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A reconsideration of the definition of a heat exchanger

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INTRODUCTION

THE DEFINITION of a heat exchanger has been used for many years in its primarily well known and unchanged form. It is as follows: "The heat exchanger is a device used to transfer thermal energy between two or more fluids at different temperatures" [1]. This definition can be found either explicitly or implicitly in many student textbooks and engineering manuals. The statement is not incorrect and is unavoidable for design purposes. However, it seems to be inappropriate for the interpretation of some consequences of the Second Law of Thermodynamics.

There are a few reasons for this claim. A heat exchanger as a *system component* in many applications represents a device which provides an adequate 'thermal environment' for adjusting the required levels of thermal energy potentials of different fluids involved. The transfer of thermal energy is an unavoidable *consequence* of the thermal contact, but outlet thermal energy (or exergy) levels are the *targets* of the physical process mentioned. For example, this definition is, in fact, useless for multi-fluid heat exchangers, especially concerning the definition of the single, overall heat exchanger effectiveness [2, 3]. The pragmatic usability of the same definition is dubious in transient phenomena, too [4]. Furthermore, higher heat exchanger effectiveness (based on the above-mentioned heat exchanger definition) does not necessarily mean a better quality of energy transformation (based on the Second Law analysis [5]). At least but not last, the so-called 'entropy generation paradox' [6, 7], is the consequence of an inappropriate use of the conventional heat exchanger definition.

The purpose of this note is to point out the need for a more rigorous definition of a heat exchanger as a system component, especially in a thermodynamic analysis of a system.

DISCUSSION

Let us consider the inconsistency which might appear if the conventional heat exchanger definition (i.e. heat exchanger effectiveness) is used with no restriction in the analysis of the influence of thermal size of a heat exchanger regarding First and Second Law effectiveness.

What is the main reason for the possibly misleading interpretation of the heat exchanger definition? The present definition promotes the heat transfer rate ($\dot{Q}$) implicitly as the primary purpose of the existence of a heat exchanging device. The obvious proof for this statement is the useful definition of 'heat exchanger effectiveness' [4]:

$$\varepsilon = \frac{\dot{Q}}{\dot{Q}_{\max}} = f(\omega, N_{tu}, \text{flow arrangement}). \tag{1}$$

Consider a heat exchanger as a device used to change the quality of the energy (enthalpy or thermal exergy) level of the fluids in mutual thermal contact. The set of the relevant fluid variables will be defined as $\Gamma_i \equiv \{(\dot{m}c_p)_i, T_i, \ldots\}$. Therefore, the basic task of a heat exchanger can be expressed by the following logical propositional function:

$$(\Gamma_i^{\text{in}} \cap \dot{Q}) \supset \Gamma_i^{\text{out}}. \tag{2}$$

The thermal interaction of the fluids involved ($\Gamma^{\text{in}} \cap \dot{Q}$) implies the existence of the outlet set Γ^{out}. However, the heat transfer rate $\dot{Q}$ manifested itself only inside the imposed boundaries of the exchanger. Consequently, for the outside world, the result of bringing the set Γ^{in} into a thermal contact is only the outlet set Γ^{out} (the adiabatic heat exchanger). Having only the First Law of Thermodynamics in mind, the recognition of the heat transfer rate causes no inconsistency regarding the definition of a heat exchanger. However, when one considers the Second Law of Thermodynamics, the hidden inconsistency appears.

The entropy rate generated by a heat transfer process in a heat exchanger can be expressed by [5] (see the Appendix)

$$\frac{\dot{S}}{\dot{S}_{\max}} = f(\omega, N_{tu}, \tau, \text{flow arrangement}). \tag{3}$$

For the sake of simplicity in expression (3), only the irreversibility caused by the finite temperature differences has been taken into account (i.e. the contribution of the fluid friction to the overall entropy generation has been neglected). The irreversibility generated by the fluid friction is not a function of the thermal size of a heat exchanger, and consequently the conclusions would not be different if a more general expression for the entropy rate is considered.

It will be useful to reformulate the fundamental question regarding the heat exchanger definition in the following way: what are the limits of the quantitative consequences of the First and Second Laws of Thermodynamics (i.e. equations (1) and (3)), either for infinitely small ($N_{tu} \to 0$) of infinitely large ($N_{tu} \to \infty$) heat exchangers? The two heat exchanger flow arrangements will be considered:

(i) cocurrent—the worst, and
(ii) countercurrent—the best.

Figure 1 shows the result of the analysis performed. In addition to the well-known shape of the heat exchanger effectiveness curves, the $\dot{S}/\dot{S}_{\max}$ vs N_{tu} correlations are shown.

