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Heat transfer entropy resistance for the analyses of two-stream heat exchangers and two-stream heat exchanger networks

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HIGHLIGHTS

- The concept of entropy resistance is defined.
- The minimum entropy resistance principle is developed.
- Smaller entropy resistance leads to better heat transfer.

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ABSTRACT

The entropy generation minimization method is often used to analyze heat transfer processes from the thermodynamic viewpoint. In this paper, we analyze common heat transfer processes with the concept of entropy generation, and propose the concept of heat transfer entropy resistance. It is found that smaller heat transfer entropy resistance leads to smaller equivalent thermodynamic force difference with prescribed heat transfer rate and larger heat transfer rate with prescribed equivalent thermodynamic force difference. With the concept of heat transfer entropy resistance, the performance of two-stream heat exchangers (THEs) and two-stream heat exchanger networks (THENs) is analyzed. For the cases discussed in this paper, it is found that smaller heat transfer entropy resistance always leads to better heat transfer performance for THEs and THENs, while smaller values of the entropy generation, entropy generation numbers and revised entropy generation number do not always.

1. Introduction

The analyses of heat transfer attract great attention because about 80% of the total energy consumption is related to heat and improving the performance of heat transfer is of great significance to the energy conservation [1,2]. From the viewpoint of thermodynamics, the entropy generation minimization method [3,4] is widely used in the analyses of heat convection [5,6] and evaporators [7,8], as well as other engineering problems [9].

Two-stream heat exchanger (THE) is widely used in industry to deliver thermal energy from a hot stream to a cold one [9–14]. For a two-stream heat exchanger network (THEN), it is composed of a group of heat exchangers which are connected in series or parallel, and is also widely used to deliver heat in industry [10,11]. The analyses of THE and THEN are very important for engineers. The entropy generation minimization method is also popularly used in THEs and THENs analyses [1,3,9–11,15–17]. However, there is an entropy generation paradox [3] when entropy generation is used to analyze two-stream balanced counter flow heat exchangers. The entropy generation number does not always decrease with increasing heat exchanger effectiveness ε. Instead, it increases when ε is in the range of [0, 0.5]. A special case is that the entropy generation number is zero for $\varepsilon = 0$. Bejan [3] explained that the behavior in the $\varepsilon \to 0$ extreme is neither expected nor intuitively obvious and that the vanishing entropy generation number seen in the limit is first and foremost a sign that the heat exchanger disappears as an engineering component. Therefore, the $\varepsilon \to 0$ limit will never happen in practical applications. However, this explanation is not satisfactory in the vicinity of $\varepsilon \le 0.5$ in the balanced counter flow heat exchanger. Shah and Skiepko [17] demonstrated that the heat exchanger effectiveness can be the maximum, an intermediate value or the minimum at the maximum entropy generation for eighteen different kinds of THEs. For the THENs, Cheng and Liang [18] showed that the entropy generation

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and the entropy generation number both increase first and then decrease with increasing effectiveness when the heat capacity flow rates and the inlet temperatures of the streams are prescribed. Therefore, the entropy generation paradox also exists in THENs. It means that the applicability of the minimization of entropy generation number is conditional in the analyses of heat transfer rate in THEs and THENs.

To remove the entropy generation paradox, the concept of revised entropy generation number was proposed [19,20]. The effectiveness increases with decreasing revised entropy generation number for fixed heat capacity flow rates and the stream inlet temperatures, so there is no paradox between the revised entropy generation number and the effectiveness. This conclusion is also true for THENs since the expression for the entropy generation in THENs is the same as that in THEs [18]. However, for the case in which the inlet temperatures and the ratios of the heat transfer rate to the heat capacity flow rates are prescribed, the revised entropy generation number keeps constant with increasing heat transfer rate [18]. Therefore, the minimum revised entropy generation number does not always lead to the best performance of THEs and THENs, either.

To evaluate the performance of heat transfer, other theories have been developed, such as the entransy theory [21]. There is no paradox similar to the entropy generation paradox in THEs and THENs [18,22]. The minimum entransy-dissipation-based thermal resistance always leads to the largest heat transfer rate.

