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Simulation of transport phenomena in coke oven with staging combustion

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HIGHLIGHTS

- The application of staging combustion in coke ovens and its effects are analyzed.
- A 3D model is proposed to describe flow–combustion–thermo behaviors in coke oven.
- Optimizing operation parameters in full-scale coke oven are studied.

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ABSTRACT

A three-dimensional transient mathematical model was developed for coupled coking chamber and staging combustion chamber in large-capacity coke ovens, to describe the flow–combustion–thermo behavior. The model was solved numerically using CFX CFD package and was validated by the central temperature evolution of coke bed. The fields of temperature, fluid flow and combustible gas concentration were analyzed, with special reference to the temperature difference of coke bed and NO concentration of exhaust. The results show that staging combustion plays an important role in improving temperature uniformity of the coke bed and reducing NO concentration of exhaust, especially for the large-capacity coke oven. It is beneficial for production optimization to decrease the gas mass flow rate at the bottom inlet while increase the rate at the upper inlet in the combustion chamber. In addition, it turns out that some measures such as coal preheating, adjustment of moisture content or/and coal densification may be used to improve the coke production efficiency. It is expected the developed model and relevant data in the present research will be beneficial to realize large-scale coke oven with a higher energy efficiency and lower emission.

1. Introduction

Coke produced from blends of coking coals has a wide range of applications and 90% of the coke is used for iron production in the blast furnace [1,2]. Regenerative coke oven is widely used in the world and it contributes more than 90% of the total coke production [3,4]. The combustion chamber and coking chamber are essential components of a regenerative coke oven. The combustion chamber provides thermal energy to the coking chamber where the coal isolated from the air is carbonized to be carbon coke. To guarantee the coke quality, the final temperature of coke bed needs to be in the range of 950 °C–1050 °C, and the temperature uniformity of the bed is satisfied with the largest temperature difference less than 50 °C [5].

Much attention has been paid to the transport phenomena in the coking chamber of coke oven and the related simulation. Tian [6] proposed a simple one-dimensional transient heat conduction model with constant physical properties. Rodhe [7] improved the model by taking into account the temperature-dependent properties, moisture evaporation and chemical reaction. D. Merrick [8,9] developed a series of mathematical models for coking process, to predict the release of volatile matter, the physical properties of the coal/semi-coke/coke during coking, the charge temperature history and effect of blend composition on coke strength and so on. Guo and Tang [10] simultaneously calculated the transient composition, temperatures of the gas and the solid phases, velocity of the gas phase and porosity and density of the semi-coke phase for a coking process using PHOENICS CFD package.

To evaluate the effects of the adjacent combustion chamber and improve the accuracy of simulation, coupling adjacent combustion and coking chambers were further pursued by researchers. Chen

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Nomenclature

A	anisotropic phase function coefficient
C	specific heat capacity, J kg^{-1} K^{-1}
$C_{1\varepsilon}$,$C_{2\varepsilon}$,C_μ	$k-\varepsilon$ turbulence model constant, $C_{1\varepsilon} = 1.44$, $C_{2\varepsilon} = 1.92$, $C_\mu = 0.09$
E	activation energy, J mol^{-1}
F_1,F_2,F_3	cross-sectional area of the flue, gas inlet and air inlet, m^2
$\bar{f}$	mixture fraction, %
G	incident radiation
G_b	turbulence kinetic energy due to buoyancy, kg m^{-1} s^{-1}
G_k	turbulence kinetic energy due to velocity gradient, kg m^{-1} s^{-1}
H	specific enthalpy, J kg^{-1}
H_g	height of flue, m
H_m	latent heat of vaporization, J kg^{-1}
k	turbulent kinetic energy, m^2 s^{-1}
K_{av},K_{sv}	absorption and scattering coefficient, m^{-1}
P	pressure, Pa
P_B,P_h	bottom pressure of upward and downward flowing, Pa
R	molar gas constant, J mol^{-1} K^{-1}
S	energy source term, W m^{-3}
S_G	radiative source term
T	temperature, K
u_i	fluid velocity in i direction, i = 1,2,3, m s^{-1}
V_1,V_2,V_3	mass flow of air, gas and waste gas, m^3/s
x	amount of vapour condensation, %
Y_M	contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate, kg m^{-1} s^{-3}
α	thermal diffusion coefficient, m^2 s^{-1}

