Formation of Vertically Inverse Pressure Distribution Due to Packing Structure of Near Wall Region of Blast Furnace

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Realizing stable and highly efficient operation of blast furnace under low reducing agent rate condition is one of the key issues to contribute problems of energy, resources and global warming. Under low reducing agent rate operation, chemical and thermal driving force in the blast furnace is weakened, and it is considered that the capability of recovering the process from the fluctuation is deteriorated. Therefore the probing the state inside the blast furnace by utilizing the information from the various sensors is important. This study focused on the relation between pressure distribution on furnace wall and packing structure inside the furnace. The blast furnace is a packed bed reactor with upward gas flow, thus the pressure generally decreases from the tuyere to the top. Partially inverse pressure distribution is sometimes observed as an instable phenomenon of the furnace. This study proposed a mechanism to produce such pressure distribution with simple structural change in packed bed. When a vacant space is formed in the packed bed, the gas flow concentrates to this space and the gas velocity increases. At the downstream end of the space, the gas velocity decreases and generates dynamic pressure. This increase of the pressure forms the inverse pressure distribution. In this study, this mechanism was confirmed through experimental and numerical approaches.

KEY WORDS: blast furnace; pressure inversion; gas flow; packing structure.

1. Introduction

To realize low carbon operation of ironmaking processes, especially blast furnace, is urgently required because it is considered to contribute largely to solve problems of environment, resources and energy. The low carbon operation of the blast furnace brings the supplies of energy and materials for progress of reduction and melting toward the lower limit. Although the tolerance to fluctuation of operation diminishes in such condition, it is indispensable to keep the blast furnace operation highly efficient and stable. The blast furnace process is characterized by non-uniform and broad distributions of temperature, pressure, chemical composition, and so on, that are formed in the furnace. Recent expansion of furnace volume and diversification of raw material properties increase possibility to disorder proper distributions of these process variables in the furnace. In extreme situation, such disorders initiate the operation trouble. Detecting such fluctuations and predicting their effects on future operation

status would help to keep the blast furnace operation stable.

There are various methods to acquire in-furnace information of blast furnaces by inserting probes or settling the sensors on the furnace wall. Former methods are usually impermanently used and the insertion of such probes disturbs in-furnace distributions of process variables and flow patterns, more or less. For detecting the operation fluctuations, permanent and non-disturbing methods are desirable. The sensors settled on the furnace wall permanently and continuously measure pressure and temperature in near wall region inside the blast furnace. Recently a system which visualizes temperature and pressure on the wall of the blast furnace as 2-dimensional map was developed¹⁻⁴⁾ and utilized in actual operations. Even in such system, obtained information is limited within the region vicinity to the wall. For detecting fluctuations, predicting the causes of generation of the fluctuations and estimating effects of such fluctuations on the future trend of the operation, it is necessary to understand the relationship between the three-dimensional structure in the furnace and two-dimensional distribution on the wall. As one of such relationships, this study discusses the relationship between two-dimensional pressure distribu-

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tion on the wall and three-dimensional structure of packed bed in the blast furnace.

The packing structure of burden materials in blast furnace was formed by burden distribution at the top of the furnace, rearrangement of particles with burden descent, variation of properties of the burden materials with progress of reaction and heating, accumulation of powders, and so on. Troubles of burden descent like hanging, slip, fluidization, and so on are considered to occur due to the extreme structural change of packed bed. Since peculiar pressure distributions are often observed when such incidences occur, several studies have made on the relationship between the wall pressure distribution and in-furnace packing structure. Inverse pressure distribution is one of such peculiar pressure distributions that are related to operation instability.^{3,5-8)} In the packed bed, the pressure drop occurs when the gas flows through the bed. Thus the pressure in the bed is higher in upstream and lower in downstream. Since the reducing gas flows upward in the blast furnace, the pressure is usually higher in the lower part and lower in the upper part. In some case, partly opposite pressure distributions, namely lower in the lower part and higher in the upper part, are observed.^{1,2,5)} In this study, such pressure distributions are defined as “inverse pressure distribution”. This study discusses the formation mechanism of the inverse pressure distribution from the viewpoints of fluid dynamics and packing structure.

