Effect of Preheated Top Gas and Air on Blast Furnace Top Gas Combustion

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The coke consumption in blast furnaces (BF), directly related to the energy consumption and CO$_2$ emission from BF, is reduced with the increase of hot blast temperature. To establish the flame temperature of more than the blast furnace gas (BFG) adiabatic flame temperature of 1 587 K by using only BFG without any additional high caloric value gases such as coke oven gas, the effect of preheating of BFG and/or air on the BFG combustion temperature was investigated based on thermodynamic heat balance and the computational fluid dynamic (CFD) simulations. Thermodynamic evaluation and CFD simulated results showed that air preheating was not effective to raise the BFG combustion temperature compared with BFG preheating or simultaneous preheating of air and BFG at the same preheating temperature. The less efficiency of air preheating was explained based on the small heat content of preheated air. The blast temperature of 1 700 K was obtained without adding high caloric value gases by preheating only BFG to 873 K or simultaneous preheating both BFG and air to 700 K. Compared with air or simultaneous preheating of air and BFG, BFG preheating will be a suitable approach to increase BFG combustion temperature. This is not only because of the supply of heat content to the combustion zone, but also the enhanced mixing introduced by the large inlet gas velocity difference between air and BFG promotes rapid CO burn-up.

KEY WORDS: hot stove; adiabatic flame temperature; blast furnace top gas; hot blast; preheating.

1. Introduction

Steel industries are now strongly expected to decrease CO$_2$ emissions. The conventional ironmaking process based on blast furnaces (BF) requires approximately 500 kg of carbon (coke and pulverized coal) to produce 1 ton of hot iron, so about 2 ton of CO$_2$ is emitted. To reduce CO$_2$ emission from BF, many efforts have been made. The BF is a well-established system and is highly optimized already so there is very little room to decrease the CO$_2$ emission from BF. In addition to the BF, other ironmaking sub-processes such as coke ovens, sintering plants and hot stoves are sources of CO$_2$ emission. Intriguingly, about 1/3 of CO$_2$ gas emission in the ironmaking process comes from hot stoves, comparable to that from the BF.$^{1)}$

Hot stoves are used to preheat the air used in the BF to combust coke. The hot stove works as a counter current regenerative heat exchanger. The high temperature exhaust gas (about 1 673 K) is produced by blast furnace gas (BFG) and this high temperature gas is used to raise the air up to 1 473 K by heat exchange system. The heated air is called the hot blast. It is known that coke consumption will be decreased by 10–15 kg per ton of pig iron with increase of hot blast temperature of 100 K.$^{2)}$ Namely, BF energy consumption and CO$_2$ emission will be reduced by increasing the hot blast temperature. The maximum temperature of hot blast, however, will be restricted by the cost of injected fuel and high temperature properties of refractories.

The hot stoves mainly use low cost and low caloric value BFG combined with a small amount of higher calorific value coke oven gas (COG) and sometimes other high calorific value gases of liquefied petroleum gas (LPG) or natural gas (NG) to increase of the hot blast temperature. Due to the high calorific value of COG along with the decrease of the amount of N$_2$, a higher combustion temperature can be easily achieved by the addition of COG and is currently a common practice. Increased recent energy prices, however, induced steel industries to consider the possibility of utilizing greater quantities of BFG in conjugation with waste-heat recovery system.$^{3–5)}$ If we can use only BFG and eliminate COG and other high calorific gases without lowering the flame temperature in hot stoves, the total process cost and energy consumption can be decreased.

One of the possible approaches to increase the blast temperature is the preheating of inlet gases of fuel and/or air. The hot stove waste gas has a temperature of about 500 K on average and its sensible heat was used to preheat air and BFG by waste heat recovery system in many steel works. This preheating temperature of about 500 K is certainly helpful to increase the combustion temperature, but not high enough to fully eliminate the COG addition for the practical
hot stove operating temperature. The further increase of preheating temperature of BFG and air without COG can be established by additional heating of these gases by using burners fuelled by BFG itself.\textsuperscript{6,7} The whole preheating system is schematically shown in Fig. 1.

