MATHEMATICAL MODELLING OF LIME KILNS

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ABSTRACT

A three-dimensional steady-state model to predict the flow and heat transfer in a rotary lime kiln is presented. All important phenomena are included for the pre-heat and calcination zones. The model is based on a global solution of three sub-models for the hot flow, the bed and the rotating wall/refractories. Information exchange between the models results in a fully coupled 3-D solution of a rotating lime kiln. The overall model is validated using UBC's pilot kiln trials (5.5 m laboratory kiln). Results are presented and potential implications are discussed.

INTRODUCTION

Rotary kilns have wide use in industry from the calcination of limestone to cement manufacturing to calcining of petroleum coke etc. Problems such as low thermal efficiency and low product quality have plagued rotary kiln operations yet these machines have survived and have been continuously improved (fuel efficiency, automation) for over a century.

Modeling has aided the design and operation of rotary kilns over the years. Many one-dimensional models have appeared in the literature [1-12]. There are others but these are generally available to the public. The common dimension of interest in one-dimensional models is the kiln longitudinal axis. A series of equations representing conservation of mass, energy and species averaged over the cross-section are solved using appropriate numerical methods. The critical assumption that must be made is that uniform conditions exist across the cross-section in the freeboard gas, the walls/refractories and bed. The bed for example is assumed to be well mixed and isothermal in any given transverse plane. Although these models have been successfully used in industry, they are limited in the amount of information that can be extracted. Flame positioning for example can be predicted in multi-dimensional models rather than used as an input.

Evidence (such as a non-uniform product) has suggested that large temperature gradients exist near and within the bed. As a result a number of researchers have begun the quest for a more encompassing modeling effort. Boateng and Barr [13] have coupled a conventional one-dimensional plug flow model with a two-dimensional representation of the bed's transverse plane. This improves the ability to simulate conditions within the bed. Alyaser [14] has modeled for axisymmetric conditions. The model was validated using thermal measurements from UBC's pilot kiln. This effort demonstrates how a model may be used to capture flame phenomena for rotary kilns (adjustment of primary air ratio, primary jet momentum, extracting flame length etc.).

Bui et al. [15-17] were the first to construct a three-dimensional model for a rotary petroleum coke calciner. Four submodels (gas, bed, refractory and radiation) were coupled using four grid domains. The model takes into account the major phenomena of interest including the gas flow, all modes of heat transfer, combustion, bed motion and thermal effects of the refractories.

In the present study, fully coupled three-dimensional modeling is applied to the rotary lime kiln. Care is taken when modeling the geometry: The capability of capturing details of the burner and hood/kiln interactions is illustrated. The granular material is modeled through a 3-D energy and species transport in the bed including the calcium carbonate chemistry specific to lime kilns.

MODEL DESCRIPTION

Three sub-models are coupled, namely the hot flow model, the bed model and the wall/refractories model. Each is briefly described below.

Hot Flow Model

The hot flow model uses block-structured body-fitted coordinates with domain segmentation. This results in a capability of simulating flows in complex three-dimensional geometries with local refinement that captures details of the burner geometry and hood/kiln interactions. Although modeling of UBC's pilot kiln is described here, to take advantage of existing experimental data, the capabilities (as shown in an accompanying paper to this conference) also apply to industrial kilns. Figure 1 shows the burner, firing hood, and individual jets for fuel and air used in the present study. Eight primary and 8 secondary air jets are modeled.

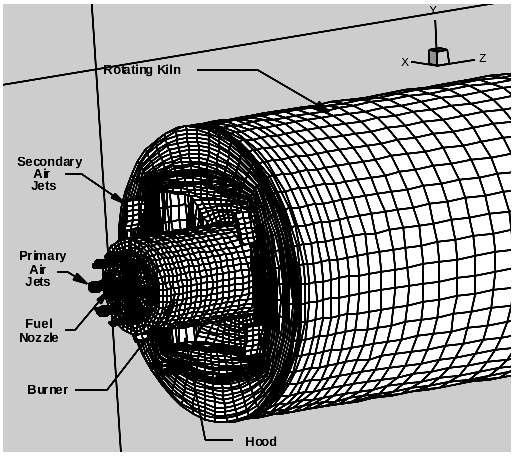


Figure 1: Grid used for pilot kiln modeling

The CFD solver was developed by Nowak within the Department of Mechanical Engineering at the University of British Columbia [18]. The method is based on the finite volume method. The model includes buoyancy effects, turbulence (using the standard k-ε model [19]), evolution and combustion of gaseous species (through Magnussen's model [20]), and radiation through the ray-tracing technique (Discrete Ordinate Method [21-23]). Combustion of natural gas or oil may be modeled.

Bed Model

The bed model is based on the finite element method and was developed by Georgallis [Internal Report, UBC 2000]. It solves for a three-dimensional energy and species transport balance for both the active layer and plug flow regions, illustrated in Figure 2. The approach taken is similar to that of Bui et al. [15]. The active layer depth, angular bed position, etc. are imposed a priori. The grid shown in figure 2 is obtained by solving for two Poisson-type solutions. Note the packed grid structure in the lower left of the figure. Larger thermal gradients are expected in this region due to wall heat regeneration.

