ANSYS CFD Modelling of Heat Transfer Effects on Gas-Solid Hydrodynamics in Fluid Catalytic Cracking (FCC) Riser Reactors

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Abstract
The application of fluid catalytic cracking (FCC) reactor in the oil and gas refining can never be over emphasised, because it offers critical advantages in the combustion of solid fuels, having higher fuel flexibility and the challenges to controlling the combustion temperature is very effective. Therefore, the fluidisation process allows for near isothermal operation which is a resound practice that is good to FCC unit systems. FCC units are used in modern refineries all over the world to convert high molecular weight gas oils (heavy gasoil) or residuum stocks from the crude distillation unit (CDU) into lighter hydrocarbon products in a riser reactor within a few second.

In this paper, CFD was used to validate the experimental data from the open literature. The predicted heat transfer coefficients in the riser for case 3.1 was in the ranges of 147 to 180 W/m^{2}K, while for case 3.2 was between 122 to 144 W/m^{2}K. In a similar trend, the prediction of heat transfer coefficients for case 3.1 in a replica industrial FCC riser was 271 to 332 W/m^{2}K and for case 3.2 was found to be between 262 to 230 W/m^{2}K.

Keywords: *ANSYS CFD, adiabatic, G-S Hydrodynamics, and isothermal*

1.0 INTRODUCTION

The FCC units have been considered the most successful applications of circulating fluidised beds (CFBs) all over the world in recent decades. Records show that about 46% of the global gasoline productions come either directly from FCC units or indirectly from combination with downstream units, such as alkylation etc., Idris and Burn (2008), and Idris (2010).

Heat transfer model can be used to predict the temperature profiles throughout the FCC riser reactors, where the cracking fluids (heavy gas oil) gain heat from the aerated catalyst. Heat transfers by conduction and convection processes are prominent in fluidisation of this kind. Heat transfer between gas and solid phase particles tend to be efficient due to the large volumetric concentration of interface surface. In the present knowledge, the heat problems involving multi-dimensional conductive and convective heat transfer can be resolved using application of CFD codes. In flow phenomena like this case, the resulting convective heat transfer problem is solved by tracking the enthalpy equation alongside the Navier-Stokes equations and the continuity equation. The boundary conditions for the enthalpy equation take care of heat transfer into and out of the computational domain across its boundaries. The third mechanism of heat transfer process is referred to as thermal radiation is caused by energy emission in the form of electromagnetic waves, and is assumed insignificant in FCC riser system.

1.1 Problem Statement

The ozone layer depletion has resulted due to increase in human activities globally, which caused global warming. This resulted in the emission of certain hydrocarbons (HCs) and their sister pollutants from the petroleum industry possess serious threat to the survival of life on the planet earth. Therefore, when there is less quality mixing regime of flowing fluids with inefficient heat transfer in the FCC riser system for optimum reactivity, these pose threats as a result of incomplete combustion and in turn ozone depletions.

1.2 Significance of the Study

An excellent performance of an FCC riser and regeneration systems are influenced by the quality of mixing regime and the efficiency of heat transfer in the operation units. Good mixing rate and heat transfer contributes to effective distribution of reactants, whereas sufficient mixing with poor heat distribution can lead to incomplete combustions, these pose a serious threat. Therefore, adequate understanding of the heat transfer with the dynamic behaviours is very important to ensure a high combustion efficiency and quality control of emissions.

2.0 BACKGROUND ON HEAT TRANSFER

The studies on the effect of heat transfer in FCC riser reactor systems (*circulating fast fluidisation*), similar to a commercial FCC unit, was to assist in understanding the mechanism of heat (energy) transfer in the riser bed. Initially, effort was to establish the adiabatic effect on FCC reactor, in order to study the heat transfer effect when there no heat gains or loss to the system. In addition, isothermal conditions (non-adiabatic) of heat transfer were also studied. Then, validations of the CFD predictions were carried out using experimental data reported by Zhu and Ying (2001) and subsequently study the heat transfer in a replica FCC riser reactor system.

With improving understanding on the study of the hydrodynamics of gas-solid in CFB/FCC risers, many researchers are succeeding in the study of heat transfer effect. From the previous studies Grace (1986), (Wu et al., 1989), and Ma and Zhu (2000), has shown that the heat transfer behaviour is controlled by the hydrodynamics of the flow in risers. They have equally found that different radial and axial gas and solid flow structures in CFBs have caused different heat transfer behaviours Basu and Nag (1996), (Wu et al., 1989), and (Wu et al., 1987). Based on these, the proceeding contribution to the study of heat transfer in FCC riser reactor system was achieved.

In a commercial unit, changes in the independent process variables (which are cracking temperature, catalyst-oil ratio, space velocity, catalyst type and activity, and recycle ratio) that affect the heat balance will result in changes in the conversion of heavy gas oil and coke yield, and on the overall bring the unit back into heat (energy) balance. The heat input in FCC unit includes the heat from feed (heavy gas oil), riser reactor/regenerator and heat from combustion air; these are the heat transfer between the two-phase medium and submerged surfaces. While the heat outflows, are heats leaving with riser reactor products stream, regenerator flue gas, heat loss from reactor/regenerator and the endothermic heat of cracking reaction Idris (2010).

3.0 SIMULATION EQUATIONS AND METHODOLOGY

3.1 Modelling Equations

In modelling the heat transfer coefficient h_{sg} in the FCC riser reactor, the ANSYS CFD (CFX and Fluent) were used. The computational modelling using the enthalpy equation for both the gas and solid phase are represented as in Equations (1) and (2).

