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DETERMINING THE PERFORMANCE OF A HEAT EXCHANGER USED IN THE FOOD INDUSTRY

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ABSTRACT

The study of heat transfer in the food industry is as important as in any other industry. Food products are constantly subjected to heat treatments. For this reason, a sunflower food oil, which undergoes heat treatment in the manufacturing process, was chosen for this study. The study was carried out on a laboratory plant and aimed to determine the heat transfer coefficients for three sets of determinations: partial heat transfer coefficient inside - where the warm sunflower oil circulates, partial heat transfer coefficient in the annular space - where cold water circulates and overall heat transfer coefficient, in a tube-in-tube heat exchanger made of copper. The obtained values of heat transfer coefficients were compared with literature data for the same type of food oil. This type of heat exchanger, tube-in-tube, is specific to the food industry. Countercurrent circulation of flows through the appliance was established from the outset, as this type of circulation is preferred from the point of view of determining the performance of heat exchange appliances. Efficiency values were also established for the three sets of experimental determinations. For the calculations, the values for the temperatures of the fluids, both at the inlet and outlet of the apparatus and the values for the volume flow rates of the fluids were required.

Keywords: food oil, conduction, convection, heat exchanger

INTRODUCTION

There is little literature data on the study of heat transfer for food products. For thermal calculations, the physical properties of fluids are important. These data are needed when sizing the apparatus used during processing. In engineering applications, mainly in the food industry, many processes use high viscosity fluids. In these cases, the laminar flow regime is associated with low values of the partial heat transfer coefficients. In many industrial applications using heat exchangers, energy costs account for a large part of the total process costs, which is why methods to improve them are required. Thus, analyses of product behaviour at temperatures different from storage temperatures are required [1-8].

MATERIALS AND METHODS

For food oil, data on the physical properties of various types are presented in the literature [1-4]. For the present work, those properties of food sunflower oil (oil type) were chosen that were closest to the data obtained experimentally in the laboratory (density and viscosity). These properties are presented in Table 1. The physical properties of water, used in the calculations, are shown in Table 2.

Table 1. *Physical properties for sunflower oil* [1-4]

Physical properties	**Unit of measurement**	**Symbol**	**Temperature, ^{0}C**				
			10	20	30	40	50
Density	kg/m^3	ρ	925.9	919	912.2	904.6	896.5
Specific heat	J/kg °C	c_p	2202	2217	2234	2254	2276
Thermal conductivity	W/m°C	λ	0.169	0.168	0.167	0.165	0.164
Dynamic viscosity 10^4	kg/ms	μ	740.7	593.6	465.4	356.3	250.2

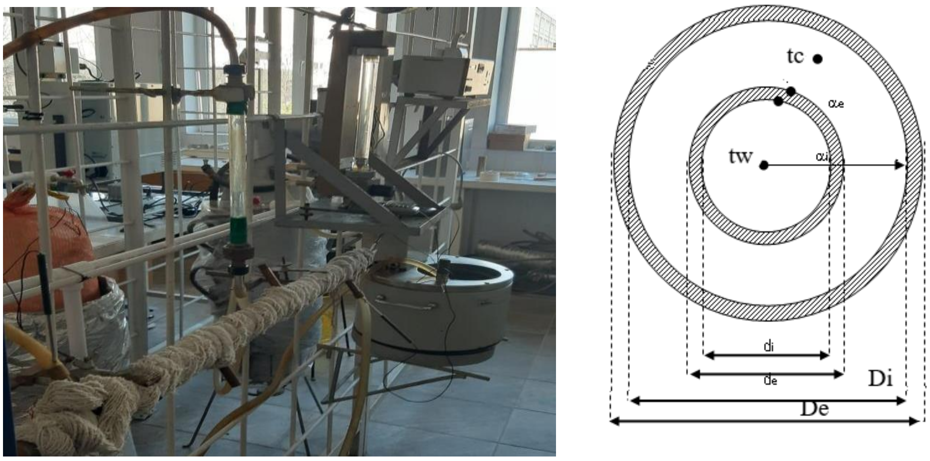
Table 2. *Physical properties for water* [9]

Physical properties	**Unit of measurement**	**Symbol**	**Temperature, ^{0}C**				
			10	20	30	40	50
Density	kg/m^3	ρ	999.7	998.2	995.7	992.2	988.1
Specific heat	J/kg °C	c_p	4190	4180	4173	4173	4173
Thermal conductivity	W/m°C	λ	0.575	0.599	0.617	0.634	0.648
Dynamic viscosity 10^4	kg/ms	μ	12.99	9.98	8.02	6.53	5.39

The experimental determinations were made on an existing apparatus in the laboratory, shown in Figure 1, for which all the geometrical characteristics, shown in Table 3, were known.

