Entransy Dissipation Analysis for Optimal Design of Heat Exchangers

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***Abstract*—Recently the entransy has been introduced as a physical quantity to describe the heat transfer ability of an object. The optimization of heat exchangers is an important issue, and the principle of minimum entropy generation is sometimes used for optimal design of heat exchangers. In this work performance analysis based on the entransy dissipation-based thermal resistance is carried out for optimal design of heat exchangers with parallel or counter flow. Parametric analyses of heat transfer rate, entropy generation and entransy dissipation with the key parameters of hot-stream inlet temperature, thermal conductance and heat capacity rate are also presented for comparison. Results show that the minimum entropy generation or the entransy dissipation does not represent the optimum performance for a counter-flow heat exchanger while the minimum entransy dissipation-based thermal resistance corresponds to the maximum heat transfer rate. It is found that the behavior of entropy generation is very similar to that of entransy dissipation.**

***Index Terms*—heat exchanger, entransy dissipation, entropy generation, entransy dissipation-based thermal resistance (EDTR)**

I. Introduction

The heat transfer through a medium as an irreversible process is just like fluid flow through a pipe where mechanical energy is dissipated due to flow friction. It also resembles electricity flow through a conductor where electrical energy is dissipated due to the electrical resistance. Guo *et al*. [1] proposed the concept of entransy by the analogy between heat and electrical conductions. The entransy of the new physical quantity can be used to optimize heat transfer processes. An analysis of the heat transfer from an object shows that the entransy, which corresponds to the electric potential energy in a capacitor, possesses the nature of energy. Then, Objects can be described as thermal capacitors which simultaneously store heat and thermal potential energy.

For one body whose internal energy is U and temperature is T, its entransy is defined as $G = UT/2$. Furthermore, they derived the minimum entransy dissipation principle for prescribed heat flux boundary conditions and the maximum entransy dissipation principle for prescribed temperature boundary conditions, which are referred to as the extreme entransy dissipation principle. Cheng *et al*. [2] proved that this concept could be used to describe the irreversibility of heat transfer. Heat transfer optimization methods to effectively improve heat transfer performance are of great importance for energy conservation and pollution reduction. Chen *et al*. [3] reviewed a recently developed heat transfer optimization method based on entransy and the related peer-reviewed papers published between 2003 and 2010 to describe entransy, entransy dissipation, optimization criteria and optimization principles and their applications to different heat transfer modes and to different levels.

The entransy expression of the first law is that the entransy of any thermodynamic system is in balance, and that of the second law is that the entransy flow will never be transported from a low temperature body to a high temperature body automatically and the entransy dissipation always exists [4]. The concept of entropy can be replaced with entransy for describing the second law of thermodynamics and the entransy dissipation can be employed to quantify the irreversibilities occurring in thermodynamic systems. The entransy is a state variable and can be employed to describe the second law of thermodynamics [5], [6]. The heat entransy flow and the work entransy flow are defined with the consideration of heat interaction and work interaction, respectively. The work entransy flow can be input from low temperature to high temperature and vice versa. The heat entransy flow can only be transferred from high temperature to low temperature spontaneously, leading to entransy dissipation [7].

Traditional heat transfer is analyzed from the analogy with the electric resistance. The thermal resistance, *R*, is typically defined as the ratio of the temperature difference between the hot and cold end to the heat flux. The entransy-dissipation-based thermal resistance (EDTR) was proposed for the analyses of various heat exchangers. It is found that the minimum thermal resistance based on entransy dissipation always corresponds to the best performance of heat exchangers, while the minimum entropy generation and the extreme entransy dissipation do not always correspond to the best performance of heat exchangers [8], [9].

In engineering, both designing and checking heat exchanger performance are generally used such approaches as the logarithmic mean temperature

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difference method (LMTD), the heat exchanger effectiveness - number of transfer units method (ε-NTU), the P-NTU method, the ψ-P method and the P_1-P_2 method [10]. Qian and Li [11] analyze various heat exchangers. Entropy generation analyses are also presented for comparison. They show that the minimum entransy-dissipation-based thermal resistance always corresponds to the highest heat transfer rate, while the design with the minimum entropy generation is not always related to the design with the highest heat transfer rate. Based on the entransy theory, Chen [12] deduced the formula of EDTR for different types of heat exchangers, analyzed the factors influencing heat exchanger performance and, more importantly, developed an alternative EDTR method for the design and optimization of heat exchanger performance.

In this work, the performance of heat exchangers with parallel or counter flow are analyzed based on the entransy dissipation-based thermal resistance. Parametric analyses of heat transfer, entropy generation, and entransy dissipation are also presented for comparison with the key parameters of the inlet temperature of hot stream, ratio of mass flow rate of hot stream to cold stream, and thermal conductance of heat exchanger.

