Combustion Behaviors of Fine Coal and Its Impact on Gas Permeability at Lower Part of Blast Furnace under High Pulverized Coal Rate Operation

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Practical ways of estimating temperatures of coke flowing into raceway as well as the gas core depth validated by direct measurement were suggested for the purpose of better describing the combustion behaviors of injected coal fine in blast furnace raceway. The numerical simulation model was refurnished with the scheme, and helped clarifying an intriguing effect of coal gasification or decomposition degrees before exiting tuyere tip on attained combustibility of coal at raceway boundary.

Another scheme for quantitative expression of pressure losses caused exclusively by coal fine residence in and around raceway was also developed by shutting off coal injection for minutes at practical operation. The obtained results lead to developing the advanced tuyere, CD (converged and diverged) tuyere which enabled reducing the interaction between injectants and hot blast inside tuyere and thus improving overall gas permeability even under conditions of massive coal injection over 250 kg/tHM.

KEY WORDS: blast furnace; raceway; gas core; CD tuyere; PCI shutoff.

1. Introduction

PCI (pulverized coal injection) in blast furnace operation has quickly and widely been spread since the oil crises of 1970s as an auxiliary reducing agent for substituting oil.1) Although the recent movements seeking for other reducers’ injection technologies such as the waste plastics injection2,3) as a successor to PCI has been expected remarkably effective as measure to reduce CO2 emissions as well as costs, the technology has so far been practically available only in limited mills. There would be, therefore, very few points to argue about the fact that high rate PCI combined with low coke rate operation is still and will be the main stream target for blast furnace mills in order to reduce coke cost and save some energy in coking process. Figure 1 is a typical representation calculated by BF operation diagram4) of changing rates of reducing agent as well as emitted CO2 from the practical operation condition at Kakogawa 3 BF as a function of PCI rate for different shaft efficiencies. The changes of by-product gases both in content and in amount from coke oven and blast furnace are, in this calculation for the sake of simplicity, balanced by outside electricity so as to realize the constant energy supply to other processes in steel works. The increased PCI rate inevitably worsens reducing agent rate, nevertheless indicates good chance of decreasing the total CO2 emission rate as long as the shaft efficiency or the coke to coal replacement ratio maintained to an allowable level.

Kobe Steel is currently relying only on external purchases for all the coke supply, and has necessarily promoted this technology and increased coal injection rate to reduce coke rate since the system installation in 1983 at Kakogawa 2 and Kobe 3 BFs.

As has already been reported by many researchers and
engineers in iron making field, one significant operational problem in increasing coal rate must be the increased pressure losses or the worsened gas permeability through the furnace. The phenomenon is caused by increased gas volume and also by decreased amount of bed spacer (lump coke) which occurs in increasing PCI rate.

The invention of CCC (Center Coke Charging) has become a technological breakthrough for Kobe Steel to further enhance the coal injection because of its outstanding features to secure central gas flow and then to contribute to stable forming of an inverted V shaped cohesive zone which is also appropriate for improving gas permeability.\(^5\)

On the other hand, it seems highly likely that more emission of un-burnt char under higher PCI conditions should yield higher degrees of fine holdup at the lower part of the furnace, which results in more fine trapped on the deadman surface or at roots of the cohesive zone and then causes increased pressure losses. Consequently, techniques such as Double Lance Injection,\(^7\) Excentric Double Lance,\(^8\) Oxy-coal Lance,\(^9\) Coal Preheating,\(^10\) and Co-axial Lances,\(^11\) etc., have been developed or been under development for better coal combustibility. Another viewpoint mainly remarked by Kobe Steel is that the emitted un-burnt char prior to bed coke be gasified by the solution loss reaction and be fully utilized to replace lump coke.\(^12\) The one month operation at an ultra-high rate PCI done by Kobe has shown only the minimal discharge of char from the furnace top.\(^13,14\)

