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Energijska in eksergijska analiza sotočnih in protitočnih prenosnikov toplote z uporabo merilnih podatkov

Energy and exergy analysis of a parallel and counter-flow heat exchangers using measured data

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Prispevek podaja energijsko in eksergijsko analizo sotočnih in protitočnih ločilnih prenosnikov toplote z uporabo marilnih podatkov. Sestavili smo merilno progo, na kateri smo merili vstopne in izstopne temperature in masni tok vode. Za določitev brezrazsežnega razmerja izgubljene eksergije in prenešenega toplotnega toka v odvisnosti od brezrazsežnih parametrov prenosnika toplote: razmerja absolutnih temperatur na vstopu π_T*, razmerja toplotnih moči* π_3 *in števila enot prenosnika toplote* π_2*, smo razvili analitični model. Za vse primere smo izračunali tudi učinkovitost prenosa toplote. Rezultate smo prikazali v ustreznih brezrazsežnih diagramih.*

(Ključne besede: prenosniki toplote, energijske analize, eksergijske analize, izmerjene vrednosti)

This paper presents an energy and exergy analysis of a parallel and counter-flow recuperative heat exchangers using experimental data. An experimental rig was constructed to measure the inlet and outlet temperatures and the mass flow rates of streams. The analytical model was developed to obtain a non-dimensional relationship between the destroyed exergy and exchanged heat-flow rate as a function of the non-dimensional parameters of a heat exchanger: the ratio of inlet absolute temperatures, π_T*, the ratio of the heat-capacity rates,* π_3*, and the number of heat-transfer units,* π_2*. The effectiveness of the heat exchange is also calculated for each case. The results are shown in appropriate non-dimensional diagrams.*

(Keywords: heat exchangers, energy analysis, exergy analysis, measured values)

0 INTRODUCTION

Energy-exergy analyses of heat exchangers have been the subject of much research over the past few decades, [1] to [7]. These analyses are based on the first and the second laws of thermodynamics. From such analyses the parameters for the improved operation of a heat exchanger can be obtained.

The destroyed exergy or the lost available work of a heat exchanger is due to two factors: the transfer of heat across the stream-to-stream temperature difference and the frictional pressure drop that accompanies the circulation of fluid through the apparatus. Taking into account these two parameters it is possible to optimize a heat exchanger on an entropy-generation minimization or on a minimum destruction of exergy ([8] and [9]). In this work the exergy destruction due to the pressure drop is neglected, because from experimental data it was clear that the pressure drop was very small.

1 DESCRIPTION OF THE MEASURING RIG

Figure 1. shows the experimental setup of the heat exchanger.

The studied heat exchanger was “double pipe” type with only one passage of every stream. The streams were a hot-water stream (as the stronger stream) and a cold-water stream (as the weaker one). The mass flow rate of the weaker stream was kept constant and equal to 0.002 kg/s. The values of the mass flow rate of the stronger stream were 0.004, 0.006, 0.008 or 0.01 kg/s. As can be seen from Figure