2. Theory

2.1. Formation Mechanisms of Inverse Pressure Distribution

Inside blast furnace the reducing gas flows through the packed bed that consists of coke and ore particles. The reducing gas is viscous fluid and its flow behavior can be described by the continuity equation and the equation of motion. For the blast furnace condition, these equations take into account the voidage and flow resistance.

Continuity equation

$$\frac{d}{dt}(\varepsilon \rho) + \nabla \cdot \varepsilon \rho \vec{u} = 0 \quad (1)$$

Equation of motion

$$\frac{\partial}{\partial t}(\varepsilon \rho \vec{u}) + \nabla \cdot \varepsilon \rho \vec{u} \vec{u} = -\varepsilon \nabla p - \nabla \cdot \tau + \varepsilon \rho \vec{g} + \vec{F} \quad (2)$$

where, the fourth term of the right side of equation of motion, $\vec{F}$, is the flow resistance of packed bed, and the Ergun's equation⁹⁾ is widely used for the flow analysis in the blast furnace.

$$\vec{F} = - \left[150 \frac{(1-\varepsilon)^2 \mu}{\varepsilon^2 \phi^2 d_p^2} + 1.75 \frac{(1-\varepsilon) \rho |\vec{u}|}{\varepsilon \phi d_p} \right] \vec{u} \quad (3)$$

Generally for the blast furnace packed bed flow, inertia term (second term of left side), viscous term (second term of right side) and buoyancy (third term of right side) are negligibly small compared to the flow resistance term. By omitting these terms, the equation of motion under steady state can be expressed as:

$$\varepsilon \nabla p = -C_D \vec{u} \quad (4)$$

In this equation, the flow resistance is rewritten as the product of the gas velocity and apparent drag coefficient C_D which is expressed by the inside terms in brackets of Eq. (3).

The flow expressed by this equation is potential flow in which the fluid motion is determined by the gradient of pressure. In this flow scheme, the potential decreases with the increase in the distance from the gas inlet unless the gas feed source, which raises the velocity potential, exists. Therefore it is impossible to form the inverse pressure distribution under the condition that the gas simply flows through the packed bed, like blast furnace.

One of the possible mechanisms to form the inverse pressure distribution with potential flow scheme is formation of individual parallel flow paths. **Figure 1** shows the concept of this mechanism. In this mechanism, two flow paths, A and B, that have no mutual effect are generated in the packed bed. These two paths connect each other at upstream and downstream ends. This means the pressures in these paths are common at both ends. The flow directions in these paths are the same and the pressures drop toward the downstream. These two paths have different patterns of permeability. In the path A, the upstream part is highly permeable and the downstream part is low permeable. In this arrangement, the

Fig. 1. Pressure distributions generated by flow paths having different permeability patterns.

Fig. 2. An example of packing structure to produce inverse pressure distribution.

pressure gradient in the upstream region is smaller, and one in the downstream region is larger. Contrarily the path B has low permeable upstream region and highly permeable downstream region. Comparing these paths, the pressure in path A is always higher at the same height. If such paths generate in the blast furnace, in addition, the path B touches the furnace wall in the lower part of the furnace, and the path A touches the wall in the upper part of the furnace, the inverse pressure distribution is observed at the furnace wall. An example of the packed bed structure to realize such situation is shown in Fig. 2. In this structure, a highly permeable channel which is surrounded by impermeable layer locates longitudinally in the packed bed, and the downstream end of the highly permeable channel locates near wall. With the impermeable layer, the highly permeable channel and the other region have individual pressures at the same height. The channel and the other part correspond to the paths A and B in Fig. 1, respectively. The pressure in the packed bed decreases upward direction to point P2. At the same time, the pressure in the channel is kept higher due to the low flow resistance. Thus the gas flow drawn to the point P1 still has higher pressure than that of point P2, and the inverse pressure distribution is observed on the wall. In this structure, the gas is supplied to near wall region through the channel, and this gas feed source raises the pressure (velocity potential). Consequently, the gas that is supplied from the channel radially expands from the point P1, then flows upward, and the main stream gas flows avoiding this high pressure region around P1. As explained here, the inverse pressure distribution can be formed by the packed structure even if the gas flow follows the potential flow scheme. It, however, is considered that the possibility to form such complex packed bed structure is little, and the other simpler mechanisms exist.

