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Mathematical Modelling of Operating Temperature Variations of Shell-and-Tube Heat Exchanger (10-E-01)

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Abstract

The technique of modeling operating temperature variations of shell-and-tube heat exchanger 10-E-01 of kerosene-crude oil streams of Port Harcourt refinery crude distillation unit is presented in this research. Appropriate first-order model equations were developed applying principles of energy balance. The differential equations developed for the process streams which exchanged heat was evaluated numerically to predict the temperature variations as a function of time. The relevant parameters associated with typical heat exchanger works were calculated using plant data of 10-E-02. The model strives to predict the final kerosene temperature from 488 to 353.6 K. While the crude oil streams temperature rose from 313 to 353.6 K. The developed model enables the operator to predict the final temperature at the kerosene hydro-treating unit and thereby prevent regular emergency shutdowns due to excessive temperature rise.

Keywords

Shell-and-Tube Heat Exchanger 10-E-01, Modeling, Kerosene-Crude Streams, Differential Equations

1. Introduction

Heat exchangers are equipment designed using thermodynamic principles for seamless and efficient heat transfer from one medium to another [1]. They are often used in petroleum refineries, pharmaceutical industries, petrochemical industries, power plants, etc. There are various classes of heat exchanger and the classification is based on: method of construction e.g. shell-and-tube, plate type, plate fin heat exchangers; flow arrangement e.g. cross flow, parallel flow, counter flow [2].

Heat transfer is one of the major processes in crude oil refining; the separation of crude into its components can only be possible by the application of heat. Hence, it is impossible to have a Petroleum refinery without installations of heat transfer systems [3]. The separation process uses the difference in boiling point of the various components to separate the raw crude. This is achieved by the process of fractional distillation where the crude oil is first preheated with the aid of heat exchangers before it is sent to the distillation unit for separation. In the distillation column, the temperature of the preheated crude is further raised to the boiling point of the various component and the components are allowed to vaporize and thus condensed to different fractions [4].

Nigeria has three major refineries; Port Harcourt refinery, Kaduna refinery and Warri refinery. The Port Harcourt refinery with a staggering capacity of 60,000 BPSD was built in 196 to serve the energy demand within the southeastern part of the country. However, the refinery is operated below 60 %, a recent report shows that the refinery is not producing, reasons the Nigerian national petroleum cooperation is planning turnaround maintenance for all three refineries [5]. The refinery consists of the following units; Crude distillation unit (CDU), Vacuum distillation unit (VDU), Catalytic reforming unit (CRU), Kerosene hydro-treating unit (KHT), Fluid catalytic cracking unit (FCC), Dimersol unit, butarmer unit and the Alkylation unit. The focus of this research is on one of the heat exchangers in the crude distillation unit attached to the kerosene hydrotreating unit.

The products of the CDU are Whole Naphtha, Straight Run Kerosene, Light Diesel Oil, Heavy Diesel Oil and Atmospheric Residue. These products are withdrawn from the side stream of the fractionating column and condensed. The 10-E-02 Heat exchanger is used in cooling the straight run kerosene before it is further treated by addition of additives for aviation fuel [6].

Several works on this area have been carried out and such are reviewed as thus: [7] carried out research work on modeling and stimulation of the Double Tube Heat Exchangers Case studies. A hypothetical Elaborate model was used and specifically for this type of exchanger for the modeling process. Data used for the simulation of these models were from exchanger geometry and the input temperatures and flow rates of the two flows. The elaborated model was validated with numerical simulation carried out and the plant data (Experimental data); [8] worked on mathematical model and simulation of a plate heat exchanger operating as steam generator. One-dimensional mathematical model for a plate heat exchanger generator was developed. The heat transfer coefficient and the friction factor of the generator process were considered. Agilent HP vee Pro 4.5 was the simulator which displayed the concentration and temperature profiles; [2], developed a theoretical design of shell and tube heat exchanger and then applied fluid dynamics for performance optimization. A computational model was developed with ANSYS and process parameters were consequently altered for purpose of optimization. Six different models were developed and used to analyze the following process parameters, flow vortices, heat transfer, pressure drop and mass flow rate; [9] used four heat exchangers and developed mathematically model for each heat exchanger. Their focus was on a model that predicts the fouling factor. The developed model was tested and showed 98% reliability in predicting the fouling factor of operating process heat exchanger. The focus of present study is on development of model equations for analyzing operating temperature variation on 10-E-01.

