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Heat Transfer Analysis on Changing the Flow Arrangement in a Triple Tube Heat Exchanger

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Abstract

The heat transfer analysis on changing the flow arrangement in a triple tube heat exchanger has been investigated experimentally for counter-current flow and co-current flow. The aim of the study is to establish how the mean temperature difference between the three fluids is calculated and to present the influence of the flow arrangement on the heat exchange. For both variants (counter-current flow and co-current flow) there are kept the same flow experimental conditions and there are compared the values obtained for the heat flows, the mean temperature difference, the convective heat transfer coefficients and the overall heat transfer coefficient.

Key words: *heat transfer, triple tube heat exchanger, mean temperature difference*

Introduction

The thermal design and checking of the heat exchangers are strictly related to the overall heat transfer coefficient and to the mean temperature difference between fluids. For the calculation of the overall heat transfer coefficient, by applying Newton's law of cooling, the most discussed parameter is the mean temperature difference, whose expression should accurately model the achieved heat transfer.

In a triple tube heat exchanger (i.e. a triple concentric - tube heat exchanger) there are identified three flow spaces: the circular space (inner tube), the inner annular space (created between the inner and intermediate tube) and the outer annular space (created between the intermediate and outer tube). Depending on the process, the hot fluid can circulate through the inner annular space or through the inner tube and through the outer annular space.

Regarding the flow arrangements of fluids in the heat exchanger, this can be achieved as both counter-current flow (case in which two fluid circulate in co-current flow and in counter-current flow with the third fluid) and co-current flow. In the counter-current flow, the fluids enter opposite ends, flow in opposite directions and exit at opposite ends of heat exchanger. In the co-current flow, the hot and cold fluids are introduced at the same end, flow in the same direction and leave at the same end of the heat exchanger.

In previous studies, Zuritz [10] discussed the design of a triple tube heat exchanger for cooling a food liquid product with water in counter-current flow and Unal obtained the analytical expressions for fluids temperature variations along the heat exchanger [4] and presented a series of theoretical studies [8] under which he derived analytical expressions for the effectiveness of the triple tube heat exchanger for both counter-current flow and co-current flow [9]. Also, Batmaz and Sandeep [2] developed a mathematical model to calculate the overall heat transfer coefficients in a triple tube heat exchanger and to determine the distribution of the axial fluid temperature for both counter-current flow and co-current flow.

In this paper there are analyzed and compared, in terms of the heat transfer, the experimental results obtained from water - water heat transfer in a triple tube heat exchanger for counter-current flow and for co-current flow.

In the experimental heat exchanger, the hot water stream circulates through inner annular space being cooled with two cold water streams (i.e. a cold water stream circulates through the inner tube and the other cold water stream circulates through the outer annular space). The purpose of this paper is to establish how the mean temperature difference between fluids is calculated and to investigate the influence of the flow arrangement on the heat exchange. Also, it is investigated the effect of changes in hot fluid flow rate on the heat flows, the mean temperature difference, the convective heat transfer coefficients and the overall heat transfer coefficient.

Experimental Part

The experimental setup on which the experimental measurements were carried out is the one presented by Radulescu et al. [4, 5] in previous studies on the analysis of heat transfer in a triple tube heat exchanger. The experimental setup consists of: a triple tube heat exchanger, a thermostatic bath, and flow meters and digital thermometers with probe. In the heat exchanger hot water flow through the inner annular space and cold water - through the inner tube (cold water stream C1) and through the outer annular space (cold water stream C2). The heat exchanger tubes have the following outer diameters: 0.014 m for the inner tube, 0.028 m for the intermediate tube and 0.042 m for the outer tube (tube wall thickness is 1 mm). The inner and the intermediate tubes length is L_1 = 1.193 m and the outer tube length is L_2 = 0.935 m.