As coal combustion behavior in raceway affects heat balance of the furnace via its effect on coke consumption rate, its accurate expression has significant importance for blast furnace operator to optimize blast conditions to achieve stable PCI practice. The paper deals with the practical estimation methods of the raceway coke temperature and the gas core depth relevant to coal combustion. One dimensional numerical model\(^15\) was refurnished with the results and clarified some intriguing coal combustion behaviors. The authors also revealed the impact of fine introduction on gas permeability of blast furnace using PCI shut off test at actual commercial furnace and adopting a scheme for evaluation on coal derived pressure losses at furnace lower part. The present study has finally focused on the magnitude of pressure loss at tuyere zone and attained an solution by altered tuyere design. Advantageous effects of CD tuyere (convergent and divergent tuyere) are also mentioned in the paper as potential breakthrough technology for massive coal injection.\(^5\)

2. Estimation of Coke Temperature and Gas Core Depth in Front of Tuyere for Numerical Coal Combustion Model

The gas flow resistance through the packed bed is thought to be increased in the course of PCI increase by above mentioned reasons, among which there remains the concern about the increased degree of injected fine’s interaction with gas and coke in and around the raceway. It seems hardly practical to zero the effect by complete coal combustion while the retention of coal inside raceway can marginally exceed 10 milliseconds or so. Although this has driven researchers to better understand coal reaction behaviors by developing numerical models, it is undeniably true that the simulation models need some parameters or functions to modify the calculated results as rational outputs. In most cases, however, verifying parameters setting requires direct samplings or observations at practical operating furnaces and is fairly difficult for an objective appraisal.

Kobe Steel commissioned Raceway Simulator\(^16\) or the coke packed combustion furnace equipped with single tuyere and PCI system to accurately study the complex reaction field in raceway before adopting massive coal injection at commercial furnaces. The obtained results varied from axial distributions of raceway void fractions, gas compositions, coke temperatures, etc., and helped in adjusting some essential parameters for the one dimensional raceway simulation model. Temperatures of coke inflowing to raceway \((T_c)\) has showed having the higher ratio to \(T_f\) (theoretical flame temperature) at the higher rate of PCI with this test furnace, and thus indicated an underlying influence of HCR (burden/gas heat content ratio) on \(T_c/T_f\). The present paper further deepens the study on temperature of coke flowing into raceway by analyzing many samples obtained from actual blast furnace and suggests a practical and a simple estimation based on a rational mechanism of heat exchange between gas and coke. It seems quite common to calculate \(T_f\) by assuming \(T_c/T_f = 0.75\) after Ramm, or likewise \(T_c/T_f = 0.80\) adopted by Kuwabara\(^17\) in their development of raceway coal combustion model. However, \(T_c/T_f\) as mentioned above, is supposed to be influenced by the degree of heat exchange activated between bosh gases and descending coke above raceway, and \(T_c/T_f\) should not possibly be a fixed value for different operation conditions. The effects of \(T_c/T_f\) on coal combustibility and on maximum gas temperature along the tuyere axis are demonstrated in Fig. 2, showing apparently small but characteristic change in calculated combustibility with the highest degree around \(T_c/T_f = 0.80\) while having the constant rise in peak gas temperature, which indicates that under conditions of higher \(T_c\) with \(T_c/T_f > 0.8\) the coal fine begins to lose its chance of gasification against the incoming coke particle.

Although, an accurate estimation of heat exchange between the bosh gas and the coke above raceway is complex, the behavior seems somewhat related to HCR at furnace top which can easily be calculated with operational data. Figure 3 represents the relationship between \(T_c/T_f\) and HCR. \(T_c\) values were estimated from the crystal form of

![Fig. 2. Effects of \(T_c/T_f\) value on calculated results of coal combustibilities and peak gas temperature.](image)
coke carbon for many periods with varying conditions, and the approximate expression is given by Eq. (1).

$$T_c/T_f = -0.733 \times HCR + 1.410$$  \hspace{1cm} (1)

The higher HCR yielding the lower $T_c/T_f$ in Fig. 3, corresponds to the lower root position of cohesive zone ($H_{smz}$) as shown in Fig. 4 and its approximation is given by Eq. (2).

$$H_{smz} = -0.861 \times HCR + 1.017$$  \hspace{1cm} (2)

With Eqs. (1) and (2), $T_c/T_f$ is also likely to be expressed as a function of $H_{smz}$ as follows.

$$T_c/T_f = 0.851 \times H_{smz} + 0.545$$  \hspace{1cm} (3)

Equation (1) adjusts the calculation results of theoretical flame temperature, and then gives the in-flow coke temperature to raceway for the numerical coal combustion model.