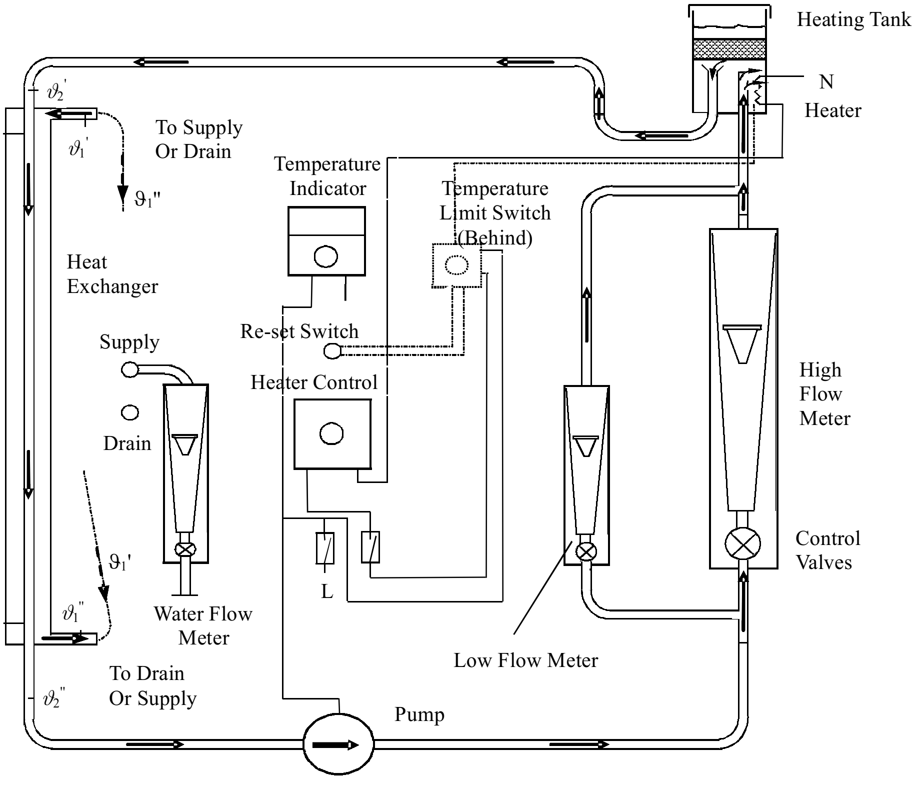

Fig. 1. *The experimental rig*

1, the inlet and outlet temperatures of the streams were measured. In each of four cases (for the each value of the mass flow rate), the inlet temperature of the stronger stream was kept constant and the inlet temperature of the weaker stream was varied four times. From the obtained four sets of the measured data, for each of the four cases, both for a parallel and a counter-flow heat exchanger, two non dimensional parameters (π_1 and π_3) were calculated. The parameters are presented in the appropriate diagrams, as shown in Figures 2 and 3.

The total heat exchanger area was 0.08 m^2.

For each point the exchanged-heat flow rate and the exergy destruction (entropy generation) are calculated by using the equations of the following mathematical model.

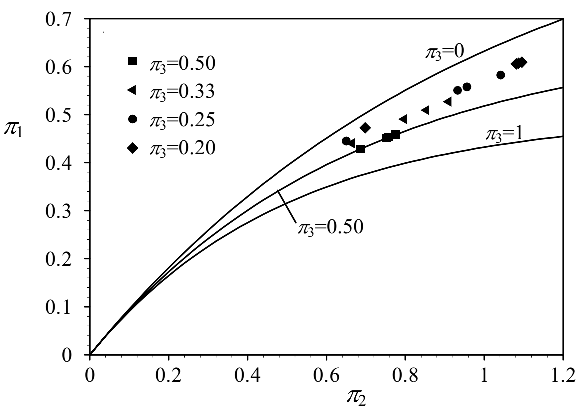

Fig. 2. *The positions of the measured operation points for a parallel-flow heat exchanger*

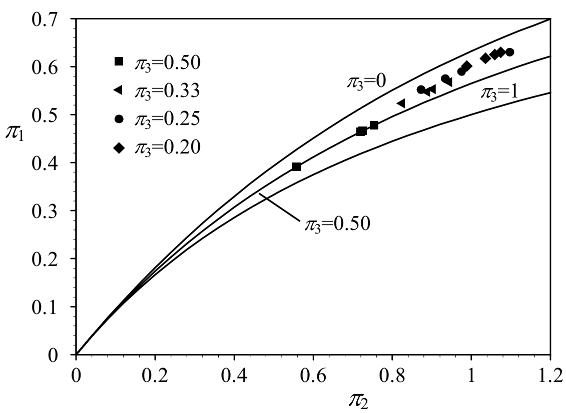

Fig. 3. *The positions of the measured operation points for a counter-flow heat exchanger*

2 MATHEMATICAL MODEL

The exchanged-heat flow rate between two streams can be calculated using the following equation ([10] and [11]):

$$\dot{Q} = C_1\left(\vartheta_1' - \vartheta_1''\right) = C_2\left(\vartheta_2'' - \vartheta_2'\right) \qquad (1).$$

