A NOVEL METHOD FOR CALCULATING EFFECTIVE THERMAL CONDUCTIVITY OF PARTICULATE FOULING

by

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The accurate thermal conductivity of fouling plays a very significant role in designing heat exchanger. In this paper, a novel method of calculating the effective thermal conductivity of particulate fouling is put forward by using IMAGE-PRO-PLUS image processing, the finite element method and ANSYS parametric design language. First of all, according to the analysis on the particulate fouling samples features, the particulate fouling is considered as porous media with fractal characteristics, whose microscopic network model is established using the finite element method, and each unit body material properties are randomly assigned by ANSYS parametric design language. Secondly, effective thermal conductivity of particulate fouling model is calculated by the steady-state plate method. Then, the influence of particulate fouling micro-structure on effective thermal conductivity is explored. Last, it is also show that the calculation resulting of effective thermal conductivity agrees well with available experimental data and empirical correlation. Moreover, it has been shown that effective thermal conductivity of particulate fouling is closely associated with the porosity and pore size. The method can be used to research on the thermal conductivity of fouling, discuss the influence of micro-structure on effective thermal conductivity of fouling, and provide the guidelines for designing of heat exchanger on calculating accurate thermal conductivity of fouling.

Key words: *effective thermal conductivity, fouling, finite element, porous media*

Introduction

Heat exchangers are being widely used throughout industry today, but the problems associated with fouling have been around for many years [1-3]. Fouling is generally defined as the unwanted deposition or growth of suspended, dissolved or chemically generated species from process fluids onto heat transfer surfaces. The particulate fouling is a type of fouling. It is known to all that the fouling deposits increase the thermal resistance to heat flow, which causes serious technical and economic problems in industry [4]. For instance, the reduction in the overall heat transfer coefficient results in the performance degradation of the heat exchangers due to the increasing of fouling thermal resistance. As a consequence, the industry suffers an annual loss of billions of dollars [5-7].

The fouling deposit is a complex phenomenon and its thermal resistance accurate prediction based on current knowledge is quite a difficult task. However, fouling thermal resistance plays a very significant role in the field of designing heat exchanger. Therefore, it is

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an important task to calculate the accurate thermal conductivity of fouling, instead of empirical value. Since the micro-structure of particulate fouling is loose and porous, it has the obvious porous media features and fractal features [8, 9]. So we may solve the thermal conductivity problem of particulate fouling using the way of porous media and the fractal theory.

Despite the fact that the heat transfer through porous media is different from continuous medium, effective thermal conductivity (ETC) method is to view porous media as a continuous medium. Several studies dealing with estimation of ETC of porous media have been reported since the pioneering work of Maxwell [10]. The series model are generally used to investigate ETC of porous media [11-19].

Although there is immense literature related to the depositions of fouling [20-22], only a few works concerned ETC of particulate fouling. Therefore, a pointed study is necessary to calculate and evaluate ETC of particulate fouling. In this paper, a novel method was proposed to calculate ETC of particulate fouling based on IMAGE-PRO-PLUS image processing and calculated its thermal conductivity by using finite element method. The porosity and the pore size are considered as the important structural parameter, since its influence on the conduction heat transfer is known to be relevant. Results presented here would aid in calculating of overall heat transfer coefficient for the design of heat exchanger and other industrial applications.

Method

Experimental set-up

An experimental set-up has been developed to investigate the particulate fouling characteristics of the plate heat exchanger (PHE) as shown in fig. 1. The experimental set-up mainly includes two flow loops: for the cold and hot fluids. Hot water loop comprises with an insulated hot water tank with immersion heaters. The temperature of hot water inlet to PHE has been controlled through temperature controller. Hot water has been circulated through PHE using hot water pump. Cold water loop comprises with a cold water container and an air cooler, which is circulated by means of a centrifugal pump. Before entering the PHE, the inlet temperature of cold water and hot water are maintained at a constant value. Commercial PHE manufactured by HTH has been used for this purpose. The geometric details of the plates and the heat exchangers are provided in tab. 1 and fig. 2.

