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RATING OF HEAT EXCHANGER FOR REACTOR PLANT

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ABSTRACT

This research presents a technique to rating of heat exchanger for reactor plant operation. Appropriate design models specific to exchanger's studies were invoked and applied to fruition. The linear thermodynamic models and physical process data from Refinery to predict the performance of the heat exchanger unit by determining the size of heat exchanger, heat load, log-mean temperature, heat transfer coefficient and capacity ratio to get an exchanger effectiveness of 74.1%. Evaluation of surface area, heat transfer coefficient, quantity of heat, log-mean temperature and outer diameter of the heat exchanger in other to optimize the fractional conversion of the feed components.

Keywords: Rating, heat exchanger, kinetics, reactor plant, heat transfer, Coefficient.

INTRODUCTION

Heat transfer is a principle of thermal engineering that concerns the generation, uses, conversion and exchanger of thermal energy and heat between physical systems. Heat transfer is classified into various mechanisms, such as conduction, convection, radiation and transfer of energy by phase changes (Donald Kern, 2006). Engineers also consider the transfer of mass differing chemical species, either cold or hot to achieve heat transfer. While, these mechanisms have distinct characteristics, they often occur simultaneously in the same system. Heat conduction also called diffusion, are the direct microscopic exchange of kinetic energy of particles through the boundary between two systems. When an object is at a different temperature from another body or is surroundings heat flows to the body and the surroundings reach the same temperature, at which points they are in thermal equilibrium. Such spontaneous heat transfer always occurs from a region of high temperature to another lower region temperature, as required by second law of thermodynamic (Coulson and Richardson, 1999). Heat convection occurs when bulk flow of a fluid (gas or liquid) carried heat along with the flow of matter in the fluid, the flow of the fluid maybe forced by external process or sometimes by buoyancy forces caused when the thermal energy expands the fluid, thus influencing its own transfer. The process is sometimes called "natural convection". All convective process also moves heat partly by diffusion, as well another form of convection. In this case the fluid is forced to flow by use of pump or other mechanical means. The final major form of heat transfer is by radiation, which occurs in any transparent medium (solid or fluid) but may also even occur across vacuum. Steady heat transfer and thermal resistance, radiation is the transfer of energy through space by means of electromagnetic waves, in much the same way as electromagnetic light waves transfer light.

This research employs the fundamental heat exchanger model equations to rating an industrial heat exchanger that will meet the operations of an Industrial catalytic reformer reactor without failure. Therefore, to achieve this, knowledge of heat energy, heat transfer equations and transport phenomena must be incorporated and analyzed. Furthermore, It creates a rating method of determining the best size, pass geometry and other physical constraints to achieve heat exchanger performance characteristics.

In most refineries, optimum yield of products is achieved by proper design principles; and therefore, the operation of catalytic reformer reactor for the production of reformate, the heat exchanger rating efficiency is maximized to improve the refinery economics.

DESIGN MODEL

Essentially, it is fundamental to relate the total heat transfer rate to quantities such as the inlet and outlet fluid temperature, overall heat transfer coefficient and total surface area for heat transfer; an overall energy balance to the hot and cold fluid must be stated. Critical to this research is to state the effects of heat generated per unit volume as a function of kinetic parameters of the reaction process, and equating the kinetic terms with the quantity of heat generated in the given reactor. Consequently, this determines the coefficient of the reformer reactor under study.

Enthalpy balance in heat exchanger

For a hot fluid, enthalpy balance is given by;

$$\frac{1}{M_h Cp_h} = \frac{Th_2^h - T_{n1}}{Q_h} \qquad \textbf{(1)}$$

Similarly, for a cold fluid, we have

$$\frac{M_c dH_c}{dx} = \frac{dQ_h}{dx} \qquad \textbf{(2)}$$

Overall enthalpy balance

$$McCpc\,(Tc2 - Tc1) = MhCph\ (Th2 - Th1) \qquad \textbf{(3)}$$

Heat Load

$$Q = UA \frac{(\Delta T_2 - \Delta T_1)}{in\left[\frac{\Delta T_2}{\Delta T_1}\right]} \qquad \textbf{(4)}$$

$$Q = UA\Delta T_m \qquad \textbf{(5)}$$

where

$$\Delta T_m = \frac{\Delta T_2 - \Delta T}{in\left[\frac{\Delta T_2}{\Delta T_1}\right]} = \frac{(T_{h1} - T_{c1}) - (T_{hi} - T_{c2})}{in\left[\frac{Th_2 - T_{c1}}{T_{h1} - T_{c2}}\right]} \qquad \textbf{(6)}$$

