Analysis of the heat transfer in double and triple concentric tube heat exchangers

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Abstract. The tubular heat exchangers (shell and tube heat exchangers and concentric tube heat exchangers) represent an important category of equipment in the petroleum refineries and are used for heating, pre-heating, cooling, condensation and evaporation purposes. The paper presents results of analysis of the heat transfer to cool a petroleum product in two types of concentric tube heat exchangers: double and triple concentric tube heat exchangers. The cooling agent is water. The triple concentric tube heat exchanger is a modified constructive version of double concentric tube heat exchanger by adding an intermediate tube. This intermediate tube improves the heat transfer by increasing the heat area per unit length. The analysis of the heat transfer is made using experimental data obtained during the tests in a double and triple concentric tube heat exchanger. The flow rates of fluids, inlet and outlet temperatures of water and petroleum product are used in determining the performance of both heat exchangers. Principally, for both apparatus are calculated the overall heat transfer coefficients and the heat exchange surfaces. The presented results shows that triple concentric tube heat exchangers provide better heat transfer efficiencies compared to the double concentric tube heat exchangers.

1. Introduction

The tube in tube heat exchanger (TTHE) is the same double concentric tube heat exchanger and it is composed by two concentric tubes with identical length and different diameters. This heat exchanger has the advantage to work in counter-current flow, with a better heat exchange, it can be operating to high temperatures and has a good resistance to high pressure. In industry, the tube in tube heat exchangers are used as condensers, vaporizers, sub-coolers, heat recovery exchangers, crystallizers etc. [1 - 3].

The triple concentric tube heat exchanger (TCTHE) is a modified constructive version of double concentric tube heat exchanger by adding an intermediate tube. Thus, triple concentric heat exchanger is constructed by three concentric tubes and it is possible to have the different lengths. The triple concentric heat exchangers have some advantages compared to tube in tube heat exchangers, as larger surface area for heat transfer per unit length and higher overall heat transfer coefficients [4 - 8]. Adding the third tube the thermal contact between the fluids was improved. Also, by using these types of heat exchangers can be obtained technical and economic advantages due to the possibility of heat exchange between three fluids in one equipment. The heat exchangers with three concentric tubes are used specially in heating processes food industry, cooling processes, pasteurization/sterilization, congelation and concentration. In literature were found several studies of thermal analysis in TCTHE.
with streams used in food industry [9 - 11], but the applicability domain of these heat exchangers is expanding [12, 13]. The fact that TTHE is used in petroleum processing industry and the theoretical advantages to TCTHE versus TTHE, they constituted the starting point of the experimental study of heat transfer to cooling a petroleum product with water in a TCTHE [8, 14] and in a TTHE and comparing of the thermal performances for the two equipments. In this paper are presented the results of heat transfer obtained to cooling a petroleum product with water in a TTHE and in a TCTHE. The aim of the study is to compare the heat transfer areas, the convective heat transfer coefficients and the overall heat transfer coefficients between the two heat exchangers and finally highlighting the advantages to TCTHE.

2. Experimental part

The pilot plant used in experimental heat transfer study to cool petroleum product with water is composed by concentric tube heat exchangers, thermostatic bath, centrifugal pump, electronic thermometers with sensor and flow meters with magnetic floating.

The experimental setup was performed first with TTHE and then with TCTHE for the same operating conditions. The petroleum product heating in thermostatic bath (stream H - petroleum product) is circulated by flow meter were it is adjusted the flow rate, then through the heat exchanger. In TTHE the petroleum product circulates through the inside tube and yield heat to cold water which circulates through the annular space creating between the outside surface of the inside tube and the inside surface of the outside tube. In TCTHE the petroleum product circulates through the inner annular space creating between the outer surface of the inside tube and the inside surface of the intermediate tube, and yield heat to two cold water streams C1 and C2. The stream C1 circulates through the inside tube and stream C2 circulates through the outer annular space creating between the outside surface of the intermediate tube and the inside surface of the outside tube. The petroleum product has the density \(d_{15} = 0.885\) and the Watson factor 11.8. In figure 1 are presented the two heat exchangers, (a) TTHE and (b) TCTHE, with operating parameters: streams of fluids, inlet and outlet temperatures of hot and cold fluids.

