Process simulation of activated carbon production using a rotary kiln

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Abstract−The rotary kiln used for the activation of charcoal is simulated using mass and energy balances to obtain the temperature distributions of environmental gas and solid in the kiln. The computed results are used to find the optimal operation condition. In finding the optimal gas temperature for the reductive gas environment necessary to the charcoal activation, the outcome gives the amount of fuel required and the effects of other operational variables, such as feed and steam rates. While the fuel and feed rates give large variation of gas and solid temperatures, the activation steam and moisture and volatile contents in feed do not affect the temperatures significantly. It was found that the temperature distribution has a similar pattern to that of coal pyrolysis because of the similarity of heat transfer mechanism.

Key words: Charcoal Activation, Rotary Kiln, Heat Transfer, Numerical Simulation

INTRODUCTION

Activated carbon is made from charcoal by activation using thermal or chemical treatment. The common raw material, coconut shell, is an abundant waste in most tropical countries, obtained after taking water for drinking and fiber for fatty oil. Charcoal from the waste coconut shell has been the most popular feed stock for the activated carbon. Though relatively expensive, activated carbon has been widely used for the removal of impurities in food products. Its production has been significantly increased ever since it has been used in the production of municipal tap water.

In the production process of activated carbon, material and gas temperature in a rotary kiln is the key to determining the product quality. The activation is obtained in the reductive gas environment. The reductive environment is acquired when a water gas reaction occurs to generate hydrogen. The reaction temperature is between 850 °C and 1,100 °C [1], and the reaction is endothermic to consume a large amount of heat. Due to the reaction heat, the material and heat balances in the kiln are complex, making the process modeling difficult. Unlike most chemical processes, the production of activated carbon involves the handling of solid material instead of liquid or gas. Two main processes in the production are the heating of the solid and maintaining the reductive gas environment.

Coal pyrolysis in a rotary kiln has been modeled to examine the role of operating parameters, such as the kiln rotation speed for the process optimization [2,3]. A review of charcoal production technology was published to explain the production technique and its relation to the charcoal properties [4]. Chemical activation of paper mill sludge has been introduced by Kang et al. [5], and the kinetics of water gas reaction was examined in the hydrogen production process [6]. The surface modification and adsorption application were investigated with a wood-based activated carbon [7].

In this study, the role of operation variables in the rotary kiln process of coconut-shell activated carbon is evaluated through simula-

tion study. The variables include feed and fuel rates, moisture and volatile component contents and steam rate. The simulation model is composed of mass and energy balances in the rotary kiln and the reaction kinetics of water gas reaction. The calculated temperatures of solid and environmental gas are used to determine the operating variables.

DESCRIPTION OF ROTARY KILN

The structure of a rotary kiln is relatively simple. It is a cylindrical tube lined with fire brick inside. For the simulation of the kiln the process data from a local manufacturer is used. The dimensions of the kiln and operating data are shown in Table 1. It is horizontally placed and rotated once in about 2 minutes to move the material one-and-a-half meters per hour. The processing time of the feed stock is about 12 hours. At the inlet of feed, coconut-shell charcoal, a burner consuming bunker-C is installed and steam is fed for the water gas reaction, generating the reductive environment in the middle of the kiln. Two rollers support the kiln as shown in Fig. 1. The front rollers hold the kiln from moving horizontally, while the rear

Table 1. Equipment characteristics and base operation conditions

Length (m)	18
External diameter (m)	2
Raw material	Coconut shell charcoal
Solid flow rate (kg h^{-1})	250
Moisture content (%)	10
Volatile content (%)	10
Activation gas	Water vapor
Water vapor flow rate (kg h^{-1})	375
Burner oil	Bunker-C
Rotary kiln pressure	Atmospheric
Rotation speed (rpm)	0.5
Residence time (h)	12
Solid input temperature	Room temperature

