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Calculation of the heat power of a tube heat exchanger

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Abstract In this paper, the logarithmic mean temperature difference method is used to determine the heat power of a tube-in-tube exchanger. Analytical solutions of the heat balance equations for the exchanger are presented. The considerations are illustrated by an example solution of the problem. In particular, the heat power of the tube-in-tube heat exchanger is determined taking into account the variants of work in the co-current and counter-current mode. Apart from the analytical solutions, appropriate numerical calculations in Matlab environment have been carried out.

Keywords: Heat power; Tube-in-tube exchanger; Analytical solutions; Numerical calculations

Nomenclature

η	–	Einstein coefficient
A	–	heat transfer surface area, m^2
$c_c,\ c_h$	–	specific heat of the cold and hot medium, kJ/kgK
d	–	exchanger tube diameter, m
d_m	–	average pipe diameter, m
k_A	–	overall heat transfer coefficient, W/m^2K
L	–	length of exchanger pipe, m
$\dot{m}_c,\ \dot{m}_h$	–	mass flow rate of the cold and hot medium, kg/s
$\dot{Q}$	–	heat flux, W

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$T_{h1},\ T_{h2}$	–	temperature of the hot medium at inlet and outlet, °C
T_{c1}	–	temperature of cold medium at inlet (co-current flow), °C
T_{c2}	–	temperature of cold medium at inlet (counter-current flow), °C
U_A	–	pipe perimeter, m
$U_c,\ U_h$	–	pipe perimeter on the cold and hot medium side, m
x	–	coordinate along the exchanger axis

1 Introduction

Tube-type heat exchangers, due to their high flexibility in terms of the construction materials that can be used, simplicity of calculation and the possibility of operating in a wide range of temperatures and pressures, are currently very often used in industry [3,4].

The tube-in-tube exchanger is the most basic exchanger of this type. Its structure usually consists of two thin-walled concentric tubes of different diameters. One medium flows in the inner tube, while the other flows in the annular space between the tubes. Depending on the direction of flow we distinguish co-current, counter-current or cross-flow tube heat exchangers. In the co-current heat exchanger hot and cold media flow in parallel in the same direction. In the case of a counter-current heat exchanger, the media flow in opposite directions [8,9].

Issues in experimental research and heat exchanger design are also frequently presented in scientific articles. An extensive experimental study for four different heat exchanger designs made of different materials was performed in [1]. As a result, the heat transfer efficiency was determined for the heat exchanger designs studied. The significant influence of flow disturbing inserts on the intensification of momentum and heat exchange in the investigated exchangers was demonstrated. Roetzel and Luo developed a way to predict the thermal efficiency of exchangers [7]. In particular, a genetic algorithm was developed whose general solutions can be an effective tool for the design and control of heat exchanger networks. In the paper [2], experimental and numerical thermodynamic analyses of gas-liquid cross heat exchangers were performed. On the basis of the analyses, a significant effect of non-uniform air supply on the efficiency of the considered heat exchangers has been shown.

This paper presents the method of determining the thermal power of a tube-in-tube heat exchanger operating in the co-current as well as the counter-current system. It is worth noting that in practice one usually has the following parameters of exchanger operation: $\dot{m}_h$, $\dot{m}_c$, c_h, and c_c, as well as its dimensions and inlet temperatures. The corresponding temperatures of the media at the exchanger outlet are usually unknown, which in practice makes appropriate calculations difficult. The method described in this paper enables calculation of heat power of the exchanger also in case of unknown temperatures of the media at the outlet.

2 Method for calculating the heat power of the exchanger

Two main calculation methods can be used to determine the values of the parameters of the exchanger under study [4,8]. The logarithmic mean temperature difference method is mainly used in Europe. Another one, applied more frequently in the USA, is known as the NTU (the number of transfer units) method [8,10]. In this paper, the logarithmic mean temperature difference method will be used. In order to simplify calculations, it has been assumed that there is a steady state in the exchanger and that the exchanger has thermal insulation completely eliminating losses to the surroundings.

