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Thermo-hydraulic design of a multi-tube heat exchanger for methanol heating.

Diseño térmico-hidráulico de un intercambiador de calor multi-tubo para el calentamiento de metanol.

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Abstract.
A type of heat exchanger that has gained adequate attention owing to its simplicity, robustness and extensive variety of applications is the multi-tube heat exchanger. In the present work a multi-tube heat exchanger was designed form the thermo-hydraulic point of view, in order to heat a methanol stream to 60 ºC using water condensate as the heat transfer agent. To design this equipment, a classical, well known calculation methodology was employed, where several important design parameters were calculated such as the overall heat transfer coefficient (575.17 W/m^2.K), the required heat exchange area (2.025 m^2) and the Log Mean Temperature Difference (38.02 ºC). The calculated pressure drop values of the methanol and water streams were 3,257.66 Pa and 752.88 Pa, respectively, which are lower than the maximum limits set by the heat exchange service for both streams. The designed multi-tube heat exchanger will present a total length of 5.76 m.

Keywords.
Heat exchange area, multi-tube heat exchanger, pressure drop, tube length.

Resumen.
Un tipo de intercambiador de calor que ha ganado adecuada atención debido a su simplicidad, robustez y extensa variedad de aplicaciones es el intercambiador de calor de multi-tubo. En el presente trabajo, un intercambiador de calor de multi-tubo fue diseñado desde el punto de vista térmico-hidráulico, con el fin de calentar una corriente de metanol hasta 60 ºC usando agua condensada como agente de transferencia de calor. Para diseñar este equipo, se empleó una metodología de cálculo clásica y bien conocida, donde varios parámetros de diseño importantes fueron calculados tales como el coeficiente global de transferencia de calor (575,17 W/m^2.K), el área de transferencia de calor requerida (2,025 m^2) y la Diferencia de Temperatura Media Logarítmica (38,02 ºC). Los valores de caída de presión calculados de las corrientes de metanol y agua fueron 3 257,66 Pa y 752,88 Pa, respectivamente, los cuales están por debajo de los límites máximos fijados por el servicio de intercambio de calor para ambas corrientes. El intercambiador de calor multi-tubos diseñado presentará una longitud total de 5,76 m.

Palabras clave.
Área de intercambio de calor, intercambiador de calor multi-tubo, caída de presión, longitud del tubo

1. Introduction

Heat exchangers are thermal apparatuses aimed for the efficient heat exchange between two fluids, whether the fluids are in direct contact, mixed, or separated by a thin solid wall (unmixed). They are proposed in a range of sizes, shapes, and construction types depending on the industrial purpose. The performance of heat exchangers can be upgraded by suitable design and establishing optimal operating specifications. Therefore, the continued improvement of different design aspects and the performance characteristics of heat exchangers is the main target of both researchers and manufacturers who are working in this field [1].

Heat exchanger thermal design heavily rely on physical properties for obtaining heat transfer coefficients and therefore performing design calculations such as heat exchange area and overall heat transfer coefficients [2].

Among the common tubular heat exchanger used today in many industries are the multi-tube heat exchangers (MTHE) which comprise several smaller diameter pipes aligned in parallel within a larger diameter outer shell (Figure 1). In welded designs, the inner tubes and shell are welded to the tube sheets [3].

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Fig. 1. An overview of a multi-tube heat exchanger. Source: [3].

Appropriate for heating, cooling, sterilization and thermal treatment, MTHE can process a wide variety of liquids (dairy, juices, sauces, beverages, processed food) from low viscosities up to medium/high viscosities, depending on the purpose. They can also be used for products with particles when fitted with a conical tube-sheet [3].

Due to their assembly with distinctive configurations of inner tubes bundled inside an outer shell, MTHE generate a significant heat exchange area in a reasonably small volumetric space. This configuration makes this heat exchanger valuable for handling an extensive range of flowrates. Among the main features that these types of heat exchanger present are [3]:

1) The use of thermal expansion bellows to absorb difference of expansion.
2) Conical tube sheet for liquids containing particles.
3) Baffles are commonly installed for mechanical strength and better heat transfer on the shell side.
4) Product side can be scrutinized by eliminating bends between units. All inner tubes are observable.
5) Low cost, straightforward maintenance with the only requisite of periodically replacing gaskets on connections.

