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SIMULATION OF THE ROTARY LIMEKILN AND LIME COOLER

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ABSTRACT. A mathematical model of the calcium carbonate decomposition process has been developed in order to determine the time and space evolution of temperature, solid and gaseous products distribution in the rotary limekiln.

The model incorporates a detailed mathematical description for the two phases (gas and solid) present into the system, also taking into account the heat transfer through the kiln wall. The gas phase, solid phase and kiln wall have been modeled using mass and heat balance equations for counter-current flow systems. Both time and spatial distribution for gaseous and solid components are described revealing the interactions between different subsystems considered in the study.

1. INTRODUCTION

The thermal decomposition of limestone is a very important process. In 2006, 271000 thousand metric tones of lime were produced in the entire world [1]. Lime, the main product of limestone thermal decomposition process, is a basic chemical; practically the lime is used in every human activity domain. The breakdown of consumption by major end-users was as follows: 36 % for metallurgical use, 27 % for environmental use, 24 % for chemical and industrial use and 13 % for construction use.

The decrease of energy consumption and efficient use of raw materials for the decomposition process of the limestone in a limekiln leads to important economic benefits (it decreases the operational costs; it increases the gross margin of the process; it makes lime manufacture processes more sustainable etc.).

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2. MATHEMATICAL MODEL OF ROTARY LIME KILN

The rotary limekiln consists of a cylindrical shell with its long axis having a small inclination from the horizontal direction. Calcium carbonate is introduced at the highest end of the shell and moves towards the lower end due to the rotation and the inclination of the cylinder. In the lower end of the kiln, a natural gas flux is burning in order to produce the heat necessary for the endothermic reaction (calcium carbonate decomposition)

The rotary limekiln with a gas heat recovery is presented in figure 1.

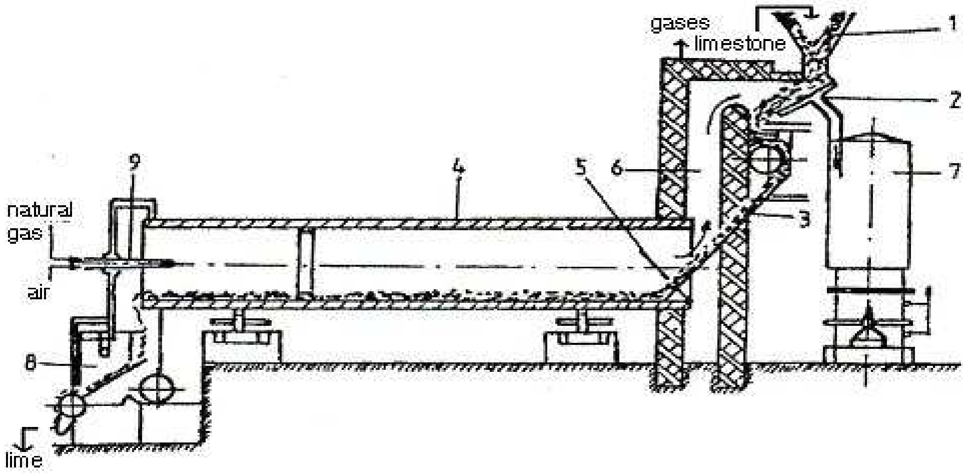

Figure 1. Rotary limekiln with a gas recovery system [2]
1 – calcium carbonate tank, 2 – grid, 3 – feed chute , 4 – rotary limekiln, 5 – cross wall , 6 – gas tower, 7 - scrubber , 8 – lime cooler, 9 – gas burner

Three zones can be distinguished along the kiln in the direction of the movement of the solid material. The first zone starts at the calcium carbonate feed and is the solid heating zone. The second zone is the reaction zone where most of the decomposition process is taking place. The last one is the combustion zone where the fuel flame is developed.

The produced lime is cooled with primary cool air in a lime cooler, figure 2.