We assume the invariability of the overall heat transfer coefficient k_A, as well as the specific heat of fluids, hot c_h and cold c_c, from the x-coordinate measured along the exchanger axis and from the temperature changes of the mediums under consideration. In case of single-phase flow, the above assumptions are usually easily met, in case of phase change of one of the media, it is necessary to divide the length of the exchanger into several parts in which the overall heat transfer coefficient takes constant values [9,10].

Under the discussed conditions, it can be assumed that the heat flux received from the hot medium is equal to the heat flux transferred to the cold medium ($\dot{Q}_h = \dot{Q}_c = \dot{Q}$). The power of a co-current and counter-current heat exchanger is calculated by the formula [4,9,10]:

$$\dot{Q} = k_A A \Delta T_m \,. \tag{1}$$

The logarithmic mean temperature difference is described by

$$\Delta T_m = \frac{\Delta T_2 - \Delta T_1}{\ln \dfrac{\Delta T_2}{\Delta T_1}} \,, \tag{2}$$

where ΔT_1 and ΔT_2 denote:

$$\Delta T_1 = T_{h1} - T_{c1}, \qquad \Delta T_2 = T_{h2} - T_{c2} \,. \tag{3}$$

The hot medium temperatures T_{h1} and T_{h2}, and cold medium temperatures T_{c1} and T_{c2} in relations (3) are shown in Fig. 1.

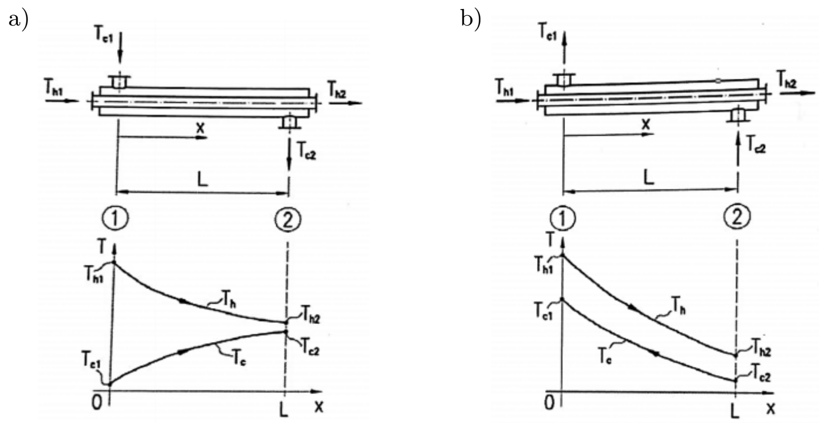

Figure 1: Temperature profiles in the tube-in-tube heat exchanger: a) co-current flow, b) counter-current flow.

The considered method of calculation for the heat exchangers, based on the logarithmic mean temperature difference, requires knowledge of the inlet and outlet temperatures of the two media. Usually it is assumed that the three mentioned temperatures are known, while the fourth one can be determined from the exchanger power formulae. In addition to formula (1), the following relations defining the exchanger power can be written down:

- for co-current fluid flow (Fig. 1a)

$$\dot{Q} = \dot{m}_c c_c \left(T_{c2} - T_{c1}\right) = \dot{m}_h c_h \left(T_{h1} - T_{h2}\right), \tag{4}$$

- for counter-current flow (Fig. 1b)

$$\dot{Q} = \dot{m}_c c_c \left(T_{c1} - T_{c2}\right) = \dot{m}_h c_h \left(T_{h1} - T_{h2}\right). \tag{5}$$

Usually, the inlet temperatures T_{h1} and T_{c1} for the co-current or T_{h1} and T_{c2} for the counter-current are known for discussed exchanger (Fig. 1), the heat transfer surface (A) and the overall heat transfer coefficient ($k_{A)}$ are also known. Then, as can be seen from Eq. (1), it is difficult to calculate the heat output of the exchanger due to the lack of knowledge of the outlet temperatures of the fluids T_{h2} and T_{c2} for the co-current or T_{h2} and T_{c1} for the counter-current.

