MEASUREMENT OF BF SLAG VISCOSITY AND APPLICATION TO THE IN-FURNACE SIMULATION

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ABSTRACT

Viscosity of BF slag having various composition consisted of CaO,SiO_2,Al_2O_3,MgO were measured by rotating visco-meter. Furthermore, viscosity were also measured concerning the slag added FeO to the basic 4 component slag. After that, the numerical formulation were proposed for the purpose the estimation of slag viscosities under various slag composition and temperature. Slag composition of sample taking out from the dissected Nagoya No.1 blast furnace were analysed. At the same time ,temperature distribution in the lower part of BF were estimated by coke graphatization method. Viscosities of many BF points were estimated by using viscosity estimatuion model. Un-melted deadmann was found out in the dissected BF. It was found that viscosity of slag along the deadmann surface showed good agreement with 6 poise line. At present,this slag viscosity estimation system effectively applied to liquid flow simulation in the Blast Furnace Total Model "BRIGHT"[2)]

1. Introduction

The flow of molten slag at the dripping zone of blast furnace including a deadman exerts a great influence upon gas permeability, heat transfer of deadman and reduction reaction of SiO_2 or FeO. The liquid flow is supposed to distribute in the radial direction of blast furnace and its distribution condition has control of the temperature and reaction distribution at the lower part of blast furnace. Thus, estimating the two-dimensional distribution of the liquid flow with high precision in the blast furnace would be important for grasping the furnace internal phenomena more exactly.

Then, in this study, for the purpose of simulating the liquid flow in the blast furnace, an attempt was made to quantify the viscosity of blast furnace slag having a sigificant influence on the liquid flow to conjoin with a mathematical model.

Further, with reference to the results gained from the study, a mathematical model on the two-dimensional liquid flow in the blast furnace was made up to make analysis of the flowing characteristic of the liquid inside the blast furnace.

2. Viscosity measurement of BF slag

The viscosity was measured by a rotary viscometer. As the material of the crucible and rotor, a graphite was taken for a slag group not including FeO and a pure iron for a slag group including FeO. The temperature of the slag layer was measured by means of a thermocouple put on the side of the crucible.(Fig.1)

3. Viscosity estimation formula of slag without FeO

The viscosity of slag composed of 5 components, CaO, SiO_2, Al_2O_3, MgO and FeO was measured. Based on the results, an attempt was made to prepare a model used to estimate the viscosity of blast furnace slag at a desired composition and temperature. When the slag viscosity measured at a composition range of basicity (CaO/SiO_2) being 1.2 to 1.5, Al_2O_3 being 10 to 20wt% and MgO being 0 to 20wt% was expressed as a function of CaO/SiO_2, Al_2O_3 concentration, MgO concentration and temperature, a formula (1) below has been obtained. A relation between the viscosity calculated by this formula and the measured value was as follows ;

$CaO/SiO_2 > 1.2$, $W_{Feo}=0$

$$\log_{10}\eta = A1(W_{cao}/W_{sio_2})^2 + A2(W_{cao}/W_{sio_2}) + A3(W_{Mgo})^2 + A4(W_{Mgo}) + A5(W_{Al_2o_3})^2 + A6(W_{Al_2o_3}) + A7/T^2 + A8/T + A9 \qquad (1)$$

Where A1=1.709, A2= - 4.742, A3=0.933, A4= - 1.886, A5=7.991, A6= - 1.032, A7=4.269×10^6, A8=2.675×10^3, A9=0.258□

Standard deviation σ= 0.06 and Correlation coefficient r = 0.97.