II. System Analysis

A heat exchanger can be defined as any device that transfers heat from one fluid to another or from or to a fluid and the environment. Assume that there are two process streams in a heat exchanger, a hot stream flowing with a thermal capacity rate $C_h = m_h c_{ph}$ and a cold stream flowing with a thermal capacity rate $C_c = m_c c_{pc}$. Here, m and c_p are mass flow rate of the stream and isobaric specific heat of the fluid, respectively, and subscripts h and c denotes hot and cold streams, respectively.

Then, energy balance equation can be written as

$$Q = C_h(T_{hi} - T_{ho}) = C_c(T_{co} - T_{ci}) \tag{1}$$

where Q is the heat transfer rate between the streams, T is the temperature, and subscripts i and o indicates inlet and outlet of the heat exchanger, respectively. Equation (1) represents an ideal state that must hold in the absence of losses and it describes the transferred heat or the duty of the heat exchanger.

For the case of prescribed flow and temperature conditions, it does not provide an indication of the size of the heat exchanger necessary to perform this duty. The size of the exchanger derives from a statement of the rate equation [13];

$$Q = UA\Delta T_m \tag{2}$$

where A, U, and UA are the surface areas on the hot and cold sides of the exchanger, the overall heat transfer coefficient, and thermal conductance of the heat exchanger, respectively.

ΔT_m is the mean temperature difference between the hot and cold streams in a heat exchanger, and it can be obtained in terms as logarithmic mean temperature difference (LMTD) for the heat exchangers with parallel or counter flow:

parallel flow:
$$\Delta T_m = \frac{(T_{hi} - T_{ci}) - (T_{ho} - T_{co})}{\ln\left(\dfrac{T_{hi} - T_{ci}}{T_{ho} - T_{co}}\right)} \tag{3}$$

counter flow:
$$\Delta T_m = \frac{(T_{hi} - T_{co}) - (T_{ho} - T_{ci})}{\ln\left(\dfrac{T_{hi} - T_{co}}{T_{ho} - T_{ci}}\right)} \tag{4}$$

Let us assume that the heat exchanger is a control volume and the outer surface is adiabatic, so there is no heat transfer between the outer surface and environment. Since the effect of the viscous fluid friction is much smaller than the effect of the heat transfer, the entropy generation rate, S_g, resulting from heat transfer through a finite temperature difference is only evaluated by considering the fluids as pure simple single phase compressible substances [11];

$$S_g = C_h \ln\left(\frac{T_{ho}}{T_{hi}}\right) + C_c \ln\left(\frac{T_{co}}{T_{ci}}\right) \tag{5}$$

The expression of the governing heat transfer relations in the form of thermal resistances greatly simplifies the first-order thermal analysis of system. Recognizing that heat flow Q is analogous to electrical current and that the temperature drop ΔT is analogous to a voltage drop, it is possible to define a general thermal resistance R as

$$R = \frac{\Delta T}{Q} \tag{6}$$

Although, strictly speaking, this analogy applies only to conduction heat transfer, it is possible to generalize this definition to all the modes of thermal transport [13].

Guo *et al*. [1] introduced the entransy as a physical quantity to study heat transfer processes;

$$G = \frac{1}{2}UT \tag{7}$$

where U and T are the internal energy and the temperature of an object, respectively. Accompanying the thermal energy during heat transfer, the entransy will be transported and partly dissipated, which is similar to electric energy transportation and dissipation along with the charge during electric conduction [12]. The entransy dissipation can be obtained as

$$\begin{aligned} G_\phi &= \frac{1}{2}C_h\left(T_{hi}^2 - T_{ho}^2\right) - \frac{1}{2}C_c\left(T_{co}^2 - T_{ci}^2\right) \\ &= C_h(T_{hi} - T_{ho})\frac{T_{hi} + T_{ho}}{2} - C_c(T_{co} - T_{ci})\frac{T_{ci} + T_{co}}{2} \\ &= Q\left(\frac{T_{hi} + T_{ho}}{2} - \frac{T_{ci} + T_{co}}{2}\right) \end{aligned} \tag{8}$$

The thermal resistance based on entransy dissipation was defined by Zhu [14] to study heat conduction optimization;

$$R_\phi = \frac{G_\phi}{Q^2} \tag{9}$$

where $R_ø$ is the entransy-dissipation-based thermal resistance, $G_ø$ is the entransy dissipation during the heat transfer process. The minimum thermal resistance principle was developed by using the concept of entransy dissipation-based thermal resistance for heat conduction optimization. His experimental results showed that the entransy-dissipation-based thermal resistance can be significantly reduced using the minimum thermal resistance principle and the optimized results are much better than those using the minimum entropy generation principle