It is easy to conclude that the following limits exist:

$$\lim_{N_{tu} \to 0} (\dot{S}/\dot{S}_{\max}) = \lim_{N_{tu} \to 0} (\varepsilon) = 0 \, (0 \leqslant \omega \leqslant 1) \tag{4}$$

$$\lim_{N_{tu} \to \infty} (\dot{S}/\dot{S}_{\max})^{\rightrightarrows} = 1 \, (0 \leqslant \omega \leqslant 1);$$

$$\lim \varepsilon^{\rightrightarrows} = \begin{cases} 1 & \text{for} \quad \omega = 0 \\ <1 & \text{for} \quad \omega > 0 \end{cases} \tag{5}$$

$$\lim_{N_{tu} \to \infty} (\dot{S}/\dot{S}_{\max})^{\rightleftarrows} = \begin{cases} 1 & \text{for} \quad \omega = 0 \\ 0 & \text{for} \quad \omega = 1 \end{cases}; \quad \lim_{N_{tu} \to \infty} \varepsilon^{\rightleftarrows} = 1 \, (0 \leqslant \omega \leqslant 1) \tag{6}$$

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NOMENCLATURE

c_p	specific heat at constant pressure [J kg^{-1} K^{-1}]
$\dot{m}$	mass flow rate [kg s^{-1}]
N_{tu}	number of heat transfer units [dimensionless]
$\dot{Q}$	heat transfer rate [W]
$\dot{S}$	entropy generation within the heat exchanger [W K^{-1}]
T	temperature [K].

Greek symbols

Γ	set of relevant fluid variables
ε	heat exchanger effectiveness [dimensionless]
τ	fluids inlet temperature ratio, (T_1^{in}/T_2^{in}) [dimensionless]
ω	heat capacity rate ratio, $[(\dot{m}c_p)_{min}/(\dot{m}c_p)_{max}]$ [dimensionless].

Subscripts

i	fluid stream ($i = 1, 2$)
min	minimum value
max	maximum value.

Superscripts

$\rightrightarrows$	cocurrent
$\rightleftarrows$	countercurrent
*	at maximum entropy generation
in	inlet
out	outlet.

Miscellaneous

@	at
$\cap$	logical product ($a \cap b \equiv$ both a and b are true)
$\supset$	implies ($a \supset b \equiv a$ implies b).

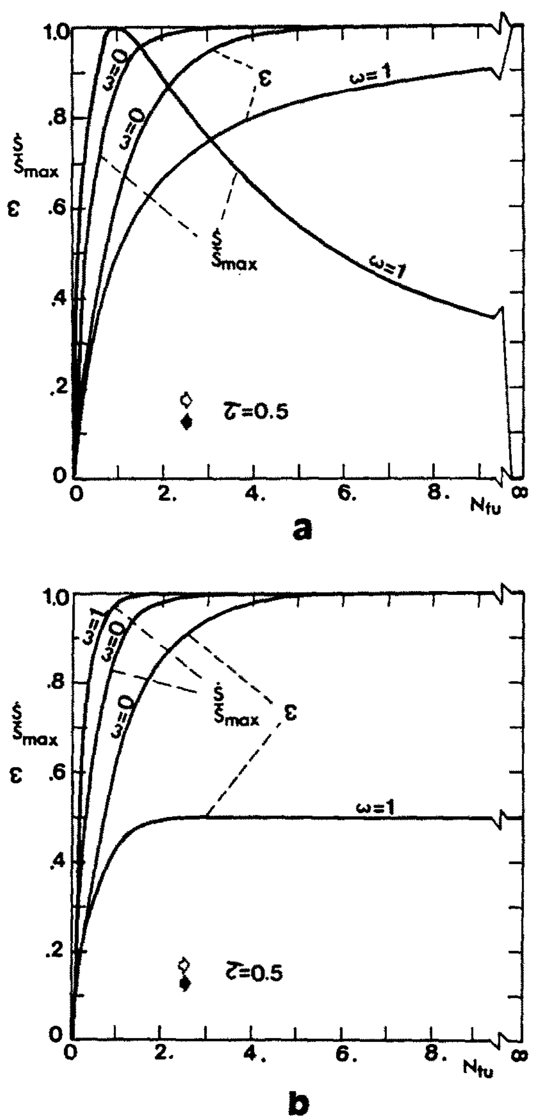

FIG. 1. The entropy generation and heat exchanger effectiveness: (a) countercurrent flow arrangement; (b) cocurrent flow arrangement.

$$\lim_{N_{tu} \to N_{tu}^*} (\dot{S}/\dot{S}_{max})^{\rightleftarrows} = 1 \; (\omega \neq 0). \tag{7}$$

