THE FOUR E's OF A HEAT EXCHANGER

by

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This paper is addressed to the Energy, Entropy generation and Economy concepts met jointly in the heat exchanger performance Evaluation procedure at the stage of decision making in design. How these four E's are interrelated in sizing the counterflow heat exchanger for energy recovery application is discussed.

Introduction

In the development and operation of effective energy systems the cast of characters does not give featuring but starring roles to heat exchangers. It is, therefore, advantageous and justifiable to study such subsystems individually as well. The fundamental sense of a device called a heat exchanger is to make the existing temperature differences useful. The inherent necessity of finite temperature differences for heat exchanger operation brings close the conflicts imposed by the natural laws (the first and the second law of thermodynamics). Namely, entropy generation seems to be desirable phenomenon in a real heat exchanger if one copes with design principles originating just from the first law of thermodynamics. On the contrary, from the standpoint of the second law, greater irreversibility means worse heat exchanger.

However, in addition to the natural laws, in the world of societies, technical systems and their components are involved with the "economic laws". In other words, the engineering economy principles must be combined with the natural laws as a clarifier of the pragmatistic design. In that sense it appears indispensable to have complete insight into the energy-entropy-economy scenography where a heat exchanger operating point evaluation procedure and thermal sizing takes place. Thus, the four E's analyses are unavoidable in every design decision nowadays.

The present work proposes a joint diagram where the first three E's are combined to help the fourth one. A simple cost equation is adopted to illustrate how the decision can be based on three E's in the case of heat recovery application of a counterflow exchanger.

The first three E's

(1) The Energy Concept

Thermodynamically speaking the heat exchanger is an open adiabatic system without any work transfer. The behavior of such system is governed by the energy conservation principle: the first law of thermodynamics. In the basic heat exchanger, the first law is usually applied twofold:

- at the macro level where the system is seen as a "black box" and the macro energy balance is formulated;
- at the micro level where the energy transformations are seen and the micro balances are formulated.

Both ways lead to the same result – a definition of the heat exchanger effectiveness as a dimensionless measure of energy transfer:

$$\varepsilon = \frac{\text{actual heat transfer rate}}{\text{maximum posible heat transfer rate}} =$$

$$= \frac{(\dot{m}c_p)_i |\Delta T|_i}{(\dot{m}c_p)_{\min} |\Delta T|_{\max}} = \varepsilon(NTU, \omega, \text{flow arrangement}) \qquad (1)$$

The influence of relevant parameters on heat exchanger effectiveness is usually shown on ε-NTU-ω charts – see Fig. 1(a). An increase of the heat exchanger thermal size *(NTU)* ad infinitum in most cases means a monotonous increase of effectiveness. Thus, the first law of thermodynamics does not provide selectivity even for such as "good" flow arrangements as the counterflow one. "Optimal thermal size" (read "optimal" *NTU*) cannot be chosen just from the energy concept.

(2) The Entropy Generation Concept

The second law of thermodynamics has been just recently used for heat exchanger evaluation by various authors as summarized by Bejan (1987).

When the finite temperature differences are the sole sources of irreversibilities, a dimensionless measure of the entropy generation, termed the Enthalpy Exchange Irreversibility Norm (EEIN), (Sekulić and Bačlić, 1984), can be used for the study of energy transformation quality in heat exchangers:

$$N_S = \frac{\text{actual irreversibility}}{\text{maximum possible irreversibility}} = \frac{I}{I_{\max}} =$$

$$= \frac{\omega \ln[1+\varepsilon(\tau^{-1}-1)] + \ln[1+\varepsilon(\tau-1)]}{(1+\omega)\ln\dfrac{1+\omega\varepsilon}{1+\omega} - \omega \ln\tau} = N_S(NTU, \omega, \tau, \text{flow arrangement}) \qquad (2)$$