Another parameter discussed here is gas core depth ($D_c$), or jet penetration depth at tuyere front. The authors’ former experiments showed that the void fraction just in front of tuyere was kept nearly constant at 0.9 to 1.0 to form the gas core, and decreased toward the end of raceway linearly. $D_c$ was experimentally obtained for various conditions in Eq. (4), where $D_t$ was tuyere diameter and $R_f$ was the corrected raceway factor.

$$D_c/D_t = 0.0963 \times R_f^{0.546}$$  \hspace{1cm} (4)

Figure 5 represents the axial void fractions ($\varepsilon$) in raceway and its relationship can simply be expressed in Eq. (5) and (6), where $D_e$ is raceway depth, $\varepsilon_0$ is voidage in gas core and $\varepsilon_B$ is the one at raceway boundary.

$$\varepsilon = \varepsilon_0 : 0 < x < D_c$$  \hspace{1cm} (5)

$$\varepsilon = \varepsilon_0 - (\varepsilon_0 - \varepsilon_B)(x - D_c)/(D_e - D_c) : D_c < x < D_e$$  \hspace{1cm} (6)

The data of raceway measurement through the view port by $\mu$-wave sensor for different wind rates are displayed alongside the calculated values of $D_c$ and $D_e$ in Fig. 6.
processing software for statistical procedure. Therefore, the fact that the minimum measured values conform practically well to \( D_c \) for varying blast conditions provides sufficient validation in adopting Eq. (4) for gas core depth estimation.

Figure 7 represents comprehensive combustion characteristics of various conditions in PCI operation for coal injection loads (C/O) defined as molar ratios of carbon from coal fine to input oxygen brought by the blast and by coal itself. As seen in the figure, the higher coal rate leads to the lower combustibility, while other operation parameters except the lance tip position can encourage or retard coal combustion. As for the effects of lance tip position on combustibility, the less variation can be found especially at higher coal rates for the certain tip positions closer to tuyere tip. Coal combustibility at raceway boundary, carbon gasification degree and devolatilization degree of coal at tuyere tip are estimated in Fig. 8 for three different coal rates in order to clarify the phenomena. Figure 8 reveals there exists the certain position of lance tip for each operation condition, beyond which closer to tuyere tip the achieved combustibility at raceway end becomes almost constant. At these particular points significant plunge occurs in gasification degrees and especially in devolatilization degrees at tuyere tip. Reaction rate of coal thermal decomposition is controlled by the temperature of fine. Smooth and fast progress of coal devolatilization can be realized by sufficient preheating to the particle or remarkably be prevented without it. In case with possible coal decomposition by ample preheating to coal before reaching tuyere tip, emitted volatile contents can be combusted by utilizing profuse blast oxygen, and the produced heat accelerates char combustion and achieves higher gasification rates at tuyere exit for farther lance tip positions allowing the longer retention. If, on the other hand, the preheat shortage inside tuyere is brought by increased coal load or by the close setting of lance to tuyere tip, severe retardation of coal devolatilization gives almost no advantageous pre-combustion before entering raceway. Under that situation, the coal fine despite its injected tip points has achieved almost the same level of gasification degree at the tuyere exit, and so becomes the achieved combustibility at raceway boundary.

3. Quantitative Expression of Pressure Drop Induced by Fine Hold-up in Lower Part of Furnace

As seen in Fig. 7, the coal combustibility worsens and the hold up of un-burnt char is to be increased at higher PCR conditions. Although the dynamic and the static hold up of coal fine theoretically cause interactions between other phases and affect the pressure loss and the gas flow stability at lower part of furnace, its influential magnitude on furnace stability is extremely difficult to quantify in practical operation.
To depict the fine holdup effect on pressure loss, following scheme has been designed including brief shut off of PCI at actual blast furnace. Pressure losses exclusively induced by PCI are defined here as coal derived pressure losses (CDPL : $\Delta P_{pc1}-\Delta P_{pc3}$) for each portion of blast furnace lower part as shown in Fig. 9. In-furnace condition after the brief span of PCI shut off can inherit the bed structure of the high ore/coke condition at high PCR operation with no additional generation of CDPL and helps estimating genuine bed’s permeability (bed’s permeability resistance indices : $K_1$, $K_2$) without coal interaction. PCI shut off causes naturally an abrupt rise of $T_f$, the scheme has to adopt a unique derivation as follows to consider gas temperature correction. Equation (7) is Carman’s expression of pressure drop.

\[
\frac{dP}{dL} = A_0 \rho v^2 \tag{7}
\]

where, $P$ is pressure, $L$ is vertical position on the basis of tuyere axis, $\rho$ is gas density, and $v$ is gas velocity.