$$\underbrace{\frac{\partial}{\partial t}\left(\varepsilon_g \rho_g h_g\right)}_{\text{Transient}} + \underbrace{\nabla.\left(\varepsilon_g \rho_g \vec{v}_g^{\,2} h_g\right)}_{\text{Convective}} = \underbrace{-\varepsilon_g \frac{\partial p_g}{\partial t}}_{\text{Pressure}} + \underbrace{\bar{\bar{\tau}}_g : \nabla \vec{v}_g}_{\text{Stress}} - \underbrace{\nabla \cdot \vec{q}_g}_{\text{Heat flux}} + \underbrace{S_g}_{\text{Sources}} + \underbrace{\sum_{p=1}^{n}}_{\text{Heat}} \underbrace{\left(\vec{Q}_{pg} \pm \Delta \dot{m}_{pg} h_{sg}\right)}_{\text{Interphase exchange enthalpy change}} \tag{1}$$

$$\underbrace{\frac{\partial}{\partial t}\left(\varepsilon_s \rho_s h_s\right)}_{\text{Transient}} + \underbrace{\nabla.\left(\varepsilon_s \rho_s \vec{v}_s^{\,2} h_s\right)}_{\text{Convective}} = \underbrace{-\varepsilon_s \frac{\partial p_s}{\partial t}}_{\text{Pressure}} + \underbrace{\bar{\bar{\tau}}_s : \nabla \vec{v}_s}_{\text{Stress}} - \underbrace{\nabla \cdot \vec{q}_s}_{\text{Heat flux}} + \underbrace{S_s}_{\text{Sources}} + \underbrace{\sum_{p=1}^{n}}_{\text{Heat}} \underbrace{\left(\vec{Q}_{ps} \pm \Delta \dot{m}_{ps} h_{sg}\right)}_{\text{Interphase exchange enthalpy change}} \tag{2}$$

enthalpy h_s, are obtained by solving the Equations (1) and (2), where

$$h_{sg} = f\left(P_r, R_{ep}\right) \tag{3}$$

That is, is a function of Prandtl number and Reynolds number. Applying the study of Zhang et al. (1998), the local heat transfer coefficient is given as

$$h_{sg} = \frac{IV}{A\left(T_{sf} - T_b\right)} \tag{4}$$

Where power (watts) = IV = 50 watts and heat transfer area, A = 0.007853 m^2. Therefore;

$$h_{sg} = \frac{6366.2}{\left(T_{sf} - T_b\right)} \int_{T_{ref}}^{T} c_{p.j}\, dT \tag{5}$$

The corresponding values of T_g and T_s were determined from each h_{sg} calculated using the CFD approaches.

3.2 CFD Modelling Methodology for Heat Transfer in FCC Riser

The modelling strategies adopted in simulating gas-solid temperature distribution in the riser reactor system are represented in Figure 1. Initially, the simulation data from the completed for ambient condition of gas-solid flow using transport modelling in Fluent solver, where the introduction of temperature values for the gas and solid flow into the riser were carried out. The first stage of this simulation reflects the 'Two-phase gas/solid flow simulation at ambient condition of temperature T = 298 K modelled using algebraic/transport equation in granular temperature Idris (2010). In an isothermal situation, temperatures along the axial flow are constant throughout the riser length. The second stage of the simulation involve the use of 'Two-phase gas/solid flow and heat transfer simulation in adiabatic condition of flow'; while the fourth stage involve simulation of heat transfer in industrial gas/solid flow. The differences between the simulation strategies mentioned in the first and second stage is that, in the first stage; the temperature along the axial flow remains constant (ambient condition). While in the second stage (adiabatic simulation), the wall boundary condition allows no heat transfer across the wall of the riser, $q_w = 0$, but on the overall heat transfer ΔQ = 0 and ΔT ≠ 0. In addition, the heat flux in the wall boundary is specified as $q_w = q_{spec}$. Since the heat transfer by radiation is negligible, the wall is assumed to be perfectly absorbing and emitting surface, that is, emissivity = 1. As a result, no further boundary conditions (e.g. source term) need to be defined. The wall is non-catalytic, that is, it does not take part in the chemical reaction.

The simulation carried out in fourth stage is similar to that of third stage, but the difference is on boundary conditions of temperature used in the input domain of the solver. In this stage, higher temperature ranges between 500^{0}C and 800^{0}C were used.

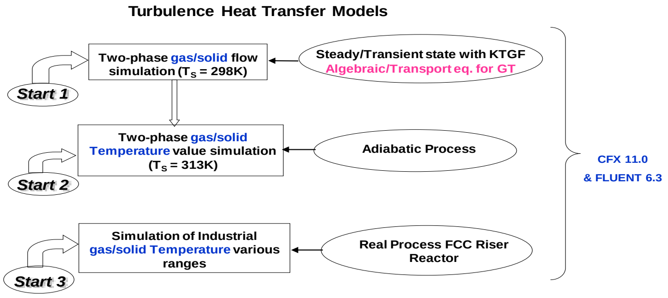


Figure 1 CFD Modelling Methodology for Heat Transfer in FCC Riser Reactor

3.3 Adiabatic Conditions Heat Transfer Effect between Gas and Solid in the FCC Riser Case 1.2 (U_g = 5.5 m/s at G_s = 50 kg/m^{2}s)

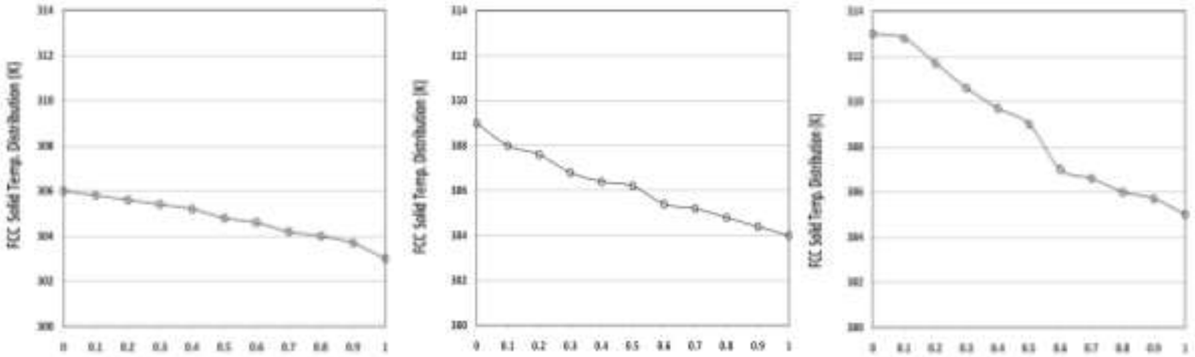
Initial simulation was carried out under adiabatic condition in the FCC riser. An adiabatic process or an isocaloric process is a thermodynamic process in which no heat is transferred to or from the working fluid in a system. But within the system of the riser, which comprises of the two-phase flow of gas-solid, there is transfer of heat between them. Adiabatic changes in temperature occur due to changes in pressure of a gas while not adding or subtracting any heat. The reason was to study the effect of heat transfer from the catalyst particles to the working fluid (e.g. gas or heavy gas oil in FCC process). In the modelling setup, were carried out at a condition slightly above that of standard temperature and pressure (STP) conditions, that is at T = 313 K. Table 1 represents the percentage error in prediction for Case 1.2 setup (U_g = 5.5 m/s at G_s = 50 kg/m^{2}s) based on transient calculations.

