Three-dimensional Mathematical Modeling and Designing of Hot Stove

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A three-dimensional mathematical model that can simulate the transient heat and mass transfer phenomena in a hot stove has been developed. This mathematical model can treat the turbulent mixing of fuel and air, combustion of fuel, buoyancy convection, heat radiation, and the heat exchange between the gas and heat storage bricks. Comparison of the calculated results with actual measured data was done in order to verify the availability and accuracy of the mathematical model, and computational results gave good agreement with measured data. Brick alignment and operating conditions for a new hot stove can be designed by using this mathematical model.

KEY WORDS: hot stove; heat exchange; mathematical model; combustion; radiation; three-dimensional; unsteady.

1. Introduction

A hot stove is a huge heat exchange facility generating high temperature air of more than 1 200°C. This hot air is blown into tuyeres of the lower part of blast furnace and converted into the reducing gas reacting with coke, iron ore is reduced by this reducing gas, and melted pig iron is generated. A hot stove is important facility supporting blast furnace operation; therefore, the hot stove should be designed to achieve a longer life time than the life of the blast furnace and to operate stably for a long time.

As shown in Fig. 1, the hot stove consists of “combustion chamber” in which air and fuel are mixed and burned, and “checker chamber” in which heat storage bricks are piled up. A hot stove is operated in two modes, namely combustion and blast mode. In the combustion mode, fuel and air are mixed and burned in the combustion chamber, the combustion gas is blown to the checker chamber, and heats the heat storage bricks. As shown in Fig. 2, the heat storage bricks have many tubular holes through which the combustion gas passes. In blast mode, almost 200°C air is blown into the bottom of the checker chamber, and passes through the holes in the bricks where it heated by the bricks up to 1 200°C or more. In practical use, 3 or 4 hot stoves are operated with changing combustion and blast modes at different timing, for constant interval time periodically, then hot air is supplied to the blast furnace at a constant temperature and flow rate. In blast mode, with decreasing temperature of heat storage bricks in checker chamber, temperature of blast exiting from combustion chamber decreases. Therefore, a mixing chamber for mixing hot blast exiting from combustion chamber with cold blast, which is not passed through checker chamber, is set up to supply a constant temperature hot blast to blast furnace.

In the hot stove, various complex phenomena occur such as turbulent mixing of fuel and air, combustion of fuel, buoyancy convection, heat radiation, and heat exchange between the gas and the heat storage bricks. Moreover, the scale of the system ranges widely from several cm which is...
the diameter of brick hole, to several tens meter which is the size of whole furnace. In addition, this system has two different time scales. One is a very short time scale which represents fluid flow and chemical reaction and is about $10^{-3}$ s, and the other is a long time scale which represents the heating rate of the heat storage bricks and is about 10 s.

In the 1930's, Hausén et al. modeled heat transfer in a hot stove and solved analytically the model. After the 1960's, Butterfield et al. and Willmott numerically investigated the performance of the heat transfer in a hot stove with computer. In the latter half of the 1970's when the energy saving technology began to be noticed, the research on operation technology to improve thermal efficiency, slow cooling, waste heat recovery and the preheating technology were advanced. Some researches were based on mathematical models, but they assumed uniform gas flow, and ignored the heat conduction in the height or radial directions. Zhong et al. predicted the inside temperature profile of brick in three dimensions, however, these models in the past are inadequate for performing a detailed design of hot stove. Since there is not a mathematical model that can simulate the temperature distribution of the whole region of the hot stove, a mathematical model that can estimate the phenomena exactly in the hot stove is strongly required.

Therefore, in this study, a three-dimensional mathematical model that can simulate various complex phenomena (turbulent mixing of fuel and air, combustion, buoyancy convection, heat radiation, heat exchange between the gas and heat storage bricks) and cyclic operations in a hot stove has been developed, and comparison of the calculated results with measured data is conducted in order to verify the availability and accuracy of the model. Finally, brick alignment and operating conditions for new hot stove have been designed by using this mathematical model.

