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Specific surface and porosity relationship for sandstones for prediction of permeability

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ABSTRACT

Porosity and specific surface are two prominent factors in describing the hydraulic properties of porous media. Determination of these two important parameters leads to identify the capability of porous media to conduct the fluids. In the present study, a new relationship between porosity and specific surface of sandstones has been developed. Micro-CT data from 10 types of sandstones has been utilized in order to present a porosity–specific surface correlation. This correlation also contains the average grain radius of each rock obtained by image processing algorithms. Finally, the correlation is tested on the provided data to evaluate its precision. The simplicity and applicability of the presented relationship can be attended to modify the Carman–Kozeny equation for sandstones.

1. Introduction

Specific surface area of a porous material has different definitions in various fields of application. In order to study the hydraulic characteristics of permeable rocks, it is usually defined as the interstitial surface area of pores per unit of solid volume of porous material. Specific surface is an important parameter with regard to the fluid conductivity or permeability of a porous material [1–3]. Since specific surface is the ratio of area to volume, it has dimensions of L^{-1}. The definition for specific surface of porous media is [3,4]

$$S = A_g / V_g \tag{1}$$

where A_g and V_g are the total surface area and the total volume of grains, respectively. Several methods for estimation of specific surface of porous materials have been discussed in the literature till now. Collins [1] is one of the first researchers of methods for specific surface measurement. Generally, three major techniques have been invented in order to estimate the ratio of surface area to volume of arbitrary particles in porous medium [2]: A) adsorption measurement of specific chemicals and gases onto the pore walls, B) measuring the fluid flow through medium based on Carman–Kozeny equation. [4–6] and C) statistical methods such as stereological [7], optical [8] and NMR analysis [9].

In the adsorption based methods, methylene blue dye, as well as gas adsorption, has been used to determine the surface area of clay minerals for several decades [10]. Dogan et al. [11] measured the specific surface of clay minerals by the Brunauer, Emmett and Teller (BET) method of adsorption of nitrogen gas. Nuclear Magnetic Resonance (NMR) methods are also wieldy applied to characterize the pore geometry of rocks. Pape et al. [9] developed a fractal analysis method for estimation of specific surface area of rocks using NMR data.

Fluid flow methods which are basically an application of Kozeny equation are widely attended in the literature. The Kozeny–Carman equation is the most famous permeability–porosity relation, which is widely used in the field of flow in porous media and is the starting point for many other permeability models [6,5]. The Kozeny–Carman equation can be written as [12,13]

$$K = \frac{\phi^3}{c(1-\phi)^2 S^2} \tag{2}$$

where K is the permeability, c is the Kozeny constant that depends on pore shapes, ϕ is porosity and S is the specific surface area of porous media. McGregor [14] assumed the specific surface of textile porous materials as $S = 4/\overline{d}$, where $\overline{d}$ is the average grain size of the porous medium. This formulation is proposed by considering a bundle of tubes model. Consequently the Carman–Kozeny equation is modified as

$$K = \frac{(\overline{d})^2 \phi^3}{16c(1-\phi)^2} \tag{3}$$

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Bear [15] and Kaviany [16], by assuming the rock grains to be spheres, estimated the specific surface as follows:

$$S_{sphere} = \frac{4\pi r^2}{4\pi r^3/3} = \frac{3}{r} = \frac{6}{d} \tag{4}$$

This assumption rearranges the Carman–Kozeny equation into

$$K = \frac{(\overline{d})^2 \phi^3}{36\tau^2 (1-\phi)^2} \tag{5}$$

where τ is the tortuosity. The optical method which is based on statistical image processing has been developed by Chalkley [7].

This method is based on random tests on two-dimensional images from cross sections of synthetic porous medium [7]. In this regards a specified needle with length L is randomly thrown on the surface of cross section and number of pores and grains in which the needle is lying on them should be counted. The modified equation which estimates the specific surface of particles using Chalkley method can be expressed as [1]

$$S = \frac{4\phi C}{LH} \tag{6}$$

where C is the number of particle perimeters intersected by needle (cuts), H is number of pore spaces recumbent under the needle (hits), L is needle length and ϕ is porosity of the porous medium. Chalkley et al. [17] applied this method on a system of wooden cubes embedded in paraffin by cutting the produced object into thin sections. They have shown that by increasing the number of falling needles and averaging the total number of intersected particle perimeters, the margin of error will reduce significantly. Weible et al. [18] organizes the Chalkley method into a systematic approach considering many parallel short lines to play as needles in volumetry of single particles. They presented a straightforward combination of point-counting volumetry with surface estimation by line intersection which was successful for approximation of specific surface of single particles.

