrm{out}}^2 - T_{c,i,in}^2) \quad (4)$$

where CP denotes heat capacity flowrate, the subscripts in and out denote the inlet and outlet states, respectively.
In addition, the calculation of the quality of entransy can be obtained by the integration of the cold and hot composite curves with the Q-axis in T-Q diagram (Wu and Guo, 2013). The entransy dissipation of the whole heat transfer process is:

$$\Delta E = \sum_{\mathrm{i=1}}^{\mathrm{h_n}} E_{h,i} - \sum_{\mathrm{i=1}}^{\mathrm{c_n}} E_{c,i} = \frac{1}{2} \sum_{\mathrm{i=1}}^{\mathrm{h_n}} CP_{h,i}(T_{h,i,in}^2 - T_{h,i,out}^2) - \frac{1}{2} \sum_{\mathrm{i=1}}^{\mathrm{c_n}} CP_{c,i}(T_{c,i,out}^2 - T_{c,i,in}^2) \quad (5)$$

Therefore, the entransy transfer efficiency is:

$$\eta_0 = \frac{E_C}{E_H} = \frac{\sum_{\mathrm{i=1}}^{\mathrm{n}} CP_{c,\mathrm{i}}(T_{c,out,\mathrm{i}}^2 - T_{c,in,\mathrm{i}}^2)}{\sum_{\mathrm{i=1}}^{\mathrm{n}} CP_{h,\mathrm{i}}(T_{h,in,\mathrm{i}}^2 - T_{h,out,\mathrm{i}}^2)} \quad (6)$$

According to the calculation of different entransy transfer efficiency of different energy targets, the maximum heat transfer capability of hot streams of HENs is determined.
From the whole process, the calculation of entransy and entransy dissipation in entransy analysis are not affected by ambient temperature, but the calculation of exergy and exergy loss in exergy analysis are affected. In addition, the exergy loss needs to be calculated by the integral method, and the calculation process is complex. The entransy analysis greatly simplifies the calculation process.

3. Comparison of exergy analysis and entransy analysis in HENs of S-zorb unit

S-zorb technology is a kind of adsorption desulfurization technology developed by ConocoPhillips company for FCC gasoline fraction. The process flowsheet of S-zorb unit is shown in Figure 1.The hot and cold stream data of HENs is shown in Table 1, the utilities data can see Table 2 (Li et al., 2011).

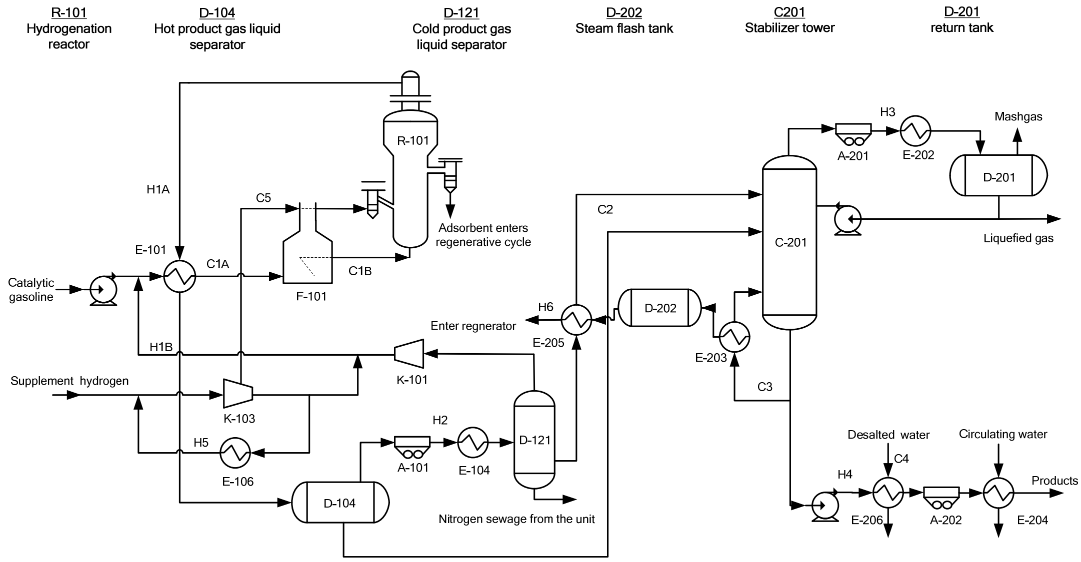

Figure 1: The process flowsheet of S-zorb unit

Table 1: Stream data

Stream	**Stream description**	**Supply Temperature [K]**	**Target Temperature [K]**	**CP [kW·K^{-1}]**
H1A	The top export stream of R101	707	519	83.06
H1B	The top export stream of R101	519	405	120.06
H2	The top stream of D104	405	308	12.06
H3	The top stream of C201	324	303	4.25
H4	The bottom product of C201	424	313	62.2
H5	The stream of E106	345	313	0.63
H6	The condensated water of D202	419	316	1.95
C1A	Mix hydrogen materials	353	523	104
C1B	Mix hydrogen materials	523	685	82.72
C2	The bottom of D121	300	352	3.86
C3	The bottom reboiler of C201	424	427	543.38
C4	Demineralized water	313	370	69.93
C5	The circulating hydrogen through F101	320	632	0.89