![Diagram](image)

**Figure 1.** (a) Double tube heat exchanger; (b) Triple concentric tube heat exchanger.

The heat exchangers are constructed of copper pipes, straights, with flat surfaces. In table 1 are presented the geometrical dimensions for the two heat exchangers.
Table 1. The sizes for the heat exchangers.

| Size                                      | TTHE | TCTHE |
|-------------------------------------------|------|-------|
| Inner diameter of the inside tube, \(d_{1i}\), mm | 26   | 12    |
| Outer diameter of the inside tube, \(d_{1o}\), mm | 28   | 14    |
| Inner diameter of the outside tube, \(d_{2i}\), mm | 40   | -     |
| Outer diameter of the outside tube, \(d_{2o}\), mm | 42   | -     |
| Inner diameter of the intermediate tube, \(d_{3i}\), mm | -    | 26    |
| Outer diameter of the intermediate tube, \(d_{3o}\), mm | -    | 40    |
| Inner diameter of the outside tube, \(d_{3o}\), mm | -    | 28    |
| Length of the inside tube, \(L_{1}\), mm | 1193 | 1193  |
| Length of the intermediate tube, \(L_{i}\), mm | -    | 1193  |
| Length of the outside tube, \(L_{2}\), mm | 1193 | 935   |

For each experimental setup were set the inlet temperature to petroleum product and the flow rates for each stream and were read the inlet and outlet temperatures to water and the outlet temperature for petroleum product. The inlet temperature to petroleum product was kept between 60 - 86.4 °C, while for water the inlet temperature has varied between 10.9 - 19.3 °C, depending on weather conditions. In table 2 are presented data sets for the tests.

Table 2. Temperatures and flow rates data.

| No. det. | \(V_{H}\) l/h | \(V_{C}\) l/h | \(t_{H, in}\) °C | \(t_{H, out}\) °C | \(t_{C, in}\) °C | \(t_{C, out}\) °C | \(V_{C1}\) l/h | \(V_{C2}\) l/h | \(t_{C1, in}\) °C | \(t_{C1, out}\) °C | \(t_{C2, in}\) °C | \(t_{C2, out}\) °C |
|----------|---------------|---------------|-----------------|-----------------|----------------|-----------------|---------------|---------------|----------------|-----------------|----------------|----------------|
| 1        | 180           | 290           | 60.0            | 52.3            | 12.1           | 14.6            | 110           | 120           | 52.1           | 14.5            | 14.7           |                |
| 2        | 120           | 220           | 60.4            | 50.4            | 12.6           | 15.1            | 100           | 100           | 50.3           | 14.9            | 15.2           |                |
| 3        | 150           | 250           | 60.2            | 51.4            | 11.3           | 14.0            | 100           | 100           | 51.2           | 13.9            | 14.2           |                |
| 4        | 150           | 250           | 70.3            | 59.8            | 10.9           | 14.2            | 100           | 100           | 59.6           | 14.0            | 14.4           |                |
| 5        | 150           | 250           | 86.4            | 72.4            | 11.3           | 15.5            | 100           | 110           | 72.3           | 15.4            | 15.6           |                |
| 6        | 120           | 210           | 70.4            | 58.3            | 13.4           | 16.6            | 90            | 100           | 58.2           | 16.4            | 16.7           |                |
| 7        | 50            | 140           | 60.5            | 45.4            | 17.2           | 18.8            | 90            | 100           | 45.0           | 18.7            | 19.0           |                |
| 8        | 50            | 140           | 60.5            | 46.4            | 19.3           | 21.4            | 90            | 50            | 46.2           | 20.8            | 22.4           |                |