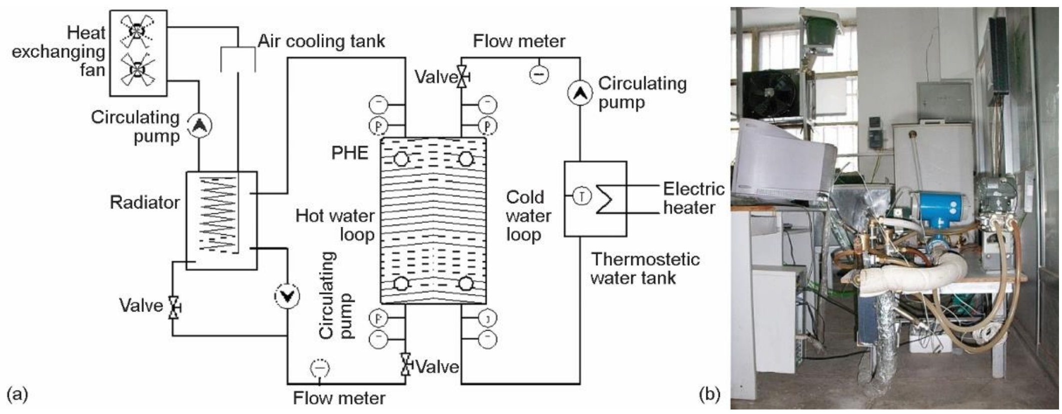

Figure 1. Experimental set-up; (a) schematic of the test facility and (b) photograph of the test facility

Table 1. Specifications of PHE

Heat exchanger area [m²]	Length [m]	Width [m²]	Hydraulic diameter [mm]	Chevron angle [°]	Plate thickness [m²]	Plate separation [mm]
0.15	0.258	0.1	4	60	0.6	2

In the fouling tests, the foulants, such as particulate or inverse solubility salt ($CaCO_3$ and $CaSO_4$), were added in the cold water, and the deposit can occur on the heat exchanger surface. The thickness of the fouling layer deposited on the heat exchanger surface was measured at the end of each run.

Figure 2. Examined PHE

When ETC of fouling develops, the overall heat transfer coefficient is given by:

$$\frac{1}{U}=\frac{1}{h_1}+\frac{\delta_w}{\lambda_w}+\frac{\delta_f}{\lambda_f}+\frac{1}{h_2} \tag{1}$$

Where, fouling thermal resistance:

$$R_f=\frac{\delta_f}{\lambda_f} \tag{2}$$

where δ_f and λ_f are the thickness of the fouling layer. The overall heat transfer coefficient U decreases, since fouling thermal resistance R_f is increasing with time.

Fouling example and characterizations

Accordingly, a comprehensive and rigorous set of laboratory fouling runs was performed with calcium sulphate solution (particulate) as foulants. Figure 3 shows typically the formation of fouling deposit on the surface of PHE.

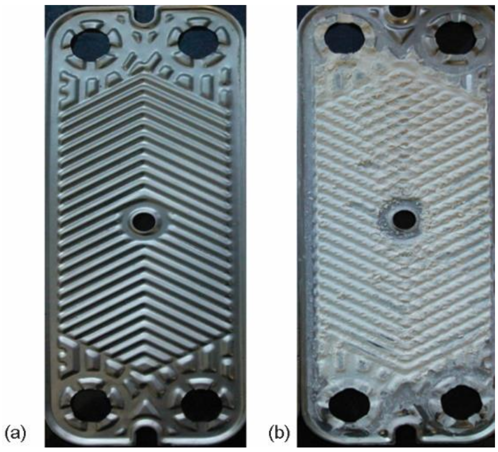

Figure 3. Photos of the surface of PHE; (a) clean surface and (b) fouled surface

For reproducibility testing, two similar samples (named tests a and b), were produced. Figure 4 gives the SEM photos in particulate fouling test of different operational parameters and it can be found that the particulate fouling deposit as the same looser and porous structure. In the analyses, particulate fouling deposit is considered as the porous structure and definite absorbent ability, so ETC of particulate fouling is a function of micro-structure properties such as porosity, pore size and pore structure. The particulate fouling deposit on the surface of PHE is immersed in water at operation of heat exchanger. Therefore, the overall thermal conductivity of particulate fouling is an *effective* thermal conductivity with contributions from its constituents in solid and liquid phases (water). It is very difficult to obtain the accurate ETC of particulate fouling for its complex micro-structure. At the same time, due to the coupling between the fluid-flow and heat transfer processes, ETC of particulate fouling has to be estimated using empirical value.