Table 2: Utilities data

Utilities	**Number**	**Stream**	**Supply Temperature[K]**	**Target Temperature[K]**	**CP [kW·K^{-1}]**
Hot	HU1 [F101]	Mix hydrogen materials	650	685	89.17
utilities	HU2 [E203]	The reboiler of C201	424	427	543.33
	HU3 [F101]	Circulating hydrogen	320	632	0.89
Cold	CU1 [H1A]	The top export stream of R101	421	404	86.18
utilities	CU2 [E104,A101]	The top stream of D104	405	308	12.06
	CU3 [E204]	The bottom product of C201	363	313	58.38
	CU3 [E202,A201]	The top stream of C201	324	303	4.24
	CU4 [E106]	The stream of E106	345	313	0.63

3.1 Analysis of existing HENs

Select the ambient temperature T_0 = 298.15K, pressure = 0.1013MPa.
(1) Exergy analysis
The exergy of hot streams and cold streams are 14,270 kW and 13,860 kW, respectively. The exergy loss is 3,125kW, the exergy efficiency is 78.10%, the total exergy loss rate is 21.90%. In addition, the exergy loss rates of HU1, CU1, CU3 are highest in the utilities. The values are 55.25%, 12.99% and 10.86%, respectively.
(2) Entransy analysis
The entransy of hot streams and cold streams are 18,970 MW·K and 18,090 MW·K. The entransy dissipation is 13,430 MW·K, the entransy transfer efficiency is 80.04 %, the total entransy dissipation rate is 19.96 %. In addition, the entransy dissipation rates of HU1, CU1, CU2, CU3 are highest in the utilities. The values are 10.98%, 2.31% and 5.45%.
Exergy analysis and entransy analysis has obtained the location of the energy loss for S-zorb unit. Compared with exergy analysis method, the results of entransy analysis method are closer to reality.

3.2 The maximum energy recover HENs

It is assumed that ΔT_{min} is 20 K. Pinch Temperature 363 K is determined (see Figure 2).
Selecting different ΔT_{min}: 15 K, 20 K and 25 K, the results calculated by exergy analysis and entransy analysis are shown in Table 3, Table 4. The efficiency of different ΔT_{min} is shown in Figure 3.When ΔT_{min} is 15 K, 20 K and 25 K, the exergy efficiency is 89.89 %, 88.21 %, 86.49 %, saving utilities is 82.90 %, 72.13 %, 67.46 %. It is indicated that the larger the temperature difference, the lower quality of hot streams. When ΔT_{min} is 15 K, 20 K and 25 K, the entransy transfer efficiency is 92.41 %, 91.07 %, 89.73 %, saving utilities is 80.03 %, 72.33 %, 64.63%. It is obvious that the larger the temperature difference, the more entransy dissipation, the more utility requirements, and the lower entransy transfer efficiency.