2. Materials

The material input content is purely analytical and identified as follows:

Process Conditions:
Hot fluids: $T_1, T_2, W, C, S, \mu, K, R_d, \Delta P$.
Cold fluids: $t_1, t_2, w, c, s, \mu, k, R_d, \Delta P$.

For the heat exchanger the following parameters with data must be known.

Shell side, tube side, internal diameter (ID), number and length, baffle space passes, outer diameter, BWG, and pitch passes.

3. Methods

The fundamental energy balance model equation is stated as follows.

3.1. Energy Balance

The general energy balance equation for the shell and tube heat exchanger is stated as follows.

3.2. Energy Balance Equation for the Shell Side

$$\text{Rate of accumulation of heat within the shell side of the heat exchanger}\left(\text{kj/s}\right) = \frac{\mathrm{d}}{\mathrm{d}t}\left(\rho_S V_S C_{PS} T_{s,n}\right) \tag{1}$$

$$\text{Rate of input of heat from shell side of the heat exchanger}\left(\text{kj/s}\right) = f_S C_{PS} T^1_{s,n} \tag{2}$$

$$\text{Rate of output of heat from shell side of the heat exchanger}\left(\text{kj/s}\right) = f_s C_{PS} T^o_{s,n} \tag{3}$$

Substituting the parameters into the general energy balance equation, we have;

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\rho_S V_S C_{P_S} T_{S,n}\right) = f_S C_{P_S} T^1_{S,n} - f_S C_{P_S} T^O_{S,n} + Q_n \tag{4}$$

Equation (4) is the general energy balance equation

$$\left(\rho_S V_S C_{P_S} \frac{\mathrm{d}}{\mathrm{d}t} T_{S,n}\right) = f_S C_{P_S} T^1_{S,n} - f_S C_{P_S} T^O_{S,n} + Q_n$$

$$\frac{\mathrm{d}}{\mathrm{d}t}T_{S,n}=\frac{f_D C_{PS} T_{S,n}^{1}}{\rho_S V_S C_{PS}}-\frac{f_S C_{PS} T_{S,n}^{O}}{\rho_S V_S C_{PS}}+\frac{Q_n}{\rho_S V_S C_{PS}} \tag{5}$$

3.2.1. Energy Balance on the Tube Side

Rate of accumulation of heat within the tube in the heat exchanger, $(\mathrm{kj/s})$

$$=\frac{\mathrm{d}}{\mathrm{d}t}\left(\rho_t V_t C_{P_t} T_{t,n}\right) \tag{6}$$

Rate of input of heat into the tube of the heat exchanger, $(\mathrm{kj/s}) = f_t C_{P_t} T_{t,n}^{1}$ (7)

Rate of output of heat into the tube of the heat exchanger, $(\mathrm{kj/s}) = f_t C_{P_t} T_{t,n}^{o}$ (8)

Substituting the above equation into the general energy balance equation we have:

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\rho_t V_t C_{P_t} T_{t,n}\right)= f_t C_{P_t} T_{t,n}^{1} - f_t C_{P_t} T_{t,n}^{O} + Q_n$$

$$\left(\rho_t V_t C_{P_t}\frac{\mathrm{d}T_{t,n}}{\mathrm{d}t}\right)= f_t C_{P_t} T_{t,n}^{1} - f_t C_{P_t} T_{t,n}^{O} + Q_n$$

$$\frac{\mathrm{d}T_{t,n}}{\mathrm{d}t}=\frac{f_t C_{Pt} T_{t,n}^{1}}{\rho_t V_t C_{Pt}}-\frac{f_t C_{Pt} T_{t,n}^{o}}{\rho_t V_t C_{Pt}}+\frac{Q_n}{\rho_t V_t C_{Pt}} \tag{9}$$

$$Q_n = UA_n\left(T_{t,n}-T_{S,n}\right) \tag{10}$$

But,

$$A_n = \pi D_{ext}\Delta L \tag{11}$$

Hence,

$$Q_n = U\pi D_{ext}\Delta L\left(T_{t,\bar{\bar{n}}}-T_{S,n}\right) \tag{12}$$

where,

A_n = Heat transfer for element n.

D_{ext} = Tube external diameter.

V= Element volume occupied by the tube or shell side.

N= Total number of elements in which the heat exchanger is divided.

But,

$$V_t = \pi r_{i,t}^{2}\Delta L \tag{13}$$

$$V_t = \pi\left(r_{i,s}^{2}-r_{ext}^{2}\right)\Delta L \tag{14}$$

where,

$r_{i,t}, r_{ext}$ and $r_{i,S}$ are the internal and external tube radius and internal shell radius respectively?

ΔL A small element region obtained as:

$$\Delta L=\frac{L}{N} \tag{15}$$

In order to compute the entering and leaving fluid temperatures for both the shell and tube sides, a simple arithmetic average of two adjacent regions could be used. For instance, the entering and leaving temperatures for the shell side will be given as:

$$T_{S,n}^{1}=\frac{1}{2}\left(T_{S,n}+T_{S,n}+1\right) \tag{16}$$

$$T_{S,n}^{O}=\frac{1}{2}\left(T_{S,n}+T_{S,n}-1\right) \tag{17}$$

Similarly, for the tube side,

$$T_{t,n}^{1}=\frac{1}{2}\left(T_{t,n}+T_{t,n}-1\right) \tag{18}$$

$$T_{t,n}^{O}=\frac{1}{2}\left(T_{t,n}+T_{t,n}+1\right) \tag{19}$$

Temperature variation in the shell and tube side of heat exchanger

$$\frac{\mathrm{d}T_{s,1}}{\mathrm{d}t}=\alpha_1\left(T_{s,1}+T_{s,2}\right)-\alpha_1\left(T_{s,1}+T_{s,0}\right)+\frac{\frac{U\pi D_{ext}L}{N}}{\alpha_2}\left(T_{s,1}-T_{s,1}\right) \tag{20}$$

$$\frac{\mathrm{d}T_{s,2}}{\mathrm{d}t}=\alpha_1\left(T_{s,2}+T_{s,2}\right)-\alpha_1\left(T_{s,2}+T_{s,1}\right)+\frac{\frac{U\pi D_{ext}L}{N}}{\alpha_2}\left(T_{t,0}-T_{s,2}\right) \tag{21}$$

$$\frac{\mathrm{d}T_{t,1}}{\mathrm{d}t}=\beta_1\left(T_{t,1}+T_{t,0}\right)-\beta_1\left(T_{t,1}+T_{t,2}\right)-\frac{\frac{U\pi D_{ext}L}{N}}{\beta_2}\left(T_{t,1}-T_{t,1}\right) \tag{22}$$

$$\frac{\mathrm{d}T_{t,2}}{\mathrm{d}t}=\beta_1\left(T_{t,2}+T_{t,1}\right)-\beta_1\left(T_{t,2}+T_{t,2}\right)-\frac{\frac{U\pi D_{ext}L}{N}}{\beta_2}\left(T_{t,2}-T_{t,2}\right) \tag{23}$$

Equations (20), (21), (22) and (23) are applied to investigate the temperature profiles of heat exchanger. From the basic principles of heat transfer, the following step-wise analytical calculation will be adopted.