Table 1 Comparison of the input parameters with predicted outlet values for unsteady calculations

Parameters	Gas (kg/s)	FCC Solid (kg/s)	Energy-FCC Particles
Calculated (input inlet)	5.0372E-02	3.8628E-01	2.3436E+05
Simulation (outlet)	5.0558E-02	3.8219E-01	2.3186E+05
Imbalance (difference)	5.1368E-08	4.0783E-04	1.4941E-01

Table 1, depicts an adiabatic situation for heat transfer in the FCC riser reactor. Although the heat transfer is of significant value and has shown that, there is transfer of heat in the riser reactor. However, in comparing with an isothermal situation, where there is no change in temperature along the riser length, that is, $\Delta T = 0$. In the case of adiabatic condition, the net heat transfers in the riser reactor although is negligible but has a significant value. That is, the energy transfer (in form of heat) was predicted to be 6.440E-07, between the inflow and outflow boundary. Therefore, we can conclude that the predictions from these calculations, is approximately in good agreement within the capability limit of the solver code.

Figure 2 depicts the CFD predictions of both the adiabatic conditions at various planes (z = 0.95 m, z = 10.0 m and z = 14.08 m) along the FCC riser reactor. At near the inlet of the riser, that is, z = 0.95 m, a temperature variation of 303K – 306K were predicted. As we proceed further along the riser length, that is, at z = 10.0 m, a temperature variation along the radial position for the adiabatic situation was predicted between 304K to 309K. And finally at z = 14.08 m, the temperature profile was in the range of 305K to 313K. Commercial FCC riser-regeneration systems are operated under adiabatic condition as reported by Shan et al., (2001). This is the main reason why we discussed the issue of adiabatic condition of FCC riser unit operations.



Radial Position, r/R [-] at z = 0.95 m **Radial Position, r/R [-] at z = 10.0 m** **Radial Position, r/R [-] at z = 14.08 m**

Figure 2: Temperature profile in FCC particles adiabatic-isothermal process

3.4 Modelling Predictions of Pressure Drop, ΔP, in Isothermal and Adiabatic Conditions in FCC Riser Reactors Case 1.2 (U_g = 5.5 m/s at G_s = 50 kg/m^{2}s)

Details of the time-step iterations for the heat transfer simulation (Fluent) which it solution was established to be grid independent can be found from Idris (2010). In order to represent a real FCC riser operation well concerning heat transfer influence with the reacting medium, the FCC catalyst and the wall of the riser, we have to go beyond looking at non-isothermal (variable heat transfer) situation as experience in a real FCC riser reactor as shown in Figure 3. The ANSYS CFD predictions show a comparison of the pressure relations with heat transfer in isothermal and non-isothermal situations. It is been observe that the pressure drop in non-isothermal case is lower than that of isothermal.

In a real life FCC riser, the difference in pressure ΔP, decrease is non-linear along the riser length when we consider the non-linear nature of the FCC solids hold-up, the geometry and the gas velocity changed with the height of the riser. In relation to our understanding in gas-solid hydrodynamics, we can conclude that with increase in height of the riser column, the axial heat transfer decreases significantly in the exit, especially in the middle section of the riser column. The CFD simulation time is approximately 79.20 seconds for the heat transfer study. Table 2 represent the input parameters with predicted outlet values in transient-KTGF-transport modelling approach.

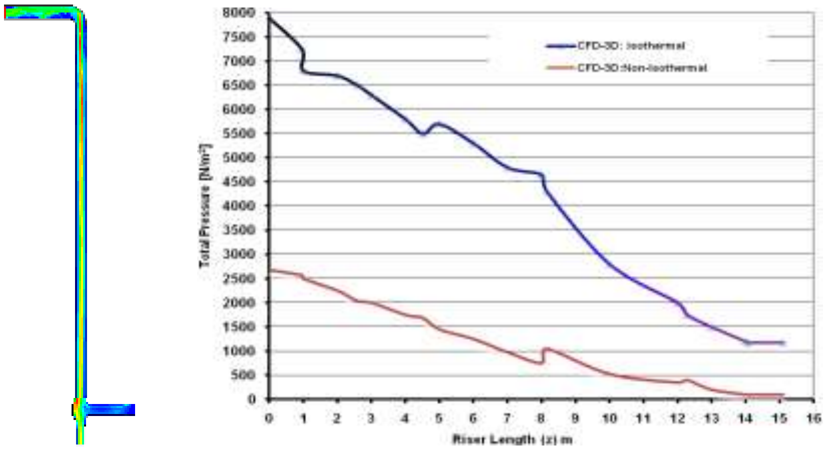
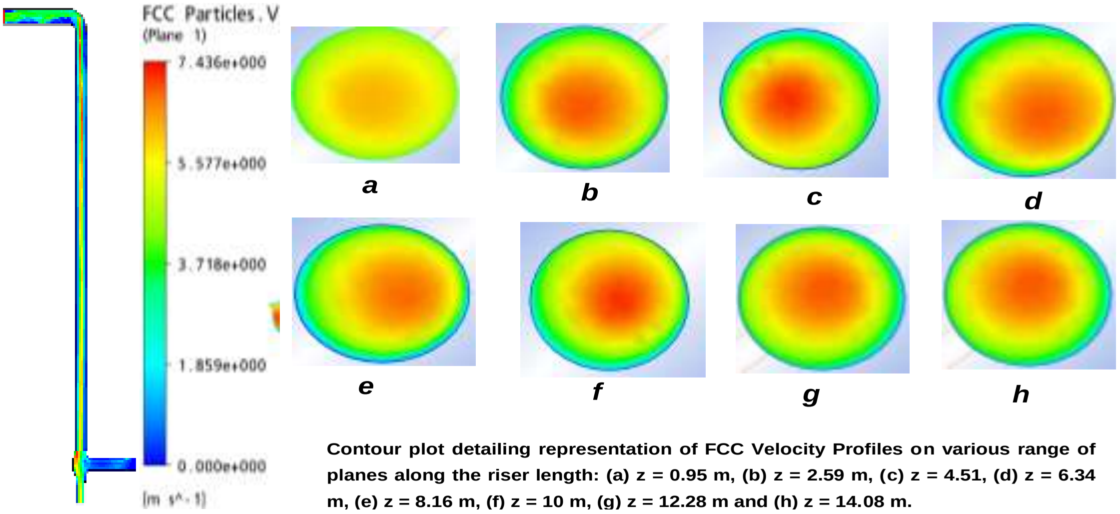


