RESEARCH ARTICLE OPEN ACCESS

The Effect of Hydrodynamics on Riser Reactor Performance of the FCCU

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ABSTRACT: *The effect of hydrodynamics on the riser reactor performance was studied. The simulation was carried out using COMSOL Multiphysics software. The simulation results showed that reaction rate increased with increase in temperature. The results also showed that an increase in pressure leads to an increases in the velocity of the riser reactor. A maximum on gasoline yield appears when the gas oil inlet temperature is 600K, the catalyst inlet temperature is 1100K and the steam inlet temperature is 400K making gasoline yield between 52% to 55%. A minimum on Coke yield appears when the gas oil inlet temperature is 300K, the catalyst inlet temperature is 800K and the steam inlet temperature is 200K making coke yield between 1% to 2%.*
Keywords: *COR, Riser reactor, hydrodynamics, simulation, temperature*

I. INTRODUCTION

A riser reactor can be divided into four parts from bottom to top according to their functions: the prelifit zone, the feedstock injection zone, the full-reaction zone, and the quenching zone [6]. In the prelift zone of the riser reactor, catalysts enter the riser reactor from the regenerator and are then conveyed by the prelift gas. When the two-phase gas-solid mixture reaches the feedstock injection zone, catalyst will mix with the feed oil injected through feedstock nozzles and begin to react rapidly. The distributions of the particle concentration and of the particle velocity form in the prelift zone and the distributions will greatly influence the contact efficiency of catalysts and feedstock. Moreover, determining the best feedstock injection position also depends greatly on the catalyst flow conditions, such as its concentration and velocity in this zone. In the feedstock injection zone, fed oil is introduced into the riser through the feed nozzles, and the heavy oil comes in contact with the high-temperature catalysts and then reacts rapidly. The contact and flow conditions of these two phases will directly affect the FCC unit. In this study, the effect of hydrodynamics on riser reactor performance of the FCCU will be considered.
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II. METHODOLOGY

2.1 The Riser Kinetic Model

Figure 1 is the riser reactor and its auxiliary parts. The model equations used were based on the schematic flow diagrams of the riser reactor as presented in Figure 2. The riser reactor is 33m long and the diameter is 0.8m. The 10-lump kinetic model and the 20-lumps kinetic model were used to describe the kinetics of the riser reactor. The details of the 10 lumps kinetic model are shown in literatures [1], [7], [8], [9]**.** The 20 lumps of pseudo components are presented in table 1.0 and the corresponding 190 rate constants from the 20 lumps as they undergo cracking are shown in table 2 and details are shown elsewhere [7].

In table 1 and 2, some of the components in one lump may appear the same as that of another in their uses but can be only differentiated with some parameters like their boiling points, their molecular weight, their heat of combustion, etc as found in [3], [7]. In table 2 row 1, L1 can be cracked to L2, L3, L4, L5, L6, L7, L8, L9, L10, L11, L12, L13, L14, L15, L16, L17, L18, L19 and L20 and the corresponding rate constants are K_{12}, K_{13}, K_{14}, K_{15}, K_{16}, K_{17}, K_{18}, K_{19}, K_{110}, K_{111}, K_{112}, K_{113}, K_{114}, K_{115}, K_{116}, K_{117}, K_{118}, K_{11} and K_{120}. The other cracked products and there corresponding rate constants are as shown from row 2 to row 20 in table 2.

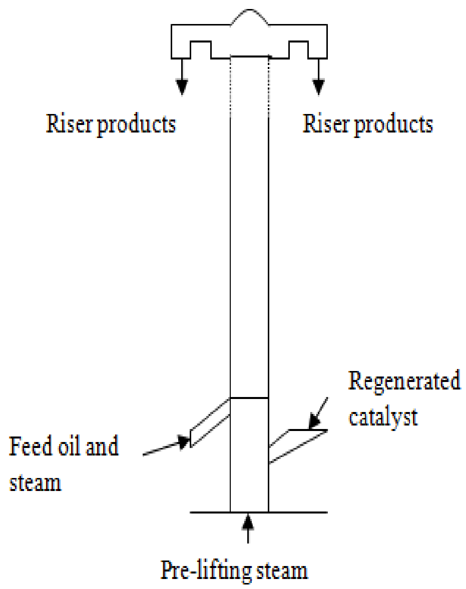

Figure 1: The FCC riser reactor

Table 1: The 20 lumps of Pseudo Components

L1 = Vacuum residue	L11 = LPG
L2 = Gas oil/HFO	L12 = LPG
L3 = LFO	L13 = n-C_5 in LPG
L4 = LFO	L14 = i-C_5 in LPG
L5 = Gasoline	L15 = n-C_4 in LPG
L6 = Gasoline	L16 = i-C_4 in LPG
L7 = LPG	L17 = C_3 in LPG
L8 = LPG	L18 = C_2 = Dry Gas
L9 = LPG	L19 = C_1 =Dry Gas
L10 = LPG	L20 = C = Coke