It is reported that the void space without packed particles is formed when hanging or channeling occur in the blast furnace.^{3,5,8)} The equation of motion for the gas flow in such void space can be simplified as following equation with the assumptions of no flow resistance of packed bed and little effect of viscosity.

$$\nabla \cdot \varepsilon \rho \vec{u} \vec{u} = -\varepsilon \nabla p \dots\dots\dots (5)$$

This means that the spatial variation of the fluid kinetic energy appears as pressure variation. In other words based on the Bernoulli's principle, the velocity head and the pressure head can be converted each other. With this equation, a formation mechanism of inverse pressure distribution can be given as follows, and its schematic diagram is shown in

Fig. 3. Concept of generation of pressure inversion.

Fig. 3. In this diagram the main stream gas flows from left to right. Once the highly permeable zone (abbreviated as HPZ, hereinafter) like a void space is formed, the gas flow is attracted to this zone and the gas velocity increases. When the concentrated gas flow reaches to the downstream end of the HPZ, it is obliged to decelerate due to the larger flow resistance of the bed. This decrease in the kinetic energy due to this deceleration is converted to the increase in the pressure. If this pressure rise is enough high, the inverse pressure distribution is formed.

2.2. Preliminary Discussion Based on the Flow Resistance Equation

Feasibility to form the inverse pressure distribution by the generation of the HPZ or void space in the packed bed is discussed based on the flow resistances of parallel flow paths. Examined flow system is unidirectional flow in a rectangular region as shown in Fig. 4(a). The flows in upstream and downstream zones are assumed uniform at u_{ave} . The test section consists of two flow paths. One has the same packing structure as up- and downstream zones, and is designated as LPZ, hereinafter. The other is the highly permeable zone, in which the voidage is set higher than that of the other zones while the particle diameter is common. The pressures in the LPZ and the HPZ are common at up- and downstream ends (p_{up} and p_{down}), in other words the pressure drops in both zone are the same. The gas velocity and flow rate in each zone are respectively constant in the flow direction. The gas flow velocities of both zones are determined by the permeabilities (or flow resistances) of each zone and the common pressure drop ΔP . This flow system can be described by an electric circuit shown in Fig. 4(b). The pressure rise due to the difference in the kinetic energy between the HPZ and

(a) Schematic diagram of flow path

(b) Equivalent electric circuit

Fig. 4. Analyzing condition for parallel paths.

the downstream zone is examined by changing the voidage of the HPZ (ε_{HPZ}) and the ratio of cross sectional area of the HPZ ($\alpha_{\text{HPZ}}/(\alpha_{\text{HPZ}} + \alpha_{\text{LPZ}})$).

The following conditions are set. The length of the test section is 1.0 m, and the superficial velocity, density and viscosity of the gas are 1.0 m/s, 1.2 kg/m³ and 1.8×10^{-5} Pa·s, respectively. The diameter and the shape factors of the packed particles are 50 mm and 1.0 [–]. The voidage in the up-, downstream and LPZ are set at 0.445 [–]. The ranges of the voidage and the area ratio of the HPZ are from 0.445 to 0.99 [–] and 0.01 to 0.5 [–], respectively. The flow resistance of the packed bed is calculated by the Ergun's equation, irrespective of the HPZ voidage.

The gas velocity in the HPZ is calculated by the following manner. As mentioned above, the pressure drops in the HPZ and the LPZ are the same, thus

$$150 \frac{(1 - \varepsilon_{\text{HPZ}})^2 \mu}{\varepsilon_{\text{HPZ}}^2 \phi^2 d_p^2} u_{\text{HPZ}} + 1.75 \frac{(1 - \varepsilon_{\text{HPZ}}) \rho}{\varepsilon_{\text{HPZ}} \phi d_p} u_{\text{HPZ}}^2 = 150 \frac{(1 - \varepsilon_{\text{LPZ}})^2 \mu}{\varepsilon_{\text{LPZ}}^2 \phi^2 d_p^2} u_{\text{LPZ}} + 1.75 \frac{(1 - \varepsilon_{\text{LPZ}}) \rho}{\varepsilon_{\text{LPZ}} \phi d_p} u_{\text{LPZ}}^2 \quad \dots (6)$$

