The Modeling of the Gas Flow and Its Influence on the Scale Accumulation in the Steel Slab Pusher-type Reheating Furnace

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The gas flow in the pusher-type reheating furnace coupled with fluid dynamics, combustion and radiation was modeled in this work. CFD Simulation results described a detailed flow distribution in the steel reheating furnace and indicated a reverse flow existing under the slab near the burners in the lower heating zone. This reverse flow could be the main reason for the scales accumulation in the front part of the heating zone. The oxygen distribution in the furnace was also calculated and the mass fraction is about 4%. The oxygen distributes uniformly inside the most parts of the furnace except the areas near the burners.

KEY WORDS: computational fluid dynamics; pusher-type reheating furnace; flow pattern; scales accumulation; oxygen distribution.

1. Introduction

In the plate mill, scales peeled off from the slab surface sometimes build up in some areas in the heating zone of the furnace, which may cause poor combustion conditions and low efficient heat transfer. Industry experiences indicate that such scale sedimentation is closely related with the flow type in the furnace. Since it is very hard to observe the gas flow phenomena in the high temperature furnace, the modelling of gas flow in the pusher-type reheating furnace was the objective of the current work.

Some models have been set up on the fields of slab reheating furnace.1,2) However, most of those works are about the thermal calculation of reheating furnace and the skidmark generation because they are the most interests of the industry. Other investigations of gas flow patterns in a reheating furnace were carried out in physical simulation experiments such as Matsunaga’s water model.3) There are some numerical modelling reports about the flow in the pusher-type reheating furnace in recent years,4,5) but some of the simplification in those simulations may not stand for the real industrial process.

Gas flow pattern in the reheating furnace is an important factor affecting the scale sedimentation on the floor of the furnace. With the aid of CFD, gas flow distribution in the reheating furnace can be simulated under different conditions. The current paper couples fluid dynamics with thermal model to outline gas flow and temperature in the pusher-type reheating furnace with the consideration of skid rail support pillars.

2. Description of Mathematical Model

2.1. Structure of Pusher-type Slab Reheating Furnace

The pusher-type steel slab reheating furnace modelled is shown in Fig. 1. This furnace is currently run in the industry, which is about 28 m in length, 8 m in width and the highest roof is almost 6 m inside. There are three zones in the reheating furnace: soaking zone (discharge), heating zone and convection zone (charge). There are eight burners in the soaking zone. In the heating zone, six burners are arranged at the upper section while seven burners are installed at the lower part as shown in the figure.

Because of its symmetry, a half of the furnace is modelled in order to reduce computing time. Three-dimensional modelling was employed for the flow simulation. The commercial CFD code, PHOENICS 3.1, was used.

2.2. The Governing Equations

Flow in the pusher-type reheating furnace is turbulent because of fast flow injected from the burners and intermingles of gas with various streams from different burners. Since the fuel of this reheating furnace is coke oven gas (assuming components are only H₂, CO and CH₄ for simplification) and the combustion mixture consists of N₂, CO₂, H₂O and O₂, the gas flow can be assumed single phase, steady state and Newtonian non-isothermal fluid.

The governing equations of steady turbulent flow in Cartesian coordinates can be expressed as follows6–8):

The continuity equation:

\[
\frac{\partial (\rho u_j)}{\partial x_j} = 0 \quad \text{(1)}
\]
The momentum equation:
\[
\frac{\partial}{\partial x_j} (\rho u_i u_j) = -\frac{\partial P}{\partial x_j} + \frac{\partial}{\partial x_j} \left( \mu \frac{\partial u_i}{\partial x_j} \right) + \frac{\partial}{\partial x_i} \left( \rho u_i u_j \right) + F_i
\]

The turbulent part in Eq. (2) can be derived from high Reynolds number k-ε turbulent equation. \( F_i \) is the momentum source including buoyancy caused by temperature.

For low Reynolds number region near the wall, wall functions are employed to bridge viscous sub layer and provide near wall boundary conditions for the turbulence transport equations.