According to [4] these units are usually constructed by specialized companies, and there are several patent-protected closure systems. They can be an economical solution in cases where the flowrates are relatively small and it is required to apply a countercurrent configuration.

They are restricted to a few inner tubes because for higher sizes this type of assembly becomes challenging. They are not a competitive solution against the shell and tube heat exchangers (STHE), although they are cheaper than STHE [5], and are limited to applications where the required heat transfer area is less than 10 or 15 m^2 [4].

Efficient and accurate thermal analysis of MTHE provides a basis for successful design [6]. The primary attention of MTHE design is the efficiency of heat dissipation by solid conduction and forced flow convection. A good MTHE should have an optimum multi-tube configuration to dissipate as much heat as possible [6].

There are few studies reported in the open published literature where a multi-tube heat exchanger is designed or sized. According to this, in [7] a co-axial multi-tube heat exchanger (CMTHE) is proposed and integrated with a 50 kW geothermal Organic Rankine Cycle (ORC), in order to perform tow field tests to examine the response of the ORC system subject to changes applied to the CMTHE. In this study the working fluid in the tube-side of the heat exchanger is pure water with a flowrate of 13 tons per hour, while in the shell side the working fluid is geothermal hot water (~ 120 ºC). The CMTHE used in this work has a total length of 11 m, an effective heat transfer area of 18.6 m^2, and the internal and external diameter of the tubes are 10.7 mm and 12.7 mm, respectively. Other authors [1] investigated the influence of several operating parameters on the performance of concentric finned tube and bare multi-tube hairpin heat exchangers. A computer program was written and developed to carry out thermo-hydraulic computations using the MATLAB. The developed MATLAB code was then verified for reliability and precision against some of the existing and acceptable designs of single-finned tube and bare multi-tube hairpin heat exchangers. The existing counter flow bare multi-tube heat exchanger evaluated in this study used fresh water on the shell side, and oily water on the tube side with a mass flowrate of 6,622 kg/h for both streams; the internal and external diameters of the tubes are 17.95 mm and 22.21 mm, respectively; the number of internal tubes is 7; the inlet temperatures of the tube side fluid (oily water) and the shell side fluid (fresh water) were 247 ºC and 80 ºC, respectively; and the total length of the heat exchanger is 60.96 m. Finally, the allowable pressure drops for both fluid streams were 137,895.15 Pa, while the actual pressure drop of the oily water in the tube side was 22,063.22 Pa. Likewise, [6] proposed a general mathematical model for the optimal heat-transfer efficiency design of compact multi-tubular heat exchangers using topology optimization concepts. For optimization objectives, the multi-tubular configuration was transformed into an equivalent cellular material distribution within a given cross-section, which was then exemplified by two design variables: local relative cell density and cell size. Also, in [8] a numerical performance investigation of a phase change material-based multi-tube heat exchanger incorporated with two new fin configurations was carried out, in order to enhance the heat transfer. Finally, in a comprehensive experimental and numerical investigation, [9] studied smooth and rectangular-finned double pipe and multi tube heat exchangers with the prospect of presenting the most optimum operating conditions.

Certain chemical plant erected in Cuba needs to heat a liquid methanol stream to 60 ºC using hot water (condensate), and for that a multi-tube heat exchanger was proposed because the flowrates of the fluids are relatively small, there is enough space availability and there is limitation of budget. In this context, in the present paper a MTHE is designed applying the methodology reported in [10], where several important parameters are determined such as the overall heat transfer coefficient, the required heat exchange area, the length of the heat exchanger, and the pressure drop of both fluids.

2. Materials and methods.

2.1. Problem statement.

It's required to preheat 2,000 kg/h of a liquid methanol stream from 30º C to 60 ºC using 3,000 kg/h of hot water (condensate) available at 90 ºC. For that, a multi-tube heat exchanger was proposed with a shell internal diameter of 72.1 mm, equipped with seven inner tubes with an internal and external diameter of 14 and 16 mm, respectively. The pressure drops for the methanol and water stream must not exceed 3,500 and 1,000 Pa, respectively. The material of the tubes is carbon steel; the fluids will flow in a countercurrent arrangement inside the heat exchanger, while the fouling factors for methanol and water are 0.000352 and 0.000088 K.m^2/W, respectively [11].

