Abridged version

KAWASAKI STEEL TECHNICAL REPORT

No.38 (April 1998) Ironmaking Technology and Tubular Products Technology

Prediction of Blended Coal Fluidity and Lateral Contraction of Coal in Coke Ovens -Technology for Increasing the Charging Ratio of Low Quality Coal in Cokemaking-

Takashi Matsui, Katsutoshi Igawa, Ken-ichi Sorimachi

Synopsis :

New models for estimating the maximum fluidity (MF) of blended coal and the clearance between the coke oven wall and coke cake were developed to reduce hard pushing rate in coke ovens. In the MF model, heated coal during carbonization is regarded as a suspension composed of melted coal, unmelted coal and solidified coke. The viscosity of the suspension was evaluated by Mori's equation, which included the viscosity of the solvent and volume fractions of solid. The clearance model is based on the balance between the contraction force and coking pressure. A clearance begins to appear when the contraction force exceeds the coking pressure in this model. The contraction force is calculated in consideration of the visco-elastic behavior of the thermal shrinkage of coke. The coking pressure is calculated from the generation and dispersion of gas in the melting layer. Use of these models in the coal blending design system has successfully reduced the hard pushing rate. Moreover, precise control of coke strength with the new system has make it possible to increase the use of low-grade coal.

(c)JFE Steel Corporation, 2003

The body can be viewed from the next page.

Prediction of Blended Coal Fluidity and Lateral Contraction of Coal in Coke Ovens —Technology for Increasing the Charging Ratio of Low Quality Coal in Cokemaking—*





Takashi Matsui Ironmaking Lab., Technical Res. Labs.

Katsutoshi Igawa Senior Researcher, Ironmaking Lab., Technical Res. Labs.



Dr. Eng., General Manager, Steelmaking Lab., Technical Res. Labs

1 Introduction

It is desirable to decide the coke blending design in consideration of coke quality and pushing performance. Although the empirically-derived methods of controlling the volatile matter in blended coal and gas pressure proposed in the past¹⁻²⁾ as means of pushing performance have been improved, it cannot be termed adequate. Moreover, in recent years, the composition of blended coal has become more diverse due to the increased use of low-grade coals, and the problem of hard pushing has become the most critical task for extending the life of coke ovens, heightening the necessity of a blending design which considers pushing performance.

To secure adequate pushing performance, it is essential to control the contraction of the coke cake, i.e, the widthwise clearance between the coke cake and coke oven walls.³⁾ Various methods of predicting clearance have been researched, including calculation of the clearance from the total dilation and contraction of the coke cake,⁴⁾ calculation of the amount of contraction using an apparent coefficient of contraction obtained experimentally,⁵⁾ and others. However, because these methods do

Synopsis:

New models for estimating the maximum fluidity (MF) of blended coal and the clearance between the coke oven wall and coke cake were developed to reduce hard pushing rate in coke ovens. In the MF model, heated coal during carbonization is regarded as a suspension composed of melted coal, unmelted coal and solidified coke. The viscosity of the suspension was evaluated by Mori's equation, which included the viscosity of the solvent and volume fractions of solid. The clearance model is based on the balance between the contraction force and coking pressure. A clearance begins to appear when the contraction force exceeds the coking pressure in this model. The contraction force is calculated in consideration of the visco-elastic behavior of the thermal shrinkage of coke. The coking pressure is calculated from the generation and dispersion of gas in the melting layer. Use of these models in the coal blending design system has successfully reduced the hard pushing rate. Moreover, precise control of coke strength with the new system has make it possible to increase the use of low-grade coal.

not treat the interaction of dilation and contraction dynamically, it cannot necessarily be said that they have clarified the nature of contraction behavior in the coke oven.

On the other hand, the maximum fluidity (MF) of blended coal is important for controlling both the coke strength and the clearance between the coke oven wall and coke cake. MF is generally calculated by taking the arithmetical mean of the MF values of single coals. However, the estimation accuracy of this method deteriorates as the range of reflectance of the single coals increases. Various improvements have been proposed, such as estimation by superposition of the fluidity curves of the single coals^{6 8)} and estimation from the petrography of the blended coal,⁹⁾ but the none of these methods offers adequate estimation accuracy.