Figure 3: Comparison of Isothermal and Non-Isothermal Heat Transfer Process

Table 2 Comparison of the input parameters with predicted outlet values for unsteady calculations

Parameters	Gas (kg/s)	FCC Solid (kg/s)	Energy-FCC Particles
Calculated (input inlet)	5.0555E-02	3.8628E-01	2.3436E+05
Simulation (outlet)	5.0551E-02	3.9134E-01	2.5597E+05
Imbalance (difference)	4.8662E-08	1.0581E-05	1.6842E-04
Fractional agreement	$\frac{4.8662E-08}{5.0551E-02}=9.6263E-05$	$\frac{1.0581E-05}{3.9134E-01}=0.00027$	$\frac{1.6842E-04}{2.5597E+05}=6.5796E-10$

Figure 4 represents the transient state simulation results with heat transfer effect on a loading of case 1.2: *Ug* = 5.5 m/s (at T_g = 293 – 298 K) and *Gs* = 50 kg/m^{2}s (at T_s = 303 – 313 K). At various stage of the FCC riser, various stages of gas-solid hydrodynamic affect especially the FCC solid holdup, prone to be the main factor militating the riser heat transfer. From Figure 5, the resultant effect of this heat transfer show that the pressure and temperature profile in the isothermal heat transfer riser and non-isothermal (temperature varies) case show greater comparison. Figure 5 also depict the contour plot of FCC velocity profile with heat transfer effect. It was seen that the maximum velocity and mass flux of the solids was at the centre of the riser pipe and lower toward the walls. This is in accordance with this figure and the previous hydrodynamic predictions studied from Idris (2010), which the gas and solid (due to drag) velocity increases with increase in the height of the FCC riser.



Contour plot detailing representation of FCC Velocity Profiles on various range of planes along the riser length: (a) z = 0.95 m, (b) z = 2.59 m, (c) z = 4.51, (d) z = 6.34 m, (e) z = 8.16 m, (f) z = 10 m, (g) z = 12.28 m and (h) z = 14.08 m.

Figure 4: Transient Calculation of gas-FCC solid Flow with Heat Transfer Effect: Case 1.2: $U_g = 5.5$ m/s (at T_g = 293 – 298 K) *at* $Gs = 50$ kg/m^{2}s (at T_g = 303 – 313 K) *Huang et al (2007)*

4.0 Experimental Case Study 3 (Zhang et al., 1998): Similar to (Huang et al., 2007)

The same pilot plant used by (Huang et al., 2007) was used by (Zhang et al., 1998) to conduct the heat transfer experiments as previously shown at Idris (2010). The solid particles used in this study were the fluid catalytic cracking catalyst, and have a mean particle diameter of 67 µm and a density of 1500 kg/m^3 in a 15.1 m riser with 0.1 m inner diameter. The superficial gas velocity employed, U_g, was ranging from 3.5 to 10 m/s and the solid circulation rate, G_s, ranging from 50 to 200 kg/m^{2}s (Huang et al., 2007) and (Zhang et al., 1998).

The detail of this experimental study can be referred to (Zhang et al., 1998). With the assumption of the minimal heat losses through the Teflon ends, the following equation was used to calculate the local heat transfer coefficient.

$$h = \frac{IV}{A(T_s - T_b)} \tag{6}$$

Where I is the electric current [mA] through the probe, V is the voltage applied on the probe [V], A is the heat transfer surface area [m^2], T_s is the probe surface temperature (30^0C< T_s <40^0C) and T_b is the average bed temperature (20^0C<T_b<25^0C), measured by the thermocouple inserted inside the bed Ma and Zhu (2000). The effort in this study is to use CFD to validate the reported experimental data of (Zhang et al., 1998), so that we can establish the solver limitations in predicting heat transfer characteristics. These experimental cases are of low density and high gas velocity (fast fluidisation) as represented in Table 3 below.

Table 3 Heat transfer of operating conditions in riser (Zhang et al., 1998)

Operating conditions	Experimental cases			
	Case 3.1	**Case 3.2**	**Case 3.3**	**Case 3.4**
G_s (kg/m^{2}s)	98.0	180.0	180.0	180.0
U_g (m/S)	7.6	7.8	7.6	8.0

The gas/solid temperature modelling steps for each case (cases 3.1 – 3.4) in this study was carried out in the same way as previously described in chapter 5 of Idris (2010). The focus in this study is the CFD heat transfer predictions against the temperature data. More so, studies on the effect of the axial and radial voidage along the riser length with respect to the heat transfer coefficient when heat is added to the system. The details of the heat transfer boundary condition are shown in Figure 5.

4.1 Computational Modelling Procedure

In the CFD modelling, for an incompressible flow the *h* for gas-solid was obtained as stated in Equation (7) by Zhang et al. (1998).

$$h = \sum_j Y_j h_j + \frac{p}{\rho} \tag{7}$$

The same boundary conditions used by Zhang et al. (1998) was also applied in the modelling which is between T_s = 303 and 313K with corresponding values for T_b = 293 and 298K for each case. More so, higher temperature ranges between 500K and 800K was also used to test the predictions in the CFD modelling heat transfer.