For the estimation formula of viscosity of slag whose basicity (CaO/SiO_2) is less than 1.2, the measured value given by Gultyai[1)] was adopted. By converting Al_2O_3 concentration into SiO_2 concentration, Na equivalent to the viscosity, it has been arranged by a formula (2) as shown below. Where, Na can be expressed by a formula (3) below.(Fig.2)

$CaO/SiO_2 < 1.2$, $W_{Feo}=0$

$$\log_{10}\eta = 32.30\,(M_{SiO2}+Na)^2 - 27.60\,(M_{SiO2}+Na) - 7.637\times10^5/T^2 + 8.638\times10^3/T + 0.894 \qquad (2)$$

$$Na = B1 + B2(M_{CaO})^2(M_{Al2O3})^2 + B3(M_{CaO})^2(M_{Al2O3}) + B4(M_{CaO})^2 + B5(M_{CaO})(M_{Al2O3})^2 + B6(M_{CaO})(M_{Al2O3}) + B7(M_{CaO}) + B8(M_{Al2O3})^2 + B9(M_{Al2O3}) \qquad (3)$$

Where B1=0.148, B2= 70.93, B3= -15.07, B4= 0.635, B5= -125.43, B6= 26.02, B7= - 0.745, B8=37.41, B9= - 6.479

However, when $M_{Al2O3}=0$, Na=0 and M_{CaO} indicates a sum of molar fractions of CaO and MgO.

Through the formulas (2) and (3), in the data of Gultyai the measured value at a range of SiO_2 =0.6 ~1.2 wt%, Al_2O_3 = 0 ~ 20 wt%, MgO =0 ~ 10wt% and temperature = 1350 ~ 1550° has been able to be expressed with a standard deviation of 0.07 and a correlation coefficient of 0.99.

The above results enable estimating the viscosity of blast furnace slag at a desired composition and temperature and as for the basicity, a smoothing treatment has been made nearby a joining point of the formulas (1) and (2). (Fig.3,4)

4. Viscosity estimation formula of slag including FeO

Fig. 5 shows the viscosity measurement results obtained when FeO has been added to a slag containing basicity (CaO/SiO_2) of 1.2, Al_2O_3 of 15.0wt% and MgO of 5wt% as far as 20wt% which is average Japanese BF slag composition. It is found therefrom that FeO lowers the slag viscosity at the above range. Assuming that a ratio of the viscosity of slag not including FeO to that of slag including FeO is a relative viscosity, ηr, the influence of FeO shown in Fig. 2 on the viscosity can be expressed by the following formula.

$$\eta r = 1 / \{C1(W_{FeO})^2\ T^2 + C2(W_{FeO})^2\ T + C3(W_{FeO})^2 + C4(W_{FeO})\ T^2 + C5(W_{FeO})\ T + C6(W_{FeO}) + C7\,T^2 + C8\,T + C9\} \quad (4)$$

Where $C1= -1.721\times10^{-3}$, $C2= 4.338$, $C3= - 2.634\times10^{3}$, $C4= 1.538\times10^{-4}$, $C5= - 5.824\times10^{-1}$, $C6= 5.336\times10^{2}$, $C7=4.049\times10^{-6}$, $C8= -1.390\times10^{-2}$, $C9= 12.76$

A relation between the viscosity calculated by the above formula and the measured value was as follows ; Standard deviation : 0.30 and Correlation coefficient : 0.99.

5. Estimation of slag viscosity distribution at lower part of blast furnace:

Fig. 6 shows the result obtained by estimating the viscosity distribution of slag at the lower part of blast furnace based on the slag composition (CaO, SiO_2, Al_2O_3 and MgO) acquired from the investigation undertaken by dismantling Nagoya No. 1 blast furnace of NSC and a coke graphitizing temperature. Thought isoviscosity lines can be drawn with the tuyere taking the chief part, a boundary of so-called unmelted deadman and 6 poise line are in accord with each other.

And, it is supposed that such slag viscosity as this extent would be one critical point of the fluidity of slag at the lower part of blast furnace.

6. Liquid flow model of BF

At the present stage, it is least possible to measure directly the velocity distribution of slag and metal inside the blast furnace, and for making a quantitative estimation from the experimental facts, a method taken with a mathematical model would be most suitable. The author et al. simulated the liquid flow in the blast furnace based on the following assumptions.