2. Mathematical Modeling

2.1. Modeling of the Heat Storage Brick

Figure 2 shows the structure of the heat storage brick. The heat storage brick has many holes penetrating it so that the heat exchange gas can pass through. The area of heat exchange bricks is approximated as porous media in order to suppress the calculation load. A void fraction of the brick is calculated by Eq. (1), where $A$ is the outside length of the heat storage brick and $D_b$ is the diameter of the brick hole. The ratio of heat transfer area to volume is expressed by Eq. (2).

$$\varepsilon_b = \frac{8\pi D_b^2}{\sqrt{3} A^2} \quad (1)$$

$$a_p = \frac{12\pi D_b^2}{3\sqrt{3} A^2(1-\varepsilon_b)} \quad (2)$$

2.1.1. Pressure Drop

Pressure drop in a pipe is calculated by Eq. (3) (Fanning’s equation), and the friction factor $f$ including the influence of surface roughness is described by Eqs. (4) and (5), where $D$ is the diameter of the pipe, $l$ is the length of the pipe, and $e$ is unevenness height.

$$\frac{\Delta p}{l} = \frac{4f}{D} \rho u^2 \quad (3)$$

$$f = \frac{16}{Re} \quad (Re<3000) \quad (4)$$

$$f = 2.28 - 4 \log(e/D) \quad (Re>3000) \quad (5)$$

2.1.2. Heat Transfer Coefficient

In Eq. (6), characteristic length $Le$ is defined as the equivalent diameter of sphere whose ratio of heat transfer area to volume is equal to that of the brick. Heat transfer coefficient $h$ between gas and brick can be estimated from the relationship between Nu and Re expressed by Eq. (7) for pipe flow. Overall heat transfer coefficient is expressed in total of the resistance between the gas and the brick and the resistance of the heat conduction in the brick, and can be described by the Eq. (8), where $\eta$, the correction factor for shape of brick hole, is equal to 5.

$$Le = \frac{6}{8} \frac{\sqrt{3} A^2(1-\varepsilon_b)}{12\pi D_b} \quad (6)$$

$$Nu = \frac{hD}{\lambda_g} = 0.023 Re^{0.8} Pr^{0.4} \quad (7)$$

$$Re = \frac{D u p D_b}{\mu} \quad , \quad Pr = \frac{C_p \mu}{\lambda_g}$$

$$\frac{1}{h_i} = \frac{1}{h} + \frac{1}{\eta \lambda_s / (Le / 2)} \quad (8)$$

2.2. Other Assumptions

The following assumptions and simplifications are made in this model in order to simulate complex phenomena exactly and shorten calculation time.

1. Seven gas components (CO, CO$_2$, H$_2$, H$_2$O, CH$_4$, O$_2$, and N$_2$) are considered.
2. Three overall reactions which are controlled by the mixing rate of chemical components are considered as shown in Table 1.
3. Gas is compressible viscous fluid and follows the ideal gas law.
4. $k$–$\varepsilon$ model is employed as a turbulent model.

Table 1. Chemical reactions.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO + 1/2O$_2$</td>
<td>CO$_2$</td>
</tr>
<tr>
<td>H$_2$ + 1/2O$_2$</td>
<td>H$_2$O</td>
</tr>
<tr>
<td>CH$_4$ + 2O$_2$</td>
<td>CO$_2$ + 2H$_2$O</td>
</tr>
</tbody>
</table>
2.3. Governing Equations

Under the above assumptions, phenomenon in a hot stove can be expressed by governing Eqs. (9)–(15). Equations (9) and (10) denote mass balance of chemical species and total mass balance, respectively. Equation (11) denotes momentum balance, and the 3rd term of the right-hand side shows the flow resistance of brick hole. Equations (12) and (13) denote energy balance for gas and solid. The 2nd term of the right-hand side expresses reaction heat, and the 3rd term expresses radiant heat transfer. The 4th term of the right-hand side of Eq. (12) and the 2nd term of the right-hand side of Eq. (13) express the heat exchange between the gas and bricks in the heat storage brick region.

- [Mass Balance] \[ \rho \frac{\partial u}{\partial t} + \nabla \cdot (\rho u u) = \nabla \cdot (\rho D \nabla u) + R \] ....(9)
- [Momentum Balance] \[ \rho \frac{\partial U}{\partial t} + \nabla \cdot (\rho U U) = \nabla \cdot (\rho D \nabla U) + 0 \] ...........(10)
- [Energy Balance] (Gas) \[ \frac{\partial T_g}{\partial t} + \nabla \cdot (\rho C_{pg} T_g \nabla u) = \nabla \cdot (\varepsilon \lambda_{ge} \nabla T_g) + \sum_i R_i (\Delta H_i) + Q_g + C_i h_i (T_s - T_g) \] ........................................(12)
- (Solid) \[ (1 - \varepsilon_g) \frac{\partial T_s}{\partial t} = \nabla \cdot [(1 - \varepsilon_g) \lambda_{se} \nabla T_s] - a_i h_i (T_s - T_g) \] ........................................(13)
- [Turbulent kinetic energy and its rate of dissipation] \[ \frac{\partial k}{\partial t} + \nabla \cdot (k \nabla u) = \frac{v_x}{\sigma_1} \nabla k + P_k - \varepsilon \]
\[ \frac{\partial \varepsilon}{\partial t} + \nabla \cdot (\varepsilon \nabla u) = \frac{v_x}{\sigma_2} \nabla \varepsilon + \frac{\varepsilon}{k} (C_k P_k - C_\varepsilon \varepsilon) \]
\[ v_i = C_\mu k^2 \varepsilon, \quad \varepsilon = v + v_i \]
\[ C_\mu = 0.09, \quad C_1 = 1.44, \quad C_2 = 1.92, \quad \sigma_1 = 1.0, \quad \sigma_2 = 1.3 \] ..............................................(14)

