Original Article

Effect of coke rate and basicity on computed tomography-measured pore parameters and effective thermal conductivity of iron ore sinter

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During iron ore sintering structural transformation occurs as liquid melt is formed in flame front. This study aimed to compare differences in X-ray computed tomography (XCT) measured pore parameters, and examine relationships between pore parameters and sinter effective thermal conductivity based on actual structure. Nine sinter samples (three coke rates multiply three basicity levels) were carefully prepared from pilot-scale sinter pot tests and scanned by XCT with the resolution ratio of 40 μm. The results demonstrate that higher coke rate and basicity promote melt formation during sintering, transforming sinter from particulate structure to melt-bonded structure. Under the tested conditions, sinter porosity is in the range of 36.3% ~56.3% and its effective thermal conductivity decreases from 1.276 W/mK to 0.597 W/mK correspondingly. The anisotropic porous structure of sinter leads to different heat conduction and complicated temperature field in three spatial directions. Of all the XCT-measured pore parameters, porosity and number of +1 mm pores generally decrease with the increasing basicity at the same coke rate. The sinter effective thermal conductivity could be negatively correlated to porosity and number of +1 mm pores while there are no clear correlations with parameters including mean pore area and area of the largest pore. The statistic analysis confirms that pores in sinter could be divided into different groups to distinguish their behavior. The pores larger than 1 mm, namely macropores, contribute more than 90% to the total pore volume and set up the main orientation of pore network, determining the sinter thermal behavior predominantly.

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1. Introduction

In most integrated steel mills, the importance of iron ore sinter cannot be overemphasized, not only as lumpy feed for ironmaking, but also as a major component of many
related processes such as reaction front propagation in sinter machine [1–3], waste heat utilization in sinter coolers [4–6] and heat transfer in blast furnaces [7,8]. Comprehensive cognition of the thermophysical characteristics of sinter is strongly required for achieving optimal process performance. Iron ore sinter generally has complex porous structures which consist of irregular solid-matrix, interparticle voids and intraparticle pores [9,10]. Both the pore properties and the thermal conductivity of sinter have received much attention recently in parallel with advanced development of measurement and simulation technologies [11–13].

Optical microscopy was traditionally applied to quantify the pore properties in the sinter samples, however, this technique only characterizes the cross section of the sample and can not provide enough information on the connections between pores [14]. In this respect, X-ray computed tomography, as a non-destructive technique, has the advantages of being able to observe the shape and connections of pores in three-dimensions. Japanese researchers first applied X-ray CT to the sintering process in 1990s, focusing on the evaluation of gas channels and its effects on the sinter metallurgy quality [15] and sinter bed permeability [16–19]. As the large samples were used in these work, the resolution ratio was limited to ~0.25 mm therefore some fine pores could not be resolved. In a recent work by Shatokha et al. [11], they investigated the effects of basicity and concentration ratio on the sinter porosity using high resolution scans with sample size of 9–25 mm and voxel size of 20 µm.

On account of the importance of sinter thermal conductivity, methods including the experimental measurement and numerical modeling have been subjected to a considerable amount of prior research. Specific to the experimental measurement, Akiyama et al. [20] prepared disk samples with the diameter of 1 cm and thickness of 1–1.5 mm, then applied laser flash technique to measure the thermal conductivities of reduced sinter and pure iron oxides. Sundarmutri et al. [21,22] adopted the hot wire method to determine the thermal conductivities of iron ore pellets, temperatures at centre and surface of the heated 10–16 mm pellet were recorded and hence the radial heat balance problem could be solved. Tian et al. [12] mixed the ball-milled powder of sinter (below 75 µm) into water with different concentrations, then measured the sinter effective thermal conductivity using transient plane source method. As for the numerical modelling approaches, Nishio et al. [14] obtained the microstructure image of sinter and performed 2-dimensional heat transfer simulation in a region of 300 µm × 273 µm to estimate the sinter effective thermal diffusivity. Aizawa et al. [23] proposed a new meso-porous unit-cell model for predicting sinter thermal conductivity, which is a combination of phase field method with finite element method. Some analytical models such as fractal model [12] were also found to be able to get acceptable predicted values when compared with experimental results. Zhou et al. [13] introduced and validated the XCT-simulation approach to estimate sinter thermal conductivity, they found that the sinter porosity decreases and the thermal conductivity increases with the increasing granulation moisture. Among the above mentioned methods, XCT-simulation is a promising approach for understanding the relationship between the thermal properties and pore properties since it captures the real geometric details such as the pore shapes, orientations and connections [24].