Step 1: Heat balance, Q is given as:

$$Q=WC\left(T_1=T_2\right)=wc\left(t_2-t_1\right) \tag{24}$$

Step 2: True temperature difference, Δt is given as follows:

LMTD:

$$R=\frac{T_1-T_2}{t_2-t_1},\quad S=\frac{t_2-t_1}{T_1-t_1} \tag{25}$$

$$\Delta t=LMTD\times F_t \tag{26}$$

Step 3: Caloric temperature T_c and t_c

Hot fluid: Shell side.

Step 4: flow area,

$$a_3=ID\times C^1B/144P_T\left(\mathrm{ft}^2\right) \tag{27}$$

Step 5: Mass velocity,

$$G_S = \frac{w}{a_S}\left(\text{Ib}/\text{hr}\cdot\text{ft}^2\right) \tag{28}$$

Step 6:

$$D_e = \frac{4\times\left(P_T^2 - \pi d_0^2/4\right)}{\pi d_0} \tag{29}$$

where,

p_t Is the tube pitch, m.

d_o Is the tube outside diameter, m.

Step 7:

$$R_{es} = \frac{D_e G_S}{\mu}$$

Step 8:

$$h_0 = j_H \frac{K}{D}\left(\frac{C\mu}{K}\right)^{1/3} \phi_3 \tag{30}$$

Step 9: Tube-wall temperature,

$$t_w = t_c + \frac{h_o/\phi_s}{h_{i,o}/\phi_t + h_o/\phi_s}\left(T_c - t_c\right)$$

where,

$$\phi_S = \left(\frac{\mu}{\mu_w}\right)^{0.14} \tag{31}$$

Step 10: Corrected coefficient,

$$h_o = \frac{h_o\phi_s}{\phi_s} \tag{32}$$

Step 11: Clean overall coefficient U_O

$$U_O = \frac{h_{i,o}h_o}{h_{i,o} + h_o} \tag{33}$$

where,

U_O Is the overall coefficient base on the outside tube, W/m^2.

Step 12: Heat transfer surface,

$$A = a^{11}LN_t\left(\text{ft}^2\right) \tag{34}$$

Step 13: Design overall coefficient,

$$U_D = \frac{Q}{A\Delta_t}\left(\text{W}/\text{m}^2\cdot{}^\circ\text{C}\right) \tag{35}$$

Step 14: Dirt factor,

$$R_d = \frac{U_C - U_D}{U_C U_D}\left(\frac{\text{m}^2\cdot{}^\circ\text{C}}{\text{W}}\right) \tag{36}$$

Cold fluid: Tube side

Step 1: Flow area

$$a_t = \frac{\text{Number of tubes} \times \text{flow area/tube}}{\text{number of passes}}$$
$$a_t = \frac{N_t a^1 t}{144n}\left(\text{m}^2\right) \tag{37}$$

Step 2: Mass velocity:

$$G_t = \frac{w}{a_t}\left(\text{kg/s}\cdot\text{m}^2\right) \tag{38}$$

Step 3:

$$R_{et} = \frac{DG_t}{\mu}$$
$$\text{But } \mu \text{ is obtained at } t_C \tag{39}$$
$$C_P \times 2.42\left(\text{kg/m}\cdot\text{s}\right)$$

Step 4:

$$h_i = j_H \frac{K}{D}\left(\frac{C\mu}{K}\right)^{1/3}\phi_t \tag{40}$$

Step 5:

$$\frac{h_{i,o}}{\phi_t} = \frac{h_i}{\phi_r} \times \frac{ID}{OD} \tag{41}$$

But ϕ_w and $\phi_t = \left(\frac{\mu}{\mu_w}\right)^{0.14}$

Step 6: corrected coefficient,

$$h_{i,o} = \frac{h_{i,o}}{\phi_t}\phi_t \tag{42}$$

Step 7: overall heat transfer coefficient $U\left(\text{W/m}^2\cdot{}^\circ\text{C}\right)$ for shell and tube heat exchanger can be estimated from the relationship.