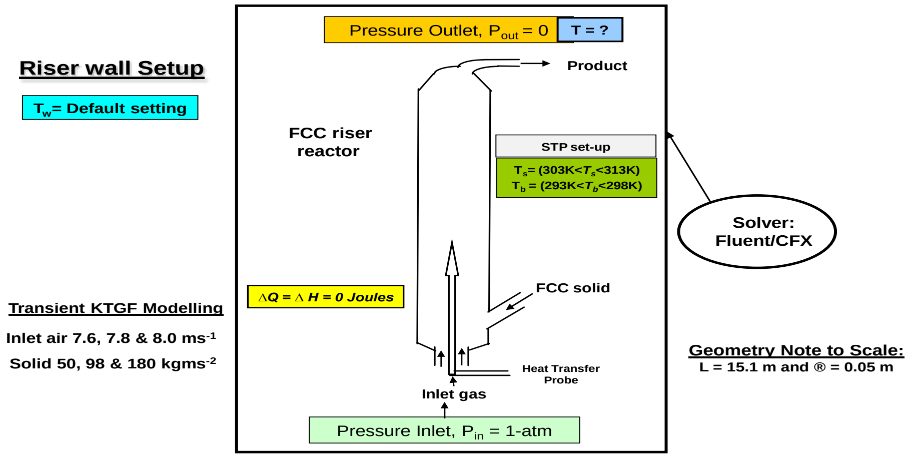


Figure 5: Heat transfer boundary conditions Zhu and Ying (2001)

Initial conditions:

Initially both gas and FCC particle temperatures were set at 298K (cold flow system). The velocities, turbulent kinetic energy, and dissipation energy are specified as:
At z = 0: T_g, T_s, and P are defined based on the inlet conditions of the riser.

Boundary conditions:

For air (gas) temperature:

At inlet:

- T_g = 303 – 313 K
- T_w = Default setting (FCC riser wall temperature = 293 and 298 K

Free slip:

- $U_{n,wall} = 0$
- $\tau_w = 0$

Adiabatic:

- $q_w = 0 = q_{rad} + q_{cond}$

Wall:

- $q_w = h_c(T_w - T_{nw}) = q_{rad} + q_{cond}$

At outlet:

- $P_{sat,out} = P_{spec}$

For solid particles temperature:

At inlet:

- $T_s = 303 - 313$ K

At outlet:

- No/Free slip condition $\frac{\partial \overrightarrow{v_s}}{\partial z} = 0$

Where T_w is the near-wall temperature and h_c involves the use of turbulent wall functions

4.2 Validation of Heat Transfer Predictions against Temperature Data

Figure 6 represents the temperature profiles along the radial axis of the riser reactor at different locations (z= 2.59 m, z= 10.0 m and z = 14.08 m). It is observed that the temperature decreases towards the riser wall in both cases (a and b). More so, there is slight difference in profiles only at the centre axes of the riser at various locations. The predictions were carried out for the 360^0 of the FCC riser reactor.

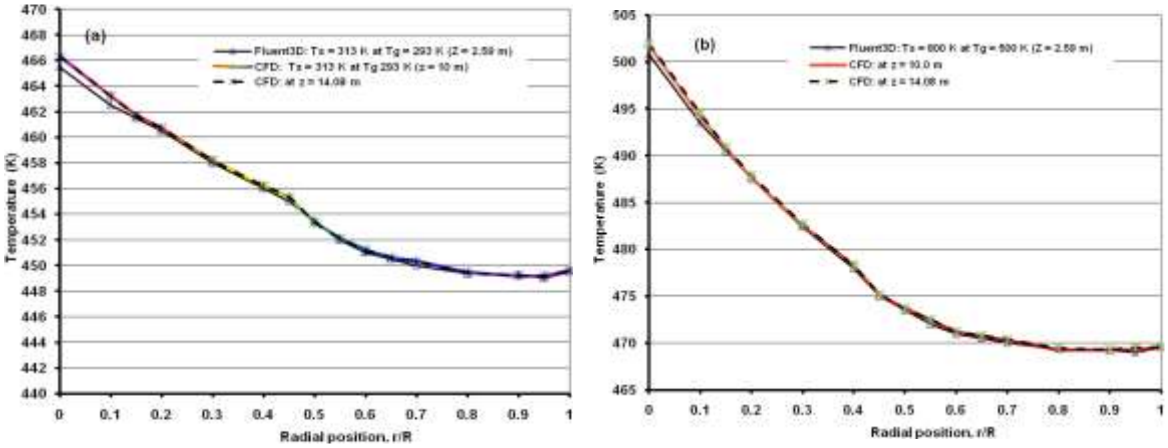


Figure 6: Temperature profile along the radial axial of the FCC Riser Reactor. (a): $T_s = 313$ K and $T_g = 293$ K, and (b): $T_s = 313$ K and $T_g = 293$ K at various location along the riser length.

Furthermore, to prove these predictions, we proceed to validate the temperature with the heat transfer coefficient along the riser length as shown in Figure 7. The temperature difference, ΔT, is inversely proportional to the heat transfer coefficient, h_{gs}. In addition, the effect of this variations is more noticeable at a low temperature ranges when compared the two cases (a and b).

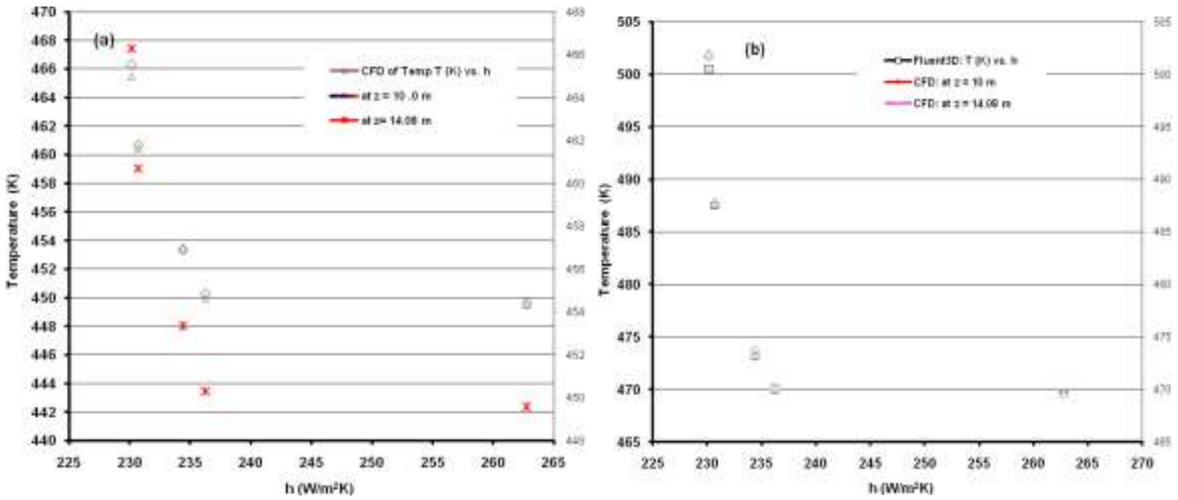


Figure 7: Temperature profile vs. heat transfer coefficient along the FCC Riser Reactor. (a): T_s = 313 K and T_g = 293 K, and (b): T_s = 313 K and T_g = 293 K at various location along the riser length.