To determine the outlet temperatures of the two fluids for the co-current heat exchanger T_{h2} and T_{c2}, we will use Eqs. (1) and (4) and the relationships (2) and (3). After the transformation we obtain:

$$\dot{Q} = k_A A \frac{\dfrac{\dot{Q}}{\dot{m}_h c_h} + \dfrac{\dot{Q}}{\dot{m}_c c_c}}{\ln\left[\dfrac{T_{h1} - T_{c1}}{(T_{h1} - T_{c1}) - \left(\dfrac{\dot{Q}}{\dot{m}_h c_h} + \dfrac{\dot{Q}}{\dot{m}_c c_c}\right)}\right]}. \tag{6}$$

Moving all the terms in Eq. (6) to one side, we get one nonlinear algebraic equation to determine $\dot{Q}$ for the co-current exchanger. We have:

$$1 - k_A A \frac{\dfrac{1}{\dot{m}_h c_h} + \dfrac{1}{\dot{m}_c c_c}}{\ln\left[\dfrac{T_{h1} - T_{c1}}{(T_{h1} - T_{c1}) - \left(\dfrac{\dot{Q}}{\dot{m}_h c_h} + \dfrac{\dot{Q}}{\dot{m}_c c_c}\right)}\right]} = 0. \tag{7}$$

Performing a similar operation of the counter-flow heat exchanger, we obtain an appropriate algebraic equation for determining the thermal power $\dot{Q}$:

$$1 - k_A A \frac{\dfrac{1}{\dot{m}_h c_h} - \dfrac{1}{\dot{m}_c c_c}}{\ln\left[\dfrac{(T_{h1} - T_{c2}) - \dfrac{\dot{Q}}{\dot{m}_c c_c}}{(T_{h1} - T_{c1}) - \dfrac{\dot{Q}}{\dot{m}_h c_h}}\right]} = 0. \tag{8}$$

The nonlinear algebraic equations (7) and (8) to determine the heat power $\dot{Q}$ can be solved using the simple iteration method or another method used to solve similar equations. Once the heat power $\dot{Q}$ is determined, the outlet temperatures of the fluids T_{h2} and T_{c2} can be easily determined from Eq. (4) for a co-current heat exchanger; or the corresponding temperatures T_{h2} and T_{c1} from Eq. (5) for a counter-current heat exchanger.

It is worth noting that the appropriate formulas describing the discussed outlet temperatures of the fluids T_{h2} and T_{c2} for the co-current heat exchanger or corresponding temperatures T_{h2} and T_{c1} for the counter-current heat exchanger can also be determined starting from the energy balance equations written in differential form for the exchangers under consideration:

$$\dot{m}_h c_h \left(\frac{dT_h}{dx}\right) = -k_A U_A \left(T_h - T_c\right), \tag{9}$$

$$\dot{m}_c c_c \left(\frac{dT_c}{dx}\right) = \pm k_A U_A (T_h - T_c). \tag{10}$$

After transforming Eqs. (9) and (10), the following differential equation with separated variables is obtained:

$$\frac{d(T_h - T_c)}{(T_h - T_c)} = -k_A U_A \left(\frac{1}{\dot{m}_h c_h} \pm \frac{1}{\dot{m}_c c_c}\right) \mathrm{d}x \tag{11}$$

whereby in equations (10) and (11) the "$-$" sign on the right-hand side of the equation denotes the case of a counter-current heat exchanger, while the "+" sign refers to a co-current heat exchanger. As a result of integrating Eq. (11), we one obtain

$$\ln\left(T_h - T_c\right) = -k_A U_A \left(\frac{1}{\dot{m}_h c_h} \pm \frac{1}{\dot{m}_c c_c}\right) x + C. \tag{12}$$

Assuming that the inlet temperatures of the fluids, both hot and cold, are known for the same coordinate, e.g. $x = 0$ we can write:

$$T_h|_{x=0} = T_{h1}, \qquad T_c|_{x=0} = T_{c1}\,. \tag{13}$$

After transformation of Eq. (12) and considering conditions (13) the following equations are obtained describing the values of the local temperature difference for a co-current heat exchanger:

$$T_h - T_c = \left(T_{h1} - T_{c1}\right) \exp\left[-k_A U_A \left(\frac{1}{\dot{m}_h c_h} + \frac{1}{\dot{m}_c c_c}\right) x\right], \tag{14}$$

and respectively for the counter-flow heat exchanger:

$$T_h - T_c = \left(T_{h1} - T_{c1}\right) \exp\left[-k_A U_A \left(\frac{1}{\dot{m}_h c_h} - \frac{1}{\dot{m}_c c_c}\right) x\right]. \tag{15}$$

