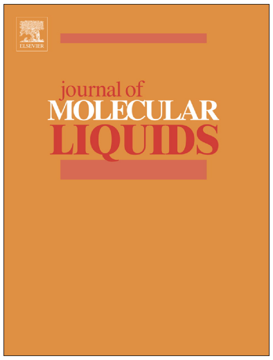


Fractal characterization of dynamic structure of foam transport in porous media

Fei Wang, Zhaomin Li, Hailong Chen, Qichao Lv, Wanambwa Silagi, Zhuo Chen

PII: S0167-7322(17)30616-5
DOI: doi: 10.1016/j.molliq.2017.06.056
Reference: MOLLIQ 7502

To appear in: *Journal of Molecular Liquids*

Received date: 28 February 2017
Revised date: 12 June 2017
Accepted date: 12 June 2017

Please cite this article as: Fei Wang, Zhaomin Li, Hailong Chen, Qichao Lv, Wanambwa Silagi, Zhuo Chen , Fractal characterization of dynamic structure of foam transport in porous media, *Journal of Molecular Liquids* (2017), doi: 10.1016/j.molliq.2017.06.056

Fractal Characterization of Dynamic Structure of Foam Transport in Porous Media

Fei Wang[1], Zhaomin Li[1], Hailong Chen[1], Qichao Lv[1] , Wanambwa Silagi[1], Zhuo Chen[2]*

(1.College of Petroleum Engineering, China University of Petroleum, Qingdao, 266580, Shandong, China 2. Geoscience Department, University of Calgary, Canada, T2N 1N4)

Abstract

The evaluation and simulation of foam fluid are still matters of significant debate despite the large number of available studies due to the excellent properties of foam and its successful applications, especially in oil and gas field development. The properties of foam fluid are substantially determined by its dynamic structure in porous media; however only a few studies that investigate and perform measurements related to such structure have been reported. In this research, a new method based on fractal theory is proposed for evaluation of aqueous foam in porous media. As a first step, the fractal characteristics of foam in porous media are confirmed by image processing and calculations. Accordingly, the foam dynamic structure is quantitatively studied by defining and calculating the foam fractal dimension. Secondly, a concise relation is established which reveals that the foam fractal dimension is nearly time-independent. Finally, a sensitivity analysis is carried out by discussing three major factors affecting foam structure in porous media. These results are expected to be helpful for further understanding the dynamic characteristics of foam fluids and their advanced applications.

Keywords: Foam Fluid; Fractal theory; Dynamic Structure; Porous Media; Image Processing;

1 Introduction

Foam fluid is a gas-liquid dispersion system whose range of applications covers various fields due to its excellent properties, especially in oil and gas field development[1] which include enhanced oil recovery, matrix acidizing[2,3], gas breakthrough control, plugging removal, etc. The control of gas mobility and the liquid production profile show the great potential of foam as an intelligent fluid [4]. Previous studies have shown that the key to a successful use of foam in oil field development lies in its stability and ability to trap gas molecules [5-7]. Therefore, it is important to study the structure of foam in porous media. A great number of previous studies have been carried out by experiments and simulations and some characteristics of foam transport in porous media have been obtained.

Core displacement experiment results have shown that the presence of foam could increase apparent viscosity of the flowing gas hence reducing gas mobility [8-13]. It was observed that foam did not increase water viscosity, but rather directly reduced gas mobility in porous media by trapping a large percentage of gas in place [14]. Besides, the presence of oil in a porous medium decreased the effectiveness of foam in reducing gas permeability; apparently oil acts as a foam depressant. However, it was found that certain foaming agents were very effective in reducing permeability even in the presence of oil. Also, continuous injection of other foaming agents increased their effectiveness, when oil was present. In recent years, computed tomography (CT) was used to study the distribution of foam during flooding in porous media. These results have shown that liquid fingered through foam rather than displacing it evenly. In different experiments in the same core, with similar initial foam states, the liquid finger took different paths through the core.The liquid injected after foam did not simply follow the path of mobile gas in the foam.

Pore-level investigations have been carried out to observe the structural change of foam, such as foam generation and rupture. Direct visual observations showed the following foam generation mechanisms: lamella leave-behind, gas-bubble snap-off, and lamella division. David J. Manlowe has shown that foam decays as a result of breakage of pseudo-emulsion films. Foam films collapse whenever nearby thin aqueous films separating gas bubbles and oil rupture. Consequently, surfactant formulation for foam insensitivity to oil in porous media should be based on stabilizing pseudo-emulsion films.