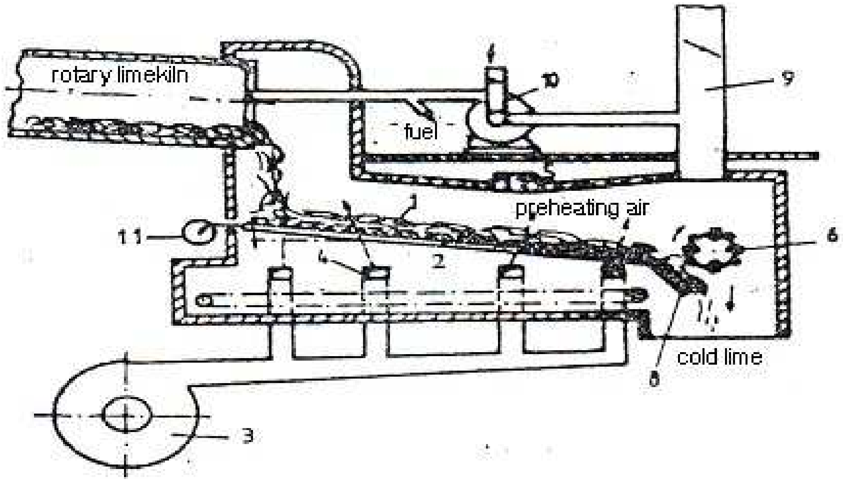

Figure 2. Lime cooler [2]
1 – grid, 2 – bars , 3 – ventilator , 4 – air distributor, 5 – connection ,
6 – disintegrator with hammers, 7 – conveyer, 8 – lime outlet,
9 – secondary chimney, 10 – primary air ventilator, 11 – engine

The following assumptions have been considered for model development:

- Model parameters are constant in the radial cross section of the kiln;
- Both gas and solids velocity is considered constant.
- Limestone is uniformly distributed across the kiln section;
- Flowing regime is ideal for both phases (plug flow);
- Heat transfer by conduction and radiation are negligible in the axial direction;
- Coefficients of convection, emissivities, latent heat and heat of reaction are independent of temperature.

Heating zone:

The mass balance for solid and gas flows is described by the equations:

$$\frac{1}{V_m}\cdot\frac{\partial}{\partial t}\left(Q_m\right)=-\frac{\partial}{\partial z}\left(Q_m\right)-\frac{h_t\cdot A_T\cdot\left(T_g-T_m\right)}{L_v\cdot\left(0.1\cdot Q_m\right)}\cdot Q_h$$

$$\frac{1}{V_g}\cdot\frac{\partial}{\partial t}\left(Q_g\right)=-\frac{\partial}{\partial z}\left(Q_g\right)+\frac{h_t\cdot A_T\cdot\left(T_g-T_m\right)}{L_v\cdot\left(0.1\cdot Q_m\right)}\cdot Q_h$$

The heat balance equations for gas, solid and kiln wall are presented in the following equations:

$$\frac{Q_g \cdot C_g}{V_g} \cdot \frac{\partial}{\partial t}\left(T_g\right) = -Q_g \cdot C_g \cdot \frac{\partial}{\partial z}\left(T_g\right) - H_{gm} - H_{gp}$$

$$\frac{Q_m \cdot C_m}{V_m} \cdot \frac{\partial}{\partial t}\left(T_m\right) = -Q_m \cdot C_m \cdot \frac{\partial}{\partial z}\left(T_m\right) + H_{gm} - H_{pm}$$

$$M_p \cdot C_p \cdot \frac{\partial}{\partial t}\left(T_p\right) = H_{gp} + H_{pm} - H_{p0}$$

Reaction zone (calcium carbonate decomposition):

The mass balance equations for the gaseous and solid productions are:

$$\frac{1}{V_g} \cdot \frac{\partial Q_g}{\partial t} = -\frac{\partial Q_g}{\partial z} + \frac{Q_m}{V_m} x_{CaCO_3} k_{CaCO_3} \frac{M_{CO_2}}{M_{CaCO_3}}$$

$$\frac{1}{V_m} \cdot \frac{\partial Q_m}{\partial t} = -\frac{\partial Q_m}{\partial z} - \frac{Q_m}{V_m} x_{CaCO_3} k_{CaCO_3} \frac{M_{CO_2}}{M_{CaCO_3}}$$

The kinetics of calcium carbonate decomposition reaction is considered to follow Arrhenius' law.