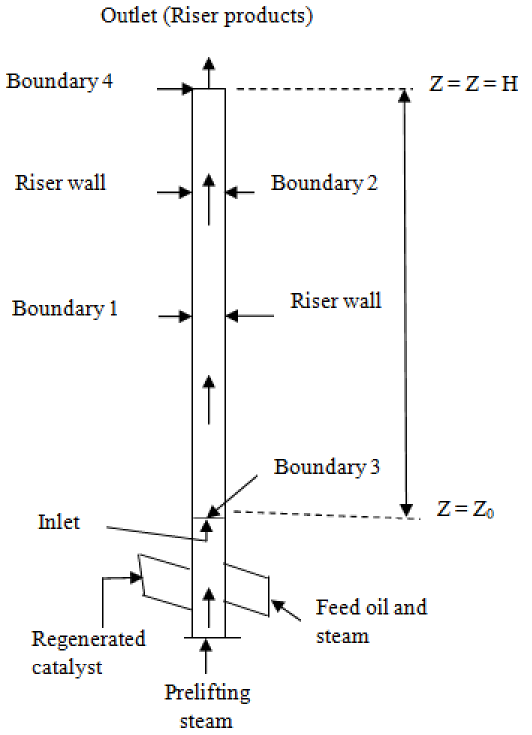

Figure 2: The FCC riser reactor without termination device simulated

A. The riser reactor equations

In addition to the kinetic equations the the reactor model equations as explained in [9] were used to describe the riser system. The model is an ideal plug-flow reactor, described by the mass balance in equation (1). Assuming constant reactor cross section and flow velocity, the species concentration gradient as fraction of residence time (τ) is given in equation (2). The reaction rates are given by $r_f = K_j C_i$ and to account for the different time scales, two different activity functions are used. For the non-coking reactions the activity function is given in equation (3).

$$\frac{dF_i}{dV} = \sum_j V_{ij} r_j = R_i \qquad (1)$$

$$\frac{dF_i}{dV} = \frac{d(VC_i)}{dV} = \frac{dC_i}{d\tau} = R_i \qquad (2)$$

$$a = e^{-k_d C_c} \qquad (3)$$

The reaction rates are modified by the activity according to equation (4). For the coking reactions, the activity function is given by equation (5) where α is a deactivation constant depending on the residence time. The modified reaction rates are given by equation (6). The coke content is given by equation (7) and equation (8). The values of a, b, φ and α are obtained from [[7], [8], [9] as shown in equation (9) and (10) respectively.

$$r_f = aK_j C_i \qquad j = 1,2,3,4,5,6,7,8,13,14,15 \qquad (4)$$

$$b = e^{-\psi t} = e^{-\alpha t} \qquad (5)$$

$$r_f = bK_j C_i \qquad j = 9,10,11,12,16,17,18,19,20 \qquad (6)$$

$$C_c = 2.43 \times 10^{-3} t_c^{\,0.2} \qquad (7)$$

$$Q(C_c) = \frac{1}{1 + 69.47(100C_c)^{3.8}} \qquad (8)$$

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$$\phi = \exp(-\alpha . t_c) \qquad (9)$$

$$\alpha = \alpha_0 \exp\left(\frac{-E}{RT}\right) \qquad (10)$$

For the mass transport, the inlet and outlet concentrations are obtained from equation (11) and the velocity and pressure for ideal gases are obtained from equation (12) and (13) respectively. The static head of catalyst in the riser can be calculated using equation (14). The details on choosing the void fraction variable, assumed gas velocity, slip factor and the vapourisation heat of the feed in the riser inlet are shown in [7], [9].

Inlet: $c = c_{in}$, Outlet: $c = c_{out}$ (11)

$$v = \frac{R_g T}{p} \Sigma F_i \qquad (12)$$

$$p = R_g T \sum C_i \qquad (13)$$

$$-\frac{dp}{dz} = \rho_{cat}\, g.(1-\varepsilon) \qquad (14)$$

For momentum transport, the inlet and outlet pressure are obtained from equation (15)

$$p = p_{in} - \rho_{cat}\, g(1-\varepsilon)(z - z_0) \qquad (15)$$

For energy balance, neglecting pressure drop, the energy balance for an ideal reacting gas, as well as an incompressible reacting liquid is given by equation (16) and (17). The inlet temperature is calculated putting into consideration the energy balance of the components. Equation (18) is used in calculating the inlet temperature while equation (19) is used for calculating the outlet temperature.