The porous sinter is produced by moving grate combustion, which proceeds as a carefully prepared packed bed subjected to a partial melting process in high temperature. The first stage is the cold bed preparation. Several kinds of raw materials are granulated and then charged onto the grate, including iron ores, fluxes, fuel and return fines [25,26]. The second stage, the so-called hot bed transformation, involves the establishment of an ignition front on the top of the layer followed by the travel of the flame front along the bed, causing the granules to react and form melt [1–3,27]. As a result, the intrinsic random cold bed structure undergoes a continuously transformation within the flame front, further adding complexity and heterogeneity to the porous structure of final sinter product. Some factors, such as moisture [13] and hydrated lime level [28] in the cold bed preparation stage have been investigated, but assessment of the sinter porous structure and its influence on effective thermal conductivity requires further studies not only of the preparation of the initial green bed structure [13,28], but also the melt formation during the hot transformation stage. Moreover, the effect of detailed pore parameters including pore number, mean pore area, and area of the largest pore on the sinter thermal conductivity had not been examined adequately.

This paper explores the effect of melt formation factors, namely coke rate and basicity, on the sinter pore properties using X-ray computed tomography at a high resolution of 40 µm. In particular, the effective thermal conductivity was estimated based on the reconstructed actual porous structure and the relationship between the key pore parameters and thermal conductivity values was elucidated.

## 2. Methodology

### 2.1. Sample preparation

The sinter samples used in the investigation were obtained by pilot-scale sinter pot tests. Fig.1 shows the layout for the sinter pot system schematically. The diameter and height of the pot are 300 mm and 600 mm, respectively. The ore blend composition, sintering conditions and tested cases are listed in Table 1. Total nine sinter pot tests, corresponding to three levels of coke rate (4.05%, 4.50%, 5.00%) and three levels of basicity (CaO/SiO$_2$ = 1.5, 1.9, 2.5), were operated according to standard procedures [29]. It needs to be mentioned that a chemistry of sintering operations (TFe ~56.5%, CaO ~9.50%, SiO$_2$ 5.0%, basicity 1.90, Al$_2$O$_3$ ~1.80%, MgO ~1.70%, return fines ratio 20%, fuel rate 4.05%) represents a typical blend widely used in Asia–Pacific region and reaches return fine balance, to pay more attention to this condition, coke rate of 4.05% was tested instead of 4.00% and basicity of 1.9 was tested instead of 2.0. The weighted raw materials were mixed with 6.5 wt.% of moisture using a two-stage granulating machine, after which around 90 kg granules were charged into the pot. Then the top surface of the packed bed was ignited for 90s with a natural gas burner. Ambient air was forced to flow through the bed with a negative pressure of 6 kPa during ignition and 16 kPa during sintering. As the flame front forms and propagates
downwards, complex physical and chemical reactions occur transforming the granules into the agglomerated sinter product. After the sintered block was cooled down and emptied out of the pot, a ∼35 × 35 × 35 mm³ sinter cake was excavated from the middle block for the following XCT measurement.

2.2. X-ray computed tomography

The apparatus used for the XCT scans and the related setting parameters are illustrated in Fig. 2 and Table 2, respectively. The sinter sample was placed on a rotating stage, which is between the plat detector and the X-ray source. The CT data were collected at a current of 65 μA and a source voltage of 148 kV, achieving a pixel size of 40 μm. To analyze the sinter pore properties including porosity, pore number, largest pore area etc, the CT images were processed in a sequence of four steps: Extraction of an interested region, binarisation, segmentation and pore data statistics. Fig. 3(a) shows an original 8-bit grayscale CT image, from which a 25 mm × 25 mm region in Fig. 3(b) was extracted. Then the sinter solid-matrix and pores were identified according to a classical threshold value. The binarisation step sets the gray value of pores to 0 and gray value of solid phase to 255, resulting in the blue zone and black zone in Fig. 3(c), respectively. Then segmentation of pores was performed by using 3D watershed algorithm therefore the quantitative information of different pores could be analyzed.

2.3. Effective thermal conductivity simulation

CT-simulation has been proved to be a valid approach to predict thermal behavior of iron agglomerates with complex porous structure [13]. Referring to the medium size of sinter charged into the blast furnace and considering the trade-

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### Table 1 – Ore blend composition, sintering conditions and the tested cases.

