CFD STUDY ON THE PERFORMANCE OF OXYGEN LANCE FOR PARTIAL COMBUSTION UNIT AT DIRECT REDUCTION PLANT

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***Abstract*-This paper presents Computational fluid dynamics (CFD) study of temperature profile generated by the partial oxidation process at the direct reduction plant. The simulation was performed using standard k-ε (SKE) viscous model and Eddy Dissipation (ED) turbulence-chemistry interaction model. Two different designs of different oxygen lances being used in predicting the temperature profile generated; the normal configuration according to local industry and lances attached with wings at the bottom part. The predicted turbulence velocity and the temperature reading inside the system were found to be increased when using the second lances configuration as compared to the current configuration used in the plant. Predictions from CFD model were found to be in good agreement about 10% difference to the experimental data obtained from experimental work. This modelling exercise has demonstrated a cost effective route of design optimisation for Partial Combustion Unit (PCU) and hence should be used as tool for troubleshooting a design in future.**

I. INTRODUCTION

In Malaysia, local company produced both iron and steel. The raw material is iron ores and normally imported. The process started with the production of iron by reducing the oxides inside the iron ores and then furthered to the steel production as the final product. The plant optimization should be performed in order to be profitable to the company. The plant consists of three main part, which are Direct Reduction Plant (DRP), Direct Reduced Iron Shed (DRIS), and Steel Melting Shop (SMS). This study focuses on the Partial Combustion Unit (PCU) which is located inside the DRP; between the process gas heater and oxides removal reactor. Figure 1 shows the process flow diagram of the iron making process.

Partial combustion process is also known as partial oxidation process. It generates high concentration of reducing gases; hydrogen and carbon monoxide. It provides additional energy in terms of heat generation for the process gas to remove oxides inside the iron ores.

$CO + ½ O_2 \rightarrow CO_2$ (1)
$H_2 + ½ O_2 \rightarrow H_2O$ (2)
$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ (3)
$CH_4 + ½ O_2 \rightarrow CO + 2H_2$ (4)
$CO_2 \rightarrow CO + ½ O_2$ (5)

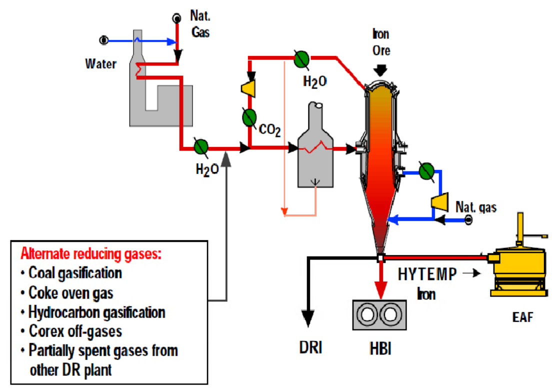

Figure 1. Process flow diagram of iron making process [5]

The self-reformation process starts to take place in the reduction furnace[2]. The self-reformation process then generated the reducing gases in the reduction reactor, feeding natural gases as make-up to the reducing gas circuit and oxygen injection at the inlet of the reactor. Below is the self-reforming of NG [6].

$CH_4 + ½ O_2 \rightarrow CO + 2H_2$ (6)
$CH_4 + H_2O \rightarrow CO + 3H_2$ (7)
$2H_2 + O_2 \rightarrow 2H_2O$ (8)
$CO_2 + H_2 \rightarrow CO + H_2O$ (9)

After the self-reformation of the natural gases, the composition of the single component of gases is observed as stated in table 1 below. The temperature at the outlet of the process gas heater is to be observed at 930°C.

Table 1. Mass fraction of gas component in process gases

Components	Mass Fraction	Temperature
H_2	15.3619439	
CO	48.5971809	
CO_2	7.24909020	1203K @ 930°C
CH_4	13.2101121	
N_2	12.6151629	
H_2O	10.9665102	

Partial oxidation of NG with oxygen generates reducing gases in-situ (H_2 and CO) and also provides additional energy required for natural gas carburization of metallic iron and reforming process [2]. Because of that, the gas temperature increases which is required for the iron ore reduction. As the intermediate product from DR Plant after underwent HYL III Process, Direct Reduced Iron (DRI) is produced. The main reactions are as following [9]:

$Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O$ (10)
$Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$ (11)