(1) Two-dimensional cylindrical axisymmetric model
(2) A material balance relation of flowing-in and -out liquid is satisfied at each micro-area
(3) Hot metal and slag display an independent behavior.
(5) For the circulating resistance of liquid, a liquid viscosity resistance formula of Darcy formula type can be used.

An equation of continuity satisfaying the material balance of liquid flowing in and out of a micro-cylindrical cell can be expressed by a formula (5) below.

$$\frac{\partial}{\partial r}(rGlr)+\frac{\partial}{\partial z}(rGlz)=0 \quad (5)$$

An equation of motion has been expressed by a formula (6) below taking the following into account ; viscos resistance force of liquid, a force that the liquid receives from gas and gravity. It has also assumed that an external force having a velocity potential φ works virtually for indicating the move of liquid in a radial direction as seen in the foregoing increase in the liquid flow rate.

$$F\vec{G}l + S\vec{G}g + grad\phi + \rho\,l\vec{g} = 0 \quad (6)$$

Where, the contact frictional resistance F of the liquid with the particles has been expressed by a formula (7) below taking only a part for holdup in the whole space into account with consideration of the fact that the space is not filled completely with the liquid.

$$F=\frac{18k(1-\varepsilon)^2\mu l}{gcDp\varepsilon^3}\frac{ht}{\varepsilon}\frac{1}{\rho l} \quad (7)$$

In the blast furnace, a dripping liquid is subject to the force of gas coming up.Therefore, as a frictional resistance coming between the liquid surface and gas, Fanning formula has been used. The stream function Ψ has been defined by the equation combined formula(5) and formula(6).

A numerical calculation method has been solved by differentiating stream and using SOR method under the boundary condition.

This liquid flow model can be placed as the one of sub models in Blast Furnace Total Model "BRIGHT"[2)]

7. Analysis of liquid flow behavior in Liquid flow in BF

The liquid flow in the dripping zone of blast furnace at a simplified system was simulated to make examination of the effect of each factor. The viscosity of slag having a significant influence on the liquid flow has been calculated by the aforesaid slag viscosity estimation model.

7.1 Influence of coke particle diameter and void fraction (Fig.7)

A change in coke particle diameter D_{PD} and void fraction ε_D at the deadman is a factor having a great influence on the liquid flow. When D_{PD} is made smaller than a coke particle diameter D_{PM}, 50mm at the dripping zone, both slag and hot metal no longer flow through the deadman in the case of D_{PD} being 20mm. With decrease in the coke particle diameter D_{PD} and the void fraction ε_D at the deadman, the liquid flow ratio (liquid velocity at deadman/liquid velocity in dripping zone) at the deadman lowers. And, as soon as D_{PD} becomes less than 35% of D_{PM} or ε_D becomes less than 65% of that of the dripping zone, the liquid does not flow through the deadman any longer.

At the inside of actual furnace, the change in particle diameter D_{PD} and void fraction ε_D is taking place compositely and the respective limits are presumed to be higher than this change.

7.2 Influence of deadman temperature (Fig.8)

In case that the deadman temperature has been lowered in a condition where the temperature of the dripping zone, Tm is 1600°, at the deadman temperature, T_D of 1350°, slag no longer flows through the deadman though hot metal flows there. At an area where the deadman temperature is not higher than 1400°, the slag viscosity rises sharply.

This would be because that on account of the increase in the circulating resistance, the mass velocity of slag becomes very low at the deadman and slag flows along the furnace wall where the temperature is high.

The slag viscosity in this case is about 6 poises and when giving thought to the fact that the slag viscosity at s boundary between the unmelted deadman and dripping zone was found to be 6 poises in the investigation made by dismantling Nagoya No.1 blast furnace, it is to be understood that the slag viscosity of about 6 poises is an upper limit debasing the fluidity of slag in the deadman.