^{*} Originally published in Kawasaki Steel Giho, 29(1997)1, 6-10

The authors believe it is indispensable to make a precise evaluation of the MF of the blended coal and clearance of the coke cake in the oven when using low-grade coal at high charging ratios, and therefore developed a model for estimating the MF of blended coal as the viscosity of a suspension and a model which considers the contraction of coke in the oven dynamically. This report presents an outline of these models and the results of their use.

2 Model for Estimating Maximum Fluidity of Blended Coal

2.1 Concept of Model

As shown in Fig. 1 if it is assumed that spherical coal particles (Stage 1) melt from the particle surface when heated (Stage 2), then it can be thought that molten coal forms a suspension containing an unmelted component in a molten solvent, which also contains gas (Stage 3). Although various equations for estimating the viscosity of this suspension have been reported, 10-13) the equation of Mori et al. was used as the fundamental equation in the present model. According to Mori et al., in a solvent of viscosity, $\eta_{\rm L}({\rm Pa} \cdot {\rm s})$, the suspension viscosity, $\eta({\rm Pa} \cdot {\rm s})$ of a suspension of particles of particle diameter d(m)can be expressed by Eq. (1). Here, $Sr(m^2)$ is the surface area of all particles, S is the solid fraction, and g_{scr} is the solid fraction in limiting concentration. In the case of spherical particles, the relationship of the particle diameter d and Sr is as shown in Eq. (2). Therefore, if the solid fraction in limiting concentration is 0.52, Eq. (1) can be rewritten as Eq. (3):

$$\eta = \eta_{\rm L} \{ 1 + (d \cdot \operatorname{Sr}/2)/(1/S - 1/g_{\rm scr}) \} \cdots (1)$$

$$d \cdot \operatorname{Sr}/2 = 3 \cdots (2)$$

$$\eta = \eta_{\rm L} \{ 1 + 3/(1/S - 1/0.52) \} \cdots \cdots (3)$$

Eq. (4), which was calculated by Morotomi et al.,¹⁴⁾ was adopted for the conversion of viscosity to Gieseler fluidity, F(ddpm). Here, K_1 , K_2 are constants.

$$\log F = K_1 \cdot \log \eta + K_2 \cdot \dots \cdot \dots \cdot (4)$$

Figure 2 shows the calculation flow with this model. First, the solid fraction and solvent viscosity of each of the single coals are obtained based on measurements of the MF of the single coals. Next, the solid fraction of the blended coal is calculated as the arithmetical average of



Fig. 1 Concept of MF calculation model



Fig. 2 Calculation flow of MF

each single coal and the solvent viscosity is calculated by Arrhenius' equation,¹⁵⁾ and finally, the viscosity of the blended coal is found.

2.2 Method of Estimating the Temperature Function of Single Coal MF

The solid fraction and solvent viscosity of each single coal are calculated on the basis of the following hypotheses.

- (1) The reduction in volume due to gas release is ignored.
- (2) The solid fraction S is determined by the particle diameter d.
- (3) All material is in a molten state at the maximum fluidity temperature, with the exception of the inert component.

The solid fraction, S_T , at temperature $T(^{\circ}C)$ is calculated from Eq. (5) using the particle diameter. d_T is the particle diameter at temperature T, and d_0 is the initial particle diameter before melting. The rate of change in the particle diameter is calculated by Eq. (6) as the primary equation for temperature.

$$S_T = (d_T/d_0)^3 \cdots \cdots (5)$$

The constants *A*, *B* are calculated from the softening point and particle diameter at the maximum fluidity temperature in the softening process, and from the solidification point and particle diameter at the maximum fluidity temperature in the solidification process, respectively. The solvent viscosities at the softening point, solidification point, and maximum fluidity temperature are calculated by Eqs. (3) and (4) using the calculated values of the solid fraction and the measured values of fluidity. The solvent viscosity $\eta_{L,T}$ at temperature *T* is calculated respectively for the softening process and for the solidi-