Heat exchanger size

$$L = \frac{Q}{\pi S U \Delta T_{im}} \qquad (7)$$

Individual heat coefficient

$$J_H = \left(\frac{hid}{k}\right) \left(\frac{C\mu}{k}\right)^{1/3} \left(\frac{\mu}{\mu w}\right)^{-0.14} \qquad \textbf{(8)}$$

$$H_o = J_H \frac{k}{D\varepsilon} \left(\frac{C\mu}{k}\right)^{1/3} \left(\frac{\mu}{\mu w}\right)^{0.14} \qquad \textbf{(9)}$$

h_{io} is defined as the area corresponding to the inside and outer sides diameter.

$$h_{10} = hi \frac{Ai}{A} = hi \frac{ID}{OD} \qquad \textbf{(10)}$$

Overall clean coefficient, U_c is defined as:

$$U = \frac{hio \quad ho}{hio - ho} \qquad \textbf{(11)}$$

Design overall coefficient, U_D

$$\frac{1}{U_D} = \frac{1}{U_C} + R_d \qquad \textbf{(12)}$$

The dirt factor R_d:

$$Rd = \frac{U_c - U_D}{U_c - U_D} \tag{13}$$

Pressure Drop

The fanning equation is given as:

$$\Delta F = \frac{4FG2l}{2sp2De'} \tag{14}$$

Similarly,

$$V = \frac{a}{3600p} \tag{15}$$

Capacity ratio

$$\boldsymbol{C = \frac{M_C C_{PC}}{M_h C_{ph}}} \tag{16}$$

Heat exchanger

$$\varepsilon = \frac{M_C C_{PC}(t_2 - t_1)}{M_h C_{PC}(T_1 - t_1)} = \frac{T_2 - t_1}{T_1 - t_1} \tag{17}$$

Rating of heat exchanger

Mathematically, heat generated per unit reactor volume expressed as a function of kinetic parameters of the reaction process is stated as,

$$q = \frac{Q}{V_R} = \frac{\Delta H_R F_{AO} X_i}{V_R} \tag{18}$$

Heat generation for a typical reactor unit is given by;

$$Q = F_{AO} \; X_A \; \Delta H_R \tag{19}$$

The Kirchhoff's relationship for a given reaction process is the quantity of heat released or absorbed (Yunus and Michael, 2006) given by;

$$\Delta H_R = \Delta H_O + \int_{T_0}^{T_2} \Delta C_P \, dT \tag{20}$$

$C_P = (1 / D_F{}^{0.5}$ $(0.762 + 0.0034\ T)$ $M_F)$ $(y(N) + y(P) + y(A)) / N_T + \ldots$
$(6.62 + 0.00081T)$ 4.18 $(H_2) / N_T$ **(21)**

Considering heat generation per unit reactor volume as a function of kinetic parameters, divide both sides of equation (19) by V_R (Octave levenspiel, 2004).

$$q = \frac{Q}{V_R} = \frac{\Delta H_R F_{AO} X_i}{V_R} \tag{22}$$

From equation (5)

$$Q = UA\Delta T \tag{23}$$

Since equation (22) is the total heat the exchanger will remove from the reactor, therefore, equating (22) and (23) we have;

$$\frac{\Delta H_R F_{AO} X_i}{V_R} = UA\Delta T \tag{24}$$

$$U = \frac{\Delta H_R F_{AO} \ X_i}{V_R A \Delta_T} \tag{25}$$

MATERIALS

The parameters and control variables for the effective rating of the heat exchanger used in operating the reformer reactors were evaluated numerically. (Oboho, 2005), (Wordu, 2012) applied constrain optimization to determine the control parameters of hydrocarbon lumps as stated below:

Reactions type	Heat of reaction, ΔH_R (kj/kmol) of H_2librated
Conversion of Naphthenes to Aromatics	70928
Conversion of Paraffin's to Naphthenes	-44185
Naphthenes cracking	-51860
Paraffin's cracking	-51860

$$\sum \Delta H_R = 70928 - (44185 + 51860 + 51860)$$

$$\sum \Delta H_R = 70928 - 147905$$

$$\sum \Delta H_R = 76977 \, kj/kmol \ of \ H_2 \ liberated$$

Net heat of reaction generated as a result of the series-parallel reactions taking place for the 3 reactors:

$$\sum \Delta H_R = 3 \times 76977 kj/kmol \ of \ H_2 \ liberated$$

$$\sum \Delta H_R = 230931 kj/kmol \ of \ H_2 \ librated$$

Table 1: Plant operating data of 12–E-01 A/B of Port Harcourt Refinery

Parameters	General value	Shell side	Tube-side
Fluid flow quantity (kg/h)		97882	97882
Temperature (in/out) ^{O}C		480/126	380/94
Viscosity, (vapor)		14.5	9.6
Thermal conductivity (kcal/hm^{2} ^{O}c)		0.1164	0.0099
No of passes per shell		1	1
Conversion allowance		3	3
Tube length (m)			20

Baffle 5% cut (Dia/Area)			25^o
Tag number	12-E-01A/B		
Heat capacity of Reformate (kj/kg^{O}C)	1.347		

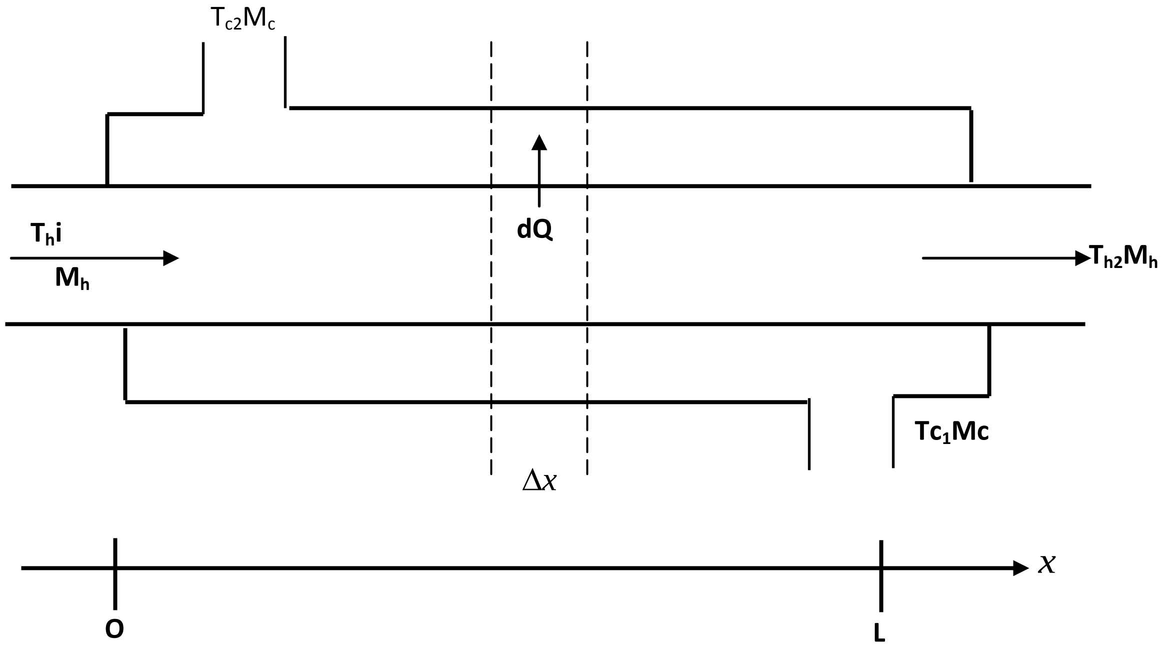


Figure 1: Schematic of heat exchanger

SOLUTION TECHNIQUES

The linear models were resolved iteratively on the various parameters controls using a linear algorithm. The following functions were plotted to give the profiles in figures 1-6 .

