CODEN STJSAO ISSN 0562-1887
ZX470/1371 UDK 536.73:536.24:519.87

Analysis of Exergy Destruction of an Evaporator or/and a Condenser

Antun GALOVIĆ[1], Marija ŽIVIĆ[2] and Mato KOKANOVIĆ[2]

1) Fakultet strojarstva i brodogradnje Sveučilišta u Zagrebu (Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb), Ivana Lučića 5, HR - 10000 Zagreb, **Republic of Croatia**

2) Strojarski fakultet Sveučilišta J. J. Strossmayera u Osijeku (Faculty of Mechanical Engineering, J.J. Strossmayer University of Osijek), Trg Ivane Brlić-Mažuranić 2, HR - 35000 Slavonski Brod, **Republic of Croatia**

antun.galovic@fsb.hr

Keywords

Analytical model
Condenser
Evaporator
Evaporator and condenser
Exergy destruction

Ključne riječi

Analitički model
Eksergijski gubitci
Isparivač
Isparivač i kondenzator
Kondenzator

Received (primljeno): 2008-01-15
Accepted (prihvaćeno): 2008-12-19

Preliminary note

This paper presents the exergy destruction of an evaporator or a condenser or evaporator and condenser. The exergy destruction can be analytically calculated by using the same non-dimensional variables which have been used by its energy analysis. The one additional variable is the ratio of absolute input temperatures of both streams. This means that the given model enables the simultaneous calculation of heat transfer effectiveness and exergy destruction respectively. The exergy destruction is put in the ratio to the heat capacity of the weaker stream. The limited values of the exergy destruction are estimated, taking into account the zero and infinite values of relevant variables. Further, exergy destruction for the case when both streams change phase is calculated, which means that the appropriate heat exchanger is condenser and evaporator simultaneously. The given model is derived as a special case of the model for calculation of exergy destruction by parallel and counter flow heat exchangers respectively.

For all presented cases the only temperature differences between the streams have been taken into account. This means that the effect of a frictional pressure drop of the streams on exergy destruction has been neglected.

Analiza eksergijskih gubitaka u izmjenjivaču topline tipa kondenzator i/ili isparivač

Prethodno priopćenje

Ovim je radom pokazano da se eksergijski gubitci u isparivaču ili kondenzatoru mogu analitički izraziti istim bezdimenzijskim značajkama koje se koriste u njihovoj energijskoj analizi uz dodatnu bezdimenzijsku temperaturnu značajku koja predstavlja omjer ulaznih temperatura jače i slabije struje. To znači da prikazani algoritam omogućuje istovremeni izračun kako energijske efikasnosti tako i eksergijskog gubitka. Eksergijski gubitak je normiran s ukupnim toplinskim kapacitetom slabije struje. Analitički su utvrđene granične vrijednosti eksergijskih gubitaka u smislu nultih i beskonačnih vrijednosti relevantnih bezdimenzijskih varijabli.

Nadalje je dana poveznica između slučaja kada samo jedna struja mijenja svoje agregatno stanje i slučaja kada obje struje mijenjaju svoja agregatna stanja. Prikazani algoritam proračuna eksergijskih gubitaka izveden je kao specijalni slučaj modela proračuna eksergijskih gubitaka za izmjenjivače topline u kojima obje struje mijenjaju temperaturu.

Za sve analizirane slučajeve uzet je samo utjecaj temperaturnih razlika struja, dok je utjecaj pada tlaka uslijed trenja na iznos eksergijskog gubitka u izmjenjivaču topline zanemaren.

1. Introduction

There is a wide range of applications of evaporators and condensers. They are mainly used in thermo-electric power plants, processing plants, etc. The basic characteristic of this type of heat exchangers is change of phase of one or both streams. In an evaporator, one stream evaporates, i.e., it undergoes a phase change from liquid to vapor, while in the condenser, the direction of phase change is opposite. In these heat exchangers, the temperature of the stream which undergoes a phase change is constant, while the temperature of the other stream is variable. This constant temperature is called the saturation temperature and it depends on the saturation pressure and on the type of pure substance which changes the phase.