The experiments were carried for two flow arrangements of fluids in the heat exchanger. In the former case, hot water (stream H) circulates in counter-current flow (CC-1) with cold water streams whose circulation is in co-current flow. In the latter mode, all three fluids flow in co-current flow (CC-2). The flow rate and inlet temperature of cold water streams were kept constant, whereas the hot water flow rate varied. For both cold water streams, C1 and C2, the flow rate was 100 l/h and the inlet temperature was 10.8 °C. The flow rates for hot water were between 60 and 250 l/h and the inlet temperature of hot water was adjusted to 55,3 °C. For the above-mentioned conditions, in table 1 there are given the outlet temperatures of the three fluids and the hot water flow rates.

In figure 1 it is shown a longitudinal section through the heat exchanger tubes. The heat transfer from hot water to cold water streams occurs in two opposite directions. A direction is for the heat exchange between hot water and cold water stream C1 and the other direction is for heat exchanger between hot water and the cold water stream C2.

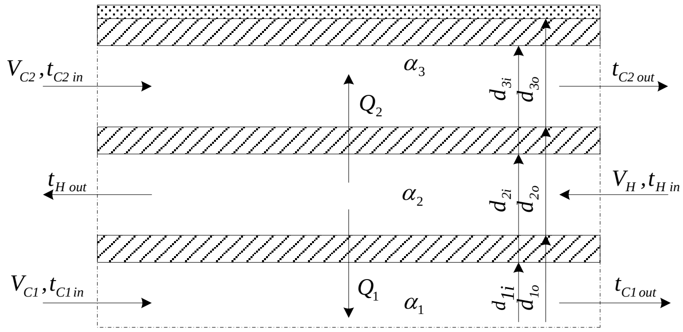

Fig. 1. The longitudinal section of the heat exchanger tubes

Table 1. Temperature and flow rates data

Flow arrangement	No. det.	Cold water stream C1	Hot water		Cold water stream C2
		$t_{C1\ out}$, °C	V_H, l/h	$t_{H\ out}$, °C	$t_{C2\ out}$, °C
CC - 1	1	16.7	60	33.7	17.6
	2	18.0	80	35.7	19.0
	3	19.2	100	37.0	20.3
	4	21.0	130	38.7	21.8
	5	21.7	150	40.0	22.4
	6	22.3	170	40.8	23.4
	7	23.0	200	42.0	24.6
	8	23.9	250	43.8	25.8
CC - 2	1	16.5	60	34.4	17.4
	2	17.8	80	36.3	18.7
	3	18.8	100	37.6	20.1
	4	20.8	130	39.2	21.3
	5	21.5	150	40.3	22.1
	6	22.0	170	41.1	23.2
	7	22.7	200	42.3	24.3
	8	23.6	250	44.1	25.5

The significance of the terms from Figure 1 is the following: VC1 - volumetric flow rate of cold water stream C1; VH - volumetric flow rate of the hot water; VC2 - volumetric flow rates of cold water stream C2; $t_{C1\ in}$, $t_{C1\ out}$ - inlet and outlet temperatures of cold water stream C1; $t_{H\ in}$, $t_{H\ out}$ - inlet and outlet temperatures of the hot water; $t_{C2\ in}$, $t_{C2\ out}$ - inlet, outlet temperatures of cold water stream C2; Q_{C1} - received heat flow from cold water stream C1, Q_{C2} - received heat flow from cold water stream C2, α_1 - heat transfer coefficient for the heat transfer between the inside surface of the inner tube and the cold water stream C1, α_2 - heat transfer coefficient for the heat transfer between hot water and the outside surface of the inner tube and the inside surface of the intermediate tube, α_3 - heat transfer coefficient for the heat transfer between the outside surface of the intermediate tube and the cold water stream C2, d_{1i}, d_{1o} – inner and outer diameters of the inner tube, d_{2i}, d_{2o} - inner and outer diameter of the intermediate tube, d_{3i}, d_{3o} - inner and outer diameter of the outer tube.

Results and Discusions

For the heat transfer analysis it was used the overall thermal balance equation:

$$Q_H = Q_{C1} + Q_{C2} + Q_L \tag{1}$$

where Q_H is the yielded heat flow and Q_L is the lost heat flow to the environment.

