# 고로하부 액체유동에 대한 수치해석 사례 - 냉간유동

진홍종* · 최상민*† · 정진경**

# Numerical Simulation of the Liquid Flow in the Lower Part of the Blast Furnace - A Cold Flow Case

Hongjong Jin, Sangmin Choi and Jinkyung Jung


## ABSTRACT

The high permeability of the gas in the molten iron of the dripping zone of the blast furnace is a major factor in achieving the stable operation of a furnace with high productivity. Basic studies of the liquid flow behavior in a packed bed are necessary to grasp the effect of various operational changes on conditions in the dropping zone. Molten iron and slag together play a critical role in the lower zone, transporting mass and energy, while impairing and redistributing the gas flow. In turn, molten iron and slag undergo physical and chemical changes, and are redistributed radially as they descend to the hearth.

In this research, mathematical formulations are derived for the gas and the liquid. The solid phase is fixed with constant porosity. The information for the molten iron and slag includes the hold-up, velocity, pressure, and information related to the areas of interaction between the gas and the liquid, and the solid and the liquid. Predictable results include the velocity, pressure and temperature distribution. Additional parameters include the packed particle size and the air blast rate.


**Key Words** : blast furnace, liquid flow, hold-up, numerical simulation, packed bed

## Nomenclature

$\epsilon_s$ volume fraction of i phase

$\epsilon_g$ porosity of gas

$h_t$ total hold-up of liquid

$\varepsilon_{static}$ static hold-up of liquid

$\varepsilon_{dynamic}$ dynamic hold-up of liquid

$\phi$ shape factor

$P$ pressure

$g$ acceleration of gravity

$\theta$ contact angle between solid and liquid

$\mu_i$ viscosity of phase i

$\rho_i$ density of i phase

$C_d$ drag coefficient

$a_{ij}$ contact area between i and j

$d_s$ diameter of solid particle

$u_i$ velocity of phase i

$\sigma$ surface tension

$F_j^i$ effect of i phase on j phase


* KAIST Dept. of mechanical engineering

** POSCO(Pohang Steel Company)

† corresponding author, smchoi@kaist.ac.kr


## 1. Introduction

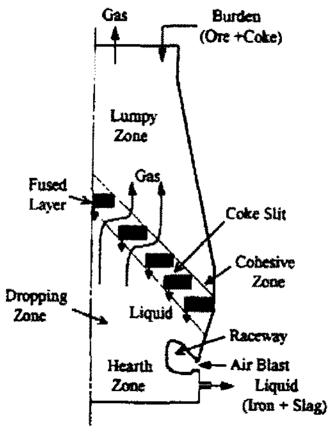



Fig. 1 Schematic diagram of the blast furnace[1]

### 1.1 Background

A blast furnace process is one of most important processes which produces molten iron from iron ore. The furnace can be classified as a counter current moving bed reactor. Iron ore can be charged together with cokes from the top of the furnace while hot blast air of 1100°C is injected from the lower part which is called the raceway. Reduction gases which is from the combustion by coke and hot blast air heat up, reduce and melt the charged iron ore. Finally the molten iron and slag are discharged in the hearth bed[1].

Stabilization of operation, productivity increase and economy of the fuel consumption are main technologies for the blast furnace. But there are many difficulties in measuring the inside of the furnace for observation the internal status.

So many researchers are modeling the blast furnace process. Partial modeling which includes solid flow, cohesive zone, liquid flow, burden profile, deadman and raceway have been studied for blast furnace analysis.

### 1.2 Goal

The purpose of this modeling is to simulate the liquid flow and understand the physical flow of the molten iron. Viscosity and coke size which can change the porosity of the lower part can be parameters to analyze the simulation. They can make different liquid flow by the porosity change. Quality of coke which is charged to the furnace is the size of coke and operating conditions change the liquid flow. And the viscosity affects the hold-up of liquid flow and the whole flow pattern of the furnace.

In this research, liquid and gas flow in the lower part of the furnace would be the target to do modeling and this research need several assumptions because thermo fluid, physical and chemical reactions take place simultaneously. This cold flow model can play an important role to construct the reaction modeling in the lower part. So the final model of the lower part can be combined with the layer structure and iron ore reduction models in the stack zone to make comprehensive model of the blast furnace.