The energy equation used in the model is as following:
\[
\frac{\partial (\rho u_i H)}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \frac{\mu}{\sigma_h} \frac{\partial H}{\partial x_j} \right) + S_h
\]

\( S_h \) is the energy source related with radiation and combustion heat.

The chemical species conservation equation is:
\[
\frac{\partial (\rho u_i m_l)}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \rho F_{ij} \frac{\partial m_l}{\partial x_j} \right) + R_l
\]

Here \( R_l \) is the chemical reaction rate of species \( l \).

Finally, one thing should be pointed out that the gas properties such as density, viscosity and specific heat, are the functions of species and temperature. Those properties are derived during the iteration by PHOENICS.

### 2.3. The Combustion Modeling

Accurate combustion reacting process modeling is rather complicated. In this combustion model, extended simple chemically reacting system (ESCRS) is employed in order to simplify the problems.

| Table 1. Composition of gas fuel used in the steel reheating furnace (volume fraction). |
|-----------------|----------------|----------------|----------|----------|
| CO %            | H₂ %           | CH₄ %          | N₂ %     |
| 7.4             | 54             | 28             | 10.6     |

The assumptions for this reacting system are: combustion products are generated via the reaction of fuel and oxidant; the reaction is assumed as irreversible; the reaction rates are often more greatly affected by local turbulence than by chemical-kinetic factors.

Table 1 is the composition of the fuel used in this furnace. The oxidizer is air. The simplified chemical reactions are expressed below.

\[ 2\text{CH}_4 + \text{O}_2 \rightarrow 2\text{CO} + 4\text{H}_2 \]  
\[ 2\text{CO} + \text{O}_2 \rightarrow 2\text{CO}_2 \]  
\[ 2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O} \]

Eddy-Break-Up (EBU) model in ESCRs is applied. For this case, the combustion stage is controlled by the mixing rate of the reactant in a turbulent scale, which is expressed in Eq. (8).

\[ R = -C_{\text{EBU}} \cdot \text{Min} \left( \frac{m_{\text{fuel}}}{m_{\text{air}}}, \frac{m_{\text{O}}}{m_{\text{air}}} \right) \cdot \rho \cdot \frac{\varepsilon}{k} \]

Here, the EBU constant \( C_{\text{EBU}} = 4.0 \). The expression Min(...) implies that \( R \) is dependent on the species in the shortest supply. The reaction rate and further enthalpy source are linked with the solution of momentum, continuity, enthalpy and chemical species conservation equations mentioned before. The thermodynamic data and properties of gas, such as specific heat, reaction heat and density, are derived from the CHEMKIN interface in PHOENICS codes while solving the gas composition and temperature.

### 2.4. The Radiation Modeling

According to the energy Eq. (3), radiation is taken into account in the form of heat resource.
sumptions are given in this radiation model: radiation is transmitted in coordinate directions only; no interlinkages, apart from scattering, arise between the radiation fluxes in the respective coordinate directions; the scattering term presumes that the scattering is isotropic with angle, which is probably reasonable only if the total contribution of scattering is not large. These assumptions will not bring much inaccuracy since the gas in the furnace is mixture of CO2, H2O and N2, and the geometry of the furnace is not complicated.

In this furnace simulation, composite-flux model is chosen,11,12) which has been widely used in combustion chambers and furnaces. Composite-flux model is the simplification of random heat flux method. When assuming the medium is grey and diffuse, the effects of radiation are accounted for by reference to the positive and negative radiation fluxes in each of the coordinate directions, as follows in the PHOENICS:

\[ I, J, \text{ and } K \text{, the radiation fluxes (W/m}^2\text{) in the positive and negative } x \text{ directions, respectively; } K \text{ and } L, \text{ the radiation fluxes (W/m}^2\text{) in the positive and negative } y \text{ directions, respectively; and } M \text{ and } N, \text{ the radiation fluxes (W/m}^2\text{) in the positive and negative } z \text{ directions, respectively. Thus, radiation flux transfer equations can be deduced as:}

