The effect of heat energy on/of iron direct reduction process

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Abstract. Direct Reduction is one of the process to converted iron ore 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. Iron ore direct reduction is the process involved high temperature because temperatures will provide heat energy. Sufficient heat energy will ensure all stages of converted phase completely reacted. To analyze heat energy inside of the specimen. Ansys software was utilized to simulated iron ore direct reduction process. This simulation using agglomerate spherical and cylindrical form. Temperatures simulation take place at 973 into 1373 Kelvin for 30 and 60 minute. This simulation also simulated carbon monoxide (CO) as reduction gas at 1 atm. According to simulation spherical pellet in the diameter 3 requires higher energy to convert iron oxide into metallic iron.

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 energy is one essential component to produce metallic iron from their oxide. According to the thermodynamic data, iron direct reduction process is exothermic reaction. Although this process generated some heat, but it also needed heat supply to generates gas reductant from carbon. So that it necessary to analyse heat energy transfer inside of the pellet in order to maintain supply of gas reductant.

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[1] Several studies regarding the reduction of hematite iron ore for heat transfer processes have been carried out, by Jingyu Shi and Bayu Alamsari

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[1,2]. 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]:

\[
2CO \rightarrow CO_2 + C
\]  

(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]

\[
\begin{align*}
\text{Fe}_2\text{O}_3 + CO & \rightarrow \text{Fe}_3\text{O}_4 + \text{CO}_2 \\
\text{Fe}_3\text{O}_4 + CO & \rightarrow \text{FeO} + \text{CO}_2 \\
\text{FeO} + CO & \rightarrow \text{Fe} + \text{CO}_2
\end{align*}
\]  

(2) \hspace{1cm} (3) \hspace{1cm} (4)

Heat transfer is the process of moving heat energy due to temperature differences. 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, Fe$_2$O$_3$ (hematite) is not directly reduced to Fe but through several stages of reaction, namely Fe$_3$O$_4$ (magnetite), FeO (wüstite) and the final product in the form of Fe. Changes in the chemical composition of Fe$_2$O$_3$ to metallic Fe are strongly influenced by the parameters of heat transfer through iron ore. [7,8]

2.2 Heat Transfer

On this simulation assumed heat transfer mechanism occurs are conduction and convection since gas reductant and iron oxide particles are in the spherical and cylindrical form and the distance between particle is very small. Conduction is a heat transfer mechanism which involved solid media to delivered the energy. This mechanism can be explained by the Fourier Law as the equation 5.[8]

\[
q_x = -kA \frac{dT}{dx}
\]  

(5)

While convection is the other heat transfer mechanism which is needed gaseous media to delivered the heat energy and explained by the Newton Law.

\[
q_x = hA \frac{dT}{dx}
\]  

(6)

The heat transfer coefficient is a fluid characteristic that is an important parameter in a process involving heat such as the process of reducing iron ore. Each fluid has different heat transfer coefficient values, including CO gas. Based on equation 7 it can be obtained the CO gas heat transfer coefficient for temperature variations of 973 K, 1173 K and 1373 of 17.7 W/m$^2$K, 20.6 W/m$^2$K and 23.3 W/m$^2$K, respectively.

\[
h = \frac{0.88 \nu^{0.8} \rho_p^{0.2} \gamma^{0.5} m^{0.3}}{8
\]  

(7)

This equation will be basis of the simulations.

2.3 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 have 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.
According to the equation (5) and (6) this process need some thermal coefficients. So that thermal data used in the simulation can be seen in table 1. In Transient Thermal, the parameter needed were the initial pellet temperature and the reduction time (10, 15, 30, 45, or 60 minutes). Convection and conduction was chosen as the heat transfer mode. Reduction temperature was held at 973°C, 1173°C and 1373°C and input into simulation along with time reduction. 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. Final stage of simulation was 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 was reduced the size of iron ore using milling machine. 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. After that pellets were reduced at muffle furnace for 10 to 60 minutes in 973 K to 1373 K until it is converted into sponge iron. Chemical analysis of iron metal was carried out to verify iron content of sponge iron.

| Phase   | Heat Conductivity k (W/m.K) | Heat Capacity Cp (J/Kg.K) | Density ρ (kg/m³) |
|---------|-----------------------------|---------------------------|-------------------|
| 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 heat energy to time and temperature process

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.