Taking into account relation (14) in Eqs. (9) and (10) written for a co-current heat exchanger, and then integrating the obtained equations, we further obtain, similarly as in the paper [7], appropriate equations describing local changes of the hot medium:

$$T_h = T_{h1} - \frac{T_{h1} - T_{c1}}{1 + \frac{\dot{m}_h c_h}{\dot{m}_c c_c}} \left\{ 1 - \exp\left[-k_A U_A \left(\frac{1}{\dot{m}_h c_h} + \frac{1}{\dot{m}_c c_c} \right) x \right] \right\} \quad \text{for} \quad 0 \leq x \leq L, \tag{16}$$

or the cold medium:

$$T_c = T_{c1} + \frac{T_{h1} - T_{c1}}{1 + \frac{\dot{m}_c c_c}{\dot{m}_h c_h}} \left\{ 1 - \exp\left[-k_A U_A \left(\frac{1}{\dot{m}_h c_h} + \frac{1}{\dot{m}_c c_c} \right) x \right] \right\} \quad \text{for} \quad 0 \leq x \leq L. \tag{17}$$

Performing similar transformations with Eq. (15) as before with Eq. (14), we obtain the corresponding equations describing the local temperature changes of the hot and the cold media for the counter-current heat exchanger:

$$T_h = T_{h1} - \frac{(T_{h1} - T_{c2}) \left\{ 1 - \exp\left[-k_A U_A \left(\frac{1}{\dot{m}_h c_h} - \frac{1}{\dot{m}_c c_c} \right) x \right] \right\}}{1 - \frac{\dot{m}_h c_h}{\dot{m}_c c_c} \exp\left[-k_A A \left(\frac{1}{\dot{m}_h c_h} - \frac{1}{\dot{m}_c c_c} \right) \right]} \quad \text{for} \quad 0 \leq x \leq L \tag{18}$$

and

$$T_c = T_{h1} - \frac{(T_{h1} - T_{c2}) \left\{ 1 - \frac{\dot{m}_h c_h}{\dot{m}_c c_c} \exp\left[-k_A U_A \left(\frac{1}{\dot{m}_h c_h} - \frac{1}{\dot{m}_c c_c} \right) x \right] \right\}}{1 - \frac{\dot{m}_h c_h}{\dot{m}_c c_c} \exp\left[-k_A A \left(\frac{1}{\dot{m}_h c_h} - \frac{1}{\dot{m}_c c_c} \right) \right]} \quad \text{for} \quad 0 \leq x \leq L. \tag{19}$$

It is worth noting that Eqs. (16), (17), (18), and (19) allow for the determination of the local temperature of the hot and cold fluids in the co-current and counter-current exchanger, respectively.

The corresponding outlet temperatures of the hot and cold fluids T_{h2} and T_{c2} in the co-current exchanger and T_{h2} and T_{c1} in the counter-current exchanger are obtained from Eqs. (16)–(19) after substituting the final value of the longitudinal coordinate ($x = L$).

3 Analysis of a selected heat exchanger

In this paper, the performance analysis of a tube-in-tube heat exchanger with counter-current and co-current flow will be carried out. We assume that hot oil is cooled by cooling water in the exchanger under consideration [5]. The heat transfer area for the exchanger under consideration is $A = 1\ \mathrm{m}^2$. The mass fluxes of hot and cold media are $\dot{m}_h = 0.5$ kg/s and $\dot{m}_c = 0.75$ kg/s, respectively. Specific heats for oil (hot medium) and water (cold medium) are constant and are: $c_h = 88$ kJ/kgK and $c_c = 4.18$ kJ/kgK [5]. The oil inlet temperature is $T_{h1} = 116°\mathrm{C}$, while the corresponding cooling water temperature is $T_{c1} = 38°\mathrm{C}$ for a co-current heat exchanger or $T_{c2} = 38°\mathrm{C}$ for a counter-current heat exchanger. The value of the overall heat transfer coefficient is the same for the co-current and counter-current heat exchanger and equals $k_A = 440\ \mathrm{W/m^2K}$. The assume length of the exchanger is $L = 10$ m, with the given heat transfer surface area the value of the pipe perimeter is $U_A = \dfrac{1\,\mathrm{m}^2}{10\,\mathrm{m}} = 0.1\,\mathrm{m}$ and average pipe diameter $d_m = 0.03185$ m.