III. Results and Discussions

The basic data of the system variables are as follows: T_{hi} = 600℃, T_{ci} = 300℃, UA = 1 kW/℃, C_h = 2 kW/℃, C_c = 3 kW/℃, respectively. Figures 1-3 show the effect of inlet temperature of hot stream, thermal conductance, and heat capacity rate of hot stream on the variables for a heat exchanger of parallel flow, where the superscript of star indicates the magnitude relative to the maximum value of the corresponding parameter in the calculation range. Fig. 1 shows that the three variables of heat transfer rate, entropy generation and entransy dissipation increases with increasing the inlet temperature. That is to say, the larger the entropy generation or entransy dissipation is, the larger heat transfer rate will be. But it is worth to note that the entransy dissipation-based thermal resistance remains constant irrespective of the inlet temperature.

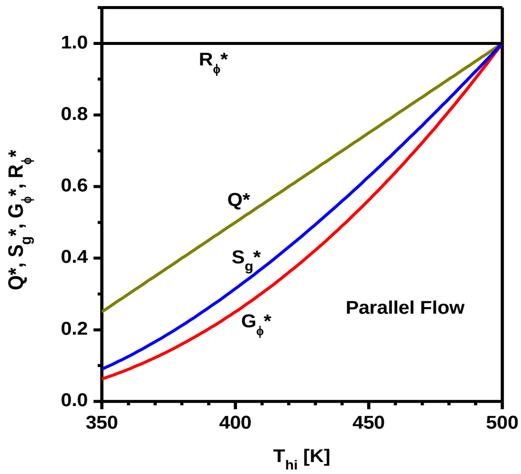

Figure 1. Performance with hot stream temperature for parallel flow.

Fig. 2 shows that with the increase of the thermal conductance, each of the heat transfer, the entropy generation and the entransy dissipation increases, and approaches a corresponding maximum value as the thermal conductance tends to infinity. On the other hand, the entransy dissipation-based thermal resistance decreases with increasing the thermal conductance, and approaches a minimum value as the thermal conductance tends to infinity. It is also worth to note that the behaviors of the entropy generation and the entransy dissipation with respect to the thermal conductance are almost same. Fig. 3 indicates that with the increase of heat capacity rate of hot stream, each of the heat transfer rate, the entropy generation and the entransy dissipation increases, while the entransy dissipation-based thermal resistance decreases.

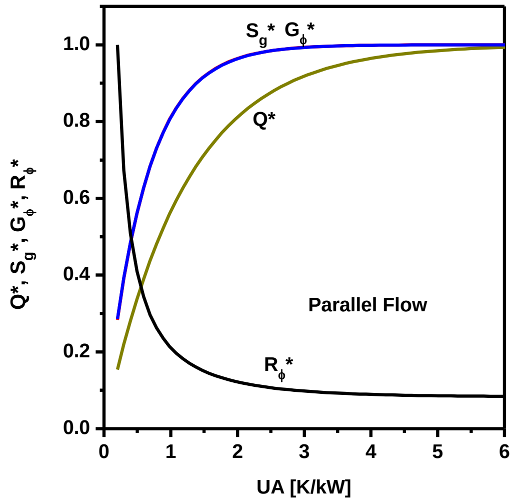

Figure 2. Performance with thermal conductance for parallel flow.

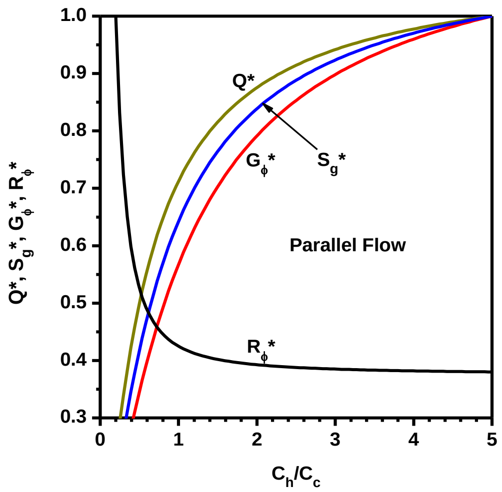

Figure 3. Performance with heat capacity rate for parallel flow.

