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On Effectiveness and Entropy Generation in Heat Exchanger

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Some conceptual problems were discussed in the present paper. Firstly, according to the physical meaning of effectiveness, a new expression of effectiveness was developed by using an ideal heat exchanger model and temperature histogram method, in which the non-uniform inlet temperature profile was considered. Secondly, the relation of entropy generation number to effectiveness was studied, it was pointed out that both of them could express the perfect degree of a heat exchanger to the second thermodynamic law. Finally, to describe both quantity and quality of heat transferred in a heat exchanger, a criterion named as comprehensive thermal performance coefficient (CTPE) was presented.

Keywords: heat exchanger, effectiveness, entropy generation number, comprehensive thermal performance coefficient.

INTRODUCTION

Heat exchangers are widely used in engineering fields, for example, in oil refining, oxygen production, thermal management in space station, etc.. Hence how to upgrade the thermal performance of a heat exchanger is continuously an important topic in heat exchangers' study. There are several criteria used to evaluate the performance of a heat exchanger, such as quantity of heat transferred, effectiveness, entropy generation, and so on. Usually, effectiveness is regarded as a criterion based on the first law of thermodynamics and entropy generation number is a criterion to express the perfect degree of the heat exchanger to the second law. It is necessary to make further discussion on the effectiveness and entropy generation in order to optimize the design of heat exchangers.

The layout of this paper is as follows. In section two, an ideal heat exchanger model and temperature histogram method are introduced to obtain maximum possible quantity of heat transferred under different conditions and a new expression of effectiveness of a heat exchanger with non–uniform inlet temperature profiles is given. In section three, a new definition of entropy generation number different from that defined by Bejan (1982) is put forward. The relationship between effectiveness and entropy generation number is discussed and analyzed in detail in section four. Finally, a new assessment criterion named as comprehensive thermal performance coefficient is developed.

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Analysis of Effectiveness

1. Expressions of effectiveness

It is well known that the effectiveness of a heat exchanger is defined as:

$$\text{effectiveness} = \frac{\text{real quantity of heat transferred}}{\text{maximum possible quantity of heat transferred}} \tag{1}$$

When the inlet and outlet temperatures are both uniform, the effectiveness can be expressed as:

$$\varepsilon = (\Delta T, \Delta t)_{\max}/(T_{\text{in}} - t_{\text{in}}) \tag{2}$$

and if the inlet or outlet temperature is not uniform, the following expression is used:

$$\varepsilon = (\overline{\Delta T}, \overline{\Delta t})_{\max}/(\overline{T_{\text{in}}} - \overline{t_{\text{in}}}) \tag{3}$$

Guo (1984) pointed out that the effectiveness may be greater than unity when Eq.(3) is used under some special non–uniform inlet temperature profiles. So it

Nomenclature

C_p	special heat capacity
C_r^*	$(mc_p)_c/(mc_p)_h$
L	distribution length of fluid
m	mass flow rate
NTU	number of heat transfer unit
N_s	entropy generation number
Q	quantity of heat exchange
R_t	$t_{\text{in}}/T_{\text{in}}$
S_{gen}	entropy generation
t	temperature of cold fluid
T	temperature of hot fluid
x	coordination
ε	effectiveness
ε^*	$(t_{\text{out}}-t_{\text{in}})/(T_{\text{in}}-T_{\text{out}})$
η	comprehensive thermal performance coefficient
Δ	difference between two coefficients

Superscript

$-$	average

Subscripts

c	cold fluid
C_r	imbalance
eq	equivalent entropy generation
h	hot fluid
ideal	ideal heat exchangers
in	inlet
max	maximum value
new	Ns defined by Xu (1993)
ntu	finite area of heat exchange
old	Ns defined by Bejan
out	outlet
s	entropy

does not satisfy the definition of effectiveness. Hence Guo (1984) gave another expression when the inlet temperature is non–uniform:

$$\varepsilon = (\overline{\Delta T}, \overline{\Delta t})_{\max}/(T_{\text{in, max}} - t_{\text{in}}) \quad (4)$$

It means that the potent of heat transfer of hot fluid is lowered and the potent of absorbing heat of cold fluid is reduced when its non–uniform inlet temperatures are averaged. Therefore, the expression $(mc_p)_{\min}(\overline{T_{\text{in}}})$ in Eq.(3) can not represent the maximum possible quantity of heat transferred. For Eq.(4), although the effectiveness can be never greater than unity, but its application is confined within a limit of the heat capacity rate of hot fluid being much more than that of cold fluid. In fact, the deficiency of above two expressions is that the maximum possible quantity of heat transferred of the heat exchanger is not exactly expressed.