<table>
<thead>
<tr>
<th>Ore blend composition (wt%)</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore 1 (Australia)</td>
<td>33.33</td>
</tr>
<tr>
<td>Ore 2 (Australia)</td>
<td>16.67</td>
</tr>
<tr>
<td>Ore 3 (Australia)</td>
<td>16.67</td>
</tr>
<tr>
<td>Ore 4 (Brazil)</td>
<td>16.67</td>
</tr>
<tr>
<td>Ore 5 (Brazil)</td>
<td>16.67</td>
</tr>
<tr>
<td>Sintering conditions</td>
<td></td>
</tr>
<tr>
<td>Return fine (wt% total mix basis)</td>
<td>20.0</td>
</tr>
<tr>
<td>Granulation time (min)</td>
<td>10</td>
</tr>
<tr>
<td>Bed height (mm)</td>
<td>600</td>
</tr>
<tr>
<td>Ignition suction (kPa)</td>
<td>6</td>
</tr>
<tr>
<td>Ignition temperature (°C)</td>
<td>∼1100</td>
</tr>
<tr>
<td>Ignition time (s)</td>
<td>90</td>
</tr>
<tr>
<td>Sintering suction (kPa)</td>
<td>16</td>
</tr>
<tr>
<td>Aim moisture (%)</td>
<td>6.5</td>
</tr>
<tr>
<td>Tested factors and levels</td>
<td></td>
</tr>
<tr>
<td>Coke rate (wt% total mix basis)</td>
<td>4.05</td>
</tr>
<tr>
<td>Basicity (CaO/SiO₂)</td>
<td>1.5</td>
</tr>
</tbody>
</table>

### Table 2 – Set up of the Micro-XCT scanning conditions.

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage (kV)</td>
<td>148</td>
</tr>
<tr>
<td>Current (μA)</td>
<td>65</td>
</tr>
<tr>
<td>Exposure time (s)</td>
<td>0.2</td>
</tr>
<tr>
<td>Source-to-sample distance (mm)</td>
<td>80</td>
</tr>
<tr>
<td>Detector-to-sample distance (mm)</td>
<td>160</td>
</tr>
<tr>
<td>Pixel size (μm)</td>
<td>40</td>
</tr>
</tbody>
</table>
off between the high computational cost and the instrument capability, a computational domain of 25 mm³ cube is used. In processes relating to the sinter utilization, radiation at the representative temperatures plays a much lesser role when compared to conductive and forced convective heat transfer. For instance, in sintering bed, the sinter belongs to the upper sintered zone where temperature range is from ∼330 K to ∼573 K and exchanges heat with the sucked fresh air [1]. In sinter ring coolers, sinter is generally cooled from ∼873 K to ∼423 K by blasting fresh air [4–6]. Therefore, the contribution

![Diagram of X-ray computed tomography system for sinter sample.](image)

**Fig. 2** – X-ray computed tomography system for sinter sample.

![Diagram of CT slice processing.](image)

**Fig. 3** – Typical CT slice processing: (a) Original 8-bit CT image, (b) selected region of interest (25 mm³ cube), (c) binary image after removing noise (black: solid matrix, blue: pore), (d) image after watershed procedure.
of radiation to the effective thermal conductivity is neglected in present evaluation.

Fig. 4 depicts the computational domain for the simulation of effective thermal conductivity, which is an extracted 25 mm$^3$ cube domain meshed with hexahedral grid. The boundary conditions were also sketched in Fig. 4. An arbitrary temperature difference of 100 K was applied to two opposite faces in the simulated direction while the four peripheral faces were considered adiabatic. The sinter solid-matrix is considered to be homogeneous with a thermal conductivity value of 2.881 W/mK, which is referred to the value used in fractal model [12]. The air is simultaneously considered in stagnant state ($k_a = 0.023$ W/mK). As the air was considered as motionless, only the energy equation was solved.

$$
\rho C_p \frac{\partial u}{\partial t} = \frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right)
$$

(1)

Where $\rho$, $u$, $C_p$, $T$ and $\lambda$ are the local values of the gas density, velocity, specific heat of air, gas temperature and thermal conductivity of air, respectively.