According to suggestions reported by [12], the cold fluid (methanol) will be located on the tube side, while the hot fluid (water) will be located on the shell side. The internal diameters of the nozzles in the tube side and shell side are 32 mm and 50 mm, respectively, and the wall thickness of the tubes is 2 mm. It's necessary to know the tube length required by this multitube heat exchanger, as well as the pressure drops of both streams, for the requested heat transfer service. The calculation methodology proposed by [10] should be employed in this work to design the MTHE.

2.2. Calculation of the tube length.

Step 1. Definition of the initial data available:

- Methanol mass flowrate (m_c).
- Water mass flowrate (m_h).
- Inlet temperature of methanol (t_1).
- Outlet temperature of methanol (t_2).
- Inlet temperature of water (T_1).
- Internal diameter of shell (D_i).
- Internal diameter of tubes (d_i).
- External diameter of tubes (d_e).
- Internal diameter of the tube side nozzle (d_N).
- Internal diameter of the shell side nozzle (D_N).
- Thermal conductivity of tube material (carbon steel) (k_t).
- Tube wall thickness (e_t).
- Fouling factor of methanol (R_c).
- Fouling factor of water (R_h).
- Number of internal tubes (n).
- Maximum allowable pressure drop for methanol [$\Delta P_{c(a)}$].
- Maximum allowable pressure drop for water [$\Delta P_{h(a)}$].

Step 2. Average temperature of methanol ($\bar{t}$):

$$\bar{t} = \frac{t_1 + t_2}{2} \quad (1)$$

Step 3. Physical parameters of methanol at the average temperature determined in step 1:
The following parameters must be defined for the methanol at the average temperature:

- Density (ρ_c) [kg/m^3].
- Viscosity (μ_c) [Pa.s].
- Heat capacity (Cp_c) [J/kg.K].
- Thermal conductivity (k_c) [W/m.K].

Step 4. Heat duty (Q):

$$Q = \frac{m_c}{3{,}600} \cdot Cp_c \cdot (t_2 - t_1) \quad (2)$$

Step 5. Heat capacity of water (Cp_h) at the inlet water temperature (T_1).
Step 6. Outlet temperature of water (T_2):

$$T_2 = T_1 - \frac{Q}{\frac{m_h}{3{,}600} \cdot Cp_h} \quad (3)$$

Step 7. Average temperature of water ($\bar{T}$):

$$\bar{T} = \frac{T_1 + T_2}{2} \quad (4)$$

Step 8. Physical parameters of water at the average temperature determined in step 6:

The following parameters must be defined for the water at its average temperature:

- Density (ρ_h) [kg/m^3].
- Viscosity (μ_h) [Pa.s].
- Thermal conductivity (k_h) [W/m.K].

Step 9. Cross section area of tube (a_t):

$$a_t = n \cdot \frac{\pi \cdot d_i^2}{4} \quad (5)$$

Step 10. Velocity of methanol on the tube-side (v_c):

$$v_c = \frac{\frac{m_c}{3{,}600}}{\rho_c \cdot a_t} \quad (6)$$

Step 11. Reynolds number of methanol (Re_c):

$$Re_c = \frac{d_i \cdot v_c \cdot \rho_c}{\mu_c} \quad (7)$$

Step 12. Prandtl number of methanol (Pr_c):

$$Pr_c = \frac{Cp_c \cdot \mu_c}{k_c} \quad (8)$$

Step 13. Nusselt number of methanol (Nu_c):
As stated by [10], the Nusselt number depends on the value of the Reynolds number of the fluid inside the heat exchanger. Accordingly:

- Laminar region ($Re_c \leq 2{,}300$):

$$Nu_c = 1.86 \cdot Re_c^{0.33} \cdot Pr_c^{0.33} \cdot \left(\frac{d_i}{L}\right)^{0.33} \quad (9)$$