$$\sum_i M_i C_{p,i} \frac{dT}{dV} = w_s + Q + Q_{ext} \quad (16)$$

$$Q = -\sum_j H_j r_j \quad (17)$$

At $z = z_0 = 0$, $w_s = 0$, $Q_{ext} = 0$, equation (16) and (17) becomes $\sum_i M_i C_{p,i} \frac{dT}{dV} - Q = 0$

This implies that

$$M_{cat}.Cp_{cat}.(T - T_{cat}) + M_{go}.Cp^{l}_{go}.(T_{vap} - T_{go}) + M_{go}.Cp^{v}_{go}.(T - T_{vap}) + M_{go}.\Delta H_{vap} + M_{ds}.CP_{ds}.(T - T_{ds}) = 0$$

That is

$$T_0 = \frac{T1}{T2} \quad (18)$$

Where

T1= $(M_{cat}Cp_{cat}T_{cat}) - (M_{GO}Cpl_{GO}(T_{vap} - T_{GO})) + (M_{GO}Cpv_{GO}T_{vap}) - (M_{GO}\Delta H_{vap}) - (M_{ds}Cp_{ds}T_{ds})$

T2= $M_{cat}Cp_{cat} + M_{GO}Cpv_{GO} + M_{ds}Cp_{ds}$

At z = h or z, $w_s = 0$, $Q_{ext} = 0$, equation (16) and (17) becomes $\sum_i M_i C_{p,i} \frac{dT}{dV} = Q$

That is, $\sum_i M_i C_{p,i} \frac{dT}{dV} = -\sum_j H_j r_j$

This implies that $T_z - T_0 = -\frac{\sum_j H_j r_j}{\sum_i M_i C_{p_i}} dv = -\frac{\sum_j H_j r_j}{\sum_i M_i C_{p_i}} (\pi D)(z - z_0)$

That is,

Outlet: $T = T_z = T_0 - 7.7 * t\text{^}0.35 \quad (19)$

Details of the riser equations are presented in [7], [8], [9].

2.3 The Materials and Boundary conditions

The average molecular weight, the thermodynamic properties of the feed, the plant operating conditions and the properties of the catalyst used in this study, the specific heat of different lumps, the kinetic parameters for cracking reactions and boundary conditions are found elsewhere [3], [4], [5], [2], [7], [8], [9].

III. SIMULATIONS

The extra fine mesh generator of the COMSOL Multiphysics software was used to produce grid refinement in the riser reactor. The detail procedures for the simulation process in [7], [8], [9].

IV. RESULTS AND DISCUSSION

4.1 The effect temperature on the riser reactor performance

Figure 3 shows the reaction rates of various species with respect to the temperature. Reaction rate increased with increase in temperature. At the same conversion level, an increase in temperature results in a lower gasoline yield since the gasoline cracking rate increases faster than the gasoline formation rate. In figure 4, an increase in the inlet temperature leads to lower gasoline yield.

4.2 The effect of pressure on the reactor riser performance

As the catalyst oil ratio (COR) increases, the pressure in the riser reactor decreases. Hold up of catalyst (1-ε) increased with increase of COR, so for all investigated input catalyst temperature, the increase of hold up can lead to higher conversion and pressure drop (Figure 5). Figure 6 shows the effect of COR on yield. Increase in pressure leads to increase in the velocity in the riser reactor.

Figures 7 to 12 are 3-D graphics showing the effects of temperature on FCC yields. The ten lumps kinetic model is used in order to illustrate our results for a heavy gasoil. The effect of feed inlet temperature on light gasoline yield is given in figure 7. A maximum on gasoline yield appears when the gas oil inlet temperature is 600K making gasoline yield going up to almost 52%.

Figure 8 shows the effect of feed inlet temperature on coke yield. At 600K, Coke (C_1- C_4 + coke) yield is 15% by weight. That is C_1- C_4 yield is 7.5% by weight and coke yield is 7.5% by weight. A minimum on Coke yield appears when the gas oil inlet temperature is 300K making coke yield up to 2%

Figure 9 shows the effect of catalyst inlet temperature on gasoline yield. A maximum on gasoline yield appears when the catalyst inlet temperature is 1100K making gasoline yield going up to almost 52%.

Figure 10 shows the effect of catalyst inlet temperature on coke yield. At 1,100K and Coke (C_1- C_4 + coke) yield is 18%. That is C_1- C_4 yield is 9% by weight and coke yield is 9% by weight. A minimum on Coke yield appears when the catalyst inlet temperature is 800K making coke yield up to 1%.

