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Similarity and Distinction of Exergy and Entransy Analyses in Air-conditioning System

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Abstract
To improve the performance of air-conditioning system, thermodynamic analysis is supposed to be an effective approach. Exergy and entransy are two common thermal parameters, taking influences of both Q *and* T *into account. In the present study, similarity and distinction between exergy analysis and entransy analysis are investigated. Exergy is a theoretical parameter based on the second law of thermodynamics, characterizing heat-work transformation. Entransy is a theoretical parameter for analyzing a transfer process, focusing on transfer ability. Taking a sensible heat exchanger as an example, formulas of exergy destruction and entransy dissipation are given. Compared with entransy dissipation, exergy destruction is related to a coefficient equaling to reference temperature* T_R *divided by the product of fluids' temperatures (*$T_h \cdot T_c$*). In the common temperature range, variance of this coefficient is limited, indicating that exergy destruction and entransy dissipation tend to be in accordance with each other. In coupled heat and mass transfer processes, there are also similarities in exergy and entransy analyses. It's helpful to improve performance of a handling process through reducing exergy destruction or entransy dissipation. The present analysis is beneficial to choose an appropriate theoretical tool for performance optimization in air-conditioning system.*

Keywords - exergy destruction; entransy dissipation; performance optimization; air-conditioning system

1. Introduction

Energy consumed by air-conditioning system accounts for an increasing ratio of the entire energy consumption. It's of great importance to improve energy efficiency of the air-conditioning system and reduce its energy consumption. Thermal analysis according to thermodynamic parameters are treated as a theoretical tool for performance optimization in the air-conditioning system. The thermal analysis method is to identify the losses occurring in the HVAC system and try to find approaches for performance optimization through reducing loss.

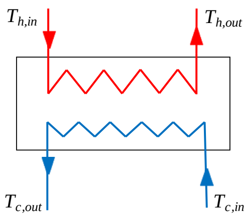
Exergy or entropy analysis is a common thermodynamic tool adopted in HVAC system and exergy destruction is utilized as the index reflecting the thermodynamic performance of a certain handling process or entire system [1]. There are plenty of exergy analyses on heat transfer process, refrigeration or heat pump cycle, coupled heat and mass transfer processes and so on [2-4]. On the other hand, entransy is a new theoretical parameter proposed for analyzing heat transfer process and it has gained rapid progress in the recent 10 years [5-7]. In the Annex 59 project, entransy is chosen as a theoretical tool to evaluate and optimize the performance of HVAC system.

However there are fewer studies on the comparison between exergy analysis and entransy analysis in the air-conditioning system. Present research will focus on the similarities and distinctions between exergy and entransy analyses. Choosing typical handling processes as examples, exergy destruction and entransy dissipation will be emphasized investigated. This study will be helpful for choosing an appropriate theoretical tool for performance optimization in air-conditioning system.

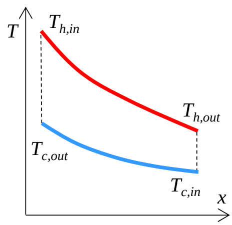
2. Exergy and entransy analyses of a sensible heat exchanger

2.1 Exergy destruction and entransy dissipation of a sensible heat exchanger

To improve the performance of air-conditioning system, thermodynamic analysis using exergy or entransy is supposed to be a theoretical approach. This section focuses on exergy and entransy analyses of sensible heat transfer process. Taking a typical sensible heat exchanger shown in Fig. 1(a) as an example, temperature variances of the two fluids with a counter flow pattern are illustrated as Fig. 1(b), where T is the temperature; subscripts h and c refer to the hot and cold fluids respectively, in and out denote inlet and outlet.