$$A = f(\alpha_i)\ ,\ U = f(\alpha_i) \quad Q = f(\alpha_i)\ ,\ \Delta T_m = f(U_i)\ ,\ \Delta T_m = f(\alpha_i)\ \ and\ \ OD = f(L)$$

RESULTS AND DISCUSSION

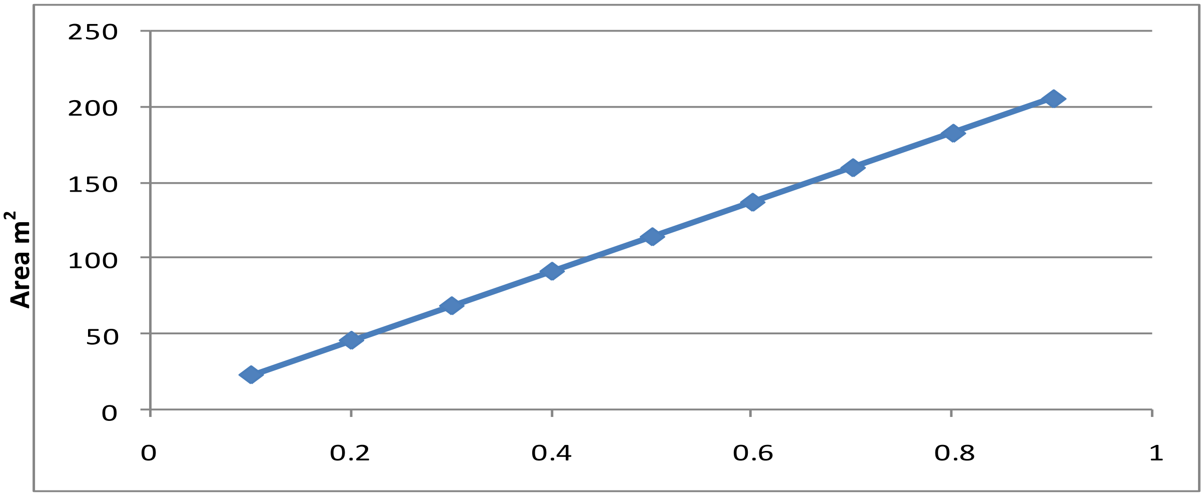
(Wordu and Nwidoo, 2012) reactor plant heat exchanger performance evaluation gave the following results in table 2.

Table 2: Computed sensitive parameters of reactor heat exchanger

Parameter	General Values	Hydro-treated Naphtha (tube side)	Reformate (Shell side)
ΔT_M (^{O}c)	47.72		
Heat Load, Q (kw)	12965		
Fouling Factor, F_t ($m^{2\ O}C/W$)		0.0004	0.0004

Heat Transfer Area A, (m^2)	2716.9		
Number of Tubes, N_t		2161	
Length of the heat Exchanger, L (m)	20		
Tube per pass		1081	
Velocity of flow, U_t (m/s)		0.192	
Volumetric flow rate V_t (m^3/s)		0.0409	
Area per pass A_t, (m^2)		1.96×10^{-4}	
Shell Diameter D_s, (mm)			1296
Baffle spacing L_B, (mm)			259.2
Shell Side Transfer Area A_s (m^2)			0.067
Shell Side equivalent Diameter, D_e (mm)			14.4
Heat Transfer Co-efficient h_i and h_s (w/m^2 ^oC)		3.24	49.37
Pressure Drop; ΔP_t and ΔP_s, (kpa)		9.01	256.8
Capacity Ratio	0.3823		
Exchanger Effectiveness (%)	74.1		