2. Maximum possible quantity of heat transferred

Sekulic (1990a) thought "a heat exchanger is a device which provides for change of the mutual thermal energy (exergy) levels between two or more fluids in thermal contact without external heat and work interactions," we think it is better than the well–known definition of "the heat exchanger is a device used to transfer thermal energy between two or more fluids at different temperatures", so we'll analyze the maximum possible quantity of heat transferred from the viewpoint of the analysis on thermal energy (exergy) levels.

Let's imaging that there exists an ideal heat exchanger: it can transfer the maximum possible quantity of heat for given inlet parameters. Then, what characters will it have? Firstly, it should have an infinite potent of heat exchange, that is, any possibility of heat transfer from hot fluid to cold fluid can be realized. Secondly, the heat exchanger should be perfect to the second law, i.e., no entropy generation.

Based on above discussion, the maximum possible quantity of heat transferred may be obtained from the inlet parameters by using the ideal heat exchanger model and temperature histogram method no matter what is the structure of heat exchanger. The temperature histogram method is explained in detail as follows:

Consider the mass flow distributions of hot fluid and cold fluid being uniform and the temperature profiles monotone decreasing (in an ideal heat exchanger, non–monotone distribution of temperature profile can be adjusted equivalently to monotone distribution). Overlap the temperature blocks of the hot fluid and the cold one with a special rule (explain in detail later). In the area overlapped, the outlet temperature of the hot fluid is equal to the inlet temperature of cold fluid, the outlet temperature of the cold fluid is equal to the inlet temperature of the hot fluid, that is to say, the hot fluid exchanges its energy degree with the cold fluid completely. In the other area, no energy is exchanged. The schematic is shown in Fig.1.

It is obvious that: 1) The temperature of the "hot fluid" is lower or equal to the temperature of the "cold fluid" at the outlet of the ideal heat exchanger. It means that the "hot fluid" can never transfer its energy to the "cold fluid", so the whole potent of heat exchange between the two strands fluids was realized. Therefore, the heat transferred by the ideal heat exchanger is equal to the maximum possible quantity of heat transferred. 2) There is no entropy generation due to heat exchange.

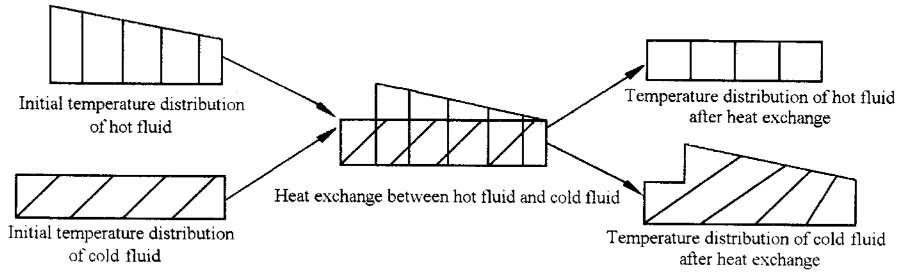

Fig.1 Schematic of temperature histogram method

3. Effectiveness of heat exchanger with non-uniform inlet temperature

As mentioned above, the maximum possible quantity of heat transferred can be obtained by using the ideal heat exchanger model and temperature histogram method. The monotone decreasing inlet temperature of the ideal heat exchanger can be got from redistributing any given inlet temperature profile. The overlapped rule in the temperature histogram method is: i) when the heat capacity rate of hot fluid is less than the cold fluid, they will overlap from their low temperature side (Fig.2(a)), ii) when the heat capacity rate of hot fluid is more than the cold fluid, they will overlap from higher temperature side (Fig.2(b)), iii) when the heat capacity rate of hot fluid equals to the cold fluid, they can overlap from any side (Fig.2(c)). So we can obtain a more accurate expression of effectiveness of heat exchangers with non-uniform inlet temperature from Fig.2:

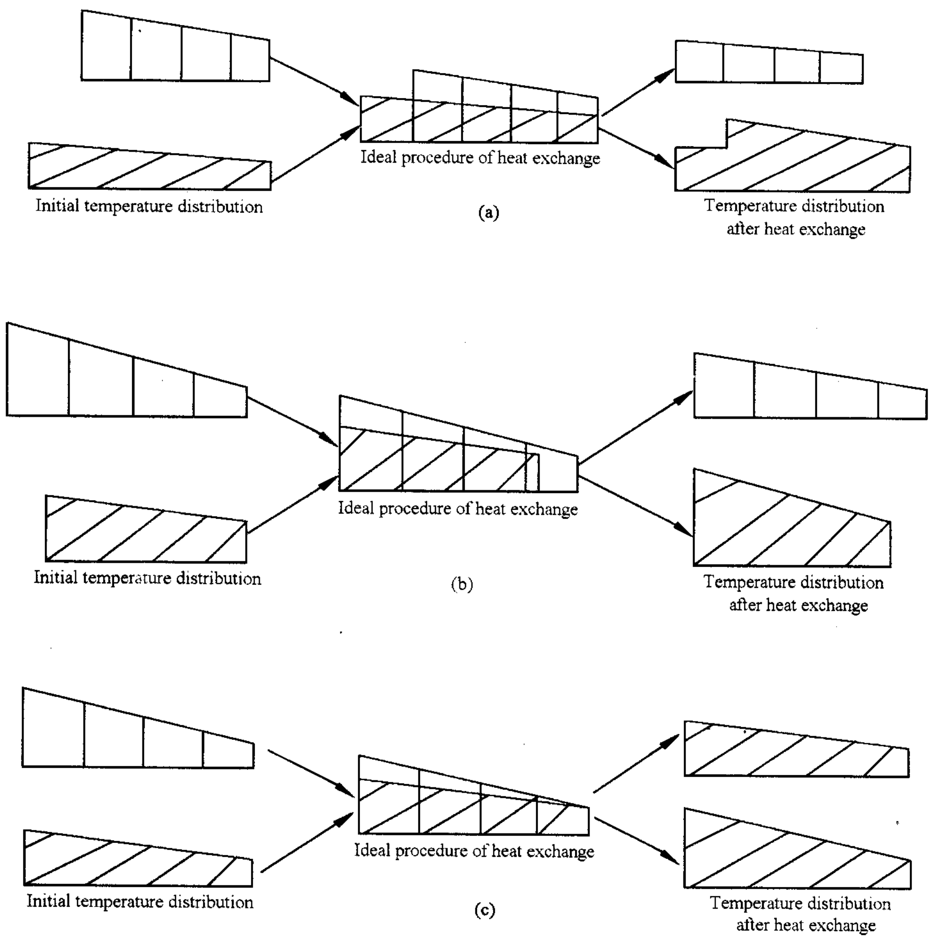

Fig.2 Determination of maximum possible quantity of heat transfer

$$Q_{\max} = \frac{(mc_p)_{\min}}{L_{\min}} \int_0^{L_{\min}} \max(T_{\text{in}}(x) - t_{\text{in}}(x), 0)dx \quad (5)$$

$$\varepsilon = Q/Q_{\max} = (\overline{\Delta T}, \overline{\Delta t})_{\max} / \int_0^{L_{\min}} \max(T_{\text{in}}(x) - t_{\text{in}}(x), 0,)/L_{\min} dx \quad (6)$$

From the expression of effectiveness of heat exchanger, Eq.(6), we can conclude that:

1) If the inlet temperature profiles of cold fluid and hot fluid are uniform, the definition of effectiveness, Eq.(1) is equivalent to Eq.(6);

2) If the heat capacity rate of hot fluid is equal to the cold fluid, Eq.(2) can be derived from Eq.(6);

3) If the heat capacity rate of hot fluid is much larger than the cold fluid, Eq.(3) is a good approximation of Eq.(6);

Therefore, Eq.(6) is a better expression of effectiveness than equations (1)~(3). The reason is that not only the maximum possible quantity of heat transferred can be calculated from Eq.(5), but also it is suitable to any inlet conditions.

Analysis of Entropy Generation

1. Deficiency of entropy generation number defined by Bejan

To express the efficiency of the second thermodynamic law in a heat exchanger, Bejan firstly defined a parameter named entropy generation number, its meaning is the entropy generation per unit smaller heat capacity rate of the fluid flow. The expression is:

$$N_s = S_{gen}/(mc_p)_{\min} \quad (7)$$

Many scholars have done plenty of works since then (Chiou, 1982; Guo, 1986; Li, 1990; Guo, 1990; Linetskil, 1988). Fig.3(a) shows the relation of entropy generation number vs. effectiveness. It can be seen from Fig.3(a) that N_s will tend to zero when ε towards zero. Bejan (1987) thought it is difficult to explain clearly why N_s rises to maximum at the point where ε is equal to 0.5 and why N_s tends to zero as ε tends to zero. Xu (1993) also enumerated some troubles due to Eq.(7), especially in phase change heat exchangers. All this proved that the definition of the entropy generation, Eq.(7), exists drawback.

