Quantitative Evaluation for Relationship between Development of Pore Structure and Swelling of Coal in Carbonization of Single Coal Particle

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(Received on December 11, 2012; accepted on May 28, 2013)

The objective of this paper are to study the formation process of coke pore structure in relation to the swelling of coke during the thermoplastic stage and the pore structure at the initial carbonization. The swelling ratios were measured, and the cross-sectional images of coal particles at different heating temperatures were observed with an optical microscope. Before carbonization, all pores in both coals were a diameter of less than 100 μm. When the temperature increased up to the level at which the swelling started, the pores with greater than 100 μm-diameters were formed, and they had also simultaneously coalesced. However, each coal had a different temperature for starting swelling and observing the generation and coalescence of pores with a diameter of more than 100 μm. At this point, the formation of pores were expressed with Laplace equations. The results showed the volatile matter inflow affected the change of pore structure. Furthermore, the pore structures within coal particles before and after carbonization were compared by micro-X-ray Computed Tomography. Carbonization up to the temperature for the softening stage increased pore diameters, which provided evidence that the proportion of pores existing within post-carbonized coal had grown based on the pores already existing in pre-carbonized coal.

KEY WORDS: coal particle; thermoplastic stage; pore structure; swelling ratio.

1. Introduction

In the blast furnace method, coke plays an important role as a spacer that secures permeability and drainage.1,2) Coke needs strength that can endure mechanical loads when coke descends into the blast furnace.

Coke is produced by heating a packed bed of coal particles with a diameter of less than 3 mm. During carbonization, coal reaches a thermoplastic stage. This process releases a large amount of volatile matter, forming pores in coal particles. The volatile matter inflows into pores and increases the size of pores, leading to swelling of coal particles.3) Swollen particles become cohesive and solid to form a lump coke. The produced coke is a porous solid with a porosity of around 50%, and it is thought that the coke strength is influenced by the pore structure of the coke.4)

Previous researches have mainly focused on the effect of the microscopic structure after carbonization on coke strength for producing high strength coke. Matrix (pore) geometric structure may affect coke strength because coke is a porous solid.5,6) Arima et al.7) suggested that the produced coke strength decreased by complex shaped and connected pores. Ueoka et al.4,8) numerically indicated the stress concentration occurred not around a round pore but around a complicated pore and the coke strength decreased. Kubota et al.9) and Kanai et al.10) suggested that pores whose roundness and diameter were less than 0.2 and more than 1 mm mainly decreased the strength. In addition, for swelling behavior of coal which affects coke making, Arima et al.7) have shown that the degree of swelling of coal results difference in coke strength and it is caused by adhesion between coal particles. Though the produced coke is discussed among these studies, the formation process of pore structure and swelling behavior of coal particle are not well investigated.

In order to reveal the formation process of coke, it is needed to list and quantify the factors which affect pore growth behavior and particle swelling in thermoplastic phase. The researchers have, then, studied the effect of coke microscopic structure on coke strength and the clarification of pore growth behavior and particle swelling. Hays et al.11)
clarified that open pores were formed by the appearance of pores and coalescence of these pores. Past research shown by Hays et al. was obtained in order to figure out pore structure in a lump coke formed by the adhesion of coal particles. The pore structure is directly affected by the formation of pore structure and particle growth before forming a coke lump. For understanding the formation mechanism of pore structure and particle swelling of coal particles in the lump coke, a coal particle as a standard unit must be focused.

The phenomenon around a single particle during carbonization is pore growth and swelling. Oh et al. conducted a numerical analysis considering the rate of pore growth with volatile matter and the yield released out of the coal particle. The simulation replicated yield of volatile matter. However, it was not able to represent the connection between pore growth in the coal particle and swelling behavior. Takizawa et al. measured the swelling ratio of a single coal particle which swelled freely by pore growth, but the pore structure in coal particles has not been experimentally investigated. They constructed a coupled model of pore growth and coal particle swelling considering the rate of pore growth using coal pyrolysis model and Laplace equation. However, because the model did not consider the mechanical interaction of each pore, pore shape and viscoelasticity behavior of coke matrix in thermoplastic phase, the swelling behavior of carbonization of coal could not be simulated. The additional discussion is required for clarifying the swelling process with the change of pore structure.