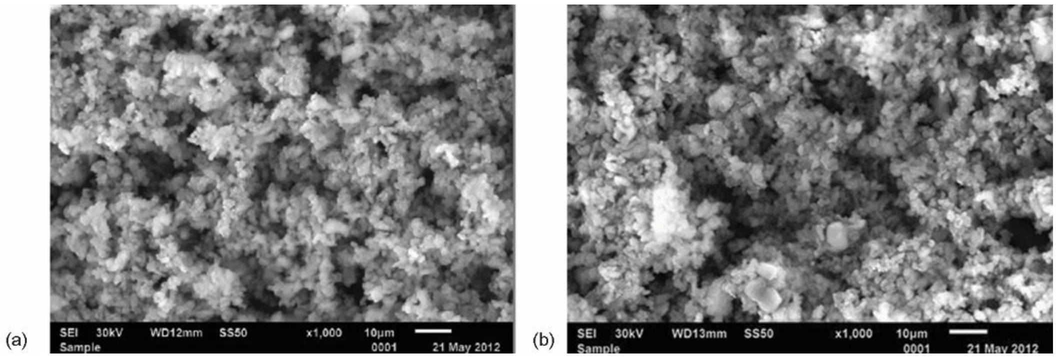

Figure 4. The SEM micro-structures of particulate fouling; samples (a) and (b)

The IMAGE-PRO-PLUS processing

The IMAGE-PRO-PLUS analysis program has been applied to extract significant information from the captured images to determine the particle size distribution of polymer, catalysts and other civil engineering materials [23, 24]. The ETC is a function of the fluid and solid thermal conductivities of the porous structure geometrical parameters. Maybe the most important geometric parameter is the porosity. In this paper, the image processing and analysis were used to calculate the porosity of particulate fouling.

The process of image analysis is shown in fig. 5.

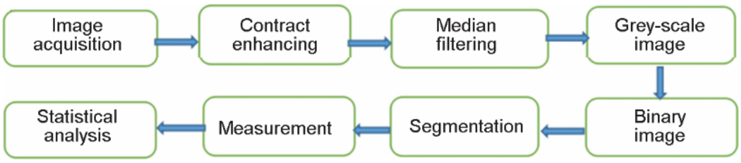

Figure 5. Process of image analysis

After the images of fouling had been captured by SEM, they were transformed to grey scale as shown in fig. 6. Since there is a great different between the pores and the solid skeleton, the dark areas are pores, and the white areas are solid skeleton. It can be seen clearly from the binarization the distribution of pores. Using the algorithms within the IMAGE-PRO-

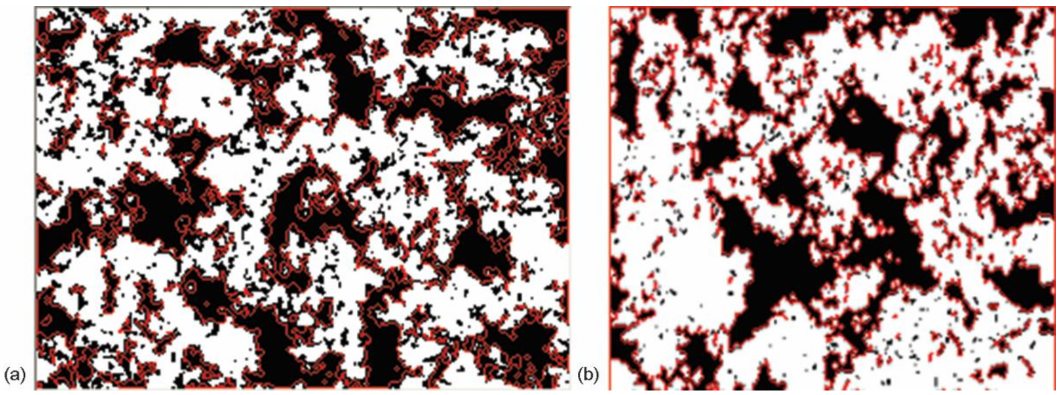

Figure 6. The SEM of particulate fouling after binarization process; samples (a) and (b)

PLUS program, the area of pores was measured and statistical analysis, which can calculate the porosity of the particulate fouling sample. In order to calculate ETC of particulate fouling, the particulate fouling is considered as porous media with fractal characteristics. The fouling fractal system with statistic self-similarity has the same porosity in various layers, so the porosity change due to the depth in the layer is neglected in this study. The extraction of porosity is an important step to reconstruct geometric model of particulate fouling.