### 1.3 Literature review

Several simplifications are necessary because there are physical and chemical reactions simultaneously in the lower part of the furnace. At first the internal structure of furnace can be assumed by packed bed because solid particles like coke and sintered iron are charged and the gas and liquid flow through the porous space. Mathematical modeling for this kind of packed bed is referred by Yagi. J and the detail is described in the governing equation[2].

The mathematical modeling covers to 4 phases which include gas, liquid, solid particle and fine particle. The continuity and momentum balances are based on the Navier-stokes equation. Fine particles are negligible and the solid particle are assumed stationary. So 2 phase flow of gas and liquid are to be simulated. The relation between gas and liquid in the porous media are expressed by Ergun's equation. The resistance between gas and liquid or solid particle can be considered.

Initial modeling of liquid flow was by potential model which have

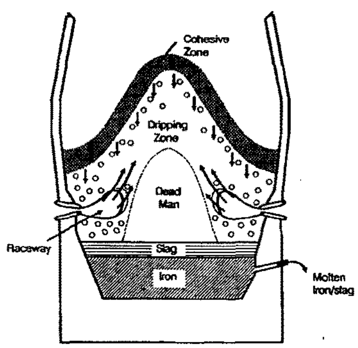



Fig. 2 Schematic diagram of the lower part of the blast furnace[3]

difficulties of modeling discontinuous characteristics. Continuous model which appeared later can make velocity distribution only in a specified area and can't make boundary of liquid flow[3]. Probability model can find the liquid flow boundary which the continuous model can't simulate. This model get the liquid flow distribution based on the probability that is generated by drag force of gas flow or gravity force of particle.

The packed bed filled with liquid is expressed by the correlation between pressure and velocity of liquid which is called Darcy's equation. Extended Darcy's equation that is, continuous model, expresses the 2 phases of gas and liquid. On the other hand probability model describes based on the probability process of liquid that pass through the packed bed. Combination of continuous and probability model can complement each other. The former determine the liquid flow region and the latter calculate the velocity distribution of liquid flow.

Szekely and Kajiwara made the counter current type flow in the packed bed which neglect all effects except for volume fraction of liquid. That is, change of contact area between gas and solid, friction force and interactions between gas and liquid were neglected.

The model calculated in 2D rectangular shape is shown in Fig. 3. Gas flows from lower left to the top and liquid flows downwards uniformly. This shows the stream line of liquid and gas flow. Dotted line indicates the constant liquid hold-up and solid line is from the calculation of the governing

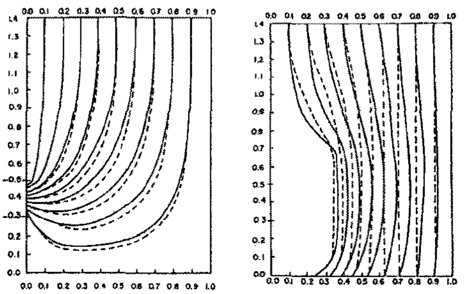


**Fig. 3 Gas and liquid flow in the simplified region by Szekely and Kajiwara[4]**

**Table 1 Continuity equations**

| | |
|---|---|
| Gas | $\frac{\partial}{\partial t}(\epsilon_g \rho_g) + \nabla \cdot (\epsilon_g \rho_g \vec{u_g}) = \sum_i \sum_k S^k_{g,i}$ |
| Liquid | $\frac{\partial}{\partial t}(\epsilon_l \rho_l) + \nabla \cdot (\epsilon_l \rho_l \vec{u_l}) = \sum_i \sum_k S^k_{l,i}$ |
| Solid | $\frac{\partial}{\partial t}(\epsilon_s \rho_s) + \nabla \cdot (\epsilon_s \rho_s \vec{u_s}) = \sum_i \sum_k S^k_{s,i}$ |

equation. Gas flow seems not to be influenced by liquid hold-up while liquid flow changes by the hold-up. And the dry zone appears around gas inlet.

## 2. Mathematical modeling

### 2.1 Governing equation

Continuity and momentum equation for each phase are summarized in Table 1, 2[2]. Source term of gas phase are from chemical reaction, phase change and variation of gas species in surface of liquid or solid.