KAWASAKI STEEL TECHNICAL REPORT

fication process on the basis of Andrade's equation,¹⁶ which is shown here as Eq. (7). The constant C_1 and the activation energy, Ea(kcal/mol), are calculated from the numerical values of the solvent viscosity at the softening point, solidification point, and maximum fluidity temperature.

$$\eta_{\Gamma,T} = C_1 \cdot \exp\left(\operatorname{Ea}/RT\right) \cdots \cdots \cdots \cdots \cdots \cdots \cdots (7)$$

2.3 Blended Coal Fluidity

The solid fraction, S_{all} , of blended coal is calculated from the solid fraction, S_K , and blending ratio, Ra_K , of single coal K using Eq. (8). Based on the fact that the solvent viscosity, η_{L} when liquids having differing viscosities are mixed is expressed by Eq. (9), the solvent viscosity of the blended coal, $\eta_{\text{L,all}}$, is calculated from Eq. (10) using the solid fraction. The viscosity, η_{all} , of the blended coal is calculated by Eq. (11), based on the fact that S_{all} and $\eta_{\text{L,all}}$ are used.

$$S_{\text{all}} = \sum_{K=1}^{n} \operatorname{Ra}_{K} \cdot S_{K} \cdot \cdots \cdot \cdots \cdot \cdots \cdot \cdots \cdot (8)$$

$$\eta_{\text{L,all}} = \left[\sum_{K=1}^{n} \{(1 - S_K) \cdot \text{Ra}_K\} \log \eta_{\text{L,K}}\right] / (1 - S_{\text{all}}) \cdots (10)$$

$$\eta_{\text{ail}} = \eta_{\text{L,ail}} \{ 1 + 3/(1/S_{\text{ail}} - 1/0.52) \} \cdots \cdots \cdots \cdots \cdots (11)$$

The η_{all} obtained here is converted to fluidity using Eq. (4). This operation is repeated at 380–500°C, and the common logarithm of the maximum value of fluidity is used as MF.

2.4 Verification of Model

The appropriateness of the model was verified by blending 10 to 16 brands of single coal. The definition of low-grade coal was a coal with either a maximum reflectance ratio of vitrinite, $\overline{\text{Ro}}$ (%) < 0.7, or MF > 1.0. **Figure 3** shows the relationship between the low-grade coal blending ratio and the absolute value of the difference between the calculated value and observed value of MF, Δ MF. When calculated by the arithmetical average method, the value of Δ MF increases as the low-grade coal blending ratio increases. However, with this model,



Fig. 3 Relationship between ratio of slightly coking coal and ⊿MF

No. 38 April 1998

 Δ MF is 0.1 or under at low-grade coal blending ratios of 0–15%, confirming that the model enables improved accuracy in the estimation of the MF of blended coal.

3 Coke Clearance Estimation Model

3.1 Concept of Model

In the coke oven, there exists a melting layer which dilates at the inner side of the contracting coke layer. As shown in **Fig. 4**, if it is hypothesized that the coke layer contracts toward the interface between the melting layer and the coke layer, then both the coking pressure of the coal and the contractile stress of the coke act in this area. Therefore, supposing a one-dimensional balance of forces in the oven width direction, a model was developed in which a clearance is generated between the coke oven wall and the coke cake at the point in time when the contractile stress exceeds the coking pressure.

3.2 Composition of Model

Figure 5 shows the calculation flow for clearance.



Fig. 4 Modelling of clearance generation



Fig. 5 Calculation flow of clearance

7

The model consists of a heat transfer model, gas generation estimation model, coking pressure calculation model, and contractile stress calculation model.

3.2.1 Heat transfer model

The temperature distribution in the coal layer was calculated using Eq. (12), which was obtained by introducing transformed temperature, $\phi_T(J/(m \cdot s))$, and enthalpy, H(J/kg), into Fourier's heat transfer equation, considering the temperature dependence of specific heat, $C(J/kg \cdot K)$, and thermal conductivity, $\lambda(W/m \cdot K)$.