The concept of entropy generation has very wide applications. With the thermodynamic viewpoint, we try to further develop the performance evaluation of THEs and THENs based on this concept so as to remove the paradox. The largest heat transfer rate of THEs and THENs depends on structure or operation parameters. This problem can be expressed as

$$\begin{cases} \max Q \\ Q = Q(G, O) \end{cases}, \tag{1}$$

where Q is the heat transfer rate of THEs and THENs, G represents the structure parameters, and O represents the operation parameters. In this paper, we mainly focus on the influence of the operation parameters. A new concept, *heat transfer entropy resistance*, is defined and applied to analyzing the problem.

2. Entropy generation and entropy resistance in heat transfer

For any steady heat transfer process, the entropy balance equation gives [23,24]

$$dS = dS_f + \delta S_g, \tag{2}$$

where dS is the entropy change, dS_f is the entropy flow, and δS_g is the entropy generation. As the system is steady, dS equals to zero. Therefore, the entropy generation of the system is

$$\begin{aligned} S_g &= \int \delta S_g = -\int dS_f = S_{f-out} - S_{f-in} \\ &= \int_{A_{out}} \frac{q_{out}}{T} dA - \left(\int_{A_{in}} \frac{q_{in}}{T} dA + \int_V \frac{Q_V}{T} dV \right). \end{aligned} \tag{3}$$

where T is the temperature, Q_V is the inner heat source, V is the volume of the system, A is the area of the system surface, q_{out} is the heat flux out of the system through the area A_{out}, q_{in} is the heat flux into the system through the area A_{in}, $S_{f\text{-}out}$ is the entropy flow out of the system, and $S_{f\text{-}in}$ is the entropy flow into the system.

Considering the energy conservation, we can define the heat transfer rate of the system as

$$Q = \int_{A_{out}} q_{out} dA = \int_{A_{in}} q_{in} dA + \int_V Q_V dV. \tag{4}$$

The reciprocal of temperature $(1/T)$ is regarded as the thermodynamic force and the heat transfer rate is the corresponding flow [25–27]. The equivalent thermodynamic forces for the heat flow into and out of the system can be defined as

$$H_{in} = \frac{S_{f-in}}{Q} = \left(\int_{A_{in}} \frac{q_{in}}{T} dA + \int_V \frac{Q_V}{T} dV \right) \Big/ Q, \tag{5}$$

$$H_{out} = \frac{S_{f-out}}{Q} = \int_{A_{out}} \frac{q_{out}}{T} dA \Big/ Q, \tag{6}$$

respectively. Then, Eq. (3) can be changed as

$$S_g = Q(H_{out} - H_{in}) = Q\Delta H, \tag{7}$$

where ΔH is the equivalent thermodynamic force difference. According to the non-equilibrium thermodynamics and the Onsager's theory [25,26], entropy generation is the product of the generalized force and the corresponding generalized flow. Therefore, Eq. (7) shows that ΔH is the driving force and Q is the corresponding flow. Larger entropy generation leads to larger heat transfer rate for prescribed equivalent thermodynamic force difference, while smaller entropy generation leads to smaller equivalent thermodynamic force difference. This is the extremum principle of entropy generation in heat transfer.

Considering that ΔH is the thermodynamic force difference and Q is the corresponding flow in heat transfer, we can define the heat transfer entropy resistance as

$$R_S = \frac{\Delta H}{Q} = \frac{S_g}{Q^2}. \tag{8}$$

It can be found that smaller heat transfer entropy resistance leads to smaller equivalent thermodynamic force difference with prescribed heat transfer rate and larger heat transfer rate with prescribed equivalent thermodynamic force difference. The extremum principle of entropy generation can be replaced by the minimum principle of heat transfer entropy resistance. Smaller heat transfer entropy resistance leads to better heat transfer from the viewpoint of thermodynamics.

For heat transfer analyses, the entropy generation minimization method [3,4] is often used, and the concepts of entropy generation numbers [3,4] and revised entropy generation number [19,20] were developed. The definitions of the entropy generation numbers [3,4] and the revised entropy generation number [19,20] are

$$N_{S1} = \frac{S_g}{C_{min}}, \tag{9}$$

$$N_{S2} = \frac{S_g}{S_{g-min}}, \tag{10}$$

$$N_{RS} = \frac{T_{in-c} S_g}{Q}, \tag{11}$$

where $S_{g\text{-}min}$ is the minimum entropy generation of THEs and THENs, and C_{min} is the minimum heat capacity flow rate in the heat transfer process. The first entropy generation number N_{S1} has the same variation tendency as that of the entropy generation when the heat capacity flow rates of the streams are prescribed, while the