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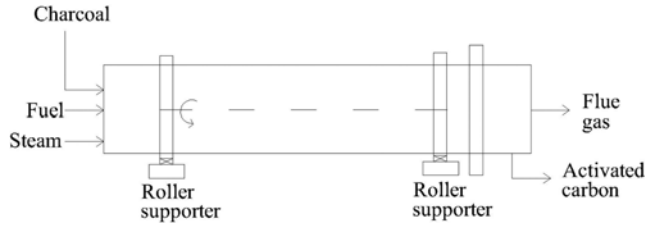
Fig. 1. A schematic diagram of the rotary kiln for the activation of coconut shell charcoal.

rollers control the horizontal sliding of the kiln due to thermal expansion. Two pieces of rollers are placed at each location for stable support. Because the kiln wall is hot, the rollers are contained in a shallow water tank for cooling. The product, the activated carbon, and flue gas are evacuated from the rear side of the kiln. There occurs an explosion by external air supply, when the burner flame is extinguished. The reductive gas is full in the kiln, and its temperature is high enough for the explosion. Therefore, a large excessive space is equipped at the rear section of the kiln for the safety reasons. However, it was not considered in the modeling of this study.

MATHEMATICAL MODEL

Balance equations were used for the simulation of temperature distributions of solid and environmental gas in the kiln. Though various kinds of chemical reactions occur in the processing of the solid, the heat transfer between gas and solid is the most important in monitoring the activation process. At the inlet of feed material, the oil-burning burner raises the gas temperature, but it takes time until the solid gets hot to release volatile matter for the water gas reaction in gas phase. The pores of the activated carbon are formed after the volatile escapes from the solid during the processes of charcoal production and activation. Volatile material, moisture and a portion of solid carbon become carbon dioxide and water vapor, but the main process of the kiln operation is the charcoal activation in which solid temperature is a key factor of the activation. Heating directly the solid carbon having low thermal conductivity leads to surface burning. This is the reason for using the rotary kiln in charcoal activation.

When the heat transfer among the gas, solid and kiln wall is considered, the following energy balance can be formulated from Ortiz et al. [1]:

$$\frac{1}{V_g}\frac{\partial(Q_g C_g T_g)}{\partial t} = \frac{\partial(Q_g C_g T_g)}{\partial z} - C_3(T_g - T_s) - C_4(T_g^4 e_g - T_s^4 A_v)$$
$$- C_5(T_g - T_w) - C_6(T_g^4 e_g - T_w^4 A_v) + \frac{\partial Q_h}{\partial z} C_v(T_s - 373) \quad (1)$$

where the left-hand side is the unsteady stage term, and the first of the right-hand side denotes axial heat flow. The next terms are the conduction and radiation between gas and solid, the conduction and radiation between gas and wall, and the heat of water vapor, respectively.

Likewise, the energy balance for solid is

$$\frac{1}{V_s}\frac{\partial(Q_s C_s T_s)}{\partial t} = -\frac{\partial(Q_s C_s T_s)}{\partial z} + C_3(T_g - T_s) + C_4(T_g^4 e_g - T_s^4 A_v)$$
$$+ C_7(T_w - T_s) + C_8(T_w^4 e_g - T_s^4 A_v) - \frac{\partial Q_h}{\partial z} H_v - k_e e_s^{-8033/T_s} \frac{Q_s}{V_s} Q_a \Delta H \quad (2)$$

where the terms from the second of the right hand side are the conduction and radiation between gas and solid, the conduction and radiation between wall and solid, and heat consumption for the generation of water vapor, respectively. The last is the heat consumption by the water gas reaction. The energy balance for kiln wall is found from the same procedure as follows.

$$\frac{\partial(M_w C_w T_{ws})}{\partial t} = C_5(T_g - T_w) + C_6(T_g^4 e_g - T_w^4 A_v)$$
$$- C_7(T_w - T_s) - C_8(T_w^4 e_g - T_s^4 A_v) \quad (3)$$