Source term of liquid phase is from liquid formation by chemical reaction and melting of solid particles. In the case of solid phase, break up or melting by physical change or stick by fine particles make source term. And generation by chemical reaction or accumulation by liquid flow forms the source of fine particle.

**Table 2 Momentum equations**

| | |
|---|---|
| Gas | $\frac{\partial(\epsilon_g \rho_g \vec{u_g})}{\partial t} + \nabla \cdot (\epsilon_g \rho_g \vec{u_g u_g})$ $= \nabla \cdot (\epsilon_g \mu_g \nabla \vec{u_g}) - \epsilon_g \nabla P_g + \vec{F^s_g} + \vec{F^l_g} + \vec{F^f_g}$ |
| Liquid | $\frac{\partial(\epsilon_l \rho_l \vec{u_l})}{\partial t} + \nabla \cdot (\epsilon_l \rho_l \vec{u_l u_l})$ $= -\epsilon_l \nabla P_l + \vec{F^s_l} + \vec{F^l_l} + \vec{F^f_l} + \vec{F^g_l} + \epsilon_l \rho_l \vec{g}$ |
| Solid | $\frac{\partial(\epsilon_s \rho_s \vec{u_s})}{\partial t} + \nabla \cdot (\epsilon_s \rho_s \vec{u_s u_s})$ $= -\epsilon_s \nabla P_s + \vec{F^l_s} + \vec{F^g_s} + \vec{F^f_s} + \vec{F^s_s} + \epsilon_s \rho_s \vec{g}$ |

**Table 3 Correlations for the interactions**

| |
|---|
| $\overrightarrow{F_g^s}=-[150\mu_g \frac{a_{gs}^2}{36\epsilon_g}(\overrightarrow{u_g}-\overrightarrow{u_s})+1.75\rho_g a_{gs}(\overrightarrow{u_g}-\overrightarrow{u_s})\lvert\overrightarrow{u_g}-\overrightarrow{u_s}\rvert]$<br>Effect of solid on gas flow |
| $\overrightarrow{F_g^l}=-\frac{a_{gl}}{a_{gl}+a_{sl}}[\frac{3}{4}C_d\rho_g\lvert\overrightarrow{u_g}-\overrightarrow{u_l}\rvert(\overrightarrow{u_g}-\overrightarrow{u_l})/d_l]$<br>Effect of liquid on gas flow |
| $\overrightarrow{F_l^s}=-[\frac{180(\epsilon_s+\epsilon_l(s))^2\mu_l\epsilon_l^2}{d_s^2(\epsilon_l+\epsilon_l(s))^3}](\overrightarrow{u_l}-\overrightarrow{u_s})$<br>Effect of solid on liquid flow |
| $\overrightarrow{F_l^g}=-\overrightarrow{F_g^l}$<br>Effect of gas on liquid flow |
| $\overrightarrow{a_{ls}}=(a_{gs}+a_{ls})[1-\exp(-1.45(\frac{\rho_l u_l}{(a_{gs}+a_{ls})\mu_l})^{0.1}\times(\frac{(a_{gs}+a_{ls})(\rho_l u_l)}{g\rho_l^2})^{-0.05}(\frac{(\rho_l u_l)^2}{\rho_l\sigma_l(a_{gs}+a_{ls})})^{0.2}(\frac{\delta_c}{\delta_l})^{0.75})]$<br>Contact area between liquid and solid |
| $a_{gl}=0.34/d_s(Fr_l)^{-1/2}(We)^{2/3}$<br>Contact area between gas and liquid |
| $a_{gs}=6\epsilon_s/\phi_s d_s-a_{ls}$<br>Contact area between gas and solid |

Momentum equation of gas phase consists of unsteady, convection, diffusion, pressure gradient and source term. The source term have 3 force interactions by solid, liquid and fine particles. Momentum equations of liquid and solid have same terms of gas except for diffusion term which include viscosity.

Usually, the blast furnace have four phases which are packed bed particle, fine particle, gas and molten iron or slag. For simplification, it is assumed that fine particles are neglected and the packed bed particles are stationary.