![Figure 2](image)

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

Pellet with diameter 3 cm shown higher value of heat energy which is 12 kJ, 17 kJ dan 23 kJ at surface while inner pellet have heat energy 1.7 kJ, 2.5 kJ dan 3.2 kJ Time of reduction will also increasing heat energy received by iron particle. From first 15 minutes reduction process, heat energy at all diameters pellet continue to increase until 60 minutes.

| $\Phi_{\text{pellet}}$ | 973 K | 1173 K | 1373 K |
|------------------------|-------|--------|--------|
| 2 cm                   | ![image](image) | ![image](image) | ![image](image) |
| 3 cm                   | ![image](image) | ![image](image) | ![image](image) |

**Figure 3.** Temperature profile for 2 and 3 cm pellet at 973 k, 1173 k and 1373 k for 15 minutes.
From figure 3 it can be seen that reduction temperatur which given to pellet will lead to uniformity temperature profile at pellet surface and core. Pellet with diameter 2 cm at 973 K shown the most smallest temperature difference between surface and inner pellet, which is 15 K. Following with 1173 K which have temperature differences 17 K and the most higher temperature differences is achieved by reduction at 1373 K that is 43 K. Although pellet at 973 K received heat energy with small quantity but temperature differences between inner and surface relatively uniform compared to pellet at 1173 and 1373 K. This phenomenon happened because iron ore reduction is a process which involved intermediate phase, as shown in eq.2 – eq. 4. Intermediate phase involved such as hematite, wustite, and magnetite phase has different heat conductivity value, which lead to heat convenience for passing through intermediate phase.

3.2. Effect of Diameter Pellet To Temperature Received by Pellet

![Figure 4](image-url)

**Figure 4.** Profile of temperature differences compared to pellet diameter.

According to figure 4 diameter also has a significant influence on the temperature received by pellet. It shows that pellet with bigger diameter has higher temperature difference compared to smallest one. Temperature differences at pellet in 3 cm diameter will be increasing with the increased of temperature reduction. At 973 K temperature differences between inner and surface achieved 33 K. It will continue to rise at 1173 and 1373 K.

Heating rate of pellet with 2 cm is much faster than pellet with 3 cm in diameter, particularly at temperature reduction above 1173 K. Higher temperature will caused temperature differences become greater in any diameter pellet. This phenomenon is in accordance with Fourier Law, which state that distance will be inversely proportional to the heating rate of an object.

3.3. Effect of heat energy on the metallic iron conversion

Effectiveness of reduction process indicated by metallic iron and total iron value in sponge iron. Figure 5 showing metallic and total iron value of reduction process at 973 k for 3600 s in any diameter pellet. Pellet with 2 cm diameter has metallic iron value 54% with total iron value 71%. On the contrary pellet with bigger pellet has lowest value of iron metallic and iron total value, which is 46 % and 66 %, respectively.

Corresponding to discussion 3.1 and 3.2 pellet with diameter 3 cm has a bigger surface area than pellet 2 cm. Iron particle in bigger surface area will be received more higher energy than the smallest one, although they are exposed with higher heat energy, but the overall conversion of oxide will influenced by the conductivity of each intermediate phase. It is show in figure 3, the surface of green
area which is indicated as magnetite to wustite is much more wider than the red and blue area. The red and blue area are indicated as wustite to iron and hematite to wustite phase.

![Graph](image)

Figure 5. Profile metallic conversion to diameter pellet at temperature reduction 973 K for 3600 s.

4. Conclusion

From the discussion above, it can be concluded that iron particle in 3 cm pellet will be exposed with higher energy than pellet in 2 cm. In 3 cm pellet, surface area at 1373 K for 3600 s will be received 48 kJ heat energy, inner are received 7 kJ heat energy. While pellet in 2 cm received heat energy at surface area 12 kJ and inner surface received 1.6 kJ heat energy. Differences heat energy received by pellet also influenced temperature differences between inner and surface of the pellet. Pellet with 3 cm has a bigger differences temperature compared to pellet with 2 cm diameter. Coefficient conduction of each phase influenced the heat energy transfer inside of the pellet. Heat energy received by the pellet show the opposite result of the metallic iron conversion value.

References

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