Heat transfer analysis of iron ore spherical pellet in the direct reduction process

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Abstract. The aim of iron ore direct reduction process is to convert iron oxide into metallic iron. The conversion of iron oxide into metallic iron occurs through several stages of intermediate phase. This intermediate phase included of hematite, magnetite and wustite. Temperatures is one of the important variables to ensure the transformation of the phase completely. Generally in the direct reduction process, iron oxide process should be agglomerated into 1.5 cm – 2 cm in diameter spherical or cylindrical pellet. Agglomerates form, caused uneven temperature distributions within pellet inside. The objectives of this work is to observed energy and the rate of heat flux during reduction process so that intermediate phase can be transformed perfectly into metallic iron. To analyze temperature pellet inside, Ansys software was utilized to simulated iron ore direct reduction process. This simulation using agglomerate spherical form. Temperatures simulation take place at 900 into 1100 Celcius for 30 and 69 minute. This simulation also simulated carbon monoxide (CO) as reduction gas at 1 atm

1. Introduction

The process of making iron from iron ore is a reduction process. In the reduction process there is a process of reducing the oxygen content in the oxide ore. In the process of reducing iron ore, Fe₂O₃ (hematite) is not directly reduced to iron metal but through several stages of reaction. The iron ore reduction process must go through several phases between Fe₃O₄ (magnetite), FeO (wustite) and Fe. In the process of reducing the existence of intermediate phase it is very difficult to observe, since the reduction of iron oxide reaction is simultaneous whereas the existence of the intermediate phase is very influential on the speed of the reaction rate, besides the speed of the reaction rate is also strongly influenced by the mechanical heat transfer that occurs.

Heat transfer in the reduction process occurs through the mechanism of convection and conduction. The conduction process is the transfer of heat through solids. Conduction and convection mechanisms in the reduction of iron ore are affected by temperature, properties and reducing gas. High thermal conductivity will increase the rate of reaction. Several studies regarding the reduction of hematite iron ore for heat transfer processes have been carried out, by Jingyu Shi [1] and Bayu Alamsari [2]. In both studies discussing the iron ore reduction model, it was assumed that

In the iron ore reduction process, the phenomenon of heat transfer occurs in non steady-state conditions because the temperature passing through the pellets will vary with time. Therefore, to simplify the calculation, and study the effect of heat transfer on iron ore reduction, it is necessary to use a special tool, then a simulation is performed using ANSYS 17.2 simulation software. By using this software, it can facilitate the analysis of heat transfer rate in the reduction of hematite (Fe₂O₃) iron ore pellets.
2. Experiment

2.1. Iron Ore Direct Reduction Process

Direct reduction reactions of oxide ore are heterogeneous reactions, it is known that heterogeneous reactions generally involve several phases [3,4]. Iron oxide reduction process also involved CO serves as a reducing agent. CO is produced generally from the Boudouard reaction [5]:

$$2CO \rightarrow CO_2 + C \quad (1)$$

This reaction is exothermic. However, the standard enthalpy negativity of the Boudouard reaction decreases if the temperature increases. Overall reaction of this process can be written as in equations 2 to 4. Besides being heterogeneous, the reaction of direct reduction of iron oxide also runs simultaneously [5,6].

1. $Fe_2O_3 + CO \rightarrow Fe_3O_4 + CO_2$ \quad (2)
2. $Fe_3O_4 + CO \rightarrow FeO + CO_2$ \quad (3)
3. $FeO + CO \rightarrow Fe + CO_2$ \quad (4)

Heat transfer is the process of moving heat energy due to temperature differences[7]. Heat energy moves from a higher temperature to a lower temperature. Heat transfer not only explains how heat energy moves from one condition to another, from one place to another or from an object to another object, but can also estimate how much the rate of movement occurs in certain conditions. In the reduction of iron ore heat transfer is a factor that supports the success of reduction. In the process of reducing iron ore, Fe2O3 (hematite) is not directly reduced to Fe but through several stages of reaction, namely Fe3O4 (magnetite), FeO (wüstite) and the final product in the form of Fe. Changes in the chemical composition of Fe2O3 to metallic Fe are strongly influenced by the parameters of heat transfer through iron ore[8].

2.2. Simulation Using ANSYS

The simulation process begins with running ANSYS 17.2 software, Workbench 17.2, then the analysis system is selected by the Transient Thermal module. After that, Engineering Data was selected (Fig 1) and then the thermal physical data of hematite iron ore such as density, heat conductivity and heat capacity also input to the simulation system. This simulation using spherical as geometry with dimension 2 cm and 3 cm in diameters. This geometry was chosen because naturally iron ore pellet has same geometry with sphere. On the model menu there is Solid, then the hematite material data is selected which was previously included in the Engineering Data and meshed.

![Figure 1. Engineering data selections input](image-url)
In Transient Thermal, the parameter parameters needed are the initial pellet temperature and the reduction time (10, 15, 30, 45, or 60 minutes). Convection is chosen as the heat transfer mode, then the reduction temperature is $973^\circ K$, $1173^\circ K$ and $1373^\circ K$ also input into the simulation. In addition to the reduction temperature, the convection mode also requires CO heat transfer coefficients for each temperature variation. After that the solution is selected, the solution output is chosen i.e. the temperature and total heat flux. The final step is to do the simulation process with selected Solve, then the simulation results obtained in the form of changes in temperature and total heat flux.

