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Adaptation of the experimental facility at Moa's University boiler area for the study of the Cuban crude oil

Adaptación de la instalación experimental en área de la caldera de la Universidad de Moa para el estudio del crudo cubano

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Abstract: This study describes the adaptation of an experimental installing in the boiler area of Moa University, intended to study of Cuban crude CM 650. Incorporation a heat exchanger is fundamental to raise the crude temperature and reduce its viscosity, which allows a more detailed analysis of its behavior at different temperature. The design of heat exchanger is based on the LMTD, showing a convective heat transfer coefficient of 1524 W/m2°C and a heat transfer of -215 W, the negative rate indicates that heat flows from cold fluid to hot fluid, which is typical in heat exchangers. Finite Element methods are used to determine fluid conditions, including heat flow, density and velocity analysis. The results show remarkable maximum values: a heat flux of 1023.57 °C, a density of 825.81 kg/m³ and a velocity of 2260.20 m/s.

Keywords: heat exchange, Cuban oil, fuel transport

Resumen: Se describió la adaptación de la instalación experimental en el área de la caldera de la Universidad de Moa, destinada al estudio del crudo cubano CM 650. La incorporación de un intercambiador de calor es fundamental para elevar la temperatura del crudo y reducir su viscosidad, lo que permite un análisis más detallado de su comportamiento a diferentes temperaturas. El diseño del intercambiador de calor se basa en el método de la diferencia de temperatura media logarítmica, revelando un coeficiente de transferencia de calor por convección de 1524 W/m^2°C y una transferencia de calor de -215 W, la tasa negativa indica que el calor fluye del fluido frío al fluido caliente, lo que es típico en los intercambiadores de calor. Los métodos de Elementos Finitos se utilizan para determinar las condiciones del fluido, incluyendo análisis del flujo térmico, densidad y velocidad. Los resultados muestran valores máximos notables: un flujo térmico de 1023,57 °C, una densidad de 825,81 kg/m³ y una velocidad de 2260,20 m/s.

Palabras claves: intercambio de calor, petróleo cubano, transporte de combustible

Introduction

Fuel transportation is an essential issue for the industries operations (García Muñoz & Vargas-Galvis, 2017; Gilbert *et al.,* 2016; Laurencio *et al.,* 2022; Rodríguez & Rosabal, 2023). The use of piping systems is widely recognized, due to their economic and environmental efficiency (García & Haoulo, 2009; Quintero, Villamizar & Fonseca, 2014; Meléndez-Pertuz *et al.,* 2017), but the Cuban crude oil faces unique challenges due to its high viscosity and non-Newtonian behavior. The Cuban fuel CM-650, formulated from the high viscosity Cuban oil mixtures, provides low fluidity and unique characteristics, such as the low degree of API as well as the high content of aromatic hydrocarbons, asphaltenes, sulphur and nitrogen, which require special techniques for their efficient transportation and handling.

Moa’s University has focused on the adaptation of an experimental facility that is located at the Fluid Mechanics Laboratory (Romero Gé *et al.,* 2024). This paper objective is to study the Cuban crude oil behavior during its transportation and to find out practical solutions for the challenges that it faces. Although the present facility was not designed specifically for this purpose, some alternatives have been considered, with the aim to carry out some modifications, which may be a useful tool for a better comprehension of the Cuban crude oil properties.

This paper describes the adaptation of the experimental facility at Moa’s University boiler area, for the investigation on the Cuban crude oil CM 650.