Correlations among 3 phases are summarized in Table 3 and the solid velocity is zero by the assumption of stationary packed bed.[2] Effect of solid phase on gas flow is the function of gas velocity, viscosity and contact area between gas and solid. Effect of liquid on gas phase is from drag coefficient, density and velocity difference between gas and liquid

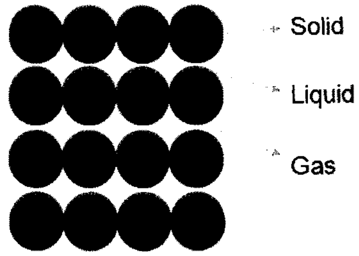



**Fig. 4 Schematic diagram of 3 phases**

velocity. Effect of solid on liquid flow consists of particle diameter, viscosity, velocity and liquid hold up. Contact area between liquid and solid is determined by liquid velocity, density, surface tension and contact area between gas and solid. Contact area between gas and liquid is by particle diameter and 2 dimensionless numbers. And the contact area between gas and solid consists of volume fraction of solid, shape factor, particle diameter and contact area between liquid and solid.

## 2.2 Liquid hold-up

Hold-up is used for the volume fraction of liquid flow. In this research summation of volume fractions of gas, solid and liquid is unity because fine particles are negligible.

$$\epsilon_s+\epsilon_s+h_t=1 \qquad \text{(Eq. 1)}$$

Volume fractions of gas and liquid affect each other because volume fraction of solid is constant. So, the Eq. 1 is used for coupling

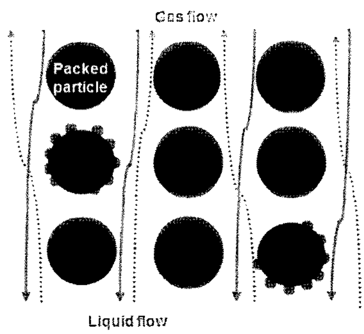



**Fig. 5 Schematic diagram of liquid flow**

**Table 4 Correlations for liquid hold-up**

| | |
|---|---|
| $\varepsilon_l = 8.1220\,\mathrm{Re}_m^{0.581}\,Ga_m^{-0.482}Cp_m^{0.298}$ | Dynamic hold-up |
| $\varepsilon_l(s) = 0.0194Ga_m^{0.0254}Cp_m^{-0.0044}$ | Static hold-up |
| $\mathrm{Re}_m = \rho_l\mu_l\phi d_s / \mu_l$ | Reynolds number |
| $Ga_m = \rho_l^2 g(\phi_s d_s)^2 / \mu_l^2\varepsilon_s^2$ | Galilei number |
| $Cp_m = (1/\cos\theta_l)\{\rho_l g(\phi_s d_s)^2/(\sigma_l\varepsilon_s^2)\}$ | Capillary number |
| $Fr_m = \dfrac{u^2}{d_p\phi g(1-\varepsilon)^2}$ | Froud number |
| $We_m = \dfrac{\rho u^2 d_p\phi}{\sigma(1-\varepsilon)^2}$ | Weber number |

between gas and liquid flow momentum equations[2].

Hold-up of liquid phase consists of static hold-up accumulated on the surface of solid particles and dynamic hold-up flowing downwards. Table 4[5] shows the detail relations for the liquid hold-up which is function of dimensionless numbers like Re, Ga and Cp. Cp is the function of contact angle between solid and liquid phase. Static hold up is regardless of liquid velocity even though dynamic hold up depends on the liquid velocity.

## 3. Numerical modeling

### 3.1 Numerical approach

Stationary packed bed are assumed for simplification of this modeling. Assumptions of steady state and neglecting fine particle make the final governing equation of gas phase like Eq. 2. This equation shows the correlation between pressure gradient and velocity and interaction between gas and liquid phase. The interaction includes several physical properties, porosity, contact area with liquid or solid phase and velocity difference. It is similar Ergun's equation except for the interaction term.

$$\varepsilon_l\nabla p_l = \frac{180\varepsilon_s^{\ 2}\mu_l}{d_s^{\ 2}\varepsilon_l}\overline{u_l} + \varepsilon_l\rho_l\overline{g} + \frac{a_{gl}}{a_{gl}+a_{sl}}\left[\frac{3}{4}C_d\rho_g\left|\overline{u_g}-\overline{u_l}\right|(\overline{u_g}-\overline{u_l})/d_l\right] \quad \text{(Eq. 2)}$$