- Intermediate region ($2{,}300 < Re_c < 8{,}000$):

$$Nu_c = (0.037 \cdot Re_c^{0.75} - 6.66) \cdot Pr_c^{0.42} \quad (10)$$

- Turbulent region ($Re_c \geq 8{,}000$):

$$Nu_c = 0.023 \cdot Re_c^{0.8} \cdot Pr_c^{0.33} \tag{11}$$

Step 14. Convective heat transfer coefficient for methanol (h_c):

$$h_c = \frac{Nu_c \cdot k_c}{d_i} \tag{12}$$

Step 15. Convective heat transfer coefficient for methanol based on the tube outer surface area (h_{co}):

$$h_{co} = h_c \cdot \frac{d_i}{d_e} \tag{13}$$

Step 16. Flow cross-section in the shell (a_{shell}):

$$a_{shell} = \frac{\pi}{4} \cdot (D_i^2 - n \cdot d_e^2) \tag{14}$$

Step 17. Velocity of water on the shell (v_h):

$$v_h = \frac{\frac{m_h}{3{,}600}}{\rho_h \cdot a_{shell}} \tag{15}$$

Step 18. Hydraulic diameter for heat exchange (d_h):

$$d_h = \frac{D_i^2 - n \cdot d_e^2}{n \cdot d_e} \tag{16}$$

Step 19. Reynolds number of water (Re_h):

$$Re_h = \frac{d_h \cdot v_h \cdot \rho_h}{\mu_h} \tag{17}$$

Step 20. Prandtl number of water (Pr_h):

$$Pr_h = \frac{Cp_h \cdot \mu_h}{k_h} \tag{18}$$

Step 21. Nusselt number of water (Nu_h):

- Laminar region ($Re_h \leq 2{,}300$):

$$Nu_h = 1.86 \cdot Re_h^{0.33} \cdot Pr_h^{0.33} \cdot \left(\frac{d_h}{L}\right)^{0.33} \tag{19}$$

- Intermediate region ($2{,}300 < Re_h < 8{,}000$):

$$Nu_h = (0.037 \cdot Re_h^{0.75} - 6.66) \cdot Pr_h^{0.42} \tag{20}$$

- Turbulent region ($Re_h \geq 8{,}000$):

$$Nu_h = 0.023 \cdot Re_h^{0.8} \cdot Pr_h^{0.33} \tag{21}$$

Step 22. Convective heat transfer coefficient for water (h_h):

$$h_h = \frac{Nu_h \cdot k_h}{d_h} \tag{22}$$

Step 23. Overall heat transfer coefficient (U):

$$U = \frac{1}{\frac{1}{h_{co}} + \frac{1}{h_h} + \frac{e_t}{k_t} + R_c + R_h} \tag{23}$$

Step 24. Log Mean Temperature Difference ($LMTD$):

- For a countercurrent arrangement:

$$LMTD = \frac{(T_1 - t_2) - (T_2 - t_1)}{ln\frac{(T_1 - t_2)}{(T_2 - t_1)}} \tag{24}$$

Step 25. Required heat exchange area (A_{req}):

$$A_{req} = \frac{Q}{U \cdot LMTD} \tag{25}$$

Step 26. Length of the heat exchanger (L):

$$L = \frac{A_{req}}{\pi \cdot n \cdot d_e} \tag{26}$$

2.3. Calculation of the pressure drops.

Step 27. Cross section area of tube-side nozzle ($a_{N(t)}$):

$$a_{N(t)} = \frac{\pi \cdot d_N^2}{4} \tag{27}$$

Step 28. Flow velocity of methanol in tube-side nozzle ($v_{N(c)}$):

$$v_{N(c)} = \frac{\frac{m_c}{3{,}600}}{\rho_c \cdot a_{N(t)}} \tag{28}$$

Step 29. Nozzle pressure drop of methanol in the tube side ($\Delta p_{N(c)}$):

$$\Delta p_{N(c)} = 1.5 \cdot \frac{v_{N(c)}^2 \cdot \rho_c}{2} \tag{29}$$

Step 30. Friction factor of methanol (f_c):

$$f_c = \frac{0.275}{Re_c^{0.2}} \tag{30}$$

Step 31. Frictional pressure drop of methanol in the tube side ($\Delta p_{f(c)}$):

$$\Delta p_{f(c)} = f_c \cdot \frac{L}{d_i} \cdot \frac{v_c^2 \cdot \rho_c}{2} \tag{31}$$