The received heat flows and the transferred heat flow were calculated using the following equations:

$$Q_H = m_H \cdot c_{pH} \cdot \left(t_{C\ in} - t_{C\ out}\right) \tag{2}$$

$$Q_{C1} = m_{C1} \cdot c_{pC1} \cdot \left(t_{C1\,out} - t_{C1\,in}\right) \tag{3}$$

$$Q_{C2} = m_{C2} \cdot c_{pC2} \cdot \left(t_{C2\,out} - t_{C2\,in}\right) \tag{4}$$

where: m_H – mass flow rate of hot water, c_{pH} – specific heat of hot water, m_{C1} – mass flow rate of cold water stream C1, c_{pC1} – specific heat of cold water stream C1, m_{C2} – mass flow rate of cold water stream C2, c_{pC2} – specific heat of cold water stream C2.
The calculated values of heat flows are shown in table 2.

Table 2. The values of the heat flows

Flow arrangement	No. det.	Q_{C1}, W	Q_H, W	Q_{C2}, W	Q_L, %
CC – 1	1	686	1481	790	0.32
	2	837	1792	953	0.12
	3	977	2092	1104	0.55
	4	1186	2467	1278	0.14
	5	1267	2624	1347	0.36
	6	1336	2818	1463	0.65
	7	1418	3041	1603	0.69
	8	1522	3287	1742	0.72
CC – 2	1	663	1433	767	0.22
	2	814	1737	918	0.31
	3	930	2023	1081	0.62
	4	1162	2393	1220	0.44
	5	1244	2572	1313	0.62
	6	1302	2760	1440	0.65
	7	1383	2973	1568	0.74
	8	1487	3202	1707	0.23

As shown in table 2, the values of the received heat flows and the yielded heat flow are higher for the counter-current flow than the co-current flow.

The convective heat transfer coefficients were calculated by using the relations recommended in the literature, depending on the flow regime and the form of the flow section. The flow regimes were following: transition in inner tube, laminar and transition in inner annular space and laminar in outer annular spaces.

For calculating the heat transfer coefficient on the inside of the inner tube it was used the following Gnielinski's correlation:

$$Nu = \frac{(f/8)\cdot(Re-1000)}{1+12.7\sqrt{f/8}\cdot\left(Pr^{2/3}-1\right)}\cdot\left[1+\left(d_{1i}/L_1\right)^{2/3}\right] \tag{5}$$

where Nu is Nusselt number, Re is Reynolds number and f is the Darcy factor, $f = (0.782\,ln\,Re - 1.51)^{-2}$ [1].

For calculating the heat transfer coefficient in inner annular space Devis's correlation [3, 6] was used:

$$Nu = 0.038 \cdot Re^{0.8} \cdot (Pr)^{1/3} \cdot \left(\frac{\mu}{\mu_{w2}}\right)^{0.14} \cdot \left(\frac{d_{2i}}{d_{1o}}\right)^{-0.15} \tag{6}$$

For calculating the heat transfer coefficient in outer annular space it was used the following relation [3]:

$$Nu = 4.05 \cdot Re^{0.17} \cdot Pr^{1/3} \cdot \left(\frac{\mu}{\mu_{w3}} \right)^{0.14} \tag{7}$$

In relations (5) – (7) the expression of *Nu*, *Re* and *Pr* numbers are:

$$Nu = \frac{\alpha \cdot l_c}{\lambda} \tag{8}$$

$$Re = \frac{w \cdot \rho \cdot l_c}{\mu} \tag{9}$$

$$Pr = \frac{c_p \cdot \mu}{\lambda} \tag{10}$$

where: w – linear average velocity, ρ - density, l_c - characteristic length, μ - dynamic viscosity, c_p - specific heat, λ - thermal conductivity. All physical properties were calculated at the arithmetic average between the inlet and the outlet temperatures of the fluids. The characteristic length in inner tube is the inner diameter of the tube and for the annular spaces, it is the equivalent hydraulic diameter (for inner annular space $d_{h1} = d_{2i} - d_{1o}$ and for outer annular space $d_{h2} = d_{3i} - d_{2o}$).