Figure 11 shows the effect of steam inlet temperature on gasoline yield. A maximum on gasoline yield appears when the steam inlet temperature is 400K making gasoline yield going up to almost 55%.

Figure 12 shows the effect of steam inlet temperature on coke yield. At 400K Coke (C_1- C_4 + coke) yield is 12%. That is C_1- C_4 yield is 6% by weight and coke yield is 6% by weight. A minimum on Coke yield appears when the steam inlet temperature is 200K making coke yield up to 1%.

V. CONCLUSION

The effect of hydrodynamics on the riser reactor was studied and simulation was carried out using COMSOL Multiphysics software. The results showed that reaction rate increased with increase in temperature. At the same conversion level, an increase in temperature results in a lower gasoline yield since the gasoline cracking rate increases faster than the gasoline formation rate. The results also showed that as the catalyst oil ratio (COR) increases the pressure in the riser reactor decreases. Hold up of catalyst (1-ε) increased with increase of COR and so for all investigated input catalyst temperature, the increase of hold up can lead to higher conversion and pressure drop. An increase in pressure leads to an increases in the velocity of the riser reactor. A maximum on gasoline yield appears when the gas oil inlet temperature is 600K, the catalyst inlet temperature is 1100K and the steam inlet temperature is 400K making gasoline yield between 52% to 55%. A minimum on Coke yield appears when the gas oil inlet temperature is 300K, the catalyst inlet temperature is 800K and the steam inlet temperature is 200K making coke yield between 1% to 2%.

Nomenclature

The nomenclature is given in table 3 and table 4.

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Table 2: The 20 Lumps and 190 rate constants of Pseudo Components

S/N	LUMP	CRACKED TO	RATE CONSTANTS
1.	L1	L2, L3, L4, L5, L6, L7, L8, L9, L10, L11, L12, L13, L14, L15, L16, L17, L18, L19, L20	K_{12}, K_{13}, K_{14}, K_{15}, K_{16}, K_{17}, K_{18}, K_{19}, K_{110}, K_{111}, K_{112}, K_{113}, K_{114}, K_{115}, K_{116}, K_{117}, K_{118}, K_{119}, K_{120}
2.	L2	L3, L4, L5, L6, L7, L8, L9, L10, L11, L12, L13, L14, L15, L16, L17, L18, L19, L20	K_{23}, K_{24}, K_{25}, K_{26}, K_{27}, K_{28}, K_{29}, K_{210}, K_{211}, K_{212}, K_{213}, K_{214}, K_{215}, K_{216}, K_{217}, K_{218}, K_{219}, K_{220}
3.	L3	L4, L5, L6, L7, L8, L9, L10, L11, L12, L13, L14, L15, L16, L17, L18, L19, L20	K_{34}, K_{35}, K_{36}, K_{37}, K_{38}, K_{39}, K_{310}, K_{311}, K_{312}, K_{313}, K_{314}, K_{315}, K_{316}, K_{317}, K_{318}, K_{319}, K_{320}
4.	L4	L5, L6, L7, L8, L9, L10, L11, L12, L13, L14, L15, L16, L17, L18, L19, L20	K_{45}, K_{46}, K_{47}, K_{48}, K_{49}, K_{410}, K_{411}, K_{412}, K_{413}, K_{414}, K_{415}, K_{416}, K_{417}, K_{418}, K_{419}, K_{420}
5.	L5	L6, L7, L8, L9, L10, L11, L12, L13, L14, L15, L16, L17, L18, L19, L20	K_{56}, K_{57}, K_{58}, K_{59}, K_{510}, K_{511}, K_{512}, K_{513}, K_{514}, K_{515}, K_{516}, K_{517}, K_{518}, K_{519}, K_{520}
6.	L6	L7, L8, L9, L10, L11, L12, L13, L14, L15, L16, L17, L18, L19, L20	K_{67}, K_{68}, K_{69}, K_{610}, K_{611}, K_{612}, K_{613}, K_{614}, K_{615}, K_{616}, K_{617}, K_{618}, K_{619}, K_{620}
7.	L7	L8, L9, L10, L11, L12, L13, L14, L15, L16, L17, L18, L19, L20	K_{78}, K_{79}, K_{710}, K_{711}, K_{712}, K_{713}, K_{714}, K_{715}, K_{716}, K_{717}, K_{718}, K_{719}, K_{720}
8.	L8	L9, L10, L11, L12, L13, L14, L15, L16, L17, L18, L19, L20	K_{89}, K_{810}, K_{811}, K_{812}, K_{813}, K_{814}, K_{815}, K_{816}, K_{817}, K_{818}, K_{819}, K_{820}
9.	L9	L10, L11, L12, L13, L14, L15, L16, L17, L18, L19, L20	K_{910}, K_{911}, K_{912}, K_{913}, K_{914}, K_{915}, K_{916}, K_{917}, K_{918}, K_{919}, K_{920}
10.	L10	L11, L12, L13, L14, L15, L16, L17, L18, L19, L20	K_{1011}, K_{1012}, K_{1013}, K_{1014}, K_{1015}, K_{1016}, K_{1017}, K_{1018}, K_{1019}, K_{1020}
11.	L11	L12, L13, L14, L15, L16, L17, L18, L19, L20	K_{1112}, K_{1113}, K_{1114}, K_{1115}, K_{1116}, K_{1117}, K_{1118}, K_{1119}, K_{1120}
12.	L12	L13, L14, L15, L16, L17, L18, L19	K_{1213}, K_{1214}, K_{1215}, K_{1216}, K_{1217}, K_{1218}, K_{1219}, K_{1220}