Material balance for the solid is given as

$$\frac{1}{V_s}\frac{\partial Q_s}{\partial t} = -\frac{\partial Q_s}{\partial z} - k_e e^{-(8033/Ts)} Q_a \frac{Q_s}{V_s} - \frac{h_t A(T_g - T_s) Q_h}{H_v(0.1Q_s)} \quad (4)$$

where the terms of the right hand side are the axial mass flow, reaction and loss by water vaporization. Similarly the balance for gas is

$$\frac{1}{V_g}\frac{\partial Q_g}{\partial t} = \frac{\partial Q_g}{\partial z} - k_e e^{-(8033/Ts)} \frac{Q_s}{V_s} Q_a \frac{30}{12} - \frac{h_t A(T_g - T_s) Q_h}{H_v(0.1Q_s)} \quad (5)$$

For the moisture, the material balance is

$$\frac{1}{V_s}\frac{\partial Q_h}{\partial t} = -\frac{\partial Q_h}{\partial z} - \frac{h_t A(T_g - T_s) Q_h}{H_v(0.1Q_s)} \quad (6)$$

For the steady state simulation in this study the unsteady state terms in the balance equations disappear, and a system of ordinary difference equations results. The Euler integration was utilized in the numerical computation. The model parameters are given in Table 2. The emissivities of the solid and kiln wall are adopted from the coal pyrolysis model [3], and the data of the processing material are for the charcoal activation. The physical data of the kiln are calculated

Table 2. Model parameters

$C_3 = h_{gs} L_{cu}$
$C_4 = \dfrac{\sigma L_{cu} e_s}{1-(1-e_s)(1-A_v)}$
$C_5 = h_{gw} L_{li}$
$C_6 = \dfrac{\sigma L_{li} e_w}{1-(1-e_w)(1-A_v)}$
$C_7 = h_w L_{es}$
$C_8 = \sigma L_{cu} \varphi_{sw} e_w e_s$
$\phi_{sw} = \left\{ \dfrac{1}{1-e_g} - (1-e_w)\left[\dfrac{L_{cu}}{L_{li}}(1-e_s) + \left(1 - \dfrac{L_{cu}}{L_{li}}\right) \right] \right\}^{-1}$
$A_v = 0.07$
$C_g = 1.2$
$C_s = 0.2$
$C_v = 2.1$
$C_w = 0.7$
$e_s = 0.1$
$e_w = 0.9$
$h_{gs} = 0.01$
$h_t = 4.3$
$h_w = 0.001$
$L_{cu} = 1.848$
$L_{es} = 2.356$
$L_{li} = 3.927$

from the kiln dimension.

RESULTS AND DISCUSSION

Because the activation occurs on the surface of charcoal, the solid temperature needs to be higher than 800 °C. At the same time the environmental gas has to be reductive, which is formed from water gas reaction occurring at the temperature between 850 °C and 1,100 °C [1]. In the practical operation of the kiln, the gas temperature is maintained at around 950 °C. At lower temperature the activation is incomplete, resulting in poor quality products. When the temperature is too high the production yield drops, meaning the charcoal burns instead of being activated. While the control of gas temperature is relatively simple by adjusting fuel consumption, the control of solid temperature is difficult. Note that charcoal is porous having low conductivity. The heating temperature of the solid can be raised to compensate for the low conductivity, but it is limited. When the charcoal is heated too high, the charcoal burns from the surface.