It is assumed that the exchanger consist of 4 parallel sections $L = 4 \times 2.5$ m $= 10$ m. On the basis of given parameters the temperature of both fluids at the outlet will be determined, as well as the thermal power of the analyzed exchanger, using the logarithmic average of the temperature difference.

In addition, calculations will also be performed to account for the effect of deposits forming on the pipe walls, reducing the overall heat transfer coefficient to a value of $k_A = 340\ \mathrm{W/m^2K}$ on the heat exchanger thermal power [3, 5, 8].

4 Determination of the heat power value of a tube-in-tube heat exchanger with co-current flow

The value of the exchanger power will be determined from Eq. (1), the corresponding temperature differences are determined from Eq. (3), considering the values given in Section 3 (for the co-current flow, the following temperature values are known $T_{h1} = 116°\mathrm{C}$ and $T_{c1} = 38°\mathrm{C}$). The unknown outlet temperature values T_{h2} and T_{c2} are determined from Eqs. (16) and (17), respectively. Thus, the temperature of the hot medium at the outlet for length $x = L = 10$ m is $T_{h2} = 88.65°$C. The corresponding cold medium temperature at the outlet of the considered co-current heat exchanger is $T_{c2} = 46.20°$C. Taking into account the given and calculated values of the temperatures of the media, we determine their respective differences according to formula (3). After substituting the appropriate values, we get:

$$\Delta T_1 = 116°\mathrm{C} - 38°\mathrm{C} = 78°\mathrm{C}, \qquad \Delta T_2 = 88.65°\mathrm{C} - 46.20°\mathrm{C} = 42.45°\mathrm{C}.$$

With all the necessary data, we can proceed to determine the heat power of the heat exchanger according to Eq. (1)

$$\dot{Q} = 440 \left[\frac{\mathrm{W}}{\mathrm{m}^2[°\mathrm{C}]}\right] \times 1\ [\mathrm{m}^2] \times \left\{\frac{42.45\ [°\mathrm{C}] - 78\ [°\mathrm{C}]}{\ln\left(\dfrac{42.45\ [°\mathrm{C}]}{78\ [°\mathrm{C}]}\right)}\right\} = 25710.82\ [\mathrm{W}].$$

Taking into account the reduced value of the heat transfer coefficient $k_A = 340$ W/m^{2}K due to the accumulation of deposits on the pipe walls, the new values of the temperatures T_{h2} and T_{c2} and the corresponding value of the heat power of the co-current heat exchanger were determined, they are: $T_{h2} = 93.49°$C, $T_{c2} = 44.75°$C and $\dot{Q} = 21158.39$ W

For the analyzed values of the co-current exchanger, we will again determine its heat power using Eq. (7). Applying the interval halving method, we obtained after solving the algebraic Eq. (7) the value of heat transfer rate equal to $\dot{Q} = 25710.18$ W ($k_A = 440$ W/m^{2}K) and $\dot{Q} = 21157.92$ W ($k_A = 340$ W/m^{2}K), respectively. The residual values were respectively: $\Delta = -7.301 \times 10^{-8}$ and $\Delta = 8.34 \times 10^{-9}$.

5 Determination of heat power of a tube-in-tube heat exchanger with counter-current flow

The heat transfer rate value of the counter-flow heat exchanger will also be determined from Eq. (1), and the corresponding temperature differences are also determined from Eq. (3). Considering the values given in Section 3 for temperatures $T_{h1} = 116°$C and $T_{c2} = 38°$C, the unknown values of outlet temperatures T_{h2} and T_{c1} are determined from Eqs. (18) and (19), respectively. Thus, the temperature of the hot medium at the outlet for length $x = L = 10$ m is ($k_A = 440$ W/m^{2}K), in the considered case, $T_{h2} = 88.19°$C.