Step 32. Total pressure drop of methanol in the tube side (Δp_c):

$$\Delta p_c = \Delta p_{N(c)} + \Delta p_{f(c)} \tag{32}$$

Step 33. Cross section area of the shell-side nozzle ($a_{N(s)}$):

$$a_{N(s)} = \frac{\pi \cdot D_N^2}{4} \tag{33}$$

Step 34. Flow velocity of water in the shell-side nozzle ($v_{N(h)}$):

$$v_{N(h)} = \frac{\frac{m_h}{3{,}600}}{\rho_h \cdot a_{N(s)}} \tag{34}$$

Step 35. Nozzle pressure drop of water in the shell side ($\Delta p_{N(h)}$):

$$\Delta p_{N(h)} = 1.5 \cdot \frac{v_{N(h)}^2 \cdot \rho_h}{2} \tag{35}$$

Step 36. Hydraulic diameter for the pressure drop (d'_h):´

$$d'_h = \frac{D_i^2 - n \cdot d_e^2}{D_i + n \cdot d_e} \tag{36}$$

Step 37. Reynolds number of water for pressure drop (Re'_h):

$$Re'_h = \frac{d'_h \cdot v_h \cdot \rho_h}{\mu_h} \tag{37}$$

Step 38. Friction factor of water (f_h):

$$f_h = \frac{0.275}{Re'^{0.2}_h} \tag{38}$$

Step 39. Frictional pressure drop of water in the shell side ($\Delta p_{f(h)}$):

$$\Delta p_{f(h)} = f_h \cdot \frac{L}{d'_h} \cdot \frac{v_h^2 \cdot \rho_h}{2} \tag{39}$$

Step 40. Total pressure drop of water in the shell side (Δp_h):

$$\Delta p_h = \Delta p_{N(h)} + \Delta p_{f(h)} \tag{40}$$

3. Results.

The steps followed to determine the required tube length and the pressure drop of both streams, among other important parameters, are presented next, in order to design the multitube heat exchanger from the thermo-hydraulic point of view.

3.1. Tube length.

Step 1. Definition of the initial data available:

- Methanol mass flowrate (m_c): 2,000 kg/h.
- Water mass flowrate (m_h): 3,000 kg/h.
- Inlet temperature of methanol (t_1): 30 ºC.
- Outlet temperature of methanol (t_2): 60 ºC.
- Inlet temperature of water (T_1): 90 ºC.
- Internal diameter of shell (D_i): 0.0721 m.
- Internal diameter of tubes (d_i): 0.014 m.
- External diameter of tubes (d_e): 0.016 m.
- Internal diameter of the tube side nozzle (d_N): 0.032 m.
- Internal diameter of the shell side nozzle (D_N): 0.050 m.
- Thermal conductivity of carbon steel (k_t): 43 W/m.K [11].
- Tube wall thickness (e_t): 0.002 m.
- Fouling factor of methanol (R_c): 0.000352 K.m^2/W [11].
- Fouling factor of water (R_c): 0.000088 K.m^2/W [11].
- Number of tubes (n): 7.
- Maximum allowable pressure drop for methanol [$\Delta P_{c(a)}$]: 3,500 Pa.
- Maximum allowable pressure drop for water [$\Delta P_{h(a)}$]: 1,000 Pa.

Step 2. Average temperature of methanol ($\bar{t}$):

$$\bar{t} = \frac{t_1 + t_2}{2} = \frac{30 + 60}{2} = 45\ ºC \tag{1}$$

Step 3. Physical parameters of methanol at the average temperature determined in step 1:

According to [13], the methanol has the values presented next for the requested physical parameters:

- Density (ρ_c) = 770.12 kg/m3.
- Viscosity (μ_c) = 0.000423 Pa.s.
- Heat capacity (Cp_c) = 2,657.53 J/kg.K.
- Thermal conductivity (k_c) = 0.1943 W/m.K.

Step 4. Heat duty (Q):

$$Q = \frac{m_c}{3{,}600} \cdot Cp_c \cdot (t_2 - t_1) \tag{2}$$

$$Q = \frac{2{,}000}{3{,}600} \cdot 2{,}657.53 \cdot (60 - 30)$$

$$Q = 44{,}292.17\ W$$

Step 5. Heat capacity of water (Cp_h) at the inlet water temperature (T_1).

