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Numerical modeling of a rotary cement kiln with improvements to shell cooling

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ABSTRACT

Numerical models are developed by researchers to analyze and understand the trends occurring within rotary kilns, and allow for improvements in terms of energy quantification and usage. The present study develops a one-dimensional kiln model using elements of existing models and then links the model to the surroundings via a composite resistance model and a forced convection model that enables proper inclusion of the effects of shell-cooling fans. Shell-cooling fans are common in industry and allow for a reduction in shell temperature and promotion of internal coating formation. Thermal conductivity through the kiln shell is treated as a calibration parameter to allow for a more accurate shell temperature profile to be generated, while a forced convection model developed for a bank of jets impinging on a large cylinder is implemented to quantify the external convective resistance. The governing heat transfer and chemistry equations are implemented into the Matlab R2014a software to produce one-dimensional solutions of the temperature distributions and species mass fractions observed in a rotary cement kiln. A validation study is performed against an existing one-dimensional model showing reasonable quantitative and qualitative results of temperature profiles and species outputs. Using operational parameters from a partner organization, a profile of internal and external temperature profiles and the corresponding axial development of species products is also presented. Scanned shell temperature data is then compared against the results of the model considering only free convection, and forced convection from the kiln shell cooling fans in operation. An error of ⩾20% was observed when the effects of forced convection on the kiln shell are neglected.

1. Introduction

The goal in cement production is inherently to produce as much cement as possible while consuming the least amount of energy possible. Measurements of energy consumption at a cement plant, and within the cement industry as a whole, are typically expressed as energy/weight of clinker, which is the fundamental building block of the process. Rotary cement kilns are used for the production of cement clinker and are by far the highest consumer of thermal energy in the operation, requiring a continuous input of fuel to facilitate the chemical reactions necessary for clinker production. Not surprisingly, 30–40% of the heat released from a cement plant is from the kiln as a by-product of the clinker production process [1,2]. With such large amounts of heat being input, consumed, and generated within the rotary kiln, there is also a large amount of heat released from the kiln. Engin and Vedat [3] performed a case study on heat recovery for dry-type cement rotary kiln systems and observed that approximately 40% of the total input energy to the kiln was released in the form of hot flue gas (19.15%), cooler stack emissions (5.61%), and via convection and radiation from the kiln shell (15.11%). From these releases, the hot flue gas is typically reused throughout the plant in preheating and drying operations; however, the cooler stack emissions and all of the heat released from the kiln shell due to radiation and convection are lost to the surroundings. Thus, the rotary kiln is the largest source of waste heat in the plant, and this has prompted researchers to conduct analyses on the rotary cement kiln through the use of one-dimensional mathematical models and three-dimensional CFD simulations.

At its core, the rotary cement kiln is a large chemical reactor; a simple schematic of the layout of a rotary cement kiln is shown in Fig. 1. Tilted at an angle of 2–5° with respect to horizontal, and operating at a slow rotating speed of approximately 1–5 rpm, the raw feed (typically limestone, silica, aluminum and iron oxide, [4]) enters at the elevated end, and travels through the cylindrical kiln due to gravity/tumbling. The kiln is comprised of a steel shell for strength and rigidity, lined on the inner surface with refractory brick to enhance the thermal resistance, and to isolate the steel shell from the high temperature process taking place inside. Raw