(a) operating schematic



(b) temperature variance

Fig. 1 Schematic and temperature variances of a counter-flow heat exchanger

Using exergy or entransy as the theoretical parameter, losses of this heat exchanger could be derived. Formulas of exergy destruction $\Delta E_{x,des}$ and entransy dissipation $\Delta E_{n,dis}$ are given as Eqs. (1) and (2) respectively, where E_x refers to exergy and E_n denotes entransy. It shows that either $\Delta E_{x,des}$ and $\Delta E_{n,dis}$ equals to the exergy or entransy difference between inlet and outlet states.

$$\Delta E_{x,des} = (E_{x,h,in} + E_{x,c,in}) - (E_{x,h,out} + E_{x,c,out}) \tag{1}$$

$$\Delta E_{n,dis} = (E_{n,h,in} + E_{n,c,in}) - (E_{n,h,out} + E_{n,c,out}) \tag{2}$$

$\Delta E_{x,des}$ or $\Delta E_{n,dis}$ of this sensible heat exchanger can also be obtained by the integral of exergy destruction or entransy dissipation of an infinitesimal, expressed by Eqs. (3) and (4) respectively, where T is the absolute temperature in K, T_0 is the temperature of reference state, T_h and T_c are fluids' temperatures respectively, and δQ denotes the heat transfer rate with an infinitesimal dA.

$$\Delta E_{x,des} = \int \left[\left(1-\frac{T_0}{T_h}\right) - \left(1-\frac{T_0}{T_c}\right) \right] \delta Q = \int \frac{T_0}{T_h T_c}\left(T_h - T_c\right)\delta Q \tag{3}$$

$$\Delta E_{n,dis} = \int \left(T_h - T_c\right)\delta Q \tag{4}$$

Fig. 2(a) shows the (1-T_0/T)-Q diagram of the sensible heat transfer process. As indicated by Eq. (3), exergy destruction $\Delta E_{x,des}$ could be expressed by the shaded area of this diagram. Temperatures of fluids varying with heat flux in this heat exchanger is illustrated as Fig. 2(b). Assuming the specific heat capacities of the fluids are constant, the shaded area in this T-Q diagram represents the entransy dissipation $\Delta E_{n,dis}$ of this heat transfer process as indicated by Eq. (4). As indicated by these two figures, both exergy destruction and entransy dissipation can be expressed in a diagram related with fluid's temperature and heat flux. However, variances of two fluids are nolinear in the expression of exergy destruction shown as Fig. 2(a). While fluids' temperature variances are linear in the T-Q diagram shown as Fig. 2(b). It's to say that entransy dissipation $\Delta E_{n,dis}$ could be expressed in a T-Q diagram, more intuitively compared with $\Delta E_{x,des}$ in a (1-T_0/T)-Q diagram.

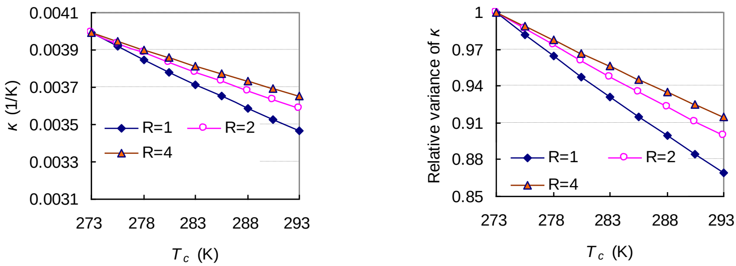
(a) (1-T_0/T)-Q diagram (b) T-Q diagram

Fig. 2 Exergy and entransy analyses of a counter-flow heat exchanger

As indicated by the expressions of exergy destruction and entransy dissipation shown as Eqs. (3) and (4), $\Delta E_{x,des}$ or $\Delta E_{n,dis}$ is always higher than 0 for an actual heat transfer process. Besides, there is only a coefficient difference between $\Delta E_{x,des}$ and $\Delta E_{n,dis}$, expressed as $T_0/(T_h \cdot T_c)$. Then the relation between exergy destruction and entransy dissipation for an infinitesimal could be expressed as Eq. (5).