Bisio studied the effect of BFG combustion preheating to raise hot blast temperature without COG based on heat balance.\textsuperscript{6,7} However, to optimize BFG combustion in hot stoves with preheated inlet gases, it is necessary to understand not only the overall thermodynamic evaluation of the heat balance but also the BFG combustion characteristics. For the effective preheating of gases to raise hot blast temperature, a rapid CO burn-up rate must be ensured by optimizing the flow and mixing conditions with preheating gas introduction. This cannot be done by thermodynamic evaluation. However, it is not easy to study the details of the BFG combustion behaviour due to the experimental difficulties, especially the effect of preheating gas on the combustion.

As a complement of experimental studies, computational fluid dynamics (CFD) based on a very local resolution of the flow can help to determine the influence of each parameter, which is experimentally hard to obtain because dissociating one parameter from the others is almost impossible in combustion processes. Thus, the CFD approach to combustion studies has now become an essential tool.\textsuperscript{8} With ever more powerful computers and increasingly sophisticated softwares, numerical solutions of the governing equations of turbulent reacting flow have become practical. By far, numerical solutions through CFD provide the most detailed information such as the each dependence of various factors. At this moment, direct numerical simulation which fully resolves the length scale and time scale of turbulence is not possible for the turbulence combustion flow of practical importance. Thus, a particular simplified combustion model must be used to analyse the combustion process, however, these models still provide very useful information of combustion characteristics.

The objective of this study is to investigate the effect of the preheating of BFG and air on the BFG combustion in an operating hot stove based on the macroscopic thermodynamic heat balance evaluation and CFD simulation of BFG combustion. The analysis is especially focused on CO burn-up and flow mixing behaviors during BFG combustion.

2. Computational Procedure

2.1. Governing Equation

The simulation of BFG combustion was carried out by using commercial code Fluent 6.3. Fluent solves the following governing equations of (1) to (5) under particular boundary conditions.\textsuperscript{9} They are the continuity equation, Navie-Stokes equation, energy equation, chemical species conservation equations and ideal gas state equations.

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0 \quad \text{(1)}
\]

\[
\frac{\partial (\rho u)}{\partial t} + \nabla \cdot (\rho uu) + \nabla \cdot (P) + \rho g = 0 \quad \text{(2)}
\]

\[
\frac{\partial (\rho Y_i)}{\partial t} + \nabla \cdot (\rho uu Y_i) - \nabla \cdot (\lambda T Y_i) - w_i = 0 \quad \text{(3)}
\]

\[
\frac{\partial (\rho T)}{\partial t} + \nabla \cdot (\rho uu T) - \frac{1}{C_p} \nabla \cdot (\rho TT) + \frac{1}{C_p} \sum h_i w_i - \frac{T}{C_p} \left(C_p \frac{D_i Y_i}{T} \right) = 0 \quad \text{(4)}
\]

\[
p = \rho R^0 T \sum \frac{Y_i}{m_i} \quad \text{(5)}
\]

where \( \rho \) is density, \( P \) pressure, \( u \) gas velocity, \( T \) temperature, \( C_p \) specific heat, \( \lambda \) thermal conductivity, \( Y_i \) mass fraction, \( D_i \) diffusivity, \( h_i \) specific enthalpy, \( R \) gas constant and \( w_i \) mass production rate of species.

2.2. Non-premixed Combustion Model

The numerical simulations of BFG combustion was based on the non-premixed combustion model.\textsuperscript{9,10} This model readily derives the transport equation for the mean mixture fraction from the gas species equation under the assumption of equal diffusivities and single fuel and oxidizer streams. The assumption of the equal diffusivities is reasonable because at high Re, turbulent diffusion overwhelms laminar diffusion and turbulent eddies convert species equally in our simulation conditions. The combustion chemistry is described by a parameter called mixture fraction\textsuperscript{9,11,12} and the equilibrium chemistry approximation. The equilibrium chemistry approximation means that the chemical reaction rates are fast in comparison with fluid mixing rates, so \( Da \gg 1 \) (\( Da \) is Damköhler number). Namely, the reactions are controlled by the mixing rate of chemical species. The mixture fraction equation is very useful because it does not have a reaction source term with its associated difficulties.\textsuperscript{11,12}

The turbulent flow in the non-premixed combustion model was described using the standard \( k-\varepsilon \) model.\textsuperscript{9,13} The turbulent parameters were introduced through the value of turbulent intensity \( I \) and the length scales \( l \) using the following equations.