$$U_o = QA_oT_m$$
$$\frac{1}{U_o} = \frac{1}{h_o} + \frac{1}{h_o d} + \frac{d_o In\left(d_o/d_i\right)}{2KW} + \frac{d_o}{d_i} \times \frac{1}{h_i d_i} + \frac{d_o}{d_i} \times \frac{1}{h_i} \tag{43}$$

3.2.2. Solutions Techniques

The developed models were solved numerically by applying MATLAB solver of version 4.5 to obtain the following:

How Inlet Temperatures ($T_{S,1}$) and Outlet Temperatures ($T_{S,2}$) of the Shell for the Heat Exchanger vary with Time (t). This will be obtained by solving differential Equations (20) and (21).

How Inlet Temperatures ($T_{t,1}$) and Outlet Temperatures ($T_{t,2}$) of the Tube for the Heat Exchanger vary with Time (t). This will be obtained by solving differential Equations (22) and (23).

How the Temperatures of the Shell and Tube for 1 - 2 Multi-pass Heat Exchanger of Kerosene and crude oil species vary with time (t). Differential Equations (20), (21), (22) and (23) would be solved simultaneously to obtain the required solutions.

These systems of differential equations would all be solved using the Runge-Kutta function embedded in MATLAB 4.5. (*i.e.* "ODE45" for more accurate results).

The Inlet Temperature ($T_{s,1}$), Outlet Temperature ($T_{s,2}$), Inlet Temperature ($T_{t,1}$) and Outlet Temperature ($T_{t,2}$) results would be presented for only outlet temperatures for the shell and tube heat exchanger and solved numerically using MATLAB 4.5.

The graphs plotted show how the outlet temperatures vary with time over a wide time range.

The graphs plotted are presented in figures and discussed.

3.2.3. Declaration of Data for Iterative Process [10]

Tube outside diameter, $d_o = 20\text{ mm}$.

Tube inside diameter, $d_i = 15.78\text{ mm}$.

Tube pitch (triangular pitch), $P_t = 25\text{ mm}$.

Shell clearance (mm) = 56 mm

$$T_{S,O} = 40^\circ\text{C} = 313\text{ K}$$

$$T_{S,i} = 80.60^\circ\text{C} = 353.6\text{ K}$$

$$T_{t,O} = 215^\circ\text{C} = 488\text{ K}$$

$$T_{t,O} = 76.0^\circ\text{C} = 349\text{ K}$$

$$\alpha_1 = \frac{0.5 f_S}{\rho_S V_S}$$

$$\alpha_2 = \rho_S V_S C_{P_S}$$

where; $f_S = 60000\text{ kg/h}$

$$\rho_S = 730\text{ kg/m}^3$$

$$V_S = \pi\left(r_{i,S}^2 - r_{ext}^2\right)\Delta L$$

$$r_{t,i} = 15.78\text{ mm}$$

Lentht, $L = 5$.

Number of pass = 2.

Inlet temperature of crude = 313 K.

Outlet temperature of crude = 353.6 K.

Inlet temperature of kerosene = 488 K.

Outlet Temperature of kerosene = 349 K.

