MRAC STRATEGY FOR THE TEMPERATURE PROFILE CONTROL OF A LIME KILN

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ABSTRACT

A dynamic model of a lime kiln is considered based on first principle mass and heat transfer equations. This model is validated using mill data. It is used in the IDEAS simulation environment together with a model reference adaptive control (MRAC) scheme.

INTRODUCTION

The dynamic lime kiln object models the dynamics of mass and heat transfer phenomena in a rotary kiln. The fuel ultimate analysis is defined in the object dialog box, thus accounting for any type of fuel including oil, natural gas or other non-condensable gases (NCG). The calculations required by the calcination reaction take place if $CaCO_3$ and CaO are present in the lime mud stream. All other components are treated as inerts.

KILN MODEL

The kiln model is both a chemical reactor and a counter-flow heat exchanger as noted in [1]. Fig. 1 represents the kiln block diagram. The software model captures the process functional stages: (1) lime mud **heating**, (2) water **evaporation**, (3) dried mud **heating**, (4) **calcination**, and (5) **cooling** (if equipped with cooling). Heat is released by combustion of the fuel (oil, natural gas or NCG) [1, 4].

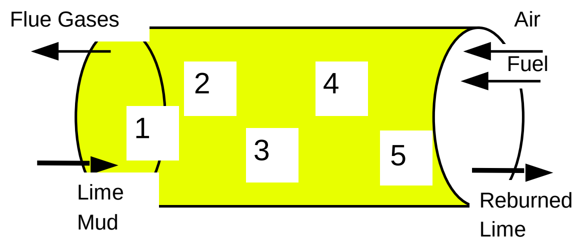

FIG. 1. BLOCK DIAGRAM OF THE LIME KILN OBJECT

The solid flow stream input is the lime mud, which is a mixture of calcium carbonate ($CaCO_3$), inerts and water (H_2O). The object receives another two stream flow inputs: fuel and air. The solid stream output contains the produced lime (CaO), and the residual $CaCO_3$. The flue gas stream output includes combustion products, water vapors from the drying zone, and carbon dioxide (CO_2) from the calcination zone. Dust is carried out in gas stream, and then recycled to solids feed.

The total rate of heat transfer to the solids is the sum of:

- Convective heat transfer from the flue gas to the solid surface
- Radiation from the hot radiant surface of the inner wall
- Conduction through the wall

The heat transfer calculations are based on the results published in [2].

The kiln is divided in N zones of dL length. The kiln fill angle θ is expressed in radian and assumed to be constant and equal to 70 degrees (1.22111 radian).

The volume of each zone is:

$$dV = dL \cdot \frac{R^2}{2}\left(\frac{\pi \cdot \theta}{180} - \sin\theta\right)$$

For each kiln zone the area of contact for heat transfer per unit length (dL) is calculated as:

Area gas to inner wall: $A_1 = dL \cdot (\pi - \theta/2) \cdot D_i$

Area gas to solid: $A_2 = dL \cdot D_i \cdot \sin(\theta/2)$

Area inner wall to solid $A_3 = dL \cdot D_i \cdot (\theta/2)$

Area inner wall to outer wall $A_4 = \pi \cdot dL(D_o - D_i)$

Area outer wall to ambient $A_5 = \pi \cdot D_o \cdot dL$

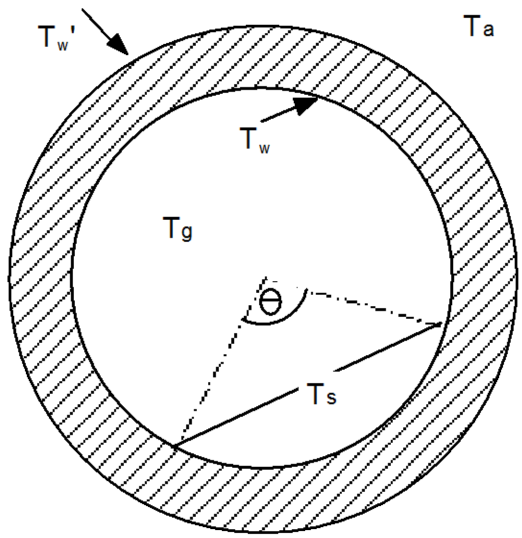

FIG 2. KILN CROSS SECTION DIAGRAM

In these equation G is the gas flow (kg/sec) and $Az = \frac{\pi \cdot D_i^2}{4}$ is the kiln cross-sectional area.