The heat exchanger effectiveness ε is usually defined as:

$$\varepsilon = \pi_1 = \frac{\vartheta_1' - \vartheta_1''}{\vartheta_1' - \vartheta_2'} = \frac{\dot{Q}}{\dot{Q}_{\max}} \qquad (2).$$

The exchanged-heat flow rate $\dot{Q}$ can be re-written as:

$$\dot{Q} = \varepsilon\dot{Q}_{\max} = \varepsilon C_1\left(\vartheta_1' - \vartheta_2'\right) \qquad (3).$$

Since the pressure drop of the two streams is neglected, the entropy generation can be calculated from the following equation [11]:

$$\dot{S}_{\mathrm{gen}} = C_1 \ln\frac{T_1''}{T_1'} + C_2 \ln\frac{T_2''}{T_2'} \qquad (4).$$

Using Equations (1) and (2), it is easy to transform Equation (4) into the form:

$$\dot{S}_{\mathrm{gen}} = C_1 \ln\left(1\text{-}\varepsilon\left(1\text{-}\frac{T_2'}{T_1'}\right)\right) + C_2 \ln\left(1+\frac{C_1}{C_2}\varepsilon\left(\frac{T_1'}{T_2'}-1\right)\right) \qquad (5).$$

If the following terms for two non-dimensional parameters

$$\pi_{\mathrm{T}} = \frac{T_2'}{T_1'}; \quad \pi_3 = \frac{C_1}{C_2} \qquad (6)$$

are introduced into Equation (5), the equation for the entropy generation assumes the following form:

$$\dot{S}_{\mathrm{gen}} = C_1 \ln\left(1\text{-}\varepsilon\left(1\text{-}\pi_{\mathrm{T}}\right)\right) + C_2 \ln\left(1+\pi_3\varepsilon\left(\frac{1}{\pi_{\mathrm{T}}}-1\right)\right) \qquad (7).$$

After multiplying the above equation by the environmental temperature, T_0, the equation for the irreversibility or the exergy destruction is obtained as:

$$\dot{I} = Ex_{\mathrm{destr}} = T_0\dot{S}_{\mathrm{gen}} = T_0\left(C_1 \ln\left(1\text{-}\varepsilon\left(1\text{-}\pi_{\mathrm{T}}\right)\right) + C_2 \ln\left(1+\pi_3\varepsilon\left(\frac{1}{\pi_{\mathrm{T}}}-1\right)\right)\right) \qquad (8).$$

The above equation can be written in a non-dimensional form. For that purpose, it will be divided by the product of the heat capacity rate of the weaker stream, C_1, and the environmental temperature, T_0, as follows:

$$i_1 = \frac{\dot{I}}{T_0 C_1} = \ln\left(1\text{-}\varepsilon\left(1\text{-}\pi_{\mathrm{T}}\right)\right) + \frac{1}{\pi_3}\ln\left(1+\pi_3\varepsilon\left(\frac{1}{\pi_{\mathrm{T}}}-1\right)\right) \qquad (9).$$

Because the scope of this work is to show the ratio of the irreversibility and the exchanged-heat flow rate, it is useful to write Equation (1) in a non-dimensional form, dividing it by the product $C_1 T_1'$:

$$q_1 = \frac{\dot{Q}}{C_1 T_1'} = \varepsilon\left(1-\pi_{\mathrm{T}}\right) \qquad (10).$$

Finally, Equation (9) is divided by Equation (10), and a relevant ratio is obtained:

$$\frac{i_1}{q_1} = \frac{\ln\left(1\text{-}\varepsilon\left(1\text{-}\pi_{\mathrm{T}}\right)\right) + \frac{1}{\pi_3}\ln\left(1+\pi_3\varepsilon\left(\frac{1}{\pi_{\mathrm{T}}}-1\right)\right)}{\varepsilon\left(1-\pi_{\mathrm{T}}\right)} \qquad (11).$$