Greek letters

ε	turbulent dissipation rate, m^2 s^{-1}
η	ratio of circulation, %
λ	thermal conductivity, W m^{-1} K^{-1}
μ,μ_t	molecular viscosity and turbulent viscosity, Pa s^{-1}
ρ	density, kg m^{-3}
σ	Stefan–Boltzmann constant, W m^{-2} K^{-4}
σ_k,σ_z	turbulent Prandtl number, $\sigma_k = 1.0$, $\sigma_\varepsilon = 1.3$
$\omega_{moisture}$	water content
$\omega_{moisture,0}$	water content of charging coal
$\omega_{moisture,i}$	amount of water evaporation in temperature range i, $\omega_{moisture,1}$ about 75–80%, $\omega_{moisture,2}$ about 20–25%
w_{NO}	NO reaction rate, kmol m^{-3} s^{-1}
τ	time, s
$[O_2]$,$[N_2]$	oxygen and nitrogen concentration, kmol m^{-3} s^{-1}

Subscripts

m	moisture
g	gas
j	c represent coal/coke, w represent inter-wall

et al. [11] first proposed a one-dimensional coupled heat transfer model from the flue in the combustion chamber to the inter-wall and coking chamber. Matsubara et al. [12] presented a one-dimensional coupled simulation model, including not only coking chamber, vertical and horizontal flue, but also regenerator with fuel flow rate supplied as inlet boundary conditions. Luo et al. [13] introduced a two-dimensional model, consisting of a couple of vertical flues and two adjacent chambers, and predicted flue temperature variation during a coking cycle and showed the same trend of concavity as experimental measurements, but less fluctuation in quantity. Recently, we [14] developed a three-dimensional transient mathematical model for coupled coking and combustion chambers. This model was proven to be valid with good accuracy in revealing the temperature-field evolution of coke bed.

Coke ovens without staging combustion (the height of coking chamber is equal to or less than 6 m) have been widely used in actual production [15]. For this kind traditional coke oven, the inlets of BFG (Blast Furnace Gas) and air are only located at the bottom of the flue. With the requirements of improving coke production and quality, along with energy saving, large-capacity coking oven is being developed. To overcome the deficiencies of relatively high local combustion temperature and NO*x* concentration, the staging combustion technology is employed in the large-capacity coking oven [16]. As we know, the staging combustion has been widely applied in various industrial combustions such as coal-fired boilers [17] and electrically heated tube reactor [18]. However, little data and literature are available for large-capacity coke oven and its related staging combustion, where the fuel gas and air are supplied into the combustion chamber via more than one inlet along the height direction of combustion chamber. In order to provide some basis and data for the design of large-capacity coke oven and the optimization production with staging combustion, transport phenomena in coke oven were simulated and analyzed in this paper. A three-dimensional transient model was built for coupled coking and staging combustion chambers. Combustion, fluid flow, heat and mass transfer were studied and compared with traditional coke ovens. Effects of staging combustion were evaluated and its optimization was further discussed for improving the temperature uniformity and reducing NO. More operation parameters were also investigated such as the temperature, moisture content and density of charging coal.

2. Three-dimensional model of transport phenomena in coupled coking and combustion chambers

2.1. Physical model

The combustion chambers including serials of flues and coking chambers are arranged alternatively in parallel in the upper part of the coke oven. The air and BFG or COG (Coke Oven Gas) are supplied into the flues of combustion chamber and burn off. The high-temperature fume rises along the flue, via the turning port, then goes down. At the bottom of the chamber, some fume goes through the circulation port and mixes with fresh gas for recirculation, the others just flow out of the combustion chamber. The high-temperature fume (1400–1600 °C) transfers heat to the inter-wall between combustion chamber and coking chamber by radiation and convection. Then heat is conducted through the wall to the coking chamber, where the coal isolated from the air is heated up gradually until it is stratified to the carbon coke.

Three-dimensional model in this paper consisted of a pair of flues in the combustion chamber and two 1/2 coking chamber, as shown in Fig. 1. Different from traditional coking ovens, a large-capacity coke oven is often operated with staging combustion along the height of the chamber, to guarantee the temperature uniformity of the coke bed [16]. The channels of BFG and air for staging combustion are set in parallel in the walls between flues, as illustrated in the combustion chamber of Fig. 1b.