Once the blast condition fixed, the $\rho v$ value is expressed by bosh gas volume $V_{bosh}$ at normal state in Eq. (8), and in turn, $v$ by Eq. (9) via temperature/pressure correction.

\[
\rho v = A_1 V_{bosh} \tag{8}
\]

\[
v = A_2 V_{bosh} T/P \tag{9}
\]

Substituting Eqs. (8) and (9) into Eq. (7) yields Eq. (10) and then the Eq. (11) is given as a basic form for seeking $K_1$ and $K_2$ by PCI shut off procedure.

\[
\frac{dP}{dL} = A_3 V_{bosh}^2 T \tag{10}
\]

\[
\frac{dP^2}{dL} = A_4 V_{bosh}^2 T \tag{11}
\]

Supposed the gas temperatures at each section in Fig. 9 be represented as $T_1$ and $T_2$ for simplification, following equations are obtained by integrating Eq. (11) for those two sections.

\[
P_r^2 - P_b^2 = K_1 V_{bosh}^2 T_1 \tag{12}
\]

\[
P_b^2 - P_s^2 = K_2 V_{bosh}^2 T_2 \tag{13}
\]

where, $P_r$, $P_b$, and $P_s$ are static pressures, respectively at raceway boundary, at bosh, and at lower shaft. $T_1$ and $T_2$ are average temperatures for each section estimated by taking a hypothesis of linearization of gas temperatures on vertical positions from raceway (at theoretical flame temperature) to lower shaft (at the constant temperature assumed 1273 K as another simplification), $P_t$ in Eq. (12) is assumed pressure at raceway boundary calculated by Eq. (14).

\[
P_t = P_B - \frac{\rho_B}{2g} U^2 \tag{14}
\]

where $P_B$ is blast pressure, $\rho_B$ and $U$ are blast density, blast speed at tuyere tip, respectively.

Furnace pressures, flame temperature, and bosh gas rate observed during the PCI shutoff are taken into Eqs. (12) and (13) to give $K_1$ and $K_2$. The restarted PCI renews $V_{bosh}$, $T_1$, $T_2$, and pressure values, and then with $K_2$ obtained above, CDPL for the section from bosh to lower shaft is thus represented below in Eq. (15).

\[
\Delta P_{pc3} = P_b - (P_s^2 + K_2 V_{bosh}^2 T_2)^{0.5} \tag{15}
\]

$\Delta P_{pc2}$ for the section from raceway boundary to bosh is approximately expressed by Eq. (16).

\[
\Delta P_{pc2} = (L_1/L_2) \Delta P_{pc3} \tag{16}
\]

$\Delta P_{pc2}$ by Eq. (16) allows the estimation of $P_r$ at PCI in Eq. (17), and then CDPL inside raceway zone can be quantified in Eq. (18). $\Delta P_{pc1}$ includes the pressure loss due to chemical reaction mainly brought by combustion. Adopting the same $K_1$ value obtained above into Eq. (17) may not be accurate, because the combustion rate of raceway coke differs in PCI operation. Nevertheless, the rate of blast oxygen consumption inside raceway is roughly the same and its share of pressure loss is anyhow reflected in $P_r$ estimation, and thus the overall estimation of this method for CDPL is still available.

\[
P_r = (P_b^2 + K_1 V_{bosh}^2 T_1)^{0.5} + \Delta P_{pc2} \tag{17}
\]

\[
\Delta P_{pc1} = P_B - \frac{\rho_B}{2g} U^2 - P_t \tag{18}
\]