To monitor the activation process in the rotary kiln the temperature distributions of gas and solid were calculated from the energy and mass balances. The computation was conducted along the kiln length. As a base case of the simulation, a case of the feed rate of 200 kg/h, fuel of 2,000 L/d and steam 200 kg/h was used. The feed contained 10% of volatile and 10% of moisture. Fig. 2 demonstrates the temperature distributions of solid and gas in the base case. The measured gas temperatures from a practical kiln are represented in circles. The burner installed at the inlet raised the gas temperature to the maximum at the early stage, and the temperature dropped steadily as moved to the exit. The drop was caused by the heat transfer to the solid and heat loss through the kiln wall. Also, the water gas reaction is endothermic to reduce the temperature. A portion of charcoal burns in the process of activation, but the amount is too small to affect the gas temperature. The volatile components contained in the charcoal also release heat while burning. The components are evaporated in the early stage, when the solid temperature exceeds 350 °C. Therefore, no significant heat source is provided in the activation 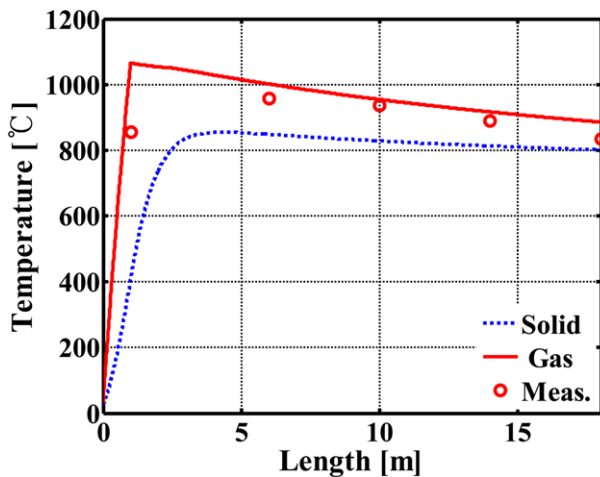process except the fuel burning at the burner. The solid temperature was slowly elevated at the inlet by heating from the gas, and decreased slightly as moved to the kiln rear. In addition, there is conduction between the solid and kiln wall to lower the solid temperature. In the coal pyrolysis using a kiln 55 m long, the gas temperature dropped significantly at the rear section of the kiln [3]. The temperature was the highest at the middle of the kiln and decreased sharply in the rear half. The solid temperature was slowly elevated after the gas temperature was raised. Though the coal burning supplies additional heat in the coal pyrolysis, the patterns of temperature variation of this study and the pyrolysis have a certain similarity. It is largely due to the same mechanism of heat transfer-radiation from the gas to the solid-in the two kilns. In the charcoal activation [1], the temperatures of gas and solid were slightly increased as moving to the rear of the kiln, but the length of the kiln was less than four meters. In the short kiln the gas temperature has to be much higher to heat the solid in a short period of time, and therefore a higher portion of charcoal burns to raise the solid temperature in the middle of the kiln.

The role of fuel amount to the gas temperature is shown in Fig. 3. The temperature is at the center of the kiln. More fuel raised the gas
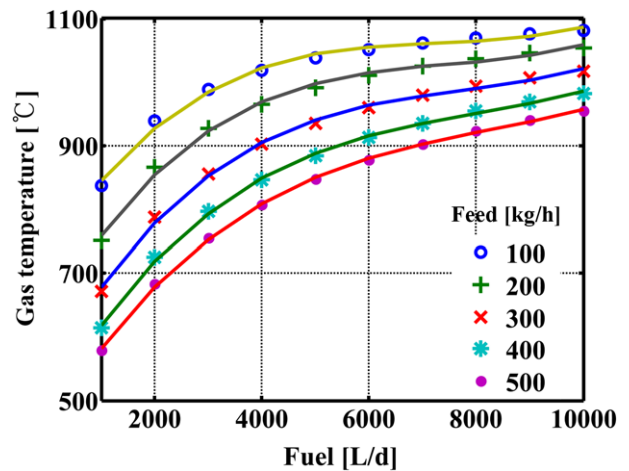

Fig. 3. Gas temperature with different fuel supply for various feed rates.

Fig. 2. Temperature distributions of solid and environmental gas along the kiln length and measured gas temperature in a practical kiln.
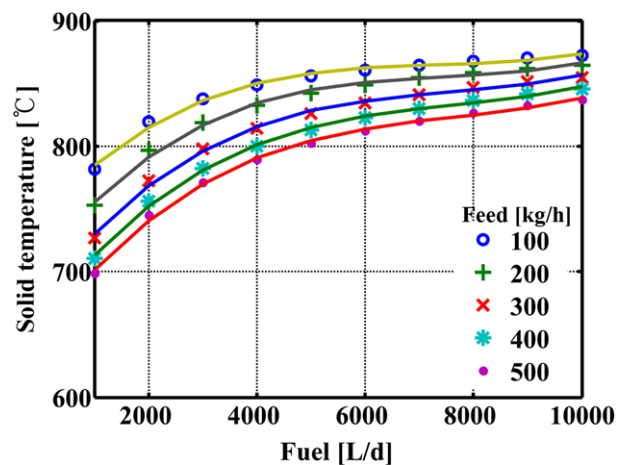