In fact, it is more reasonable to evaluate the irreversibility due to heat transfer in a heat exchanger using the entropy generation per unit heat transferred, i.e.

$$N_{\text{s,new}} = S_{\text{gen}}(T_{\text{in}} - t_{\text{in}})/Q \quad (8)$$

It is named as new entropy generation number. When the entropy generation due to pressure drop irreversibility is negligible, the expression of entropy generation is:

$$S_{\text{gen}} = (mc_p)_h \ln(T_{\text{out}}/T_{\text{in}}) + (mc_p)_c \ln(t_{\text{out}}/t_{\text{in}}) \quad (9)$$

Using energy conservation law and combining Eq.(8) and (9) we have:

$$N_{\text{s,new}} = \left\{ \ln\left[+ \varepsilon^*(1/R_t - 1)\right] + \ln\left[1 - \varepsilon^* C_r^*(1 - R_t)\right]/C_r^* \right\}/\varepsilon^* \quad (10)$$

Here ε^* equals to $(t_{\text{out}} - t_{\text{in}})/(T_{\text{in}} - T_{\text{out}})$, C_r^* equals to $(mc_p)_c/(mc_p)_h$, R_t equals to $t_{\text{in}}/T_{\text{in}}$.

Fig.3(b) shows the relation of entropy generation number vs. effectiveness defined by Eq.(10). It can be seen from Fig.3(b) that though the entropy generation is small at the position where effectiveness is small, the entropy generation number is larger and hence the efficiency of the second thermodynamic law is still

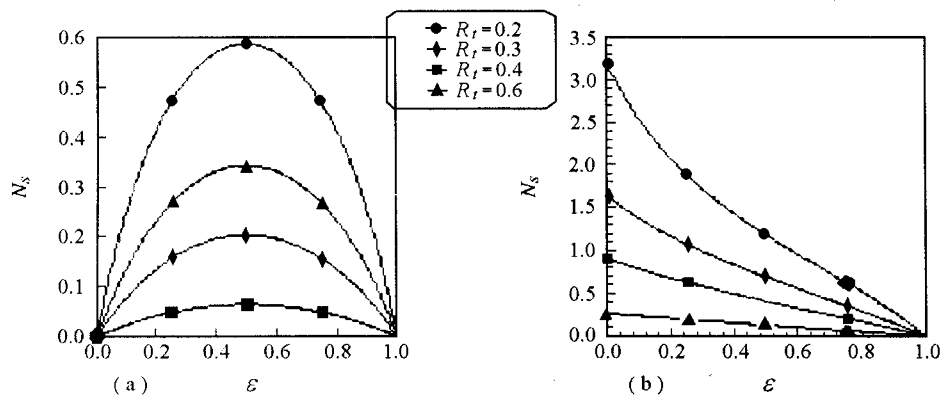

Fig.3 Curves of effectiveness vs. entropy generation number

lower. It means that at this region the relative irreversibility is larger than other region. The new definition can well explained what Bejan was puzzled. From the analysis on new and old definitions of effectiveness, we find:

$$N_{s,new} = \frac{S_{gen}(T_{in} - t_{in})}{Q} = \frac{S_{gen}(T_{in} - t_{in})}{(mc_p)_{min}(\Delta T, \Delta t)_{max}} = N_{s,old} \cdot \varepsilon \quad (11)$$

In fact, the essence of the entropy generation number should be entropy generation per unit heat transferred, S_{gen}/Q, and $(T_{in} - t_{in})$ is only a characteristic temperature difference. The difference between the old and new definitions of entropy generation number is the selection of the characteristic temperature difference. In the old definition it is $(\Delta T, \Delta t)_{max}$ and in the new one is $(T_{in} - t_{in})$. We think the characteristic temperature difference should depend on the inlet parameters and not on the result of heat exchange. Fig.4 shows the comparison between entropy generation numbers calculated according to the old and new definitions for counterflow, parallelflow and two-side-mixed crossflow heat exchangers.

2. Classification of entropy generation number

Bejan (1982) divided entropy generation of counterflow heat exchanger into two parts: one is due to flow imbalance and the other is due to finite surface area of heat transfer (i.e. NTU is finite). In fact, this classification can be used for all heat exchangers. We use $N_{s,cr}$ and $N_{s,ntu}$ to express the two parts of entropy generation number respectively, where $N_{s,cr}$ is due to flow imbalance and $N_{s,ntu}$ is due to finite surface area of heat transfer. Eq.(12) and (13) are their expressions under the conditions of the inlet and outlet temperature profiles being uniform.