To reveal pore growth behavior of coal particle, it is needed to clear up the initial stage of pore growth during thermoplastic phase. Oh et al. and Takizawa et al. considered pore generation by homogeneous nucleation and built in the equation of nucleation rate, while it is suggested that the pores in coal particle grow because pores already exists in coal particles before carbonization. Oh et al. also refer to pore growth from the existing pores before carbonization. However, meaning of these two theories uniformly and theoretically has not been verified, and the pore growth behavior has not been chased. Thus, a unified view on the origin of the pores has not been obtained.

In this context, we examined (1) how a single coal particle swelled with pore growth, and (2) original pores in the coal grew by heating. For (1), the swelling ratio and changing of pore structure in single particles of different two kinds of caking coal were investigated by image analyses. Moreover, the difference of pore growth behavior was analyzed using Laplace equation. For (2), focusing the pore growth of the proportion of pores originally existing within post-carbonized coal, micro focus X-ray computed tomography was used to observe the pore growth in the particle before and after carbonization.

2. Experimental Methods
2.1. Materials
Table 1 shows characteristics of coal particles used in this experiment. Coal A and Coal B, caking coals with a particle diameter of 2 mm, were used as materials.

2.2. Experiment in Carbonizing Single Particles of Coal (RHL-P610 produced by ULVAC-RIKO)
Figure 1 shows a schematic diagram of the experimental apparatus. Coal particles were heated in a nitrogen atmosphere in an ULVAC-RIKO infrared gold image furnace (RHL-P610). They were placed on a quartz table, and heated with graphite particle to control temperature. This is because the infrared emissivity of graphite is almost the same as that of coal. The graphite particle was in a 2-millimeter cube, whose size was the same as that for the coal particles. An R-type thermocouple was connected to the graphite particles, whose contact point was set at the center of the graphite particle sample. The heating profile is shown in Fig. 2. After reaching a preset carbonizing temperature, heating was stopped and a nitrogen inflow rapidly increased to quench the samples.

2.2.1. Measurement of Swelling Ratio
Table 2 shows the experimental conditions. In the range of 110–700°C, the coal particles were photographed at 10°C increments using a digital camera. The projected area of samples in the image was measured with image analysis software (WinROOF Ver. 6.1.0) and its swelling ratio was

<table>
<thead>
<tr>
<th>Table 1. Characterization Data for the Coals Used.</th>
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<tbody>
<tr>
<td>Coal A</td>
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<tr>
<td>Proximate analysis</td>
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<tr>
<td>Volatile matter [mass% db]</td>
</tr>
<tr>
<td>Ash [mass% db]</td>
</tr>
<tr>
<td>Fixed carbon [mass% db]</td>
</tr>
<tr>
<td>Gieseler plastometry</td>
</tr>
<tr>
<td>Softening temp. [°C]</td>
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<tr>
<td>Max. fluidity temp. [°C]</td>
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<td>Resolidification temp. [°C]</td>
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Fig. 1. Schematic Diagram of Experimental Apparatus.

Fig. 2. Heating Profile.
to gain pore area ratio distribution for every 100 μm-pore diameter. The number of pores in the image was also measured to get pore number distribution for every 100 μm-pore diameter. Furthermore, Sauter mean diameter $D_{32}$ and pore volume in the particle sample were found by:

$$
\epsilon [-] = \frac{\text{(Total area of pore)} [\mu m^2]}{\text{(Total area of images)} [\mu m^2]} \quad \text{(3)}
$$

$$
V [mm^3] = 4\pi \sqrt{\frac{\text{(Area of the sample during carbonization)} [mm^2]}{4\pi}} \quad \text{4} \frac{3}{4}
$$

$$
V_{pore} [mm^3] = \epsilon V \quad \text{(5)}
$$

to generate a graph showing the relationship between mean pore diameter and pore volume depending on temperatures.

2.2.3. Pore Growth Behavior Calculated Using Laplace Equations

In order to address differences in swelling behavior and pore structure for each coal, a Laplace equation that considered viscosity and the inflow of volatile matter for each sample was used to examine the changes in pore diameter.