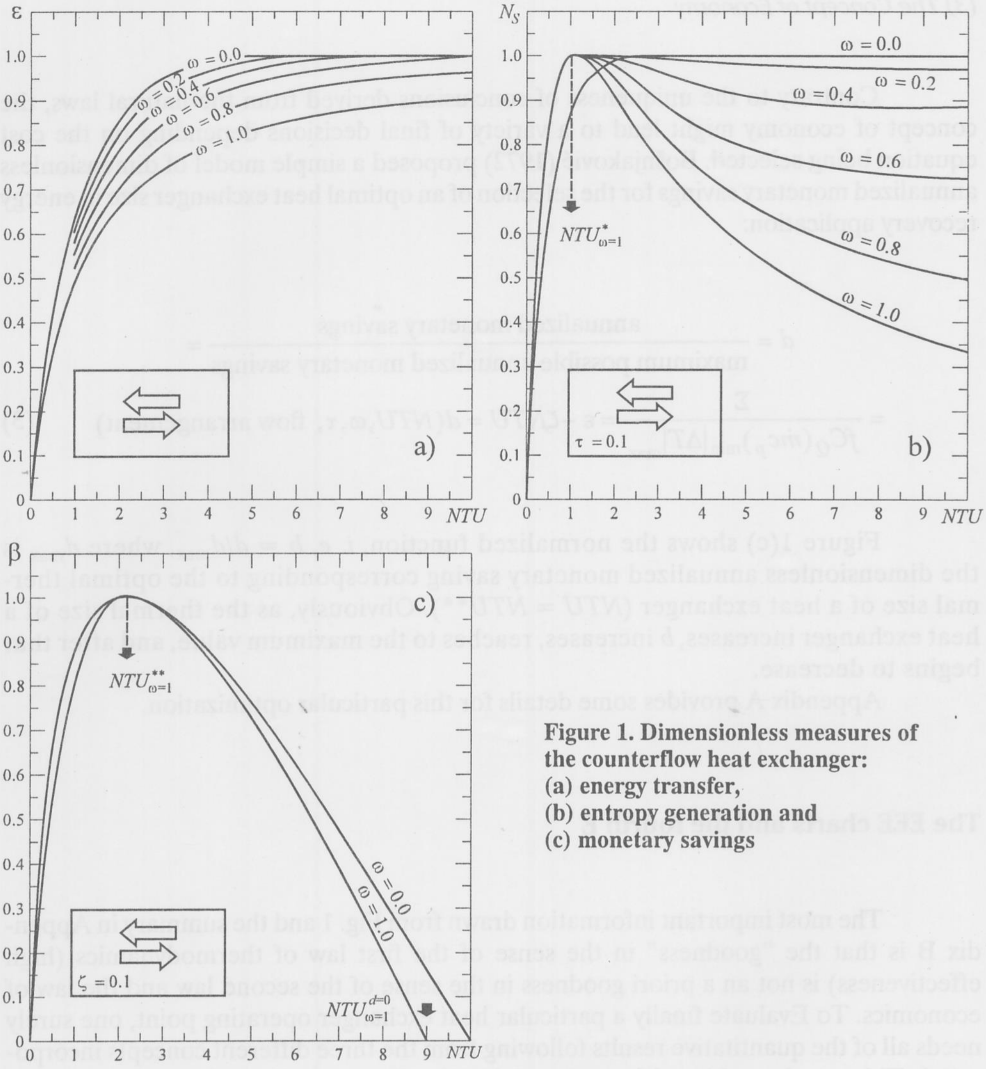

Figure 1. Dimensionless measures of the counterflow heat exchanger: (a) energy transfer, (b) entropy generation and (c) monetary savings

In Fig. 1(b) this function is shown for the countercurrent flow arrangement. The EEIN increases, reaches its maximum value at *NTU* and afterwards any further increment of heat exchanger thermal size causes the EEIN to decrease.

Obviously, the entropy generation concept does not provide means for the selection of optimal thermal size of an exchanger. But it prohibits some heat exchanger operating points, those corresponding to the highest irreversibility level, and clearly indicates the region of favorable thermal sizes ($NTU > NTU^*$) from the second law point of view.

(3) The Concept of Economy

Contrary to the uniqueness of conclusions derived from the natural laws, the concept of economy might lead to a variety of final decisions depending on the cost equation being selected. Bošnjaković (1972) proposed a simple model of dimensionless annualized monetary savings for the selection of an optimal heat exchanger size in energy recovery application:

$$d = \frac{\text{annualized monetary savings}}{\text{maximum possible annualized monetary savings}} =$$

$$= \frac{\Sigma}{fC_Q(\dot{m}c_p)_{\min}|\Delta T|_{\max}} = \varepsilon - \zeta NTU = d(NTU, \omega, \tau, \text{ flow arrangement}) \qquad (3)$$

Figure 1(c) shows the normalized function, *i. e.* $b = d/d_{\max}$, where $d_{\max}$ is the dimensionless annualized monetary saving corresponding to the optimal thermal size of a heat exchanger ($NTU = NTU^{**}$). Obviously, as the thermal size of a heat exchanger increases, b increases, reaches to the maximum value, and after that begins to decrease.

Appendix A provides some details for this particular optimization.

The EEE charts and the fourth E

The most important information drawn from Fig. 1 and the summary in Appendix B is that the "goodness" in the sense of the first law of thermodynamics (high effectiveness) is not an a priori goodness in the sense of the second law and the law of economics. To Evaluate finally a particular heat exchanger operating point, one surely needs all of the quantitative results following from the three different concepts incorporated. This can be achieved by constructing the Energy-Entropy-Economy chart as presented in Fig. 2 for countercurrent flow arrangement.