The mass balance equations for calcium carbonate contained in solid is:

$$\frac{1}{V_m} \cdot \frac{\partial x_{CaCO_3}}{\partial t} = -\frac{\partial x_{CaCO_3}}{\partial z} - \frac{1}{V_m} x_{CaCO_3} k_{CaCO_3}$$

The heat balance equations for gas, solid and kiln wall are presented in the following equations:

$$\frac{Q_g c_g}{V_g} \cdot \frac{\partial T_g}{\partial t} = -Q_g c_g \frac{\partial T_g}{\partial z} - H_{gm} - H_{gp}$$

$$\frac{Q_m c_m}{V_m}\cdot\frac{\partial T_m}{\partial t} = -Q_m c_m \frac{\partial T_m}{\partial z} + \frac{Q_m}{V_m} x_{CaCO_3} k_{CaCO_3} \Delta H_{CaCO_3} + H_{gm} - H_{pm}$$

$$M_p \cdot C_p \cdot \frac{\partial T_p}{\partial t} = H_{gp} + H_{pm} - H_{p0}$$

Flame zone:

The heat balance equations for gas, solid, flame and kiln wall are:

$$\frac{Q_g \cdot C_g}{V_g}\cdot\frac{\partial}{\partial t}\left(T_g\right) = -Q_g \cdot C_g \cdot \frac{\partial}{\partial z}\left(T_g\right) + H_{fg} - H_{gm} - H_{gp}$$

$$\frac{Q_m \cdot C_m}{V_m}\cdot\frac{\partial}{\partial t}\left(T_m\right) = -Q_m \cdot C_m \cdot \frac{\partial}{\partial z}\left(T_m\right) + H_{gm} + H_{pm} + H_{fm}$$

$$\frac{Q_c \cdot C_c}{V_g}\cdot\frac{\partial}{\partial t}\left(T_f\right) = -Q_c \cdot C_c \cdot \frac{\partial}{\partial z}\left(T_f\right) - H_{fp} - H_{fm} - H_{fg}$$

$$M_p \cdot C_p \cdot \frac{\partial}{\partial t}\left(T_p\right) = H_{gp} - H_{pm} - H_{p0}$$

The heat fluxes considered in the above equations are:
- heat flux to the environmental

$$H_{p0} = h_0 \cdot \pi \cdot D \cdot \left(T_p - T_0\right) + \sigma \cdot \pi \cdot D \cdot e_{p\cdot} \cdot \left(T_p{}^4 - T_0{}^4\right)$$

The heat fluxes H_{gm} (gas to solid), H_{gp} (gas to kiln wall), H_{pm} (kiln wall to solid) are different for each zone:

- heat zone (and lime cooler)
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$$H_{gm} = h_g \cdot L_2 \cdot \left(T_g - T_m\right) + \sigma \cdot L_2 \cdot e_m \cdot e_g \cdot \left(T_g{}^4 - T_m{}^4\right)$$

$$H_{gp} = h_g \cdot L_3 \cdot \left(T_g - T_p\right) + \sigma \cdot L_3 \cdot e_p \cdot e_g \cdot \left(T_g{}^4 - T_p{}^4\right)$$

$$H_{pm} = h_p \cdot L_1 \cdot \left(T_p - T_m\right) + \sigma \cdot L_2 \cdot e_p \cdot \left(1 - e_g\right) \cdot e_m \cdot \left(T_p{}^4 - T_m{}^4\right)$$