$$d\Delta E_{x,des} = \kappa \cdot d\Delta E_{n,dis}, \text{ where } \kappa = \frac{T_0}{T_h T_c} \tag{5}$$

The common fluids for transportation are air, water, refrigerant and etc. in air-conditioning system. Fluid's temperature variance for a single handling process is usually less than 20 ℃. Then the corresponding variance of κ, indicating the relation between exergy destruction and entransy dissipation, is not significant. As the reference temperature T_0 is 303.15K, Fig. 3(a) shows the influence of temperature on the coefficient κ between $\Delta E_{x,des}$ and $\Delta E_{n,dis}$ with different heat capacity ratios of two fluids, where R is the heat capacity ratio between hot and cold fluids, temperature of the cold fluid T_c varies in the range of 273.15K~293.15K, temperature difference between $T_{h,in}$ and $T_{c,out}$ is 1 ℃. The relative variance of κ is shown in Fig. 3(b).



(a) temperature influence (b) relative variance of κ

Fig. 3 Influence of temperature on the coefficient κ between $\Delta E_{x,des}$ and $\Delta E_{n,dis}$

As indicated by these two figures, there is no significant variance of κ in this temperature range. Taking R is 2 as an example, relative value of κ is 1, 0.95 and 0.90 as T_2 is 273.15K, 283.15K and 293.15K respectively. It's to say that relative variance of κ is only about 10% when the temperature variance of cold fluid (T_2) is 20 ℃. The reason is that fluid's temperature is expressed as thermodynamic temperature in K. Then exergy destruction and entransy dissipation for the entire heat transfer process could be generally represented as Eq. (6).

$$\Delta E_{x,loss} \approx \bar{\kappa} \cdot \Delta E_{n,dis} \tag{6}$$

Thus in a common temperature range of air-conditioning system, there is no significant variance of the coefficient κ indicating the relation between exergy destruction and entransy dissipation. It will lead to a similar conclusion according either exergy destruction analysis or entransy dissipation analysis.

2.2 Reasons leading to exergy destruction or entransy dissipation

Based on entransy dissipation analysis, equivalent resistance R could be defined for characterizing a transfer process. Eq. (7) shows the definition of thermal equivalent resistance [8], where UA is the transfer ability and ΔT is the temperature difference of the heat transfer process.

$$R = \frac{\Delta E_{n,dis}}{Q^2} = \frac{1}{UA} \cdot \frac{\int \Delta T_x^2 dx}{\left[\int \Delta T_x dx\right]^2} = \frac{1}{UA} \cdot \xi \tag{7}$$

Unmatched coefficient ξ, which is adopted to evaluate the distribution uniformity of driving force, is always higher than or equal to 1. Only the driving force (ΔT) is uniform can ξ be equal to 1. Then entransy dissipation for the heat transfer process could be divided into two parts, as presented in Eq. (8). One ($\Delta E_{n,dis}^{(UA)}$) is caused by limited transfer ability UA and the other ($\Delta E_{n,dis}^{(\xi)}$) is caused by unmatched property.

$$\Delta E_{n,dis} = \Delta E_{n,dis}^{(UA)} + \Delta E_{n,dis}^{(\xi)}, \text{ where } \Delta E_{n,dis}^{(UA)} = \frac{1}{\xi}\Delta E_{n,dis} \tag{8}$$

For a heat transfer process, if the proportion of entransy dissipation caused by unmatched property is dominant, only through increasing input *UA* is not as efficient as expected for performance improvement. Then it's suggested to improve the match property to reduce the unmatched entransy dissipation.