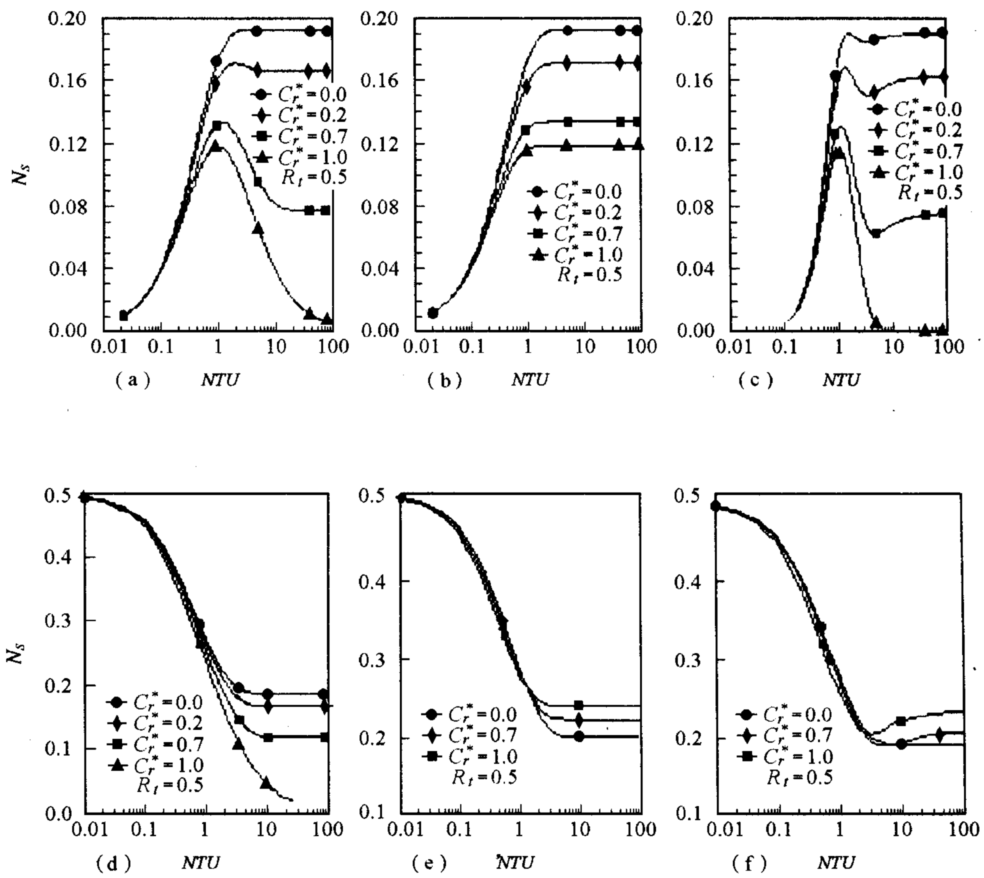

Fig.4 Relation curves of NTU vs. entropy generation number
(a) (b) (c) is "old" definition by Bejan (1982), (d) (e) (f) is new definition entropy generation number (a) and (d) are counterflow, (b) and (e) are parallelflow, (c) and (f) are two-side-mixed crossflow

$$N_{s,cr}=\begin{cases}\Big\{\dfrac{1}{C_r^*}\ln\left[1-\varepsilon C_r^*(1-R_t)\right] \\ \quad -\ln\left[1-\varepsilon(1-R_t)\right]\Big\}/\varepsilon \quad C_r^*<1.0 \\ \Big\{C_r^*\ln\Big[1+\dfrac{\varepsilon}{C_r^*}\Big(\dfrac{1}{R_t}-1\Big)\Big] \\ \quad -\ln\Big[1-\varepsilon\Big(\dfrac{1}{R_t}-1\Big)\Big]\Big\}/\varepsilon \quad C_r^*>1.0\end{cases} \tag{12}$$

$$N_{s,ntu}=\begin{cases}\Big\{\ln\Big[1+\varepsilon\Big(\dfrac{1}{R_t}-1\Big)\Big] \\ \quad +\ln\left[1-\varepsilon(1-R_t))\right]\Big\}/\varepsilon \quad C_r^*<1.0 \\ \Big\{\ln\Big[1+\varepsilon\Big(\dfrac{1}{R_t}-1\Big)\Big] \\ \quad +\ln\left[1-\varepsilon(1-R_t))\right]\Big\}/\varepsilon \quad C_r^*>1.0\end{cases} \tag{13}$$

Fig.5 shows the relations of $N_{s,cr}$ and $N_{s,ntu}$ vs. effectiveness for a given $C_r^* = 0.5, R_t = 0.5$. In the figure, $N_{s,ntu}$ decreases monotonically with the decrease of effectiveness. At the point that ε equals to zero, $N_{s,ntu}$ is also equal to zero. $N_{s,cr}$ decreases with the increase of ε and reaches maximum when ε equals to unity. And when C_r^* approaches unity, $N_{s,cr}$ will reach minimum for a given effectiveness.