In Fig. 2, the ordinate is the thermal size of a heat exchanger (NTU), the abscissa is the heat capacity rate ratio (ω), and the parameters are ε and ζ. The NTU^* (shaded area) and a "good" one from the point of the second law of thermodynamics. Small values of z mean economically better situation. It is obvious that in the second law unfavorable region ($NTU < NTU^*$) maximum monetary savings ($b = 1$ for $NTU = NTU^{**}$) can be achieved mostly for large values of ζ. In other words, profitable region is compatible with the region, which is seen as the second law favorable.

Note that $\zeta_{NTU}^{d=0}$ lines, given also in Fig. 2, correspond to the zero profit.

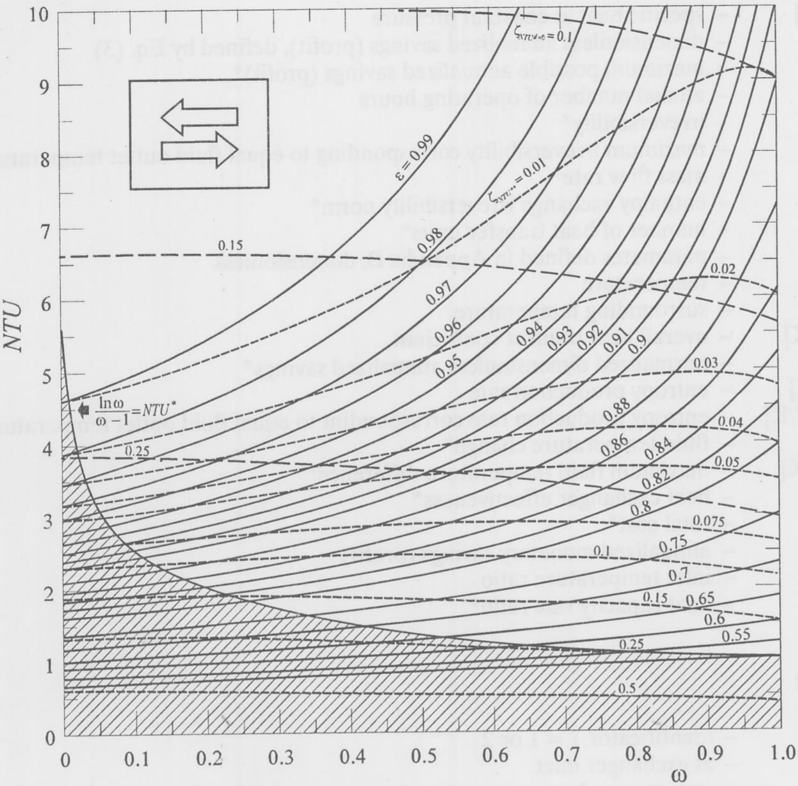

Figure 2. Energy-Entropy-Economy chart for counterflow heat exchanger

Concluding remarks

It appears useful to construct a joint Energy-Entropy-Economy chart, where each single point is an information carrier for quantitative and qualitative judgments as well as economic evaluation of heat exchangers. This can be readily done for any particular heat exchanger application and tailored for any structure of the cost equation.

Nomenclature

A [m^2]	– heat transfer area,
a [\$/\$ year]	– annual capital recovery and interest
C_A [\$/m^2]	– heat exchanger cost
C_O [\$/m^{2}h]	– operating cost
C_Q [\$/kWh]	– price of energy

c_p [J/kgK]	– specific heat at constant pressure
d	– dimensionless annualized savings (profit), defined by Eq. (3)
d_{max}	– maximum possible annualized savings (profit)*
f [h/year]	– annual number of operating hours
I	– irreversibility*
I_{max} [W]	– maximum irreversibility corresponding to equal fluid outlet temperatures*
$\dot{m}$ [kg/s]	– mass flow rate*
N_S	– enthalpy exchange irreversibility norm*
NTU	– number of heat transfer units*
r	– parameter defined in Appendix B, dimensionless
T [K]	– temperature
T_0 [K]	– surrounding temperature
U [W/m²K]	– overall heat transfer coefficient
b	– normalized dimensionless annualized savings*
$\Delta\dot{S}$ [W/K]	– entropy production rate
$\Delta\dot{S}_{max}$ [W/K]	– entropy production rate correspondint to equal fluid outlet temperatures
$\|\Delta T\|_i$ [K]	– fluid temperature change*
$\|\Delta T\|_{max}$ [K]	– maximum fluid temperature difference*
e [K]	– heat exchanger effectiveness*
ζ	– total cost*
Σ [$/year]	– annualized monetary savings (profit)
τ	– inlet temperature ratio
ω	– heat capacity rate ratio*

Subscripts

i	– identificator, $i = 1$ or 2
in	– at exchanger inlet
max	– maximum value
min	– minimum value
out	– at exchanger outlet
1	– refers to fluid with $(\dot{m}c_p)_{min}$
2	– refers to fluid with $(\dot{m}c_p)_{max}$

Superscripts

*	– at maximum irreversibility
**	– most profitable

Combined subscripts (used as subscripts of ζ in Fig. 2.)