\[
\begin{align*}
\frac{dl}{dx} &= -(K_s + K_e)I + K_e I_b + K_s \cdot \text{SUM} \quad \ldots (9) \\
\frac{dl}{dy} &= -(K_s + K_e)J - K_e I_b + K_s \cdot \text{SUM} \quad \ldots (10) \\
\frac{dk}{dy} &= -(K_s + K_e)K + K_e I_b + K_s \cdot \text{SUM} \quad \ldots (11) \\
\frac{dl}{dy} &= -(K_s + K_e)L - K_e I_b + K_e \cdot \text{SUM} \quad \ldots (12) \\
\frac{dm}{dz} &= -(K_s + K_e)L + K_e I_b + K_s \cdot \text{SUM} \quad \ldots (13) \\
\frac{dn}{dz} &= -(K_s + K_e)N + K_e I_b + K_s \cdot \text{SUM} \quad \ldots (14)
\end{align*}
\]

The term SUM from Eqs. (9) through (14) is the average of all the radiation flux in the furnace modelled. For three-dimension:

\[
\text{SUM} = (I+J+K+L+M+N)/6 \quad \ldots (15)
\]

Each of the above differential equations indicates a flux reducing with distance in consequence of absorption and scattering, and its augmentation by emission and scattering from other directions. This six-flux composite model is practical and simplicity in the algebraic equation iteration.

In this furnace radiation model, the mean absorption coefficient of gas in the furnace \( K_e = 0.1 \), mean scattering coefficient \( K_s = 0.01 \) according to Hoffmann and Markatos’ hydrocarbon combustion model,13 the mean emissivity coefficient of wall \( \varepsilon_w = 0.8 \) for its materials is refractory.

2.5. Boundary Conditions and Solution Method

Because the movement of slab in the furnace is slow and the steady model was used in CFD simulation, the slabs can be considered static in order to simplify the problem. In the model, slabs are contacted with each other so that they form a whole block region (or slab stream) along the longitudinal direction shown in Fig. 1. The slab arrangement also agrees with the real industry operation of the furnace modelled.

The aim of this model is simulating gas flow and atmosphere temperature distribution in the reheating furnace. Consequently, the following boundary conditions should be known for the calculation: surface temperature of slabs, surface temperature of inside walls and roof of furnace. The inlet boundary conditions, such as flow rate, temperature and composition of fuel injected from burners should also be known.

Surface temperatures of slabs in the furnace were obtained from the measurement in the furnace operation process by embedding some thermocouples into one slab. The measurement of one slab was taken from the beginning of its charge to the end of discharge. Figure 2 shows the measured temperature history of the slab when moving from the charge zone to the discharge zone. Since the furnace operating state is considered steady, the temperature measured at different time can be referred to the surface temperature of slab layer at different location along the moving direction. Slabs stream was divided into nine regions. Each region was given a temperature on the top surface, bottom surface and side surface according to the temperature measured.

The inlet boundary conditions such as mass flux, velocity, composition, enthalpy and turbulent kinetic energy \( k \), dissipation rate \( \varepsilon \) of gas from burner inlets can be derived from pre-calculations. Table 2 shows some conditions of inlet flow. Kinetic energy and dissipation rate \( \varepsilon \) of flow from inlets are obtained in the equations below14:

\[
k = \frac{3}{2} (T_{\text{inlet}} \cdot u)^2 \quad \ldots (16)
\]

\[
\varepsilon = \frac{0.09u^3}{2} \quad \ldots (17)
\]

There are two outlets (exhaust pipes) at the end of the reheating furnace. External pressure is assumed to be atmospheric pressure (1.01×10^5 Pa).

The sidewall and roof of furnace are divided into several sections. Each section is given a boundary temperature according to the thermal monitor system in the operation. It is necessary to take skid rail support pillars into account in the energy and momentum simulation. Surface temperatures of these skid pillars are evaluated by the values of slab surfaces measured, freeboard inside and some reference literature data mentioned above. Temperatures on the pillars’ surface range from 1420 to 823 K along the heating zone to the convection zone.