Materials and methods

Characteristics of the crude oil CM 650

The samples of heavy crude oil of 11º API were studied. Nine levels of the velocity gradient and five levels of temperatures were taken, for three replicas of each experiment, from the temperature under environmental conditions up to the maximum temperature as recommended for the pumping operations. The specifications of the crude oil under study are shown in the Table 1 as follows:

Table 1. Specifications of the crude oil under study (Laurencio Alfonso *et al.,* 2017)

Nº	Parameters	U/M	Value
1	Viscosity at 50 ºC	mm^2/s	650
2	Total sulphur (m/m)	%	7,5
3	Inflammation temperature	ºC	34
4	Fluidity temperature	ºC	15
5	Conradson Carbon (m/m)	%	14
6	Density at 15 ºC	g/cm^3	0,9924
7	Gravity at 15 ºC	ºAPI	11
8	Net heat value	kcal/kg	9100
9	Distillation water (v/v)	%	2,0
10	Wastes for extraction (m/m)	%	0,15
11	Ashes (m/m)	%	0,1
12	Asphaltenes (m/m)	%	18
13	Vanadium	Ppm	150
14	Sodium	Ppm	150
15	Alumina + silica	Ppm	80

Laurencio Alfonso *et al.* (2017) ratifies that it is just a crude oil with high content of sulphur and asphaltenes, so that it greatly influences on the behavior of the flow under temperature variations, due to the structural change and the controlled particle size.

Methodology for the design of a heat exchanger

According to Incropera & DeWitt (1999) and Cengel (2007), the heat exchangers, as shown in the Table 1, enable the heat exchange between two fluids with different temperatures and avoid them to be mixed up among each other. According to the heat exchanger analyses, it is convenient to work with a total heat transfer coefficient U, which takes into consideration the contribution of all the effects on the transfer (Imbert-González, 2011; Satué *et al*., 2024).

The method LMTD (medium logarithmic temperature difference) is selected for the design of a heat exchanger, because with the knowledge of the inlet and outlet temperatures, as well as the mass flow of the fluids, it is possible to determine the heat transfer area (Kumar, Vijayaraghavan & Thakur, 2022; Bhattad *et al.,* 2024).

The medium temperature may be determined by applying an energy balance for the differential elements of the hot and cold fluids. The temperature medium logarithmic difference for the case of the exchanger at counterflow, with the same inlet and outlet temperatures, is determined according to Cengel (2007) as follows:

$\Delta T_1 = T_{h,ent} - T_{c,sal}$

$\Delta T_2 = T_{h,sal} - T_{c,ent}$

Where:

ΔT_1 y ΔT_2: temperature difference; (°C)

$T_{h,ent}$: inlet temperature of the hot fluid, (°C)

$T_{h,sal}$: outlet temperature of the hot fluid; (°C)

$T_{c,ent}$: inlet temperature of the cold fluid; (°C)

$T_{c,sal}$: outlet temperature of the cold fluid, (°C)

It is concluded that the suitable medium temperature difference, is the medium logarithmic temperature where:

$$\Delta T_{ml,CF} = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)}$$

The correction factor depends on the geometric configuration of the exchanger, as well as on the inlet and outlet temperatures of the currents of hot and cold fluids. For a crossed and a Shell and pipe flow heat exchanger of multiple steps, the correction factor is less than the unit. The limit value with the correction factor equal one, belongs to the counterflow exchanger. So, the correction factor F for a heat exchanger, is an indication of the deviation of the medium logarithmic temperature, regarding the corresponding values for the case of counterflow. For the common configurations of the crossed and shell and pipe heat exchangers, in function of the P and R rates between two temperatures, it is calculated as follows:

$$P = \frac{t_2 - t_1}{T_1 - t_1} \qquad R = \frac{T_1 - T_2}{t_1 - t_2}$$

Where:
t_1 y t_2: inlet and outlet temperatures of the pipe respectively; (°C)
T_1 y T_2: inlet and outlet temperatures of the shell respectively, (°C)

According to Cengel (2007) the value of P goes from 0 to 1. The value R, that goes from 0 to the infinity, belongs to the phase change (condensation and boiling) of the shell side and to the phase change of the pipe wall. The Figure 1, represents the calculation of the correction factor value according to the values that are obtained from P and R. For this case, it was obtained taking into consideration that it is a shell as well as its several steps through the pipes.