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Nomenclature

A_{rgb}	radiation area internal gas to bulk bed [m]
A_{rgw}	radiation area internal gas to internal wall [m]
A_{rwb}	radiation area internal wall to bed [m]
A_{cgb}	convection area internal gas to bulk bed [m]
A_{cgw}	convection area internal gas to internal wall [m]
A_{cwb}	conduction area internal wall to bed [m]
$A_{segment}$	area of bed segment [m]
A_{sh}	area of steel shell [m]
A_j	pre-exponential factor for jth reaction [1/s]
Ai	initial value of Al_2O_3 at input
Cp_b	specific heat of bulk bed [J/kg K]
C_{Tmax}	maximum coating thickness [m]
D_e	hydraulic diameter of kiln [m]
D	diameter of kiln [m]
E_j	activation energy for jth reaction [J/mol]
Fi	initial value of Fe_2O_3 at input
ΔH_{CaCO_3}	heat of reaction $CaCO_3$ [J/kg]
ΔH_{C_2S}	heat of reaction C2S [J/kg]
ΔH_{C_3S}	heat of reaction C_3S [J/kg]
ΔH_{C_3A}	heat of reaction C_3A [J/kg]
ΔH_{C_4AF}	heat of reaction C_4AF [J/kg]
h_{cgb}	convective heat transfer coefficient freeboard gas to bulk bed [W/m^2 K]
h_{cgw}	convective heat transfer coefficient freeboard gas to internal wall [W/m^2 K]
h_{cwb}	coefficient for conduction from wall to bed [W/m^2 K]
h_{csh}	convective heat transfer coefficient from shell to atmosphere [W/m^2 K]
k_g	thermal conductivity of freeboard gas [W/m K]
k_b	thermal conductivity of bulk bed [W/m K]
k_a	thermal conductivity of air [W/m K]
k_1	reaction rate $CaCO_3$ [1/s]
k_2	reaction rate C_2S [1/s]
k_3	reaction rate C_3S [1/s]
k_4	reaction rate C_3A [1/s]
k_5	reaction rate C_4AF [1/s]
L_{fus}	latent heat of fusion [J/kg]
L_{gcl}	chord length of bed segment [m]
$\dot{m}_{CO_2}$	mass flow rate of CO_2 [kg/s]
$\dot{m}_{CaCO_3}$	mass flow rate of $CaCO_3$ [kg/s]
M_n	molar mass of nth species [kg/kmol]
Nu_{ave}	average Nusselt number for forced convection from cylinder
Pr	Prandtl number
Q_{rgb}	radiation heat transfer gas to bulk bed [W/m]
Q_{rgw}	radiation heat transfer gas to internal wall [W/m]
Q_{rwb}	radiation heat transfer internal wall to bed [W/m]
Q_{cgb}	convection heat transfer gas to bulk bed [W/m]
Q_{cgw}	convection heat transfer gas to internal wall [W/m]
Q_{cwb}	conduction heat transfer internal wall to bed [W/m]
Q'	heat gained by bed due to heat transfer [W/m]
q_c	heat generated by chemical reactions [W/m^3]
Q_{coat}	heat transfer through coating [W/m]
Q_{ref}	heat transfer through refractory [W/m]
Q_{stl}	heat transfer through steel shell [W/m]
$Q_{conv\text{-}shell}$	heat transfer from shell by convection [W/m]
$Q_{rad\text{-}shell}$	heat transfer from shell by radiation [W/m]
Ra_D	Rayleigh number
Re_d	jet Reynolds number
Re_D	axial Reynolds number
Re_w	angular Reynolds number
R_g	universal gas constant [J/mol K]
R	internal radius of kiln [m]
Si	initial value of SiO_2 at input
S_{CO_2}	source term for heat release from CO_2 [W/m]
T_g	freeboard gas temperature [K]
T_b	bulk bed temperature [K]
T_w	internal wall temperature [K]
T_0	temperature of atmosphere [K]
T_{sh}	temperature of steel shell [K]
u_g	airspeed of freeboard gas [m/s]
v_b	velocity of bulk bed [m/s]
Y_n	mass fraction of nth species
Y_{fus}	fusion fraction
d/D	ratio of jet diameter to cylinder diameter
y/d	jet-to-cylinder spacing
z/d	jet-to-jet spacing
x/d	Jet offset from centerline

Greek characters

α_b	bulk bed thermal diffusivity [m^2/s]
α_g	absorptivity of freeboard gas
β	angle of repose [rad]
ε_{sh}	emissivity of steel shell
ε_g	emissivity of freeboard gas
ε_b	emissivity of bulk bed
ε_w	emissivity of internal wall
Γ	angle of fill of kiln [rad]
μ_g	dynamic viscosity of freeboard gas [s/m^2]
η	degree of solid fill
ω	rotational speed of kiln [rad/s]
Ω	view factor for radiation
ρ_g	density of freeboard gas [kg/m^3]
ρ_s	density of solids [kg/m^3]
σ	Stefan–Boltzmann constant
ν_g	kinematic viscosity of freeboard gas [m^2/s]

Species $CaCO_3$, SiO_2, CaO, Fe_2O_3, Al_2O_3, C_2S, C_3S, C_3A, C_4AF

feed enters the kiln at one end, and the fuel (petroleum coke which is combusted in a burner located approximately 1 m into the kiln) enters at the opposite end. There are four main regions within the rotary kiln [5] (refer to Fig. 1a):

- Preheating/drying: The initial region of the kiln is where raw material is dried and all remaining moisture is evaporated out of the mixture. The temperature of the raw material increases to approximately 1173 K (900 °C) where calcination can begin.
- Calcining/decomposition: Calcination occurs in this region, indicating that the limestone, $CaCO_3$, will decompose into calcium oxide (free lime), CaO and carbon dioxide:

$$CaCO_3 \rightarrow CaO + CO_2$$

This is one of the most important stages in the cement production process, as limestone that is not properly calcined will be difficult to burn, and can result in a poor quality product.