The gas flow rate in the USZ should be same as sum of the HPZ and the LPZ flow rates.

$$\alpha_{\text{HPZ}} \varepsilon_{\text{HPZ}} \rho u_{\text{HPZ}} + (1 - \alpha_{\text{HPZ}}) \varepsilon_{\text{LPZ}} \rho u_{\text{LPZ}} = \varepsilon_{\text{DSZ}} \rho u_{\text{ave}} \quad \dots (7)$$

Simultaneous solution of Eqs. (5) and (6) gives the velocity in the HPZ and LPZ.

Fig. 5. Effects of voidage and ratio of HPZ on pressure drop.

Fig. 6. Effects of voidage and ratio of HPZ on flow ratio in HPZ.

Figure 5 shows the variation of the pressure drop in the test section. As assumed, the HPZ and the LPZ have the same pressure drop. When the HPZ has the same packing structure as the LPZ, the pressure drop is 268.3 Pa/m. Regardless of area ratio, the pressure drop decreases with the increase in the voidage of the HPZ. The higher area ratio shows larger decrease in the pressure drop.

The variations of the gas flow ratio through the HPZ to total gas flow ($\alpha_{\text{HPZ}} \varepsilon_{\text{HPZ}} \rho u_{\text{HPZ}} / \varepsilon_{\text{DSZ}} \rho u_{\text{ave}}$) are shown in Fig. 6. The variations of the superficial velocities in the HPZ and the LPZ are shown in Fig. 7. In the HPZ, both of the gas flow ratio and the superficial velocity increase with the increase in the voidage of the HPZ regardless of the area ratio. Contrarily the flow ratio and the superficial velocity in the LPZ decrease with the increase in the voidage of the HPZ. Under the conditions of the voidage of 0.99 [–] and the area ratio higher than 0.3 [–], more than 90% of total gas flows through the HPZ. For the area ratio of 1% condition, about 20% of gas flows through the HPZ of 0.99 [–] voidage, the ratio of the flow ratio to the area ratio is quite high in this condition. Consequently the gas velocity in the voidage of 0.99 [–] and the area ratio of 0.5 [–] condition is less than twice as the up- and downstream zones, while one under area ratio of 0.01 [–] condition is about 20 times higher than u_{ave} . These suggest that the formation of highly permeable zone in packed bed concentrates gas flow to this region and it causes increase in gas velocity.

(a) HPZ

(b) LPZ

Fig. 7. Effects of voidage and ratio of HPZ on velocities in HPZ and LPZ.

Fig. 8. Effects of voidage and ratio of HPZ on kinetic energy loss at downstream end of HPZ.

Figure 8 shows the kinetic energy loss of the gas flow at the downstream end of the HPZ. The kinetic energy loss is defined by the difference between kinetic energies based on the velocity in the HPZ (u_{HPZ}) and the one in the downstream zone (u_{ave}). Under ideal condition this kinetic energy loss is converted to the pressure increase. The kinetic energy loss increases with increase in the voidage in the HPZ because the gas velocity increases. Under the conditions with larger area ratio, the kinetic energy loss is relatively small because increase in the velocity in the HPZ is fairly small. Contrarily the kinetic energy loss is large in the small area ratio condition. The kinetic energy loss in the condition of 0.01 [-] of the area ratio and 0.99 [-] of the voidage is about 243 Pa, and this value is larger than the pressure drop in the test section in this case, 175 Pa. Although this value is of simplified and ideal condition, it suggests that this mechanism is possibly to form the inverse pressure distribution.