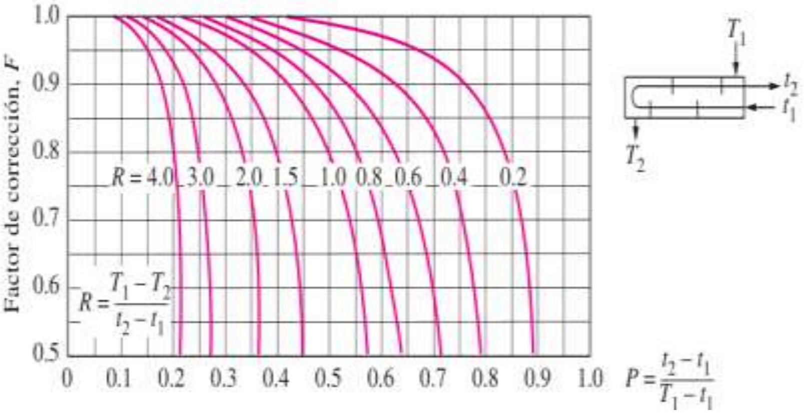

Figure 1. Correction factor (Cengel, 2007).

For the cross flow and multiple steps heat exchangers, it results convenient to relate the equivalent temperature difference with the rate of the medium logarithmic temperature difference for the case of the counterflow, which will be as follows:

$$\Delta T_{ml} = F\Delta_{ml,CF}$$

Where:
F: friction factor, (dimensionless)
$\Delta_{ml,CF}$: medium logarithmic temperature for the case of counterflow; (°C)

Heat transfer rates by convection

The heat transfer rate by convection represents the heat quantity that is transferred per area unit and per unit of temperature difference between the fluid and the surface (Incropera & DeWitt, 1999). It depends on factors such as viscosity, thermal conductivity, surface area, mass flow, velocity and surface.

$A_c = \frac{\pi}{4} D^2$.

$m = \rho \cdot A_c \cdot V$

$V = \frac{\dot{m}}{\rho A_c}$

Where:
ρ: fluid density; (kg/m^3)
A_c: cross section area; (m^2)
D: outside diameter; (m)
V: fluid velocity; (m/s)

The Reynolds' number helps to determine the behavior of the flow in movement, in the laminar flow with Re ≤ 2300 or turbulent flow with Re ≥ 4000 (Fox, Pritchard & McDonald, 2003).

$R_e = \frac{v \cdot d \cdot \rho}{\mu}$

Where:
R_e: Reynolds' number; (dimensionless)
U: Fluid velocity inside the pipes; (m/s),
d: Standardized diameter of the suction and discharge pipes a; (m)
ρ: Water density; (kg/m^3)
μ: Dynamic viscosity; (Pa·s)

Prandt's values and the thermal conductivity coefficient of the crude oil CM 650, according to Laurencio (2012), is determined by the following equations:

$$P_r = \frac{0.856 \cdot T_i + 1483}{k_p} \cdot \frac{59.86}{e^{-0.0556 \cdot T_i}} \cdot \left[\frac{8.16 \cdot v}{D_i}\right]^{-0.075}$$

$k_p = (-0.13 \cdot T_i + 149.1) \cdot 10^{-3}$

Where:
P_r: Prandt's number; (adimensional)
k_p: thermal conductivity coefficient of the oil and the ai; (W/m·ºC)
D_i: pipe inside diameter; (m)
T_i: inlet temperature; (ºC)

Nusselt's number is an adimensional quantity that is used to characterized the efficiency of the convective heat transfer in an object or system (Jouglard & Pérez, 2004). Iti s related to the Reynolds' number (Re) and Prandtl's number (Pr), through empirical correlations, such as the equation of Dittus-Boelter, that is applied for heat flows inside the pipes or channels.