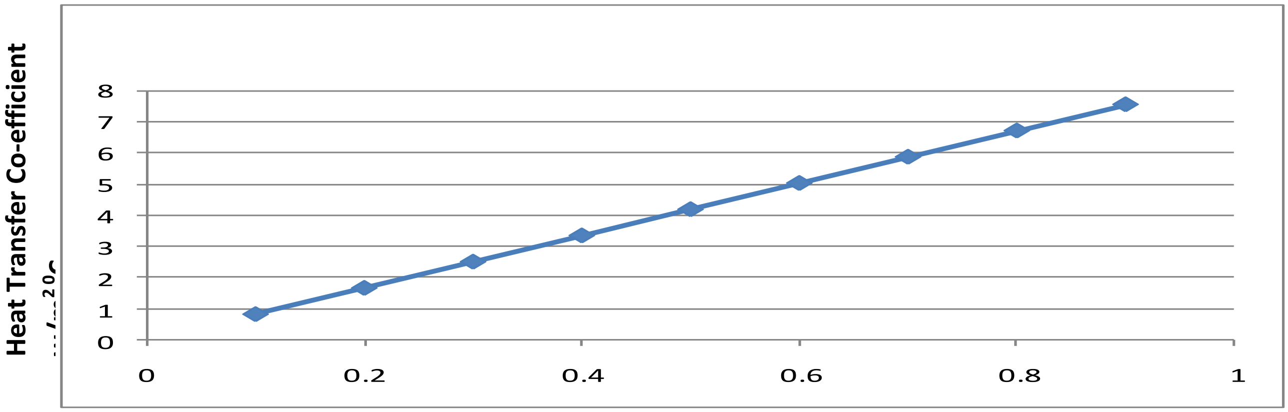
For every reactor operation, heat is either generated or consumed; and the rate at which heat is produced or consumed is a function of the effectiveness of fractional conversion of the reacting species. For the case of reformer reactor operation whose net heat effect is exothermic in nature; the quantity of heat dissipated in the reactor is a fraction of what the exchanger will remove; and this heat effect is a function of fractional conversion of the reacting species. Therefore, for any quantity of reacting species converted into product, a certain quantity of heat is dissipated which requires a particular size of exchanger for the purpose of cooling. Figure 1 shows plot of fractional conversion against the area required to remove the generated heat.



Fractional conversion (α)

Figure 1: Plot of heat exchanger surface area (m^2) against fractional conversion (α)

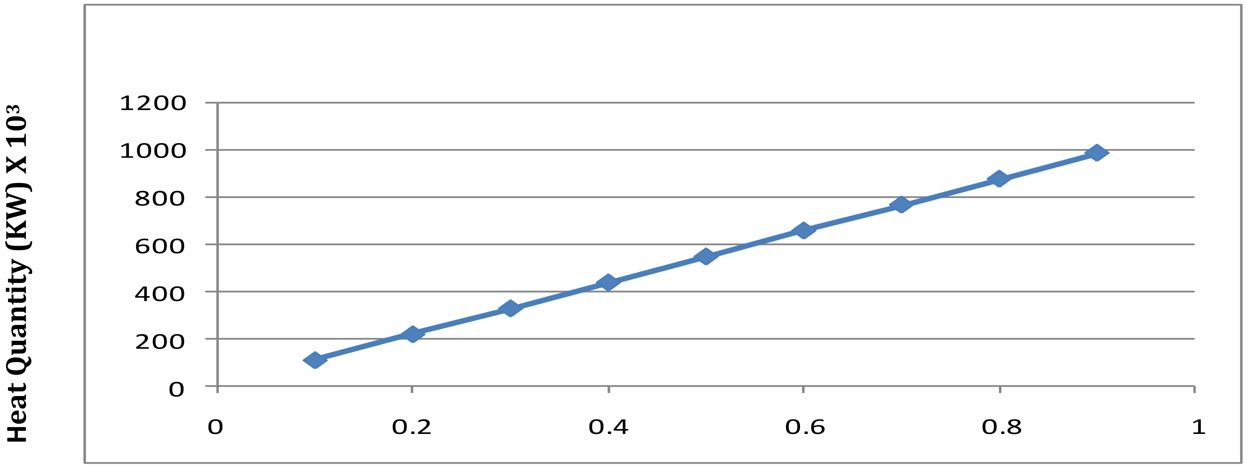
Figure 1 shows a strong dependence of the heat exchanger surface area to the fractional conversion of the reacting species. From practical point of view, it implies that as the conversion of the reacting species is increasing, requires more surface area of the heat exchanger to remove the net heat generated.