Therefore in each kiln zone the following equations are solved:

(Eq. 1) $C_s \cdot m_s \cdot \frac{dT_s}{dx} = h_{2.} A_2 (T_g - T_s) + h_{3.} A_3 (T_w - T_s) - m_w \cdot H_{w\cdot} \cdot R_w - m_c \cdot H_c \cdot k_c$

(Eq. 2) $C_g \cdot m_g \cdot \frac{dT_g}{dx} = -h_{2.} A_2 (T_g - T_s) - h_{1.} A_1 (T_w - T_g) + m_F \cdot H_F \cdot R_F$

(Eq. 3) $T_w = (h_4 A_4 + h_5 A_5)(h_1 A_1 T_g + h_3 A_3 T_s) + h_4 A_4 h_5 A_5 T_a$

(Eq. 4) $T_w^{'} = \frac{h_4 A_4 T_w + h_5 A_5 T_a}{h_4 A_4 + h_5 A_5}$

The terms $m_w \cdot H_{w\cdot} \cdot R_w$ and $m_c \cdot H_c \cdot k_c$ refer to the mass lost by the solid stream through evaporation and calcination, respectively. The term $m_F \cdot H_F \cdot R_F$ takes into account the heat of fuel combustion. The term $\varepsilon \cdot \sigma \cdot A_2 \cdot \left((T_g + 273)^4 - (T_s + 273)^4\right)$ is the radiation heat, with ε gas emissivity, and Stefan-Boltzmann Constant, $\sigma = 5.6696\text{e-}11\left(\frac{\text{kJ}}{\text{sec} \cdot \text{m}^2 K^4} \cdot\right)$. The modified heat transfer coefficients, h_1, $h_{2.}$,... $h_{5.}$ include the effect of conduction, convection and radiation.

The time of passage (minutes) in the kiln is calculated using the formula (*U.S. Bur. Mines Tech. Paper, 1927*):

(Eq. 5) $T_t = 0.19 \frac{L}{sD_i RPM}$, where L is the kiln length, s is the kiln slope, D_i is the kiln inner diameter and RPM is the kiln rotational velocity.

The total power (expressed in bhp) required to drive the rotary kiln is calculated using the following formulas (*CE Raymond Division, Combustion Engineering*):
No lifters:

$$\text{(Eq. 6)}\quad Power = RPM \cdot \frac{\left(\left(\frac{18.85 \cdot D_i}{4}\right) \cdot \sin(\varphi) \cdot (LiveLoad) + (0.1925 \cdot (D_i + 2) + 0.33) \cdot (TotalRotatingLoad)\right)}{100000}$$

With lifters:

$$Power = RPM \cdot \frac{((4.75D_i) \cdot (LiveLoad) + (0.1925 \cdot (D_i + 2) + 0.33) \cdot (TotalRotatingLoad))}{100000}$$

TEMPERATURE CONTROL

In the adaptive control problem, the plant parameters are assumed unknown. The model developed in the previous section represents the desired behavior of the control system. The objective is to formulate a control law and an adaptation law such that the resulting model following error asymptotically converges to zero.
The approach proposed in this paper is to use the model defined by Eq. 1-6 to predict the kiln temperature profiles.
The control parameters are tuned to minimize the error between model response and the plant response [6].
A simplified illustration of this control diagram is presented in Fig.3.