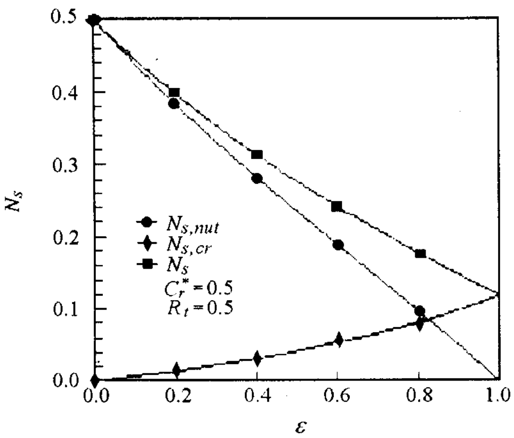

Fig.5 Classification of entropy generation

Criterion for Evaluating the Thermal Performance

1. Physical instinct of effectiveness

Usually effectiveness is regarded as a criterion based on the first law of thermodynamics. But in fact, we would like to say that effectiveness is a criterion based on the second thermodynamic law. That is to say, same as entropy generation number, what the effectiveness expresses is the efficiency of the second thermodynamic law of a heat exchanger. It can be demonstrated in two ways:

Firstly, it can be seen from Fig.3(b) that entropy generation number monotonically decreases with the increase of effectiveness when inlet and outlet temperature is uniform, i.e., they have one–to–one corresponding relationship. It indicates that effectiveness is of same physical insight with entropy generation number. Secondly, the definition of effectiveness indicates that it is a ratio of real quantity of heat transferred to maximum possible quantity of heat transferred. The maximum possible quantity of heat transferred, shown in section two, is a limit which can be realized through an ideal heat exchanger which reaches top perfection of the second law. So effectiveness can be regarded as parameter which shows the perfect degree of the real heat exchange process compared with the ideal process. Different from entropy generation number, effectiveness expresses the perfect degree of the second law from the quantity of heat transferred.

2. Deficiency of effectiveness and entropy generation number

In industry, effectiveness is a very important criterion, the higher the effectiveness, the better the heat exchanger. But on the side of energy effective utility, the less the lose of energy degree (exergy) in heat exchange, the better the heat exchanger, i.e., the entropy generation number due to heat exchange must be lower if we want to fully utilize the quality of energy. So, a good heat exchanger must have good thermal performance both in quantity and quality of heat exchange. But from our analysis, each of the effectiveness and entropy generation number can not well describe the comprehensive thermal performance. A special thing is that when the inlet and outlet temperature profiles are uniform, the higher the effectiveness, the less the entropy generation number, i.e., larger quantity of heat transferred and lower entropy generation can be expressed by effectiveness or entropy generation at the same time. Under this condition they can well describe the comprehensive performance. But in a real process of heat exchange, the inlet and outlet temperatures, especially outlet temperature distribution, are usually non–uniform, the entropy generation number has a complex relation (see Fig.6). The solid curve expresses the relation of effectiveness and entropy generation number under uniform inlet and outlet temperature profiles. With non–uniform inlet or outlet temperature distributions, the entropy generation number can be any value between zero and N_s^* for a given effectiveness, and the effectiveness can be any value between zero and ε^* for a given entropy generation number.

As a parameter to describe the thermal performance of heat exchanger, effectiveness can not describe the quality of heat exchange. Sometimes, effectiveness equals to unity but the entropy generation due to heat exchange still exists. In Fig.7, the effectiveness is unity, but in Fig.7(a) the entropy generation is zero and in Fig.7(b) entropy generation is not equal to zero. On the other hand, entropy generation number can describe the quality of heat exchange, but it can not express the quantity of heat exchange. Fig.8(a) and (b) shows although entropy generation number is zero, the corresponding effectiveness can be equal to unity and less then unity separately.