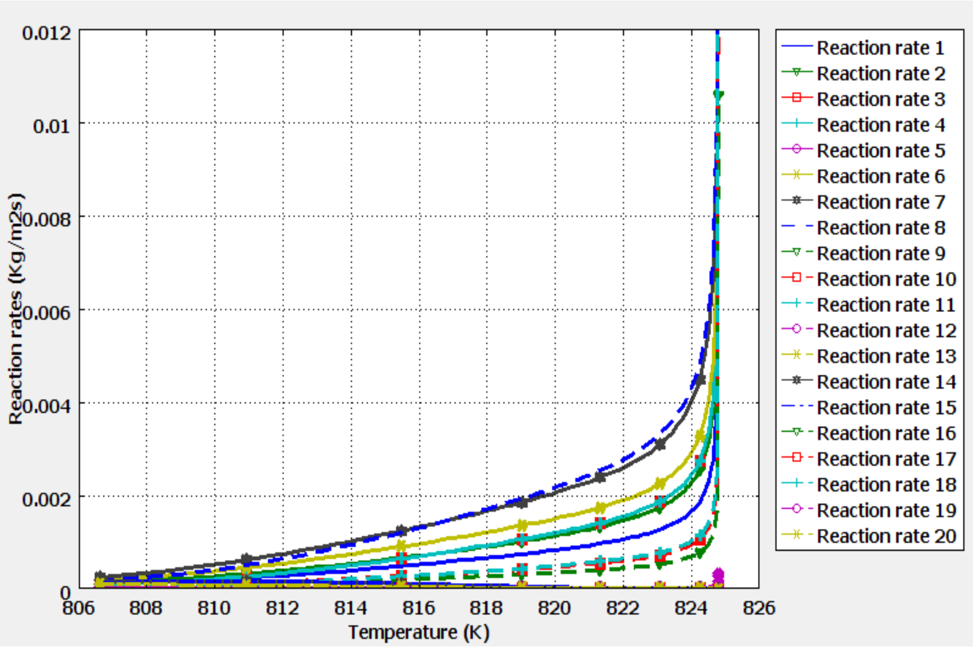

Figure 3: Reaction Rates Versus Temperature

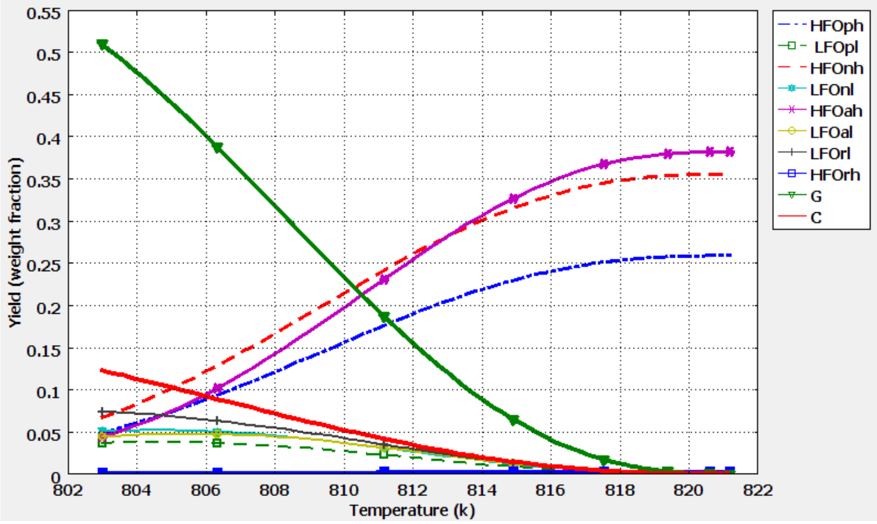

Figure 4: The Effect of Changing inlet Temperature on Yield