4. Results and Discussion

The model for the operating temperatures variations of heat exchanger running plant in Port Harcourt refinery crude distillation unit 10-E-01 is tested using literature data. From the simulation results, series of graphs were obtained as shown in **Figure 1**, **Figure 2**, **Figure 3** and **Figure 4** respectively. Furthermore, the temperatures variations model of both the inlet and outlet temperatures of the shell and tube side region of the heat exchanger was similarly tested as obtained

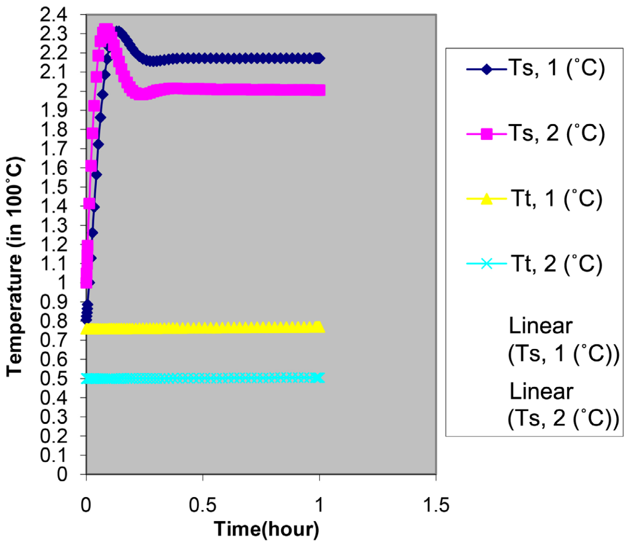

Figure 1. Plot of temperature versus time for both the inlet and outlet temperature at the shell and tube side.

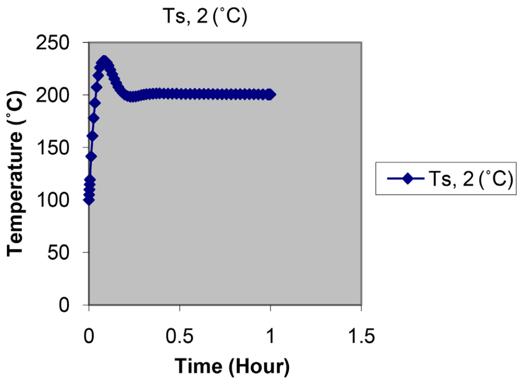

Figure 2. Plot of temperature versus time at the shell side.

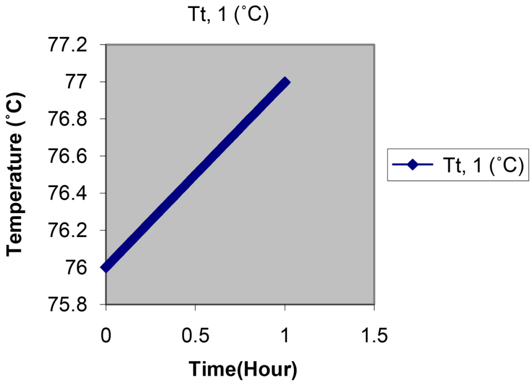

Figure 3. Plot of temperature against time at the tube region.

from values provided from the existing plant data. The variation of temperature against time (hours) of the inlet and outlet streams of both the shell and tube were explained in **Figure 1**, **Figure 2**, **Figure 3** and **Figure 4**.

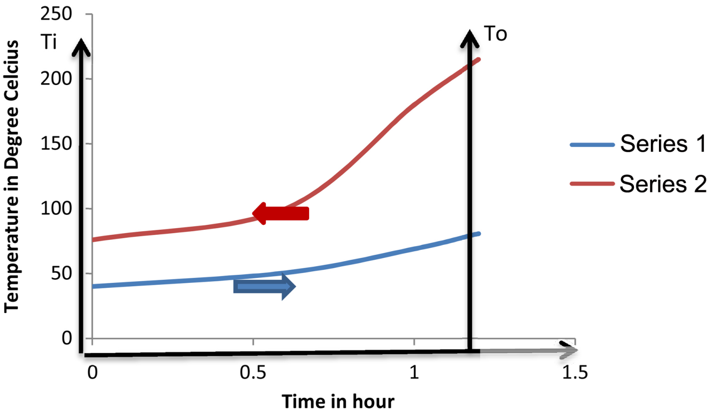

Figure 4. Plot of inlet and outlet temperature against time at the shell and tube side region. Where: Series 1 = Temperature of crude; Series 2 = Temperature of kerosene.