The initial stage of the validation process is to reduce the size of iron ore using milling. Then the results of this milling process are carried out with a 200 # sieve size and obtained iron sand concentrate on less than 200 #. After beneficiation, the iron ore powder is made into pellets with a size of 2 cm and 3 cm. The pellet is then reduced to $1173^\circ K$ for 60 minutes.

| Phase     | Heat Conductivity $k$ (W/m.K) | Heat Capacity $C_p$ (J/Kg.K) | Density $\rho$ (kg/m$^3$) |
|-----------|-------------------------------|------------------------------|---------------------------|
| Hematite  | 1.2                           | 980                          | 4,900                     |
| Magnetite | 1.5                           | 870                          | 5,000                     |
| Wustite   | 3.2                           | 725                          | 7,750                     |

### 3. Result and Discussion

#### 3.1. Effect Of Temperature And Time Reduction On The Heat Transfer On Hematite Pellet Reduction.

In Figure 2 it can be seen that higher temperature, will be generated higher value of heat energy. This happen due to temperature difference between the surface and the pellet core are very high. This temperature differences lead to heat energy received by the iron particle pellet will be even greater. From Figure 2 it can be seen that from reduction temperature 923 K to 1373 K for 10 minutes, heat energy received by the iron particle pellet 2 cm in the inner are 4.5 kJ, 6.1 kJ dan 7.1 kJ and at surface are 0.65kJ, 0.87kJ dan 1.1kJ, respectively.

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**Figure 2.** Effect of time reduction and diameter of pellet to the heat transfer flux. (a) 2 cm, (b) 3 cm

The effect of temperature and time reduction was shown in Fig 2 and Fig 3. According to that figure heat flukes will be increased with the increasing time and temperature reductions. Pellet surface with
diameter 2 cm and 3 cm at temperature 923°K for 10 minutes obtained heat fluxes of 7.61 and 21.28 J/s respectively. When temperature reduction increased from 923°K to 1173°K and 1373 °K, heat fluxes of the pellets also increasing. The phenomenon of increasing heat flux due to the reduction temperature in accordance with the formula of heat transfer rate, both by conduction (Eq 4) and by convection (Eq 5).

\[ q_x = -kA \frac{dT}{dx} \quad (4) \]

\[ q = h . A . dT \quad (5) \]

Figure 3. Temperatures profile for pellet 2 cm (Dia = 2cm) reduction at 973, 1173 and 1373°K for 45 minutes

According to equations 4 and 5 temperature gradient of pellet is directly proportional to the value of q (the rate of heat transfer), hence when temperature gradient in the surface and inner pellet more smaller, heat fluxes of process will be reduces, until there is no heat transfer when dT is 0. It also proven on Fig 3, Fig 3 shown at lower temperature, pellet have more vary color than higher temperature. At temperature 1373°K all pellet surfaces shown uniformly temperature but at 973°K, temperature inner pellet still more lower than at the surfaces. It is predicted that reaction still running inside pellet but at high temperature, oxide pellet predicted transform completely into metallic Fe.

Figure 4. Temperatures Profile of Pellet 2cm at 1373°K for 10, 15,30 and 45 Minutes
3.2. Effect Of Pellet Diameter On Reduction Of Iron Ore

Figure 5. Heat Fluxs Profile With Diameter at 973 and 1373 K for 60 minutes

In addition to the temperature and time reduction, pellet diameter also affects the results of iron ore reduction. The greater diameter of the pellet, the greater rate of heat transfer and the amount of energy received. The simulation show that the effect of pellet diameter is inversely proportional to the temperature, i.e. the smaller the pellet diameter, the faster the pellet reaches the reduction temperature furnace. Fig.5 show the effect pellet diameter to the reduction process. Temperature on 2 cm pellet will be distributed more faster than 3 cm pellet, it is caused pellet with 3 cm diameter have surface area more higher than pellet 2 cm. This higher surface area will be received more heat energy than the smaller ones. This phenomenon can be explained in equations 6 that the temperature (\(\frac{\partial T}{\partial t}\)) is inversely proportional to the surface area gradient (\(\partial x^2, \partial y^2, \partial z^2\)) but is directly proportional to time (\(\partial t\)), so the greater Pellet size will cause the temperature to increase longer or reach the reduction temperature.

\[
\frac{\partial T}{\partial t} = \left(\frac{k}{\rho C_p}\right) \nabla^2 T = \frac{k}{\rho C_p} \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right)
\]  

(6)

In the reduction of iron ore, perfect or not the reduction process takes place is determined by the content of Fe metal, the higher the content of Fe metal obtained, the more perfect the reduction process takes place. This is because the content of Fe metal is the level of pure Fe formed during the reduction process. Therefore, the high and low levels of Fe metal produced depend on the reduction process, one of which is the correct use of temperature and reduction time.

The process of converting from Fe\(_2\)O\(_3\) to metallic Fe occurs at certain temperatures and requires energy so that chemical reactions can occur. The minimum energy required for a chemical reaction is called Activation Energy\[10\] and the energy received by pellets during the reduction process of iron ore is determined by the rate of heat transfer.

4. Summary

From the discussion above, it can be concluded:

- The highest heat transfer rate for 2 cm diameter is 12.78 J/s and for pellets 3 cm diameter is 38.35 J/s on the pellet surface.
- Heat transfer rate for 2 cm and 3 cm diameters is 0.067 J/s and 0.1571 J/s respectively at the core of the pellet. This value is obtained at a reduction temperature of 1373°K.
• The greater size of the pellet, the reduction process will run slower, because bigger pellet contains higher concentration of Fe₂O₃ so that the activation energy required to convert this oxide also high.

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