

Dynamic Model for Simulation and Control of Cement Rotary Kilns

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Abstract: A dynamic mathematical model was developed for the simulation and control of cement rotary kilns. The model consists of a set of nonlinear partial differential equations, and represents the material and energy balances in the kiln. Based on some logical assumptions, the model does not only consider the reaction mechanisms but also reduces the complexity of computer simulation. The steady-state simulation shows that the behavior of the model is agreement with the results presented in the literature. Then several disturbances in the manipulated variables were tested and the dynamic response was analyzed. The good performance exhibited by the dynamic model makes it suitable for simulation and control studies as well as for optimization and design.

Key words: dynamic model; rotary kiln; simulation; control

用于仿真与控制的水泥回转窑动态模型

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摘要: 建立了一个用于仿真与控制的水泥回转窑动态数学模型。该动态模型基于回转窑内的物料和能量平衡, 由一组非线性偏微分方程组成。在合理的假设条件下, 该模型不但考虑了反应机理, 而且降低了仿真计算的复杂性。首先, 稳态仿真表明模型稳态行为与文献中给出的结果是一致的; 在此基础上, 对操纵变量加入扰动测试并对动态响应进行了分析, 结果表明该模型动态性能良好, 适合于回转窑的仿真、控制以及优化设计的研究之用。

关键词: 动态模型; 回转窑; 仿真; 控制

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Introduction

Rotary kiln is one of the key equipments in a cement industry used to convert calcineous raw meal to cement clinkers. Over the decades, the work modeling cement rotary kiln has attracted much attention. In the 1960's, Lyons *et al.*^[1] developed a model to simulate the steady-state behavior of a cement kiln. Spang [2] extended Lyons' work and developed a dynamic model of a cement kiln to understand its behavior. Another significant model was developed by Bui [3] to identify the effective controlling decisions in order to realize a desired gas temperature profile. Mintus *et al.* [4] proposed a one-dimensional cell model for wet process rotary cement kiln with chain systems to predict the influence of chain systems on solid composition and temperature, clinker throughput and fuel requirement. Mujumdar *et al.* [5,6] developed a one-dimensional steady-state model to discuss possible ways of reducing energy consumption and simulate key processes

occurring in solid bed of cement kilns. In recent years, cement rotary kiln model has been modified due to the developed cement technology. An integrated reaction engineering based mathematical model of pre-heater, calciner, kiln and clinker cooler was presented by Mujumdar [7]. Wang *et al.* [8] developed a first principle model of dry cement precalcination system for the purpose of controller's design and synthesis.

In this paper, a fundamental dynamic model of cement rotary kilns is presented. The model consists of a set of nonlinear partial differential equations, and represents the material and energy balances in the kiln. Simulation results, including steady-state temperature profiles, solids compositions and dynamic responses to practical manipulated variables for control studies, are included.

In the following section, a brief introduction to the dry cement-making process is provided and section III gives the detailed model formulation of the rotary kiln. Section IV shows simulation results of the model and analyzes the dynamic response.

1 Process Description

A schematic of the dry cement-making process is shown in Fig. 1. Typically, precalcination system, rotary kiln, and cooler are the main components of cement manufacturing. The raw meal (a mixture of predetermined proportions of limestone,

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silica, and small quantities of alumina and iron oxide) is first preheated and partially calcined in the precalcination system. Then the partly calcined charge is fed slowly to rotary kiln. The energy required for endothermic clinker reactions is provided by pulverized coal in the kiln. The pulverized coal along with the preheated air (secondary air) is fed to the kiln in a countercurrent mode with respect to the solids. In the initial region of the kiln (from the solid entrance), the remaining calcination is completed. Other clinkerization reactions also occur as the solids move forward in the kiln. The hot clinkers are discharged from kiln to clinker cooler and hot gases from kiln exhaust are sent to the precalcination system. In a clinker cooler, a part of energy of solids is recovered back by heat exchange with air. The preheated air from the cooler is passed to kiln and precalcination system as secondary and tertiary air, respectively. The major chemical reactions considered by most of the researchers in cement production are given in Table 1 [6, 8]. The operational objective of the rotary kiln is to produce “good” clinker. Secondary objectives include minimization of the energy utilization and maintaining the burning zone temperature (BZT) within specified bounds. The practical manipulated variables are the pulverized coal flow rate and kiln rotational speed. The important process disturbances include the raw meal composition and flow rate.