In equation (6), μ_{w2} represents the dynamic viscosity of the hot water at temperature of the inner annular space walls and in equation (7), μ_{w3} represents the dynamic viscosity of the cold water stream C2 at temperature on the outside wall of outer tube. The simplexes $(\mu/\mu_{w2})^{0.14}$ and $(\mu/\mu_{w3})^{0.14}$ were neglected because it was considered that for hot water $\mu \approx \mu_{w2}$ and for cold water stream C2 $\mu \approx \mu_{w3}$.

The values of the linear average velocity are 0.25 m/s for the cold water stream C1, between 0.04 and 0,18 m/s for the hot water and 0,04 m/s for the cold water stream C2. The values of *Pr* for both flow arrangements are similar and range between 7.56 - 8.49 for the cold water stream C1, 3.37 - 3.91 for the hot water 7.34 - 8.37 for the cold water stream C2. Moreover, the values of *Nu* for both flow arrangements are similar and vary between 19.2 – 21.3 for the cold water stream C1, 12.4 - 40.2 for the hot water and 22.6 - 23.2 for the cold water stream C2. The values obtained for *Re* and the convective heat transfer coefficients are shown in table 3 for both counter-current flow and co-current flow.

Table 3. The values of *Re* and the convective heat transfer coefficients

Flow arrangement	Re			α_1, W/(m²·°C)	α_2, W/(m²·°C)	α_3, W/(m²·°C)
	Cold water stream C1	Hot water	Cold water stream C2			
CC - 1	2497 – 2756	883 - 3798	446 - 499	939 - 1056	657 - 2145	1119 - 1129
CC - 2	2490- 2745	888 - 3986	445 - 497	935 - 1051	659 - 2148	1120 - 1129

Table 3 shows that the values calculated for *Re* and the convective heat transfer coefficients are similar for both counter-current and co-current arrangements, because there is no significant variation of the physical properties of fluids with temperature.

The overall heat transfer coefficient (k_e) was calculated from equation for Newton's law of cooling written as:

$$Q = k_e \cdot \left(A_{1\,o} + A_{2\,i}\right) \cdot \Delta t_m \tag{11}$$

where: A_{1o} - heat transfer area on the outside surfaces of the inner tube ($A_{1\,o} = \pi \cdot d_{1\,o} \cdot L_1$), A_{2i} - heat transfer area on the inside surfaces of the intermediate tube ($A_{2\,i} = \pi \cdot d_{2\,i} \cdot L_2$), Δt_m – the mean temperature differences between fluids.

For calculating the expression of the mean temperature difference between the three fluids, according to the flow arrangement, we started from the expression of the mean temperature difference between a hot and a cold fluid [2, 6]. It was considered that the expression of Δt_m, as the logarithmic mean temperature difference Δt_{ml} for both counter-current flow and co-current flow, resembles more the actual operation of the device. Therefore, Δt_m was calculated with the equations presented below for each flow arrangement.

The relations of the logarithmic mean temperature difference for counter-current flow ($\Delta t_{ml\,CC-1}$) were:

$$\Delta t_{ml\,CC-1} = \frac{\left(t_{H\,in} - t_{C\,out}\right) - \left(t_{H\,out} - t_{C\,in}\right)}{ln\,\dfrac{t_{H\,in} - t_{Cout}}{t_{H\,out} - t_{C\,in}}}, \tag{12}$$

where $t_{C\,in} = 0{,}5 \cdot \left(t_{C1in} + t_{C2in}\right)$ and $t_{C\,out} = 0{,}5 \cdot \left(t_{C1out} + t_{C2out}\right)$.

$$\Delta t_{ml\;CC-1} = \frac{\Delta t_{ml\,1\,CC-1} - \Delta t_{ml\,2\,CC-1}}{ln\,\dfrac{\Delta t_{ml\,1\,CC-1}}{\Delta t_{ml\,2\,CC-1}}} \tag{13}$$

$$\Delta t_{ml\;CC-1} = 0.5 \cdot \left(\Delta t_{ml\,1\,CC-1} + \Delta t_{ml\,2\,CC-1}\right) \tag{14}$$

where:

$$\Delta t_{ml\;1\,CC-1} = \frac{\left(t_{H\;in} - t_{C1out}\right) - \left(t_{H\;out} - t_{C1in}\right)}{ln\,\dfrac{t_{H\;in} - t_{C1out}}{t_{H\;out} - t_{C1in}}} \tag{15}$$

$$\Delta t_{ml\;2\,CC-1} = \frac{\left(t_{H\;in} - t_{C2out}\right) - \left(t_{H\;out} - t_{C2in}\right)}{ln\,\dfrac{t_{H\;in} - t_{C2out}}{t_{H\;out} - t_{C2in}}} \tag{16}$$