Simultaneous change of phase of both streams is also possible, i.e. one stream evaporates while the other stream condenses. In this case, the temperatures of both

Symbols/Oznake

A_0	- overall heat exchanger surface area, m^2 - ukupna ploština površina izmjenjivača
C	- heat capacity of the stream, W/K - toplinski kapacitet struje
E_{ex}	- exergy, W - eksergija
h	- specific entalpy of the stream, J/kg - specifična entalpija struje
k	- overall heat transfer coefficient, W/ (m^2·K) - koeficijent prolaza topline
q_m	- mass flow rate of the stream, kg/s - maseni protok struje
s	- specific entropy of the stream, J/(kg·K) - specifična entropija struje
T	- thermodynamic temperature, K - termodinamička temperatura
ε	- the heat exchanger effectiveness - učinkovitost izmjenjivača topline
Δ	- difference - razlika
π_T	- the ratio of input thermodynamic temperatures of the streams - omjer ulaznih termodinamičkih temperatura struja
π_1	- the temperature difference ratio of the heat exchanger - omjer temperaturnih razlika izmjenjivača topline
π_2	- Number of Transfer Units, NTU - broj prijenosnih jedinica
π_3	- the heat capacity ratio of weaker and stronger stream - omjer toplinskih kapaciteta slabije i jače struje

Indices / Indeksi

1	- weaker stream - slabija struja
2	- stronger stream - jača struja
coun	- counter flow - protusmjerni
env	- environmental - okolišno
par	- parallel flow - istosmjerni
′	- input - ulazna
″	- output - izlazna

streams are constant. The analysis of exergy destruction of such a type of heat exchanger is given in this paper. For all presented cases, only the temperature differences between the streams have been taken into account. This means that the effect of frictional pressure drop of streams on the exergy destruction has been neglected. This analysis is based on the paper [1], in which the algorithm of calculation of the exergy destruction is given generally for parallel and counter flow recuperators. This paper and paper [1] present the complete analytical model of calculation of exergy destruction in parallel and counter flow heat exchangers with one pass of each stream.

2. Mathematical model

According to the nomenclature in Figure 1, the equation of exergy balance of heat exchanger is given in the following form

$$E'_{ex1} + E'_{ex2} = E''_{ex1} + E''_{ex2} + \Delta E_{ex} \,, \tag{1}$$

from which it is possible to get the expression for the exergy destruction as follows

$$\Delta E_{ex} = E'_{ex1} - E''_{ex1} + E'_{ex2} - E''_{ex2} = \Delta E_{ex1} + \Delta E_{ex2} \,. \tag{2}$$

Figure 1. Balance of heat exchanger exergy
Slika 1. Eksergijska bilanca izmjenjivača topline

In the considered case the changes of kinetic and potential energy are neglected so change of exergy destruction of each stream can be written in the following form [2]

$$\Delta E_{ex1} = q_{m1}\left(h_1' - h_1'' - T_{env}\left(s_1' - s_1''\right)\right) \,, \tag{3a}$$

$$\Delta E_{ex2} = q_{m2}\left(h_2' - h_2'' - T_{env}\left(s_2' - s_2''\right)\right) \,. \tag{3b}$$

The following non-dimensional expressions for exergy destruction of parallel and counter flow heat exchanger are taken from [1] for the purpose of further analysis in this paper:

$$\frac{\Delta E_{\text{ex par}}}{T_{\text{env}}\dot{C}_1} = \ln\left[1-\frac{1-e^{-(1+\pi_3)\pi_2}}{1+\pi_3}\left(1-\pi_{\text{T}}\right)\right]+ \\ +\frac{1}{\pi_3}\ln\left[1+\pi_3\frac{1-e^{-(1+\pi_3)\pi_2}}{1+\pi_3}\left(\frac{1-\pi_{\text{T}}}{\pi_{\text{T}}}\right)\right], \tag{4}$$

$$\frac{\Delta E_{\text{ex coun}}}{T_{\text{env}}C_1} = \ln\left[1-\frac{1-e^{-(1-\pi_3)\pi_2}}{1-\pi_3 e^{-(1-\pi_3)\pi_2}}\left(1-\pi_{\text{T}}\right)\right]+ \\ +\frac{1}{\pi_3}\ln\left[1+\pi_3\frac{1-e^{-(1-\pi_3)\pi_2}}{1-\pi_3 e^{-(1-\pi_3)\pi_2}}\left(\frac{1-\pi_{\text{T}}}{\pi_{\text{T}}}\right)\right]. \tag{5}$$