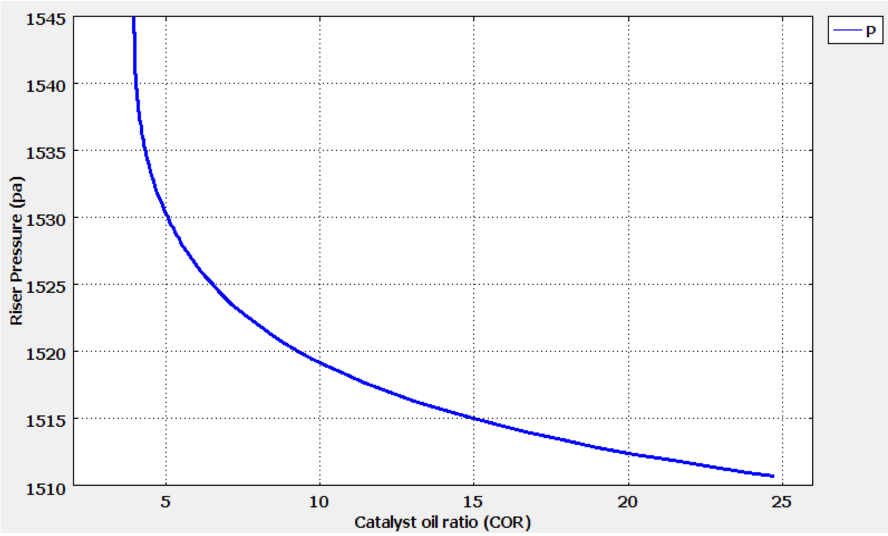

Figure 5: The Riser Pressure Versus Catalyst Oil Ratio (COR)

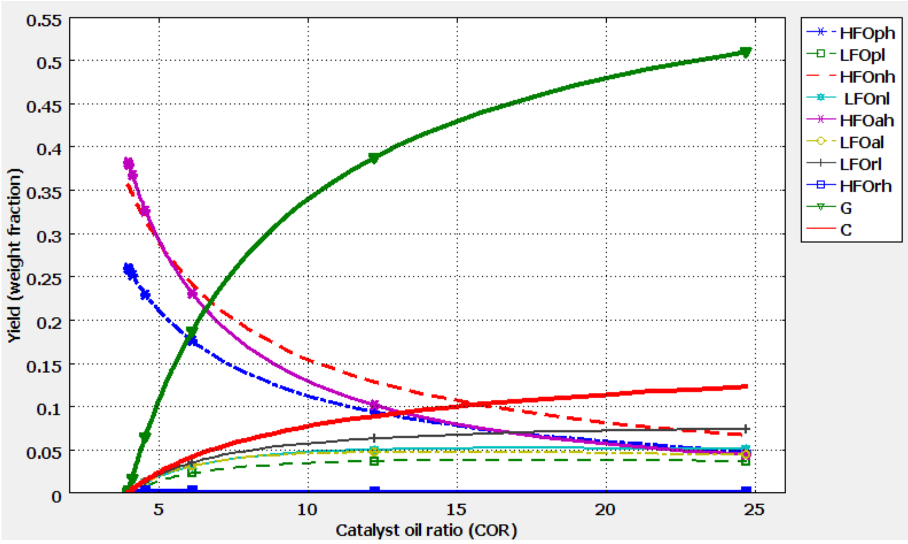

Figure 6: The Effect of Catalyst Oil Ratio (COR) on Yield.