3. Cold Model Experiments and Numerical Analysis on Pressure at Wall of Packed Bed

This study put a hypothesis for the formation of the inverse pressure distribution. In this mechanism, highly permeable zone like void space is first generated in the packed bed. The gas flow concentrates into this space and its velocity increases. This accelerated gas flow is obliged to decelerate at the downstream end of the HPZ due to high flow resistance and dispersion to the packed bed. The kinetic energy loss due to this deceleration is converted to dynamic pressure and forms the inverse pressure distribution. The results of the simplified analysis shown in the previous section showed the possibility to form the inverse pressure distribution by this mechanism. This analysis, however, used the simplified parallel flow paths, and the exchange of gas between the HPZ and the LPZ was neglected. When the highly permeable zone is generated in the packed bed, it is considered that the gas gradually concentrates to this zone and disperses back to the surrounding packed bed. Thus it is considered that the degree of the gas concentration to the HPZ is affected by not only voidage and area ratio but also length of the zone. Additionally the relation between the gas deceleration and the pressure increase is also influenced by this flow pattern. In this section, the hypothesis for the formation of the inverse pressure distribution is confirmed by

Fig. 9. Schematic diagram of experimental apparatus.

the cold model experiments and the numerical flow analysis. Furthermore the formation behavior is examined.

3.1. Experiments

Figure 9 shows the schematic diagram of the experimental apparatus. The packed bed has rectangular parallelepiped shape and its width, depth and height are 120 mm, 60 mm and 460 mm, respectively. The air is uniformly introduced from the bottom of the packed bed through diffuser at constant flow rate and the pressure distribution on the front face of the bed is measured. To represent a formation of void space, a rectangular cage which is made of wire screen of 20 mesh is inserted into the packed bed. The cage is placed as its one side fits to the front wall of the bed. On the front wall of the packed bed, 52 pressure taps (4×13 grid) were settled with 20 mm spacing. Four sets of longitudinally arranged 13 pressure sensors are designated as series 1 to 4 as shown in Fig. 9, and are referred in the following section. Some sensors of series 2 and 3 measure the pressure in the cage while the all sensors of series 1 and 4 measure the pressure in the packed bed. Glass beads of 5 and 1 mm are used as packed particles.

3.2. Analysis of Gas Flow

Three-dimensional flow behavior of the air in the packed bed is numerically analyzed. The fundamental equations are the continuity equation and the equation of motion shown as Eqs. (1) and (2), and the flow resistance of the packed bed is evaluated by the Ergun's equation (Eq. (3)). In the flow analysis, the voidage in the HPZ is set at unity, thus no flow resistance exists in the HPZ. The fundamental equations on

Cartesian coordinate system were discretized by using the control volume method, and the SIMPLER method¹⁰⁾ was employed to combine pressure field and velocity field.

3.3. Results and Discussions

The longitudinal pressure distributions in the packed bed of glass beads of 5 mm (voidage: 0.33 [–]) with 0.58 m/s of the gas superficial velocity are shown in **Fig. 10**. The wire mesh cage of which height is 120 mm is placed at the center of the packed bed and its bottom is located at 160 mm from the bottom of the packed bed. Thus the void space locates from 160 to 280 mm in the figure. Two cages having different cross section size were used. The horizontal cross section of both cages is square, and one has side of 42 mm and the other has 33 mm. In **Fig. 10**, four series of vertical pressure distributions are plotted. The series 2 and 3 are on the vertical line 10 mm from the center line, and 1 and 4 are 30 mm. Therefore the series 2 and 3 vertically crosses the void space and 1 and 4 are in the packed bed.

For the void space of 42 mm square, the regions up to 160 mm and higher than 280 mm clearly show the pressure drop. Contrarily the pressure drop between 160 and 280 mm is quite smaller. This trend is common for the void space (series 2 and 3) and the packed bed (series 1 and 4). As shown in the analysis based on the electric circuit model, once the void space is placed, the gas flow concentrates to the space. As a result the gas velocity in the packed bed region decreases then the pressure drop beside the space also decreases. For the void space, the gas velocity increases but the resistance to the gas flow is only viscous friction on the

surface of the space and quite smaller than the resistance of the packed bed. Thus this flat pressure distribution is formed. In this condition, the pressure difference between the up- and downstream end of the space is about 20 Pa, and the superficial gas velocity in the packed bed can be calculated as 0.14 m/s. This means that about 94% of the gas flow concentrates to the void space having about 25% of area ratio. The difference between the series with and without void space appears near up- and downstream ends of the space. The series including the void space show abrupt change in the pressure gradient at both ends of the space. Contrarily the series without the space show gradual change of the pressure gradient near the ends. For the series 2 and 3, the measurement lines locate close to the center line, and the gas flow direction almost coincides to the measurement line. Additionally, the differences in the gas velocity and the flow resistance between the void space and the packed bed are distinct. Consequently the difference in the pressure gradient appears clearly. In the packed bed region, it is considered that the concentration of gas flow to the void space needs some spatial range to complete. The gas velocity changes gradually in this range, thus the pressure gradient also smoothly changes in this region.