In the above mentioned expressions, the meanings of the non-dimensional parameters are as follows:

$$\pi_1 = \frac{T_1^{'}-T_1^{''}}{T_1^{'}-T_2^{'}};\quad \pi_2 = \frac{kA_0}{C_1};\quad \pi_3 = \frac{C_1}{C_2},\quad \pi_T = \frac{T_2^{'}}{T_1^{'}}. \tag{6}$$

If expressions (4) and (5) are used for evaporation (Figure 2), or for condensation (Figure 3), then the value $\pi_3 = 0$ has to be inserted in these expressions.

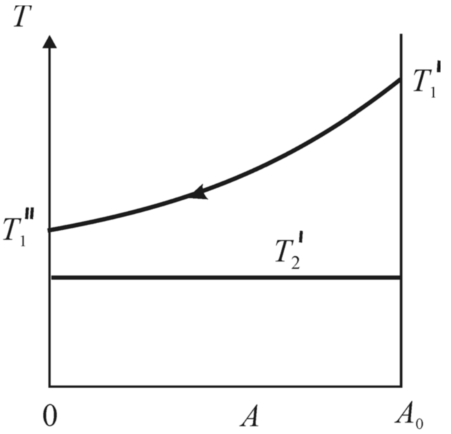

Figure 2. Variation of stream temperatures in an evaporator
Slika 2. Promjena temperatura struja u isparivaču

If $\pi_3 = 0$ is inserted into equations (4) and (5), the undefined value 0/0 is obtained, and by using L'Hospital rule, both expressions give the same solution

$$\frac{\Delta E_{\text{ex}}\left(\pi_3=0\right)}{C_1 T_{\text{env}}} = \ln\left[1-\left(1-e^{-\pi_2}\right)\left(1-\pi_{\text{T}}\right)\right]+ \\ +\left(1-e^{-\pi_2}\right)\left(\frac{1}{\pi_{\text{T}}}-1\right). \tag{7}$$

It is evident that equations (4) and (5) must give the same solution, because for $\pi_3 = 0$, the type of heat exchanger has no effect on the exergy destruction values.

Equation (7) can be simply transformed, by using equation (6), in the dimensional form

$$\Delta E_{\text{ex}}\left(\pi_3=0\right) = T_{\text{env}}\left(C_1\ln\frac{T_1^{''}}{T_1^{'}}+\frac{C_1\left(T_1^{'}-T_1^{''}\right)}{T_2^{'}}\right) \tag{8}$$

in which the first and the second term in the bracket represent the entropy change of the weaker or of the stronger stream. It is obvious that the stronger stream is the one which undergoes phase changes, whether it condenses or evaporates at T_2' = const.

If $\pi_2 = 0$ is inserted in equation (7), the physical acceptable solution is acquired:

$$\frac{\Delta E_{\text{ex}}\left(\pi_3=0;\pi_2=0\right)}{C_1 T_{\text{env}}} = 0. \tag{9}$$

By inserting the hypothetic fact that $\pi_2 \rightarrow \infty$, i.e. $A_0 \rightarrow \infty$, the expression for the exergy destruction of the condenser or evaporator with an infinite heat exchange surface area is obtained

$$\frac{\Delta E_{\text{ex}}\left(\pi_3=0;\pi_2\rightarrow\infty\right)}{C_1 T_{\text{env}}} = \ln\pi_{\text{T}}+\frac{1-\pi_{\text{T}}}{\pi_{\text{T}}}. \tag{10}$$

