The effect of x-ray micro-ct geometrical zooming on the microstructure properties of porous medium

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Abstract. Digital rock physics has evolved rapidly due to its various advantages such as being able to see rock images in 3D without non-destructively. In this study, 3D images of porous medium sample were generated from X-ray micro computed tomography scanning device SkyScan 1173. This study aims to investigate the effect of X-ray Micro-CT geometrical zooming (sample position to the X-Ray source) on the microstructure properties of porous medium such as porosity, specific surface area, tortuosity, permeability and grain size distribution. The rocks tested were concrete sand samples. The distance between source and object was varied 3 times. The scan was processed through reconstruction process until thresholding. Porosity, specific surface area and grain was calculated by CTAn software. Tortuosity was calculated by finding the path at 26 neighboring pixels and the permeability was calculated by simulating a steady state fluid flow. The result is the greater the distance between the radiation source and the object, the smaller the resolution of the image. This causes some pores that are too small that eventually are grouped into rock matrix. Therefore, pore-related properties such as porosity and specific surface area will decrease, tortuosity will increase and permeability will decrease.

1. Introduction
In the last few decades, digital rock physics (DRP) has evolved rapidly into an alternative measurement methods especially for prediction of reservoir properties. DRP has the advantage of measuring such as special core analysis that if measured conventionally takes a long time [1]. Estimation of effective rock properties (macroscopic) by analyzing the micro-pore structure is the focus of the DRP study [2].

In general, DRP workflow includes sample imaging, reconstruction and numerical simulation process to retrieve the rock physical properties of interest [3]. Currently, micro-scale x-ray computed tomography (μCT) is one of the modern methods for acquiring sample images.

In contrast to the clinical CT system, the samples on micro-CT are rotated during the scanning process to produce the 3-dimensional images. In addition, the distance between the sample and the X-Ray source on the micro-CT Scan can be adjusted so that the image of a particular area can be enlarged and the resolution can also be adjusted [4]. In this study, we investigate the effect of geometrical zooming as a result of sample positioning with the X-Ray source on the microstructure properties of porous medium.

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2. Microstructure Properties
Several microstructure properties are calculated by means of digital image analysis. The properties are porosity, specific surface area, tortuosity and permeability. Porosity ($\phi$) is defined as the ratio between the void volume ($V_v$) and the total volume of the sample ($V_t$) which can be mathematically expressed as\[\phi = \frac{V_v}{V_t}\] (1)

Specific surface area ($S_A$) is defined as the ratio between the surface area of the pore wall ($S$) to the total sample volume ($V_{total}$)\[S_A = \frac{S}{V_{total}}\] (2)

Tortuosity was firstly investigated by Carman [6]. Until now, there are several definitions of tortuosity depending on the perspective of experts in the field of science such as geology, engineering and chemistry. Palciauskas defines tortuosity ($\tau$) as the ratio of the length of the fluid flow path ($L_e$) to the shortest path of flow ($L$).\[\tau = \frac{L_e}{L}\] (3)

In a binary data, tortuosity can be calculated by using Eq. (4), where $l_p$ is the path in void space, $l_s$ is the straight line connecting the two closest points and $n$ is the number of existing paths [7].\[\tau = \frac{\sum_{i=1}^{n} l_{p_i}}{n l_s}\] (4)

Permeability, which was first examined by Darcy [8], describes a measure of the ability of a porous material to allow fluids to pass through it which define as Eq. (5) where $Q$ is volumetric fluid flow rate, $\mu$ is the dynamic viscosity, $A$ is area of the sample and $dP/dL$ is gradient of pressure [9].\[k = \frac{Q \mu}{A} \frac{1}{dP/dL}\] (5)

In this present study, the permeability is calculated using the Lattice Boltzmann Method (LBM) fluid simulation. The LBM is a powerful technique for simulating fluids in porous media, which in this case solves using Parallel Lattice Boltzmann Solver (Palabos). In Palabos, the above equation is modified to the equation below where $\langle v \rangle$ is the average velocity of the fluid when it is steady.\[k = \frac{\mu \langle v \rangle}{dP/dL}\] (6)

3. Method
In this study, use concrete sand was used as the porous medium sample to be investigated. The sand is packed inside a straw with a diameter of 1 cm. The top and bottom of the straw are clogged using plasticine. The samples were scanned with three different positioning, with respect to the X-Ray source. Variations of distance and other quantities in the measurement can be seen in the Table 1.