$$Nu = 0.3 + \frac{0.62 \cdot {R_e}^{1/2} \cdot {P_r}^{1/3}}{\left[1 + \left(\frac{0.4}{P_r}\right)^{2/3}\right]^{1/4}} \left[1 + \left(\frac{R_e}{282\,000}\right)^{5/8}\right]^{4/5}$$

Where:

Nu: Nusselt (dimensionless)

$$h = \frac{k}{D} Nu$$

Where:

h: Heat transfer coefficient; (W/m^2·ºC)

k: Thermal conductivity coefficient of the oil and air; (W/m·ºC)

Heat transfer ratio

According to Holman (1992) the heat transfer rate describes the velocity to which it is transferred from an object or system to another one, at this time influenced by several factors, including the temperature difference between the objects or systems involved. For a greater temperature difference, the heat transfer ratio will be greater. This may occur in several mechanisms, including conduction, convection and the radiation. The equation to calculate the heat transfer ratio is as follows:

$$U = \frac{1}{\frac{1}{h_i} + \frac{1}{h_o}}$$

$$A_s = \pi DL$$

$$\dot{Q} = UA_s \Delta T_{ml}$$

Where:

$\dot{Q}$: heat transfer ratio

U: total heat transfer coefficient; (W/m^2·ºC)

A_s: Surface area

h_i y h_o: Heat transfer coefficient by convection inside and outside respectively; (W/m^2·ºC).

Calculation of the pipe wall temperature

The pipe wall temperature is calculated as follows:

$$t_w = t_a + \frac{h_i}{h_i + h_o}(T_a - t_a)$$

Where:
t_w: pipe wall temperature; (ºC)
t_α: average cold fluid temperature (crude); (ºC)
T_α: average hot fluid temperature (steam); (ºC)

Results and discussion

Temperature variations calculation results:

The hot fluid inlet temperature is 150°C, while the cold fluid outlet temperature is 85°C. The resulting temperature difference is 65°C, which indicates that the hot fluid enters at a temperature that is higher than the cold fluid outlet temperature. In this case, the hot fluid outlet temperature is 100°C, while the cold fluid inlet temperature is 27°C. The resulting temperature difference is 73°C, so that it shows a significant difference between the fluid’s temperatures in the heat exchanger.

Calculation results of medium logarithmic temperature for counterflow.

The negative value of -0,95 °C for the case of counterflow, shows that the medium logarithmic temperature is less than the average arithmetic temperature difference (single medium of ΔT1 and ΔT2). It suggests that the heat transfer rate is a little lower from what the simple average temperature difference would suggest.

Results of the correction factor selection

According to Sánches & Góngora (2018), the correction factor F takes into consideration the geometric configuration of the heat exchanger as well as the inlet and outlet temperatures of both fluids. An F value less than 1 show that the Shell and pipe heat exchanger medium logarithmic temperature, is slightly less than the one of the ideal counterflow exchanger. This is typical for cross flow and shell and pipe heat exchangers where heat transfer may be less efficient due to the flow configuration.

The value P for 0,67 indicates that the hot fluid outlet temperature is relatively close to the inlet temperature of the cold fluid, which shows an efficient heat transfer. The value R for 1,67 shows the temperature difference between the Shell and pipe, is greater than the temperature difference between its outlets, which is also consistent with an efficient heat transfer. For this heat exchanger, according to the given conditions, the correction factor value is 0.75.

Medium logarithmic temperature results

The resulting value of -0,71 °C shows that the medium logarithmic temperature is less than 0, which suggests an efficient heat transfer in the heat exchanger. The correction factor F of 0,75 shows that the heat exchanger efficiency is a little less than the one of an ideal counterflow heat exchanger. This might be due to the configuration of the cross flow or other specific factors design of the multiple steps heat exchanger.

Calculation results of the heat transfer coefficients by convection.

