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Modeling and Simulation of a Separate Line Calciner Fueled with a Mixture of Coal and Rice Husk

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A model has been made to predict performance of a calciner in a cement plant for the use of rice husk as partial substitution of coal. The calciner was assumed as a plug flow reactor with no-mass and heat transfer limitations. The model was composed of three equations of calcination, coal and rice husk combustions with kinetic parameters obtained from literature. Two of 20 sets of operation data were used as base-lines for simulations, namely: Case-A from operation at a capacity of 532 ton h^{-1} of kiln feed (KF) with coal as a fuel; and Case-B at 530 ton h^{-1} with 20% rice husk in a mixed fuel. Two simulations were executed at constant total fuel mass flow-rate (21.94 ton h^{-1} of Case-A and 27.39 ton h^{-1} of Case-B) and at constant total energy supplied (0.946 and 1.188 GJ ton^{-1} KF for Case-A and Case-B respectively). Our simulation showed that a target CaCO3 conversion could be obtained using mixed fuel with maintaining constant total energy supplied instead of constant total fuel mass flow-rate. In Case-A as base-line, the use of mixed fuel with 20% rice husk with maintaining constant supplied energy would give a coal saving of 11.8%. This operation however would require an increase in specific fuel consumption from 0.0412 to 0.0455 ton ton^{-1} of KF. In Case-B as base-line, the CaCO3 conversion of 95% could be obtained with a mixed fuel with rice husk mass fraction up to 40%.

Keywords: calcination, coal, rice husk, co-combustion

INTRODUCTION

Cement plants in Indonesia need about 6.0 – 7.0 million tons of coal annually to produce around 34 million tons of cement in dry-process. About 60% of coal consumption in a cement plant is burnt in the calciner to provide heat for calcination $CaCO_3 \rightleftarrows CaO + CO_2$; the rest is used in the rotary kiln for clinkerization. Partial substitutions of coal with abundant biomass such as rice husk and oil palm solid wastes has already been trialed in several cement plants in Indonesia. Although the use of rice husk as partial substitution of coal in a calciner has been successful to some extent, studies are still needed to understand phenomena and to predict the performance of calciner. These are due to differences in physical and chemical properties of rice husk compared to coal, especially on energy density, moisture and ash contents. Temperature in a calciner fueled with a mixed fuel may be lower, and $CaCO_3$ conversion may decreases drastically. This paper deals with modeling and simulation of a calciner fueled with a mixture of coal and rice husk in one of existing cement plants in Indonesia. The model was verified using plant operation data and hopefully it would be useful for anticipating the performance of a calciner fueled with a mixture of coal and various fractions of rice husk. Our study was focused on the calciner at *Separate Line Calciner string* (SLC-string) where coal and rice husk were fed.

MODEL DEVELOPMENT

The calciner was a cylindrical vessel with a length of about 20.7 m and a diameter of about 7.4 m. In our model, the calciner was assumed as a plug-flow reactor with the same temperatures and flow rates of solid particle and gas. Calcination reaction was modeled as modified random pore (Khinast et al., 1996), taking into account varying of surface area of reaction on $CaCO_3$ particle during calcination. Combustion of coal was assumed as a homogeneous model (Ballester and Jiménez, 2005) taking into account varying particle size and density during combustion. Combustion of rice husk was assumed as a lump model (Mansaray and Ghaly, 1999). All of minerals in *Raw Meal* (for instance: $MgCO_3$, SiO_2, Al_2O_3, and Fe_2O_3) were assumed as solid inert, except $CaCO_3$. Raw Meal with a rate of about 520 ton h^{-1} was divided into: SLC (*Separate Line Calciner string*) and ILC (*In Line Calciner string*) with assumption of equal rates. Each string consisted of 4 stage cyclones and one calciner. The calciner in SLC got two feeds, i.e.: KF-SLC and KF-ILC. The former came from cyclones in SLC, and the later came from calciner in ILC. KF-SLC was assumed as unconverted $CaCO_3$, while KF-ILC was assumed to have a conversion of 80%.