Fractional conversion (x)

Figure 2: Plot of heat transfer co-efficient ($w/m^{2\,0}C$) against fractional conversion

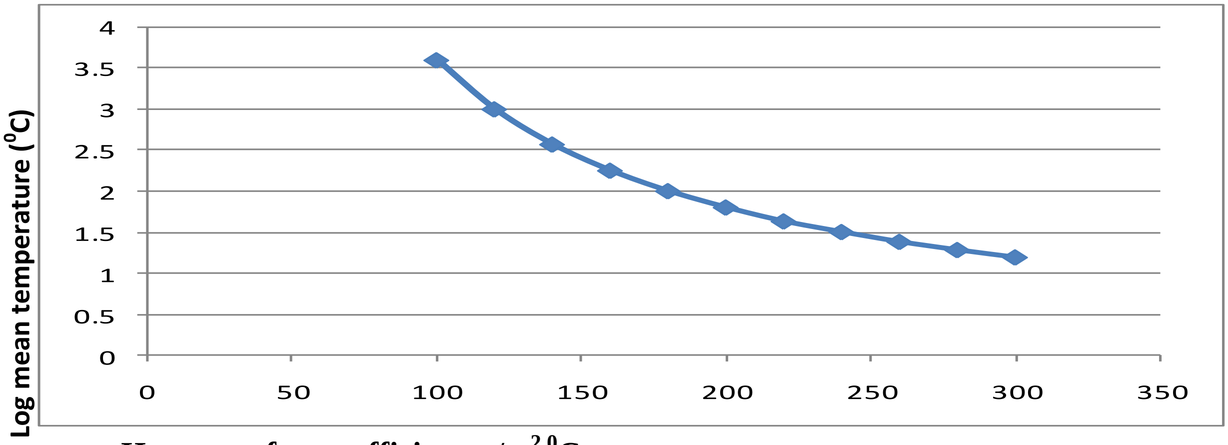
Figure 2 shows dependence of co-efficient of heat transfer to fractional conversion of the reacting species. A linear relationship between the two variables clearly obtained, an increase in the fractional conversions brings about a constant increase in the heat transfer co-efficient. The practical implication of this graph is that at higher conversional rate, the exchanger requires a higher heat transfer co-efficient.



Fractional conversion (x)

Figure 3: Plot of heat quantity (KW) against fractional conversion (x)

The quantity of heat generated by the reactor is directly proportional to the fractional conversion of the reacting species, at higher conversion, more heat is dissipated which requires more work by the exchanger



Heat transfer co-efficient w/m^2 ^{0}C

Figure 4: Plot of Log mean temperature (^{0}C) against heat transfer Co-efficient (w/m^2 ^{0}C)

From the plot of log mean temperature against the heat transfer co-efficient, it was observed that there is inverse relationship between the two variable, increase in heat transfer co-efficient bring about decrease in the log mean temperature of the exchanger. Practically for an efficient and effective heat exchanger, at higher log mean temperature, we should consider a small value of heat transfer co-efficient.