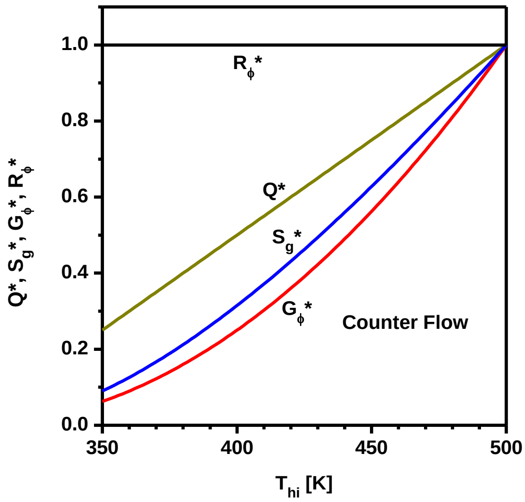

Figure 4. Performance with hot stream temperature for counter flow.

Fig. 4, Fig. 5, Fig. 6 show the effect of inlet temperature of hot stream, thermal conductance, and heat capacity rate of hot stream on the variables for a heat exchanger of counter flow. Fig. 4 shows that the three variables of the heat transfer rate, the entropy generation, and the entransy dissipation increase with increasing of the inlet temperature, while the entransy dissipation-based thermal resistance remains constant irrespective of the inlet temperature, which is similar to the case of heat exchanger of parallel flow.

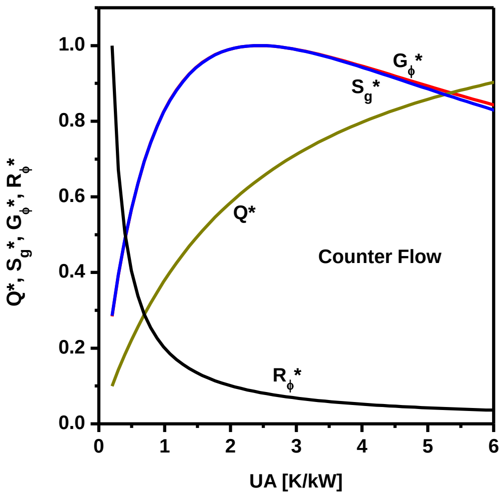

Figure 5. Performance with thermal conductance for counter flow.

Fig. 5 shows that the heat transfer rate increases and the entransy dissipation-based thermal resistance decreases with increasing the thermal conductance, while, the entropy generation and the entransy dissipation first increases and then decreases with increasing thermal conductance. Therefore, each of the entropy generation and entransy dissipation has a maximum value. It is also worth to note that the behaviors of the entropy generation and the entransy dissipation with respect to the thermal conductance are almost same for counter-flow heat exchangers.

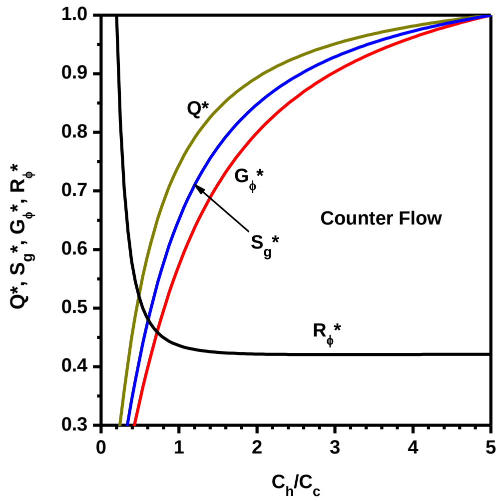

Figure 6. Performance with heat capacity rate for counter flow.

The results in Fig. 6 indicate that with the increase of heat capacity of hot stream, each of the heat transfer, the entropy generation and the entransy dissipation increases, while the entransy dissipation-based thermal resistance decreases and approaches a minimum value as the heat capacity of hot stream is larger than that of cold stream.

IV. Conclusions

The new physical quantity, entransy, is useful for optimization of heat transfer processes and optimal design of heat exchangers. This work presents the performance analysis based on the entransy dissipation-based thermal resistance for optimal design of heat exchangers of parallel and counter flow. Parametric analyses of heat transfer rate, entropy generation, and entransy dissipation are also presented for comparison with the key parameters of the hot-stream inlet temperature, the thermal conductance and the heat capacity rate.

It is found that the entransy dissipation-based thermal resistance remains constant irrespective of the inlet temperature. The behaviors of the entropy generation and the entransy dissipation with respect to the thermal conductance are almost same. As the thermal conductance increases in the case of parallel-flow heat exchanger, each of the heat transfer, the entropy generation and the entransy dissipation increases and approaches a corresponding maximum value, but the entransy dissipation-based thermal resistance decreases and approaches a corresponding minimum value. In the case of counter-flow heat exchanger, the entransy dissipation-based thermal resistance decreases with increasing the thermal conductance, but each of the entropy generation and the entransy dissipation has a maximum value with respect to the thermal conductance.

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