Figure 10 shows the results of CDPL estimation at Kakogawa 3BF for three different PCR levels expressed in ratios against total pressure losses. Both $\Delta P_{pc2} + \Delta P_{pc3}$ representing CDPL by fine holdup in packed bed and $\Delta P_{pc1}$: CDPL in raceway, grow with increasing PCR. However, their impacts on total pressure losses or on the gas permeability in the operating furnace are considerably small with 0.5%, 2.0% at PCR 175 kg/tp for $\Delta P_{pc2} + \Delta P_{pc3}$, $\Delta P_{pc1}$ respectively. Although $\Delta P_{pc1}$ occupies the dominant portion in CDPL, it
seems less likely for $\Delta P_{pc1}$ in raceway to suffer from the increased fine holdup than for $\Delta P_{pc2} + \Delta P_{pc3}$ in packed bed. The result thus indicates other factor’s involvement to affect $\Delta P_{pc1}$ along the coal distribution process from lance tip to tuyere exit for increasing PCR, which then leads to the next move of developing CD tuyere explained in the following section.

4. Development of Converged and Divergent Tuyere for Massive Coal Injection

In the early stage of PCI operation where coal was used for oil replacement the more distant tip position of PC injection lance from tuyere exit was favored to attain better coal combustibility. Coal combustibility surely improves by that action already shown in Fig. 8, however, the severe increase of pressure loss at tuyere and its fluctuation becomes obvious in practical operation. The former study on this phenomena has clarified the effects of an excess fusion of coal ash and its deposition on tuyere inner surface.22–24 On the other hand, the increased emission of fine char particles from raceway can help preventing lump coke from being attacked by solution loss reaction in the lower portion of the furnace. The rational outlook then seems to locate the lance tip as close as possible to the tuyere tip so as not to promote coal gasification inside tuyere and to minimize the pressure loss and the pressure fluctuation. Conventional tuyere has a convergent inner surface and the converging blast toward the tuyere tip inevitably finds the injected coal plume as stymie. This partly accounts for the increase of $\Delta P_{pc1}$ under increasing PCR. Although setting the lance tip at the very exit of tuyere or farther inside raceway would minimize the frictional interaction between coal plume and convergent blast, it is hardly practical to realize if considered the extremely severe thermal and physical condition at the tuyere front. The CD tuyere has its inner shape literally with a convergent portion connected with a divergent part toward the exit so as to inject the coal in a divergent blast flow. The conceptual comparison of CD tuyere with the conventional one is shown in Fig. 11. Coal reaction behaviors for two tuyere types from its injection point to tuyere exit are calculated by the above mentioned numerical simulation and compared in Fig. 12. The case of CD tuyere shows lower degree of coal decomposition or volatilization (Fig. 12(a)) and the lower particle temperature (Fig. 12(b)) than the case of the conventional one. The blast in CD tuyere is managed to keep higher speed at around the lance tip, however, it rapidly diminishes along with the path expansion toward the exit, while the conventional case shows continuous increase in speed (Fig. 12(c)). The particle movement corresponding to the gas velocity shows in CD tuyere an initial acceleration followed by a deceleration in Fig. 12(d). Figures 12(c) and 12(d) lead to an analysis of slip velocity arisen between the blast and the coal particle in Fig. 12(e). The case of CD tuyere particularly indicates the possible no slip region inside tuyere which is responsible for less coal reactivity in Fig. 12(a) due to less efficient heat exchange between the two phases. Figure 13 represents the change in wind rate of the individual tuyere right after coal shut off. Compared with the conventional ones, the trifle change observed in CD tuyere means the least interference the blast suffers from accompanying coal plume, and proves its advantageous characteristic to lower the pressure loss as well as the pressure fluctuation at tuyere part.

In Fig. 14 the fluctuation indices of blast pressure and burden descending speed (PI and KI, see appendix for definitions) are shown for different PCR operation at Kakogawa No.1 blast furnace. Both indices became much lower (better) even at over 250 kg/tHM of PCR with CD tuyeres than at PCR of 200 kg/tHM without ones.

