A Modified Entropy Generation Number for Heat Exchangers

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This paper demonstrates the difference between the entropy generation number method proposed by Bejan and the method of entropy generation per unit amount of heat transferred in analyzing the thermodynamic performance of heat exchangers, points out the reason for leading to the above difference. A modified entropy generation number for evaluating the irreversibility of heat exchangers is proposed which is in consistent with the entropy generation per unit amount of heat transferred in entropy generation analysis. The entropy generated by friction is also investigated. Results show that when the entropy generated by friction in heat exchangers is taken into account, there is a minimum total entropy generation number while the NTU and the ratio of heat capacity rates vary. The existence of this minimum is the prerequisite of heat exchanger optimization.

Keywords: entropy generation, heat exchanger.

INTRODUCTION

Heat exchangers are widely used in various industrial branches. In the interests of effective use of energy, heat exchanger analysis from the viewpoint of the second law of thermodynamics has attracted some researchers' attention. Of course, it would be nice to have a reversible heat exchanger, but since heat transfer process is inherently irreversible, the only thing we can do in engineering applications is to reduce the irreversibility of the heat transfer process. Bejan (1977) is the first one introducing the concept of "entropy generation" to the design of heat exchangers. This concept provides a common conceptual basis for thermal optimization of heat exchangers and the entropy generation number method of heat exchanger optimization proposed by him was the subject of several recent studies by Bejan (1978, 1980, 1982, 1988, 1994), Baclie and Selulic (1978), Sarangi and Achowdburg (1982), Huang (1984), Sekulic and Balic (1984), de Costa and Saboya (1986), Sekulic and Nerman (1986), Sekulic (1985-1986, 1986), Lanzhou Petroleum Machinery Institute (1985), Sekulic (1990), Guo (1992) and Demirel (1995).

COMMENTS ON BEJAN'S ENTROPY GENERATION NUMBER

In order to evaluate the irreversibility loss in heat exchangers, Bejan (1982) redefined the entropy generation number as

\[ N_s = \frac{S_{gen}}{(mcp)_{min}} \]  \hspace{1cm} (1)

and he indicated that the smaller the entropy generation number, the better the performance of the heat exchanger would be.

In order to clear up the physical interpretation of Bejan's entropy generation number multiplying both the numerator and denominator by \( \Delta T_{min} \) (the temperature rise or drop of the fluid with the smaller heat capacity rate) yields
Nomenclature

\begin{align*}
A & \quad \text{heat transfer area} \\
c_p & \quad \text{specific heat at constant pressure} \\
d & \quad \text{inside diameter} \\
D & \quad \text{outside diameter} \\
E_u & \quad \text{Euler number} \\
f & \quad \text{friction factor} \\
h_{fg} & \quad \text{latent heat} \\
k & \quad \text{specific heat ratio} \\
L & \quad \text{length of tube in a single pass} \\
m & \quad \text{mass flow rate} \\
n & \quad \text{number of tubes} \\
N_s & \quad \text{entropy generation number} \\
N_s' & \quad \text{modified entropy generation number} \\
NTU & \quad \text{number of heat transfer units} \\
p & \quad \text{pressure} \\
\Delta p & \quad \text{pressure drop} \\
Q & \quad \text{heat transfer rate} \\
\dot{S}_{\text{gen}} & \quad \text{entropy generation rate} \\
St & \quad \text{Stanton number} \\
T & \quad \text{temperature} \\
\Delta T_b & \quad \text{maximum possible temperature difference} \\
U & \quad \text{overall heat transfer coefficient} \\
W & \quad \text{capacity ratio} \\
z & \quad \text{number of rows} \\
\beta & \quad \text{fouling layer thickness} \\
\zeta & \quad \text{local friction coefficient} \\
\lambda & \quad \text{thermal conductivity} \\
\xi & \quad \text{shell side friction coefficient} \\
\rho & \quad \text{density} \\
\text{Subscripts} \\
c & \quad \text{cold fluid} \\
h & \quad \text{hot fluid} \\
i & \quad \text{inlet} \\
o & \quad \text{outlet}
\end{align*}

\[ N_s = \frac{\dot{S}_{\text{gen}} \Delta T_c}{(mc_p)\Delta T_c} = \frac{\dot{S}_{\text{gen}} \Delta T_c}{Q} \quad (1a) \]

Obviously, the physical interpretation of \( N_s \) is the dimensionless overall entropy generation rate, or the entropy generated per unit amount of heat transferred in the heat exchanger multiplied by the temperature change of the fluid with smaller heat capacity rate. The overall entropy generation rate can not be used to evaluate the performance of a heat exchanger. Although the entropy generated per unit amount of heat transferred in the heat exchanger is the criteria, multiplying the \( \Delta T_{\text{min}} \), which becomes larger when the area of the heat transfer surface of the heat exchanger increases, makes the \( N_s \) dimensionless, might lead to some ambiguities as illustrated in the following examples.

Example 1: Entropy generation due to heat transfer in condensers or evaporators.

Take a condenser as an illustrative example. In a condenser the fluid with larger heat capacity rate is the hot fluid, i.e. the condensing vapor, its temperature keeps constant through the process. Then the entropy generation rate of the whole condenser can be expressed as:

\[ \dot{S}_{\text{gen}} = -(\dot{m}h_{fg})_h + (mc_p)\ln(T_{co}/T_{ho}) \quad (2) \]

where entropy changes associated with the frictional pressure drops have not been included which will be described shortly. The outlet temperature of the cold fluid is

\[ T_{co} = T_{ci} + \Delta T_0(1 - e^{-NTU}) \quad (3) \]

in which \( \Delta T_0 = T_{hi} - T_{ci} \) is the maximum possible temperature difference. Combining Eqs.(1), (2) and (3), noticing \( (\dot{m}h_{fg})_h/(mc_p)_c = \Delta T_c \), and setting \( \theta = T_{in}/T_{ci} \), one obtains the entropy generation number of the condenser

\[ N_s = \ln[1 + (T_{hi}/T_{ci} - 1)(1 - e^{-NTU})] \]

\[ -(1 - T_{ci}/T_{hi})(1 - e^{-NTU}) \quad (4) \]

Curve 1 in Fig.1 shows the relationship between \( N_s \) and \( NTU \).

On the other hand, the problem might be analyzed directly on the basis of unit amount of heat transferred as follows. The total amount of heat transferred in the condenser

\[ Q = (mc_p)_c \Delta T_c \quad (5) \]

Then, from Eqs.(2) and (5), the entropy generation per unit amount of heat transferred in the condenser is

\[ \frac{\dot{S}_{\text{gen}}}{Q} = -\frac{1}{\Delta T_0(1 - e^{-NTU})} \]

\[ \cdot \ln\left[1 + (T_{h}/T_{ci} - 1)(1 - e^{-NTU})\right] - \frac{1}{T_h} \quad (6) \]

and shown diagrammatically in Fig.1 (curve 2).

Similar results were obtained for evaporator. It is surprising to see that variations of \( N_s \) are conceptually opposite to those of \( \dot{S}_{\text{gen}}/Q \). As a matter of fact, in a condenser or evaporator, the mean temperature