The corresponding cold medium temperature at the outlet is $T_{c1} = 47.54°C$. Taking into account the given and calculated values of the temperatures of the factors, we determine their respective differences according to formula (3). After substituting appropriate values, we obtain for the counter-flow heat exchanger ($k_A = 440$ W/m^{2}K): $\Delta T_1 = 68.46°C$, $\Delta T_2 = 50.19°C$. The thermal power according to formula (1) is in the considered case: $\dot{Q} = 25895.33$ W.

Taking into account the reduced value of the heat transfer coefficient $k_A = 340$ W/m^{2}K, the corresponding values of the calculated parameters for the counter-current flow heat exchanger are: $T_{h2} = 93.26°C$, $T_{c1} = 45.97°C$, $\Delta T_1 = 70.03°C$, $\Delta T_2 = 55.26°C$ and $\dot{Q} = 21200.26$ W.

In this paper, for the assumed values of parameters of the counter-current heat exchanger, numerical calculations have also been performed using Matlab program [6].

Matlab was used to solve differential Eqs. (9) and (10) resulting from the heat balance in the counter-current heat exchanger. The boundary conditions were also identical to those in the counter-current exchanger discussed above. The considered two-point boundary problem was solved using the functions *bvp4c* and *bvp5c* [6]. The results obtained are presented in Figs. 2 and 3.

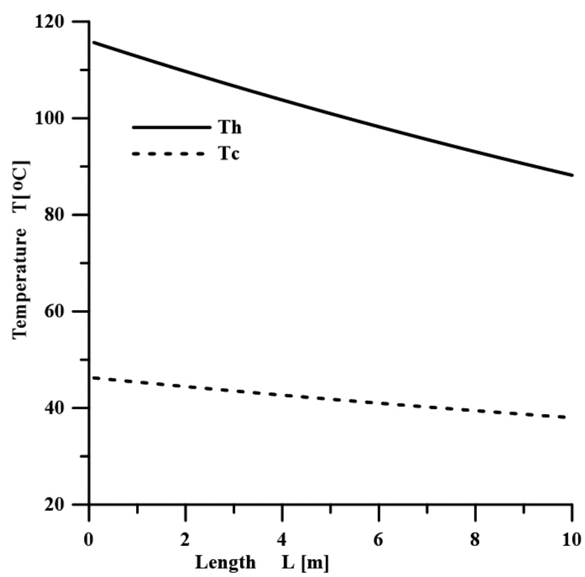

Figure 2: Temperature changes of the hot and cold media along the length of the counter-current heat exchanger.

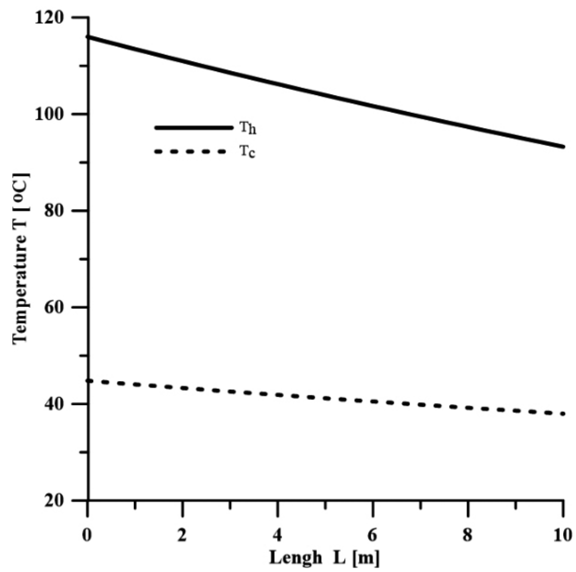

Figure 3: Temperature changes of the hot and cold media along the length of the counter-current flow heat exchanger with depositions.