Properties of coal and rice husk were adopted from literature (see Table 1). Based on practical information from the cement plant, a complete combustion with excess air of 20% was applied in all simulations. The model was a set of ordinary differential equations consisting of nine mass balances and one energy balance (see Table 2). The model was solved using *fourth-order Runge-Kutta-Feldberg* (available in MATLAB R2008a).

RESULTS OF SIMULATION

The model was verified using 20 sets of operation data. The model was solved using initial based from on the respective operation data and the results of calculation were compared to measured temperature and $CaCO_3$ conversion at the outlet of calciner (see examples in Table 3). From 20 sets of operation data, the average error of approximation for temperature was 1.40%, while that for $CaCO_3$ conversion was 1.09%.

Temperature and Conversion Profiles

Two among 20 sets of operating data and calculation results have been used as base-lines for further simulation, namely: Case-A (fueled with coal) and Case-B (fueled with a mixture of coal and 20%-mass rice husk). Initial values derived from the operating data and results of calculation are presented in Table 3. Based on operation data, the use of rice husk up to 20%-mass did not affect $CaCO_3$ conversion (94.7% for Case-A and 94.2% for Case-B). But our calculations showed a higher $CaCO_3$ conversion in Case-A than Case-B (98.9% vs 93.6%). Moreover, the trend in difference between results of calculation against operating data in Case-A and Case-B were different. These discrepancies might be due to our rough assumption of excess air of 20% for all calculations. Increasing excess air in calculation in Case-A and reducing excess air in Case-B might improve the prediction of $CaCO_3$ conversion.

Temperature profile, and $CaCO_3$, coal and rice husk conversions profiles in calciner could also predicted (see examples in Figure 1). Our simulation clearly showed that the use of rice husk influenced the conversion and temperature profiles very much. Although the final $CaCO_3$ conversion in Case- B was lower than that in Case-A, conversion of $CaCO_3$ took

Table 1. Properties of Coal and Rice Husk

Proximate analysis(db)	Coal[a]	Rice husk[b]	Ultimate analysis (db)	Coal[a]	Rice husk[b]
a. Moisture	14.20 %	9.93 %	a. Ash	5.36 %	22.82 %
b. Fixed carbon	43.71 %	16.63 %	b. Carbon	58.96 %	33.97 %
c. Volatile matter	50.93 %	60.55 %	c. Hydrogen	3.96 %	5.31 %
d. Ash	5.3 %	22.82 %	d. Nitrogen	1.18 %	0.11 %
			e. Sulfur	0.37 %	0.02 %
			f. Oxygen	30.18 %	37.78 %
Miscellaneous:					
HHV, kJ kg^{-1}	22,970	13,416			
Particle density, kg m^{-3}	1600	144			
Particle diameter, μm	90	3000			

[a]Nugroho et al. (1998)
[b]Hartiniati and Youvial (1989)

Table 2. Mathematical model of calciner

1. Mass balance of $CaCO_3$

$$\frac{dF_{CaCO3}}{dz} = -3.85 \times 10^{12}(1-\varepsilon_R)(1-X_{CaCO3})^{1.7}[1-37\ln(1-X_{CaCO3})]^{0.69} exp\left(-\frac{201000}{RT} - 11.92\frac{p^*_{CO2}}{p^e_{CO2}}\right)$$

2. Mass balance of CaO

$$\frac{dF_{CaO}}{dz} = -\frac{dF_{CaCO3}}{dz}$$

3. Mass balance of coal

$$\frac{dF_{coal}}{dz} = -3.0816(1-\varepsilon_R)\frac{W_{coal}}{d^0_P\rho^0_d}U^{0.16}p_{O2,s} exp\left(-\frac{99000}{RT}\right)$$

4. Mass balance of rice husk

$$\frac{dF_{RH}}{dz} = -476.84(1-\varepsilon_R) exp\left(-\frac{14300}{RT}\right)W^{0.2}_{RH}$$

5. Mass balance of O_2

$$\frac{dF_{O2}}{dz} = -\left[\frac{q}{p}\frac{dF_{coal}}{dz} + \frac{q'}{p'}\frac{dF_{RH}}{dz}\right]$$