For a parallel heat exchanger the effectiveness ε is obtained using the following formula [10]:

$$\varepsilon = \frac{1-\mathrm{e}^{-(1+\pi_3)\pi_2}}{1+\pi_3} \qquad (12).$$

and for a counter heat-transfer heat exchanger ε is estimated as [10]:

$$\varepsilon = \frac{1-\mathrm{e}^{-(1\text{-}\pi_3)\pi_2}}{1-\pi_3\mathrm{e}^{-(1\text{-}\pi_3)\pi_2}} \qquad (13).$$

where:

$$\pi_2 = \frac{kA_0}{C_1} \qquad (14).$$

As can be seen, this ratio is a function of the non-dimensional parameters π_3 and $\varepsilon = \pi_1$, which represent the operation points of the heat exchanger and which are obtained by the energy analysis of heat exchangers. The additional parameters for irreversibility or exergy destruction are the input temperature ratia, π_{T}, and the ambient temperature, T_0.

3 CALCULATION RESULTS AND DISCUSSION

The diagrams in Figures 4 and 5 present the values of i_1 and i_1/q_1 for a parallel-heat-flow heat exchanger, and the diagrams in Figures 6 and 7 for a counter-flow heat exchanger. These values are calculated using Equations (9) to (11) and Equations (12) and (13) for the parallel and the counter heat exchanger, respectively. The black points in the diagrams represent the values of the operating points, which are presented in Figures 2 and 3.

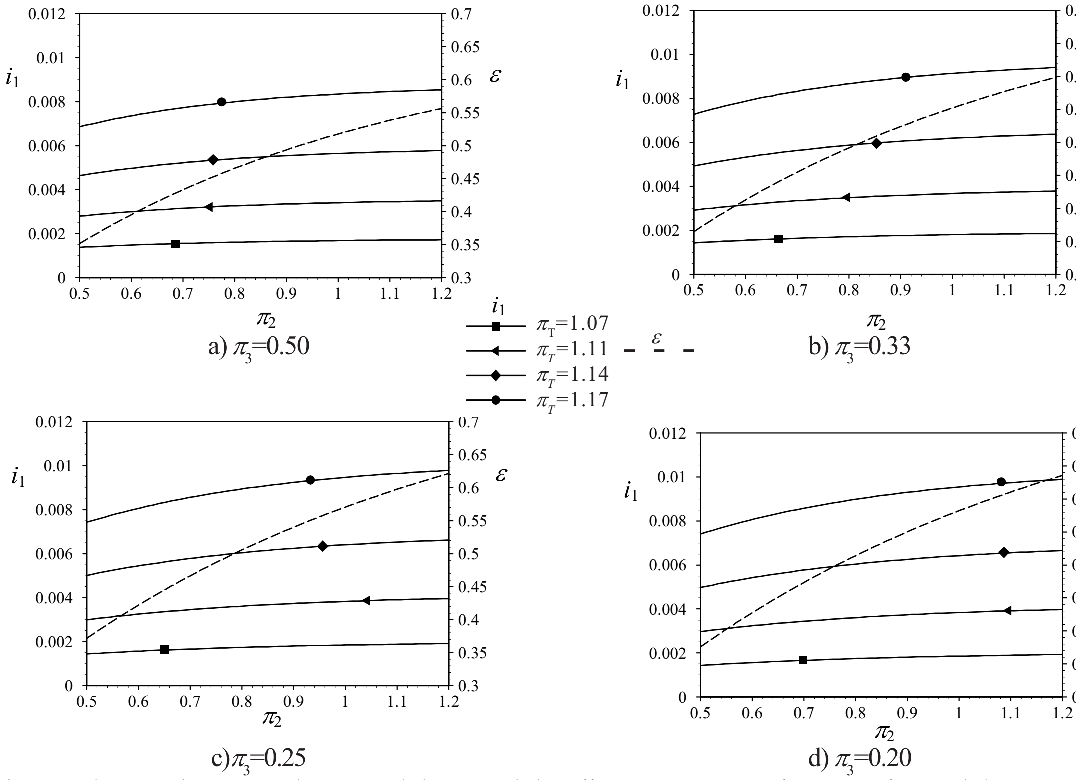

Fig. 4. *The non-dimensional irreversibility i_1 and the effectiveness ε as a function of π_2 and the parametric curves π_T for a) π_3=0.50, b) π_3=0.33, c)π_3=0.25 and d) π_3=0.20 for a parallel flow heat exchanger*