Evaluation of foam fluid performance by model simulation has been extensively investigated in the available literature. Foam fluid models are generally divided into static and dynamic models, the latter being more significant for practical applications. Research on dynamic models of foam fluid is mainly taking two directions; the first is foam drainage simulation: in this field, the results by I. Saye Robert brought a major contribution by describing the evolution of the foam membrane rearrangement, drainage, and rupture through a multi-scale model [15]. The second research direction pursues foam flow simulation [16-47] which needs to focus on the description of rheological characteristics in order to obtain successful results. The simulation of foam flow in porous media is widely used in petroleum engineering. It can also be performed upon properly adapting the model to this system, but most methods for this task are based on a gas-liquid two-phase flow model. The relative permeability and viscosity of a gas are known to vary during foam generation in porous media. Both parameters appear in the Darcy equation, and different methods have been employed to alter the mobility in the various models, i.e. reduction of the gas relative permeability, increasing of the effective gas viscosity, or a combination of both. These models are generally divided into two types: local-equilibrium models and population balance models [48]. Local-equilibrium models, especially the implicit texture model, involve a small number of parameters and are easy to solve, however they cannot properly account for the dynamic change of foam texture during foam transport in porous media, which influences foam mobility. On the other hand, population balance models can successfully achieve this goal and are therefore widely used.

The results of displacement experiments were general, ignoring internal feature and the microscopic experiments were just the opposite. The simulations of foam fluids have gradually taken foam structure into account. Furthermore, foam density has been introduced into population balance models to account for foam structure in porous media, although its value is based on empirical parameters. In summary, the majority of models fail to provide a clear description for foam structure in porous media, which is of primary importance for all foam fluid properties.

In this paper, we attempt to carry out a quantitative investigation of foam structure in porous media based on fractal theory directly without bothering to consider the changing of gas and liquid or lamella. This is mainly accomplished by image processing and derivation of the foam fractal dimension. One of the primary objectives is to analyze the dynamic characteristics of foam structure in porous media. Furthermore, we discuss the major factors influencing the foam structure in porous media. Our results are of potential interest for the dynamic studies of foam fluids and their advanced applications.

2 Image Acquisition and Processing

2.1 Image Acquisition

Foam image acquisition is the basis of the analysis of the foam structure, and its realization requires a highly accurate imaging device. A microscopic visualization device was used for image acquisition of aqueous foam. The glass-etched micromodel used was made by etching a two-dimensional network of pores and throats by a photochemical method. Then a high definition camera was employed to accurately record the changes of foam structure during the processes of foam transport in porous media. A back-pressure regulator (BPR) was used to control the back-pressure. Besides, there was a heating muff outside of the micromodel; therefore, the micromodel could be heated to a certain temperature.

Experimental materials: Glass-etched micromodel, the size of the micromodel was 10 cm × 10 cm × 6mm, and the depth and width of the channel were about 40μm and 50μm −300μm, respectively. (Model1: 150μm −300μm, Model2: 50μm −300μm, Model3: 50μm −300μm,Model4: 150μm −300μm,Model5: 180μm −300μm); Surfactant ,SDS (sodium dodecyl sulfate); Deionized water.

Experimental preparation: Surfactant solution with different concentration (0.2wt%, 0.3wt% and 0.5wt %).

Experimental procedures: The schematic of the microscopic experimental apparatus is shown in Fig.S1. Gas injection rate and liquid injection rate were both 0.01mL/min, back-pressure was 2MPa. Foam was injected through micromodels under different situations, to reveal the effects of foam ability, temperature and pore structure on the foam dynamic structure.

The images of the displacement processes are shown in Figure 1. These images track the structure of foam at different time in porous media and different micromodels (Model1, Model2, Model3, and Model4) with different permeability and porosity were used to represent different pore structure.