Using the same procedure, *the relations of logarithmic mean temperature difference for co-current flow* ($\Delta t_{ml\,CC-2}$) were:

$$\Delta t_{ml\;CC-2} = \frac{\left(t_{H\;in} - t_{C1in}\right) - \left(t_{H\;out} - t_{C1out}\right)}{ln\,\dfrac{t_{H\;in} - t_{C1in}}{t_{H\;out} - t_{C1out}}}, \tag{17}$$

$$\Delta t_{ml\;CC-2} = \frac{\Delta t_{ml\,1\,CC-2} - \Delta t_{ml\,2\,CC-2}}{ln\,\dfrac{\Delta t_{ml\,1\,CC-2}}{\Delta t_{ml\,2\,CC-2}}}, \tag{18}$$

$$\Delta t_{ml\;CC-2} = 0.5 \cdot \left(\Delta t_{ml\;1\,CC-2} + \Delta t_{ml\;2\,CC-2}\right) \tag{19}$$

where:

$$\Delta t_{ml\,1CC-2} = \frac{\left(t_{H\,in} - t_{C1in}\right) - \left(t_{H\,out} - t_{C1out}\right)}{ln \dfrac{t_{H\,in} - t_{C1in}}{t_{H\,out} - t_{C1out}}}, \tag{20}$$

$$\Delta t_{ml\,1CC-2} = \frac{\left(t_{H\,in} - t_{C2in}\right) - \left(t_{H\,out} - t_{C2out}\right)}{ln \dfrac{t_{H\,in} - t_{C2in}}{t_{H\,out} - t_{C2out}}}, \tag{21}$$

For both counter-current flow and co-current flow it was observed that when the cold water streams flow rate and inlet temperature were kept constant, the yielded heat flow, the convective heat transfer coefficients and the overall heat transfer coefficient increased with increasing the hot water flow rate.

The transferred heat flow and the mean temperature differences are higher for counter-current flow than for co-current flow (for the same inlet temperatures and flow rates). In table 1, one can notice that the hot water is cooled in the counter-current flow better than in the co-current flow (the outlet temperature of the hot water is less for counter-current flow than co-current flow), therefore the cold water streams receiving more heat to counter-current flow.

The equations (12) – (14) for counter-current flow and the equations (17) – (19) for co-current flow led to similar values of Dt_{ml} on each flow arrangement. For the calculation of Dt_{ml}, the equation (12) for counter-current flow and the equation (17) for co-current flow were considered to be more practical as compared with other forms of equations. In figure 2 there are represented the variations of the Dt_{ml} with Re for hot water for both counter-current and co-current flows.