The Surface area is calculated using the pipe diameter (0,0508 m), which results in an area of 0,0020 m^2. The mass flow is calculated by applying the fluid density of 900 kg/m^3, the area is the surface and the fluid velocity is 2 m/s, which results in a mass flow of 3,6 kg/s. These values indicate a reasonable surface for the heat transfer and a suitable flow rate through the heat exchanger. In this case, the Reynolds' number for a value of 100 000, indicates a turbulent flow that may improve the heat transfer efficiency, at promoting the mixture and increasing the convection. A value of Re that is very high, suggests that the fluid will experience a chaotic and agitated flow inside the pipes.

The thermal conductivity coefficient and Prandt's number are calculated using an inner temperature of 300 °C. The resulting value of 14,3 indicates that the fluid has a relatively low thermal conductivity and a relatively high specific heat capacity. It is calculated from the inner temperature and it results in 0,097 W/m·°C. These values indicate that the crude oil CM 650, is not an excellent heat conductor, but its specific heat capacity may help to moderate the temperature variations.

The Nusselt's number is 130. This value is calculated by using Reynolds' number and Prandt's number, which shows that the flow configuration and the fluid property have a significant impact on the heat transfer.

A Nu value of 130 indicates a reasonably high heat transfer rate, which is positive for effective heat exchange. For a thermal conductivity of 0,6 W/m·°C for water steam at 150 °C, the heat transfer coefficient value is 1524 W/m^2 ·°C.

Results of the heat transfer ratio calculation

The calculation of the surface area by using the pipes outer diameter of 0,0635 m and their length of 10 m, results in an area of 2,01 m^2. A greater surface area provides more space for the heat transfer to be carried out, which generally results in a higher heat transfer rate.

For convective heat transfer coefficients inside with a value of 50 W/m^2·°C and the convective heat transfer coefficient outside with 30 W/m^2·°C, resulting in a value of U = 15 W/m^2·°C. A value of -215 W was obtained. The negative rate indicates that the heat flows from the cold fluid to the hot fluid, that is typical in the heat exchangers.

Calculation results of the pipe wall temperature

The pipe wall temperature influences on the heat transfer rate between the hot and the cold fluids. A higher wall temperature indicates a higher heat transfer of the hot fluid to the col done. In the given case, the temperature of the tube wall is 350 °C. This intermediate temperature suggests that the tube wall is absorbing heat from the hot fluid and transferring it to the cold fluid, which is the main objective of a heat exchanger (Pérez Sánchez, 2020).

The heat transfer coefficients inside and outside the tube play a significant role in determining the tube wall temperature. In this case, it means that the fluid inside the tube (hot fluid) has a higher heat transfer rate than the fluid outside (cold fluid). This is because it is inversely proportional to the thermal resistance of the inner fluid; therefore, a higher value indicates lower resistance to heat transfer.

Thermal flow analysis

The thermal flow analysis (Figure 2), shows how the heat is distributed inside the heat exchanger. The set of colors in the figure represents different temperature values, showing a representation of the heat transfer in the system.

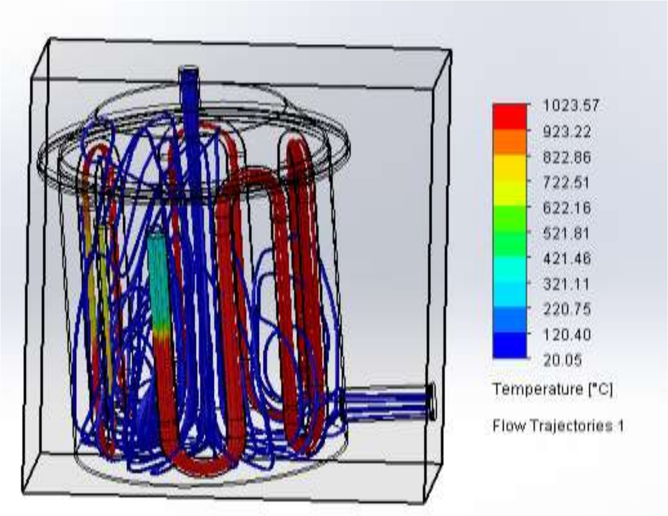

Figure 2. Analysis of the thermal flow in the heat exchanger.