\[
k = \frac{3}{2} (IV)^2 \quad \text{(6)}
\]

\[
\varepsilon = \frac{k^3}{l} \frac{C_k}{n} \quad \text{(7)}
\]

where \( v \) is the inlet velocity magnitude, \( I \) is the inlet turbulence intensity, \( C_k \) is a \( k-\varepsilon \) model parameter whose value is typically
given as 0.09 and $l$ is the turbulence or eddy length scales. The details of the $k$-$\varepsilon$ model are described elsewhere.\textsuperscript{9,13}

Since CO\textsubscript{2} can absorb infrared radiation, it was expected that CO\textsubscript{2} could influence the gas phase radiation in the BFG combustion. The preliminary simulations, however, showed to a negligibly small effect, so it was neglected in the present study. The negligible effect of CO\textsubscript{2} on the radiation may be due to the small volume fraction of CO\textsubscript{2} in the gas phase. Swirling flow was often introduced to enhance mixing in industrial burners, however, the swirling effect was neglected in the present study. Other assumptions included in the present study are; (1) steady state, (2) mass diffusion occurs only due to concentration gradients, (3) negligible viscous heating, (4) body force are ignored, (5) radiant heat transfer is ignored and (6) unity Lewis number, i.e. equal thermal and mass diffusivities. These assumptions can greatly simplify the governing equations for reacting flow.

\subsection*{2.3. Simulation Conditions and Computational Domain and Boundaries}

The actual combustion system in the hot stove is quite complex. The main purpose of the present study is to investigate the BFG combustion characteristics itself. Therefore, a simple geometry was used in simulations, as shown in Fig. 2. It consists of four parts: nozzle part, combustion part (zone A), cone part (zone B) and exhaust part (zone C). The gases were introduced through the nozzle attached to the combustion part. The nozzle consisted of coaxial tubes having an inner diameter of 20 mm and outer diameter of 40 mm. The BFG gas and air were introduced through the coaxial inner and outer tube of the nozzle, respectively. Each gas flow was assumed to be a piston flow. Therefore, the calculations of the flows in the nozzle were not included in the simulation, and the supply rates of gases were given as an initial condition at the inlet end of the combustion simulations were 6.3 m/s and 40 m/s at 300 K, respectively.

The computational grids made up of a total of 100,000 rectangular cells were employed for the entire flow domain of the tubes. For an easy comparison with the thermodynamic heat balance approach, the adiabatic condition at the wall was applied in the present study.

\section*{3. Results and Discussion}

\subsection*{3.1. Thermodynamic Evaluation of the Preheating Effect of Gases on BFG Combustion}

BFG generally contains small amount of H\textsubscript{2} and H\textsubscript{2}O. For the thermal balance calculations, however, the effects of H\textsubscript{2} and H\textsubscript{2}O are neglected since it was found that their contributions to the heat balance calculation were quite small. The main combustion reaction of BFG with air is,

\[ CO + O_2/2 \rightarrow CO_2 \]  

(8)

The adiabatic flame temperature of BFG with air, $T_{\text{ad}}$, can be easily obtained thermodynamically. If BFG-air mixture burns adiabatically at constant pressure, the absolute enthalpy of the reactants, $H_{\text{react}} (T_{\text{ini}}, P)$, at the initial state (say, $T_{\text{ini}} = 298$ K, $P = 1$ atm) equals the absolute enthalpy of the products, $H_{\text{prod}} (T_{\text{ad}}, P)$, at the final state ($T = T_{\text{ad}}, P = 1$ atm).

\[ H_{\text{react}} (T_{\text{ini}}, P) = H_{\text{prod}} (T_{\text{ad}}, P) \]  

(9)

Substituting in the required values of the physical and thermodynamic properties,\textsuperscript{14,15} Eq. (9) easily yields the adiabatic flame temperature, $T_{\text{ad}}$. Using the gas compositions of the air, BFG and combusted gas shown in Table 1 gives $T_{\text{ad}} = 1387$ K. That of pure CO gas with air is about 2665 K. In the case of BFG burning with air, the heat produced by CO gas combustion was used to raise the temperature of other gases such as N\textsubscript{2}. Consequently, the adiabatic temperature of BFG combustion becomes lower than that of pure CO gas combustion, which is the main reason that BFG has a low calorific value.