According to a similar method, reasons leading to exergy destruction could also be distinguished. Exergy destruction consists of $\Delta E_{x,des}^{(UA)}$ caused by limited transfer ability *UA* and $\Delta E_{x,des}^{(\xi)}$ caused by unmatched flow rates, shown as Eq. (9).

$$\Delta E_{x,des} = \Delta E_{x,des}^{(UA)} + \Delta E_{x,des}^{(\xi)}, \text{ where } \Delta E_{x,des}^{(UA)} \approx \frac{1}{\xi}\Delta E_{x,des} \tag{9}$$

3. Exergy and entransy analyses of coupled heat and mass transfer processes

3.1 Entransy analysis in coupled heat and mass transfer processes

Taking the coupled heat and mass transfer processes between air and water as an example, unmatched coefficients ξ_h and ξ_m are defined to characterize the uniformity of driving forces in heat transfer process and mass transfer process respectively. Heat transfer resistance R_h and mass transfer resistance R_m based on entransy dissipation analysis could be expressed by Eqs. (10) and (11), respectively.

$$R_h = \frac{\Delta E_{n,dis}^{(h)}}{Q_S^2} = \frac{1}{UA}\cdot\frac{\int \Delta T_x^2 dx}{\left[\int \Delta T_x dx\right]^2} = \frac{1}{UA}\cdot\xi_h \tag{10}$$

$$R_m = \frac{\Delta E_{n,dis}^{(m)}}{\dot{m}_w^2} = \frac{1}{U_m A_m}\cdot\frac{\int \Delta \omega_x^2 dx}{\left[\int \Delta \omega_x dx\right]^2} = \frac{1}{U_m A_m}\cdot\xi_m \tag{11}$$

Similar to a sensible heat transfer process, transfer resistance R_h or R_m in coupled heat and mass transfer processes could also be divided into two parts, expressed as Eqs. (12) and (13). The first ($R_{h,UA}$ or $R_{m,UA}$) is resistance caused by limited transfer ability, equaling to $1/UA$ ($1/U_m A_m$); the second ($R_{h,\xi}$ or $R_{m,\xi}$) is resistance resulting from unmatched properties (such as unmatched flow rates, unmatched inlet parameters), with an unmatched coefficient ξ always higher than or equal to 1.

$$R_h = R_{h,UA} + R_{h,\xi}, \text{ where } R_{h,UA} = \frac{1}{UA},\ R_{h,\xi} = \frac{\xi_h - 1}{UA} \tag{12}$$

$$R_m = R_{m,UA} + R_{m,\xi}, \text{ where } R_{m,UA} = \frac{1}{U_m A_m},\ R_{m,\xi} = \frac{\xi_m - 1}{U_m A_m} \tag{13}$$

Unmatched coefficient ξ_h or ξ_m reflects the distribution characteristic of the driving force (temperature difference ΔT or humidity ratio difference $\Delta\omega$) in heat or mass transfer process. The closer ξ_h or ξ_m is approaching to 1, the more uniform the distribution of ΔT or $\Delta\omega$. Then transfer resistance or loss will be lower under a certain transfer ability UA. Otherwise the higher ξ_h or ξ_m is, the less uniform ΔT or $\Delta\omega$ is and the higher transfer resistance is.

3.2 Exergy analysis in coupled heat and mass transfer processes

As to the coupled heat and mass transfer processes between air and water, exergy destruction is composed of the exergy destruction of sensible heat transfer ($\Delta E^{h}_{x,des}$) and that of moisture transfer ($\Delta E^{m}_{x,des}$), calculated by Eq. (14).

$$\Delta E_{x,des} = \Delta E^{h}_{x,des} + \Delta E^{m}_{x,des} \tag{14}$$

Exergy destruction for sensible heat transfer process between air and water can be written as Eq. (15)，where $\overline{T}_a$ and $\overline{T}_w$ are the average temperatures of air and water (in K) respectively [9].

$$\Delta E^{h}_{x,des} = \int \frac{T_0}{T_a T_w}\left(T_a - T_w\right) dQ_S \approx \frac{T_0}{\overline{T}_a \overline{T}_w}\int \left(T_a - T_w\right) dQ_S = \frac{T_0}{\overline{T}_a \overline{T}_w}\Delta E^{(h)}_{n,dis} \tag{15}$$