Pore radius during carbonization of the coal was obtained using:

$$
R_i = R_{i-1} + \frac{dR_{i-1}}{dt} \Delta t. \quad \text{(6)}
$$

The Laplace equation,

$$
\frac{dR_{i-1}}{dt} = \frac{R_{i-1}}{4\mu_{i-1}} \left( P_{b,i-1} - P - \frac{2\gamma}{R_{i-1}} \right) \quad \text{(7)}
$$

was used to obtain the speed of increase in pore radius. It was assumed that pores are surrounded by a mean matrix and the speed of increase in pore radius would not be influenced by surrounding pores. Matrix viscosity was calculated using:

$$
\mu = \begin{cases}
10^{-11} \times \exp \left( \frac{45000}{RT_{i-1}} \right) \\
(1-\phi_{i-1}) \frac{1}{3} \times 1.0
\end{cases}
\quad \text{(8)}
$$

The weight fraction $\phi$ of the metaplast in Eq. (8) was calculated using extraction yield after CS$_2$-NMP solvent extraction of Coal A obtained by Takanohashi et al. The extraction yield was used as the weight fraction of the metaplast.

The weight fraction on the metaplast was approximated by

$$
\phi_{i-1} = \begin{cases}
-9.0 \times 10^{-8} T_{i-1}^3 + 1.0 \times 10^{-4} T_{i-1} + 0.42 \\
(\text{Coal A, } T_{i-1} < 378 [^\circ C])
\end{cases}
$$

$$
3.9 \times 10^{-7} T_{i-1}^3 - 5.5 \times 10^{-4} T_{i-1}^2 + 0.26 T_{i-1} - 38 \\
(\text{Coal A, } T_{i-1} \geq 378 [^\circ C])
\quad \text{(9)}
$$

Inner pressure was calculated using:

$$
P_{b,i-1} = \frac{nRT_{i-1}}{4\pi R_{i-1}^3}, \quad \text{(10)}
$$

and the mole number of the volatile matter within pores during carbonization was calculated using:

$$
n_{i-1} = n_{i-2} + k_\phi \frac{1.0 \times 10^{-10}}{\sqrt{2\pi \sigma}} \times \exp \left( \frac{(T_{i-2} - \alpha)^2}{2\sigma^2} \right) \quad \text{(11)}
$$

as the sum of inflow of volatile matter into the pores. It was
assumed that the changing molarity of volatile matter inflow was generally expressed in a normal distribution.

First, by using the values of maximum fluidity and volatile matter of each coal shown in Table 1, the pore growth of Coal A and Coal B was calculated. The pore growth of Coal B was found by correcting the four points below based on the equation for viscosity and inflow of volatile matter for Coal A. Table 3 shows numerical conditions that were used to get coefficients \( k_\mu \) and \( k_n \) for correction.

(i) \( k_\mu \) represents the correction coefficient of viscosity, which was 1.0 for Coal A. \( k_\mu \) for Coal B was calculated using:

\[
k_\mu = \left( \frac{\text{Min. viscosity}_{\text{Coal A}}}{\text{Min. viscosity}_{\text{Coal B}}} \right) 
\]

with viscosity that was calculated from maximum fluidity found in studies by Nomura et al.

(ii) \( k_n \) represents the correction coefficient of the inflow of volatile matter, which was 1.0 for Coal A. \( k_n \) for Coal B was calculated using:

\[
k_n = \left( \frac{\text{Volatile matter}_{\text{Coal A}}}{\text{Volatile matter}_{\text{Coal B}}} \right) 
\]

with the ratio between volatile matters in each coal.

(iii) Extraction ratio \( \phi \) was calculated using:

\[
\phi_{i+1} = \begin{cases} 
-9.0 \times 10^{-8} (T_{i+4} - 49)^2 + 1.0 \times 10^{-4} (T_{i+4} - 49) + 0.42 & (\text{Coal B, } T_{i+4} < 427 \degree C) \\
3.9 \times 10^{-7} (T_{i+4} - 49)^3 - 5.5 \times 10^{-4} (T_{i+4} - 49)^2 + 0.26 (T_{i+4} - 49) - 38 & (\text{Coal B, } T_{i+4} \geq 427 \degree C) 
\end{cases}
\]

considering differences of softening temperatures between Coal A and Coal B.

(iv) The means of each of the two normal distributions in Eq. (11) used data measured by TG weight analysis of Coal A and Coal B shown in Fig. 3, with respective inflection temperatures of 465\degree C and 500\degree C.

Furthermore, the order of inflow mole number of viscosity and volatile matter were changed to compare pore growth behavior with Coal A. Here \( k_\mu \) was set at 10 and \( k_n \) was set as 0.1 and 10.