Finite element model

The ANSYS is employed to investigate ETC of the geometrical model. An example of the finite element model is presented in figs. 7 and 8. The size of geometrical model is 10×10×10 mm as shown in figs. 7 and 8, which is divided into 8000 elements and 9561 nodes. To calculate ETC of the geometrical model, authors choose the porosity measured from the IMAGE-PRO-PLUS program. The ANSYS parametric design language (APDL) is convenient to manipulate the flow of calculations and data to realize the micro-structure controlling. Based on these considerations, authors have developed a numerical code with the APDL in ANSYS platform for simulating the porosity and pore size of the particulate fouling sample. Thus, it is another important step to obtain ETC of particulate fouling.

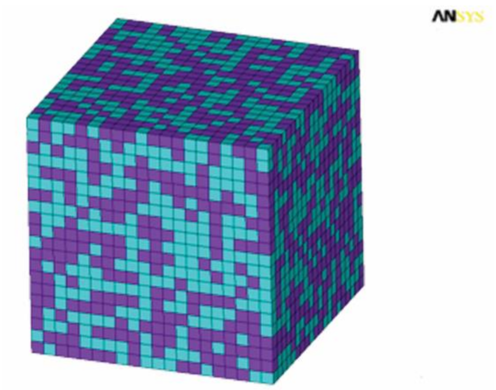

Figure 7. The finite element model of porosity of 49.95%

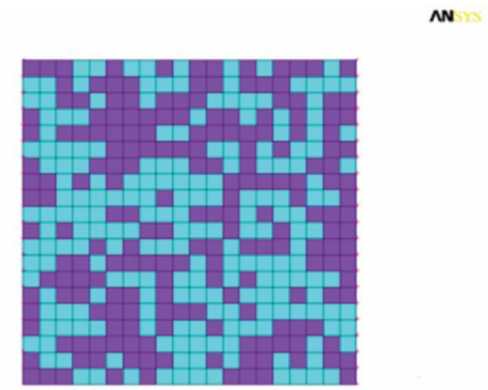

Figure 8. The finite element model section of the porosity of 49.95%

Steady-state parallel-plate method

In steady-state parallel-plate method, the measured material is subjected to a stationary temperature gradient while the heat flow is measured as a function of this gradient. The measured material is enclosed between two parallel plates and heat is generated in the upper plate. Figure 9 shows the schematic diagram of the computational model with the applied boundary conditions for the numerical computation. Therefore constant temperature boundary conditions T_1 and T_2 are prescribed on two opposing surfaces whereas all remaining surfaces are adiabatic.

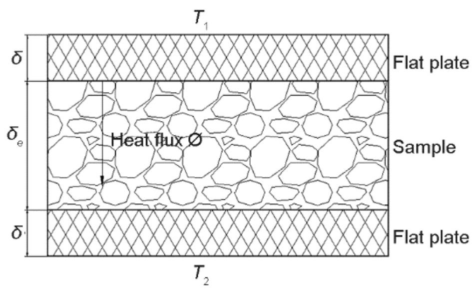

Figure 9. The schematic diagram of steady-state plate method

Xia *et al.* [25] indicated the convective between the solid skeleton and pores of fluid could be ignored when the diameter of pores was less than 5 mm. To the porous materials, if the temperature is low, the radiation heat transfer could also be ignored. As radiation and convection is neglected and based on these simplifications ETC can be calculated directly using Fourier's law:

$$\Phi = A\frac{\Delta t}{\dfrac{\delta}{\lambda_1}+\dfrac{\delta_e}{\lambda_e}+\dfrac{\delta}{\lambda_2}} \tag{3}$$

where Φ [W] is the heat flow, Δt [K] – the temperature difference, δ_e [m] – the sample thickness, and λ_e [$Wm^{-1}K^{-1}$] – the ETC of sample.