The pressure distributions for the void space of 33 mm square show same trend as the space of 42 mm. At the downstream end of the void space, the pressure of the series 2 and 3 that include the space once increases in the region from 260 to 280 mm, then decreases. This pressure distribution suggests that the inverse pressure distribution forms in this condition. Based on the analyses and the experimental results, it is confirmed that the hypothesized mechanism actually generates the inverse pressure distribution.

The gas flow behaviors under the conditions shown in **Fig. 10** were numerically simulated. The gas flow pattern near the wall and the pressure distribution on the wall are shown in **Figs. 11** and **12**, respectively. In the regions lower than the void space and higher than the space, the gas flows almost uniformly upward. In the height range of the void space, the gas in the void space flow almost vertically

(a) 42 × 42 × 120 mm

(b) 33 × 33 × 120 mm

Fig. 10. Longitudinal pressure distributions.

(a) 42 × 42 × 120 mm

(b) 33 × 33 × 120 mm

Fig. 11. Calculated velocity vectors.

Fig. 12. Calculated and measured pressure distributions on wall.

upward. In the surrounding packed bed region, the gas flows toward the void space in the lower half and disperses from the space in the upper half. The gas flow shows 3-dimensional pattern instead of unidirectional flow assumed in the electric circuit model. With this flow pattern, the gas flow velocity increases in the lower half of the void space and then decreases in the upper half. Comparing the gas velocity in two different spaces, the space of 33 mm shows the higher velocity.

Regarding the pressure distribution on the packed bed wall, the isobars are almost horizontal and spaced same distance in the regions higher and lower than the void space. In the height range of the void space, the isobars are downward convex in the lower half of this region and upward convex in the upper half. The distance between the isobars in this region is wider than that in the higher and lower regions.

Fig. 13. Longitudinal pressure distributions of series #2 with and without small particle layer.

Thus the pressure gradient in the height of the void space is smaller. In the case of the 33 mm void space, a closed isobar appears near the upper end of the void space, and this suggests the formation of the inverse pressure distribution. The calculated pressure distribution well reproduces the measured one. Therefore, these results validate the hypothesized mechanism, in which the void space generated in the packed bed concentrates the gas flow and forms the inverse pressure distribution.

In the mechanism proposed in this study, the inverse pressure distribution becomes more obvious when the concentration degree of the gas flow increases. To enhance the attraction of the gas flow to the void space, the packed structure in the surrounding packed bed was modified to increase the flow resistance. In this experiment, the glass beads of 1 mm in diameter were packed in the region surrounding the void space. The glass beads of 5 mm that was same as the previous experiments were packed from the bottom up to 200 mm, and from 260 mm to the top of the bed, and small glass beads were packed from 200 to 260 mm in height. The cage of 25 mm in width, 12 mm in depth and 100 mm in height was placed in the packed bed. The bottom of the cage locates at 180 mm. In this arrangement, the void space pierces through the low permeable layer. The vertical pressure distribution measured in this packing structure is shown in Fig. 13 with comparison to one with only 5 mm packed bed. In this figure, pressure distributions of series 2 are shown. Under the 5 mm diameter condition, the pressures at 260 and 280 mm are 760 and 770 Pa, and the inverse pressure distribution is formed around downstream end of the void space. The pressures at the same points under the condition with 1 mm particles are 830 and 930 Pa. The pressure difference in this condition is larger and the pressure inversion becomes more obvious. It is considered due to the enhanced gas flow concentration brought by the packing structure, and this result also supports the mechanism to form the inverse pressure distribution.