It is noted that the adiabatic flame temperature is not the maximum temperature that the gas mixture can reach during the combustion process; a much higher temperature is reached by preheating of air and fuel.\textsuperscript{9} The adiabatic flame temperatures with preheating gases are calculated by just changing the initial state values corresponding to the preheating temperature in Eq. (9). The changes of the adiabatic flame temperatures of BFG combustion as a function of the preheating temperature for the case of (1) preheating of air, (2) preheating of BFG and (3) simultaneous preheating of air and BFG (with the same preheating temperature) were calculated and are shown in Table 2 and Fig. 3. In the present study, "simultaneous preheating of air and BFG" is expressed by SAB preheating. The results show the preheating of BFG is more efficient than that of air to achieve the same BFG combustion temperature and SAB preheating is of most effective way to establish high combustion temperature when compared at the same preheating temperature.

The specific heat as well as density of air and BFG are not so much different each other. For the full combustion of CO in BFG, the required volume of air is about half of BFG volume. Namely, the heat content of BFG by BFG preheating has about two times larger than that of air preheating. This will be one of the reasons that the preheating of air to raise BFG combustion temperature is less efficient com-

![Fig. 2. The schematic view of the combustor.](image-url)
pared other cases.

In the actual hot stove operations, the BFG combustion temperature is found to be about 1 700 K or less. As shown in Fig. 3, the required preheating temperature for BFG or SAB preheating to establish the adiabatic flame temperature of 1 700 K, is about 773 K and 600 K, respectively. For the case of air preheating, even 1 273 K is not sufficient to establish 1 700 K. Along with the flame temperature, the comparable heat content of the preheated gas is required to raise the temperature in the preheating process. The required BFG volume for the preheating of BFG and air will be discussed in section 3.3.

The adiabatic flame temperature was calculated by assuming a macroscopically homogeneous equilibrium state in the combustion reaction, however, the actual BFG combustion process does not fully satisfy these conditions. This condition will be achieved by a rapid CO burn-up under the optimized gas mixing. For this purpose, understanding the actual BFG combustion behaviors, detailed information of the flame structure of BFG combustion and its combustion rate under the preheating condition are essential, and has been studied by CFD simulation.

Table 2. Adiabatic flame temperatures of BFG combustion as a function of preheating temperature with preheating of air, BFG and both of BFG and air.

<table>
<thead>
<tr>
<th>Preheating Temperature /K</th>
<th>Air K</th>
<th>BFG K</th>
<th>Air and BFG K</th>
</tr>
</thead>
<tbody>
<tr>
<td>373</td>
<td>1409</td>
<td>1438</td>
<td>1459</td>
</tr>
<tr>
<td>473</td>
<td>1436</td>
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</tr>
<tr>
<td>773</td>
<td>1519</td>
<td>1708</td>
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</tr>
<tr>
<td>873</td>
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<td>1775</td>
<td>1934</td>
</tr>
<tr>
<td>973</td>
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<tr>
<td>1273</td>
<td>1658</td>
<td>2044</td>
<td>2314</td>
</tr>
</tbody>
</table>

3.2. The Simulation of the Gas Preheating Effects on the Flame Structure

The calculated adiabatic flame temperatures shown in Table 2 and Fig. 3 were based on the condition with the ratio of (atomic% CO/atomic% O2/2) = 1 and evenly distributed temperature and gas species in the combustor. However, the actual BFG combustion in hot stoves is quite different. The BFG consists of CO, CO2, H2, H2O, and N2 gases. To maintain the combustion, CO in BFG and O2 in air must diffuse in the other diluent gases to meet each other for the combustion reaction. These diluent gases can influence the transport process in the combustion process. The temperature and the concentration of each gas were not evenly distributed in the actual combustion process. Thus, the physical properties such as thermal conductivities, diffusion coefficients and heat capacities have also different values depending on the location in the combustor, especially under preheating conditions of the air or BFG. Therefore, understanding of the effects of these parameters on the BFG combustion is essential to improve the efficiency of the combustion system with the preheating gas injection.