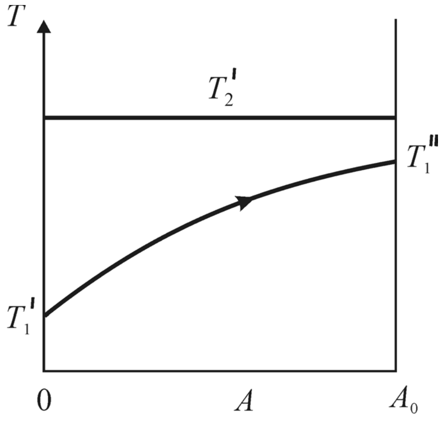

Figure 3. Variation of stream temperatures in a condenser
Slika 3. Promjena temperatura struja u kondenzatoru

Equation (10) also represents, for the given value of π_T, the maximal exergy destruction, which means that maximal exergy destruction in the evaporator or condenser can be achieved for the infinite heat exchange surface area, for $\pi_2 \rightarrow \infty$. By inserting the expression for π_T from equation (6) in equation (10) , the equation (10) can be easily transformed into dimensional form

$$\Delta E_{\text{ex}}\left(\pi_3=0;\pi_2\rightarrow\infty\right) = T_{\text{env}}\left(C_1\ln\frac{T_2^{'}}{T_1^{'}}+\frac{C_1\left(T_1^{'}-T_2^{'}\right)}{T_2^{'}}\right). \tag{11}$$

In the above-mentioned expression, the first and the second term in the bracket represent the entropy change of the weaker or of the stronger stream for the evaporator or condenser with an infinite heat exchange surface area. In this case, the output temperature of the weaker stream becomes equal to the saturation temperature of the stronger stream, i.e., $T_1'' = T_2'$, which is illustrated in Figure 4.

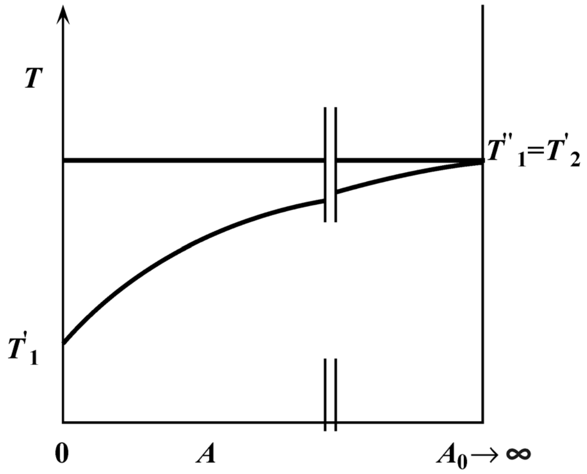

Figure 4. Variation of stream temperatures in a condenser or an evaporator with infinite value of overall heat exchanger area

Slika 4. Promjena temperatura struja u kondenzatoru ili isparivaču beskonačno velike površine

In the case when both streams undergo a phase change, i.e. one stream evaporates and at the same time the other stream condenses, Figure 5, parameter π_3 acquires undefined form ∞/∞, and it is not possible to get the solution from the specified equations.

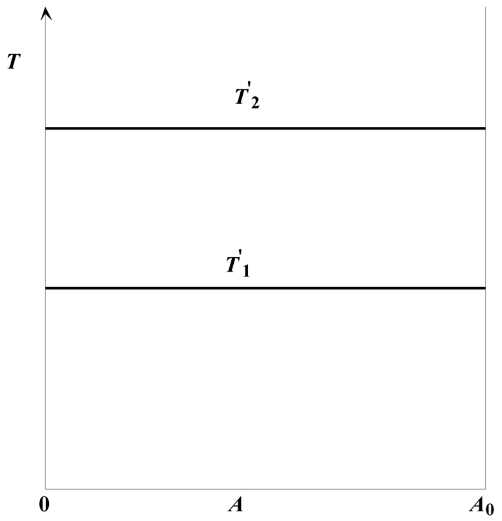

Figure 5. Variation of stream temperatures in a condenser and evaporator type of heat exchanger

Slika 5. Promjena temperatura struja u izmjenjivaču topline tipa kondenzator i isparivač