$\partial H/\partial t = (1/\rho) \cdot (\partial^2 \phi_T/\partial X^2) \cdots \cdots$	(12)
$\lambda = \partial \phi_T / \partial T \cdots$	(13)
$C = \partial H / \partial T \cdots \cdots$	(14)

3.2.2 Model for calculation of gas generation rate

The gas generation rate, $G(m^3/s)$, is expressed as shown in Eq. (16), by first approximating the amount of gas generated by thermal decomposition per unit of heat, as measured by Muroki et al.,¹⁷⁾ as a first-order equation, f(T), for the temperatures in the processes of increased and decreased gas generation, respectively, and then multiplying the result by the rate of heating.

(15)

Here, W is the weight of coal (kg), t is time (s), and the subscript g represents the type of gas.

3.2.3 Coking pressure calculation model⁵⁾

The mechanism by which coking pressure, P(kPa), is generated is considered to be as shown in Fig. 6. P is given by Eq. (17) as the sum of the pressure loss in the melting layer, $\Delta P_{\rm M}$, and the pressure loss in the coke layer, ΔP_{coke} . Here, the subscript M indicates the melting layer, and coke indicates the coke layer. $\Delta P_{\rm M}$ is expressed by Darcy's low (18). Here, D is the proportion of gas generated in the melting layer which is distributed to the coke layer. ΔP_{coke} , as shown in Eq. (20), is the sum total of the products of the gas flow rates, $Q(m^3/s)$, in section *i* and the gas flow resistance, $Re(kPa \cdot s/m^3)$.

$$P = \Delta P_{\rm M} + \Delta P_{\rm coke} \qquad (17)$$



Fig. 6 Schematic diagram of generation of coking pressure

$$Q_i = D \cdot G_{\mathsf{M}} + \sum_{i=1}^{k} G_i \cdot \dots \cdot \dots \cdot \dots \cdot \dots \cdot (19)$$

Here, k indicates the section number in the coke layer.

3.2.4 Calculation of coke contraction

The amount of coke contraction was obtained by approximating the contraction coefficient of coke, β ,¹⁸⁾ measured by Meyer by the primary function of temperature shown in Eq. (21), calculating the amount of contraction $S_i(T_i)$ at temperature T_i in section i by Eq. (22), and totaling the results.

$$\beta(T) = aT + b \cdots (21)$$

$$S_i(T_i) = \Delta x \cdot \int_{T_i}^{T_i} \beta(T) \, \mathrm{d}T \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (22)$$

Here, a, b are constants, $\Delta x(m)$ is the width of section i, and $T_{\rm e}({\rm K})$ is the starting temperature of contraction.

3.2.5 Calculation of contractile stress

Because the coke layer is considered to be a viscoelastic body of the Maxwell type,19) it is necessary to consider the phenomenon of stress relaxation. The general equation for this purpose is shown as Eq. (23). $\tau(s)$ is the relaxation time until the initial stress is attenuated by 1/e times in stress relaxation under a condition of constant strain. Eq. (24) is solved as strain ε constant (ε $= \varepsilon_0$), and the contractile stress $\sigma(kPa)$ is then calculated using the contraction of the coke as strain.

$$\frac{\partial \varepsilon}{\partial t} = (1/E) \cdot (\partial \sigma/\partial t) + \sigma/(E \cdot \tau) \cdot \cdots \cdot (23)$$

$$\sigma = E \exp(-t/\tau)\varepsilon_0 \cdot \cdots \cdot (24)$$

To find τ the strain velocity is measured under conditions of constant stress,²⁰⁾ and τ is then derived using Eq. (25). As Young's modulus, E(kPa), the experimental values obtained by Filonenko et al.²¹⁾ were arranged in terms of the maximum fluidity, MF, of the coal, and further corrected for porosity.²²⁾

$$\mathrm{d}\varepsilon/\mathrm{d}t = (\sigma/E \cdot \tau) \cdots (25)$$

The total strain of the coke layer, ε_{coke} , is expressed by the following equation.