2.4. Radiation Heat Model

In combustion chamber, radiant heat transfer is dominant. In radiant heat transfer, it is necessary to treat emission and absorption in gas and on solid surface, and Monte Carlo method\(^{15,16}\) is the most accurate way as the analysis method of radiant heat transfer. Here, radiant heat transfer is simplified as shown in Fig. 3, because the furnace shape is almost an axisymmetrical geometry, only radial radiant heat transfer is considered in order to suppress the computational load. Radiant heat transfer is expressed by Eq. (16) and emissivity of gas is calculated by Eq. (17).\(^{17}\)

\[ Q_r = \sigma \varepsilon_g \cdot S (T_g^4 - T_s^4) / V_i \] .............(16)
\[ \varepsilon_{g_e} = \varepsilon_{Re_e} \cdot \frac{T_g}{(1 - \varepsilon_{Re_e})(1 - \varepsilon_{Re_e})} \]
\[ \varepsilon_{Re_e} = 0.7 \left( \frac{p_{CO_2}}{p_{CO_2}} \right)^{1/3} / (T_g / 100)^{1/2} \] (CO\(_2\)) \( \varepsilon_{BH,O} = 7.0p_{H_2O}^{0.8} / (T_g / 100) \) (H\(_2O\))

2.5. Solving Procedure and Method

The boundary fitted coordinate system is adopted to treat the shape of hot stove precisely,\(^{18}\) the governing equations are discretized on the staggered grid. The algorithm adopted in the solving of gas flow is the SOLA method.\(^{19}\) The first-order upwind scheme is used for convection term, and the second-order central scheme is used for diffusion term. The governing equations of mass and energy conservation for gas and solid phase are discretized by the implicit scheme and solved by the point SOR (Successive Over Relaxation) method.\(^{20}\) Equations (12) and (13) are solved simultaneously. The solution procedure is according to the following.

1) Initial condition is given.
2) The velocity \( u \) and pressure \( p \) are calculated by solving Eqs. (10) and (11).
3) The mass fractions \( \omega_i \) are calculated by solving Eq. (9).
4) The gas temperature \( T_g \) and solid temperature \( T_s \) are calculated by solving Eqs. (12) and (13).
5) Procedures 2)–4) are repeated until the time reaches the specified value.

3. Verification of Mathematical Model

Comparison of the calculated results with actual meas-
ured temperature data is done in order to verify the accuracy and the availability of the mathematical model. The temperature distribution of the real plant hot stove for No. 4 blast furnace was measured at Wakayama Steel Works (Wakayama hot stove). Wakayama hot stoves are operated in single-blowing operation in which one stove supplies hot blast and other stoves are heated up. Half of the whole domain of the furnace was analyzed, since the shape is symmetrical. Figure 4 shows the computational grids for checker chamber, connecting tube, and combustion chamber which are divided into 43/11003222/1100315, 10/110036, and 40/110031814, respectively. The operating condition of the hot stove is shown in Table 2.

As the boundary condition, velocity, temperature, and chemical composition are set to inlet ports for fuel and air, and the boundary conditions of inlets and the exit are changed in order to simulate the state on both combustion and blast modes. The constant heat transfer coefficient is given at the outside surface of the hot stove.

The estimated result of gas flow and temperature distribution in the hot stove at the end of combustion mode (97.9 min) and blast mode (58.9 min) are shown in Fig. 5. In this figure, we can see the following:

- The circulating gas flow is formed in the upper section of the combustion chamber in combustion mode, and the gas flow becomes uniform passing through the heat storage bricks. Although circulating flow is also formed in upper section of the combustion chamber in blast mode, the gas flow does not become uniform in the combustion chamber and strong downward flow pattern is formed.
- Temperature distribution of the heat storage bricks in radial direction is almost uniform. However, the temperature of connecting tube side is slightly low, because the blowing-in air from one inlet at the bottom of the checker chamber collides with the wall of the connecting tube side first, goes upward in the heat storage brick along the wall.