6. Mass balance of CO_2

$$\frac{dF_{CO2}}{dz} = \frac{r}{p}\frac{dF_{coal}}{dz} + \frac{r'}{p'}\frac{dF_{RH}}{dz} + \frac{dF_{CaCO3}}{dz}$$

7. Mass balance of H_2O

$$\frac{dF_{H2O}}{dz} = \frac{s}{p}\frac{dF_{coal}}{dz} + \frac{s'}{p'}\frac{dF_{RH}}{dz}$$

8. Mass balance of N_2

$$\frac{dF_{N2}}{dz} = 0$$

9. Mass balance of solid inert

$$\frac{dF_{inert}}{dz} = 0$$

10. Heat balance

$$\frac{dT}{dz} = \frac{A_R(1-\varepsilon_R)\left(\Delta H_{R,cal,T}\gamma + \Delta H_{R,BB,T}\gamma_{coal} + \Delta H_{R,SP,T}\gamma_{RH}\right) - T\left(\sum_i \overline{Cp_i}\frac{dF_i}{dz}\right)}{\sum_i F_i Cp_i}$$

11. Initial condition

At z=0 → $T=T_0$; $X_{CaCO3}=0$; $F_i=F_{i,0}$;

For i=$CaCO_3$, CaO, coal, rice husk, O_2, CO_2, H_2O, N_2 and solid inert (see examples in table 3)

Table 3. Initial Conditions and Simulation Results o Case-A and Case-B

No.	Parameter	Symbol	Case A		Case B	
1.	Kiln feed to SLC, ton h^{-1}			532		530
2.	Fuel			100% coal		80% coal + 20% RH
			Plant data as initial conditions (see equation in Table 2)			
3.	Flow of $CaCO_3$, kmol s^{-1}	$F_{CaCO3,0}$		0.5731		0.7047
4.	Flow of CaO, kmol s^{-1}	$F_{CaO,0}$		1.0223		0.7881
5.	Flow of coal, kmol s^{-1}	$F_{coal,0}$		0.0017		0.0017
6.	Flow of rice husk, kmol s^{-1}	$F_{RH,0}$		0		0.0006
7.	Flow of H_2O, kmol s^{-1}	$F_{H2O,0}$		0.0330		0.0499
8.	Flow of O_2, kmol s^{-1}	$F_{O2,0}$		0.5743		0.6499
9.	Flow of N_2, kmol s^{-1}	$F_{N2,0}$		2.1570		2.4449
10.	Flow of CO_2, kmol s^{-1}	$F_{CO2,0}$		0		0
11.	Flow of solid inert, kmol s^{-1}	$F_{inert,0}$		0.5595		0.5554
12.	Temp. at calciner inlet, °C	T_0		783		766
			Results of calculation and comparison to operating data			
No.	Parameter	Symbol	Results	Plant data	Results	Plant data
13.	Temp. at calciner outlet, °C	T	890	882	870	857
14.	Error in temperature	ε_T	-0.91%	0.92%	1.49%	1.54%
15.	$CaCO_3$ conversion at outlet	X_{CaCO3}	94.7%	98.9%	94.2%	93.6%
16.	Error in $CaCO_3$ conversion	ε_T	-4.44%	4.43%	0.64%	0.67%
17.	Specific input energy in fuels, GJ ton^{-1} of KF	$\overline{Q_{in}}$		0.948		1.076

Table 4. Coal and Rice Husk FeedRates to Meet Certain Specific

No.	Mass fraction of rice husk	Fuel flow rate, ton ton^{-1} KF for specific energy of 0.946 GJ ton^{-1} KF				Fuel flow rate, ton ton^{-1} KF for specific energy of 1.188 GJ ton^{-1} KF			
		Coal	Rice husk	Total	Coal saving	coal	Rice husk	Total	Coal saving
1.	0%	0.0412	0	0.0412	--	0.0516	0	0.0516	--
2.	10%	0.0389	0.0043	0.0433	5.6%	0.0048	0.0054	0.0542	5.5%
3.	20%	0.03642	0.0091	0.0455	11.8%	0.0456	0.0114	0.0570	11.7%
4.	30%	0.0336	0.0144	0.0480	18.6%	0.0421	0.0180	0.0601	18.5%
5	40%	0.0305	0.0203	0.0508	26.2%	0.0381	0.0254	0.0636	26.1%

place rapidly in the first part of calciner in both cases. Moreover, rice husk conversion in Case-B was lagging significantly. This might be a reason for lowering temperature and therefore decreasing $CaCO_3$ conversion in Case-B compared to Case-A.