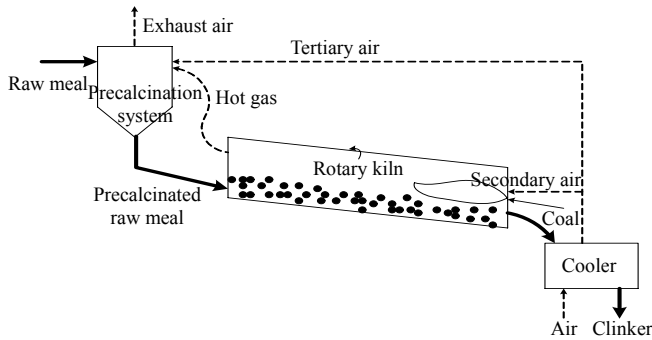


Fig. 1 Schematic of dry cement-making process

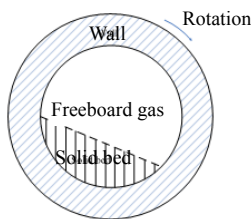


Fig. 2 Cross-section of rotary kiln

2 Dynamic Mathematical Model

The dynamic mathematical model developed includes the mass and energy balance equations for the three phases within the rotary kiln: freeboard gas (pulverized coal included), solid bed and wall. The cross-section of rotary kiln is depicted schematically in Fig. 2. Because of the main process variables such as temperature and mass flow rate change along the axial axis, a distributed parameter system (DPS) is obtained. In

addition, the dynamics of the gas are two orders of magnitude faster than the solid. Therefore, the gas phase is modeled by steady-state equations. The solid phase and the wall are modeled using dynamic equations.

In developing the model, every effort is made to make it as simple as possible while maintaining the essential dynamics that have been observed qualitatively. So the following assumptions have been made:

Reactions	k	E [kJ/mol]	ΔH [kJ/mol]
Bed			
$\text{CaCO}_3 = \text{CaO} + \text{CO}_2$	1.18×10^3 [kmol/(m ² ·s)]	185	179.4
$2\text{CaO} + \text{SiO}_2 = \text{C}_2\text{S}$	1.0×10^7 [m ³ /(kg·s)]	240	-127.6
$3\text{CaO} + \text{SiO}_2 = \text{C}_3\text{S}$	1.0×10^9 [m ³ /(kg·s)]	420	16.0
$3\text{CaO} + \text{Al}_2\text{O}_3 = \text{C}_3\text{A}$	1.0×10^8 [m ³ /(kg·s)]	310	21.8
$4\text{CaO} + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 = \text{C}_4\text{AF}$	1.0×10^8 [m ⁶ /(kg ² ·s)]	330	-41.3
Freeboard			
$3\text{C} + 2\text{O}_2 = \text{CO}_2 + 2\text{CO}$	1.225×10^7 [m/s]	99.77	392.92
$2\text{CO} + \text{O}_2 = 2\text{CO}_2$	3.25×10^7 [m/s]	133.8	284.24

- (1) Both, solid and gas axial linear velocity changes are negligible.
- (2) There is neither solid nor gas axial mixing. Then, the two phases are considered as a plug flow model. Solid drag by the gas is negligible.
- (3) Reaction rates are determined by Arrhenius equation.
- (4) Specific heats, reaction heat and heat transfer coefficients are constant.
- (5) Conduction in the solid and gas is negligible. The conduction in the axial direction of the wall is also considered negligible.

The general balance equation is presented first, then the specific material and energy balance equations of the cement rotary kiln are shown in Table 2.

2.1 The general material balance equations

The change with time in the mass of any compound in a given cross section must be equal to the amount of that compound moving into the region plus the amount generated in that region. Thus, the mass balance equations are of the form:

$$\frac{\partial m_i}{\partial t} = -v \frac{\partial m_i}{\partial z} + r_i \cdot M_i \quad (1)$$

where m is the mass of a given compound, i the given compound, v the velocity along the kiln, r the specific reaction rate and M the mole mass. According to the reactions in Table 1, the compounds include C, O₂, CO₂, CO, CaCO₃, CaO, SiO₂, Al₂O₃, Fe₂O₃, C₂S, C₃S, C₃A and C₄AF.