Fig. 4. Solid temperature with different fuel supply for various feed rates.

temperature more as expected, and higher feed rate requires more fuel to get the same gas temperature. The usual operation temperature of 950 °C for the normal operation determines the fuel amount required, which can be found from the figure. In the same manner the solid temperature is found from Fig. 4. Because the water gas reaction occurs between 850 °C and 1,100 °C, the recommended solid temperature is determined from the gas temperature. Around 800 °C is the usual operation temperature for the solid, but the measurement and manipulation of solid temperature are more difficult than those of gas temperature. Therefore, the kiln operation has been monitored with the gas temperature in practical operations. The distribution of solid temperature is similar to the gas temperature distribution. Higher fuel rate raises the temperature more, and the elevated feed rate needs more fuel.

In the base case, the amount of steam affects the solid temperature as seen in Fig. 5. Higher steam flow requires more fuel, but the effect of steam amount is not significant as found in feed flow rate. The temperature of steam supplied is much lower than the gas temperature, and therefore additional heating of the steam is necessary to raise the temperature to the gas temperature. The roles of
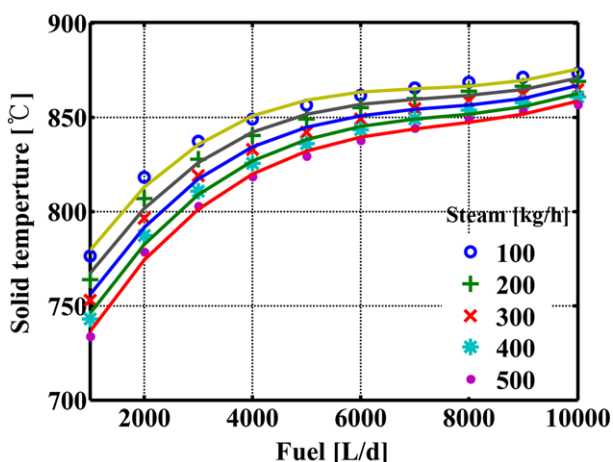

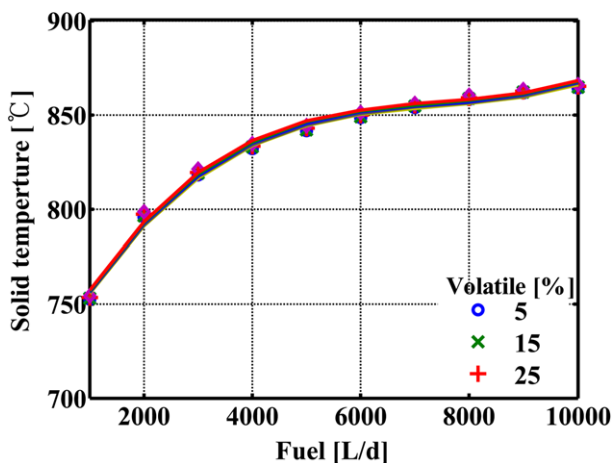Fig. 5. The effect of steam flow rate on the solid temperature with different fuel amount.

Fig. 6. The effect of volatile contents in feed on the solid temperature.
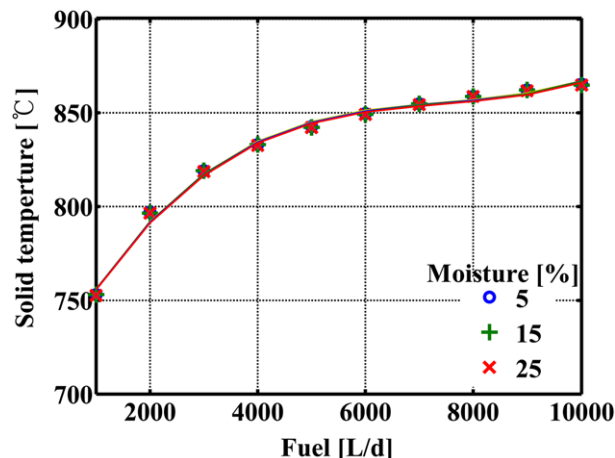
Fig. 7. The effect of moisture contents in feed on the solid temperature.

volatile components and moisture contents in charcoal are represented in Figs. 6 and 7, respectively. Because the amount of moisture contained in the charcoal is relatively small, its content does not have a significant effect on the solid temperature. The amount of volatile component is so small that its content does not affect the temperature.