For the sensible heat transfer process, heat exergy destruction could be divided into two parts: one is $\Delta E^{h(UA)}_{x,des}$ caused by finite transfer ability and the other is $\Delta E^{h(\xi)}_{x,des}$ due to unmatched coefficient ξ_h.

$$\Delta E^{h}_{x,des} = \Delta E^{h(UA)}_{x,des} + \Delta E^{h(\xi)}_{x,des} \text{, where } \Delta E^{h(UA)}_{x,des} \approx \frac{1}{\xi_h}\Delta E^{h}_{x,des} \tag{16}$$

Further exergy destruction for mass transfer process between air and water can be expressed as Eq. (17) [10].

$$\Delta E^{m}_{x,des} \approx \frac{T_0 r \overline{\lambda}}{\overline{T}_{a,d} \overline{T}_w}\int \left(\omega_a - \omega_w\right) dm_w = \frac{T_0 r \overline{\lambda}}{\overline{T}_{a,d} \overline{T}_w}\Delta E^{(m)}_{n,dis} \tag{17}$$

where $T_{a,d}$ is the dew point temperature, T_w is water temperature, λ is slope of the saturation line in air psychrometric chart, which could be regarded as constant in a limited range. $\overline{T}_{a,d}$, $\overline{T}_w$ and $\overline{\lambda}$ are the average values of the entire process correspondingly. Similarly humid exergy destruction could be split into the exergy destruction caused by limited transfer ability ($\Delta E^{m(UA)}_{x,des}$) and the destruction resulted from unmatched coefficient ξ ($\Delta E^{m(\xi)}_{x,des}$).

$$\Delta E^{m}_{x,des} = \Delta E^{m(UA)}_{x,des} + \Delta E^{m(\xi)}_{x,des} \text{, where } \Delta E^{m(UA)}_{x,des} \approx \frac{1}{\xi_m}\Delta E^{m}_{x,des} \tag{18}$$

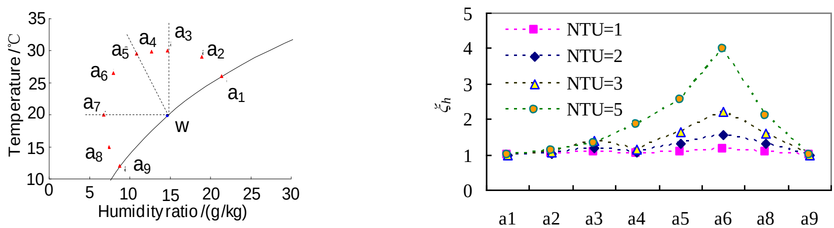
Then the exergy destruction in coupled heat and mass transfer processes between air and water could be expressed as Eq. (19).

$$\Delta E_{x,des} = \Delta E_{x,des}^{h} + \Delta E_{x,des}^{m} = \Delta E_{x,des}^{h(UA)} + \Delta E_{x,des}^{h(\xi)} + \Delta E_{x,des}^{m(UA)} + \Delta E_{x,des}^{m(\xi)} \qquad (19)$$

According to the composition of exergy destruction in coupled heat and mass transfer processes, proportions of destruction caused by either limited transfer ability or unmatched properties could be obtained. Then approaches to reduce destruction and improve performance are to be proposed: as the proportion caused by transfer ability is in a dominate position, it's recommended to increase input *UA*; while if there is significant destruction caused by ξ, matched properties should be improved in performance optimization.