It has turned out from the sampling results of tuyere coke of the actual furnace that as soon as the hysteresis temperature of the deadman coke falls below 1380°, a cohered material comes out and then, smooth burden drop cannot be achieved. From the above fact, for keeping the deadman activated, there would be a need to retain the deadman temperature at least 1400° or more.

With regard to the influence of gas flow on the liquid velocity distribution, there is a tendency that the flow line curves especially at a portion where the gas flow is high in the vicinity of the lower part of cohesive zone, and hot metal whose viscosity is low is subject to more influence than the slag.

8. Conclusion

The following knowledge has been acquired with measurement of slag viscosity exerting the influence on the liquid flowing behavior and its modeling,

(1) It has become clear that a liquid flow distribution depends on a particle diameter, viscosity of liquid and holdup and practically, resistance of liquid flow in a packed bed can be expressed by a circulating resistance formula of Darcy type.

(2) The simulation results of blast furnace have revealed that when the particle deadman coke becomes less than 35% of that of coke at the dripping zone or a void fraction at the deadman goes as far as 65% of less of that at the dripping zone, the liquid no longer flows into the deadman on account of the rise in circulating resistance at the deadman.

(3) It has made clear that as soon as the deadman temperature falls below 1450°, it debases the fluidity of slag and the slag does not flow any longer through the inside of deadman and further, that an upper limit that the slag can flow inside the deadman is about 6 poises of the slag viscosity.

SYMBOLS

D_L	: Liquid droplet diameter	(m)
Dp	: Particle diameter	(m)
F	: Visco resistance of DARCY formula	(kgf s/kgm)
Gg	: Gas mass velocity	($kg/m^2 \cdot s$)
G_L	: Mass velocity of liquid	($kg/m^2 \cdot s$)
g	: Gravitational acceleration	(m/s^2)
ht	: Total hold-up of liquid	(m^3/m^3bed))
k□	: Compensated resistance coefficient of Darcy formula (=10)	(-)
M_{CaO}, M_{SiO2}& M_{Al2O3}	: Molar fractions of slag	(-)
Na	: SiO_2 equivalent of Al_2O_3	(-)
T	: Temperature	(°)
W_{CaO}, W_{SiO2}, W_{AI2O3}, W_{MgO} & W_{FeO}	:	(Wt%)
ε	: Void fraction of packed bed	(-)
η	: Viscosity of slag	(poise)
ηr	: Relative viscosity	(-)
φ	: Velocity potential	(kgwt/m2)
μl	: Viscosity of liquid	(kg/m·s)
ρl	: Density of liquid	(kg/m3)
Ψ	: Stream function of flow	(kg/s)

REFERENCES

1) I.I.Gultyai: Izv.A.N.SSSR.Metall,(1962),p.52
2) T.Sugiyama,M.Sugata ; Nippon Steel Technical Report No.35 (1987),P.32

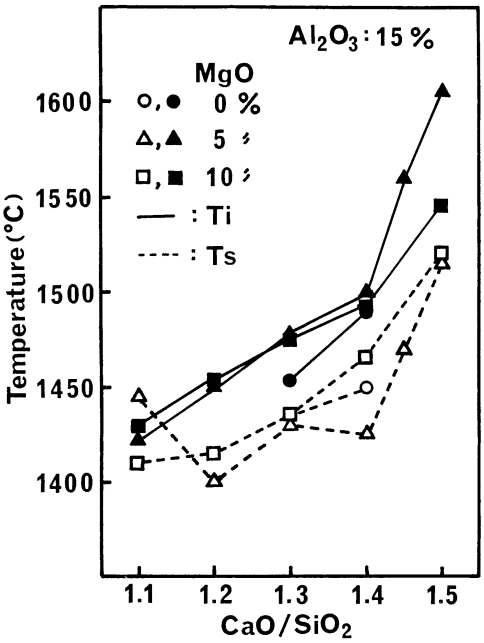

Fig. 1 Comparison between liquidus temperature(Ti) and limiting tempeature(Ts) under basicity change (present work)