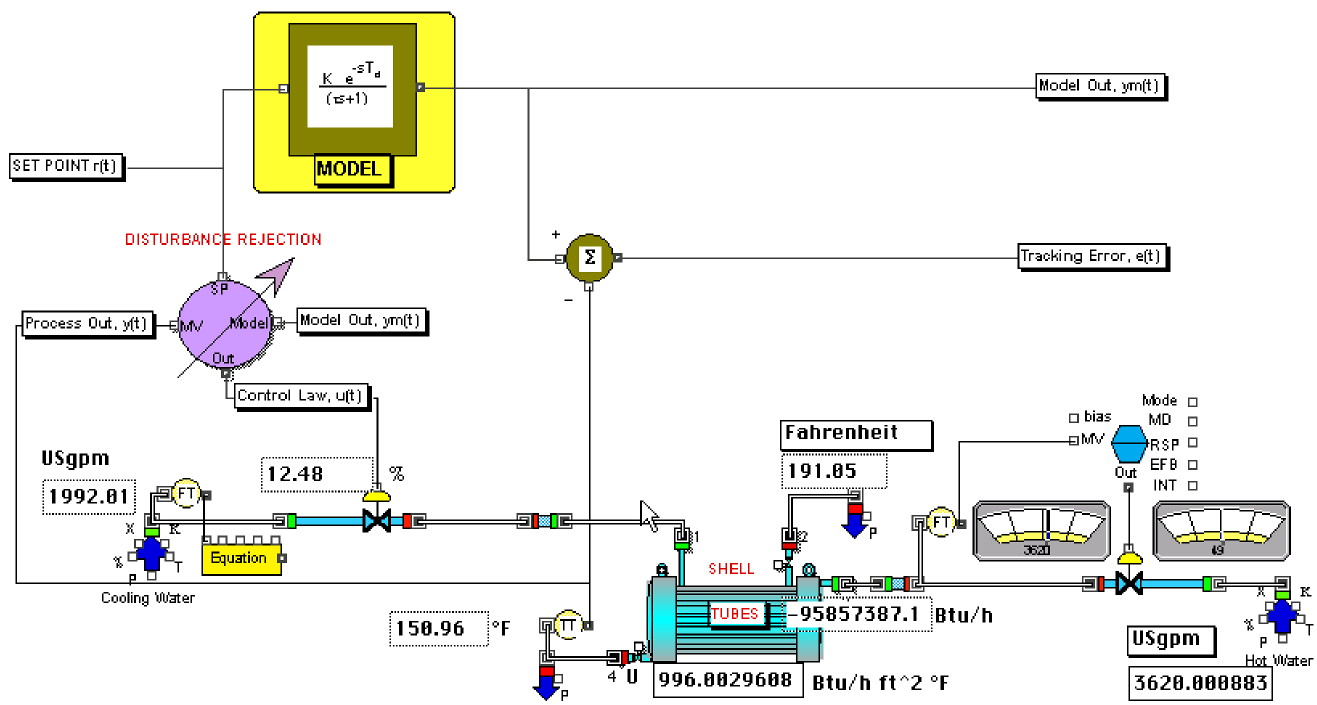

FIG 3. ADAPTIVE TEMPERATURE CONTROL DIAGRAM

The results are tested in the previously noted simulation environment using mill data obtained from a confidential client. Preliminary results show good tracking performances (see Fig.4). The parameter drift problem needs to be further investigated.

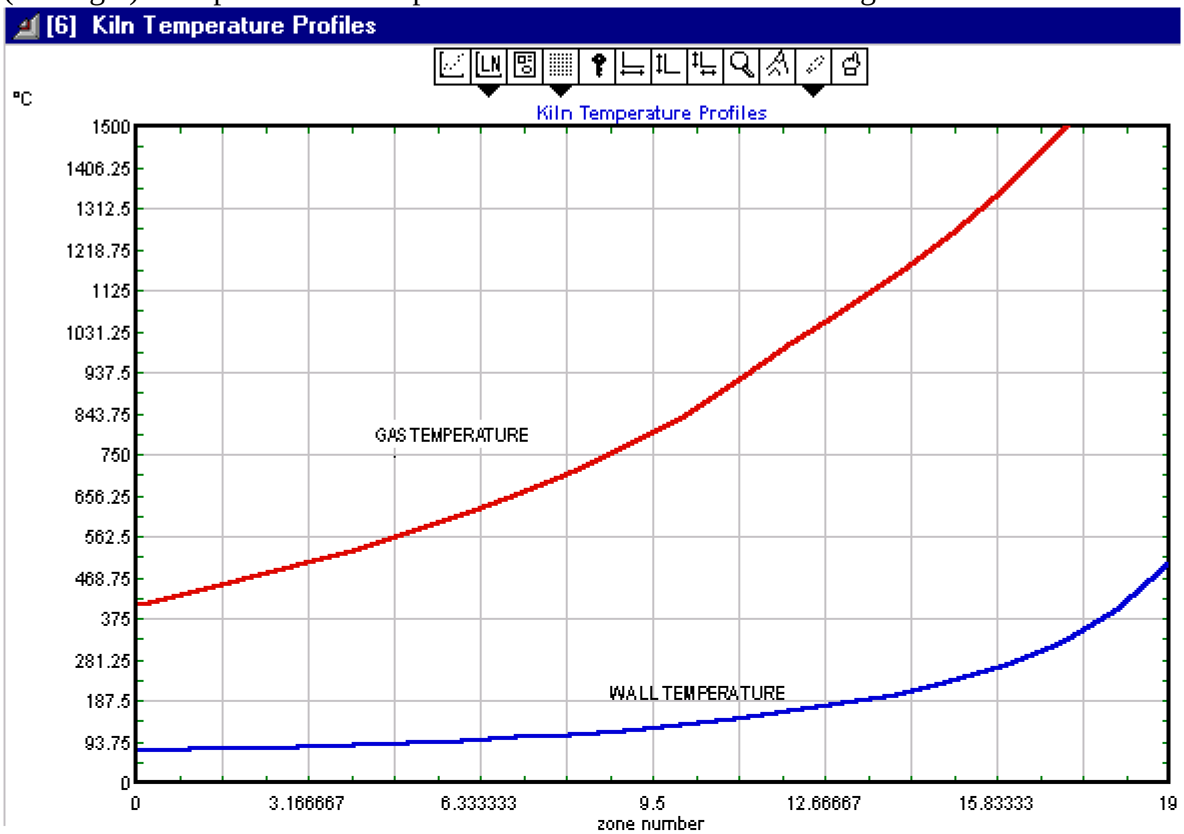

FIG 4. KILN TEMPERATURE PROFILES

Fig. 4 illustrates typical profiles predicted by the model. The line labeled "WALL TEMPERATURE" corresponds to the inner wall temperature and the line labeled "GAS TEMPERATURE" represents the flue gas temperature across the kiln length.

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