3.3 Analyses in air-water handling processes

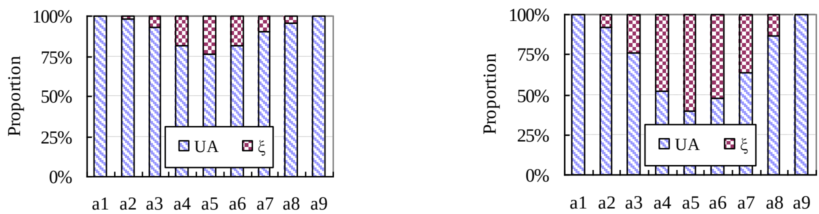
With a certain inlet water status w, the possible inlet air can have various statuses, such as a1~a9 shown in Fig. 4(a). Based on entransy analysis, unmatched coefficients ξ_h and ξ_m can be calculated and Fig. 4(b) presents ξ_h of different inlet states varying with input *NTU* (indicating input transfer ability *UA*) [8]. It shows ξ_h increases with the increase of *NTU*. For different inlet states, ξ_h are different and ξ_h of a1 or a9 (on the saturation line) is the lowest, equaling to 1.



(a) typical inlet conditions (b) unmatched coefficient ξ_h

Fig. 4 Exergy destructions in typical inlet air conditions

According to the analysis of exergy destruction in section 3.2, Fig. 5 shows the proportions of destructions caused by *UA* and ξ with different inlet *NTU*. It can be seen that there is no exergy destruction caused by ξ as inlet air state is a1 or a9, with a corresponding ξ_h or ξ_m is always 1.



(a) *NTU*=2 (b) *NTU*=5

Fig. 5 Reasons leading to exergy destructions in typical inlet air conditions

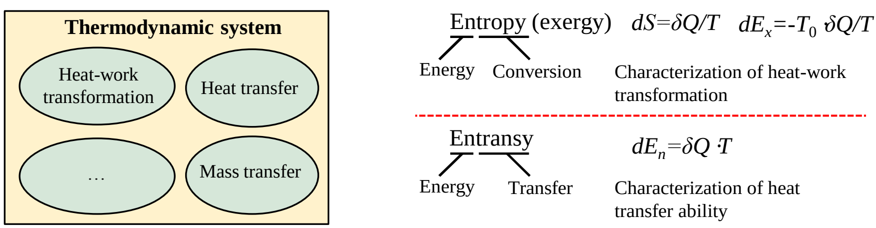
As air inlet state is away from the saturation line, there starts to be exergy destruction caused by ξ. As input *NTU* increases, proportion of exergy destruction resulted from limited transfer ability decreases while caused by ξ increases. For air inlet state a5 which is in the isenthalpic line of water, proportion of exergy destruction caused by unmatched properties is the highest. Thus with a certain input transfer ability, there will be less exergy destruction due to unmatched properties as inlet air state is on the saturation line. It's recommended to proceed along the saturation line rather than the isoenthalpic line for coupled heat and mass transfer processes between air and water.

4. Perspectives and distinctions of exergy and entransy analyses

The thermal analysis method is to identify the losses occurring in the system and try to find approaches for performance optimization through reducing losses. Different from a conventional method mainly through calculation or simulation, this method focuses on the internal losses existing in the system and aims to propose principles for construct an energy efficient system. By contrast with conventional perspective only emphasizing on Q, both heating/cooling capacity Q and temperature level T or temperature difference ΔT are concerned to calculate the internal losses.

Entransy and exergy are both thermological parameters indicating the influences of Q and T. As indicated by the exergy and entransy analyses on a sensible heat exchanger, there is only a difference in factors between expressions of exergy destruction $\Delta E_{x,des}$ and entransy dissipation $\Delta E_{n,dis}$. Although there are similarities in exergy and entransy analyses, there are significant distinctions between these two kinds of theoretical tools.

i) As to a thermal built environment, it's a complex thermodynamic system illustrated as Fig. 6(a). There are existing heat-work conversion process, heat transfer process, mass transfer process and so on. There is always loss (exergy destruction) due to the irreversibility of the thermodynamic system. For an irreversible process, exergy destruction equals to the input exergy minus the obtained exergy according to exergy balance analysis. Entransy analysis is a theoretical parameter based on heat transfer process and entransy dissipation is to characterize the loss in a transfer process. For a simple heat transformation process or a complex heat transfer network without heat-work transformation process, entransy dissipation is the index representing the irreversibility. According to the entransy balance analysis, entransy dissipation of internal transfer processes is the inlet entransy minus the outlet entransy.