Numerical simulation based on the XCT reconstruction at pore scale was performed on a workstation with the following specification: Intel Xeon E5-2686 $\times$ 2 CPU processor and 128 GB memory. The computing times for each case were in the range of 4–6 h. When all the residuals become smaller than $1.0 \times 10^{-5}$, the convergence was achieved and temperature field in the computational domain was obtained. Effective thermal conductivity of sinter was calculated as:

$$
k_e = \frac{-\int J \cdot dA}{A \left( \frac{dT}{dx} \right)} = \frac{-\int J \cdot dA_s + \int J \cdot dA_f}{(A_s + A_f) \left( \frac{dT}{dx} \right)}
$$

(2)

where $J$ is the heat flux, perpendicular to the pore cross-sectional area $A$, the subscripts $s$ and $f$ refer to the solid matrix and fluid respectively, $\frac{dT}{dx}$ is the temperature gradient along the sinter sample.

3. Results and discussion

3.1. Sinter reconstruction and porosity

Nine three-dimensional volumes of the sinter solid-matrix were reconstructed using commercial software, one for each coke rate and basicity level. The resulting geometric structure and values of their total porosity are shown in Fig. 5. A particulate structure could be clearly observed for the sinter under the condition of 4.05% coke rate and 1.5 basicity. However, for the cases with higher coke rate and higher basicity, it is rough that those sinters comprised of relict large iron ore particles bonded by the melt formed in flame front. Both increasing basicity and coke rate promote the formation of a less viscous and larger volume of melt during sintering. These changes allow more complete assimilation of the nuclei and lead to greater coalescence in the solid-matrix therefore the particulate structure of sinter becomes less obvious.

As for the sinter total porosity, defined by the total pore volume as a fraction of the total computational domain volume, generally decreases with the increasing basicity at the same coke rate level. Loo et al. [1] concluded the sinter density increases with the increasing basicity, which is strongly correlated to the sinter total porosity. Higher basicity means more melt available during sintering when the heat is sufficient, which enhances the coalescence and leads to the denser sinter with smaller porosity. However, the sinter with 4.50% coke rate and 2.5 basicity shows an unexpected high porosity in present study. This might be explained by great pore volume produced from the random distributed material loss of some large limestone and coke particles. Further research using advanced XCT instruments with larger sample size and higher resolution would be helpful to obtain more reliable porosity of the sinter cake [11,27,30].

The inhomogeneous nature of sinter results in high variability between individual directions of pore properties. Fig. 6 presents the comparison between the area porosity of high porosity sinter and low porosity sinter in three spatial directions. It is acknowledged that the shape, size and orientation of the pores and the connections between them are all random to certain degree. To understand more about these strong stochastic characteristics, detailed statistical information are further analyzed in the following section.

3.2. XCT-measured pore number and the largest pore area

Many pores with irregular shapes which exist at different scales, are believed to control the physical properties of sinter. Here we classified the pores into two groups based on its equivalent diameter value, the term “macropore” in sinter is applied to pore sizes >1 mm while “micropore” for the pores with size <1 mm. Using the post-processed CT images the pore number, the mean value and deviation of the pore area of different groups, and area of the largest pore along the sinter length in each direction in the interested region were determined. Fig. 7 presents the comparison between high porosity sinter and low porosity sinter in terms of the length distribution of number.
Fig. 5 – Comparison of three-dimensional geometric structure of sinter solid-matrix and porosity obtained for each case.

Fig. 6 – CT-measured area porosity for (a) high porosity sinter and (b) low porosity sinter along the three spatial directions.

of all pores, number of macropores (+1 mm) and area of the largest pore. For the high porosity sinter, the general patterns observed in the number of all pores and +1 mm pores were similar. However, for the low porosity sinter, number of +1 mm pores was much less variable compared to that of all pores in three directions. Sinter with smaller porosity tends to have more isotropic +1 mm pore number than larger ones, indicating that the pore networks are much more uniform, probably as a result of sufficient coalescence of solid-void-melt phases in the high temperature transformation.

Table 3 gives the related CT-measured pore parameters for different coke and basicity levels. The number of all pores is in the range of 112–189 as compared to 27–49 of the +1 mm pores. Simultaneously, the area porosity considering all pores
Fig. 7 – CT-measured number of all pores, number of +1 mm pore and area of the largest pore for (a) high porosity sinter and (b) low porosity sinter along the three spatial directions.

Table 3 – CT-measured pore parameters for different coke rate and basicity levels.