- reaction zone

$$H_{gm} = U \cdot A_T \cdot \left(T_g - T_m\right)$$

$$H_{gp} = h_g \cdot L_3 \cdot \left(T_g - T_p\right) + \sigma \cdot L_3 \cdot e_p \cdot e_g \cdot \left(T_g{}^4 - T_p{}^4\right)$$

$$H_{pm} = h_p \cdot L_1 \cdot \left(T_p - T_m\right)$$

- flame zone

The fluxes H_{fm} (flame to solid), H_{fp} (flame to kiln wall), H_{fp} (flame to kiln wall) are:

$$H_{fm} = \sigma \cdot L_2 \cdot e_f \cdot e_m \cdot \left(1 - e_g\right) \cdot F_{fm} \cdot \left(T_f{}^4 - T_m{}^4\right)$$

$$H_{fp} = \sigma \cdot L_3 \cdot e_f \cdot e_p \cdot \left(1 - e_g\right) \cdot F_{fp} \cdot \left(T_f{}^4 - T_p{}^4\right)$$

$$H_{fg} = \sigma \cdot \pi \cdot D_f \cdot e_{f\cdot} \cdot e_g \cdot \left(T_f{}^4 - T_g{}^4\right) + h_f \cdot \pi \cdot D_f \cdot \left(T_f - T_g\right) - \frac{\partial Q_c}{\partial l} \cdot C_c \cdot T_f$$

Lime cooler:

In the cooler, only heat phenomena (heat transfer and transport) takes place. The heat balance equations for gas, solid and kiln wall are presented in the following equations:

$$\frac{Q_g \cdot C_g}{V_g} \cdot \frac{\partial}{\partial t}\left(T_g\right) = -Q_g \cdot C_g \cdot \frac{\partial}{\partial z}\left(T_g\right) + H_{gm} - H_{gp}$$

$$\frac{Q_m \cdot C_m}{V_m} \cdot \frac{\partial}{\partial t}\left(T_m\right) = -Q_m \cdot C_m \cdot \frac{\partial}{\partial z}\left(T_m\right) - H_{gm} - H_{pm}$$

$$M_p \cdot C_p \cdot \frac{\partial}{\partial t}\left(T_p\right) = H_{gp} + H_{pm} - H_{p0}$$

The simulation of the calcium carbonate decomposition process was done using Matlab software package.

3. RESULTS AND DISCUSSIONS

The simulation based on the mathematical model of the calcium carbonate decomposition process reveals the time and space evolution of temperature, flows, solid and gaseous products in the rotary kiln.

Some of the most representative simulation results are presented in the figures below. The solid is the principal raw material of the process and consequently, in the figures below the bench mark "0" is the calcium carbonate feed end of the rotary kiln.