As reported by [13], the heat capacity of water at 90 ºC is 4,205.21 J/kg.K.

Step 6. Outlet temperature of water (T_2):

$$T_2 = T_1 - \frac{Q}{\frac{m_h}{3{,}600} \cdot Cp_h} \tag{3}$$

$$T_2 = 90 - \frac{44{,}292.17}{\frac{3{,}000}{3{,}600} \cdot 4{,}205.21}$$

$$T_2 = 77.36\ ºC$$

Step 7. Average temperature of water ($\bar{T}$):

$$\bar{T} = \frac{T_1 + T_2}{2} = \frac{90 + 77.36}{2} = 83.68\ ºC \tag{4}$$

Step 8. Physical parameters of water at the average temperature determined in step 6:

Consistent with [14], the water presents the values of the physical parameters presented next at the average temperature of 83.68 ºC.

- Density (ρ_h) = 969.46 kg/m^3.
- Viscosity (μ_h) = 0.000339 Pa.s.
- Thermal conductivity (k_h) = 0.6721 W/m.K.

Table 1 presents the values of the parameters calculated in steps 9-26.

Table 1. Results of the parameters calculated in steps 9-26.

Step	Parameter	Symbol	Value	Units
9	Cross section area of tube	a_t	0.001077	m^2
10	Velocity of methanol on the tube-side	v_c	0.670	m/s
11	Reynolds number of methanol[1]	Re_c	17,077.36	-
12	Prandtl number of methanol	Pr_c	5.78	-
13	Nusselt number of methanol[2]	Nu_c	99.56	-
14	Convective heat transfer	h_c	1,381.75	W/m^2.K

	coefficient for methanol			
15	Convective heat transfer coefficient for methanol based on the tube outer surface area	h_{co}	1,209.03	W/m^2.K
16	Flow cross-section in the shell	a_{shell}	0.00267	m^2
17	Velocity of water on the shell	v_h	0.322	m/s
18	Hydraulic diameter for heat exchange	d_h	0.0304	m
19	Reynolds number of water[3]	Re_h	27,993.66	-
20	Prandtl number of water	Pr_h	2.12	-
21	Nusselt number of water[4]	Nu_h	106.43	-
22	Convective heat transfer coefficient for water	h_h	2,353.01	W/m^2.K
23	Overall heat transfer coefficient	U	575.17	W/m^2.K
24	Log Mean Temperature Difference	$LMTD$	38.02	ºC
25	Required heat exchange area	A_{req}	2.025	m^2
26	Length of the heat exchanger	L	5.76	m

[1] Since $Re_c > 8{,}000$, the methanol will flow under turbulent regime in the heat exchanger.
[2] Since $Re_c > 8{,}000$, the equation employed to determine the Nusselt number of methanol was number (11).
[3] Since $Re_h > 8{,}000$, the water will flow under turbulent regime in the heat exchanger.
[4] Since $Re_h > 8{,}000$, the equation (21) was employed to determine the Nusselt number of water.
Source: Own elaboration.

3.2. Pressure drops.

Table 2 shows the results of the parameters calculated in steps 27-40.

Table 2. Results of the parameters calculated in steps 27-40.

Step	Parameter	Symbol	Value	Units
27	Cross section area of the tube-side nozzle	$a_{N(t)}$	0.00080	m^2
28	Flow velocity of methanol in the tube-side nozzle	$v_{N(c)}$	0.902	m/s
29	Nozzle pressure drop of methanol in the tube side	$\Delta p_{N(c)}$	469.93	Pa
30	Friction factor of methanol	f_c	0.0392	-
31	Frictional pressure drop of methanol in the tube side	$\Delta p_{f(c)}$	2,787.73	Pa
32	Total pressure drop of methanol in the tube side	Δp_c	3,257.66	Pa
33	Cross section area of the shell-side nozzle	$a_{N(s)}$	0.00196	m^2
34	Flow velocity of water in the shell-side nozzle	$v_{N(h)}$	0.438	m/s
35	Nozzle pressure drop of water in the shell side	$\Delta p_{N(h)}$	139.49	Pa
36	Hydraulic diameter for the pressure drop	d'_h	0.0185	m
37	Reynolds number of water for pressure drop	Re'_h	17,035.61	-
38	Friction factor of water	f_h	0.0392	-
39	Frictional pressure drop of water in the shell side	$\Delta p_{f(h)}$	613.39	Pa
40	Total pressure drop of water in the shell side	Δp_h	752.88	Pa

Source: Own elaboration.