Figure 2 shows the results of calculations taking into account the above mentioned values of parameters of the counter-current heat exchanger. It can be read that the value of the hot medium temperature at the end of the exchanger is $T_{h2} = 88.15$°C, while the corresponding value of the cold medium temperature is $T_{c1} = 46.35$°C. It is worth noting that the results shown in Fig. 2 were obtained for the value of heat transfer coefficient $k_A = 440$ W/m^{2}K, while the corresponding results obtained for the value of heat transfer coefficient $k_A = 340$ W/m^{2}K the exchanger with depositions) are quoted in Fig. 3. The corresponding numerically calculated hot and cold medium temperature values at the end of the counter flow heat exchanger with depositions are in this case $T_{h2} = 93.22$°C and $T_{c1} = 44.83$°C.

6 Results analysis

Using Eqs. (16) and (17), the unknown outlet temperatures of the hot and cold media in the co-current variant of the exchanger were determined. The determined values of the temperatures of the media enabled calculation of the heat power of the exchanger under consideration from formula (1). It is worth noting that the heat power of the exchanger in the co-current variant was also determined in a different way, by solving the algebraic equation (7). Having the value of the heat transfer rate from the solution of algebraic equation (7) at hand, the values of outlet temperatures of the agents were then calculated using formula (4). The obtained results of calculations for the co-current heat exchanger are presented in Table 1. The values marked with (*) in Table 1 were obtained from solving the algebraic equation (7).

Table 1: Comparison of calculation results for the co-current variant.

$A = 1$ m^2, $U_A = 0.1$ m, $L = 10$ m, $d_m = 0.03185$ m, $\dot{m}_h = 0.5$ kg/s, $c_h = 1.88$ kJ/kgK, $c_c = 4.18$ kJ/kgK, $\dot{m}_c = 0.75$ kg/s					
T_{h1}, °C	T_{h2}, °C	T_{c1}, °C	T_{c2}, °C	$\dot{Q}$, W	k_A, W/m^{2}K
116	88.65	38.00	46.20	25710.82	440
116	93.49	38.00	44.75	21158.39	340
116	88.65*	38.00	46.20*	25710.18*	440
116	93.49*	38.00	44.75*	21157.92*	340
* values were obtained from numerical calculations.					

The results of the calculations for the counter-current flow heat exchanger obtained in this study are summarized in Table 2. Also in this case, initially the unknown outlet temperatures of the hot and cold media were determined from Eqs. (18) and (19), respectively, and then the thermal power was calculated from Eq. (1).

Table 2: Comparison of calculation results for the counter-current variant.

$A = 1$ m^2, $U_A = 0.1$ m, $L = 10$ m, $d_m = 0.03185$ m, $\dot{m}_h = 0.5$ kg/s, $\dot{m}_c = 0.75$ kg/s, $c_h = 1.88$ kJ/kgK, $c_c = 4.18$ kJ/kgK					
T_{h1}, °C	T_{h2}, °C	T_{c1}, °C	T_{c2}, °C	$\dot{Q}$, W	k_A, W/m^{2}K
116	88.19	47.54	38.00	25895.33	440
116*	88.15*	46.35*	38.00	26121.82*	440*
116	93.26	45.97	38.00	21200.26	340
116*	93.22*	44.83*	38.00	21371.44*	340*
* values were obtained from numerical calculations.					

In addition, the outlet temperatures of the hot and cold media and the corresponding heat power of the counter-current heat exchanger were calculated using a numerical procedure in the Matlab program. We can see in Table 2 that the results obtained from the analytical relations for the counter-current mode and the corresponding ones obtained from numerical calculations are almost identical.

7 Summary and conclusions

The main objective of this study was to determine the key parameters for a tube-in-tube heat exchanger with co-current and counter-current flow of the medium. Knowing the usual exchange parameters such as inlet temperatures of the media, specific heat and mass fluxes of the media, as well as knowing the basic dimensions of the exchanger, the heat transfer surface, length and the overall heat transfer coefficient, it is not possible to determine its thermal power due to the lack of outlet temperatures of the media.

This paper shows how to determine the temperature values of the media at the outlet of an exchanger knowing the parameters usually available in practice. From the results of the calculations presented in Tables 1 and 2, we can see that the exchanger in the counter-current mode is characterized by a significantly higher power than the corresponding exchanger using the co-current mode. In addition to the results obtained using analytical relationships, corresponding results obtained numerically are also quoted. A comparative analysis of the quoted results shows their high degree of agreement.

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