The significance of the terms from this table is following: \(V_{H}\) - the volumetric flow rate of the petroleum product; \(t_{H, in}\), \(t_{H, out}\) - the inlet and outlet temperatures of the petroleum product; \(V_{C}\) - the volumetric flow rate of water; \(t_{C, in}\), \(t_{C, out}\) - the inlet and outlet temperatures of water; \(V_{C1}\) - the volumetric flow rates of stream C1; \(t_{C1, in}\), \(t_{C1, out}\) - the inlet and outlet temperatures of stream C1; \(V_{C2}\) - the volumetric flow rates of stream C2; \(t_{C2, in}\), \(t_{C2, out}\) - the inlet and outlet temperatures of stream C2. In TTHE, \(V_{C}\) is the sum of \(V_{C1}\) and \(V_{C2}\) in TCTHE.

3. Results and discussions
The heat transfer analysis of the two heat exchangers is based on the heat balance equation:

\[ Q_H = Q_C + Q_L \tag{1} \]

where \(Q_H\) is the transferred heat flow (W), \(Q_C\) is the received heat flow (W) and \(Q_L\) is the lost heat flow to the environment (W).

Thus, in TTHE:

\[ Q_H = m_C \cdot c_p \cdot (t_{H, in} - t_{H, out}) \tag{2} \]
\[ Q_c = m_c \cdot c_{pC} \cdot (t_{C\text{out}} - t_{C\text{in}}) \]  
\[ (3) \]

where: \( m_H \) - the mass flow rate of petroleum product (kg/s); \( c_{pH} \) - the specific heat of petroleum product (J/(kg\text{\degree}C)); \( m_C \) - the mass flow rate of water (kg/s); \( c_{pC} \) - the specific heat of water (J/(kg\text{\degree}C)).

For TCTHE:

\[ Q_H = Q_{C1} + Q_{C2} + Q_L \]  
\[ (4) \]

\[ Q_{H} = m_H \cdot c_{pH} \cdot (t_{H\text{in}} - t_{H\text{out}}) \]  
\[ (5) \]

\[ Q_{C1} = m_{C1} \cdot c_{pC1} \cdot (t_{C1\text{out}} - t_{C1\text{in}}) \]  
\[ (6) \]

\[ Q_{C2} = m_{C2} \cdot c_{pC2} \cdot (t_{C2\text{out}} - t_{C2\text{in}}) \]  
\[ (7) \]

where: \( Q_{C1} \) - the received heat flow by the stream C1 (W); \( m_{C1} \) - the mass flow rate of stream C1 (kg/s); \( c_{pC1} \) - the specific heat of stream C1 (J/(kg\text{\degree}C)); \( Q_{C2} \) - the received heat flow by the stream C2 (W), \( m_{C2} \) - the mass flow rate of stream C2 (kg/s); \( c_{pC2} \) - the specific heat of stream C2 (J/(kg\text{\degree}C)).

For the convective heat transfer in TTHE are identified the heat transfer coefficient for the heat transfer between the petroleum product and the inside surface of the inner tube (\( \alpha_1 \)) and the heat transfer coefficient for the heat transfer between the outside surface of the inner tube and the water stream (\( \alpha_2 \)). In TCTHE the heat transfer coefficients are: for the heat transfer between the inside surface of the inner tube and the stream C1 (\( \alpha_1 \)), for the heat transfer between the petroleum product and the outside surface of the inner tube (\( \alpha_2 \)), for the heat transfer between the petroleum product and the inside surface of the intermediate tube (\( \alpha_3 \)) and for the heat transfer between the outside surface of the intermediate tube and the stream C2 (\( \alpha_j \)). A part of convective heat transfer coefficients were calculated using the following criteria relations:

- M. Rubinstein [1] for the calculation of \( \alpha_1 \) in TTHE:

\[ Nu = 2.40 \cdot \left( Re \cdot Pr \cdot \frac{d}{L} \right)^{1/3} \]  
\[ (8) \]

in which \( Re \) is Reynolds number, \( Pr \) is Prandtl number, \( d \) is diameter and \( L \) is tube length.