As shown in the Fig. 11, the gas flow gradually changes around the up- and downstream ends of the void space. Thus it is considered that the shape of the void space effects on the formation behavior of the inverse pressure distribution. In this part, the effects of the void space shape were numerically examined by 3-dimensional flow analysis. The analyses were performed under similar conditions to the

Fig. 14. Effect of cross sectional area on velocity and pressure distributions.

Fig. 15. Effect of length on velocity and pressure distributions.

blast furnace. The diameter and the shape factor of the packed particle are 35 mm and 0.75 [–], respectively, and the voidage is 0.498 [–]. The shape of the packed bed is rectangular parallelepiped, and its height, width and depth are 4.0, 1.0 and 1.0 m, respectively. The density and the viscosity of the gas were constant and 1.2 kg/m^3 and $1.8 \times 10^{-5} \text{ Pa s}$. The gas is uniformly introduced from the bottom of the packed bed at superficial velocity of 1.0 m/s. The void space of which horizontal cross section is square was put at the center of a vertical wall to touch the bed wall. The height of the void space and the size of the horizontal cross section were changed.

The variations of the vertical distributions of the superficial velocity and the pressure with the size of the vertical cross section are shown in Fig. 14. In this analysis, the height of the void space was kept constant at 1.0 m. The effects of the height of the void space on the distributions of the superficial velocity and the pressure are shown in Fig. 15. For this analysis the cross section of the void space was kept constant at 0.3 m in its sides. In these figures, the superficial velocity is averaged over the cross section of the void space. In all condition, the superficial gas velocity in the void space gradually increases up to the middle part of the space that is a little downstream side from the center. Then the velocity decreases toward the downstream end, and its decreasing gradient is steeper than that of increase in the upstream side. Under the condition with constant height of the void space at 1.0 m, the gas velocity in the space increases with the decrease in the cross section size. Consequently the inverse pressure distribution around the downstream end of the space becomes more obvious. Under the smaller cross section conditions, the increase in the gas velocity can be brought by the smaller amount of the gas inflow to the void space. This tendency agrees with the results of the analysis by the electric circuit model. For the constant size of the cross section, the affecting area of the void space in the packed bed increases, and more gas tends to concentrate to the void space. This increases the gas flow velocity in the space, thus the inverse pressure distribution becomes more obvious. These results suggest that the longitudinally longer and perpendicularly smaller void space tends to form more obvious inverse pressure distribution.

4. Conclusions

This study discussed the relation between the inverse pressure distribution that is formed on the wall and the packed bed structure. This paper proposed a simple formation mechanism by the generation of the void space in the packed. In this mechanism, the void space generated in the packed bed concentrates the gas flow within it, and the gas flow velocity in the space increases. This gas flow decelerates at the downstream end the space, and the kinetic energy loss is converted to the pressure increase. When this pressure increase is superior to the pressure drop in the packed bed the inverse pressure distribution is formed. This formation mechanism of the inverse pressure distribution was validated through the experiments and the numerical flow analyses. With this mechanism, the faster gas velocity in the space, in other words the stronger concentration of the gas flow to the space, makes the inverse pressure distribu-

tion more obvious. Regarding the shape of the void space, longitudinally longer and perpendicularly narrower void space tends to form the inverse pressure distribution more easily and obviously, because the gas velocity increases easily in such void space. Furthermore, with the packing structure that the void space is surrounded by the low permeable packed bed, for example the vacant space pierces the cohesive layer, the inverse pressure distribution forms more obviously because the gas flow intensively concentrates to the void space.

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Nomenclature

C_D : Drag coefficient [–]
 d_p : Particle diameter [m]
 F : Drag force [N m^{-3}]
 g : Gravitational acceleration [m s^{-2}]
 p : Pressure [Pa]
 u : Velocity [m s^{-1}]

Greek symbols

ε : Voidage [–]

ϕ : Shape factor [–]
 μ : Viscosity [Pa s]
 ρ : Density [kg m^{-3}]
 τ : Stress [Pa]

Subscript

ave: Average
 HPZ: Highly permeable zone
 LPZ: Low permeable zone
 DSZ: Downstream zone
 USZ: Upstream zone

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