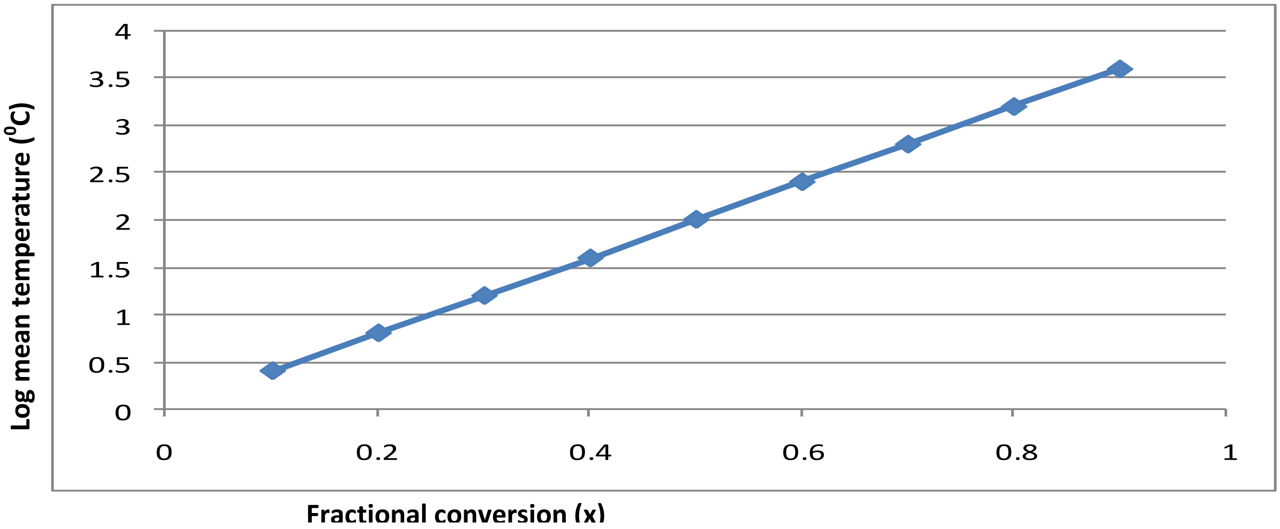


Figure 5: Plot of Log mean temperature (^{0}C) against fractional conversion

From the graph of log mean temperature against fractional conversion, it was observed that increase in the conversional rate of the reacting species requires a higher log mean temperature, provided that cooling liquid temperature is constant. This simply means that at higher conversional rate, we have higher log mean temperature.

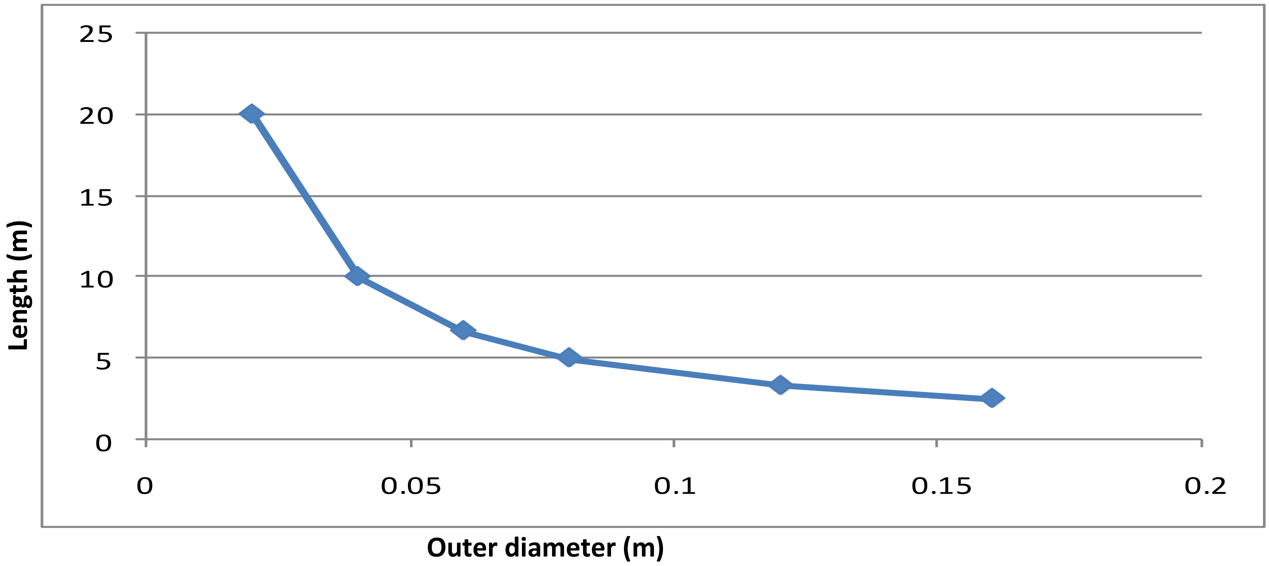


Figure 6: Plot of heat exchanger's Length (m) against its outer diameter (m)

It was observed that an increase in outer diameter of the heat exchanger brings about decrease in the heat exchanger length. The outer diameter of heat exchanger increases, its corresponding length decreases. To save cost during fabrication, this inverse relationship should be put into consideration.