Contact area which is determined by contact angle between liquid and solid and dimensionless numbers like Re, Fr and We is essential to solve this equation. In the case of liquid flow, Eq. 3 is from the assumption of steady state and neglecting fine particle. It is similar with gas equation except for the gravity force term. This equation is also the correlation between pressure gradient and liquid velocity. And it has convective term and source term which consists of drag coefficient and velocity difference between gas and liquid.

$$\varepsilon_g\nabla P_g = -(150\mu_g\frac{a_{gs}^2}{36\varepsilon_g}\overline{u_g}) - 1.75\rho_g a_{gs}\overline{u_g}\,|\,\overline{u_g}\,| - \frac{a_{gl}}{a_{gl}+a_{sl}}\left[\frac{3}{4}C_d\rho_g\left|\overline{u_g}-\overline{u_l}\right|(\overline{u_g}-\overline{u_l})/d_l\right] \quad \text{(Eq. 3)}$$

### 3.2 Physical properties

**Table 5 Physical properties**

| Properties | Value | Unit |
|---|---|---|
| viscosity_g | 1.85E-05 | [Pa·s] |
| density_g | 1.1614 | [kg/m^3] |
| viscosity_l | 0.005 | [Pa·s] |
| density_l | 6600 | [kg/m^3] |
| particle diameter | 0.0477 | [mm] |
| surface tension | 1.1 | [N/m] |
| contact angle | 103.3 | [degree] |
| solid volume fraction | 0.45 | |
| shape factor | 0.9 | |

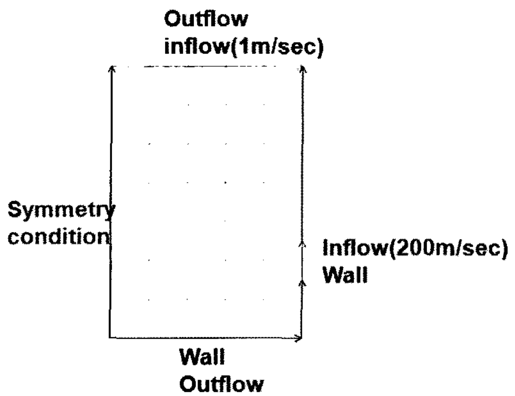



Fig. 6 Boundary condition of simple geometry

In this modeling physical properties of air and molten iron in 1800K were used for gas and liquid in Table 5[6]. Viscosity and density of liquid are 1000 times larger than gas. Particle diameter is real coke size in the furnace. Surface tension and contact angle between liquid and solid particle is used from the reference. Volume fraction of solid particle determine the gas porosity and liquid hold up by the Eq. 1.

### 3.3 Boundary conditions

Simple geometry was simulated for applying the governing equation which is derived above. The influx of gas is from the left lower part to the top by 200m/sec and liquid flows down wards uniformly by 1m/sec. For gas flow, left wall is axial symmetric and the others are wall which is set by no slip condition. In the case of liquid flow same conditions are considered except for inlet and outlet.

In the furnace geometry of Fig. 7 it is same as the above that the gas flow from the left lower part to the top and the liquid flows downwards uniformly. But the boundary condition is based on the real operating conditions. The liquid falls slowly by 0.01m/sec and the gas inlet velocity is 3m/sec.

## 4. Solver

The modeling was simulated using COMSOL Multiphysics 3.4 which can make geometry or grid and solves PDEs. The solver provided by COMSOL solves the above equations which have relative tolerance is 1E-3 and damping or relaxation factor is 1E-6. The solver iterates until the difference between previous and present value converges by convergence error. At first it solves continuity equation of the gas and the liquid flow while solving momentum equations to iterate for converging the value of pressure and velocity. Physical properties and correlations between gas and liquid phase are given to the solver by tabulated variable setting. And the governing equations explained above can be defined by user using equation system of the solver.