Component of the gas in the furnace includes N2, H2, CH4, H2O and CO2. Their heat capacity, for example, \( C_{p,N2} \), \( C_{p,H2} \), \( C_{p,CH4} \), \( C_{p,H2O} \), and \( C_{p,CO2} \) is the function of temperature \( T \). After the composition fraction of gas, such as \( y_{N2} \), \( y_{H2} \), \( y_{CH4} \), \( y_{H2O} \) and \( y_{CO2} \) are obtained in the iteration process, specific heat capacity of gas mixture at temperature \( T \) is:

\[
\frac{C_p}{C_{p,N2}} = \frac{y_{N2}}{C_{p,N2}} + \frac{y_{H2}}{C_{p,H2}} + \frac{y_{CH4}}{C_{p,CH4}} + \frac{y_{H2O}}{C_{p,H2O}} + \frac{y_{CO2}}{C_{p,CO2}}
\]
\[ C_{p,\text{gas}} = C_{p,N_2} + C_{p,H_2} + C_{p,CH_4} + C_{p,H_2O} + C_{p,CO_2} \tag{18} \]

Finite volume method is applied to discretize the governing partial differential equations. The pressure-velocity coupling is solved with SIMPLEST algorithm. HQUICK, which is one kind of the second order scheme introduced in the PHOENICS, was included in the calculation in order to reduce numerical diffusion.

Two different size meshes were tried separately in this simulation. The coarse mesh had 82,212 cells and the fine mesh had 191,520 cells. The results indicated that the simulation is independent of the mesh size. The solution was thought convergent when all of the following standards are met: the values at the monitor point stopped changing; the residuals were reduced by several orders of magnitude; the balance of mass, energy is achieved.

3. Results and Discussion

3.1. Flow Pattern and Gas Temperature Distribution

Figure 3 shows the gas flow pattern and temperature distribution along the longitudinal direction of the furnace, which cross one of the burner’s axes in the heating zone (slice I in Fig. 1). Flow pattern obtained in this numerical model is not too far away from the physical model carried out by Matsunaga as shown in Fig. 4, except some of the lower part in the heating zone. This disagreement owes to the different structure in the lower heating zone. Figure 3(b) shows that reverse flow near the roof close to the burners exists either in the heating zone or the soaking zone. There are also reverse flows at the corner between floor and burners in the lower heating zone wall. Those results are similar to Matsunaga’s water model. Moreover, simulation results indicate that there is a strong reverse flow under the slab and near the burners of the lower heating zone, which did not appear in the water model. This back flow could be caused by the floor stair step on the lower heating zone floor in this industry furnace, while the bottom floor of the heating zone was flat in the previous water model.

Figure 3(c) shows that flames of burners in the lower heating zone slant upwards when they bounce the stair of the floor. Flames of the burners in the upper heating zone inject downward because of the burners’ installation angle.

3.2. Reverse Flow and Its Influence on the Scale Accumulation

Situation of scale build-ups near the burners in the lower heating zone is shown in Fig. 5. The picture was taken in the mill plant after a long furnace operation, which indicates that scales usually accumulate between each burner in the lower heating zone. This sedimentation seldom developed in front of the burners in the lower heating zone.

Figure 5 shows that scale accumulation is parallel to the support pillars in the longitudinal direction (z dimension in Fig. 1). The peak of scale build-up do not immediately at-
Attached to the pillars. On the contrary, they are a little away from the support pillars. If observing the region near the burners in the lower heating zone and the first supporting pillar from the burners' wall, scale build-ups are higher than other accumulations far away. The scale accumulation is less after the third support pillar from the burners' wall. At the same time, the scale sedimentation is not serious along the longitudinal direction between supporting pillars. Some special slices parallel to the longitudinal direction were marked in this picture for further analysing the flow distribution and its influence on the scales sedimentation.

Fig. 3. Gas flow pattern and temperature along longitudinal furnace (slice 1 in Fig. 1).