Simulations on Constant Fuel Mass Flow Rate

This simulation was carried out with varying mass fraction of rice husk from 0% to 40% while keeping the ratio of total fuel to KF at constant values 0.040 kg/kg for Case-A and 0.052 kg/kg for Case-B. Simulation results showed that the $CaCO_3$ conversion dropped significantly from 98.7% to 80.6% in Case-A, and from 99.3% to 81.9% in Case-B due to the use of rice husk (Figure 2). Obviously, these were because of lowering the energy density of fuel with increasing rice husk mass fraction. Temperature profiles showed similar trends with conversions.

Simulations on Constant Specific Energy

Further simulations were made with maintaining constant specific supplied energy at various fraction of rice husk in the mixed fuel. In Case-A, the specific energy was kept at 0.946 GJ ton^{-1} of KF, and that in Case-B was 1.188 GJ ton-1 of KF. Coal and rice husk flow rates to meet that specific energy were calculated using mass and energy balances. Increasing fractions of rice husk clearly needed total fuel flow rates (see Table 4). In case, the fraction of rice husk in a mixed fuel was not the same with the percentage of coal substitution.

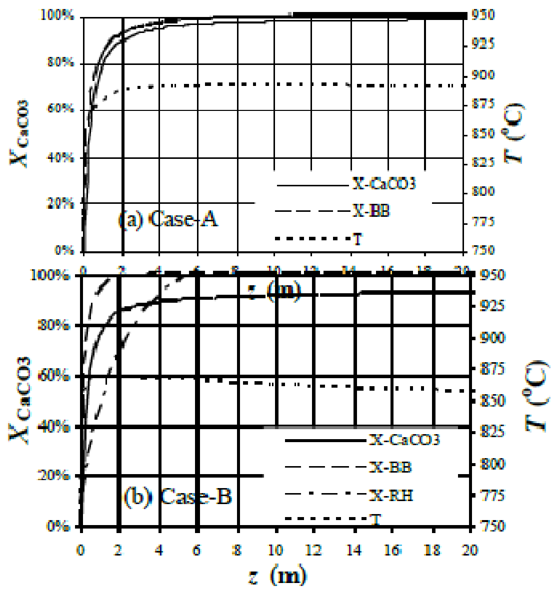

Figure 1. Temperature and conversion profiles in base-lines (see Table 3)

Although the specific total energy supplied was kept constant, partial substitution of coal with rice husk resulted in decreases in $CaCO_3$ conversion significantly. However unlike in the case of constant total fuel mass flow rates, the operation with constant specific supplied energy might still give an acceptable $CaCO_3$ conversion above 92% (Figure 3). Simulation using Case-B as a base-line showed higher $CaCO_3$ conversions than that using Case-A at a certain fraction of rice husk in the mixed fuel. This was understandable as the specific supplied energy in Case-B was higher than that in Case-A which would give higher temperature profiles. Further examination on the results of simulation showed that conversion of 95% could be achieved in Case-A using a mixed fuel with rice husk up to 30%-mass. While in Case-B with the specific energy of 1.188 GJ ton^{-1} KF, $CaCO_3$ conversion of 95% might be achieved using a mixed fuel with fraction of rice husk up to 40%. Operation mode, either with specific energy of 0.946GJ ton^{-1}KF and 30% rice husk or 1.188GJ ton^{-1} KF and 40% rice husk, should be chosen with taking various technical aspects into considerations.