CONCLUSIONS

The rotary kiln for the activation of coconut-shell charcoal is simulated, and the temperature distributions of environmental gas and solid in the kiln are calculated. The optimal operation condition of the kiln is found from the simulation results. For the reductive gas environment required in the charcoal activation, the gas temperature is adjusted to be around 950 °C and the necessary fuel amount is found from the computation outcome. The analysis of the computed results indicates that the fuel and feed amount give large variation of gas and solid temperatures. However, the activation steam and moisture and volatile contents in feed have little effect on the temperatures. The temperature distribution of the kiln of charcoal activation has a similar pattern to that of coal pyrolysis due to the similarity of heat transfer mechanism.

ACKNOWLEDGEMENTS

NOMENCLATURE

A   : gas-solid surface per unit of length [m²/m]
A_v : absorptivity [-]
C   : parameters listed in Table 2 [-]
C_g : average specific heat of gas [kJ/(kg K)]
C_s : average specific heat of solid [kJ/(kg K)]
C_v : average specific heat of water vapor [kJ/(kg K)]
C_w : average specific heat of kiln wall [kJ/(kg K)]
e_g : gas emissivity [-]

e_s : solid emissivity [-]
e_w : emissivity of internal surface of wall [-]
h_{gs} : heat transfer coefficient between the solid and gas [W/(m² K)]
h_{gw} : heat transfer coefficient between the wall and gas [W/(m² K)]
h_t : convection coefficient between the gas and solid [W/(m² K)]
h_w : heat transfer coefficient between the wall and solid [W/(m² K)]
H_v : latent heat of vaporization of water [kJ/kg]
ΔH : heat of reaction [kJ/kmol]
k_e : first-order reaction rate constant [1/s]
L_{cu} : cord length [m²]
L_{es} : covered wall surface [m²]
L_{li} : cord length [m²]
M_w : wall mass per unit kiln length [kg/m]
Q_a : water vapor flow rate [kg/s]
Q_g : gas flow rate [kg/s]
Q_h : moisture flow rate [kg/s]
Q_S : solid flow rate [kg/s]
T_g : gas temperature [K]
T_s : solid temperature [K]
T_w : temperature of internal surface of the wall [K]

t : time [s]
V_g : gas velocity [m/s]
V_s : solid velocity [m/s]
z : kiln length [m]

Greek Letters
φ_{sw} : radiation number listed in Table 2 [-]
σ : Boltzmann constant 5.57×10^8 [W/(m² K⁴)]

REFERENCES

1. O. A. Oritiz, G. I. Suárez and A. Nelson, *Comput. Chem. Eng.*, **29**, 1837 (2005).
2. F. Patisson, E. Lebas, F. Hanrot, D. Ablitzer and J.-L. Houzelot, *Metall. Mater.*, **31B**, 381 (2000).
3. F. Patisson, E. Lebas, F. Hanrot, D. Ablitzer and J.-L. Houzelot, *Metall. Mater.*, **31B**, 391 (2000).
4. M. J. Antal, Jr. and M. Gronli, *Ind. Eng. Chem. Res.*, **42**, 1619 (2003).
5. H.-Y. Kang, S.-S. Park and Y.-S. Rim, *Korean J. Chem. Eng.*, **23**, 948 (2006).
6. P. Ji, W. Feng and B. Chen, *Ind. Eng. Chem. Res.*, **48**, 3909 (2009).
7. C. Tangsathithulchai, Y. Ngernyen and M. Tangsathithulchai, *Korean J. Chem. Eng.*, **26**, 1341 (2009).