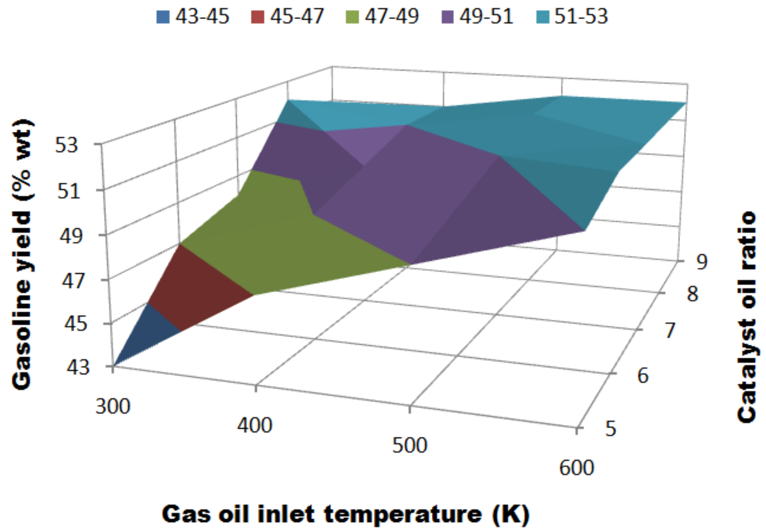

Figure 7: Effect of Gas oil Inlet Temperature on Gasoline Yields

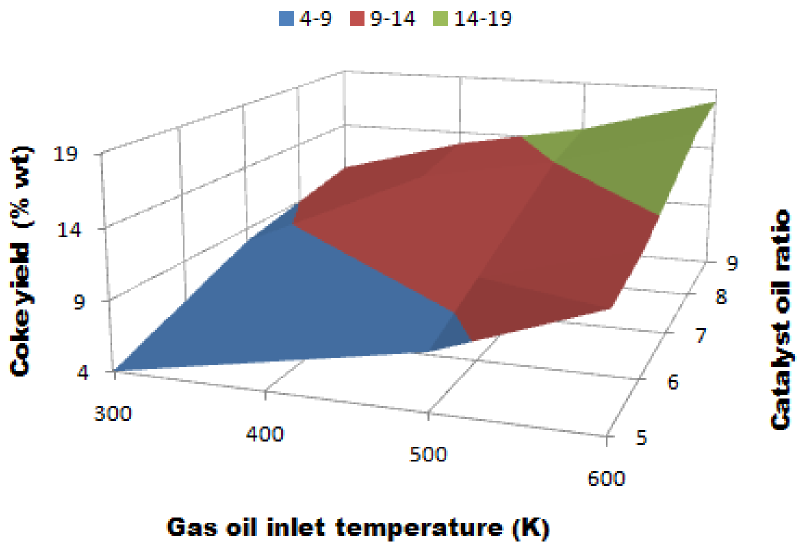

Figure 8: Effect of Gas oil inlet temperature on coke yields

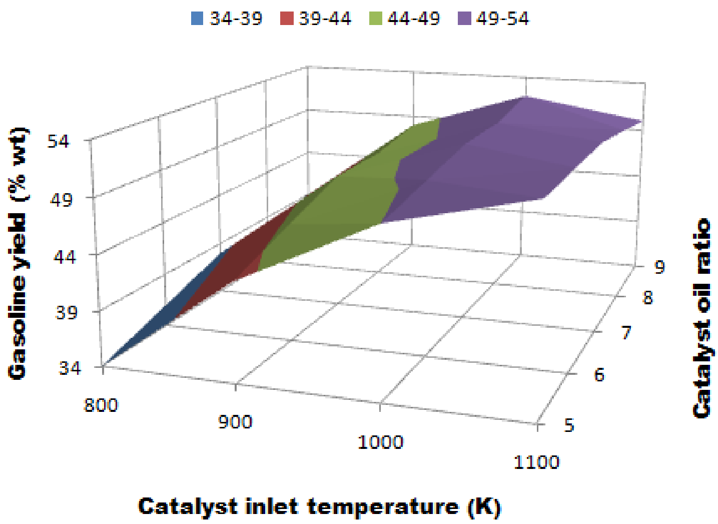

Figure 9: Effect of Catalyst inlet temperature on gasoline yields

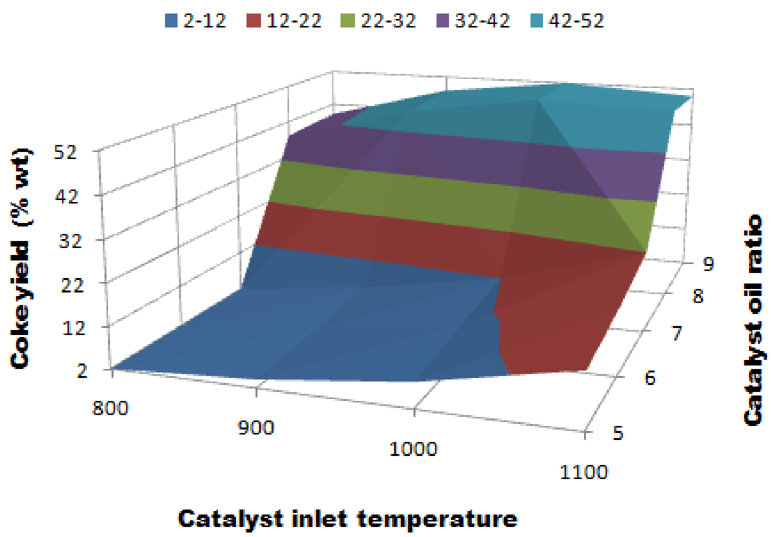

Figure 10: Effect of Catalyst inlet temperature on gasoline yields

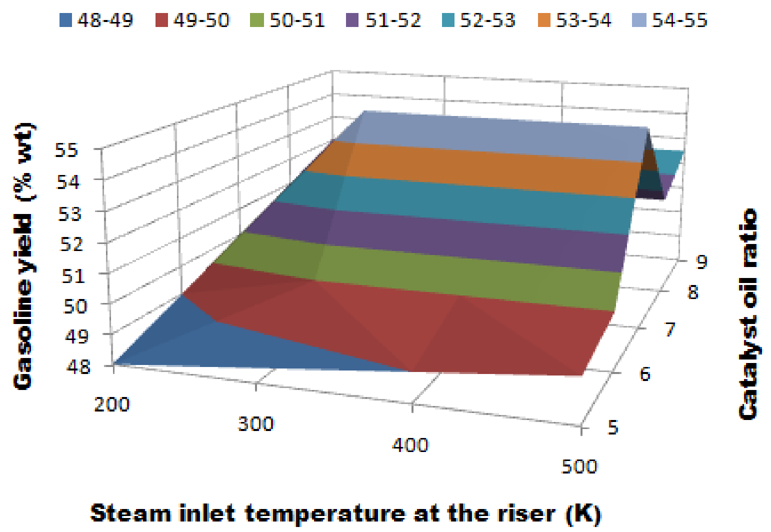

Figure 11: Effect of Steam inlet temperature on gasoline yields

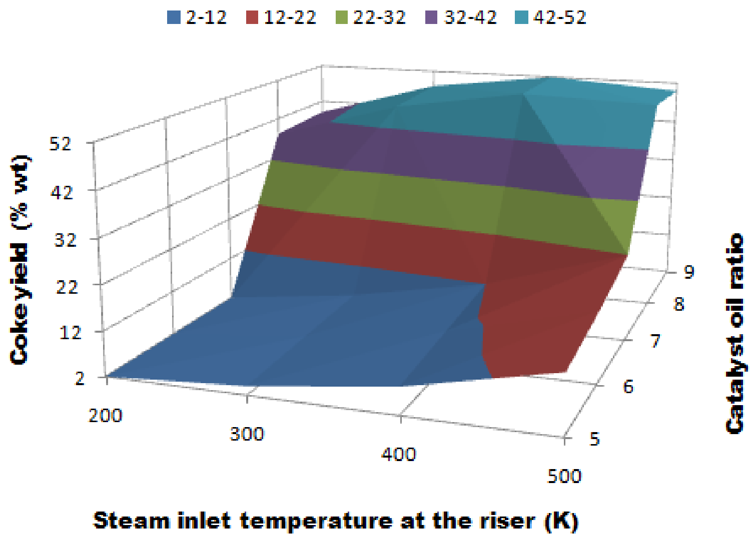

Figure 12: Effect of Steam inlet Temperature on Coke Yields

Table 3: Nomenclature

c:	Concentration, mol/m^3
E:	Activation energy for rate constant, J/mol
g:	Acceleration due to gravity, m/s^2
P:	The pressure of gases, pa
R, r:	Rate expression value
T:	Tempersature, K
t, τ:	Residence time, s
v:	Volume, m^3
z:	Axial distance from the inlet, m
CP_cat (Cp_{cat}):	Specific heat of catalyst, J/kgK
Cp_ds(Cp_{ds}):	Specific heat of steam, J/kgK