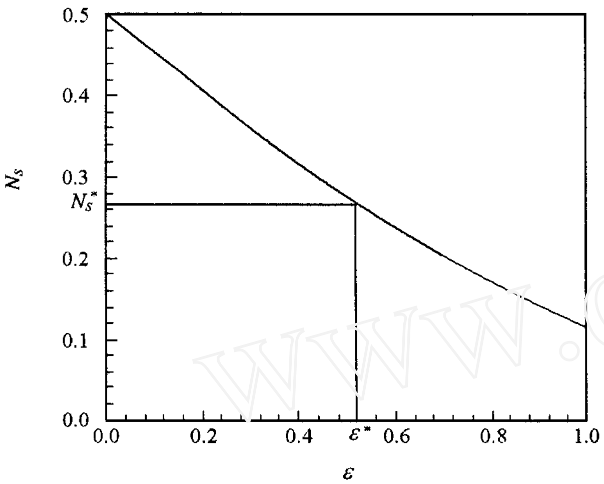

Fig.6 Curve of effectiveness and entropy generation number under non–uniform inlet and outlet temperature profiles

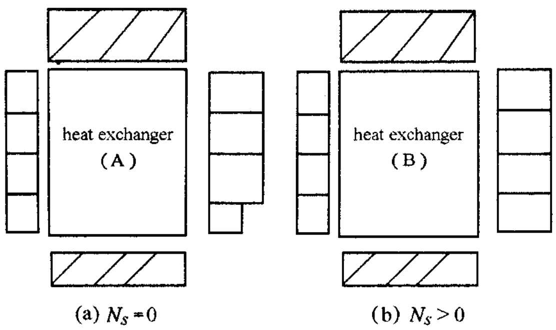

Fig.7 Entropy generation number under effectiveness is unity

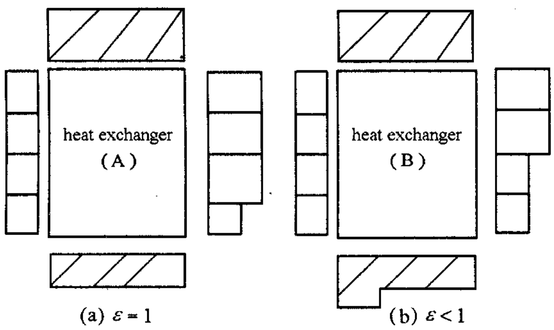

Fig.8 Effectiveness when entropy generation number is equal to zero

In brief, effectiveness and entropy generation number all have deficiency to evaluate the comprehensive thermal performance. Sekulic (1990b) presented a criterion named heat exchange reversibility norm (HERN) to evaluate the thermal performance of a heat exchanger, but it has little difference from entropy generation number. In the following, we will present new parameters to evaluate the thermal performance of a heat exchanger comprehensively.

3. Equivalent entropy generation and comprehensive thermal performance coefficient

3.1. Equivalent entropy generation From above discussion, it can be seen that effectiveness and entropy generation can well describe the quantity and quality of heat exchange in a heat exchanger separately. Why not combine them into one parameter to evaluate both in quality and quantity of heat exchange? From our analysis on new definition of entropy generation number, a parameter named equivalent entropy generation is induced as follows:

$$S_{\rm eq} = S_{\rm gen}/Q \tag{14}$$

Although it is similar to entropy generation number, there are two main difference between them: 1) Equivalent entropy generation is more comprehensive than entropy generation number, it includes all the effects on the thermal performance of heat exchange process due to inlet parameters and the structure of a heat exchanger, especially due to non–uniform inlet and outlet temperature distributions. 2) Entropy generation number is a dimensionless and equivalent entropy generation is a dimensional parameter which expresses entropy generation per unit heat transferred. Its physical meaning is more clear and directly expresses the relation of quality vs. quantity of heat transferred.

3.2. Comprehensive thermal performance coefficient (CTPE) As discussed above, the equivalent entropy generation can describe the thermal performance of a heat exchanger, in which both quantity and quality of heat transferred are concerned. Nevertheless, when two heat exchangers have same $S_{\rm eq}$ but with different quantity of heat transferred, then which is better? Obviously, the heat exchanger with larger quantity of heat transferred is better, but the equivalent entropy generation can not distinguish it.

Hence, it is necessary to find out a criterion which can describe both quantity and quality of heat transferred. The maximum possible quantity of heat transferred discussed about actually represents the top target of quantity and quality of heat exchange in a heat exchanger simultaneously. Compared with the maximum possible quantity of heat transferred (not only in quantity, but also in shape of the outlet temperature profiles), a parameter named comprehensive thermal performance coefficient (CTPE) can be defined to evaluate the thermal performance of a heat exchanger. Its expression is:

$$\eta = 1 - \Big(\frac{\int_0^{L_h} |T_{\text{out}}(x) - T_{\text{ideal}}(x)|dx}{2\int_0^{L_h} |T_{\text{in}}(x) - T_{\text{ideal}}(x)|dx} + \frac{\int_0^{L_c} |t_{\text{out}}(x) - t_{\text{ideal}}(x)|dx}{2\int_0^{L_c} |t_{\text{in}}(x) - t_{\text{ideal}}(x)|dx}\Big) \quad (15)$$

Eq.(15) is a shaped comparison parameter, i.e., the closer the distribution of outlet temperature approaches to the ideal temperature profile obtained from the ideal heat exchanger model, the higher the CTPC is. Fig.9 is a comparison of effectiveness, entropy generation number and comprehensive thermal performance coefficient.

it is obviously that CTPC can express the comprehensive thermal performance of a heat exchanger both in quantity and quality of heat transferred.