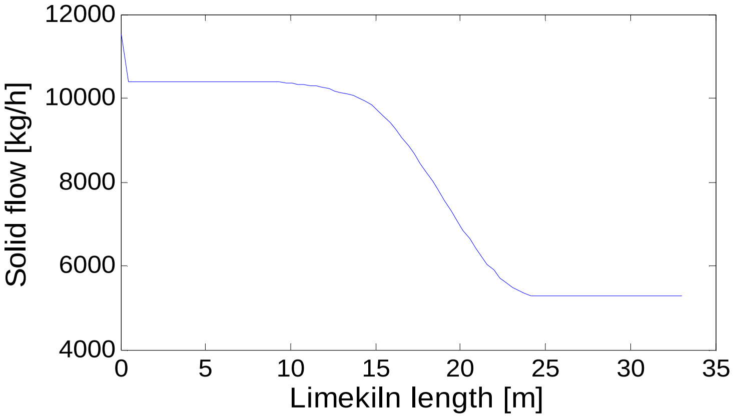

Figure 3. Solid flow profile

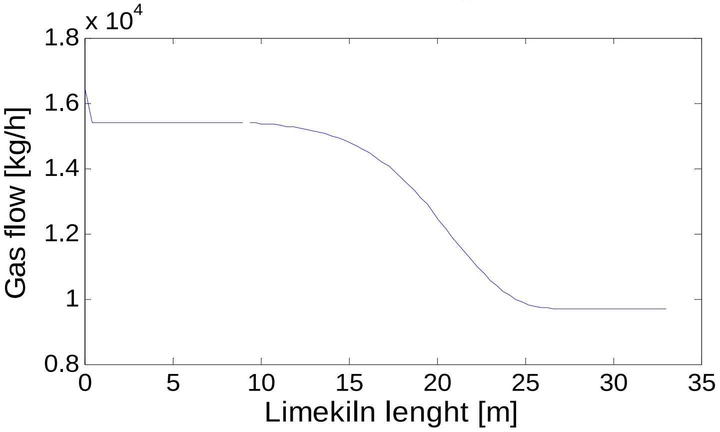

Figure 4. Gas flow profile

In the figures, 3 and 4 are presented the solid and gas flow profiles along the kiln length. The flows are almost constant in the heating zone, because in this zone only physical processes occur (heat transfer between solid and gaseous phase and limekiln wall) without mass transfers between the phases presented in the kiln. Exception is in the first part of the heating zone, when the drying of solid takes place.

The calcium carbonate content of the solid decreases along the reaction zone, reaching a value less than 4% at the discharge end, figure 5.

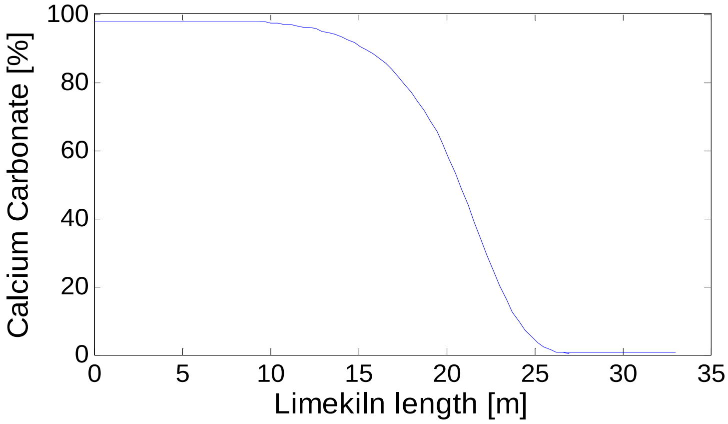

Figure 5. Calcium carbonate content profile

The lime T_m, gas T_g and inside kiln wall T_p temperatures profiles, for the lime cooler are present in the figure 6.

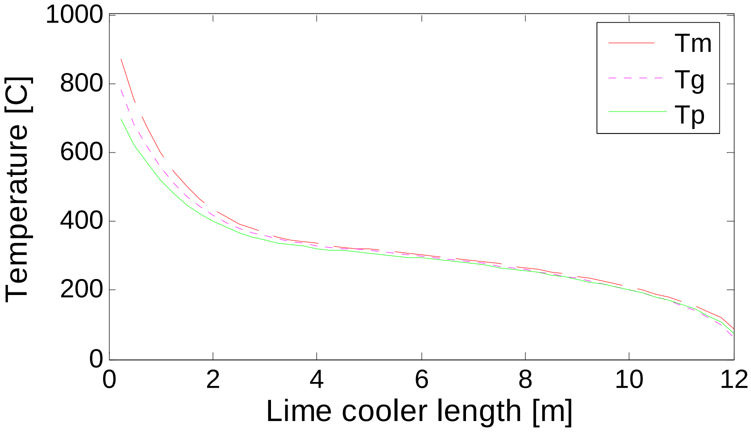

Figure 6. Lime temperature profile

The answer of the rotary kiln system was also investigated in the presence of typical disturbances. If one or more input variables are changed, the system behavior is modified to reach other stationary state (the outputs parameters of the system are changed). For example, if the solid flow rate Q_m increase with a step + 1000 Kg/h at the solid feed end, the gas flow increase with 600 kg/h at out gas kiln end. The gas flow change is presented in figure 7.