In the reduction reactor, iron carbide (Fe_3C) is also formed by the combination of carbon with metallic iron from the reduced product. The main potential carburization reactions can be as follows [5]:

$3Fe + CH_4 \rightarrow Fe_3C + 2H_2$ (Endothermic) (11)
$3Fe + CO \rightarrow Fe_3C + 2CO_2$ (Exothermic) (12)
$3Fe + CO + H_2 \rightarrow Fe_3C + H_2O$ (Exothermic) (13)

Partial oxidation process is important in increasing the temperature of the reducing gases entered the reactor. High temperature is needed because the heat transferred from the gases to the iron ore during the reduction process and gives high temperature of DRI leaving the reactor. Hot DRI feed provided additional sensible heat to the reactor and this situation reduced the power consumption and tap-to-tap time which are reflected in increasing the productivity [7].

Since the natural gas is supplied from the Gas Malaysia Berhad, the main component of the gas is mainly methane and the presence of other component of hydrocarbon is assumed to be negligible. Table 2 below shows the composition of the natural gas according to the Gas Malaysia Berhad.

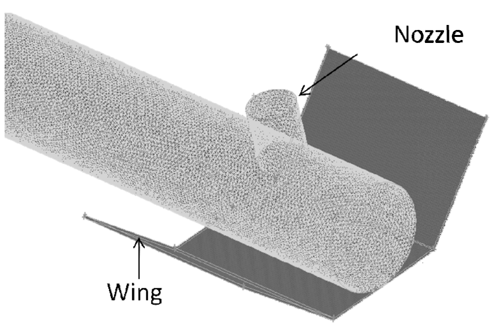

Figure 2. Lance with wings attachment

Table 2. Composition of gases in natural gas [10]

Gases	Composition (%)
Methane	92.73
Ethane	4.07
Other Hydrocarbon	3.20

In this study, the design of the oxygen lances is then modified using wings attachment in order to increase the turbulence in the transfer line. Figure 3 shows the modified lances as compared to the original design of lances.

II. Computational Approach

The commercial CFD code, FLUENT 6.3, was used to simulate the three-dimensional configuration of a combustion chamber. GAMBIT was used to draw the combustion chamber diagram illustrated in Fig. 2, which has the same dimension to the one used in the local industry. Deriving *k-ε,* it is assumed that the flows are fully turbulent and the effects of molecular viscosity are neglected. Therefore, it is only valid for fully turbulent flows such as this study. The local mass fraction of each species can be predicted through the solution of a convection-diffusion equation for the i^{th} species. This conservation equation takes the following general form:

$$-(\quad) + \nabla.(\quad \vec{} \quad) = -\nabla.\vec{} + \quad + \qquad (20)$$

where is the net rate of production by chemical reaction and is the net rate of creation by addition from the dispersed phase. An equation of this form will be solved for *N-1* where *N* is the total number of fluid phase chemical species present in the system. Since the mass fraction of the species must sum to unity, the N^{th} mass fraction is determined as one minus the sum of the *N-1* solved mass fraction.

In combustion, most of the fuels are burning quickly and the turbulent mixing will control the overall rate of reaction. For this premixed flames, the turbulence slowly convects/mixes cold reactants and produced hot products into the reaction zones where reaction occurs rapidly. In this transport phenomena, the net rate of production of species i due to reaction r, $R_{i,r}$ is given as follows:

$$\mathcal{R}_{,} = {}'_{,} \quad , \quad - \quad \mathcal{R} \frac{\mathcal{R}}{{}'_{\mathcal{R},} \quad {}_{,\mathcal{R}}} \qquad (21)$$

$$\mathcal{R}_{,} = {}'_{,} \quad , \quad - \frac{\Sigma}{\Sigma \quad {}''_{,} \quad {}_{,}} \qquad (22)$$

where is the mass fraction of any products species, P, $_{\mathcal{R}}$ is the mass fraction of a particular reactant, $\mathcal{R}$ while A and B are empirical constants which equals to 4.0 and 0.5 respectively.

For this study, the heat transport is modelled using the concept of Reynolds's analogy to turbulent momentum transfer. The 'modelled' energy equation is thus given by the following:

$$-(\quad) + -[\quad(\quad + \quad)] = - \qquad - + \qquad + \qquad (23)$$

Generally, FLUENT solves the energy equation as follows:

$$-(\quad) + \nabla.\vec{}(\quad + \quad) = \nabla \quad \nabla - \sum h \vec{} + \bar{} \quad .\vec{} \quad + \qquad (25)$$

Where $\vec{}$ is the diffusion flux of species *j*.