4. Discussion.

According to the results shown on Table 1, the velocity of methanol on the tube side was 0.670 m/s, which is 2.08 times higher than the velocity of water on the shell; this is due to the lowest value that the density of methanol (770.12 kg/m^3) and the cross section area of tube (0.001077 m^2) present with respect to the density of water (969.46 kg/m^3) and the flow cross-section in the shell (0.00267 m^2).

The Reynolds number of water (27,993.66) is 1.64 times higher than the Reynolds number of methanol (17,077.36), which is due to the highest value that present the density of water (969.46 kg/m^3) and the hydraulic diameter for heat exchange (0.0304), and the lowest value of the viscosity of water (0.000339 Pa.s) with respect to the values of the density of methanol (770.12 kg/m^3), internal diameter of tube (0.014 m) and viscosity of methanol (0.000423 Pa.s). It's worth noting that both streams flow under turbulent regime since both Reynolds number are above 8,000 [10].
The convective heat transfer coefficient of water (2,353.01 W/m^2.K) is 1.70 times higher than the convective heat transfer coefficient for methanol (1,381.75 W/m^2.K) mostly because the Nusselt number (106.43) and the thermal conductivity (0.6721 W/m.K) of water are higher than the Nusselt number (99.56) and the thermal conductivity (0.1943 W/m.K) of methanol.

The heat duty was of 44,292.17 W, while the calculated outlet temperature of water was 77.36 ºC. The value of the overall heat transfer coefficient was 575.17 W/m^2.K, which agrees with the values reported by [4] and [11], while the Log Mean Temperature Difference was 38.02 ºC. The designed MTHE will need a heat exchange area of 2.025 m^2, which corresponds to the values reported by [4] for this type of heat exchanger, thus requiring a total length of 5.76 m, which can be considered adequate [3]. In [10], a MTHE was designed and the results of heat exchange area and the total tube length were 1.01 m^2 and 2.90 m, respectively.

The nozzle pressure drop of methanol in the tube side (469.93 Pa) is 3.37 times higher than nozzle pressure drop of water in the shell side (139.49 Pa) which is due to the fact that the value of the flow velocity of methanol in the tube-side nozzle (0.902 m/s) almost double the flow velocity of water in the shell-side nozzle (0.438 m/s). This occurred because the internal diameter of the tube side nozzle (0.032 m) is lower than the internal diameter of the shell side nozzle (0.050 m), thus resulting in a lower cross section area of the tube-side nozzle (0.00080 m^2) with respect to the cross section area of the shell-side nozzle (0.00196 m^2), therefore influencing in the higher value obtained for the flow velocity of methanol in the tube-side nozzle with respect to the value of the flow velocity of water in the shell-side nozzle. On the other hand, the frictional pressure drop of methanol in the tube side (2,787.73 Pa) is 4.54 times higher than the frictional pressure drop of water in the shell side (613.39 Pa), which is because the velocity of methanol on the tube-side (0.670 m/s) is higher and the internal diameter of tubes (0.014 m) is lower than the velocity of water on the shell (0.322 m) and the hydraulic diameter for the pressure drop (0.0185 m), respectively. It's worth mentioning that the value of the friction factor of methanol is equal to the value of the friction factor of water, that is, both have a value of 0.0392, which is an inquiring result.

The above discussion explains why the total pressure drop of methanol in the tube side (3,257.66 Pa) is 4.32 times higher than the total pressure drop of water in the shell side (752.88 Pa), that is, because both the nozzle pressure drop of methanol in the tube side and the frictional pressure drop of methanol in the tube side are higher in value than the nozzle pressure drop of water in the shell side and the frictional pressure drop of water in the shell side, respectively. This result agrees with that reported by [10].