The comparison between the calculation and the measurement of the time change of the temperature at each height level, temperature distribution in direction of height and radius in checker chamber are shown in 1), 2) and 3) of the Fig. 6. In these figures, we can see the following:

- The temperature difference between the top and the bottom in the checker chamber reaches up to 1000°C, the temperature difference in combustion mode and blast mode at the same height level is almost 200°C.
- Gas temperature is higher than solid temperature in combustion mode, and solid temperature is higher than gas temperature in blast mode. The differences between gas and solid temperature are up to 50°C in each mode.
- Computational results of the temperature changes and profiles in the checker chamber are in good agreement with measured data. Thus we conclude that this mathematical model can estimate the three-dimensional unsteady phenomenon in the hot stove precisely. Moreover, by this model, we can decide brick alignment and operating conditions for new hot stove.

In the next paragraph, on the basis of the estimation of temperature distribution in the hot stove by this model, bricks alignment and operating conditions for the new hot stove are evaluated.

4. Application to Design New Hot Stove and Discussion

Performances required for a hot stove are to provide the blast to a blast furnace at constant temperature and flow rate and to keep the bricks at appropriate temperature. Brick
alignment and operating conditions for the new hot stove for New No.1 blast furnace in Kashima Steel Works (Kashima new hot stove) are investigated by the present model. As a characteristic shape for the new blast stove, the height of the combustion chamber and the checker chamber are almost same in order to decrease the mechanical stress by the elongation gap between combustion chamber and checker chamber in combustion mode and blast mode. The inner volume of the New No. 1 blast furnaces in Kashima Steel Works (Kashima blast furnace) is almost twice that of No.4 blast furnace in Wakayama Steel Works (Wakayama blast furnace). Therefore, the required hot blast volume for the Kashima blast furnace is almost twice that of the Wakayama blast furnace. Kashima new hot stoves are operated in single-blowing operation, as well as Wakayama hot stove.

4.1. Characteristics of Bricks and Bricks Alignment

Figure 7 shows the thermal expansion characteristic of bricks typically used in a hot stove. The silica bricks have high volume stability over 600°C; however, the sudden volumetric change in a silica brick at about 500°C causes thermal crack. The changes of thermal expansion for both high alumina and fireclay bricks are proportional to temperature in a wide range of temperatures. While the silica and high alumina bricks have high-temperature creep resistance, the fireclay bricks do not have. The fireclay brick contains more than 50% SiO₂. A α-β transformation of cristobalite, which is one of SiO₂ polymorphism, occurs volumetric change at almost 250°C. Therefore, the fireclay brick has a risk of cracking at the same temperature. However, the fireclay brick has an advantage from respect of costs.

4.2. Temperature Criteria for Bricks Alignment

Quartz α-β transformation and cristobalite α-β transformation are the crystal modification of SiO₂, cause a large volumetric change. The silica brick and fireclay brick contain more than 50% SiO₂. Especially, it is necessary to allocate the silica and fireclay brick, so as not to cause quartz α-β transformation and cristobalite α-β transformation with volumetric change, while operating. In consideration of transformation temperature for quartz α-β and cristobalite α-β, we set lower temperature limit for silica brick to 600°C and for fireclay brick to 250°C as temperature criteria for bricks alignment. The bricks are supported at the lower part of the checker chamber by brick support made of casting metal. From the viewpoint of high temperature strength for the support, it is necessary to keep the temperature of the bottom bricks under 400°C.

4.3. Results of Study

Operating conditions of the hot stove are changed according to the state of blast furnace. In this study, we check two conditions, namely 1 250°C and 850°C blast condition. The former is the condition at normal operation, what is called pulverized coal injection operation, and the latter is the condition at emergency operation, what is called all-coke operation. Table 3 shows operating conditions in 1 250°C blast condition.
4.3.1. Gas Flow and Temperature Distribution in the New Hot Stove

The gas flow and temperature distribution in the hot stove at the end of combustion and blast mode are shown in Fig. 8. In this figure, we can see the following:

- Temperature distribution in direction of radius in the checker chamber of new hot stove is more uniform than that of Wakayama hot stove. Because there are two blowing-in inlets in Kashima new hot stove, and blowing-in air circulates more uniformly in the space of the lower part of the checker chamber in new hot stove than in Wakayama hot stove.

4.3.2. Improvement of Brick Alignment

Under 1250°C and 850°C blast conditions, calculated temperature of heat storage bricks in the combustion and blast mode in direction of height in the center position of checker chamber are shown in Fig. 9. The arrangement of the brick was changed based on the calculated temperature distribution as follows.