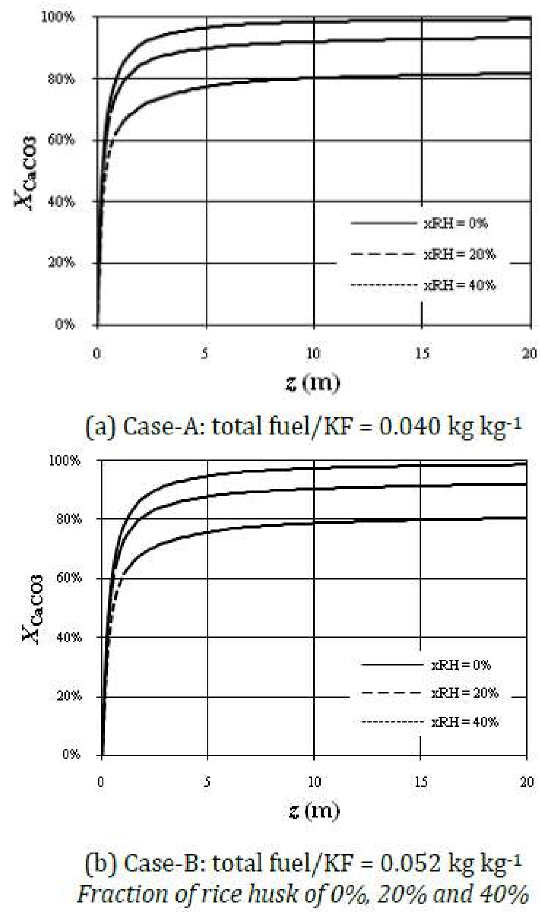

Figure 2. Results of simulation at constant total fuel mass flow rate

Specific Fuel Consumption for Target Conversion

A graph for prediction and anticipating of the performance of calciner with mixed fuel has been developed (presented in Pranolo and Susanto, 2009). As an example, a calcination to obtain $CaCO_3$ conversion of 95% might be operated with a mixed fuel containing 5%-mass of rice husk and with a specific fuel flow rate of 0.048 ton ton^{-1} KF. The flow rate of this mixed fuel was 0.002 ton ton^{-1} KF higher than that of coal as a single fuel, but a coal saving of 1.8% might obtained. The temperature at the outlet of calciner was predicted to be 873 °C. In this case, O_2 and CO_2 contents in the gas leaving the calciner are in 4.75% and 31.6% respectively.

In another case, the use of a mixed fuel with 20%-mass fraction of rice husk would give a coal saving of 8.20% without decreasing $CaCO_3$ conversion. But, the specific fuel consumption must be increase from 0.046 to 0.053 ton ton^{-1} KF compared to the use of coal as single fuel. Results of calculation showed that the outlet temperature decreased insignificantly from 873 °C to 870 °C. O_2 content in the outlet gas increased 0.5%, while CO_2 decreased from 31.5% to 30.5%. Thus in principle, a certain $CaCO_3$ conversion might be obtained in a calcination using mixed fuel with various fraction of rice husk provided with an adjustment of the specific total fuel consumption.