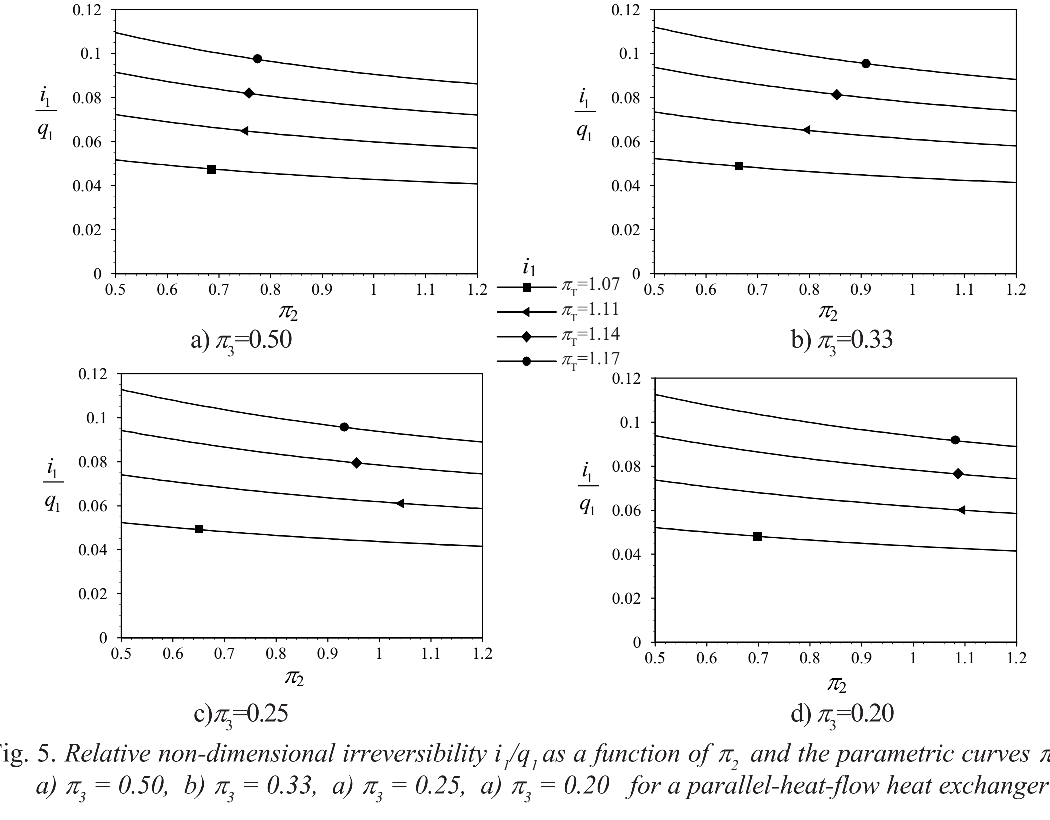

Fig. 5. *Relative non-dimensional irreversibility i_1/q_1 as a function of π_2 and the parametric curves π_T for a) π_3 = 0.50, b) π_3 = 0.33, a) π_3 = 0.25, a) π_3 = 0.20 for a parallel-heat-flow heat exchanger*