$$\varepsilon_{\rm coke} = \sum_{T_i} \int_{T_i}^{T_i} \beta(T) \, \mathrm{d}T \, \cdots \, (26)$$

Within the coke layer, assuming there are no constraining conditions, the stress, σ , in each section is equal. ε_{coke} is then expressed by Eq. (27), and the contractile stress can be obtained using Eq. (28).

$$\epsilon_{\text{coke}} = \sum_{i=1}^{k} \{ \sigma/E_i(T_i) \exp(-t/\tau) \} \cdots \cdots \cdots (27)$$

$$\sigma = \varepsilon_{\text{coke}} \sum_{i=1}^{\infty} \{ 1/E_i(T_i) \exp(-t/\tau) \} \dots (28)$$

KAWASAKI STEEL TECHNICAL REPORT

8

3.2.6 Calculation of clearance

(a) When Both a Melting Layer and a Coke Layer Are Present

The σ obtained from Eq. (28) and *P* obtained from Eq. (17) are compared, and if $\sigma \leq P$, the clearance CL(m) is 0, because the coke cake is pushed into contact with the oven wall by the coking pressure. If $\sigma > P$, the clearance is the sum of the amount of contraction CL_i(m) in each coke section, and is expressed by Eq. (30).

$$CL_{i}(T_{i}) = \Delta x \cdot \int_{T_{i}}^{T_{i}} \sigma(T) \, \mathrm{d}T \, \cdots \, (29)$$
$$CL = \sum_{i=1}^{k} CL_{i}(T_{i}) \, \cdots \, (30)$$

(b) When Only a Coke Layer Is Present

Only the contraction of the coke is calculated. When contraction begins in the center of the coke oven, cracks are generated in the center. Because contraction occurs from both sides toward the center of gravity of the coke between the walls and the coal center, the clearance is equal to the amount of contraction as far as the section, k', where the coke center of gravity is located.

3.3 Verification of Model

Changes in the clearance over time were measured in a small-scale coke oven²⁰⁾ using a laser sensor. The results are shown in **Fig. 7**. The observed results and calculated values were in good agreement. To study the effect of coal properties, the properties of the blended coal were varied, carbonization was carried out, and the final clearance was measured with the laser sensor. As shown in **Fig. 8**, the calculated and observed values are in agreement, confirming the appropriateness of the model.

4 Application to Blending Design

4.1 Flow of Blending Design

Figure 9 shows the flow of blending design. The operation conditions which are input include the working ratio of the coke oven, coal moisture, grain size of coal after grinding, and other information. The coal properties input are the mean reflectance $\overline{\text{Ro}}$ and Gieseler fluidity properties of each single coal. The $\overline{\text{Ro}}$ of the blended coal is the arithmetical mean of each single coal; MF is calculated using this model. Based on the MF and $\overline{\text{Ro}}$ thus obtained, the blending ratio of single coals is modified to satisfy the target coke strength, $\text{TI}_6(\%)$, using the coke strength estimation equation²³⁾ shown in **Fig. 10**. Next, using the clearance estimation





Fig. 7 Comparison between observed temperature of coke center (Tcenter), coking pressure(P), clearance (CL) and calculated value, and calculated contractile stress(σ) during carbonization



Fig. 8 Comparison between observed clearance (CL_{obs}) and calculated one on (CL_{calc}) at various MF and \overline{Ro}



Fig. 9 Calculation flow of coal blending ratio



Fig. 10 Relationship among \overline{Ro} , MF and coke strength (TI₆)



Fig. 11 Relationship among Ro, MF and clearance

model, the $\overline{\text{Ro}}$ and MF of the blended coal are decided so that the clearance is above the lower limit. The relationship among the $\overline{\text{Ro}}$, MF, and clearance of the blended coal is expressed as shown in **Fig. 11**.