2.3. Microfocus X-Ray CT (TOSCANER-32250μhd)

Microfocus X-ray CT (TOSCANER-32250μhd) was used to observe the pore structure of coal samples, mentioned in section 2.1., before and after carbonization with a non-destructive technique. For visualization, the X-ray tube voltage and the tube current were set at 70 kV and 250 μA respectively.

An optical microscope equipped with a heating stage was used to heat samples. A coal sample on heating stage was heated up to 450\degree C from the bottom of the sample at a rate of temperature increase of 10\degree C/min, and the sample was quenched at the temperature.

By using the images (resolving power of 3.70 μm/pixel) obtained with microfocus X-ray CT, the same pores in cross-sectional images were compared before and after heating to trace pore growth. The area of pores before and after heating was calculated with the image analysis software (WinROOF Ver. 6.1.0).

3. Results and Discussion

3.1. Swelling Behavior and Changes in Pore Structure at the Thermoplastic Stage

3.1.1. Changes of Swelling Ratio

Figure 4 shows the change of swelling ratio for Coal A and B as a function of temperature. Table 3. Numerical Conditions for Laplace Equations.

<table>
<thead>
<tr>
<th></th>
<th>Coal A</th>
<th>Coal B</th>
</tr>
</thead>
<tbody>
<tr>
<td>log(Max. fluidity/ddpm) [-]</td>
<td>3.1</td>
<td>1.49</td>
</tr>
<tr>
<td>Min. viscosity [Pa s]</td>
<td>43,976.0</td>
<td>164,467.6</td>
</tr>
<tr>
<td>Volatile matter [mass% db]</td>
<td>24.6</td>
<td>17.9</td>
</tr>
</tbody>
</table>

Fig. 3. TG Weight Loss Curve of the Coals Used.

Fig. 4. Swelling Behavior Depending on Temperature.
and Coal B. Both Coals showed rapid swelling when the temperature reached a certain level and contracted to some extent after the temperature at which swelling stopped. When coal is heated, some of the bonds in the molecular structure of the matrix are broken and volatile matter of low molecular weight is released. Then, when coal particles are resolidified, broken bond parts are combined to develop the molecular structure of matrix, causing some contraction of coal particles.

In observing each coal, the particles of Coal A rapidly swelled at around 410°C and the swelling ratio reached its highest of 1.8 at around 460°C, while the Coal B particles swelled around 450°C and the swelling ratio peaked at 1.3 around 550°C. This shows the Coal B particles have more difficulty swelling than those of Coal A.

In order to examine increasing rate of swelling ratio for each coal, the swelling ratio in the range from the temperature of first swelling to that at the maximum swelling ratio was linearly approximated. The mean increase rate of swelling ratio was 0.02°C⁻¹ for Coal A and 0.006°C⁻¹ for Coal B. This shows the particles of Coal B had a slower swelling rate compared with the rate of Coal A.

3.1.2. Changes in Pore Area Ratio

Figures 5 and 6 show pore area ratio distribution for every 100 μm of pore diameter of Coal A and Coal B. In the case of Coal A, the diameters of all pores were less than 100 μm below 350°C, but at 400°C, pores with diameters greater than 100 μm were observed. The diameters of all pores of Coal B were less than 100 μm below 400°C, and pores with a diameter of more than 100 μm were observed at 450°C. These results showed the pore diameters in coal particles rapidly increased at temperatures around the threshold of first swelling. In terms of coal type, the pore diameters of Coal B changed at a higher temperature than was the case with Coal A.

Furthermore, in focusing on large pore area ratios with pore diameters greater than 1000 μm at temperatures around the peak swelling ratio in each coal, the pore area ratio of Coal A was higher than that of Coal B, leading to the assumption that the pores of Coal A are likely to grow to a bigger size compared with those of Coal B.

3.1.3. Observing Coalescence of Pores

Figures 7 and 8 show microscope images at carbonizing temperatures for Coal A and Coal B respectively. It was found, in both samples, nearly circular pores existed separately when carbonization started and the pores coalesced above 400°C and 450°C respectively. The temperature at which initial coalescence occurs was the same as that in which pores with diameters of more than 100 μm were observed. Over this temperature most part of the coal sample became pores, and pores took up most part of cross-sectional images.

This leads to the conclusion that rapid growth of pore diameter at the temperatures around the threshold of initial swelling of coal particles can be attributed not only to growth of individual pores but also to coalescence of pores. It is assumed that coalescence of pores causes rapid increase in pore diameter and pore surface area of individual pores, leading to less influence of interfacial tension that prevents pore growth.