Some of these consequences have obvious explanations, but some do not. Let us consider the following facts:

(i) $\lim_{N_{tu} \to \infty} (\dot{S}/\dot{S}_{max}) = \lim_{N_{tu} \to \infty} \varepsilon = 1 \quad @\, \omega = 0$

(ii) $$\begin{cases} \lim_{N_{tu} \to \infty} (\dot{S}/\dot{S}_{max})^{\rightleftarrows} = A \begin{cases} A = 0 & @\, \omega = 1 \\ 0 < A < 1 & (0 < \omega < 1) \end{cases} \\ \lim_{N_{tu} \to 0} (\dot{S}/\dot{S}_{max}) = 0 \end{cases}$$

(iii) $$\begin{cases} \lim_{N_{tu} \to N_{tu}^*} (\dot{S}/\dot{S}_{max})^{\rightleftarrows} = 1 \quad (\omega \neq 0) \quad \text{i.e.} \\ \dfrac{\partial}{\partial N_{tu}} (\dot{S}/\dot{S}_{max})^{\rightleftarrows} > 0 \; @\, N_{tu} < N_{tu}^* = \dfrac{1}{1-\omega} \ln \dfrac{1}{\omega} \\ \dfrac{\partial}{\partial N_{tu}} (\dot{S}/\dot{S}_{max})^{\rightleftarrows} < 0 \; @\, N_{tu} > N_{tu}^*. \end{cases}$$

Statement (i) means that in the $N_{tu} \to \infty$ limit, for $\omega = 0$ and any fluid flow arrangement, the *best* effectiveness heat exchanger (from the First Law of Thermodynamics viewpoint) has the highest entropy generation level. Therefore, this is the *worst* situation from the Second Law of Thermodynamics viewpoint! This 'inconsistency' means, in fact, that the mutual thermal energy difference has been completely destroyed ($T_1^{out} = T_2^{out}$). Note that the only source of the entropy generation (and the most important one according to the approximation adopted) is the temperature difference.

Limits (ii) mean that the consequences of either an ideal heat exchange process ($N_{tu} \to \infty$, $\omega = 1$) or the absence of a heat exchange process ($N_{tu} \to 0$), remain the same. The mutual thermal exergy difference remains the same at the outlet of the heat exchanger as well as at the inlet but, in the case of $N_{tu} \to \infty$ with completely 'reverse' exergy levels ($T_1^{out} = T_2^{in}$ and $T_2^{out} = T_1^{in}$ for the countercurrent flow arrangement). Therefore, no symmetry exists regarding the entropy generation for $N_{tu} \to 0$ and $N_{tu} \to \infty$, as it could be concluded from the relation $\dot{S}/\dot{S}_{max} = f(\varepsilon)$ [6].

Finally, the existence of the maximum of entropy generation for a *finite thermal size* heat exchanger (all but cocurrent flow arrangement) means that the thermal exergy difference between the fluids at the outlets of the heat exchanger has been completely destroyed again (i.e. $T_1^{out} = T_2^{out}$ at $N_{tu} = N_{tu}^*$). $N_{tu} < N_{tu}^*$ holds $[\partial/\partial N_{tu}(\dot{S}/\dot{S}_{max})] > 0$, i.e. the thermal exergy difference decreases as N_{tu} increases and vice versa; $N_{tu} > N_{tu}^*$ holds $[\partial/\partial N_{tu}(\dot{S}/\dot{S}_{max})] < 0$, i.e. the exergy difference increases as N_{tu} increases.

In summary, the purpose of a heat exchanger is not 'to provide for transfer of heat' but to provide for change of the outlet mutual thermal energy (exergy) levels of the fluids involved.

CONCLUSION

An adequate definition of a heat exchanger as a *system component* would be as follows:

"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".

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APPENDIX

The non-dimensional entropy rate generated by a heat transfer process in a heat exchanger is presented in Table A1.

Table A1. Entropy generation in a heat exchanger [5]

Entropy generation $\dot{S}/\dot{S}_{max}$ [dimensionless]	
$\dfrac{\omega \ln[1-\varepsilon(1-\tau^{-1})]+\ln[1-\omega\varepsilon(1-\tau)]}{\omega \ln \dfrac{\omega\tau+1}{(\omega+1)\tau}+\ln\dfrac{\omega\tau+1}{\omega+1}}$	*Cocurrent flow arrangement* $\varepsilon=\{1-\exp[-N_{tu}(1+\omega)]\}/(1+\omega)$ *Countercurrent flow arrangement* $\varepsilon=\dfrac{1-\exp[-N_{tu}(1-\omega)]}{1-\omega\exp[-N_{tu}(1-\omega)]}$