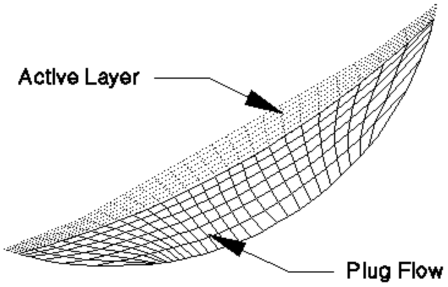


Figure 2: Grid for Bed Calculation

The calcium carbonate reaction is modeled and assumed to be dominated by heat transfer [24]. Reaction proceeds as a function of temperature, mass fraction of $CaCO_3$ and a bulk particle size diameter. An effective thermal conductivity (modified by a mass diffusion factor [25,26]) is used for the granular bed heat transfer in the active layer. The bed flow field is prescribed via simplified velocity distributions but satisfies the continuity equation. Density changes resulting from the reaction are updated in the iterative process. A 3-D temperature field results along with distributions for $CaCO_3$ and CaO. Carbon dioxide is released to the hot flow.

Wall/Refractories Model

The wall model, also developed by Georgallis [Internal Report, UBC 2000] and based on the finite element method, includes varying conductivity within the metal and refractories using manufacturer-supplied curve fits. Rotation is included through a convective plug flow term in the energy equation ($V=R \times \Omega$). Heat is lost to the ambient through free convection and radiation. Free convection is modeled as individual surface inclined planes according to Fujii and Imura [27]. Nusselt number correlations were calibrated to full cylinder correlations.

Coupling

Information exchange and directions of transfer are shown in Figure 3. Interface temperature boundary conditions for the kiln are always used in the hot flow model. Heat flux boundary conditions are used for both the inner and outer surfaces in the wall model. The bed model accepts heat flux values from the hot flow side and temperatures on the wall interface. Running the three models once amounts to one global iteration.

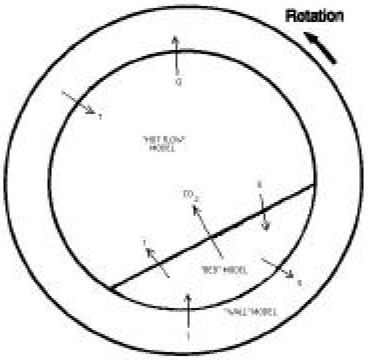
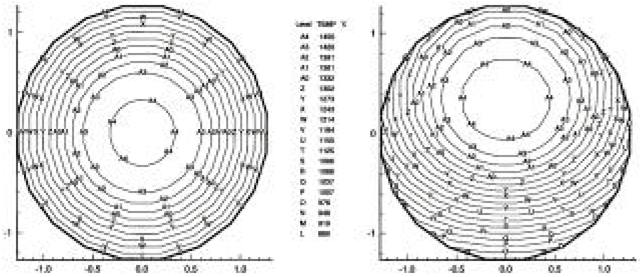


Figure 3: Data Transfer Between Models

MODEL TESTING

Each model was individually tested and where appropriate, was compared to analytical results. Two results from this initial work are worth noting here.

Figure 4 shows transverse results from the hot flow model applied to a 2.6 m internal diameter industrial kiln (60 m length). A total of 25 MW is supplied with a Craya-Curtet parameter of 2.8. Excess O_2 of 2.5% is present at the kiln exit. The two transverse planes shown are both 6.6 m downstream of the burner. The left temperature contour plot shows a solution of the hot flow model when no buoyancy is included. The plot on the right includes buoyancy effects. An analysis of this kiln indicates that in the region where the bed would be present there exists as much as a 200 ^oK difference between the two solutions.



(a) No Buoyancy (b) With Buoyancy

Figure 4: Transverse Results for an Industrial Kiln

Figure 5 gives three wall model solutions at different RPM. A locally higher heat source (heat flux boundary conditions) was placed near TDC on the interior wall. Heat loss on the outer wall was imposed through a constant heat transfer coefficient.

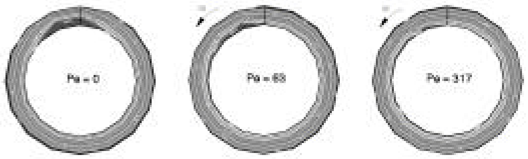


Figure 5: Effect of Rotation – Temperature (^oK)

The Peclet numbers given in the figure refer to the ratio of rotational convection to conduction heat transfer. These results compare well to an order of magnitude analysis.

RESULTS

Coupled model results are described here for the thermal measurements of Alyaser [14] on the UBC 0.41 m internal diameter pilot kiln. These measurements include gas flow temperatures on the center-line and 60 mm above and below the center-line. Measurements were also made on the inner and outer walls along the length of the kiln. The kiln did not rotate and no bed was used in these experiments. Modeling described here then only solves for coupling between the wall/refractories and the hot flow.