III. Result and Discussion

Measurement was performed in the actual PC lance unit via a thermocouple located at the position of 5.85m horizontally from the inlet of the transfer line, and the reading point is situated at 0.373m from the centre point of the transfer line. Data obtained from experiment were compared to the one obtained from CFD simulation for validation purposes. The summary of the validation is stated in the Table 3 below.

Table 3. Comparison of temperature reading

Items	Temperature (K)
Real Plant Temperature	1293.00
CFD temperature for normal configuration	1438.25
CFD temperature for modified configuration	1564.31

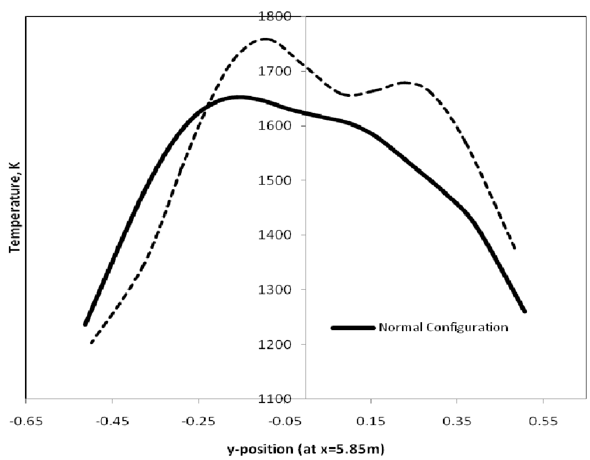

Figure 3. Temperature profile validation

From the data in Table 3, the calculated error for both normal configurations of operating mode for real plant and CFD simulation data is about 10%. This discrepancy may be attributed to the fact that the turbulence model used in this work assumed isotropic turbulence intensity, whereas, in reality, the turbulent intensity may in some extent become anisotropic especially when moving through obstacles such as the nozzle in this study. Nevertheless, prediction of the CFD model is considered reasonable since the error is about 10% and hence can be used to further evaluate the effect of design modification to the transfer line performance. The CFD result (Fig. 5) suggests that up to 8% of performance increases (i.e. temperature) can be achieved by employing a modified lances configuration. This mark a significant improvement for the PC lances design which could further increase the performance of the DRP unit.

The temperature profile for the partial combustion unit in the transfer line of direct reduction plant is shown in Figure 4. It was found that the temperature profile for both original and modified configuration of lances is differing significantly. The modified configuration of lances achieved much higher temperature compared to the original configuration. The flame structure also differs significantly compare to the original design with the modified one showing much larger flame and hence higher temperature.

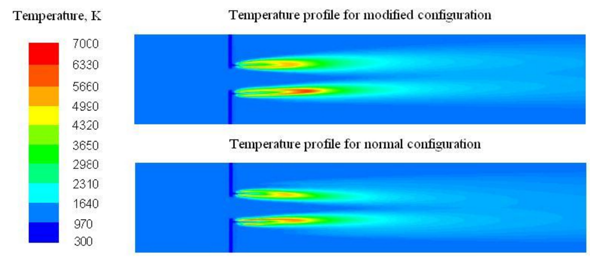

Figure 4. Temperature contour for both normal and modified configuration

The temperature profile at the centreline of the lances is shown in Figure 5, which shows the modification on the nozzle design affecting the temperature profile significantly. The modified configuration of lances shows a much higher temperature and hence could give a better performance for the partial combustion process to take place. This is because, the modified configuration of oxygen lances gives higher turbulence in the transfer line thus provides a proper condition for the process gases to be well-mix with the oxygen introduced in the unit and hence resulting in better combustion. The flame propagation of modified configuration is also shown to be somewhat better than those of original configuration of lances operating mode. The higher temperature profile may be attributed by the higher turbulence Kinetic Energy (Figure 6) of process gases in the transfer line resulted into optimization on the partial combustion reaction