CpL_GO ($CP^L go$):	Specific heat of liquid gas oil, J/kgK
CpV_GO ($CP^V go$):	Specific heat of gaseous gas oil, J/kgK
C_i:	Species molar concentrations, mol/m^3
c_{in}:	Inlet concentration, mol/m^3
c_{out}:	Outlet concentration, mol/m^3
K_d:	Deactivation constant
M_go (M_{go}):	Mass flow rate of gas oil, kg/s
M_ds (M_{ds}):	Mass flow rate of steam, kg/s
(M_{cat}):	Mass flow rate of catalyst, kg/s

Table 4: Nomenclature

P_{in}:	Inlet pressure, pa
Rg (R_g):	Gas constant, J/(mol.K)
T_{cat}:	Temperature of the catalyst, K
ε:	Void fraction
T_{go}:	Temperature of gas oil, K
T_{vap}:	Gas oil vapourization temperature, K
v_0:	Outlet velocity, m/s
T_{ds}:	Temperature of the steam, K
V_R, υ, V :	Reactor volume, m^3
W_s:	Additional work term
Q:	Heat due to chemical reaction, J/m^3.s
Q_{ext}:	Heat added to the system, J/m^3.s
μ:	Viscosity, N.S/m^2
ρ:	Density, Kg/m^3
Ψ:	Slip fact
Subscripts	
j:	Refers to lump j that is cracked
i:	Refers to lump i that is formed
p (or s):	Particle/solid
a (or f):	Air/fluid
cat:	Catalyst
c:	Coke content