In the considered case, the temperatures T_1', T_2', of both streams are constant for the required pressures, so the expressions for exergy destruction are obtained by inserting the following equations in the equations (3a) and (3b):

$$s_1' - s_1'' = \frac{h_1' - h_1''}{T_1'}, \tag{12a}$$

$$s_2' - s_2'' = \frac{h_2' - h_2''}{T_2'}, \tag{12b}$$

$$q_{m1}\left(h_1' - h_1''\right) = q_{m2}\left(h_2'' - h_2'\right), \tag{12c}$$

$$\Delta E_{\text{ex}} = T_{\text{env.}} \Phi \frac{T_2' - T_1'}{T_2' T_1'}. \tag{13}$$

The heat transfer rate is given by the following equation

$$\Phi = k \int_{A=0}^{A=A_0} \left(T_2' - T_1'\right) \mathrm{d}A = kA_0 \left(T_2' - T_1'\right). \tag{14}$$

If equation (14) is inserted into equation (13) by using equation (6), the following non-dimensional expression is obtained

$$\frac{\Delta E_{\text{ex}}}{kA_0} = \frac{\left(\pi_{\text{T}} - 1\right)^2}{\pi_{\text{T}}}. \tag{15}$$

3. Presentation and analysis of calculation results

The diagram in Figure 6 shows exergy destruction calculated according to equation (7), i.e. the effectiveness of evaporator or condenser calculated from the next equation, [3]

$$\varepsilon = \pi_1 = 1 - \exp\left(-\pi_2\right). \tag{16}$$

The diagram clearly shows the continuous increase of exergy destruction with the increase of parameter π_2. However, it is important to notice that both the gradient and the value of the increase strongly depend on the value of parameter π_{T}.

If the heat exchanger is operated in the range of $0{,}1 \le \pi_{\text{T}} \le 1{,}0$, the values of non-dimensional exergy destruction decrease (towards zero), and for $\pi_{\text{T}} > 1{,}0$, they rise again. Furthermore, it can be noticed that each parametric curve π_{T} reaches its horizontal asymptotic value, which means that further increase of π_2 has no effect on the value of exergy destruction. If $0{,}1 \le \pi_{\text{T}} \le 1{,}0$, then an increase of π_{T}

affects the start of the horizontal parts of the curves, i.e. it moves them towards the lower values of π_2, and for $\pi_T >$ 1,0, towards the higher values of π_2. For $\pi_T = 1$, the value of exergy destruction is equal to zero. From that same diagram it can be seen that effectiveness ε continuously increases with the increase of π_2, regardless of value π_T. For the given work point of the heat exchanger, it is possible to determine simultaneously not only the heat exchanger effectiveness but also the value of the exergy destruction.

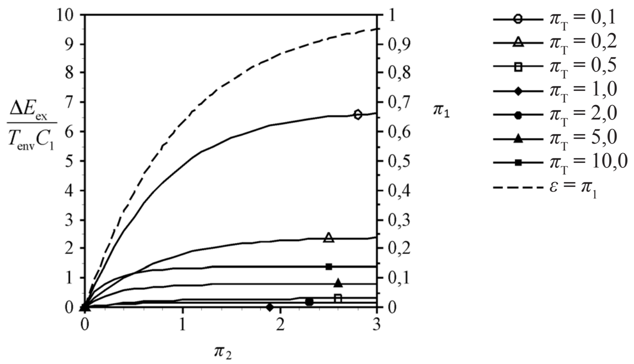

Figure 6. Exergy destruction in a condenser or evaporator as a function of non-dimensional variable π_2

Slika 6. Bezdimenzijski eksergijski gubitci u kondenzatoru ili isparivaču u ovisnosti o bezdimenzijskoj značajci π_2

Horizontal parts of the curves π_T = const represent physically the approaching of the asymptotic, i.e. maximal value of non-dimensional exergy destruction, which is expressed by the equation (10) and shown in Figure 7.