Another explanation of that prominent operation improve-
ment brought by CD tuyere is probably due to significantly lowered generation rate of fine inside raceway. Figure 15 represents the axial distributions of sampled fine ratios for three different tuyere patterns at abovementioned combustion furnace\(^{16}\) which was operated for these experiments with 650 m\(^3\)/H(at STP) of blast volume, 1 273 K for blast temperature, and 130 kg/H of PCI equivalent of 200 kg/tHM. Compared with conventional tuyeres, CD type exhibits apparently the smallest degradation load for coke in raceway, and should result in the best gas permeability through the raceway boundary. By dismantling packed bed after each experiment of varying tuyere types, we can easily determine the inner surface of raceway by tracing the hold-up of solidified sluggish materials, the “raceway shell” as shown in Fig. 16. Because the broadly expanded raceway is done by more coke involvement in that region, the case will yield more fine generation due to coke abrasion. Again in Fig. 16 the result shows the narrowest raceway expansion, therefore exemplifying the smallest load of coke degradation in the case using CD tuyere. Fundamentally well-known in the field of fluid dynamics a free jet out of a convergent nozzle forms a potential core where the maximum fluid velocity is maintained along axial distance by the simultaneously entrained surrounding fluid inside the jet. For conventional convergent tuyeres it is analogously more likely to have surrounding coke around tuyere vicinity entrained into raceway than the case of CD tuyere with smaller effect of entrainment due to its peculiar divergent flow exit.

In the present study, the greatest importance in adopting CD tuyeres is put on arranging the lance tip between the throat (the most converged portion) and the tuyere tip, while forming the throat to have the same diameter size as one of the conventional tuyeres in anticipation of sufficient axial jet penetration. And those, with an appropriate divergent angle suggested by Gibson’s experiment,\(^{25}\) give the outlet size of CD tuyeres. Although as seen in Fig. 16 the conventional tuyere with the smaller outlet exhibits deeper raceway or the stronger jet penetration than the CD type does, it seems leaving little doubt, judging from the outstanding improvements obtained, on far essential merits being brought by the CD tuyeres configuration rather than demerits done by lowered blast speed at tuyere exit.

Reviewing the last campaign of ultra high rate PCI operation,\(^{13}\) increasing coal rate over 200 kg/HHM impairs the coke replacement efficiency as shown in Fig. 17. As formerly reported with the increase of PCR from 200 to 250 kg/HHM, dust emission rate sharply increased and more than doubled while un-burnt coal emission rate was negligibly small. The increased coke fine carried away from the top as well as the increased heat load were responsible for the worsened replacement ratio. CD tuyere is a handy device for maintain-
ing proper tuyere front condition at massive coal injection, however, the key to attain an ideal operation with low coke rate and with low reducing agent rate under high PCR is to achieve an appropriate radial distribution for ascending gas via combination control of burden distribution and blast condition.

5. Conclusions

(1) Coke temperature inflowing to raceway was expressed as a function of heat content ratio of burden to gas as follows,

\[ \frac{T_c}{T_f} = -0.733 \times \text{HCR} + 1.410 \] ........................ (1)

(2) Comprehensive study on coal combustibility by the numerical model revealed an irregular tendency for the effects of lance tip positions. And the finding lead to clarifying that the achieved volatilization degree of coal fine at tuyere exit determined the combustion behaviors and the attained combustibility at raceway boundary.

(3) Coal derived pressure losses (CDPL) were quantified by the newly contrived scheme with PCI shutoff procedure in practical operation. Although relatively small impact of CDPL on the total pressure loss was found, CDPL of the region from lance tip to raceway expressed a sensitive increase along with PCR.

(4) CD tuyere was adopted to minimize the interaction between the blast and the coal plume inside tuyere region. It contributed to dramatic stability of the gas flow as well as the burden descent for increasing PCR in practical operation.

REFERENCES


Appendix

The fluctuation indices adopted here as PI and KI are defined as follows,

\[ PI = \frac{(P_{B,i} - P_{B,i-1}) + \cdots + (P_{B,i} - P_{B,i-1})}{n} \]

\[ KI = \frac{(V_{i} - V_{i-1}) + \cdots + (V_{i} - V_{i-1})}{n} \]

Where \( P_{B,i} \) and \( V_{i} \) are blast pressure [kPa] and burden descending speed [m/h] at time \( i \), respectively, and \( n \) denotes the number of sampled data.