<table>
<thead>
<tr>
<th></th>
<th>Coke rate (%)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4.05</td>
<td>4.50</td>
<td>5.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basicity</td>
<td>1.5</td>
<td>1.9</td>
<td>2.5</td>
<td>1.5</td>
<td>1.9</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>57.3</td>
<td>54.9</td>
<td>36.8</td>
<td>48.5</td>
<td>39.4</td>
<td>54.5</td>
</tr>
<tr>
<td>Pore number</td>
<td>155</td>
<td>189</td>
<td>138</td>
<td>168</td>
<td>158</td>
<td>115</td>
</tr>
<tr>
<td>Mean pore area (mm²)</td>
<td>2.4</td>
<td>1.9</td>
<td>1.7</td>
<td>1.8</td>
<td>1.6</td>
<td>3.2</td>
</tr>
<tr>
<td>Deviation of pore area (mm²)</td>
<td>8.1</td>
<td>5.9</td>
<td>6.3</td>
<td>5.1</td>
<td>5.0</td>
<td>10.2</td>
</tr>
<tr>
<td>Area porosity (%)</td>
<td>53.2</td>
<td>50.1</td>
<td>33.4</td>
<td>44.1</td>
<td>35.6</td>
<td>51.6</td>
</tr>
<tr>
<td>+1 mm pores</td>
<td>38</td>
<td>47</td>
<td>30</td>
<td>49</td>
<td>29</td>
<td>27</td>
</tr>
<tr>
<td>Mean pore area (mm²)</td>
<td>9.2</td>
<td>7.2</td>
<td>7.4</td>
<td>5.9</td>
<td>7.9</td>
<td>12.8</td>
</tr>
<tr>
<td>Deviation of pore area (mm²)</td>
<td>14.2</td>
<td>10.4</td>
<td>12.2</td>
<td>8.3</td>
<td>9.3</td>
<td>17.6</td>
</tr>
<tr>
<td>Area of the largest pore (mm²)</td>
<td>73.9</td>
<td>51.0</td>
<td>59.6</td>
<td>44.2</td>
<td>37.8</td>
<td>70.7</td>
</tr>
</tbody>
</table>

The value presents the arithmetic mean of three directions with the statistics.
is in the range of 36.8–57.3% as compared to 33.4–53.2% of +1 mm pores. Though the macropores (+1 mm) only account for a fraction of the total pore number, its contribution to the total porosity is larger than 90%. The number of +1 mm pores generally decreased with increasing basicity at the same coke rate level, which agreed well with the changing trend of porosity. This corroborates the findings of Kasama et al. [16], who pointed out that a critical diameter could be defined to distinguish the different behaviors of several pore groups. As +1 mm pores dominate the pore volume and pore network, the macropore properties would have great influence on the sinter thermal conductivity. Due to joint influences of intrinsic random pore structure and complex hot transformation with melt, the mean pore area, deviation of pore area and the largest pore area in sinter are so distinctly different among the test cases as to no clear trend could be observed. Nevertheless, it is expected that not only the porosity value but also the pore size distribution determine the thermal behaviors remarkably [14].

3.3. Effective thermal conductivity and its correlation with XCT-measured pore parameters

Fig. 8 shows the comparison between the sinter effective thermal conductivity predicted by XCT-simulation and published data of similar iron agglomerates, as a function of porosity. The effective thermal conductivity decreases obviously with the increasing porosity as the proportion of solid-matrix with stronger heat conduction capacity decreases. It is worth noting that, the porosity data of those iron agglomerates vary greatly as it depends on the measuring method and the production condition. The sintered ore particles in the work by Tian et al. [12] are probably the most similar materials to the sinter samples in present work. A porosity of 12.1%–23.8% was reported by Tian et al. [12] using the mercury intrusion method, in which the measuring range is limited and only the closed pores could be evaluated. By contrast, the 3D X-ray tomography method could measure the closed pores and open pores in the meantime as it has a much wider measuring range with relatively high resolution. Shatokha et al. [11] performed XCT scans to sinter and reported a closed porosity of 3.1%–7.6% and open porosity of 5.3%–43.6%. These results are close to the total porosity in present study, yielding a lower thermal conductivity value when compared to mercury intrusion methods. In Fig. 8, a confusing comparison exists between the pellets studied by Sundarmurti and Rao [21,22] and sinter samples in present study. These pellets have a closely thermal conductivity in the range of 0.766–1.200 W/mK while their porosity is much smaller than sinter samples. The explanation is that the pressed iron ore pellets have higher specific interfacial surface area than sinter at a constant porosity, leading to larger thermal resistance at the solid-pore interfaces.