Debye et al. [19] presented a method for estimation of specific surface of heterogeneous solids by measuring the X-ray scattering pattern from different materials. They tried to correlate the porosity of porous structure versus the specific surface of its particles and verified the results by measuring the specific surface using adsorption methods. Berryman [20] modified the Debye et al. [19] method by angular averaging between normal vectors of rock grain surface in order to estimate the specific surface value using scattering data of X-ray. Berryman and Blair [8] utilized Scanning Electron Microscopy (SEM) to estimate porous medium porosity and specific surface by applying two-point correlation functions. They compared the results obtained from Kozeny equation and experimental permeability measurement to adjust the two-point correlation function for finding the specific surface. Berryman and Blair [21] extended their work to consider tortuosity and electrical formation factor in calculation of specific surface using data available for Berea sandstone. Moreover, they presented a discussion on choosing the optimum resolution of imaging in order to estimate the specific surface from rock cross sections. Yeong and Torquato [22,23] presented a two-point correlation function to estimate the specific surface of rock grains by knowing the porosity in order to reconstruct 3D structure of porous media.

X-ray micro-tomographic imaging and visualization of rock material at the pore scale can give an important insight to understanding properties of rock structure. 3D images allow one to map the pore and grain structure in details and interconnectivity of porous medium [24]. Okabe and Blunt [25] used multiple-point statistics based on two-dimensional (2D) thin sections as training images, to generate 3D pore space representations. They used an autocorrelation function for digitized 3D structures that are expected to have the same specific surface area. Politis et al. [26] presented a process-based and stochastic reconstruction method of porous media which uses binary SEM images of rock to obtain a reconstruction method based on specific surface measurements. Blunt et al. [27] have presented a vast field of experiences in the concept of pore scale imaging and modeling by providing high resolution data bank of Micro-CT images of rock pieces. Mostaghimi [28] utilized this data bank to present a suitable size of representative elementary volume (REV) for estimation of geometry-based properties such as porosity and specific surface area.

Although reviewing the literature shows that estimation of specific surface of rock grains is generally a function of both porosity and average grain size of materials, there is no direct correlation which considers both of these two parameters at the same time. Although the proposed equation is rather simple, there is a simpler approach to estimate permeability using grain structure analysis which is developed by Shepherd [29]; meanwhile in that work, the permeability is not considered depending on the porosity and is just supposed to be dependent to the grain size.

Prediction of permeability is one of the main reasons for studying the specific surface of rock structures. Berryman and Blair [8] using statistical methods related the permeability of porous media to the grain size, specific surface and porosity for high porosity samples. Lock et al. [30] utilized BSEI imaging of rock samples to detect the real shape and size of the pores which appear in 2D section images. By performing stereological corrections on the modified area and perimeter of pore cross sections, they developed a permeability model containing bundle of rough interconnected tubes based on effective medium theory.

2. Methodology

In the present study, a new correlation is proposed in order to estimate the specific surface area of sandstones using the average grain size and porosity, which can be calculated by more conventional experiments rather than the specific surface. This relationship has been developed by examination and morphological tests on 10 different sandstones and more than 180 samples from those rocks. These 3D images have been released by Blunt et al. [27]. The specific surface area of samples has been estimated by applying the image processing algorithms on 3D data of rock structure prepared in binary matrices. Each voxel in a 3D image has been considered as cube and the specific surface of rock grains has been calculated by counting the open faces of boundary cubes for each grain or cluster. Fig. 1 shows one sample of sandstone which has been used to apply the correlation. Black parts represent the pore space.

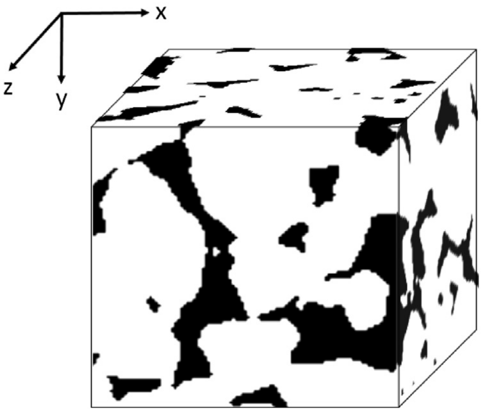

Fig. 1. 3D view of one sample of Berea sandstone reconstructed using SEM data.