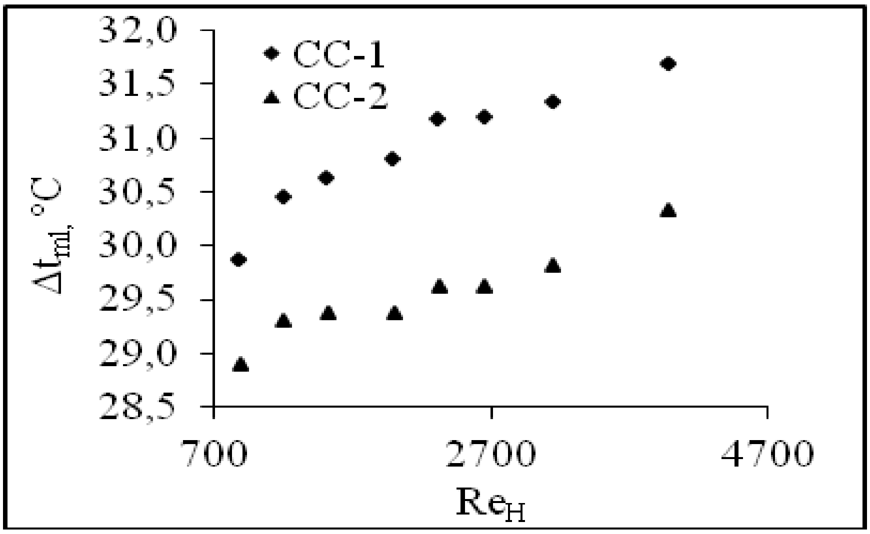

Fig. 2. The variation of Δt_{ml} with Re for hot water

As shown in figure 2, Δt_{ml} increases with increasing Re, and values of Δt_{ml} are higher for counter-current flow than for co-current flow.

Also, for both flow arrangements in figure 3 there is represented the variation of the overall heat transfer coefficient with the linear average velocity of hot water, w_H. In this figure it is shown that the values of k_e are similar for both counter-current flow and co-current flow (the curves are overlapping) and k_e increases with increasing w_H.

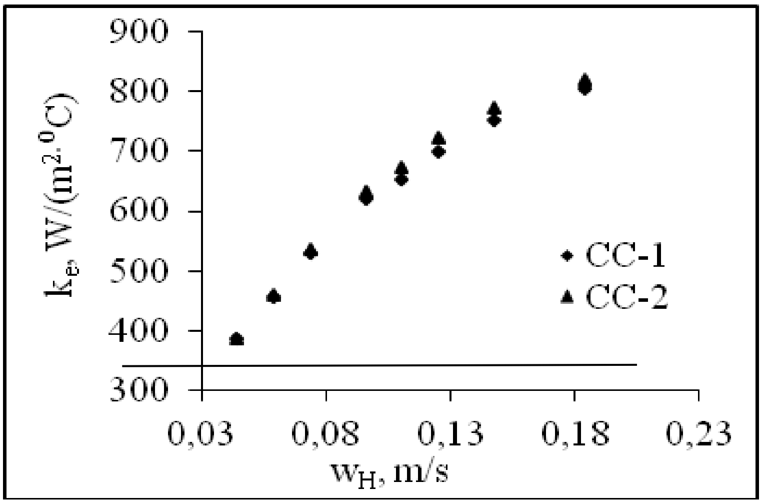

Fig. 3. The variation of k_e with the linear average velocity of hot water

Conclusions

In this paper it was investigated the effect of changes in the flow arrangement in a triple tube heat exchanger on the temperature efficiencies and overall heat transfer coefficient. The study was performed for water - water heat transfer in counter-current and co-current flow arrangements. Regarding the effect on heat transferred, the difference between counter-current flow and co-current flow is that the hot water is cooled better in the counter-current flow than the co-current flow, therefore the yielded heat flow is higher for counter-current flow than for co-current flow, although the convective heat transfer coefficients are close for both flow arrangements. Also, it is shown that the values of logarithmic mean temperature difference for counter-current flow are higher than for co-current flow. The values of Δt_{ml} and k_e increase with increasing of the linear average velocity of hot water for both counter-current flow and co-current flow when the flow rates of cold water streams and the inlet temperatures of all fluids were kept constant.

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Analiza transferului de căldură la schimbarea modului de circulaţie într-un schimbător de căldura tri-concentric

Rezumat

Analiza transferului de căldură la schimbarea modului de circulaţie într-un schimbător de căldura tri-concentric a fost investigată experimental pentru curgerea în contracurent şi curgerea în echicurent. Scopul acestui studiu este de a stabili modul de calcul pentru diferenţa medie de temperatură între trei fluide şi prezentarea influenţei modului de circulaţie a fluidelor asupra schimbului de căldură. Atât pentru curgere în contacurent cât şi pentru curgerea în echicurent, se păstrează aceleaşi condiţii experimentale şi se compară valorile obţinute pentru: fluxurile termice, diferenţa medie de temperatură, coeficienţii de transfer termic convectiv şi coeficientul global de transfer de căldură.