CONCLUSION

The research presents a technique for rating an industrial heat exchanger which takes into account sensitive control parameters for reactor plant operation and is a major aspect of chemical engineering practice. The model equations developed was used to harness the utility of the reformer reactor through accurate control of heat exchanger which has been a major focus of our refinery industries. The theoretical heat field of a fluid gives the amount of heat that needs to be transferred into or from a fluid also; and heat transfer is a function of the physical geometry of the heat exchanger, its material composition and the fluid condition. The real relationships between the reactor parameters and heat exchanger sensitive parameters were combined and analyzed, shows a progressive relationship between extent of conversion in the reactor and quantity of heat required and size of heat exchanger necessary to remove the resultant heat generation. The economics associated with building new on-site heat exchanger or replacing corroded parts is a major challenge to the refining industries, hence this research approach, will help to control and monitor the efficient use of heat exchangers in refinery operations.

NOMENCLATURE

A	Heat exchange size	m^2
A_{ASS}	Assumed heat exchanger size	m^2
A_1	Area of inner tube	m^2
A_m	mean area of inner and outer tube	m^2
C_{pc}	Specific heat capacity of cold fluid	$^{j}/kg^{0}C$
C_{ph}	Specific heat capacity of hot fluid	$^{j}/kg^{0}C$
D_i	Inner diameter of outer tube	m
D_O	Outer diameter of inner tube	m
D_{eq}	Equivalent tube diameter	m
D_m	Mean diameter of inner and outer tube	m
D_1	Inner diameter of inner and outer tube	m
d_o	Outer diameter of outer tube	m
H_{2h}	Enthalpy of hot fluid at outlet	$^{j}/_{kg}$
H_{2C}	Enthalpy cold fluid of outlet	$^{j}/_{kg}$
H_{1C}	Enthalpy cold fluid of outlet	$^{j}/_{kg}$
h_o	Outer surface heat transfer coefficient	$^{j}/_{m^2 S^{O} C}$
h_1	Inner surface heat transfer coefficient	$^{j}/_{m^2 S^{O} C}$
K	Thermal conductivity of steel	$^{j}/_{h_{r+} .s.k.m}$
K_C	Thermal conductivity of cold fluid	$^{j}/_{h_{r+} .s.k.m}$

K_h	Thermal conductivity of hot fluid	$j/h_{r+}.s.k.m$
L	Total length of exchanger from calculated	m
Lr	Total length of exchanger from assumed area	m
M_h	Mass flow rate hot fluid (benzene)	kg/hr
m_c	Mass flow rate hot fluid (water)	kg/hr
N_{nu}	Nusselts number	
N_{RE}	Reynolds number	
N_{IR}	Prandtl number	
n	Number of exchanger needed	
P	wetted perimeter	m
R_w	Tube will resistance	$hr\ s.m/j$
R_i	Tube fluid resistance	$hr\ s.m/j$
R_o	Annulus fluid resistance	$hr\ s.m/j$
r_o	outer radium of outer tube	m
r_i	Inner radium of inner tube	m
S	Annulus surface area	m^2
T_{h1}	Inlet temperature of cold fluid	^0C
T_m	Overall heat transfer coefficient with respect To inner tube	$j/m2s^oC$
T_{h2}	Outlet temperature of hot fluid	^oC
T_{c2}	Outlet temperature of cold fluid	^oC
t_i	Thickness of inner tube	m
t_o	Thickness of outer tube	m
U_i	Overall heat transfer coefficient with respect To outer tube	$j/{}_o m^2{}_o S^O c$
U_{ASS}	Assumed overall heat transfer coefficient	$J/\backslash\ m^2 s^o C$
V	Mean velocity of fluid	m/s
y	cost index in 2006	
ΔT_{lm}	Logarithmic mean temperature difference	^oC
ΔT_l	Mean driving force at inlet	
λ_h	Density of hot fluid	kg/m^3
μ_c	Density of cold fluid	kgs/m^3
μ_h	Viscosity of hot fluid	kgs/m

μ_c Viscosity of cold fluid $\left. kgs \middle/ m \right.$
U - Overall heat transfer co-efficient
ΔH_R - Overall heat of reaction
F_{AO} - Feed flow rate
X_i - Conversion term
ΔT - Log mean temperature of the exchanger
A_c - Cross sectional area of the exchanger
V_R - Volume of the reactor
C_P - Specific heat capacity at constant pressure
P - Paraffins
A - Aromatics
N - Naphthenes
H_2 - Hydrogen

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