4.3 Axial Distribution of Heat Transfer Coefficient in FCC Riser

Figure 8 represents the axial distribution of heat transfer coefficient in the FCC riser reactor. The trends of the prediction were in agreement with the data reported by Zhu and Ying (2001). It is shown that the heat transfer coefficient always decreases with increasing distance along the riser length, because of the increase in solids concentration that is associated with flow development. Figure 7(a) is CFD prediction comparison with the experimental data for case 3.1, while 7(b) represents that of case 3.2. The heat transfer coefficient *h*, differs in each case along the riser axial direction, because the solid concentration differs in both cases. It is also been observed as reported by Zhu and Ying (2001), that for a situation where the same concentration are used, the heat transfer coefficients remain almost constant along the riser axial direction. In comparison with the reported data, the predicted heat transfer coefficients are in the range of 147 to 180 W/m^{2}K (against 144 to 175 W/m^{2}K reported) for case 3.1, while 122 to 144 W/m^{2}K (against 127 to 137.5 W/m^{2}K reported) for case 3.2.

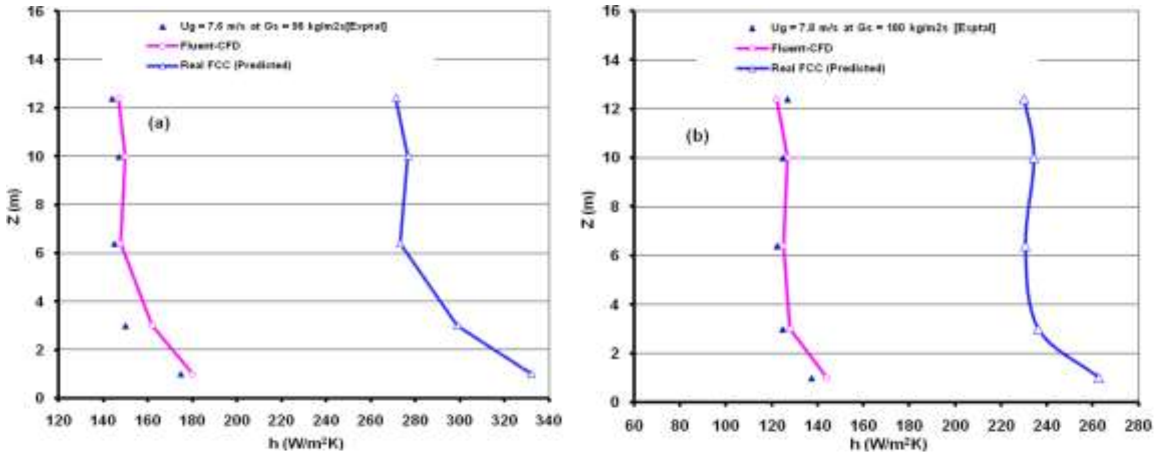


Figure 8: Axial distribution of heat transfer coefficient in the FCC riser: (a) case 3.1 and (b) case 3.2 Zhu and Ying (2001)

For the axial profiles of heat transfer coefficient, it has been reported from the study of Zhu and Ying (2001) that the operating conditions, such as the gas velocity and solids circulation rate, usually affect the values of the heat transfer coefficient, but actually have insignificant influence on the trend of the gas-solid flow development along the riser height Idris (2010).

4.4 Radial Distribution of Heat Transfer Coefficient in FCC Riser

Figure 9 represents the profiles of radial distribution of heat transfer coefficient in the FCC riser reactor system. In order to validate the prediction of the model, case 3.3 was used. In this Figure, the radial profiles show that, the heat transfer is flattened within the centre region and trending effect toward the riser wall. Correspondingly, the effect of heat transfer coefficient increases with increase in height z (m) along the riser reactor.

In this study, it was observed that, at the bottom of the riser region, the radial profiles of the heat transfer coefficient are flat in the centre region, and increase stiffly approaching the riser wall. With increase in the height of the riser reactor, the profile become flattened, that is, they have a significant increase near the riser wall. In other words, the values of heat transfer coefficients is becoming approximately constant along the radial direction except near the bottom (1.6 m from the distributor), the heat transfer coefficient is hear near the wall as a result of the obvious reason of the distributor on its solids distribution. These observations were also in agreement with the experimental work of Ma and Zhu (2000), and Zhu and Ying (2001).

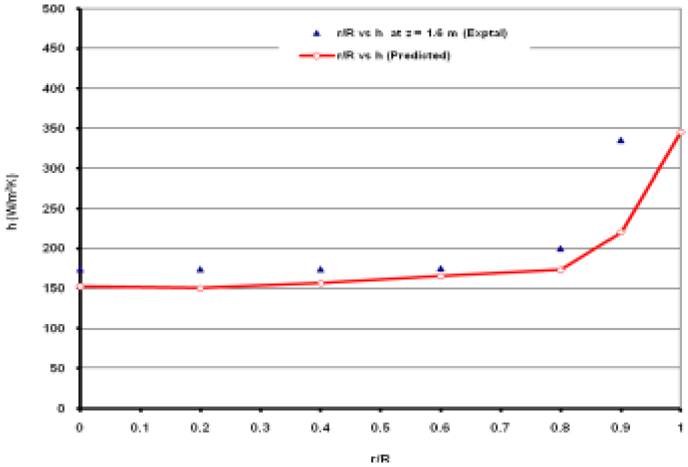


Figure 9: Radial distribution of heat transfer coefficient in the FCC riser: Case 3.3 Zhu and Ying (2001)

Furthermore, the heat transfer coefficient is non-uniform along the radial direction because, some solids tend to form clusters and sweep downwards along the riser wall and in the centre region where the solid particles are carried upwards by a high velocity of gas flow steam. Previous research Zhu and Ying (2001) has shown that the radial heat transfer in a downer reactor were more uniform than in riser reactor, especially in the developed section of the bed. The validation of the predictions from the CFD was in good agreement with the reported data from (Zhang et al., 1998).