Figure 2 displays the schematics of the designed MTHE, with its main design parameters and the numerical information of both streams.

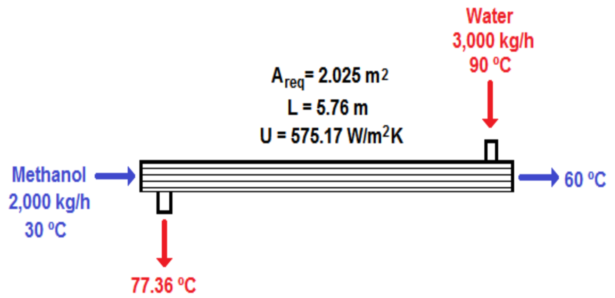

Fig. 2. Schematics of the designed MTHE.
Source: Own elaboration.

5. Conclusions.
A multi-tube heat exchanger was designed from the thermo-hydraulic point of view, in order to heat a methanol stream to 60 ºC using water condensate at 90 ºC. The calculation methodology employed in this study, in order to design the MTHE, was that reported by [10]. Several important design parameters were determined such as the Log Mean Temperature Difference (38.02 ºC), the overall heat transfer coefficient (575.17 W/m^2.K), the required heat exchange area (2.025 m^2), as well as the Reynolds, Prandtl and Nusselt numbers and the convective heat transfer coefficients for both fluids. The pressure drop of both streams were also calculated, whose values are below the maximum limits set by the heat exchange service. The designed multi-tube heat exchanger will present a total length of 5.76 m.

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8. Resources: Not applicable.
9. Software: Not applicable.

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Nomenclature

$a_{N(s)}$	Cross section area of the shell-side nozzle	m^2
$a_{N(t)}$	Cross section area of the tube-side nozzle	m^2
a_{shell}	Flow cross-section in the shell	m^2
a_t	Cross section area of tube	m^2
A_{req}	Required heat exchange area	m^2
Cp	Heat capacity	J/kg.K
d_e	External diameter of tubes	m
d_h	Hydraulic diameter for heat exchange	m
d'_h	Hydraulic diameter for the pressure drop	m
d_i	Internal diameter of tubes	m
d_N	Internal diameter of the tube side nozzle	m
D_i	Internal diameter of shell	m
D_N	External diameter of the shell side nozzle	m
e_t	Tube wall thickness	m
f	Friction factor	-
h	Convective heat transfer coefficient	$W/m^2.K$
h_o	Convective heat transfer coefficient based on the tube outer surface area	
k	Thermal conductivity	W/m.K
k_t	Thermal conductivity of the tube material (carbon steel)	W/m.K
L	Length of the heat exchanger	
$LMTD$	Log Mean Temperature Difference	ºC
m	Mass flowrate	kg/h
n	Number of tubes	-
Nu	Nusselt number	-
Pr	Prandtl number	-
Δp	Total pressure drop	Pa
$\Delta P_{(a)}$	Maximum allowable pressure drop	Pa
$\Delta p_{f(c)}$	Frictional pressure drop of cold fluid in the tube side	Pa
$\Delta p_{f(h)}$	Frictional pressure drop of hot fluid in the shell side	Pa
$\Delta p_{N(c)}$	Nozzle pressure drop of cold fluid in the tube side	Pa
$\Delta p_{N(h)}$	Nozzle pressure drop of hot fluid in the shell side	Pa
Q	Heat duty	W
R	Fouling factor	$K.m^2/W$
Re	Reynolds number	-
Re'	Reynolds number for pressure drop	
t	Temperature of the cold fluid	ºC
$\bar{t}$	Average temperature of the cold fluid	ºC
T	Temperature of the hot fluid	ºC
$\bar{T}$	Average temperature of the hot fluid	ºC

U	Overall heat transfer coefficient	$W/m^2.K$
v	Velocity	m/s
$v_{N(c)}$	Flow velocity of cold fluid in the tube-side nozzle	m/s
$v_{N(h)}$	Flow velocity of hot fluid in the shell-side nozzle	m/s

Greek symbols

ρ	Density	kg/m^3
μ	Viscosity	Pa.s

Subscripts

1	Inlet
2	Outlet
c	Cold fluid (methanol)
h	Hot fluid (water)