Base on the finite element method, heat transfer simulations were conducted taking into account the various particulate fouling micro-structure parameters such as porosity and pore size. The porosity varied between 20% and 50%, the pore size between 0.0001 and 0.002 m. The effects of porosity and pore size on ETC of particulate fouling were analyzed by using the data obtained in simulated calculation.

Calculation and analysis

Calculation of effective thermal conductivity

The heat transfer of porous material includes four parts: heat conduction between solid skeleton, heat conduction between fluid in the pore, the convective between the solid skeleton and pores of fluid, and the radiation. The thermal radiation and thermal convection is neglected as it is low temperature and static-flow for the investigation of heat transfer in micro-structure of particulate fouling. Therefore, the heat transfer of particulate fouling is mainly heat conduction, which contains heat conduction of solid skeleton and heat conduction of fluid in the pore. That means thermal conductivity can be described with Fourier's law as shown in eq. (3). Within this analysis, steady-state parallel-plate method is applied to calculate ETC of particulate fouling. The spatial distance 5 mm between two opposing boundary surfaces and the projected area 25 mm^2 are defined by the sample geometry. The sample begins the analysis with an initial temperature of 293 K. The top of sample is the cool wall boundary, whose temperature equal to 298 K. The bottom of sample is the hot wall boundary, whose temperature equals to 308 K. The temperature difference $T_2 - T_1$ is prescribed by the constant temperature boundary conditions. The conductivity for both plates is 1.0 W/mK. The sides are period boundary condition. Prior to the numerical determination of the ETC, mesh refinement analyses were performed. For finite element model, five sets of grids of 0.2, 0.3, 0.5, 0.8, and 1.6 million cells were conducted in fig. 10 and it was found that 0.8 million cells were adequate to obtain grid-independent results. The solid skeleton of fouling is chosen as $CaCO_3$, and fluid of pores is water. The conductivity of $CaCO_3$ and water is 2.9 W/mK and 0.6 W/mK, respectively.

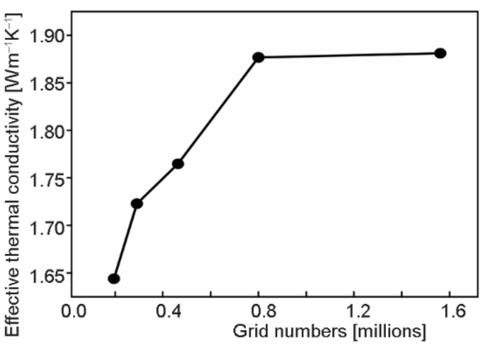

Figure 10. Grid independence analysis

To analyze the influence of particulate fouling micro-structure on ETC, the novel method is used to build the particulate fouling model, whose porosity equals to 0.1878, 0.2714, 0.3904, and 0.4995, respectively. The temperature distribution of particulate fouling model at different porosities is shown in fig. 11. From the fig. 11, we can see that the temperature distribution is a little difference in heat transfer direction