- Since the cycle time of Kashima new hot stove is half as that of Wakayama hot stove, the temperature increase of the heat storage brick in combustion mode and the temperature decrease in blast mode are small. Therefore, temperature difference of Kashima new hot stove between combustion mode and blast mode is less than that of Wakayama hot stove, and the temperature difference is about 100°C.
- At the first initial brick alignment, brick temperature estimated by the model under 1250°C blast condition is higher than the lower limit of brick temperature in both combustion and blast modes. However, under 850°C blast condition, at the end of the blast mode, brick temperature in the lower part of fireclay brick shown in area B and the lower part of the silica brick shown in area A, are below the lower limit of the brick temperature respectively.
- The final brick arrangement is shown in the upper part of Fig. 9. Each brick arrangement was changed so that both temperature of the fireclay and the silica brick should not fall below the lower limit temperature. At the same time, it is considered that a lot of fireclay bricks with low cost are used as much as possible.

4.3.3. Adjustment for Operating Condition

Figure 10 shows schematic view for controlling blast temperature by mixing hot air with cold air. Here, in this figure, mixing air means the air blown into the mixing chamber, not blown into checker chamber. Figure 11 shows change of blast temperature and air flow rate under 1250°C blast condition. In this figure, following matters can be understood.

- In the initial plan, the flow rate of mixing air is too much, and the temperature of blast is lower than the target value. However, by adjusting flow rate of mixing cold air, we could decide the operating conditions to satisfy the target value for blast temperature and flow rate to the blast furnace.
- Kashima new hot stove can produce almost two times blast rate of Wakayama blast furnace. Because both volume and heat transfer area of heat storage bricks in Kashima new hot stove are increased by about 30% com-
pared to those in Wakayama hot stove, and cycle time of Kashima new hot stove is almost 1/2 that of Wakayama hot stove.

We conclude that under both 1250°C and 850°C blast conditions, the new hot stove can supply the required temperature and flow rate of hot blast to a blast furnace, and that the bricks can be used at appropriate temperature.

5. Conclusions

In this study, a three-dimensional mathematical model that can simulate the transient heat and mass transfer phenomena in a hot stove has been developed. In this mathematical model, turbulent mixture of fuel and air, combustion reaction, buoyancy convection, heat radiation, and heat exchange in the heat storage brick region were considered. Then, comparison of the computational results with actual measured data was conducted in order to verify the accuracy and the availability of the proposed mathematical model, and computational results were in good agreement with measured data. Finally, by using this mathematical model, brick alignment and operating conditions for the new hot stove were determined. As above mentioned work, the following were obtained.

(1) The circulating gas flow was formed in the upper section of the checker chamber at the combustion mode, and the gas flow became uniform passing through the heat storage bricks.

(2) Temperature distribution in direction of radius in the checker chamber was almost uniform, and was more uniformly with two blowing-in inlets than with one blowing-in inlet.

(3) Total volume and heat transfer area of heat storage bricks in new hot stove were increased respectively by about 30% and cycle time of new hot stove was almost 1/2 compared with conventional hot stove. Therefore, new hot stove could produce almost two times blast rate of conventional hot stove.

The present model is useful, and can be applied to design of future hot stoves and temperature management for existing hot stoves.

Nomenclature

\( A \): Outside length of heat exchange brick
\( a_s \): Contact area between gas and solid phase
\( C_p \): Specific heat
\( D \): Diffusion coefficient
\( D_h \): Hole diameter of brick
\( f \): Resistance coefficient
\( g \): Gravity acceleration
\( p \): Pressure
\( Le \): Equivalent diameter
\( Q_r \): Radiant heat
\( R \): Gas constant
\( R_i \): Formation rate of reaction
\( S \): Surface area for radiant heat
\( T \): Temperature
\( h_r \): Heat transfer coefficient between gas and solid phase
\( \bar{U} \): Velocity vector
\( V \): Cell volume

Greek

\( \Delta H_i \): Reaction heat of reaction \( i \)
\( \varepsilon \): Dissipation rate of turbulent kinetic energy
\( \varepsilon_B \): Volume fraction of gas phase
\( \varepsilon_g \): Emissivity
\( \kappa \): Turbulent kinetic energy
\( \lambda \): Thermal conductivity
\( \mu \): Viscosity
\( \nu \): Kinetic viscosity
\( \rho \): Density
\( \rho_0 \): Reference density
\( \omega_i \): Mass fraction of species \( i \)
\( (i=CO, CO_2, H_2, H_2O, CH_4, O_2, N_2) \)

Subscripts

\( e \): Effective
\( g \): Gas
\( s \): Solid
\( t \): Turbulent
\( w \): Wall

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