4.5 The Relationship Between the Heat Transfer and FCC Solid Holdup

Theoretically, the thermal conductivity of FCC solids particle is much greater than gas. Therefore, in solid suspension (or solid concentration), it is the determining factor that influencing the heat transfers in CFB/FCC. Based on this argument, the heat transfer coefficient is mostly depending on the solids concentration.

Figure 10 represents the radial distribution profiles of the solids holdup and the heat transfer coefficients at axial locations (a) z = 1.1 m and (b) z = 12 m in the FCC riser reactor (Zhang et al., 1998). With respect to our understanding of hydrodynamics, the heat transfer coefficients have similar trends as the radial profiles of the FCC solids holdup (or volume fraction). It was observed that at the centre region of the riser, the heat transfer coefficient and the solids holdup are similar and are flat in profiles. At riser axial length z = 1.1 m, the heat transfer coefficient is flattered also at the centre region, and progressively higher toward the riser. However, as we proceed higher in the riser, that is, at z = 12 m the flattered effect is more pronounced. This trend is also in agreement with the prediction for case 3.3 as already shown in Figure 6.

Furthermore, these prove that with increase in solids holdup in a riser system, there is a corresponding increase in the heat transfer coefficients. Therefore, the prominent factor responsible for the effect of heat transfer coefficients is the solid concentration. The predictions agreed with the experimental data reported.

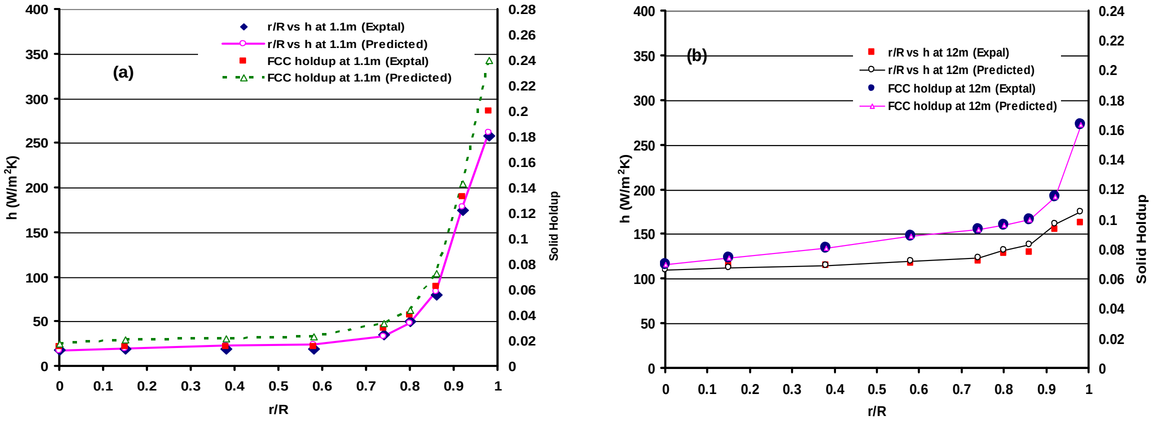


Figure 10: Relationship between the heat transfer coefficients and the FCC solid holdup at (a) z = 1.1 m and (b) z = 12 m for case 3.4 (Zhang et al., 1998).

4.6 The Influence of Operating Conditions on the Heat Transfer

Another important factor that influences the heat transfer coefficients in a riser system is the gas velocity and the solids circulation rate. Figure 6.14 represents the predicted gas velocity effect on the heat transfer in the riser at (a) z = 0.97 m and (b) z = 10 m for case 3.1. In addition, the trend of the experimental data when compared with the predictions at both locations, it is found that the predicted trends give a better agreement on the heat transfer coefficient along the riser axes.

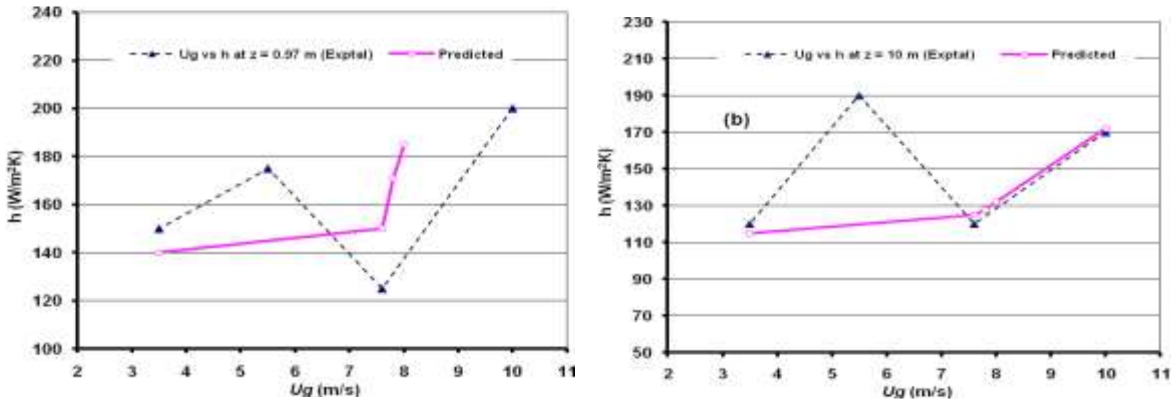


Figure 11: Gas velocity effect on the heat transfer in the riser (a) z = 0.97 m and (b) z = 10 m for case 3.1 (Zhang et al., 1998)

These figures equally proves that at a low flow velocity ranging 3.5 m/s to 7.6 m/s, due to decrease in FCC solid concentration, the heat transfer coefficient increases with decreasing gas velocity and vice versa. This trend has been reported in previous studies Basu and Nag (1987) and (Wu et al., 1987). At higher flow velocity, 7.6 m/s to 8.0 m/s, there were noticeable increase in heat transfer coefficients with increase in the gas velocity. Of course, this is due to the dilution of solid concentration at higher gas velocity. In comparing the predicted results with the experimental data, the trends are similar although there are some noticeable deviations. On the overall, the predictions are in agreement with the work of Zhu and Ying (2001).