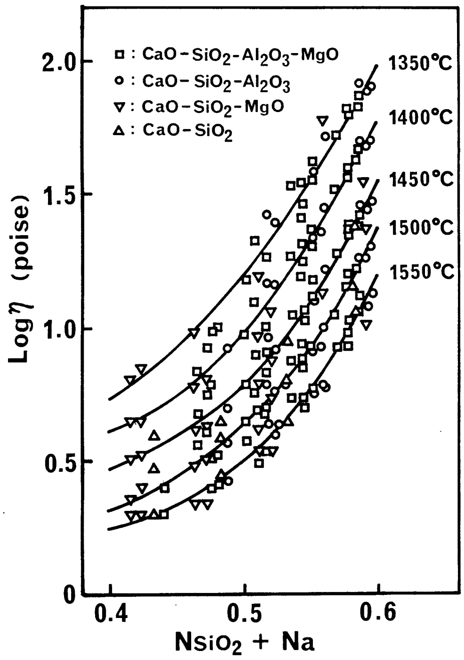

Fig. 2 Relation between slag viscosity and Nsio2+Na for various slag compositions in graphite system (using Gul'tyai's data)

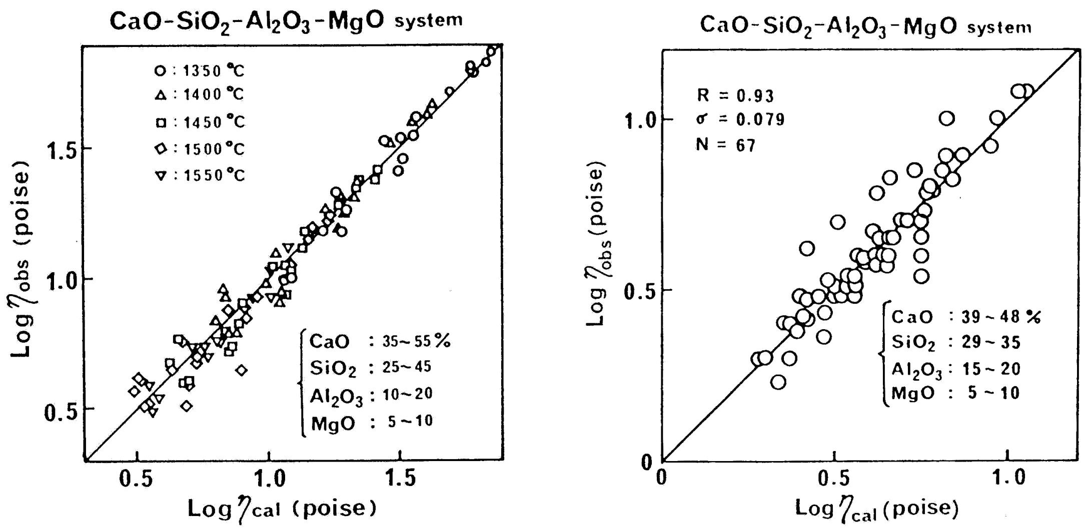

Fig. 3 Comparison of calculated viscosity with observed ones.

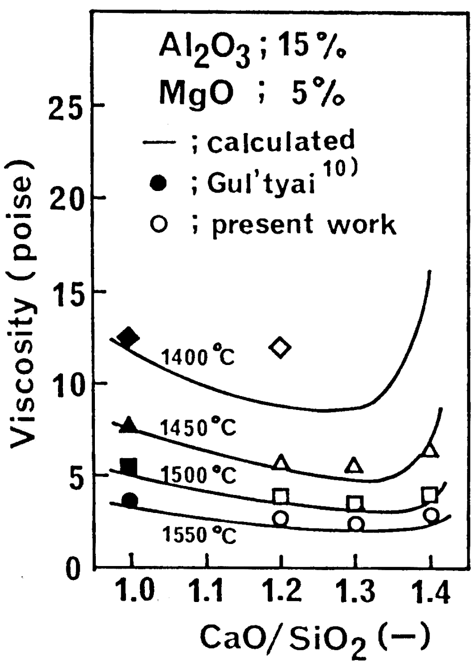

Fig. 4 Comparison between observed data and calculation value from estimation model.