Table 3. *Geometrical characteristics of the heat exchangers*

Geometrical characteristics	**Outer tube**	**Inner tube**
Outside diameter, mm	$D_e = 28$	$d_e = 14$
Inside diameter, mm	$D_i = 26$	$d_i = 12$
Wall thickness, mm	1	1
Length, m	L = 1	



a) b)

***Figure 1**. Experimental installation:*

a) general assembly; b) cross-section through heat exchanger

Table 4 shows the measured sizes for the experiments, both for water and oil. Three sets of measurements were selected from the ten that were worked with in the data processing.

***Table 4.** Measured sizes*

In the inner tube				**In the mantle (annular space)**			
Measured size	**Set 1**	**Set 2**	**Set 3**	**Measured size**	**Set 1**	**Set 2**	**Set 3**
$V_{warm,}$ l/h	120	100	48	Vr, l/h	46	41	43
t_{warm1}, °C	50	37	32	$t_{cold\ 1}$	16	16	16
t_{warm2}, °C	42	29	19	t_{cold2}	26	25	26

The heat fluxes for both fluids are calculated as follows [9,10]:

- for the warm fluid:

$$Q_{transferred} = m_{warm} \cdot c_{pwarm} \cdot \Delta t_{warm} = m_w \cdot c_{pw} \cdot (t_{w1} - t_{w2}), W \quad (1)$$

- for the cold fluid:

$$Q_{received} = m_{cold} \cdot c_{pcold} \cdot \Delta t_{cold} = m_c \cdot c_{pc} \cdot (t_{c2} - t_{c1}), W \quad (2)$$

where terms have the following definitions:

- $Q_{transferred,\ received}$ - heat flux transferred, respectively received, W;

- $m_{w,c}$ - mass flow rates of warm and cold fluid respectively, kg/s;

- t_{w1}, t_{w2} - inlet and outlet warm fluid temperatures, °C;

- t_{c1}, t_{c2} - inlet and outlet cold fluid temperatures, °C;

- $cp_{w,c}$ - specific heats for the warm and cold fluid respectively, J/kg °C.

The mass flow rates are calculated with relation 3:

$$m = \frac{\rho \cdot V \cdot 10^{-3}}{3600}, \text{ kg/s} \tag{3}$$

where:

- V- volume flows of fluids, read at rotameters, indicated in l/h;
- ρ - density at temperature of the fluid passing through the rotameter, kg/m^3.

Calculation of the partial convective heat transfer coefficient inside the central tube, α_i

$$Nu_{warm} = 0.28 \cdot Re_{warm}^{0.77} \cdot Pr_{warm}^{0.4} \tag{4}$$

$$\mathrm{Re}_{warm} = \frac{d_i \cdot w_{warm} \cdot \rho_{warm}}{\mu_{warm}} \tag{5}$$

$$\mathrm{Pr}_{warm} = \frac{c_{p\,warm} \cdot \mu_{warm}}{\lambda_{warm}} \tag{6}$$

$$Nu_{warm} = \frac{\alpha_i \cdot d_i}{\lambda_{warm}} => \alpha_i = \frac{Nu \cdot \lambda_{warm}}{d_i}, W/m^2 \cdot {}^\circ\mathrm{C} \tag{7}$$

where:

- w_{warm} - velocity of warm fluid, m/s

$$\mathrm{w}_{warm} = \frac{4 \cdot warm}{\rho_{warm} \bullet л \bullet d_i^2}, m/s \tag{8}$$

- ρ_{warm} - density of warm fluid at mean temperature, kg/m^3;
- μ_{warm} - dynamic viscosity of warm fluid at mean temperature, kg/m·s;
- λ_{warm} - thermal conductivity of warm fluid at mean temperature, W/m·°C.

Knowing this partial heat transfer coefficient, αi, one can calculate the wall temperature inside the small tube, $t_{wall\ i}$, from the relation:

$$Q_{transferred} = \alpha_i \cdot A_i \cdot (t_{warm} - t_{wall\ i}), W \tag{9}$$

$$t_{warm} = \frac{t_{w1} + t_{w2}}{2}, {}^\circ\mathrm{C} \tag{10}$$

$$A_i = \pi \cdot d_i \cdot L,\ m^2 \tag{11}$$

The temperature of the wall on the outside, $t_{wall\ e}$, is calculated from the relation for the heat flux transmitted by conduction, through the cylindrical wall:

$$Q_{transferred} = \frac{2 \cdot \pi \cdot L \cdot (t_{wall\ i} - t_{wall\ e})}{\frac{i}{\lambda_{copper}} \cdot ln \frac{d_e}{d_i}}, W \tag{12}$$

(λ_{copper} = 400 W/m·°C)

Calculation of the partial convective heat transfer coefficient outside the inner tube, α_e

The same criterial relation is used for the cold fluid, but the geometry of the annular space must be highlighted.