Under above assumptions, the specific reaction rates of these reactions are described in the following equations:

$$r_{CaCO_3} = k_{CaCO_3} \cdot \exp\left(-\frac{E_{CaCO_3}}{R \cdot T_s}\right) \cdot \frac{m_{CaCO_3}}{M_{CaCO_3} \cdot V} \quad (2)$$

$$r_{C_2S} = k_{C_2S} \cdot \exp\left(-\frac{E_{C_2S}}{R \cdot T_s}\right) \cdot \left(\frac{m_{CaO}}{M_{CaO} \cdot V}\right)^2 \cdot \frac{m_{SiO_2}}{M_{SiO_2} \cdot V} \quad (3)$$

$$r_{C_3S} = k_{C_3S} \cdot \exp\left(-\frac{E_{C_3S}}{R \cdot T_s}\right) \cdot \left(\frac{m_{CaO}}{M_{CaO} \cdot V}\right)^3 \cdot \frac{m_{SiO_2}}{M_{SiO_2} \cdot V} \quad (4)$$

$$r_{C_3A} = k_{C_3A} \cdot \exp\left(-\frac{E_{C_3A}}{R \cdot T_s}\right) \cdot \left(\frac{m_{CaO}}{M_{CaO} \cdot V}\right)^3 \cdot \frac{m_{Al_2O_3}}{M_{Al_2O_3} \cdot V} \quad (5)$$

$$r_{C_4AF} = k_{C_4AF} \cdot \exp\left(-\frac{E_{C_4AF}}{R \cdot T_s}\right) \cdot \left(\frac{m_{CaO}}{M_{CaO} \cdot V}\right)^4 \cdot \frac{m_{Al_2O_3}}{M_{Al_2O_3} \cdot V} \cdot \frac{m_{Fe_2O_3}}{M_{Fe_2O_3} \cdot V} \quad (6)$$

$$r_C = k_C \cdot \exp\left(-\frac{E_C}{R \cdot T_g}\right) \cdot \frac{m_C}{M_C \cdot V} \cdot \frac{m_{O_2}}{M_{O_2} \cdot V} \quad (7)$$

$$r_{CO} = k_{CO} \cdot \exp\left(-\frac{E_{CO}}{R \cdot T_g}\right) \cdot \frac{m_{CO}}{M_{CO} \cdot V} \cdot \frac{m_{O_2}}{M_{O_2} \cdot V} \quad (8)$$

equations can be described by the following equation [9]:

$$\frac{\partial Q}{\partial t} = -v \frac{\partial Q}{\partial z} + q \quad (9)$$

where Q is the enthalpy, q is the net amount of heat generated within and/or moving into a unit volume other than by conduction.

Particularly the time derivative of the gas and fuel compound in the balance equations should be equal to zero because their dynamics are neglected. As well as the space derivative of the wall in equation (9) should be equal to zero according to assumption (5).

In addition, the movement of solids within the kiln is dictated by the kiln dimensions, inclination slope, and rotational speed according to the following equation [10]:

$$v_s = \frac{\alpha D n}{60 \times 1.77 \sqrt{\beta}} \quad (10)$$

$$\tau = \frac{1.77 L \sqrt{\beta}}{\alpha D n} \quad (11)$$

2.2 The general energy balance equations

Based on the assumption (2), the general heat balance

Table 2 Specific Balance Equations of the Rotary Cement Kiln Model

Material balance equations	C	$\frac{\partial m_C}{\partial z} = -\frac{1}{v_g} \cdot r_C \cdot M_C$	(12)
	O ₂	$\frac{\partial m_{O_2}}{\partial z} = -\frac{1}{v_g} \cdot \left(\frac{2}{3} \cdot r_C + \frac{1}{2} \cdot r_{CO}\right) \cdot M_{O_2}$	(13)
	CO ₂	$\frac{\partial m_{CO_2}}{\partial z} = \frac{1}{v_g} \cdot \left(\frac{1}{3} r_C + r_{CO} + r_{CaCO_3}\right) \cdot M_{CO_2}$	(14)
	CO	$\frac{\partial m_{CO}}{\partial z} = \frac{1}{v_g} \cdot \left(\frac{2}{3} r_C - r_{CO}\right) \cdot M_{CO}$	(15)
	Fe ₂ O ₃	$\frac{\partial m_{Fe_2O_3}}{\partial t} = -v_s \cdot \frac{\partial m_{Fe_2O_3}}{\partial z} - r_{C_4AF} \cdot M_{Fe_2O_3}$	(16)
	Al ₂ O ₃	$\frac{\partial m_{Al_2O_3}}{\partial t} = -v_s \cdot \frac{\partial m_{Al_2O_3}}{\partial z} - (r_{C_4AF} + r_{C_3A}) \cdot M_{Al_2O_3}$	(17)
	SiO ₂	$\frac{\partial m_{SiO_2}}{\partial t} = -v_s \cdot \frac{\partial m_{SiO_2}}{\partial z} - r_{C_2S} \cdot M_{SiO_2}$	(18)
	CaCO ₃	$\frac{\partial m_{CaCO_3}}{\partial t} = -v_s \cdot \frac{\partial m_{CaCO_3}}{\partial z} - r_{CaCO_3} \cdot M_{CaCO_3}$	(19)
	CaO	$\frac{\partial m_{CaO}}{\partial t} = -v_s \cdot \frac{\partial m_{CaO}}{\partial z} + (r_{CaCO_3} - 2r_{C_2S} - 3r_{C_3S} - 3r_{C_3A} - 4r_{C_4AF}) \cdot M_{CaO}$	(20)
	C ₂ S	$\frac{\partial m_{C_2S}}{\partial t} = -v_s \cdot \frac{\partial m_{C_2S}}{\partial z} + (r_{C_2S} - r_{C_3S}) \cdot M_{C_2S}$	(21)
	C ₃ S	$\frac{\partial m_{C_3S}}{\partial t} = -v_s \cdot \frac{\partial m_{C_3S}}{\partial z} + r_{C_3S} \cdot M_{C_3S}$	(22)
	C ₃ A	$\frac{\partial m_{C_3A}}{\partial t} = -v_s \cdot \frac{\partial m_{C_3A}}{\partial z} + r_{C_3A} \cdot M_{C_3A}$	(23)
	C ₄ AF	$\frac{\partial m_{C_4AF}}{\partial t} = -v_s \cdot \frac{\partial m_{C_4AF}}{\partial z} + r_{C_4AF} \cdot M_{C_4AF}$	(24)
	Energy balance equations	Gas	$v_g \cdot c_g \cdot \frac{\partial(m_g \cdot T_g)}{\partial z} = \psi_{sg} \cdot A_{sg} \cdot (T_s - T_g) + \sigma \cdot \epsilon_s \cdot \epsilon_g \cdot A_{sg} \cdot (T_s^4 - T_g^4) + \psi_{wg} \cdot A_{wg} \cdot (T_w - T_g) + \sigma \cdot \epsilon_w \cdot \epsilon_g \cdot A_{wg} \cdot (T_w^4 - T_g^4) + (r_C \cdot \Delta H_C + r_{CO} \cdot \Delta H_{CO})$
Solid		$c_s \cdot \frac{\partial(m_s \cdot T_s)}{\partial t} = -v_s \cdot c_s \cdot \frac{\partial(m_s \cdot T_s)}{\partial z} + \psi_{sg} \cdot A_{sg} \cdot (T_g - T_s) + \sigma \cdot \epsilon_s \cdot \epsilon_g \cdot A_{sg} \cdot (T_g^4 - T_s^4) + \psi_{ws} \cdot A_{ws} \cdot (T_w - T_s) + \sigma \cdot \epsilon_w \cdot \epsilon_s \cdot A_{ws} \cdot (T_w^4 - T_s^4) - (r_{CaCO_3} \cdot \Delta H_{CaCO_3} + r_{C_2S} \cdot \Delta H_{C_2S} + r_{C_3S} \cdot \Delta H_{C_3S} + r_{C_3A} \cdot \Delta H_{C_3A} + r_{C_4AF} \cdot \Delta H_{C_4AF})$	(26)
Wall		$c_w \cdot m_w \cdot \frac{\partial T_w}{\partial t} = \psi_{wg} \cdot A_{wg} \cdot (T_g - T_w) + \sigma \cdot \epsilon_w \cdot \epsilon_g \cdot A_{wg} \cdot (T_g^4 - T_w^4) + \psi_{ws} \cdot A_{ws} \cdot (T_s - T_w) + \sigma \cdot \epsilon_w \cdot \epsilon_s \cdot A_{ws} \cdot (T_s^4 - T_w^4) + \psi_{wa} \cdot A_{wa} \cdot (T_a - T_w)$	(27)

3 Results and Discussion

The dynamic model has been simulated in MATLAB®. Before carrying out the dynamic study of rotary kiln, the proposed model is tested with the steady-state operation in order to reproduce the results obtained by Mujumdar [6]. On the other hand, a dynamic study is presented for the two practical manipulated variables.