4.2 Results of System Operation

The results of using these estimation models in the blending design system are shown in **Fig. 12**. The absolute value of the three-month average of the difference, ΔTl_6 , between the observed and estimated values of coke strength had increased to 0.5 after 1993 as a result of an increase in the blending ratio of low-grade coal, but following the introduction of this model, this parameter decreased to 0.15. Moreover, the coke pushing load also decreased after 1995. It can therefore be understood that the introduction of this model is making an important contribution to both cost reduction and operational stability.

5 Conclusion

In order to secure coke quality when using low-grade coal at high blending ratios and stabilize coke oven operation, models were developed for estimating the fluidity of blended coal and the clearance between the walls of the coke oven and the coke cake.

The fluidity estimation model treats coal in the molten state as a suspension, and expresses the viscosity of this suspension in terms of the solvent viscosity and solid fraction. The temperature dependency of these factors is quantified using the Gieseler fluidity property and the



Fig. 12 Quarterly change of $|\Delta TI_6|$ until 1995

tissue structure and composition of the coal.

The clearance model is based on the hypothesis that the coke layer contracts toward the interface between the melting layer and the coke layer. Assuming a onedimensional balance of forces between the coking pressure of the melting layer and the contractile stress of the coke at this interface, the amount of contraction of the coke is calculated at the point in time when contractile stress exceeds coking pressure.

Following the introduction of this models into the blending design system, blending designs have become appropriate, the coke pushing load has been reduced, and the accuracy of coke strength control has improved. As a result, stable continuing coke oven operation has been achieved when using low-grade coal at high charging ratios.

References

- 1) M. te Lindert and J. Tilma: Ironmaking Proc. AIME, 46 (1987), 313
- K. Yohda, T. Yamamoto, and A. Sonobe: CAMP-ISIJ, 6 (1993), 954
- 3) Valery I. Addes: Ironmaking Proc. AIME, 52(1993), 303
- N. Uyemura, H. Mabuse, T. Nakano, and S. Nishida: Ironmaking Proc. AIME, 45(1986), 453
- K. Hanaoka, K. Igawa, and T. Fujii: CAMP-ISIJ, 5(1992), 50
 Y. Funabiki, S. Sato, Y. Murakami, N. Suzuki, S. Itagaki, and M. Mizusawa: CAMP-ISIJ, 1(1988), 978
- R. Nakajima, S. Hasebe, Y. Funabiki, S. Matsumura, and H. Hiraoka: CAMP-ISIJ, 2(1989), 1003
- 8) S. Ito, T. Komatsu, and T. Sato: CAMP-ISLI, 2(1989), 1005
- 9) M. Sasaki and Y. Miura: Coke Circular, 35(1986), 225
- 10) A. Einstein: Ann. Phisik, 19(1906), 286
- 11) J. Robinson: J. Phys. Colloid Chem., 53(1949), 1042
- 12) Y. Mori and N. Ototake: Kagaku Kogaku, 20(1956), 488
- 13) S. Yagi and N. Ototake: Kogyo Kagaku Zasshi, 61(1958), 1404
- 14) H. Morotomi, N. Suzuki, T. Miyazu, and M. Shimura: J. of the Fuel Soc. of Jpn., 53(1974), 779
- 15) T. Isikawa: Kongoeki Nendo no Riron (1968), 102, [Maruzen]
- 16) T. Nakagawa: Rheology (1978), 114, [lwanamizensyo]
- 17) Y. Muroki, I. Hujisima, and H. Tanabe: Coke Circular, 34 (1985)3–181
- 18) C. Meyer: Gluckauf-Forshungshefte, 42(1981), 233
- 19) A. D. Dainton: Fuel, 41(1962), 279
- 20) K. Nushiro, T. Matsui, K. Hanaoka, K. Igawa, and K. Sorimachi: *Tetsu-to-Hagané*, 81(1995), 625
- Yu. Ya. Filonenko and V. N. Sharipov: *Khimiya Tverdogo Toplive*, 12(1978), 104
- 22) H. Suginobe and W. Klose: Tetsu-to-Hagané, 71(1985), S19
- 23) K. Igawa, S. Kasaoka, and H. Ohsima: Tetsu-to-Hagané, 78(1992), 1093