NTU^{**}	– refers to maximum profit with given value of ζ
$NTU^{d=0}$	– refers to zero profit with given value of ζ

*

$$d_{max} = fC_Q(\dot{m}c_p)_{min}|\Delta T|_{max}$$
$$I = T\Delta S$$
$$I_{max} = T_0\Delta\dot{S}_{max}$$
$$N_S = I/I_{max}$$
$$NTU = UA(\dot{m}c_p)_1$$
$$b = d/d_{max}$$

$$|\Delta T|_i = |T_{i,in} - T_{i,out}|$$
$$|\Delta T|_{max} = |T_{1,in} - T_{2,in}|$$
$$e = |T_{1,in} - T_{1,out}| / |T_{1,in} - T_{2,in}|$$
$$\zeta = (aC_A + fC_0)/fC_QU|\Delta T|_{max}$$
$$\tau = T_{1,in}/T_{2,in}$$
$$\omega = (\dot{m}c_p)_1/(\dot{m}c_p)_2$$

References

[1] Bejan, A., Thermodynamics of Heat Transfer Devices, International Symposium on Second Law Analysis of Thermal Systems, Rome, Italy, May 25–29, 1987
[2] Bošnjaković, F., Nauka o toplini, II dio, Tehnička knjiga, Zagreb, 1972
[3] Sekulić, D. P., Bačlić, B. S., Enthalpy Exchange Irreversibility, Publications of the Faculty of Technical Sciences (1984), University of Novi Sad, No. 15, pp. 114–123

Appendix A

The details of optimal sizing of counterflow heat exchanger according to Bošnjaković (1972) are as follows:

- $d = \varepsilon - \zeta\, NTU$ is regarded as $d = d(NTU)$, since $\varepsilon(NTU...)$;
- The condition $\partial d / \partial NTU = 0$ yields the equation

$$\zeta = \frac{(1-\omega)^2 e^{-(1-\omega)NTU}}{[1-\omega e^{-(1-\omega)NTU}]^2} \text{ for } \omega \neq 1, \text{ or}$$

$$\zeta = \frac{1}{(1+NTU)^2} \text{ for } \omega = 1$$

which can be solved for $NTU + NTU^{**}$ providing the maximum of d. Then $d_{max} = d(NTU)$, and $\beta = d/d_{max}$. Explicit relations for NTU^{**} are given in Appendix B.

Apendix B

Summary of Energy transfer, Entropy generation and Economy measures versus *NTU.*

Function/Origin	General tendency	Maximum	Minimum
$\varepsilon = \varepsilon$ (*NTU*, ω, flow arr.) The First Lawe	$\varepsilon \uparrow$ as $NTU \uparrow$ for $0 \le NTU \le \infty$	$\varepsilon = 1$ for $NTU \to \infty$	$\varepsilon = 0$ for $NTU = 0$
$N_S = N_S$ (*NTU*, ω, τ, flow arr.) The Second Law	$N_S \uparrow$ as $NTU \uparrow$ for $0 \le NTU \le NTU^*$ $N_S \downarrow$ as $NTU \uparrow$ for $NTU^* \le NTU \le \infty$	$N_S = 1$ for $NTU^* = \frac{1}{1-\omega}\ln\frac{1}{\omega}$ ($NTU^* = 1$ for $\omega = 1$)	$N_S = 0$ for $NTU = 0$ and $NTU \to \infty$
$d = d$ (*NTU*, ω, ζ, flow arr.) The Law of Economy	$d \uparrow$ as $NTU \uparrow$ for $0 \le NTU \le NTU^{**}$ $d \downarrow$ as $NTU \uparrow$ for $NTU^{**} \le NTU \le \infty$	$d = d_{max}$ for $NTU^{**} = \frac{1}{1-\omega}\ln\frac{\omega(r+1-\omega)}{r-1+\omega}$ where $r = \sqrt{(1+\omega)^2 - 4\omega(1-\zeta)}$ ($NTU^{**} = 1/\sqrt{\zeta}$ for $\omega = 1$)	$d = 0$ for $\varepsilon = \zeta/NTU$ and $NTU = 0$ (Note that $d < 0$ for $NTU > NTU_{\varepsilon=\zeta/NTU}$)

Counterflow heat exchanger effectiveness, *i. e.*

$$\varepsilon = \frac{1-e^{-(1-\omega)NTU}}{1-\omega e^{-(1-\omega)NTU}} \text{ for } \omega \neq 1$$

and

$$\varepsilon = \frac{NTU}{1+NTU} \text{ for } \omega = 1$$

has been used in the analysis.

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