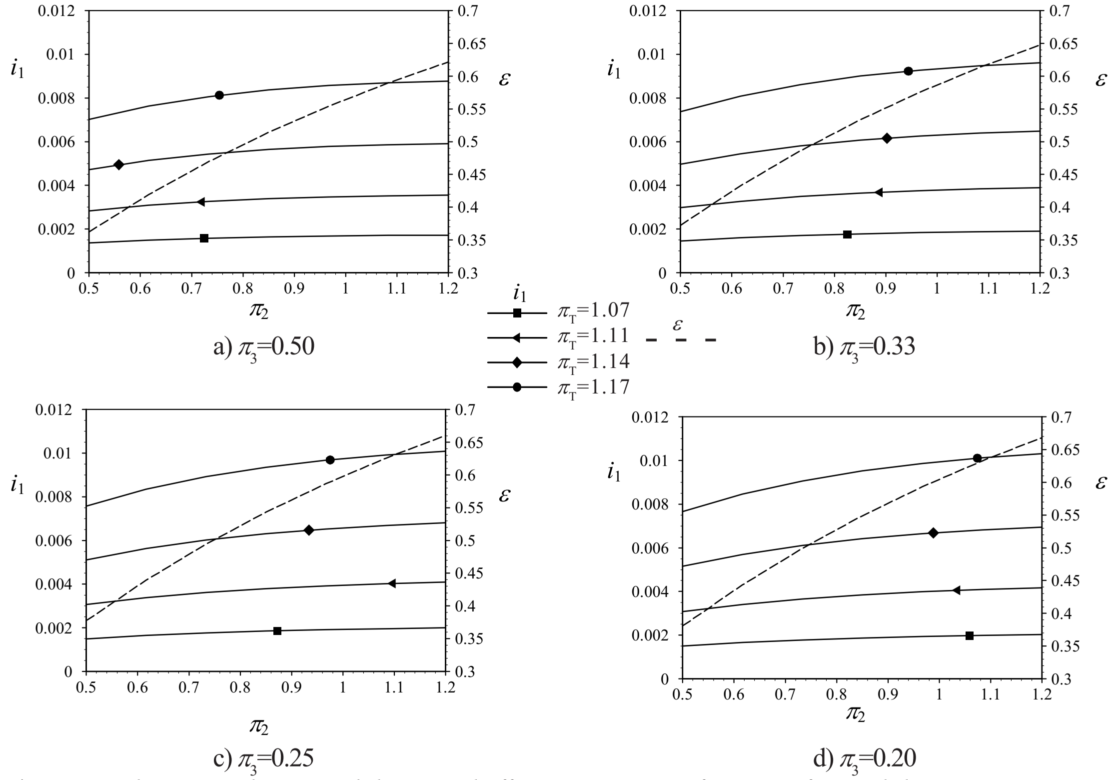

Fig.6. *Non-dimensional irreversibility i_1 and effectiveness ε as a function of π_2 and the parametric curves π_T for a) π_3=0.50, b) π_3=0.33, c)π_3=0.25 d) π_3=0.20 for a counter-flow heat exchanger*