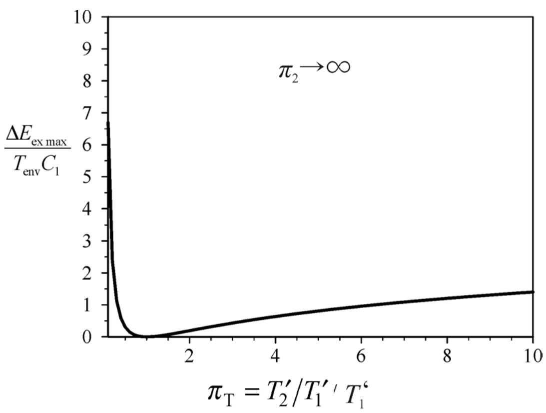

Figure 7. Maximal values of exergy destruction in a condenser or evaporator as a function of non-dimensional variable π_T

Slika 7. Maksimalni eksergijski gubitak u kondenzatoru ili isparivaču u ovisnosti o bezdimenzijskoj značajci π_T

The curve in Figure 7 quantitatively shows the values of maximal exergy destruction (asymptotic values) for the analyzed cases. The strong effect of the parameter π_T in the interval $0,1 \leq \pi_T \leq 1,0$ can be observed. For $\pi_T >$ 1,0, the effect of that parameter is less important.

For π_T =1,0 the value of max. exergy destruction is equal to zero. For all these cases, which can be seen from equation (16), when π_2 tends to infinity, the effectiveness tends to one.

The diagram in Figure 8 shows values of non-dimensional exergy destruction as a function of π_T, in the case when both streams undergo a phase change, i.e, in the evaporator or the condenser. Exergy destruction is divided by the product kA_0, because both streams have infinite values of heat capacities, and the diagram is drawn according to equation (15).

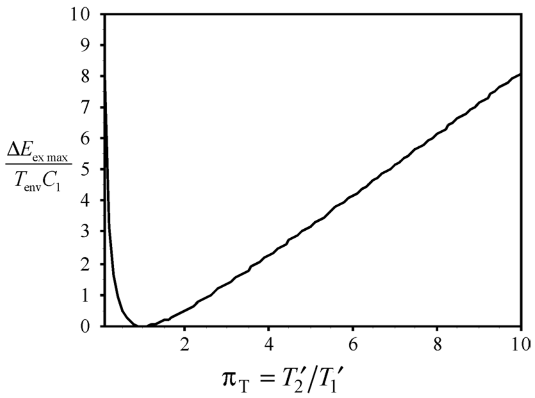

Figure 8. Exergy destruction in a condenser and evaporator type of heat exchanger as a function of non-dimensional variable π_T

Slika 8. Eksergijski gubitci u izmjenjivaču topline tipa kondenzator i isparivač u ovisnosti o bezdimenzijskoj značajci π_T

The diagram clearly shows that this non-dimensional exergy destruction decreases from infinite value to zero with the increase of π_T from 0 to 1, and then continuously rises with the increase of π_T from 1 to infinity. Furthermore, it can be concluded that exergy destruction is strongly dependent on small changes of parameter π_T, if its values are in interval zero to one , while for $\pi_T > 1,0$ these changes are not so evident.

A more detailed analysis of equation (15) confirms the obvious physical fact that the same values of the non-dimensional exergy destruction are obtained for the parameter π_T and $1/\pi_T$.

4. Conclusion

From the above-mentioned, it can be concluded that it is possible to make a user's diagram, identical to the diagram in Figure 6, from which exergy destruction and effectiveness ε could be directly read, for the given work-points of the evaporator or the condenser.

Thereby, the interval and also the number of the parameter curves π_T have to be adjusted to the values obtained in the practical use of evaporators or condensers.

Because the algorithm is presented in non-dimensional form, its application is universal. In that way, in this paper and in [1], the complete non-dimensional analytical solution is given for the parallel and counter flow heat exchangers, as well as for the derived cases, when one or both streams undergo a phase change. Only the effect of final temperature differences of streams on the values of exergy destruction is analyzed in all cases, while the effect of pressure drop is neglected.

REFERENCES

[1] GALOVIĆ, A.; MUDRINIĆ, S.: *Analiza eksergijskih gubitaka u istosmjernim i protusmjernim izmjenjivačima topline*, Strojarstvo 47, 5-6 (2005), 177-184.

[2] BOŠNJAKOVIĆ, F.: *Nauka o toplini I*, Tehnička knjiga, Zagreb, 1986.

[3] GALOVIĆ, A.: *Termodinamika II*, Sveučilište u Zagrebu, Fakultet strojarstva i brodogradnje, Zagreb, 2003.