Figures 6 and 7 show hot flow coupled results for the central vertical plane of the kiln. Flame length data may be extracted from the fuel (CH_4) contours plot of figure 6. If for example a 1% or 2% mass fraction value is used as the flame boundary, the flame is shown to penetrate approximately 1 m into the kiln. This agrees well with the burner manufacturers' expectations. Flame impingement on the upper wall refractories is also clearly visible from this data.

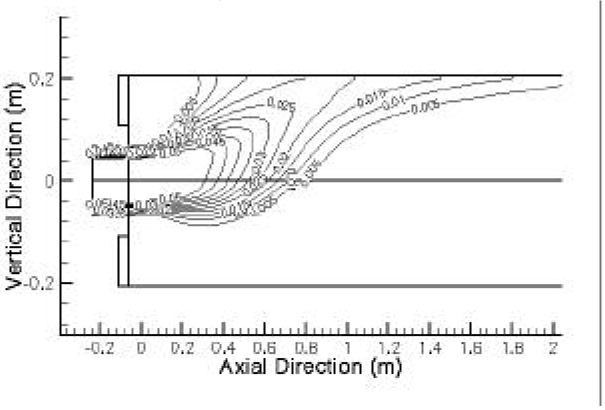


Figure 6: Fuel (CH_4) Mass Fraction (scale distorted)

The axial velocity component shown in the contour plot of Figure 7 identifies various details captured, including the Craya-Curtet type recirculation pattern downstream of the flame. Reverse flow in the burner indicates possible fouling problems. Recirculation in the completely sealed hood is also evident.

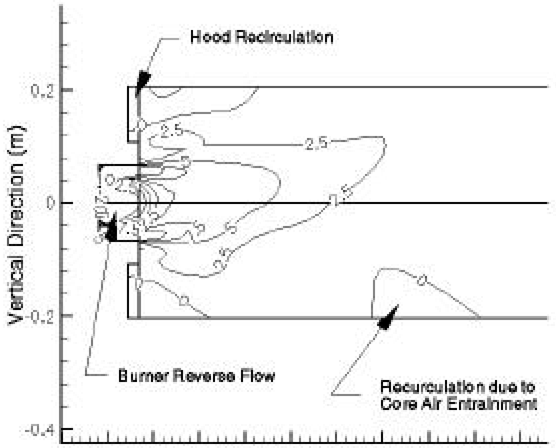


Figure 7: Axial Velocity Field (m/s) (scale distorted)

Two hot spots are indicated in the inner wall temperatures of Figure 8. The first is the hot spot due to flame impingement. Downstream of the flame zone a second hot spot is visible. This is present due to a refractory change of lower conductivity.

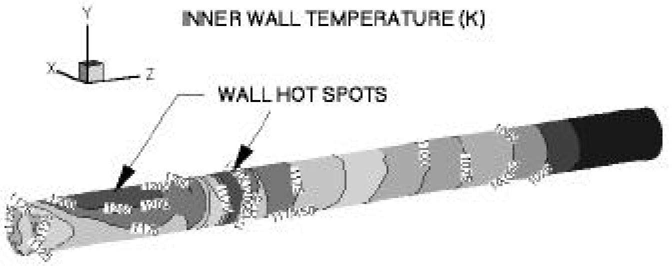


Figure 8: Wall Hot Spots in Pilot Kiln

A comparison to the experimental data is shown in Figure 9. The numerical data (lines) capture the radial thermal gradients of the buoyant field as well as the correct difference between upper and lower inner wall temperatures.

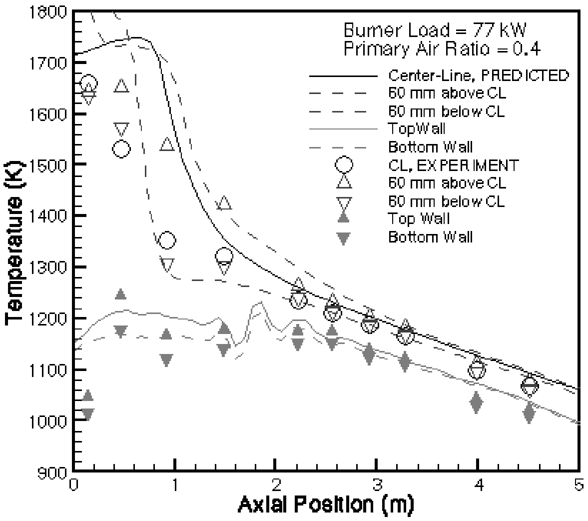


Figure 9: Axial Temperature Profiles in Pilot Kiln

CONCLUSION

The overall model (for hot flow/wall coupling) was validated using UBC's pilot kiln trials. The solution indicates that such a model may be used to identify problems of kiln operation or design. Prediction of a wealth of information is possible for various (primary air/fuel) input conditions, kiln geometries and burner designs. When the flow field, temperature distributions and species concentrations are visualized and understood for a given kiln operating condition, diagnosis of operational problems and optimization can be aided through such a tool. Identification of non-ideal aerodynamic effects (secondary flows) of hood/kiln interactions through flame visualization (and possible impingement) also has the potential of increasing refractory life.

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