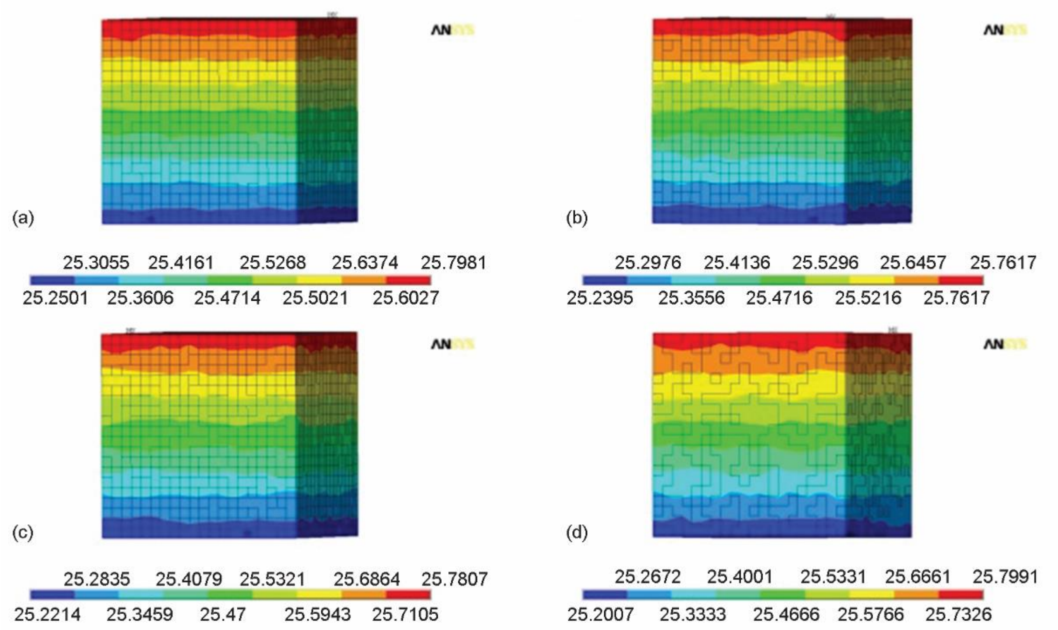

Figure 11. The temperature distribution of fouling at different porosity; (a) 18.78%, (b) 27.14%, (c) 39.04%, and (d) 49.95%

Table 2 shows ETC of particulate fouling and the error analysis between calculation results and empirical formula. From the table, we can see that the calculation results of finite element model are consisted with that by empirical formula. At the same time, it is important to point out that ETC of fouling is depended on both porosity and the cell size of pores.

Table 2. The ETC of fouling

Porosity [%]	Pore size [mm]	Empirical formula [32]	Finite element model	Absolute value of error [%]
18.78	0.05	2.468	2.496	1.134
27.14	0.05	2.276	2.293	0.747
39.04	0.05	2.002	2.004	0.010
49.95	0.05	1.751	1.740	-0.628
Average				0.630

Influence of porosity on the effective thermal conductivity of fouling

Many researchers [26-37] have proposed correlations for the prediction of ETC as a function of the fluid and solid thermal conductivities and of the porous structure geometrical parameters. Maybe the most important geometric parameter is the porosity. Therefore, the influence of porosity was carefully studied.

Figure 12 shows the porosity effect on ETC of particulate fouling for different porosity between 20% and 50%. It can be observed that ETC of particulate fouling is reduced when the porosity is increased, which is mainly attributed to the fact that for a higher void content the porous fluid thermal conductivity is lower, thereby decreasing heat transport capability. Therefore, it is important to point out that the effect of porosity on ETC of particulate fouling in the process of heat transfer are strongly coupled with the ratio of solid skeleton and porous fluid.

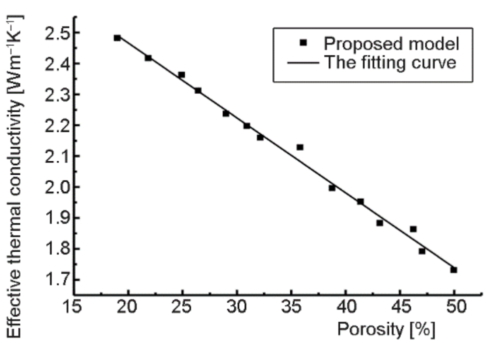

Figure 12. The regression analysis of equivalent coefficient of thermal conductivity and porosity

Through regressive analysis on the calculation results of particulate fouling, the mathematical expression between ETC of fouling and porosity were established:

$$\lambda_e = -0.02425\varepsilon + 2.95101 \quad R^2 = 0.9929 \tag{4}$$

where R^2 is the correlation coefficient, its value is over 0.99, and ε – the porosity of particulate fouling.

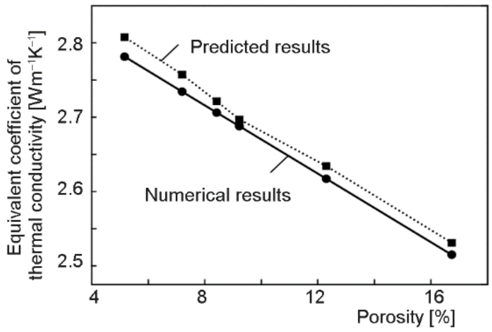

Figure 13. Comparison between numerical and predicted results

In order to validate the present model and approach, numerical simulations are conducted for ETC of particulate fouling and compared against the predicted results reported by Dyga [38]. It is seen in fig. 13 that acceptable agreement has been obtained between numerical and predicted results. In addition, the fouling samples of 31.25% and 37.14% in porosity are used in the current comparison. The ETC is 2.1932 W/mK and 2.0503 W/mK, respectively. The estimation values with eq. (4) well agree with the experimental ones (1.5~2.27 W/mK) of Hasson [2]. That proves that models and numerical methods used in the present study are accurately predicting ETC of particulate fouling.