3.1.4. Changes in Pore Number

Figures 9 and 10 show pore number distribution for every 100 μm-pore diameter of Coal A and Coal B respec-
Irrespective of the coal, almost all pores were small ones with a diameter of less than 100 μm. In focusing on pores with a diameter from 0 to 100 μm, Coal A had a constant number of pores at 350°C and 400°C and after that the number decreased. Coal B had the largest number of pores with a diameter from 0 to 100 μm at 400°C and after 450°C the number decreased.

In both coals, the number of small pores with a diameter from 0 to 100 μm increased before carbonization to the point of the first coalescence of pores, and after the temperature when coalescence of pores was observed, the pore number decreased. It is assumed that the changes in pore
number can be attributed to the following influencing factors increasing or decreasing pore numbers.
- Factors increasing the pore number: production of pores and micropore growth which were not observed by microscope before carbonization
- Factors decreasing the pore number: Coalescence of pores

It can be concluded that the decrease of pore number in the proximity of temperatures when pores started coalescing was due to less effect in increasing the pore number, leading to more coalescence of pores.

By extracting data from Figs. 9 and 10, Fig. 11 shows a comparison of the number of pores of 0–100 μm-diameter before carbonization, during carbonization when pores started coalescing, and after resolidification, for both Coal A and Coal B. At either temperature, the pore number of Coal B was less than that of Coal A.

From these results, it was determined that Coal B has a smaller diameter of individual pores and a greater number of small pores than Coal A.

3.1.5. Relationship between Pore Growth and Pore Swelling

Figure 12 shows the Sauter mean diameter $D_{32}$ and the pore volume of Coal A and Coal B depending on carbonization temperatures. It is clear that in both samples $D_{32}$ and pore volume did not change at the beginning of carbonization, but rapidly increased after the threshold of a distinct temperature for each coal, then stopped changing. The temperatures at which $D_{32}$ of Coal A and Coal B rapidly became larger were 350°C and 400°C respectively, and the temperatures at which pore volume of Coal A and Coal B rapidly became larger were 400°C and 450°C respectively. The pore volume at the temperature when coal particles started swelling accounted for 3.5 to 19.5% of pore volume after resolidification. These results show that the particle volume did
not show much change at the temperature when the pore diameter started increasing, and the particle volume rapidly changed due to the effect of pore growth at the temperature of initial swelling. The temperatures at which the diameter stopped changing were 450°C and 500°C and $D_{32}$ at the temperatures were 1 100 μm and 700 μm respectively.

From the above results, the following conclusions can be derived as behaviors irrespective of coal type.

(i) Carbonization leads to gradual increase of pore number in a coal particle sample, and pores start to grow.

(ii) At the temperature over 50°C from (i), rapid increase of pore diameter leads to coalescence of pores. Mean diameter increases to several hundred-thousand μm, and a rapid increase of pore volume at this temperature results in particle swelling.

(iii) The end of pore growth stops the swelling of the particle.

Furthermore, it was indicated that the controlling factor in swelling coal particles was rapid pore growth in the particles at stage (ii). On the other hand, it was shown that the temperature when the coalescence of pores started, large pore area ratio, and mean pore diameter after resolidification all varied depending on coal type.

### 3.2. Factors Influencing Pore Diameter

As the controlling factor of swelling coal particles is pore growth, Laplace equation is used to examine factors influencing the changes in pore diameter. This section focuses particularly on viscosity and the inflow of volatile matter and discusses how these factors influence pore growth.

Firstly, in order to confirm that viscosity and the inflow of volatile matter are factors influencing pore growth, the Laplace Eqs. (7) and (8)-(14) that calculate viscosity and the inflow of volatile matter were used to calculate the changes in pore diameter $d = 2R$ of Coal A and B. Figure 13 shows the changes in pore diameter $d$ for Coal A and B. Coal A has a lower temperature for starting growth of pores and a bigger final diameter than Coal B. As the calculated results showed a trend similar to that of the test results, this calculation enabled pore growth behavior to be recreated qualitatively. Therefore, it seems appropriate to conclude that viscosity and the inflow of volatile matter are factors influencing pore growth.