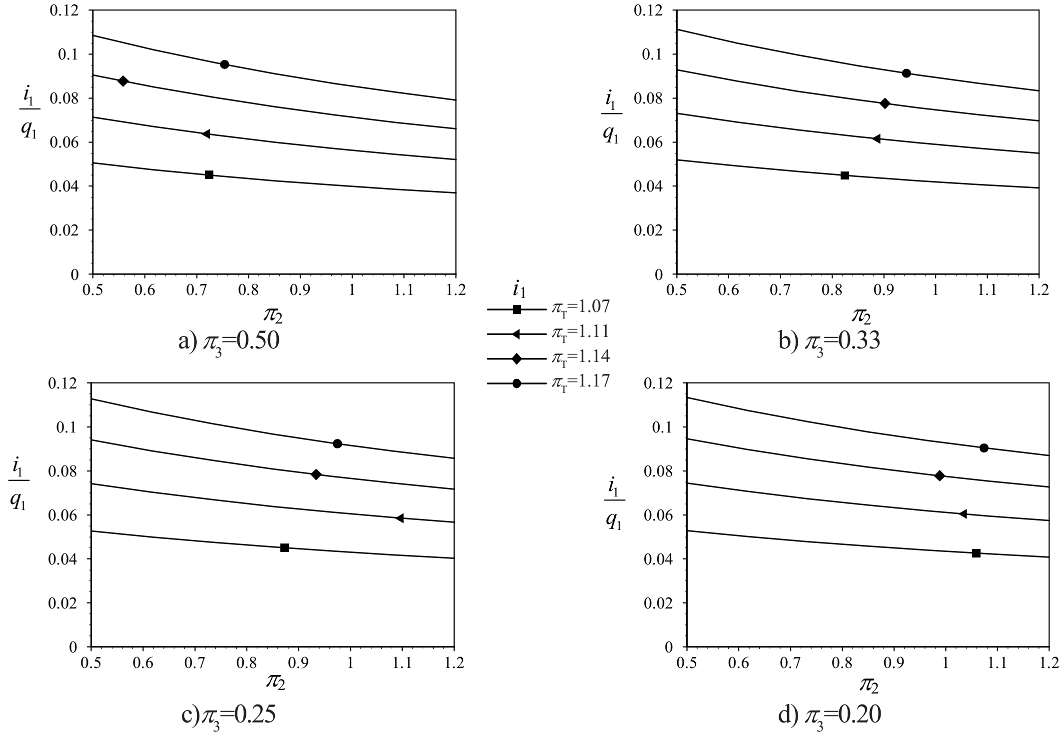

Fig. 7. *Relative non-dimensional irreversibility i_1/q_1 as a function of π_2 and the parametric curves π_T for a) π_3=0.50, b) π_3=0.33, c) π_3=0.25, d) π_3=0.20 for a counter-flow heat exchanger*

The above diagrams clearly show the relationship between the dimensionless values of i_1 and the dimensionless parameters π_2, π_3 and π_T. For each diagram it is possible to directly read the values of i_1 and ε for every case. It is obvious that the given values of π_2 and π_3 do not have a significant influence on i_1, but they have an influence on ε. The π_T ratio has the greatest influence on i_1, but it has no influence on ε. This can be quantitatively seen from Figures 4a and 4d, where the values $\pi_3 = 0.5$ and 0.2 and parametric values $\pi_T = 1.11$; 1.14 and 1.17 have the same value of $\pi_2 = 0.76$ and 1.09 respectively. For $\pi_3 = 0.5$, all operation points have the same value of ε, i.e., $\varepsilon = 0.455$, with the exergy destruction increasing from 0.0028 to 0.0078. On the other hand, for $\pi_3 = 0.2$ and the same parametric values of π_T and π_2 of 1.09, the value of ε is equal to 0.61. The associated exergy destructions are 0.0040, 0.0067 and 0.0076 respectively.

It is obvious that parallel- and counter-heat-flow heat exchangers have very small values of the ratio i_1 and i_1/q_1 for the measured operation points. It is not possible to make a comparison with respect to exergy destruction and heat-transfer effectiveness of the researched cases, because they did not have the same non-dimensional π_2 variables.

4 CONCLUSION

The presented analytical relationship between the dimensionless exergy destruction and the heat-transfer effectiveness of a heat exchanger seems to be rather convenient, because it relates the dimensionless parameters (π_3; π_2 and π_T as additional parameter) relevant to the operation of a heat exchanger and the exergy destruction of a parallel and a counter-flow heat exchanger. It is possible to include the values of the measured operation points into the presented mathematical model and simultaneously calculate the heat-transfer effectiveness and the exergy destruction of the considered heat exchangers. It can be concluded that the exergy destruction for each case of both investigated heat exchangers is small. The main reason for such a conclusion is the fact that the operation values of π_T close to 1.

Furthermore, by introducing additional exergy destruction due to the pressure drop in the model, it is possible to develop an analytical model for the minimization of heat exchangers' exergy destruction.

5 NOMENCLATURE

A_0	overall heat-transfer area, m^2
C	heat-capacity rate of the stream, W/K
Ex	exergy, W
$\dot{I}$	exergy destruction, W
i_1	non-dimensional exergy destruction
k	overall heat-transfer coefficient, W/(m^{2}K)
$\dot{Q}$	heat-transfer rate, W
q_1	non-dimensional heat-flow rate
$\dot{S}$	entropy generation rate, W/K
T	thermodynamic (absolute) temperature, K
T_0	ambient temperature, K

Greek Letters

ε, π_1	heat-exchanger effectiveness
ϑ	Celsius temperature, °C
π_T	ratio of inlet absolute temperatures, K
π_2	number of heat-transfer units
π_3	ratio of heat-capacity rates

Subscripts

1	weaker stream
2	stronger stream
destr	destruction
gen	generated

Superscripts

‘	inlet
‘’	outlet

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