Influence of pore size on effective thermal conductivity of fouling

In order to analyze influence of pore size on ETC of particulate fouling, APDL was used to control pore size of geometrical model, whose value equals to 1, 0.75, 0.5, and 0.25 mm, respectively. The pore size distribution is shown in fig. 14.

Figure 15 shows the effect on ETC of fouling for different pore size and porosity. As shown in fig. 15, ETC of fouling for all porosity increased with pore size increasing. Same trends in ETC were obtained with increased pore size at different porosity. When at the same pore size, ETC of fouling for small porosity was greater than that for large porosity. That's because of the higher heat transfer capability of the solid skeleton.

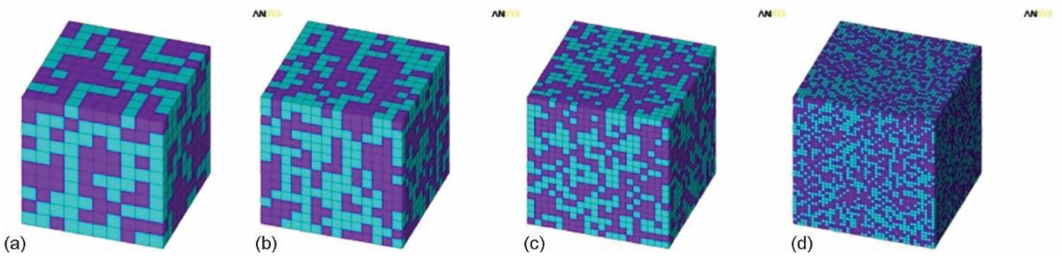

Figure 14. The pore size distribution of the porosity of 49.95%; (a) 1 mm, (b), 0.75 mm, (c) 0.50 mm, and (d) 0.25 mm

On the other hand, ETC of particulate fouling is increased with pores size increasing when the porosity is approximate. That is because the number of pores is greater and the structure is more complex when the pores size is smaller, which makes the heat conduction of particulate fouling suppressed. The heat will walk the more curved road on the condition of small pore size for the complex structure. This effect of pore size ought to be considerable, especially for a binary-constituent porous medium. From all the above, we can see that the effect of pore size on ETC of particulate fouling was smaller than that of porosity.

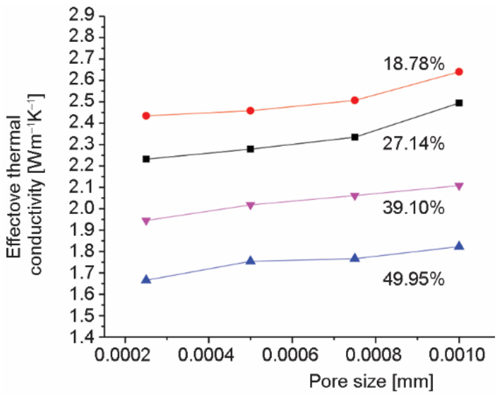

Figure 15. The regression analysis of equivalent thermal conductivity and pore size

Conclusions

In this work, ETC of particulate fouling was investigated based on porous media characteristics and heat transfer analysis. The remarkable conclusions are summarized as follows.

- A method for calculating ETC of particulate fouling is proposed. Compared with the experimental data in previous literatures and experimental data, the ETC calculated by this method presents a good agreement, which proves the feasibility of the method for research on the thermal conductivity of particulate fouling.
- The effects of porosity and pore size were studied. The calculating results indicated that ETC of particulate fouling decreases linearly with the increase of porosity, which means that the heat transfer capacity of particulate fouling is controlled by its porosity. However, the effect of pore size on ETC of particulate fouling is not evident, which means that the pore size played a minor role.
- The current study essentially contributes to calculating of overall heat transfer coefficient for the design of heat exchanger.

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