3.1 Steady-state operation

The validation test carried out with the dynamic model was addressed to reproduce the temperature and concentration profiles at steady-state operation. The calculation results are displayed in Fig. 3 and 4, respectively. As we can see, the gas and solid temperature profiles are agreement with data published in the literature. And the solids concentration profiles also exhibit the expected trends. In the initial region of kiln, a partially calcined raw meal is heated and calcium carbonate is decomposed completely. In the middle of kiln, formation of C₂S takes place, which is followed C₃A and C₄AF formation. When the BZT reaches to about 1700K mass of C₃S come into being.

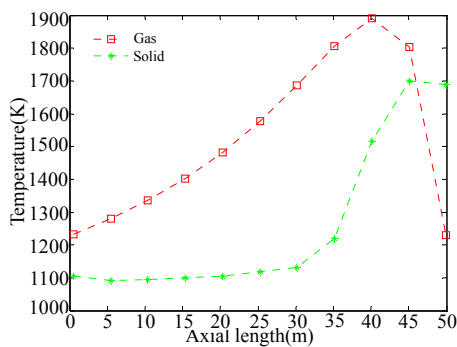


Fig. 3 Steady-state temperature profiles along the axial length in cement kiln

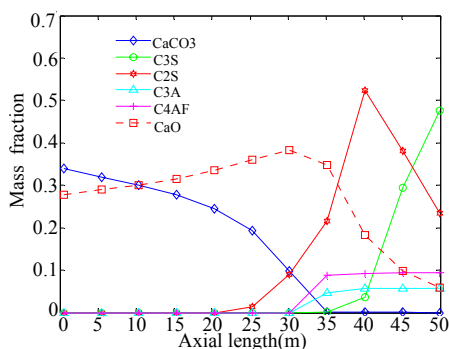


Fig. 4 Typical mass fraction profiles of solid concentration in cement kiln

3.2 Dynamic analysis

The dynamic process response to probable changes in manipulated variables must be known in order to gain understanding on the process performance. Such knowledge, allow to design an adequate control structure for the process. Normally, a step change in the input variables is used in order to analyze the dynamic open-loop response of the system. The

manipulated variables in our process are the pulverized coal flow rate and kiln rotational speed. The primary process variable is the burning zone temperature which is the highest temperature of solid in rotary kiln.

3.2.1 Change in the pulverized coal flow rate

The pulverized coal flow rate is one of main manipulated variables, therefore a step change of magnitude $\pm 5\%$ on the nominal value has been applied, and the open-loop process response for the output variables is evaluated. Fig. 5 shows the change of BZT with time. When the pulverized coal flow rate is augmented, an appreciable increase in BZT is observed. The required time to reach the new steady-state operating point is approximately 18 min and it is almost symmetric for positive vs. negative step changes. It is the same with the situation encountered in real practice.

3.2.2 Change in kiln rotation speed

The rotation speed of cement kiln is other important manipulated variable, which strongly affects the solid residence time with an inverse relationship. By means of Eq. (10), we can set the residence time and the solid velocity. Both variables are included in the model. A step change in the rotation speed of ± 1 rpm produces an appreciable decrease or increase in the burning zone temperature. Fig. 6 shows the process response at the BZT. As can be appreciated, the BZT has a rapid drop when the rotation speed has a positive step change. The reason for this result is that the solid residence time becomes shorter then can not be calcined adequately when the rotation speed augmented. Subsequently the BZT reaches the new steady-state operation in 10min. When the rotation speed has a negative step, the initial change rate of BZT is less than that of the positive step. The transition time to a new steady-state operation requires about 20min. Whereas the changing latitude is greater than the former. The reason is that the solid residence time in the kiln has been longer, and then obtained the more heat energy. In addition, the formation of C₂S and C₄AF is the exothermic reaction, which causes a positive feedback effect.