Fig. 4. Gas flow patterns in the pusher-type reheating furnace obtained by water model.3)

Fig. 5. Scale accumulation near the burners of lower heating zone and support pillars.
One thing should be pointed here that the flow modelling did not consider the scale build-ups’ influence on the flow (they may affect the flow pattern if they accumulate seriously after a long campaign). The current job intends to analyze possible scale accumulation about this type of new furnace (course no scales accumulation at the beginning). Since the objective of the work is finding the potential reasons of scales accumulation connected with the flow pattern in the furnace, some simplification is necessary. Consequently, at the moment the precise position of the scale accumulation is not the current concern and the tracking of scale peeled from the slab is not included in the CFD model.

Modelling results of gas flow velocity and temperature passing through the slice II of scale build-ups marked in Fig. 5 are shown in Fig. 6(a). Obviously, there is a flow recycling area between the slab and burners flames in the front part of the lower heating zone. This kind of reverse flow can carry back the scales falling from the slab surface to the burners’ wall. Centrifugal effects of flow would lead to scale accumulate on the floor near the burners in the lower heating zone. Since temperature modelled near the bottom of the furnace is above 1370°C, the scales with main composition of wustite could sinter very easily in these regions. The areas of reverse flow extend along the longitudinal direction until the third pillar from the burners’ wall, which explains why the scales are piling up seriously and parallel to the pillars row until the third pillar from the burners wall.

On the slice III crossing the support pillars in Fig. 6(b), the reverse flow is so weak that it could not carry enough scale back along the longitudinal direction. Consequently, the accumulations between each longitudinal support pillars are not as serious as other areas mentioned above.

Observations also find that little scales accumulate near the sidewall of a long continuous run furnace. This CFD model results can also explain the fact. Figure 7 is the velocity and temperature distribution near the sidewall. There is a small circle area near the burners in the lower heating zone. However, the location and shape of the circulating flow is very different from that close to the centre of the furnace. This circulating area is slightly far from the burners and the reverse flow is not strong enough to throw the scales back to the region near the burners in the lower heating zone. Another reason is that this area is near the sidewall and the temperature is not as high as that near the centre of the furnace. Even if there are some scales falling to the floor, gas flow can blow them away before they could be sintered.

Figure 8 also infers the phenomena that scales seldom accumulate seriously just in front of the burner's in the lower heating zone. Although there are reverse flows above such burners, gas velocity from the lower burner is very high and scale deposited just in front of the burners could be blown away in a very short time. Different velocity areas near the burners are marked in Fig. 8. Obviously, these would not give many chances for scale accumulation ahead of the burners along the blowing direction. Low velocity areas in Fig. 8 are between adjacent burners. If comparing these low velocity areas with scale accumulations positions in Fig. 5, they are almost the same places of scale build-ups between the burners in the lower heating zone.
Flow velocity transverse to the longitudinal direction and cross the first skid support pillar is shown in Fig. 9. Gas streams downwards with high velocity can be found in this figure. The higher the down velocity is, the easier the scale is carried by the flow to the furnace floor. The two areas directed by the arrows in Fig. 9 are also scale accumulation positions. They are between adjacent burners of the lower heating zone too.

Discussions above suggest that high temperature and reverse flows are the main reasons of scale accumulation on the floor near the lower burners in the heating zone. The reverse flow is related to the structure of furnace according to the CFD results. For example, one reason is that the flow blowing from the burners can bounce to the stair step on the floor of the lower heating zone, which could cause a part of gas flow back to the burners' wall. Another reason is that the slabs are contacted too closely in the current furnace operation and there is no gap for flow passing through from upper part of heating zone to the lower part or via versus. As we know, the gas flow passing through the gap between slabs could interfere with the reverse flow in the lower heating zone and reduce its recycling effects. As a matter of
fact, the industry experience has shown that the scale accumulation is not so seriously in the operation of another pusher-type reheating furnace since the arrangement style of slab is different and the gap between steel slabs is large in the heating zone. This could be an indirect proof for the influence of the reverse flow on the scale accumulation in the lower part heating zone. Anyway, the numerical model has given industry more theoretical proof on the furnace operation improvement for reducing scale accumulation.