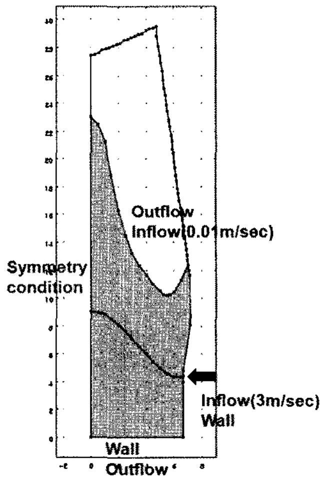



Fig. 7 Boundary condition of furnace geometry

## 5. Results

### 5.1 Simple geometry

Gas is blown from the right lower part to the top and liquid flows downwards uniformly to simulate interactions between gas liquid flow. Fig. 8 shows the streamline and x-direction velocity of liquid flow. The streamline of liquid flow curves around the gas inlet. In the right figure, negative x-velocity is found near the blast of gas. The space which is made by interaction between

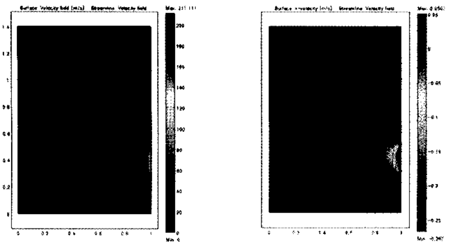


**Fig. 8 Streamline and negative velocity of liquid flow**

gas and liquid flow seems like dry zone.

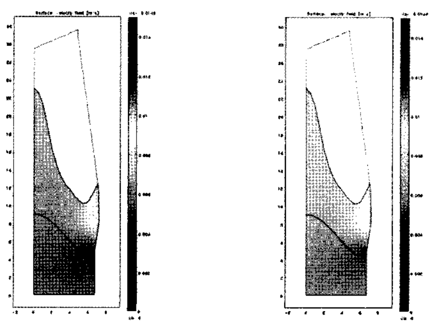
No x-velocity is found in the region far from the gas inlet because the effect of interaction decreases from the raceway. These interactions is caused from difference of each momentum which is started by correlation of the volume fraction for each phase.

## 5.2 Actual geometry

### 5.2.1 Interaction between gas and liquid

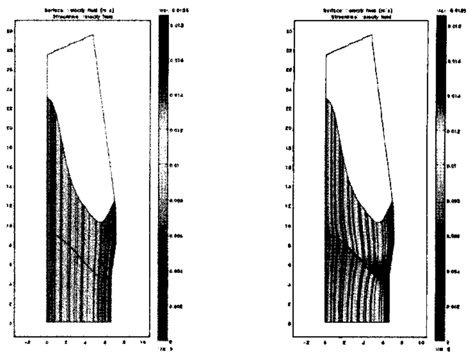
The mathematical modeling was applied to blast furnace geometry after validation the governing equation in the simple square geometry. Fig. 9 shows liquid velocity distribution for interaction and no interaction. It seems same velocity distribution because the inlet velocities of gas and liquid is small. But the maximum and average velocity of A decreases a little than B because the interaction force by gas affects liquid flow.

### 5.2.2 Porosity change



A) Interaction B) No Interaction

**Fig. 9 Effect of interaction between gas and liquid flow**



Deadman : $\varepsilon_s = 0.45$ Dripping zone : $\varepsilon_s = 0.45$

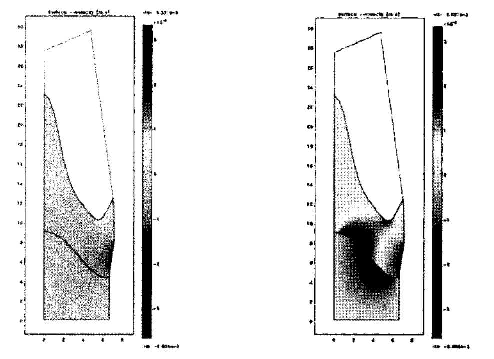
Deadman : $\varepsilon_s = 0.675$ Dripping zone : $\varepsilon_s = 0.45$

**Fig. 10 Streamline of liquid flow by porosity change in deadman**

In order to consider the porosity change, the volume fraction of deadman was changed from 0.45 to 0.675 which means the decrease of gas flow porosity or liquid hold-up as seen in Fig. 10. The liquid flows downwards uniformly when the solid volume fractions of dripping zone and deadman are same.