The stoichiometric quantity of air is defined as the amount needed to completely burn a quantity of fuel. The stoichiometric ratio of (mass of the air/mass of the fuel) is called stoichiometric air-fuel ratio. The equivalence ratio, is also commonly used to indicate quantitatively whether a fuel-air mixture is rich, lean or stoichiometric. The equivalence ratio is defined as

$$\phi = \frac{\text{mass of the air/mass of the fuel}}{\text{stoic/mass of the air/mass of the fuel}},$$

where (mass of the air/mass of the fuel) stoic is the stoichiometric air-fuel ratio. Theoretically, the highest flame temperature is established with a stoichiometric mixture of $\phi = 1$. The effect of $\phi$ on the simulated maximum flame temperature of BFG combustion without preheating is shown in Fig. 4. As expected, the maximum temperature is obtained under the condition of $\phi = 1$. Since the maximum temperature can be obtained with $\phi = 1$ and can be compared easily with the thermodynamically calculated adiabatic flame temperature that was also obtained with $\phi = 1$, all simulations were carried out at $\phi = 1$ in the present simulations. Under the preheating conditions, the mass flow rate was kept constant to maintain the stoichiometric air-fuel ratio, although the apparent flow rate of preheated gas was changed depending on the gas density at the preheating temperature.
3.3. The Effect of Preheating on the Temperature Distribution in the Combustor

The temperature distributions in the combustor for BFG combustion with air, BFG and SAB preheating as a function of preheating temperature were calculated by CFD simulation. The typical temperature distribution with SAB preheating and the radial temperature distribution at the end part of the exhaust part are shown in Fig. 5. The temperature in the combustion reactor did not change so much after the front half of the exhaust part and similar distributions were found for most of the cases. Thus, in the present study, temperature distributions of the front half of the exhaust part surrounded area by the broken line in Fig. 5 are shown. The temperature of the radial direction at the end of the exhaust tube was essentially constant and this temperature is called combusted exhaust gas (CEG) temperature in the present study.

The temperature distributions without preheating (300 K), with preheating of air at 1 273 K, with BFG preheating at 1 273 K and with SAB preheating at 1 273 K are shown in Figs. 6(a), 6(b), 6(c) and 6(d), respectively. The simulated maximum temperatures and CEG temperatures with adiabatic temperatures (shown in Table 2) for various preheating temperatures were shown in Table 3.

![Fig. 5. The temperature distribution in the reactor with SAB preheating at 1 273 K, and the radial temperature distribution at the end part of the exhaust part. The area surrounded by broken line is shown in Fig. 6 (d).](image)

![Fig. 6. The temperature distribution (a) without preheating (298 K), (b) with preheating of air at 1 273 K, (c) with preheating of BFG at 1 273 K and (d) with simultaneous preheating of air and BFG at 1 273 K. The arrows indicate the area of the maximum temperature.](image)

<table>
<thead>
<tr>
<th>Preheating</th>
<th>Air</th>
<th>BFG</th>
<th>Air and BFG</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$T_{\text{max}}$</td>
<td>$T_{\text{ad}}$</td>
<td>$T_{\text{CEG}}$</td>
</tr>
<tr>
<td>300</td>
<td>1466</td>
<td>1388</td>
<td>1371</td>
</tr>
<tr>
<td>473</td>
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</tr>
<tr>
<td>1273</td>
<td>1737</td>
<td>1658</td>
<td>1629</td>
</tr>
</tbody>
</table>

For the case with BFG preheating, the temperature did not change so much after the cone part (zone B) except small area on the axis (Fig. 6(c)). Namely, CO gas combustion was almost accomplished in the cone part. After that, temperature was gradually increased from 1 820 K to 1 963 K (CEG temperature). The simulated maximum temperature was found to be 1 996 K and was reasonably close to the
The adiabatic flame temperature of 2,044 K. The maximum temperature area was indicated by the arrow in Fig. 6(c). The CEG temperature with preheating at 1,273 K was found to be relatively close to the maximum temperature of about 1,963 K, and that without preheating was about 1,371 K.

In the case of SAB preheating shown in Fig. 6(d), the absolute temperature of each contour was about 200 K higher than those of BFG preheating, however, their relative distribution patterns were almost the same. Namely, the temperature also did not change so much after the cone part (zone B) as like the case of BFG preheating, and the temperature in the exhaust part area gradually increased from 201 K to 2,170 K (CEG temperature). The simulated maximum temperature was 2,189 K, and was lower than that the adiabatic flame temperature of 2,314 K. The maximum temperature area was indicated by the arrow in Fig. 6(d).