3.3. Oxygen Distribution in the Furnace

This CFD model can also give the composition of gas in the furnace. Figure 10 is the oxygen distribution predicted along the furnace longitudinal direction. The oxygen content in the region immediately attached to the burners is close to the air. However, the oxygen fraction drops quickly with the distance from the burner. The oxygen percentage close to the burners in the discharge zone and burners in the upper heating zone are 8 to 10%. While for other space in the furnace, oxygen content does not exceed 5%.

There are two measured oxygen value in the furnace shown in Fig. 10. One measuring point is located in the roof of the furnace and another point is installed in the sidewall and near the slab plane. Measured oxygen near the roof is about 3%, which is lower than the simulated values. The oxygen mass fraction in the gas near the plane of slab is about 3.9% that is very close to the simulation results.

4. Conclusions

Computational fluid dynamics is used to predict gas flow pattern and temperature distribution in the pusher-type reheating furnace. Since until now available measurements are limited for the details of the gas temperature distribution and flow pattern, CFD simulation plays an important role in the investigation. Momentum, combustion and radiation models are combined together in the present simulation. Reasons for scale accumulation near the burners in the lower heating zone are given. Main conclusions can be drawn as follows.

(1) Reverse flows under the slab in the heating area promote scale sediment peeling from slab surface. Since temperature of the region near the burners is very high, scales are very easy to sinter in the low velocity regions of floor. Scale accumulation is not serious between the longitudinal arranged skid supporting pillars because the back flows there are weak.

(2) Oxygen except regions close to the burners, distribute uniformly according to the numerical model results. The predicted value is similar to the measured plant data.

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Nomenclature

$C_{\text{EBU}}$: Constant of eddy-break up model ($-$/H11002)
$C_p$: Specific heat (J/kg · K)
$F_s$: Momentum source term in the momentum governing equation (N/m$^3$)
$H$: Enthalpy of fluid (J/kg)
$I_b$: Black-body emissive power with the absolute temperature of mixture gas in the furnace (W/m$^2$)
$I_x, I_y$: Radiation fluxes in the positive and negative $x$ and $y$ direction, respectively (W/m$^2$)
$I_z$: Radiation fluxes in the positive and negative $z$ direction, respectively (W/m$^2$)
$k$: Turbulent kinetic energy of fluid flow (m$^2$/s$^2$)
$K_a$: Absorption coefficient of gas in furnace (1/m)
$K_s$: Scattering coefficient of gas in furnace (1/m)
$L_{\text{charact}}$: Characteristic length of inlet (m)
$m_{\text{fuel}}$: Mass fraction of chemical species $l$ in the gas mixture ($-$)
$m_{O_2}$: Mass fraction of oxygen ($-$)
$M, N$: Radiation fluxes in the positive and negative $z$
direction, respectively (W/m²)

- \( P \): Pressure of fluid (Pa)
- \( R \): Reaction rate of the gas (kg/m³·s)
- \( R_i \): Source term in chemical species conservation equation (kg/m³·s)
- \( S_h \): Source term in energy conservation equation (W/m³)
- \( S_{\text{sto}} \): Stoichiometric requirement for chemical reaction (kg/m³·s)
- \( T \): Temperature (K)
- \( \text{TurbInt} \): Turbulence intensity of flow (%)
- \( u \): Velocity of fluid (m/s)
- \( u' \): Fluctuating component of fluid velocity (m/s)
- \( Y_{N_2}, Y_{H_2}, Y_{CH_4}, Y_{H_2O}, Y_{CO_2} \): Gas composition fraction in the furnace derived from iterations (–)

Greek symbols

- \( \delta_h \): Turbulent Prandtl number (–)
- \( \varepsilon \): Dissipation rate of flow (m²/s³)
- \( \mu \): Dynamic viscosity of fluid (kg/m·s)
- \( \mu_t \): Turbulent viscosity (kg/m·s)
- \( \rho \): Density (kg/m³)
- \( \Gamma_i \): Diffusion coefficient of species (m²/s)

Subscripts

- \( i, j \): General induces used to specify different \( x, y, z \) coordinates

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