CONCLUDING REMARKS

1) According to the physical insight of effectiveness of heat exchanger, a more accurate expression of the effectiveness of heat exchanger with non-uniform inlet temperature profile is presented.

2) The definition of entropy generation number given by Bejan is improved. After studying the relation of entropy generation number to effectiveness it is concluded that both of them are criteria to convey the perfect degree of the second thermodynamic law.

3) A criterion, comprehensive thermal performance coefficient, is developed. It can describe the thermal performance of heat exchanger both in quantity and quality of heat exchange, and it is better to describe the comprehensive performance than other criteria such as effectiveness and entropy generation number.

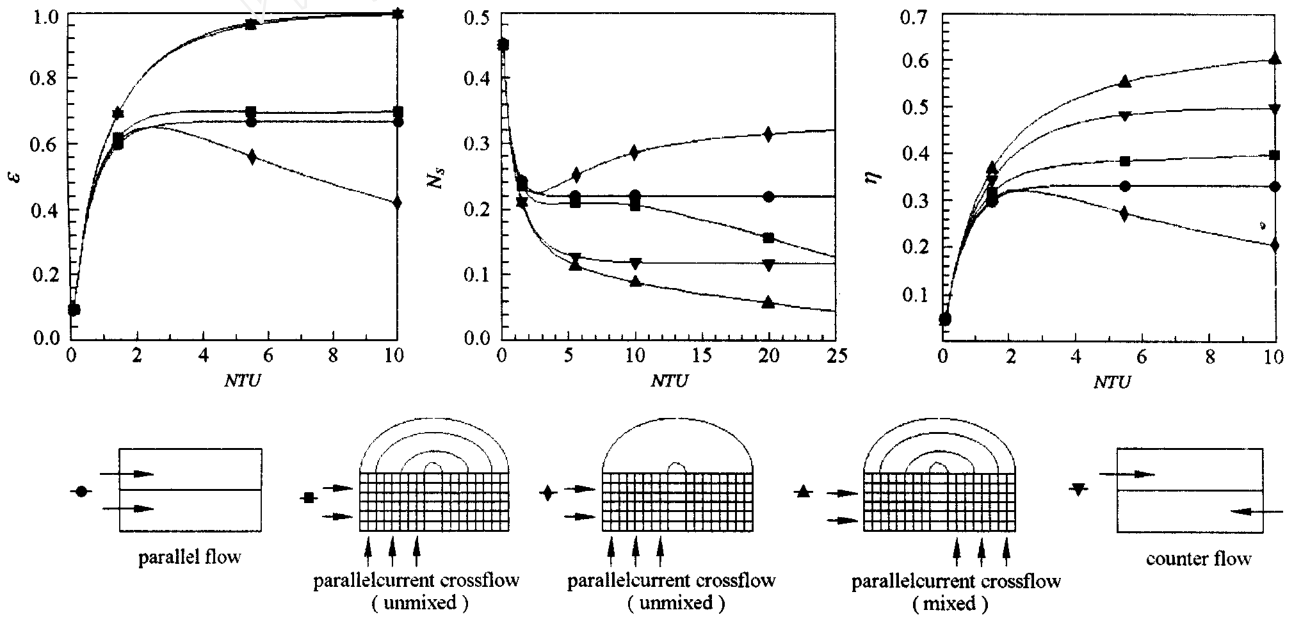

Fig.9 Comparison among ε, N_S, CTPC ($C_r^* = 0.5, R_t = 0.5$)

It is shown in Fig.9 that the counterflow heat exchanger has a little higher effectiveness than countercurrent crossflow (unmixed) device, but its entropy generation number is greater than the later, so the CTPC of counterflow heat exchanger is less than that of the countercurrent crossflow heat exchanger. The parallelcurrent crossflow (strongly mixed) heat exchanger has the least effectiveness and highest entropy generation number, hence its CTPC is the least. The results of parallelflow and parallel crossflow (unmixed) heat exchangers locate between those of parallelflow and counterflow devices. From its definition and Fig.9,

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