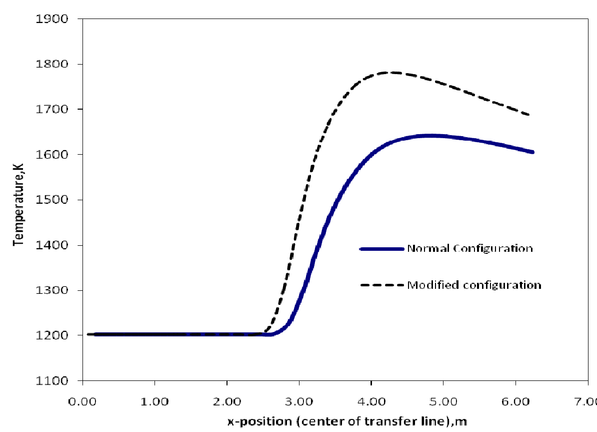

Figure 5. Effect on the temperature profile

Figure 6 shows the effect on the turbulence kinetic energy caused by the constraint of flow in the transfer line which shows greater turbulent intensity for the modified design compared to the original ones. The result suggests that the proposed modified configuration gave better turbulence for the process gases mixed properly. This high turbulent intensity occurs due to disturbance of the gases flow through the transfer line. The wings installed at the bottom side of the oxygen lances induces disturbance to the gas flow resulted into higher turbulence of gas flow due to the collision between the gases particles and the wings walls. In addition, proper mixing of the process gases gave better condition for the combustion and partial combustion reaction to take place.

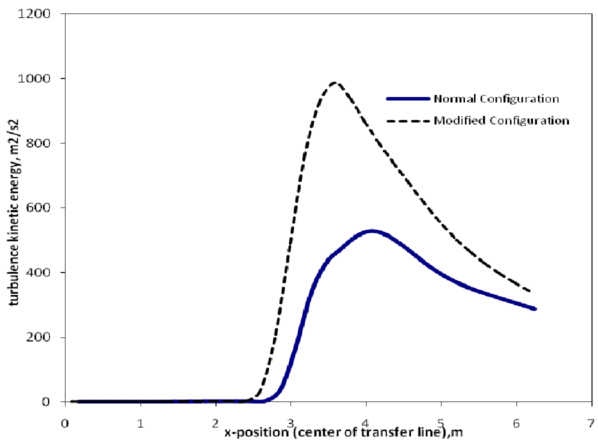

Figure 6. Effect on the turbulence kinetic energy

Figure 7 shows profile of methane consumption in the lances as result of combustion process. The methane consumption of the modified design is greater than the original ones which is attributed by the higher turbulent intensity as shown in Figure 6. The higher methane consumption in turn increases the performance of the reduction process because smaller amount of CH_4 presence in the reactor means lesser event of endothermic reaction between iron oxides and CH_4. Besides that, the CH_4 fed into the transfer line also can be reduced because smaller amount of CH_4 also can also favour better partial combustion reaction. The modified configuration of oxygen lance is proven to give better condition and favourable for the reaction to take place. For even better and more accurate result, a more rigorous CFD study may be performed using more advance turbulence model such as Large Eddy Simulation (LES).

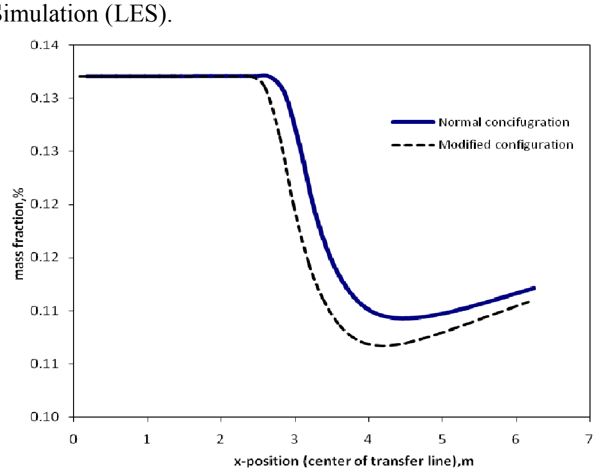

Figure 7.Effect on the methane consumption

IV. Conclusion

The performance of the partial combustion unit at the Direct Reduction plant was evaluated numerically using CFD software. The original design is not effective enough to achieve higher temperature at the outlet of the transfer line and some modification of the lance such as by adding the lance with wings gives better result in increasing the lance temperature. This is because the high turbulence in the transfer line will affect the flame distribution and thus gives higher temperature. Results from this simulation may be useful for development of a more comprehensive and accurate model for partial combustion unit in the future.

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