The temperature distribution with air preheating was shown in Fig. 6(b). It can be seen that the temperature distribution is quite different to cases (c) and (d), even after the cone part, where temperature still increases a relatively large temperature change was observed in the axial as well as the radial directions in the exhaust part. Such observations suggest that CO combustion is not completed in the cone part and continues to occur in the exhaust part.

The CO and O₂ distributions in the BFG combustion with air, BFG and SAB preheating at 1,273 K are shown in Fig. 7. For BFG and SAB preheating cases, most of O₂ was consumed in the cone part. In the case of air preheating, however, the areas of unburned CO and O₂ gases were extended to the exhaust part. Based on these results, uneven temperature distribution with air preheating was due to the less effective CO combustion compared to cases with BFG and SAB preheating. Interestingly, the burned O₂ and CO areas for BFG preheating were found to be smaller than those for SAB preheating. This behavior will be discussed in section 3.4.

To preheat air and BFG up to the targeted temperature, a sufficient amount of heat content must be produced by BFG combustion. For the stoichiometric combustion of 1.0 Nm³ BFG, about 0.547 Nm³ of air is required and 1.45 Nm³ of the combusted gas is produced. The required BFG volume for the preheating to raise the temperature of BFG and air simultaneously at Tp can be thermodynamically calculated by the following relation:

\[
Y \times (1.0 \text{Nm}^3 \times C_{p_{BFG}} + 0.547 \text{Nm}^3 \times C_{p_{air}}) \times T_p = \] 
\[
Y \times 1.45 \text{Nm}^3 \times C_{p_{cg}} \times T_F \] 
\[
\text{Nm}^3 \times T_F \] 
\[
(10)
\]

where Y is the required BFG volume (Nm³) for the combustion to preheat the gas mixture and Tp is the preheating temperature. \(C_{p_{BFG}}, C_{p_{air}} \) and \(C_{p_{cg}} \) are the heat capacity of BFG, air and combusted gas per unit volume, respectively. The left side in Eq. (10) means the total heat of the gas mixture of BFG (1 Nm³) and air (0.547 Nm³) at the preheating temperature of \(T_p \). The right side means the total heat amount of combusted gas mixture produced from Y Nm³ BFG combustion with the stoichiometric amount of air at \(T_F \).
Now waste-heat recovery system by using exhaust hot stove gas is common practice in many steel works. Substituting all required values\textsuperscript{14,15} to Eq. (10) and presuming that BFG and air are initially preheated at 500 K by using the exhaust hot stove gas, the required volume ($Y$) as a function of $T_p$ was calculated and the result is shown in Fig. 9. The required volume for the cases of BFG preheating is also easily obtained by modifying Eq. (10) and is also shown in Fig. 9. The required volume for preheating 2.5 Nm$^3$ mixture of BFG and air to 1700 K was found to be only about 0.13 Nm$^3$ for SAB preheating (up to 600 K) and 0.11 Nm$^3$ for BFG preheating (up to 873 K) with neglecting heat loss.

### 3.4. The Effect of Inlet Gas Velocities on the BFG Combustion Behavior

As shown in Figs. 3 and 8, air preheating is not so effective to raise BFG combustion temperature compared with those of BFG or SAB preheating. As shown in Figs. 7(c) and 7(d), CO gas was almost fully combusted in the cone part in the cases of preheating BFG and SAB preheating, but not for air preheating. The combustion rate is controlled by the diffusion of O$_2$ in air and CO in BFG to meet each other. This slow reaction rate for air preheating suggests that the mixing of CO and O$_2$ is not effectively carried out compared with the cases of BFG and SAB preheating.

The flow velocity magnitude distributions with air, BFG and SAB preheating at 1273 K are shown in Fig. 10. As expected, the flow velocity magnitude with air preheating was rather small compared with those with BFG and SAB preheating. This indicates that the mixing process induced by turbulent flows will not be so strong for the case of air preheating compared with other cases. Consequently, unburned areas of CO and O$_2$ will be extended.