- Gnielinsky [15, 16] for the calculation of \( \alpha_1 \) in TCTHE:

\[ Nu = \frac{\left( f / 8 \right) \cdot \left( Re - 1000 \right) \cdot Pr}{1 + 12.7 \sqrt{f / 8 \cdot Pr} - \left( 2/3 \right)} \]  
\[ (9) \]

where \( f = \left( 0.782 \ln Re - 1.51 \right)^{-2} \) [16].

- Gnilelinski [17] for the calculation of \( \alpha_j \) in TCTHE and \( \alpha_2 \) in TTHTE:

\[ Nu = 3.66 + 1.2 \cdot \left( \frac{D_i}{d_o} \right)^{0.8} + \frac{0.19 \cdot \left[ 1 + 0.14 \cdot \left( \frac{D_i}{d_o} \right)^{0.5} \right] \cdot Re \cdot Pr \cdot \frac{d_h}{L}^{0.8}}{1 + 0.117 \cdot Re \cdot Pr \cdot \frac{d_h}{L}^{0.467}} \]  
\[ (10) \]

where for two concentric tube \( D_i \) is the inner diameter of the larger diameter tube, \( d_o \) is the outer diameter of the of smaller diameter tube and \( L \) is the tube length.

\( Re, Pr \) and \( Nu \) numbers were calculated using the following equations:
\[ Re = \frac{w \cdot \rho \cdot L_c}{\mu} \]  
(11)

\[ Pr = \frac{c_p \cdot \mu}{\lambda} \]  
(12)

\[ Nu = \frac{\alpha \cdot L_c}{\lambda} \]  
(13)

where: \( \alpha \) - the heat transfer coefficient (W/(m\(^2\)·°C)), \( w \) - linear average velocity (m/s), \( \rho \) - density (kg/m\(^3\)), \( L_c \) - characteristic length (m), \( \mu \) - dynamic viscosity (kg/(m·s)), \( c_p \) - specific heat (J/(kg·°C)), \( \lambda \) - thermal conductivity (W/(m·°C)).

The physical properties were calculated at the arithmetic average between the inlet and outlet temperatures of the fluids.

In equations (11) and (13), the characteristic length is the inner diameter for flow through the inside tube and the equivalent hydraulic diameter ( \( d_h \) ) for flow through the annular spaces.

\[ d_h = \frac{4S_c}{P_w} \]  
(14)

where \( S_c \) is the flow section (m\(^2\)) and \( P_w \) is the wetted perimeter (m).

The linear average velocity has the general expression:

\[ w = \frac{V}{S_c} \]  
(15)

where \( V \) is the volumetric flow rate (m\(^3\)/s).

The convective heat transfer coefficients in inner annulus of TCTHE are calculated using Newton’s law of cooling equation written for \( Q_{C1} \) and \( Q_{C2} \). Thus,

\[ Q_{C1} = \alpha_{2i} \cdot A_{1i} \cdot (t_{w1i} - t_{C1}) = \alpha_{2j} \cdot A_{1o} \cdot (t_{H} - t_{w1o}) \]  
(16)

\[ Q_{C2} = \alpha_{2o} \cdot A_{2o} \cdot (t_{w2o} - t_{C2}) = \alpha_{2o} \cdot A_{2i} \cdot (t_{H} - t_{w2i}) \]  
(17)

where: \( A_{1i}, A_{1o} \) - inner and outer heat transfer areas of the inside tube (m\(^2\)), \( t_{C1} \) - arithmetic average temperature (from inlet and outlet temperatures) of the stream C1 (°C), \( t_{H} \) - arithmetic average temperature of the petroleum product (°C), \( t_{w1i}, t_{w1o} \) - inner and outer surface temperatures of the inside tube wall (°C), \( A_{2i}, A_{2o} \) - inner and outer heat transfer areas of the intermediate tube (m\(^2\)), \( t_{C2} \) - arithmetic average temperature of the stream C2 (°C), \( t_{w2i}, t_{w2o} \) - inner and outer surface temperatures of the intermediate tube wall (°C).