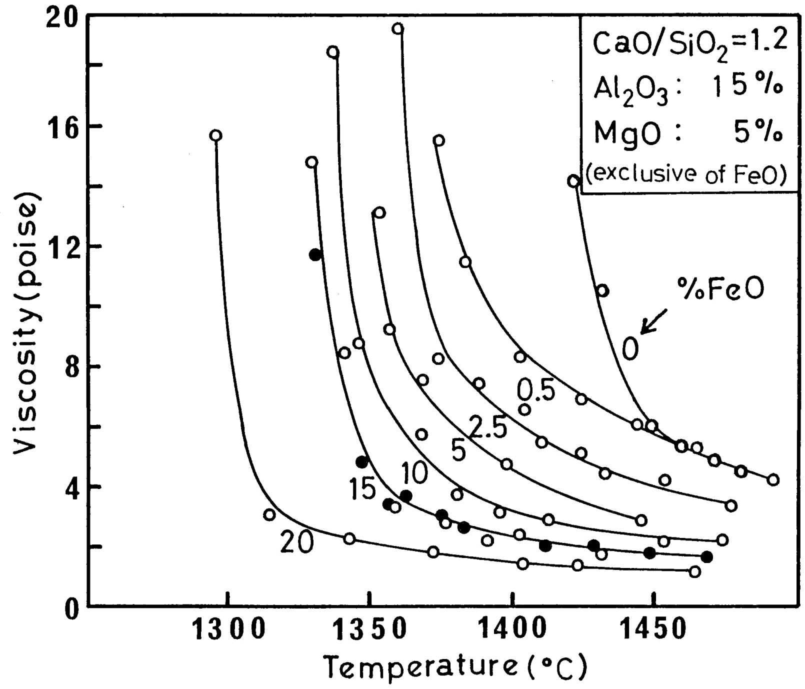

Fig. 5 Viscosity change with temperature and FeO concentration of CaO-SiO2-Al2O3-MgO-FeO slag

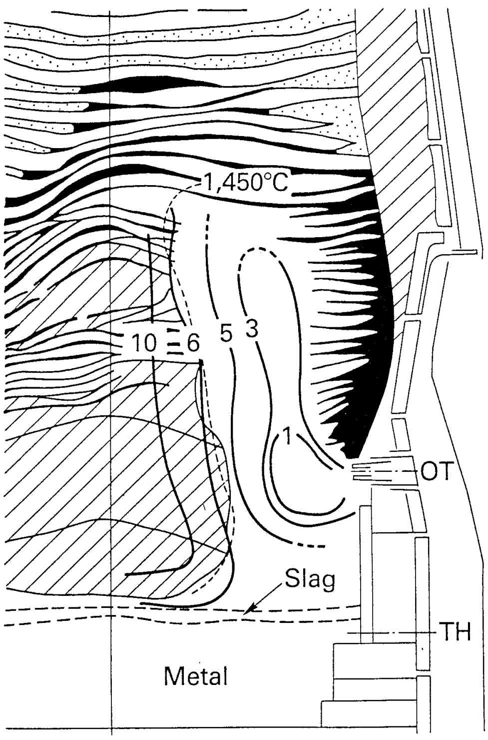

Fig. 6 Estimated isoviscosity lines in dissected Nagoya No.1 BF (poise)