To investigate the effect of inlet gas velocity magnitudes on BFG combustion, simulations were carried out by changing the inside tube radius for BFG from 10 to 16.32 mm. This change makes the inlet air and BFG gas velocities almost the same of about 15 m/s at 300 K. The simulated CO and O$_2$ distributions with air, BFG and SAB preheating at 1273 K are shown in Fig. 11. The area where CO distributes becomes larger for cases with BFG and SAB preheating, but that with air preheating becomes smaller in a geometry with large inside tube diameter. Namely, the combustion efficiency or CO burn-up rate with BFG and SAB preheating was decreased under the large inside tube diameter geometry condition. Interestingly the CO distribution area with BFG preheating was smaller than that with SAB pre-
heating. The similar behavior was also observed in the previous tube geometry condition as shown in Fig. 7. These results suggest that CO combustion with BFG preheating is much more effectively carried out than that with SAB preheating, or rapid CO burn-up occurred. The inlet gas velocities of air and BFG under the various preheating conditions are shown in Table 4. The main difference between BFG and SAB preheating with different inlet tube geometries is the inlet gas velocities of air and BFG. Namely the velocity difference between air and BFG inlet gases for BFG preheating is much larger than those with SAB preheating. This gas velocity difference can enhance the mixing of CO and O\textsubscript{2} at the reaction interface where they will meet, or surrounded O\textsubscript{2} was effectively entrained into high speed turbulent BFG stream and reacted.

The turbulent intensity\textsuperscript{(17)} distributions with BFG and SAB preheating under different inlet tube geometries were shown in Fig. 12. As shown in Figs. 12(a) and 12(b), the turbulent intensities have quite large values in the combustion part for the case of BFG preheating. In the case of SAB preheating, however, the large turbulent intensities values are found after the cone part. For both cases of BFG and SAB preheating, it was clearly shown that turbulent intensities with different gas velocities is about two times larger than those with the same inlet velocities. These results means that the mixing will be enhanced by introducing the different inlet gas velocities of air and BFG.

Thus, preheating of gas for BFG combustion has two roles. First one is to bring some amount of heat content to combustion zone, and second one is to enhance mixing for rapid CO burn-up by the increase of the apparent gas velocity of preheated gas. From this view point, BFG preheating will be a suitable approach to increase BFG combustion temperature. This is because the enhanced mixing can be expected by the large velocity difference between inlet air and BFG along with the relatively large amount heat content supply to the combustion zone.

The currently used external combustion type hot stoves are gradually replaced by top-combustion type hot stove since the top-combustion type hot stove can realize cost reduction and saving energy.\textsuperscript{(7)} Compared to conventional type hot stoves, the top-combustion type has a small combustion zone and the distance between the top-combustion zone and refractory checkers is short. Thus, the establishing a rapid CO burn-up is critically important for top-combustion type hot stoves, and BFG preheating process will help to improve the operation of the new type hot stove.
It is noted that all results in the present study were obtained by neglecting heat loss. The required preheating temperature or the required volume will alter depending on heat exchange efficiency. However, the fundamental feature of the results, such as the lower efficiency of air preheating or the importance of the velocity difference for the enhancement of mixing will not be changed. BFG gas is now mainly used as hot stove fuel simply due to its low calorific value. BFG has, however, a potential to be extensively used in many other heating processes at steel works since BFG combustion can produce much a higher temperature than the adiabatic flame temperature even more than 2 000 K by introducing preheated BFG.

4. Conclusions

Since the coke consumption in BF is decreased with increase of hot blast temperature, CO₂ emission and energy consumption in the steel works can be reduced by improving the efficiency of the BFG combustion. In the present study, to raise BFG combustion temperature without any additions of high calorific value fuel, the effect of BFG or air preheating on BFG combustion was investigated based on thermodynamic heat balance and CFD simulation of BFG combustion. The obtained results are as follows:

(1) Based on thermodynamic evaluation, air preheating is found not to be so effective to raise the BFG combustion temperature compared with that of BFG or simultaneous preheating of BFG and air under the same preheating temperature.

(2) Small contribution of air preheating to raise BFG combustion temperature is due to the small heat content of preheated air that is about half of BFG under the same preheating temperature.

(3) The combusted exhaust gas temperature of higher than 1 700 K (comparable to the actual hot blast temperature) can be established by preheating BFG greater than 873 K or by preheating BFG and air simultaneously greater than 700 K without any addition of high calorific value gases.

(4) BFG preheating will be a suitable approach to increase BFG combustion temperature compared with air and SAB preheating. This is not only because a relatively large amount heat content is supplied (smaller than SAB preheating but larger than air preheating) to the combustion zone, but also a much enhanced mixing can be expected by the large velocity difference between inlet air and BFG.

REFERENCES