From equation (16) are obtained \( t_{w1i} \) and \( \alpha_{2i} \) values and from equation (17) are obtained \( t_{w2o} \) and \( \alpha_{2o} \) values. The equations for calculating \( \alpha_{2i} \) and \( \alpha_{2o} \) can be written as

\[ \alpha_{2i} = \frac{Q_{C1}}{A_{1o} \cdot (t_{H} - t_{w1i} + \frac{Q_{C1}}{2\pi L_c \lambda_{C1}} \ln \frac{d_{1o}}{d_{1i}})} \]  
(18)

\[ \alpha_{2o} = \frac{Q_{C2}}{A_{2i} \cdot (t_{C} - t_{w2o} + \frac{Q_{C2}}{2\pi L_c \lambda_{C1}} \ln \frac{d_{2o}}{d_{2i}})} \]  
(19)
In equations (18) and (19) \( \lambda_{Co} \) represents the thermal conductivity of cooper (W/(m·ºC)).

In TTHE the values of Re number range between 33 - 213 for petroleum product and 738 - 1002 for water. In the TCTHE the values of Re number range between 2321 - 2713 for stream C1, 22 - 141 for petroleum product and 266 - 524 for stream C2. The values of Pr number are similar for both heat exchangers and vary between 7 - 9 for water and 133 - 272 for petroleum product. In TTHE the values of Nu number range between 15.1 - 23.3 for petroleum product and 5.9 – 6.0 for water. In TCTHE the values of Nu number range between 19.8 - 21.8 for the stream C1 and 4.8 - 6.1 for the stream C1. In table 3 are presented comparatively the linear average velocity and the heat transfer coefficients values obtained for both heat exchangers.

Table 3. Values of the linear average velocities and the heat transfer coefficients.

| No. det. | TTHE | TCTHE |
|---------|------|-------|
|         | \( w_{HI} \) | \( w_{HC} \) | \( \alpha_{1} \) | \( \alpha_{2} \) | \( w_{C1} \) | \( w_{HC2} \) | \( \alpha_{1i} \) | \( \alpha_{2i} \) | \( \alpha_{2o} \) | \( \alpha_{3} \) |
| 1       | 0.09 | 0.10  | 115  | 292  | 0.27 | 0.13  | 0.05 | 1062 | 169  | 174  | 283  |
| 2       | 0.06 | 0.09  | 100  | 290  | 0.25 | 0.09  | 0.04 | 939  | 153  | 141  | 281  |
| 3       | 0.08 | 0.09  | 108  | 289  | 0.25 | 0.11  | 0.04 | 901  | 174  | 158  | 280  |
| 4       | 0.08 | 0.09  | 108  | 289  | 0.25 | 0.11  | 0.04 | 896  | 170  | 156  | 280  |
| 5       | 0.08 | 0.09  | 108  | 291  | 0.25 | 0.11  | 0.05 | 925  | 179  | 171  | 282  |
| 6       | 0.06 | 0.08  | 100  | 291  | 0.22 | 0.09  | 0.04 | 832  | 158  | 155  | 282  |
| 7       | 0.03 | 0.08  | 75   | 294  | 0.22 | 0.04  | 0.04 | 925  | 100  | 107  | 285  |
| 8       | 0.03 | 0.06  | 75   | 292  | 0.22 | 0.04  | 0.02 | 988  | 104  | 101  | 282  |

As shown in table 3 the values of \( \alpha_{1} \) in TCTHE are higher than those of \( \alpha_{2} \) in TTHE (\( w_{C1} \) in TCTHE > \( w_{C} \) in TTHE), values of \( \alpha_{2} \) in TTHE are higher than those of \( \alpha_{3} \) in TCTHE ((\( w_{C2} \) in TCTHE < \( w_{C} \) in TTHE)) and the values of \( \alpha_{2i} \) and \( \alpha_{2o} \) in TCTHE are higher than those of \( \alpha_{1} \) in TTHE (\( w_{HI} \) in TCTHE > \( w_{HI} \) in TTHE).