From Figure 12, it is observed that, the heat transfer coefficient usually increases with the solids circulation rate under similar conditions of operations. The most important phenomena for the heat transfer in riser reactor are the particle convection effect, and this is controlled by the solid concentration near the heat transfer surfaces. Therefore, heat transfer coefficients in risers usually enhanced at higher solids circulation rates. A comparison of local gas velocity at 6.5 m/s at two different axial heights for case 3.1 at (z = 1.1 m and z = 13 m) were reported in Figure 9.

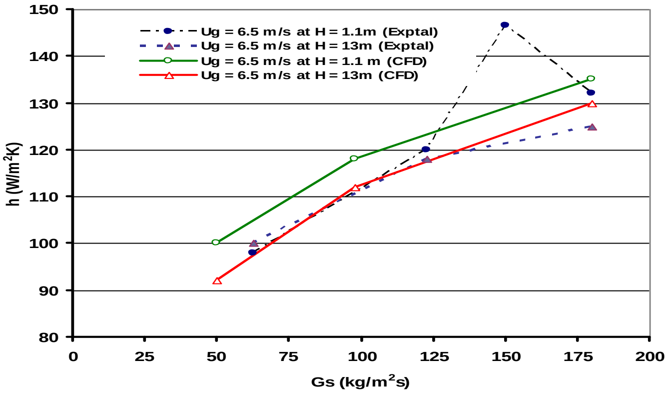


Figure 12: Solids circulation rate on the heat transfer in the riser case 3.1 (Zhang et al., 1998).

4.7 Modelling Application of Heat Transfer in Industrial FCC Operations

Typically, commercial process of FCC unit operates under adiabatic (non-isothermal) condition. CFD predictions were used to integrate the results from a piloted scale to industrial scale. Therefore, the operating condition of a typical industrial operation of FCC riser reactor system, have T_s (or T_w) of 600K and T_b of 1100 K. From Figure 13, it is observed that the axial distribution of heat transfer coefficients in a replica industrial FCC riser reactor have a similar trend in profiles with the reported data. Consequently, the heat transfer coefficients in the industrial riser system, which obviously expected to be higher than that of ideal FCC riser reactor system.

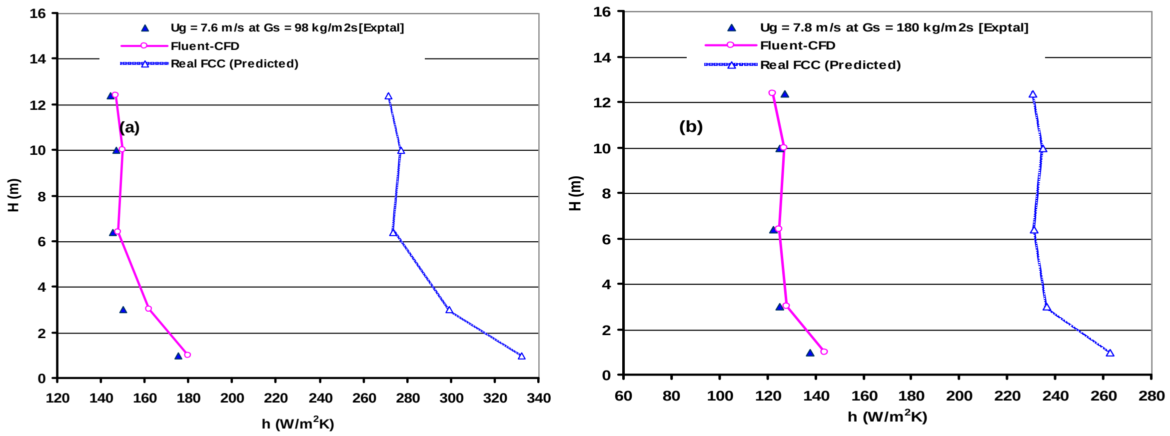


Figure 13: Axial distribution of heat transfer coefficient in the FCC riser: (a) case 3.1 and (b) case 3.2.

5.0 Conclusions

This study focused on the prediction of heat transfer coefficient in an industrial FCC riser reactor, using application of Fluent-CFD modelling incorporating in kinetic theory of granular flow (KTGF). The simulation involves the interrelation of the gas velocity, FCC solid concentration, temperature profile versus heat transfer coefficient and FCC solid holdup along the riser reactor length. Initially, efforts were made to study the adiabatic and isothermal condition of a riser reactor. In the case of isothermal condition, higher-pressure regime was noted to occur when compared with adiabatic condition of operation.

Furthermore, realistic predictions of four experimental cases were carried out to determine the heat transfer coefficients in the fluidised riser reactor of gas-solids flow suspension. The following conclusions were drawn:

a) The predicted heat transfer coefficients in the riser are in the range of 147 to 180 W/m^{2}K for case 3.1, while it was between 122 to 144 W/m^{2}K for case 3.2. In a similar trend, the prediction of heat transfer coefficients for a replica industrial FCC riser was in the range of 271 to 332 W/m^{2}K for case 3.1, and found to be between 262 to 230 W/m^{2}K for case 3.2. However, with increasing riser height, the profiles become flattered and have significant increase near to the riser wall.
b) The predictions also agree with the previous studies that, the distribution of heat transfer coefficient is mostly depends on the solids concentration. The local heat transfer coefficients increase with the solids holdup, which confirm that solids concentration is the most influential factor of heat transfer coefficient in the riser.
c) The behaviour of heat transfer in the riser reactor depends on the flow condition of operations, with the solids concentration been the determinant factor.
d) A change in gas flow velocity presents different effects on the heat transfer at different locations under the same conditions of operation. More so, higher solids circulation rate usually leads to higher heat transfer coefficient in the riser reactor due to associated increase in solid holdup.
e) The modelling validations were in good agreement with the reported data.
f) These predictions of heat transfer coefficients can be integrate into an industrial FCC unit.

Symbol and Abbreviation

CFB	Circulating Fluidised Bed
FCC	Fluid Catalytic Cracking

FF	Fast Fluidization
PC	Pneumatic Conveying

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