The fluid CM 650, that is represented in blue color, has a relatively low temperature of 20,05 °C. As soon as it approaches to the pipes of the heat exchanger, the temperature starts to increase, which results in a transition from blue to green and yellow. This temperature increase is related to the convection and conduction processes, which take place between the fluid and the surrounding elements.

As the fluid CM 650 approaches to the pipes, where the real heat exchange is carried out, the temperatures are increased to maximum values. The green and yellow colors indicate temperatures oscillating between 421,26 °C and 822,66 °C, which shows the efficiency of the heat exchange in this region. The proximity to the pipes, that are designed to enable the heat transfer, contributes to this temperature increase.

The water steam flowing inside the pipes is shown in red color, showing a temperature that is greatly higher than 1023,57 °C. The water steam absorbs and transfers the heat as it flows through the pipes. The steam high temperature is essential for the heat exchange process, as it provides the necessary thermal energy to heat the fluid of crude oil CM 650.

Analyses of the simulation for fluids density

The Figure 3 provides a visual representation showing the behavior of the density of the fluids that are involved in the simulation. The density, as an essential property of the fluids, changes as per its composition and temperature. In this figure, the Cuban crude oil density is marked with an intense red color, showing its high density of 917.53 kg/m³.

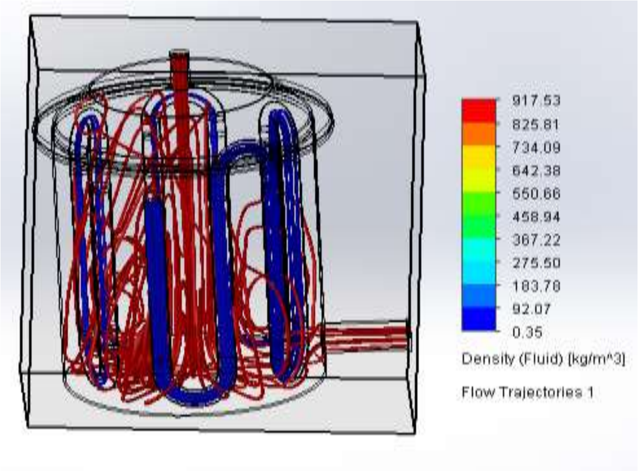

Figure 3. Behavior of the density in the fluids.

On the other hand, the water steam coming from the boilers of Moa's University, is represented with a blue color. Its density values change significantly, from 0.35 kg/m³ up to 187.78 kg/m³. This wide range shows the changing nature of the water steam, which may exist in different states, since low pressure steam to saturated high pressure steam.

Meanwhile, the surrounding areas to the heat exchangers, show a variety of colors indicating the fluid behavior in those regions. The colors go from sky blue to orange color, with density values oscillating within 275.50 kg/m³ and 825.81 kg/m³. These color variations and density provide information about the behavior and mixture of fluids in the proximity of the heat exchangers.

Conclusions

For the adaptation of the experimental facility for the investigation about the Cuban crude oil CM 650, a heat exchanger was designed, with the aim of looking into the behavior of the fluid at different temperatures.

In order to assure a better functionality of the facility, taking into consideration its characteristics, in which from the medium logarithmic temperature difference method, values for the total heat transfer ratio, of -215 W and for the medium logarithmic temperature of -0,71 ºC, were obtained.

Once the behavior of the fluid through the pipes has been determined, by applying the finite element method (MEF), taking into consideration the meshing and the border conditions, the velocity value could be obtained, with maximum values of 2269,200 m/s and for density, with maximum values of 917.53 kg/m³.

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