In TCTHE the heat transfer occurs simultaneously in two opposite directions. A direction is the heat transfer between petroleum product and stream C1 and the other direction is the heat transfer between petroleum product and stream C2. Therefore, as opposed to TTHE where the heat transfer occurs in one direction and it can calculate the overall heat transfer coefficient \( k \), for TCTHE it can calculate two overall heat transfer coefficients, \( k_{1} \) and \( k_{2} \) [4, 5]. The overall heat transfer coefficients can be calculated with the following equations (not considering the thermal resistances of fouling):

\[
k = \frac{1}{\frac{1}{\alpha_{1}} + \frac{d_{1o}}{d_{1i}} \ln \frac{d_{1o}}{d_{1i}} + \frac{1}{2 \lambda_{Cu} d_{1i}}} \quad (22)
\]

for TTHE, and

\[
k_{1} = \frac{1}{\frac{1}{\alpha_{1}} + \frac{d_{1o}}{d_{1i}} \ln \frac{d_{1o}}{d_{1i}} + \frac{1}{2 \lambda_{Cu} d_{1i} \alpha_{2i}}} \quad (23)
\]
\begin{equation}
k_2 = \frac{1}{\frac{1}{\alpha_2} + \frac{d_{2i}}{2\alpha_C \ln \frac{d_{2o}}{d_{2i}}} + \frac{1}{\alpha_3 \frac{d_{2i}}{d_{2o}}}}
\end{equation}

for TCTHE.

In table 4 are presented comparatively the values of the main measures for assessing the heat transfer between in the two heat exchangers: transferred heat flow rates, heat transfer areas and overall heat transfer coefficients (W/(m²·ºC)). The heat flow losses to the environment range from 0.1 and 1 %.

| No. det. | TTHE | TCTHE |
|---------|------|-------|
| QH | A₁o | k | QH | A₁o+A₂i | k₁ | k₂ |
| 1 | 659 | 0.082 | 78 | 676 | 0.129 | 143 | 111 |
| 2 | 569 | 0.082 | 71 | 575 | 0.129 | 129 | 96 |
| 3 | 628 | 0.082 | 75 | 641 | 0.129 | 142 | 104 |
| 4 | 757 | 0.082 | 75 | 771 | 0.129 | 139 | 103 |
| 5 | 1026 | 0.082 | 75 | 1034 | 0.129 | 146 | 109 |
| 6 | 697 | 0.082 | 71 | 702 | 0.129 | 130 | 103 |
| 7 | 356 | 0.082 | 56 | 366 | 0.129 | 89 | 79 |
| 8 | 333 | 0.082 | 56 | 338 | 0.129 | 92 | 76 |

As shown in this table:
- The heat flow rates for TCTHE is higher than for TTHE;
- For the same unit length, the heat transfer area for TCTHE is larger than for TTHE;
- The overall heat transfer coefficients for TCTHE are higher than for TTHE.

4. Conclusions

In this paper was performed an analysis of heat transfer achieved at cooling a petroleum product with water in a TTTE and a TCTHE. Based on experimental data obtained in the laboratory, the values of main parameters were compared to assess the differences in heat being transferred in the two heat exchangers. The results show that for the same length of the heat exchanger, the heat transfer area and the overall heat transfer coefficients for TCTHE are higher than for TTTE. These results are in accordance with the theoretical advantages of a TCTHE versus a TTTE, mentioned in literature [4 - 8].

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