$$Nu_{cold} = 0.28 \cdot Re_{cold}^{0.77} \cdot Pr_{cold}^{0.4} \tag{13}$$

$$\mathrm{Re}_{cold} = \frac{d_{eh} \cdot w_{cold} \cdot \rho_{cold}}{\mu_{cold}} \tag{14}$$

$$\mathrm{Pr}_{cold} = \frac{c_{p\,cold} \cdot \mu_{cold}}{\lambda_{cold}} \tag{15}$$

$$Nu_{cold} = \frac{\alpha_e \cdot d_{eh}}{\lambda_{cold}} => \alpha_i = \frac{Nu_{cold} \bullet \lambda_{cold}}{d_{eh}}, W/m^2 \cdot {}^\circ\mathrm{C} \tag{16}$$

$$d_{eh} = D_i - d_e, m \tag{17}$$

- w_{cold} - velocity of cold fluid, m/s

$$\mathrm{w}_{cold} = \frac{4 \cdot m_{cold}}{\rho_{cold} \cdot \text{л} \cdot (D_i^2 - d_e^2)}, \; m/s \tag{18}$$

Calculation of the overall heat transfer coefficient, k_e, for the clean heat exchanger

$$k_e = \frac{1}{\frac{1}{\alpha i} \cdot \frac{de}{di} + \frac{de}{2 \bullet \lambda\mathrm{copper}} \cdot ln\frac{de}{di} + \frac{1}{\alpha_e}}, \; W/m^2 \cdot {}^\circ\mathrm{C} \tag{19}$$

Determination of heat exchanger efficiency

If the term R is defined on the basis of known temperatures:

$$R = \frac{t_{w1} - t_{w2}}{t_{c2} - t_{c1}} \tag{20}$$

The efficiency of the heat exchangers can be calculated, for countercurrent only, as follows:

$$\eta = \frac{t_{c2} - t_{c1}}{t_{w1} - t_{c1}} \cdot 100, for\ R<1 \tag{21}$$

$$\eta = \frac{t_{w1} - t_{w2}}{t_{w1} - t_{c1}} \cdot 100, for\ R > 1 \tag{22}$$

RESULTS

Tables 5 and 6 show the values obtained for the previously defined sizes, including the values of the partial heat transfer coefficients. Table 7 shows the temperature values on the walls of the small tube, both on the warm fluid side - inside and on the cold fluid side - outside. All the heat transfer coefficients are shown in Table 8.

Table 9 shows the values of the heat exchanger efficiency for the three chosen determinations.

Table 5. *The calculated values for warm fluid*

No. set	**Pr**$_{warm}$	**w**$_{warm}$**, m/s**	**Re**$_{warm}$	**Nu**$_{warm}$	α_i**, W/m**^{2}**·°C**	**Q**$_{transferred}$**, W**
1.	402.74	0.29	108.75	114.08	1566.11	544
2.	576.58	0.25	62.67	86.15	1193.52	435.97
3.	695.79	0.12	24.75	45.42	633.53	358.64

Table 6. *The calculated values for cold fluid*

No. set	**Pr**$_{cold}$	**W**$_{cold}$**, m/s**	**Re**$_{cld}$	**Nu**$_{cold}$	α_e**, W/m**^{2}**·°C**	**Q**$_{received}$**, W**
1.	6.74	0.03	418.02	62.67	3137.63	532.12
2.	6.83	0.03	369.02	57.26	2860.79	427.59
3.	7.03	0.03	377.66	58.92	2935.18	348.93

Table 7. *Calculated values of wall temperatures*

No.set	**t**$_{wall\ i}$**, °C**	**t**$_{wall\ e}$**, °C**
1.	36.79	36.75
2.	23.76	23.73
3.	10.48	10.46

Table 8. *The heat transfer coefficient values*

No. set	α_i**, W/m**^{2}**·°C**	α_e**, W/m**^{2}**·°C**	**k**$_e$**, W/m**^{2}**·°C**
1.	1566.11	3137.63	937.78
2.	1193.52	2860.79	752.02
3.	633.53	2935.18	457.68

Table 9. *The heat exchanger efficiency*

Calculated sizes	**Set.1**	**Set.2**	**Set.3**
R	0.8	0.89	1.3
Efficiency, %	41.6	42.8	81.25

CONCLUSIONS

Several laboratory determinations were performed, but only those that could verify the literature-recommended criterial relationships for distinct flow domains and that could close the heat balance were presented in the paper. It is necessary to establish a criterial relation for the annular space of this heat exchanger that can verify these presented results.

According to the literature data, the overall heat transfer coefficients have the lowest value relative to the partial heat transfer coefficients, which is verified in the study in this paper.

It is observed that the value of overall heat transfer coefficient is lower (457.68 $W/m^2 \cdot {}^0C$) when the efficiency of the apparatus is higher (81.25%), when the fluid flow rates are close.

For different flow rates, the hot fluid flow rate being 2.61 times higher than the cold fluid flow rate, the overall heat transfer coefficient has the highest value (937.78 $W/m^{\cdot 0}C$) and the lowest efficiency (41.6%).

The possibility of establishing the wall temperatures shown in Table 7 and monitoring the temperature profile during the experiments may help to support the correct results obtained for the overall heat transfer coefficient value, values comparable to the few data given in the present literature.

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