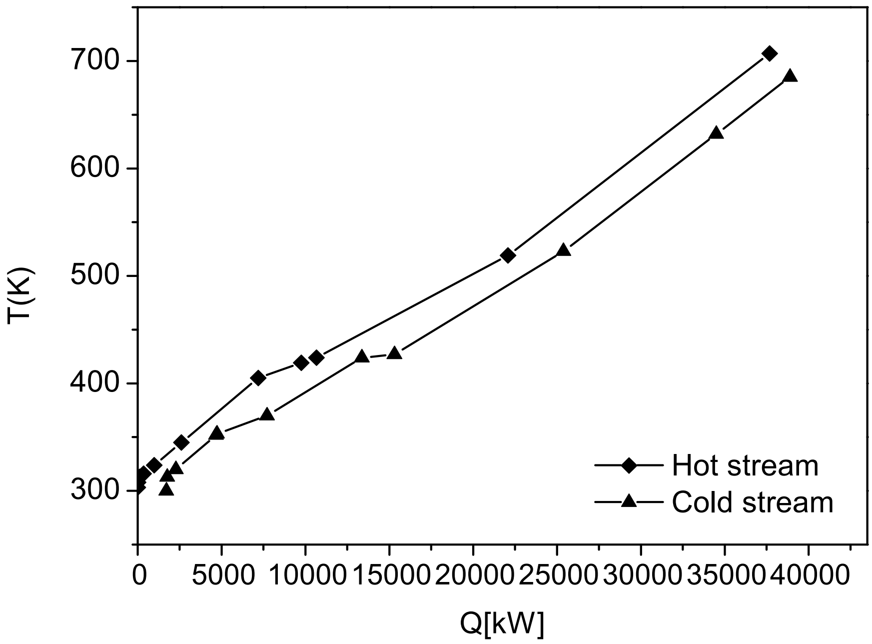

Figure 2: Composite Curves diagram

Table 3: The results of exergy analysis method

	ΔT_{min} = 15 K	ΔT_{min} = 20 K	ΔT_{min} = 25 K
Hot streams exergy [kW]	13,880	13,750	13,610
Cold streams exergy [kW]	13,730	13,860	13,990
Hot utilities exergy [kW]	466.0	677.3	887.4
Cold utilities exergy [kW]	89.488	228.2	170.0
Exergy loss [kW]	1,403	1,622	1,840
Exergy efficiency[%]	89.89	88.21	86.49

Table 4: The results of entransy analysis method

	ΔT_{min} = 15 K	ΔT_{min} = 20 K	ΔT_{min} = 25 K
Hot streams entransy [MW·K]	18,970	18,970	18,970
Cold streams entransy [MW·K]	18,090	18,090	18,090
Hot utilities entransy [MW·K]	564.3	819.6	1,073
Cold utilities entransy [MW·K]	424.6	550.6	678.6
Entransy recovery [MW·K]	17,530	17,270	17,020
Entransy dissipation [MW·K]	1,015	1,144	1,269
Entransy transfer efficiency [%]	92.41	91.07	89.73
Entransy saving [%]	80.03	72.33	64.63

According to Figure 3, the changing trend of entransy transfer efficiency is close to exergy efficiency. But entransy savings curve is more stable than exergy savings curve. In summary, exergy analysis and entransy analysis can analyse the energy utilization efficiency of the HENs. Compared with exergy analysis method, entransy analysis is more conducive to propose reasonable energy saving measures.

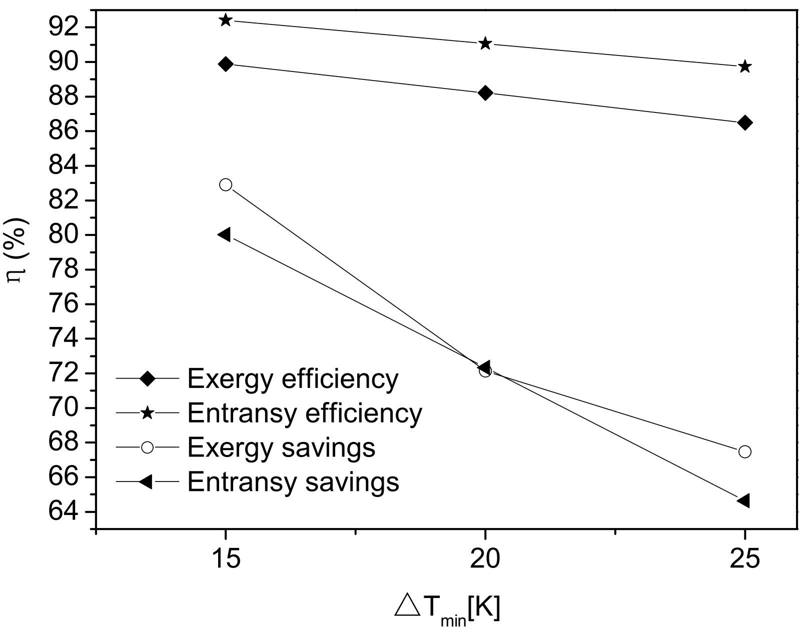

Figure 3: The efficiency of different ΔT_{min}

4. Conclusions

The exergy analysis and entransy analysis can be used to analyse the utilization of energy in the HENs. The calculation process of exergy loss in the exergy analysis is complex. Exergy analysis method is carried out under certain ambient temperature, the temperature is different in different research objects, and pay more attention to the use of heat can be converted into useful work to measure the heat quality of the entire system. But entransy analysis method is used to calculate the heat transfer efficiency of the actual system. It is obvious that the calculation process of entransy dissipation is simpler.

The S-zorb unit of the industrial case study is shown in this paper. Setting temperature differences ΔT_{min} is 15 K, 20 K, 25 K, the similar changing trend can be obtained (see Figure 3). It is found that entransy savings curve is more stable than exergy savings curve. Exergy analysis and entransy analysis has obtained the location of the energy loss for S-zorb unit. It is found that the results of entransy analysis method are closer to reality. Entransy analysis has better adaptability to the HENs than exergy analysis.

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