(a) thermodynamic system (b) definitions and emphases

Fig. 6 Thermal parameters and their corresponding emphases

ii) Fig. 6(b) illustrates a simple comparison of these two theoretical parameters. As indicated by this figure, there are different perspectives between exergy analysis and entransy analysis. Physical models are completely different from each other. Exergy (with a same theoretical basis of entropy) is a theoretical parameter based on the second law of thermodynamics, which is suitable for characterization of heat-work transformation. Exergy balance reflects the energy conservation of quantity (first law of thermodynamics) as well as the value of energy (second law of thermodynamics). Entransy is a parameter for analyzing the heat transfer process, focusing on the transfer ability. Entransy dissipation is 0 only for a reversible transfer process. Entransy dissipation provides a theoretical approach for optimizing transfer process.

iii) Either exergy or entransy could be adopted as a theoretical tool for analysis. It's to depict the loss existing in processes using different rulers figuratively speaking. If there is a uniform scale to depict the loss, a simpler analysis can be expected and principle for parameter distribution could also be deduced. As indicated by the expressions of $\mathrm{d}E_x$ and $\mathrm{d}E_n$ in Fig. 6(b), it's Q divided by T for the former while Q multiplying T for the latter. For heat-work transformation, exergy is the ruler and the scale is $1/T$ (for humid exergy is $1/T_d$). Work ability and corresponding loss are uniform using exergy analysis. While for transfer process, entransy is the ruler and the corresponding scale is T. transfer ability and corresponding loss is uniform using entransy analysis.

iv) Compared with exergy analysis, entransy dissipation could be depicted more succinctly. A transfer process can be illustrated in the T-Q diagram visually in entransy analysis, with entransy dissipation expressed as the shaded area. Slope of fluid's temperature T varying with heat flux Q is usually a constant value if thermal capacity could be regarded as unchanged. However although exergy destruction could be expressed in the $(1-T_0/T)$-Q diagram, slope of the curve is not constant and the calculation of exergy destruction is more complex.

v) In exergy analysis, a reference state is required to evaluate the work ability. Reference temperature T_0 is usually chosen as the ambient temperature while for humid exergy there is still argument in choosing an approximate reference humidity ratio. As to entransy analysis, there is no need of reference state for analyzing a transfer process.

vi) Furthermore, equivalent thermal resistance R could be deduced based on entransy dissipation analysis. R can be adopted for performance optimization of air-conditioning systems.

To sum up, both exergy and entransy could reflect the influences of Q (quantity) and T (grade) in theoretical analysis. But they are thermological parameters with different theoretical bases and with different perspectives. Thus in analyzing an actual air-conditioning system, an appropriate theoretical tool should be chosen based on different requirements: with emphasis on work ability or heat-work transformation, exergy analysis is recommended; referring to a transfer process or focusing on transfer ability, entransy analysis or entransy dissipation is more appropriate.

5. Conclusion

This paper focuses on the similarities and distinctions between exergy analysis and entransy analysis in air-conditioning system. By contrast with conventional perspective only emphasizing on Q, exergy or entransy analysis takes influences of both Q and T into account. Exergy is a theoretical parameter based on the second law of thermodynamics, while entransy is focusing on the transfer ability.

Exergy destruction and entransy dissipation of typical handling processes are investigated. As indicated by the formulas of exergy destruction and entransy dissipation, there is only a difference in factors between the expressions. Exergy and entransy analyses tend to be in accordance with each other. In sensible heat transfer process or coupled heat and mass transfer processes, reasons leading to losses could be distinguished either by exergy or entransy analysis, helping to explore the leading reasons restricting performance.

It's concluded to choose different theoretical parameters based on different purposes in air-conditioning system: for a transfer process, entransy is more appropriate; for a heat-work conversion process, exergy is more recommended.

6. Acknowledgment

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