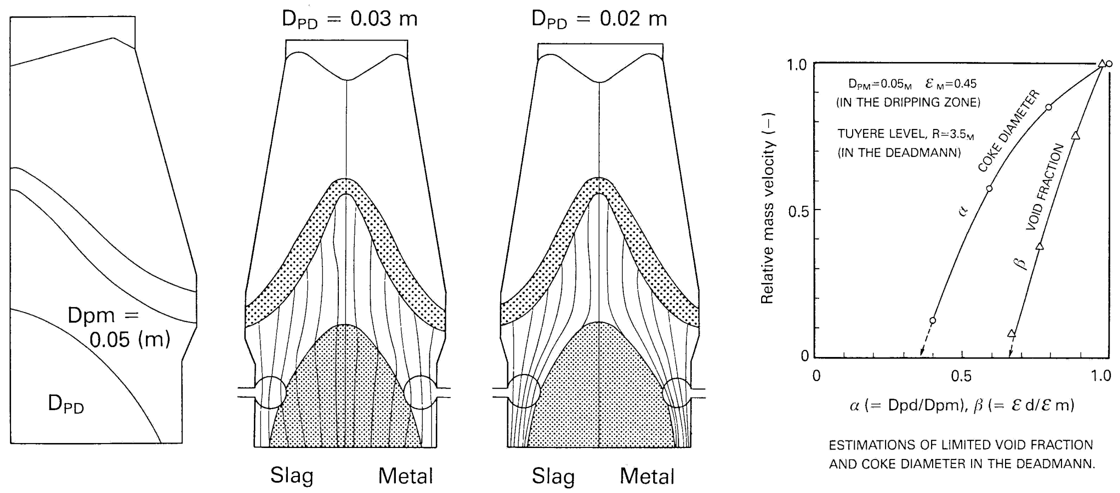

Fig. 7 Effect of coke diameter on slag and pig iron flow in the lower part of blast furnace

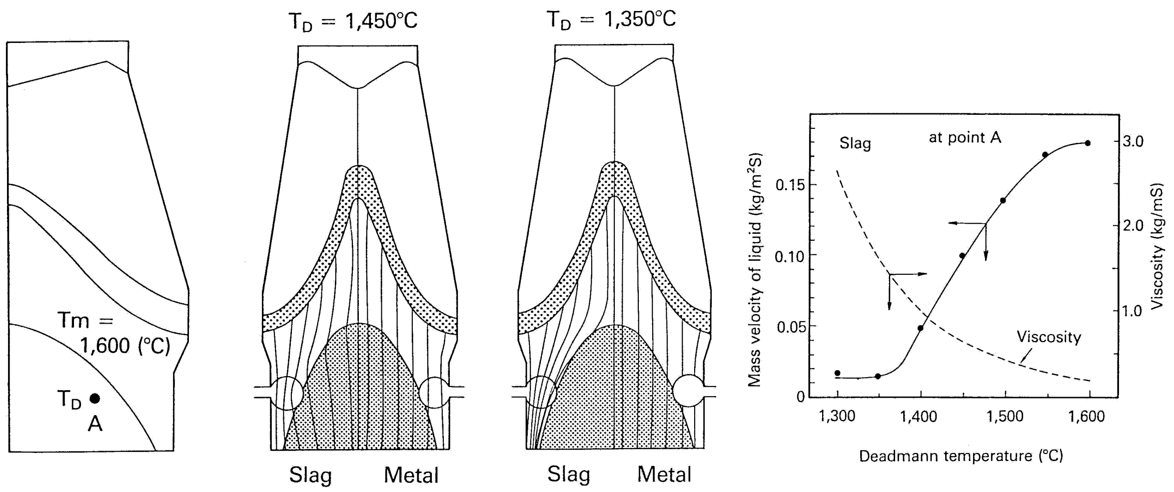

Fig. 8 Effect of deadmann temperature on slag and pig iron flow in the lower part of BF.