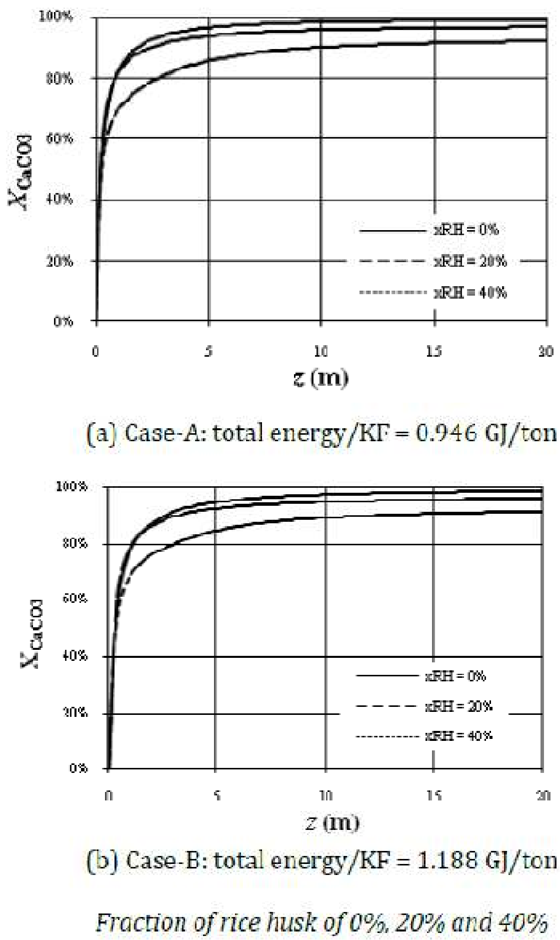

Figure 3. Results of simulation at constant specific energy

CONCLUSIONS

The effect of partial substitutions of coal with rice husk on the performance of a calciner in SLC has been studied using a chemical reaction model. A mixed fuel with 20%-mass fraction of rice husk (as targeted by a cement plant management) might be used to obtained $CaCO_3$ conversion, but the coal saving would actually only be 8.4% since the total flow rate of mixed fuel was 14.6% higher than that of coal as a single fuel. Based on our simulation, $CaCO_3$ conversion of 95% could be achieved using a mixed fuel with rice husk mass fraction up to 30% or 40% as far as the specific supplied energy could be kept at 0.946 or 1.188 GJ ton^{-1} KF respectively.

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NOTATION

A_R	Longitudinal section area of calciner, m^2
$\overline{Cp_i}$	Average heat capacity of component i, kJ kmol^{-1} K^{-1}
d_P^0	Initial particle diameter, m
F_i	Mass flow of component i, kmol s^{-1}
F_i^0	Initial mass flow of component i, kmol s^{-1}
ΔH_R	Heat of reaction, kJ kmol^{-1}
P	Total pressure in calciner, atm
p	Coefficient of reaction of coal in coal combustion
p'	Coefficient of reaction of rice husk in rice husk combustion
p_{CO2}^*	Partial pressure of CO_2 at reaction surface, atm
p_{CO2}^e	Equilibrium partial pressure of CO_2 at reaction surface, atm
q	Coefficient of reaction of O_2 in coal combustion
q'	Coefficient of reaction of O_2 in coal rice husk combustion

R	Universal gas constant, kJ kmol^{-1} K^{-1}
RH	Rice husk
r	Coefficient of reaction of CO_2 in coal combustion
r'	Coefficient of reaction of CO_2 in rice husk combustion
s	Coefficient of reaction of H_2O in coal combustion
s'	Coefficient of reaction of H_2O in rice husk combustion
T	Reaction temperature, K
U	Mass fraction of unburned coal
W_{coal}	Mass of coal during combustion, kg
W_{RH}	Mass of rice husk during combustion, kg
X_{CaCO3}	Conversion of $CaCO_3$
X_{RH}	Mass fraction of rice husk in fuel mixture
z	Axial position in the calciner, m

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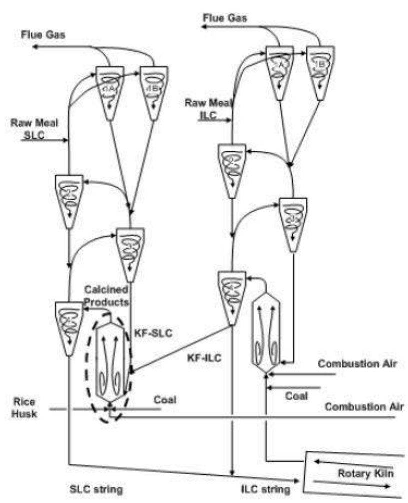
ATTACHMENT

This attachment deals with the schematic diagram of SLC- calciner (circled with dashed line) set-up. Raw meal entering the SLC-calciner came from two sources (see following figure):

a) From the top of SLC-string, underwent heating up in the ciner with as a partially calcined feed (called: KF-ILC). series of cyclones and finally entered the SLC-calciner without calcination (called: KF-SLC),
b) From the top of ILC-string, through the series of cyclone, underwent calcination in the ILC-calciner and finally entered the SLC-calciner with as a partially calcined feed (called: KF-ILC)



Separate Line Calciner with In-Line Calciner

Based on the Reynolds number, the material flow in the SLC-calciner was characterized as turbulent flow (177,600 < Re < 276,325). The reactor behavior was determined with Peclet number,

$$Pe = \frac{\bar{u}L}{D} = \frac{5.15 \times 20.69}{8.5} = 12.54$$

Based on those numbers, the calciner might be assumed as plug-flow reactor.