4. Result and discussion
Scanning with 1x1 binning camera produces projection images with the size of 2240$^2$ pixels. Projection images from the scan results are reconstructed with NRecon software using the GPUReconServer kernel. Using this kernel, reconstruction is accelerated by the NVIDIA’s Graphical Processing Unit (GPU). Reconstruction with GPU is faster than CPU, because the GPU performs reconstruction in the frequency domain while the CPU performs in the spatial domain [10]. Table 2 shows the projection images and the reconstructed images of the samples. After the reconstruction step, subsamples with the size of 300x300x300 pixels for P01, 150x150x150 pixels for P02 and 75x75x75 pixels for P03 were selected inside volume of interest (VOI) (see table 3).
### Table 1. Variation of distance and other quantities in measurement.

| Sample code | P01 | P02 | P03 |
|-------------|-----|-----|-----|
| Source Voltage (kV) | 80  | 80  | 80  |
| Source Current (uA)  | 100 | 100 | 100 |
| Image Pixel Size (μm) | 6.06 | 12.11 | 24.23 |
| Object to Source (mm) | 44.21 | 88.41 | 176.81 |
| Camera to Source (mm) | 364 | 364 | 364 |
| Rotation Step (deg) | 0.2 | 0.2 | 0.2 |
| Minimum X-ray transmission profile | 30% | 30% | 30% |
| Maximum X-ray transmission profile | 90% | 90% | 90% |

### Table 2. Scan projection result and 2D reconstruction of samples for each distance objects.

| Sample code | P01 | P02 | P03 |
|-------------|-----|-----|-----|
| Dist. between obj. and source (mm) | 44.21 | 88.41 | 176.81 |
| Imag. pixel size (μm) | 6.06 | 12.11 | 24.23 |

The projection results at the angle of rotation, $\theta = 0 ^\circ$.

Results of 2D reconstruction at the same location.
Table 3. Selection of ROI in projection result and reconstruction of samples for each distance objects.

| Subsample | ROI/slice/VOI |
|-----------|--------------|
| P01 (300³ pixel): Subsample A & B | P02 (150³ pixel): Subsample A & B | P03 (75³ pixel): Subsample A & B |

| ROI on the projection result |
|-------------------------------|
| ![ROI on the projection result](image1) |

| ROI on reconstruction results |
|-------------------------------|
| ![ROI on reconstruction results](image2) |

| 3D view of sample in VOI |
|--------------------------|
| ![3D view of sample in VOI](image3) |
The next step is thresholding. In this process, image data that is still on the scale of greyscale intensity is converted to binary. In this present paper, thresholding is done with CTAn software and applied Otsu method for thresholding (see Table 4). After segmenting/thresholding, porosity and specific surface area were calculated using CTAn software. The results are described in Fig. 1.

Tortuosity and permeability were also calculated.

The results show that the greater the distance between the source and the object (P01 → P02 → P03), the porosity value will be smaller. This is because the resolution of the imaging results depends on the distance between the X-ray radiation source and the rock sample. The greater the distance between the
radiation source and the object, the smaller the resolution of the image results. The decrease of this image resolution affects the pore detection. If the pore size is less than the smallest size of the detection, the pore is undetectable and is considered a rock matrix. In Fig. 1, the plots correspond to the distance of P01, P02 and P03. Because porosity is the ratio of pore volume to total volume, the case of undetected pore causes porosity to be lower. Therefore, the greater the distance between the radiation source and the object, the lower the porosity.

The decrease in resolution also affects the specific surface area. Reduced amount of pores yields reduced pore surface area as well as (see Fig. 1). Similarly, tortuosity is also affected by pore detectability. Small imaging resolution enables undetected pores. This causes the pores to become disconnected from each other so that the pore structure will become more complex, in other words, tortuosity increases with increasing object distance. Permeability is related to rock complexity. In this case, the influence of pore readability is the cause of the increasing complexity of rocks that affect the level of ease of rock flow through the fluid. Therefore, the permeability will decrease as the distance of the object increases.

5. Conclusion
The conclusion is the greater the distance between the radiation source and the object, the smaller the resolution of the image results. Thus, there are some pores that are too small that eventually are grouped into rock matrix. Therefore, pore-related properties such as porosity and specific surface area will decrease, the complexity of porous media (tortuosity) will increase and the ease of a porous medium through the fluid (permeability) will decrease.

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References
[1] Guice K, et al 2014 International Petroleum Technology Conference (Doha) vol 1 (NY : Curran Associates, Inc.) p 058.
[2] Andrae, et al 2013 Computers & Geosciences 50 33.
[3] Verri I, et al 2017 Journal of Petroleum Science and Engineering 156 790.
[4] Rueckel J, Stockmar M, Pfeiffer F, Herzen J Applied Radiation and Isotopes 94 230.
[5] Hilfer R 1992 Phys. Rev. B 45 7115
[6] Carman P C 1997 Chem. Eng. Res. Des. 75 150.
[7] Al-Raoush R I and Madhoun I T 2017 Powder Technology 320 99.
[8] Darcy H 1856 Hist. de l’Academie royale des sciences 1733 351.
[9] Degruyter W, Burgisser A, Bachmann O and Malaspinas O 2010 Geosphere 6 470.
[10] Latief F D E, Fauzi U, Irayani Z and Dougherty G 2017 J. Microsc 266 69.