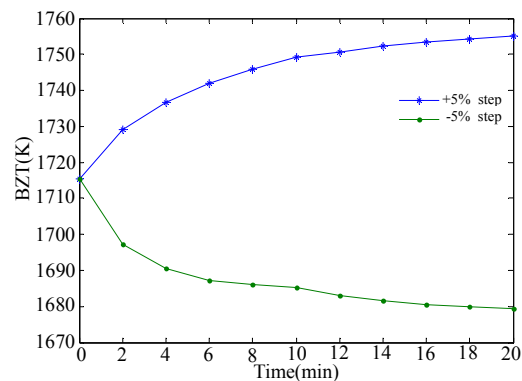


Fig. 5 Open-loop temperature response to a step change in the pulverized coal flow rate.

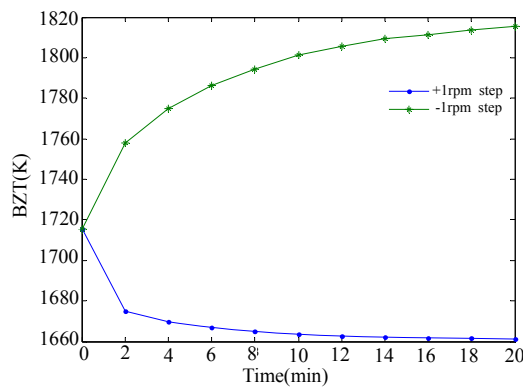


Fig. 6 Open-loop temperature variation due to a step change of ± 1 rpm in rotary speed.

4 Conclusion

The cement kiln is a complex unit operation and a challenging modeling problem. There are 3 phases present (gas, solid and wall). Since the gas balances are not equimolar (because of the contribution of calcium carbonate) the volumetric flow of the gas changes through the kiln. In addition, heat transfer occurs by conduction, convection and radiation which complicate the energy balances and can create stiffness in the numerical solution.

The gas phase was modeled using steady-state mass and energy balances. This was required for computational efficiency in the dynamic simulation. When dynamic balances for the gas phase are introduced, the problem becomes stiff and the convergence of the model takes several hours. Dynamic simulation shows that the model can reproduce the steady-state results for temperature and well as compositions. The model also exhibits the expected qualitative dynamic behavior.

Our next step is to carry out model reduction and controller's design and synthesis. The mathematic model will be part of a general model for the simulation and control of cement processes to be used for testing different plant-wide control strategies including heuristics approaches for decentralized control as well as model based methods.

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Appendix:

Nomenclature

A	surface area per unit of length [$\text{m}^2 \text{m}^{-1}$]
D	kiln internal diameter [m]
E	activation energy
L	total length of kiln [m]
M	mole mass [mol kg^{-1}]
R	perfect-gas constant [kJ mol^{-1}]
T	temperature [K]
V	volume per unit of length [$\text{m}^3 \text{m}^{-1}$]
ΔH	reaction heat
c	specific heat [kJ (kg K)^{-1}]
k	preexponential factor
m	mass [kg]
n	rotation speed [rpm]
r	specific reaction rate
t	time [s]
v	velocity [m s^{-1}]
z	distance along kiln [m]

Greek symbol

α	rotary kiln slope
β	solid angle of repose
ε	emissivity
σ	coefficient of radiation [$\text{W (m}^2 \text{K}^4)^{-1}$]
τ	material residence time in rotary kiln [s]
ψ	coefficient of convection [$\text{W (m}^2 \text{K)}^{-1}$]

Subscripts

Al_2O_3	alumina
C	carbon
C_3A	$3\text{CaO}\cdot\text{Al}_2\text{O}_3$
C_4AF	$4\text{CaO}\cdot\text{Al}_2\text{O}_3\cdot\text{Fe}_2\text{O}_3$
$CaCO_3$	calcium carbonate
CaO	calcium oxide
CO	carbon monoxide
CO_2	carbon dioxide
C_2S	$2\text{CaO}\cdot\text{SiO}_2$
C_3S	$3\text{CaO}\cdot\text{SiO}_2$
Fe_2O_3	ferric oxide
O_2	oxygen
SiO_2	silicon dioxide
a	outside air
g	gas
s	solid
sg	solid-gas
w	wall
wa	wall-outside air
wg	wall-gas
ws	wall-solid