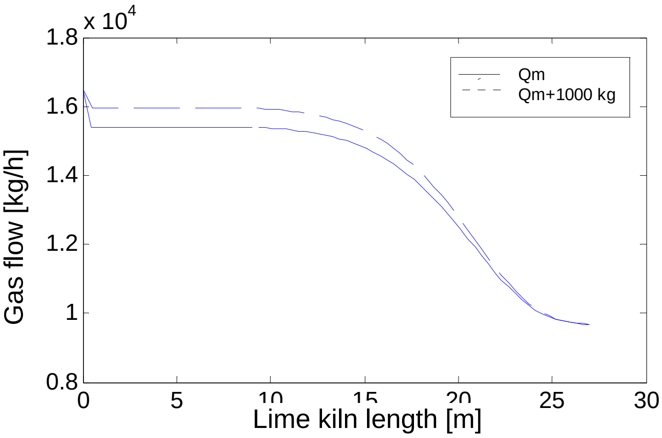

Figure 7. The gas flow change for a step increase of solid flow (Q_m + 1000 Kg/h)

The lime cooler system was also investigated. The change of the lime temperature for a step increase of the cooling air flow ΔQ_g = + 10% is presented in figure 8.

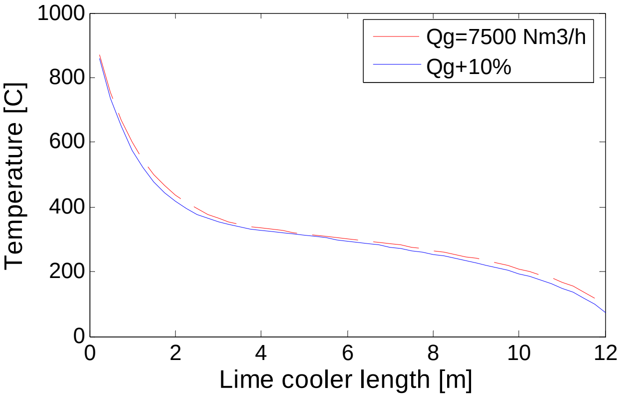

Figure 8. The lime temperature change for a step increase of natural gas flow rate of ΔQ_g =+ 10%

The simulations reveal the way that disturbances influence some important process variables and their evolution along the rotary lime kiln.

4. CONCLUSIONS

The simulation of the rotary lime kiln and lime cooler was done using MATLAB software. The time and space evolution of the main process variables (solid and gaseous flows, composition of the streams, temperature of the solid and gaseous phases) have been studied considering their complex interactions taking place during the limestone decomposition process.

The simulator based on the mathematical model and of the calcium carbonate decomposition process can be used to study the behavior of the process in changing operating conditions and the influence of different disturbances. The process simulation results can be very useful to establish the optimal operation conditions and to design the control system for the plant.

5. . NOTATION

A_T – specific area of solid exposed to gas, [m^2/m]
Cc , Cg , Cm , Cv , Cp - specific heat for combustion products, gas, solid, vapors and kiln wall [kcal/(kg·K)]
D, D_f – diameter of the limekiln and the flame, [m]
E_a – Activation Energy, [kcal/kmol]
e_f, e_g, e_p, e_m – emissivities of the flame, gas, kiln wall and solid
F_{fm}, F_{fp} – form factors for radiative heat transfer
h_f, h_g, h_p, h_m, h_0 – heat transfer coefficients, [kcal/(h·m^2·K)]
K_T – heat transfer coefficients from gas to solid, [kcal/(h·m^2·K)]
k_{CaCO3} – velocity constant of the calcium carbonate decomposition reaction, [1/h]
ΔH_{CaCO3} – heat of reaction, [kcal/kg]
M_{CaCO3} – molecular mass of calcium carbonate, [kg/kmol]
M_p – mass per unit length of the kiln wall, [kg/m]
Q_g, Q_m , Q_h – flowrate of gas, solid, moisture [kg/h]
T_g, T_m, T_p, T_f, T_0 – temperature of the gas, solid, kiln wall, flame and enviroment, [K]
V_g, V_m - gas and solids velocity, [m/h]
R – gas constant, [kcal/(kmol·K)]
U – heat transfer coefficient for the reaction zone, [kcal/(h·m·K)]
X_{CaCO3} – calcium carbonate concentration, [mass %]
σ - Stefan-Boltzmann constant, [kcal/(h·m^2·K^4)]

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