At this point, the order of viscosity and volatile matter inflow was changed to examine how these factors influence pore growth. Figure 14 shows the changes in the viscosity dependence of pore diameter $d$ and also the pore diameter $d$ of Coal A. The calculations using Eqs. (6)-(14) show that differences of viscosity have little effect on pore growth. Figure 15 shows the changes in the volatile matter dependence of pore diameter $d$ and also the pore diameter $d$ of Coal A. It was shown that different inflow of volatile matter caused bigger differences in the final pore diameter. Therefore, when Eqs. (6)-(14) were used to increase pore diameter, it was shown that the mole number of volatile matter inflow has a great influence on final pore diameter. These results lead to the conclusion that the transfer phenomenon of volatile matter in the particle sample would control swelling behavior and pore diameter.

In this calculation, viscosity had little effect on the pore growth; however, it can be considered that viscosity imposes great effects on pore growth in practice. In addition, in this study, Eqs. (6)-(14) were used for calculations to consider the effects of viscosity and volatile matter inflow, but there was no quantitative agreement with the experimental results. This may be because the concentration gradient of volatile matter around the pores, the existing ratio of open pores, the release of volatile matter from open pores, and the change of solubility of volatile matter in the matrix were not taken into consideration concerning the movement phenomena of volatile matter in the particle sample that are likely to impose effects particularly on pore growth. Furthermore, this analysis presumes a condition in which each individual pore is surrounded by a mean matrix. However, in a real coal particle sample, the matrix surrounding an individual pore does not match the mean and several pores are adjacent and influencing each other, which results in differences.
between the experimental results and the analysis, so it is thought that the difference in viscosity influences the likelihood of pore coalescence and growth.

3.3 Examination at the Initial Stage (X-ray CT Scanning)

Figures 16 and 17 show 3D stacking images and cross-sectional images of Coal A particles before and after carbonization. The pores in cross-sectional images are both almost the same before and after carbonization. Focusing on the pore circled in the image, we can see that the pore diameter and pore area were 7.2 μm and 40.8 μm² before carbonization. However, these results grew to 40.8 μm and 1306.8 μm² after carbonization. This shows the pores existing in the particle sample grew due to carbonization. By pursuing the pore, a situation in which the proportion of the pores existing in the particle sample after carbonization had grown based on the pores existing in the coal before carbonization is visualized.

4. Conclusion

To examine the mechanisms of how pore structure develops during carbonization of coal, (1) how much a coal particle swelled because of pore growth and (2) whether pores originally existing in the coal grew by heating single coal particle were revealed.

(1)-1 The following behaviors were identified during carbonization of the coals.

(i) Pore number in a coal particle gradually increased and pores started to grow because of carbonization.

(ii) At the temperature over 50°C from (i), rapid increase of pore diameter led to coalescence of pores. Mean diameter increased to around thousand μm, and rapid increase of pore volume at this temperature resulted in particle swelling.
Moreover, it was observed that the factor controlling swelling of a particle is the rapid change in pore structure in the particle sample, as shown in (ii).

(1)-2 It was shown that the temperature of initial coalescence of pores, large-pore area ratio, and mean pore diameter after resolidification were different in each coal. Qualitative examination of the factor controlling changes in the pore structure led to the conclusion that volatile matter inflow imposes a great effect on pore structure change.

(2) It was indicated that the part of the pores existing in the coal after carbonization originated in the growth of pores existing in the coal before carbonization.

The above findings ensured that if a numerical model that predicts the process of the formation of pore structure more correctly is developed in the future, the most appropriate pore structure for coke with the highest strength and the necessary production guidelines can be obtained.

Nomenclatures

- $a$: Mean of normal distribution [K]
- $k_w$: Correction coefficient of the inflow of volatile matter [–]
- $k_μ$: Correction coefficient of viscosity [–]
- $n_i$: Mole number of the volatile matter [mol]
- $P$: Surrounding pressure (=1 atm) [Pa]
- $P_{bi}$: Inner pressure of pore [Pa]
- $R$: Gas constant (=8.31) [m² kg/s²/K/mol]
- $R_i$: Pore radius [m]
- $T_i$: Particle temperature [K]
- $t$: Time [s]

$Δt$: Time step [s]
$V$: Particle volume [mm³]
$v_{pore}$: Pore volume in the particle [mm³]
$ε$: Pore area ratio in images [–]
$φ$: Weight fraction [wt. % daf]
$γ$: Surface tension (=0.3) [N/m]
$μ$: Matrix viscosity [Pa s]
$σ$: Standard deviation [K]

REFERENCES