But it curve in the boundary between dripping zone and deadman because of sudden decrease of liquid hold-up. And the flow rate through the deadman decreases while it increased in the right side of deadman. This movement of streamline direction is made by that the flow rate of gas suddenly increases just after the boundary. Consequently change of volume fraction of solid or porosity of gas can make variation of flow rate or direction.

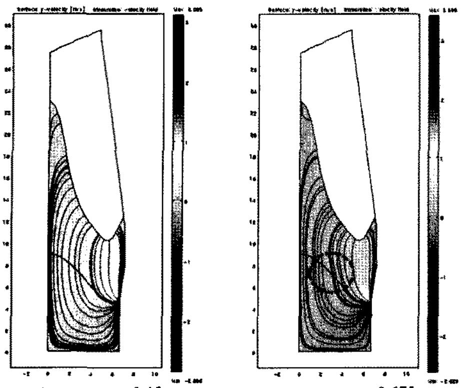
The effect of porosity change in deadman is found clearly when we check the x direction velocity of liquid flow like Fig. 11. Positive



Deadman : $\varepsilon_s = 0.45$ Dripping zone : $\varepsilon_s = 0.45$

Deadman : $\varepsilon_s = 0.675$ Dripping zone : $\varepsilon_s = 0.45$

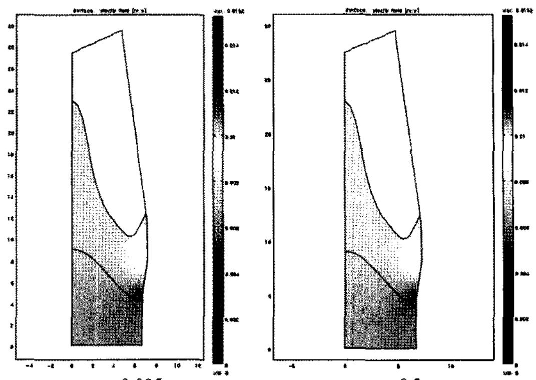
**Fig. 11 x-velocity of liquid flow**



Deadman : $\varepsilon_s = 0.45$
Dripping zone : $\varepsilon_s = 0.45$

Deadman : $\varepsilon_s = 0.675$
Dripping zone : $\varepsilon_s = 0.45$

Fig. 12 Streamline of gas flow



A) $\mu_l = 0.005$ B) $\mu_l = 0.3$

Fig. 13 Liquid velocity change by viscosity to the right side.

value of liquid velocity exists above the boundary and negative value under the boundary. This is from the abrupt change of gas porosity in the boundary between deadman and dripping zone.

The gas flow is also simulated for the change of volume fraction in deadman which means gas porosity or liquid hold-up changes. The direction of gas streamline changes through the boundary between deadman and dripping zone when the solid volume fraction of deadman increases to 0.675 as seen in Fig. 12. This movement of streamline direction is made by that the flow rate of gas suddenly increases just after the boundary. Consequently change of volume fraction of solid or porosity of gas can make variation of flow rate or direction.

### 5.2.3 Viscosity change

Viscosity change was simulated to see the change of the internal flow of the furnace. In this cold flow model, only 2 viscosities was calculated even though the reaction and temperature change should be considered to simulate viscosity change. In Fig. 13 left figure is for the molten iron in 1800[K] and the right one is for slag. Velocity distribution is similar but the maximum velocity of the molten iron increases by 0.003m/sec. This means the liquid flow rate changes radially to the raceway where the maximum velocity is generated. That is, liquid flow avoid the low porosity region by moving to the right side.

## 6. Conclusion

Liquid flow in the lower part of a blast furnace is of direct importance for the productivity of molten iron and stable operation. Literature review and mathematical modeling was summarized to simulate the liquid flow. Governing equations were reviewed to simulate the interaction between the gas and the liquid flow. Neglecting fine particles and stationary packed bed were used for simplification.

Change of the volume fraction in the deadman was simulated for parameter analysis. The volume fraction affects to porosity and gas or liquid flow. And the viscosity change made the difference of maximum velocities of the liquid flow between molten iron and slag. Consequently, those parameters can make change of liquid flow from cohesive zone to the bottom line. Convection term of gas and liquid momentum equation would be considered in the blast furnace and the parameter analysis about raceway depth would be studied more.

## Acknowledgement

The current paper are supported by POSCO and CERC(Combustion Engineering Research Center).

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