The predicted effective thermal conductivity values are further plotted in Fig. 9 against coke rate. At the same coke rate, the conductivity was generally larger when the basicity level was higher. The maximum thermal conductivity that predicted in present study is 1.276 W/mK under the condition of 4.05% coke rate and 2.5 basicity while the lowest value of the thermal conductivity range is 0.597 W/mK for the 4.05% coke and 1.5 basicity case. Fig. 10 compares the temperature isocontours of two sinter samples when simulating the thermal conductivity in X axis direction. It can be seen that the influence of scattered micropores on the temperature gradient is almost neglectable. The heat pattern is determined by the orientation of solid-matrix and macropores intensely. As the solid-matrix has a much larger thermal conductivity than the air in pores, the heat conducts much faster in the solid-matrix phase. The temperature field in a sinter with smaller porosity and more isotropic porous structure seems to be more homogeneous.

Regression analysis was conducted to estimate the relationship between thermal conductivity with the CT-measured pore parameters, some important correlations are shown in Fig. 11. The pore parameter with the best correlation with thermal conductivity was porosity. The straight lines drawn by least squares method are expressed as \( Y = -0.035X + 2.615 \) for all pores and \( Y = -0.034X + 2.436 \) for +1 mm pores respec-
Fig. 10 – Temperature isocontours for the simulation of sinter effective thermal conductivity along X axis direction (black zone: solid phase, blue zone: pore).

respectively, corresponding to the regression coefficients of 98.5% and 96.4%. The second pore parameter best fitted with thermal conductivity was the number of $+1$ mm pores, yielding a negative correlation of $Y = -0.031X + 2.042$ with the regression coefficients of 65.5%. The porosity of porous material controls its thermal conductivity by two aspects. On one hand, increase in porosity decreases solid/solid contact area decreasing solid phase conduction. On the other hand, at the similar porosity level, increase in average pore size decreases solid/pore surface area, decreasing resistance to heat conduction. The overall change in effective thermal conductivity with porosity is dependent on contribution by those two factors. Specific to the sinter samples, the $+1$ mm macropores formed from the material loss and melt flow in high temperatures play a predominant role in determining the thermal behavior.

Several studies in the field of soil reported that area of the largest pore could be well correlated with thermal conductivity [31]. However, results of sinter in present study were different. The regression coefficient of area of the largest pore is below 50% indicating this parameter is not suitable for quantitative characterization of sinter thermal conductivity. It is speculated that sinter has many more flexural pore throats than soil therefore the whole pore network could not be represented by the single largest pore.

4. Conclusion

Nine pilot-scale sinter pot tests covering a wide range of coke rate and basicity levels were conducted to get the desired sin-
ter samples for the followed X-ray computed tomography with a high resolution of 40 µm. Based on the CT images, sinter pore parameters including porosity, pore number, largest pore area for all pores and the defined macropores were analyzed respectively. Effective thermal conductivities of sinter were estimated by numerical simulation with 3D reconstructed porous structure. The obtained information was used to further elucidate the relationship between thermal conductivity and pore parameters. Main findings are concluded as follows: Higher coke rate and higher basicity favour the melt formation, transforming the sinter from particulate structure to melt-bonded structure. Of all the CT-measured pore parameters, porosity and number of +1 mm pores generally decrease with the increasing basicity at the same coke rate level. The anisotropic porous structure of sinter leads to different thermal behavior in three spatial directions. Under the tested conditions, the effective thermal conductivity increases from 0.597 W/mK to 1.276 W/mK as the sinter porosity decreases from 56.3% to 36.3%. The sinter effective thermal conductivity is well negatively correlated to the porosity value and number of +1 mm pores. However, no clear trend between the thermal conductivity with mean pore area and area of the largest pore could be found. The statistic analysis demonstrates that the definition of macropores whose diameter is larger than 1 mm could distinguish the different behaviors of several pore groups. As the +1 mm pores contribute more than 90% to the total pore volume and set up the main orientation of pore network, those macropores mainly determine the sinter thermal behavior.

**Conflicts of interest**

The authors declare no conflicts of interest.

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**References**

[27] Zhou H, Zhou MX, Cheng M, Guo WS, Chen KF. Experimental study and X-ray microtomography based CFD simulation for