Figure 1 demonstrates the relationship between the temperature streams of the shell and tube heat exchanger with time. The result obtained indicates the temperature profiles of both fluids upon the influence of time in the heating and cooling process of both fluids in the exchanger. The variation of the temperature is due to changes in the time and heat exchange taking place in the heat exchanger. As shown in **Figure 1** above, the shell fluid which is kerosene is at temperature of 235˚C when it enters the exchanger and immediately loses heat to 200˚C thereby remaining steady throughout the process. Meanwhile the cold fluid at temperature of 76˚C inside the tube side of the exchanger which is the crude gains heat to higher temperature as shown.

It is observed that the inlet and outlet temperatures of hot fluid increase as time decreases and gradually becomes steady. The shell side fluid in this study is kerosene and is at a higher temperature of 235˚C when it enters the heat exchanger when time is 0.1 hr and then loses heat to the fluid that is in the tube side heat exchanger to 200˚C at 0.4 hr and remains steady throughout the process from that 0.4 hr to 1 hr. From the graph, initially, the temperature was at 100˚C and then rises to 230˚C from 0 hr to 0.15 hr respectively. This is so because the fluid must have gained heat for it to be used to heat up the cold fluid in the tube.

It was observed that the temperature of cold fluid increases gradually with time. As shown in **Figure 3** above, the crude is at a lower temperature and seen as the cold fluid which requires heat to increase its temperature of 76˚C to higher temperature of 77˚C from 0 hr to 1 hr. At higher time, higher temperature is needed as more heat will be gained by the cold fluid than the actual heat needed for it to leave the exchanger system.

Figure 4 shows the relationship between the temperature and time. It can be seen that the temperature of the kerosene tube is very high such that it enters the tube at 488 K and leaves it at 349 K. While that of the crude inside the shell enters at 313 K gains heat from the kerosene and leaves the shell at the temperature of 353.6 K. Hence the crude is being heated by the heat from the kerosene. Heat gained by the crude equals' heat lost by the kerosene. As indicated as the main function of heat exchanger, heat is exchanged as the crude is heated up to temperature enough for it to enter fractionating column for separation of different fractions.

5. Conclusion

The investigation of behavioral change in the operating temperature variations of 10-E-01 heat exchanger of a running plant of the shell and tube side of the heat exchanger of a refinery crude distillation unit is carried out. The effect at the outlet temperature on the shell side reduces the flow streams as it transfers heat gradually to the crude oil streams to a steady state process. A mathematical model equation was developed and simulated using MATLAB 4.5 and using the experimental data obtained from the refinery 10-E-01. The relevant parameters associated with typical heat exchanger works were calculated using plant data of 10-E-02. Tube outside diameter d_o was 20 mm, tube inside diameter d_i was 15.78 mm, tube pitch (triangular pitch) P_t was 25 mm, shell clearance, (mm) was 56 mm, length was 5 m, and number of pass was 2. The inlet crude oil temperature was 313 K, outlet crude oil temperature was 353.6 K, inlet kerosene temperature was 488 K and outlet kerosene was 349 K. The model strives to predict the final kerosene temperature 488 - 353.6 K, while the crude oil streams temperature rose from 313 - 353.6 K.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Nomenclature

Symbol	Meaning Unit
Ns	Number of shell-side baffles
Pt	Tube pitch
Nt	Number of tubes
$LMTD$	Log mean temperature difference, (˚F)
R_e	Reynolds number for heat transfer
Φ	The viscosity ratio, $(\mu/\mu_w)^{0.14}$
μ	Viscosity at tube-wall temperature, centipoises Nm/s
T	Temperature ˚C
f	Mass flow rate kg/s
ρ	Density kg/s
C_P	Heat capacity kJ/kg K
V	Volume m^3
Q_n	Heat transfer rate kJ/s