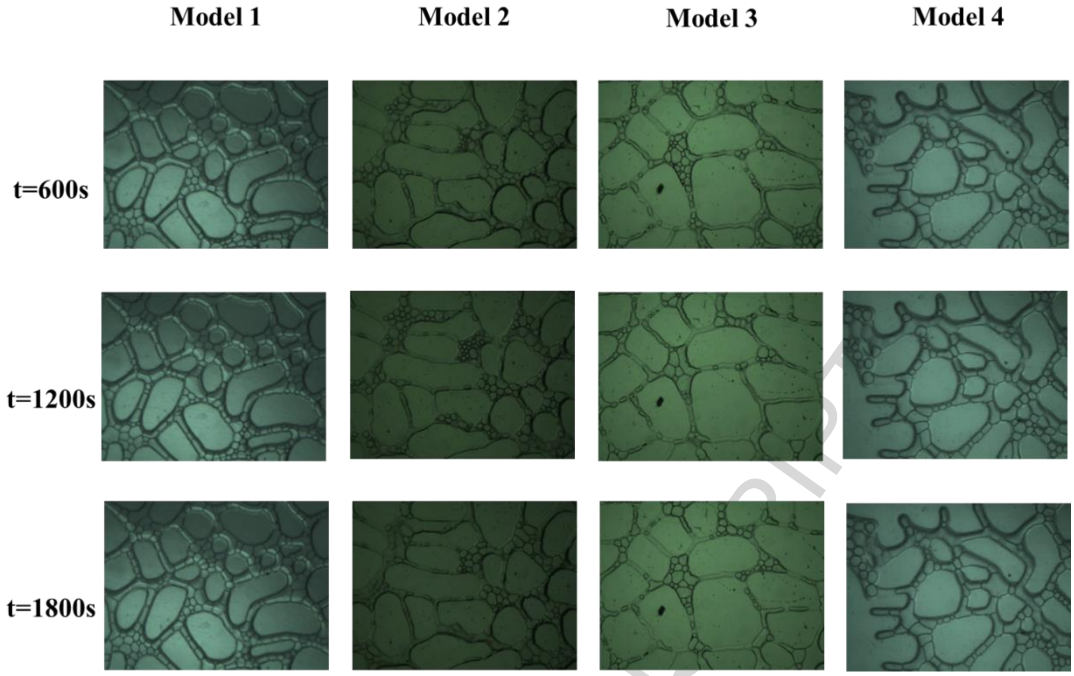


Fig.1 Chang of foam structure as a function of time during displacement

2.2 Image Processing

Some parts of the images obtained have a fuzzy appearance, especially in the foam boundary regions. As a result, image processing is required before the images can be properly analyzed; the process adopted in the present work consists of three steps:

The first step is a gray-scale transformation to improve the clarity of the image. Such transformation modifies the gray tone of each pixel, eventually changing the overall range and distribution of gray tones over the image in order to make the foam structure emerge more clearly.

The second step consists of a binarization processing which simplifies the image structure. Binary images are developed by selecting an appropriate threshold, which changes the brightness scale from the original 256-level scale to a simpler, bi-level scale. As a consequence, the boundary of foam in the image becomes clearer. This process can be described by the following function.

$$pixel'(x, y) = \begin{cases} 0, & pixel(x, y) < T \\ 1, & pixel(x, y) \geq T \end{cases} \tag{2.1}$$

Where $pixel(x, y)$ is the value assigned to initial pixel, $pixel'(x, y)$ is the value assigned to the same pixel after binaryzation, T is a certain threshold.

The foam can be clearly divided into two parts after binarization, the bubble formed by gas with some glass(displayed as white in the figure) and the lamella formed by liquid (displayed in black).(Fig.S2)

The last step is to remove the parts of the glass on the image by conventional image processing software. After this step, there are only foams left on the images. Better yet, the white part is bubble.

3 Fractal Structure of Aqueous Foam in Porous Media

3.1 Fractal Characteristics of Aqueous Foam in Porous Media

Fractal theory is a discipline which studies those geometries, based on self-similarity, which are commonly found in a number of natural systems [49, 50]. In fact, almost all fractals are at least partially self-similar. This means that parts of the fractal are identical to the entire fractal on a smaller scale. Fractals attempt to model a complex iterative process by searching for the simpler processes underneath. From the images of foam after image processing, we can see that the foam has an irregular structure which cannot be measured by conventional ways. However, foams are partially self-similar in a statistical sense (Fig.S3). In order to verify that the foam does have fractal characteristics in porous media, it is necessary to calculate the fractal dimension of the foam.

3.2 Fractal Dimension Calculation of Aqueous Foam

1. Calculation Method of Foam Fractal Dimension

In this paper, the box-counting dimension [51] is used to determine the fractal dimension. To calculate the foam fractal dimension of the foam (D_f), the fractal is thought of as set on an evenly spaced grid, and the number of boxes which are required to cover the whole white area is counted (Fig.S4). The box-counting dimension is calculated by studying how this number changes as the grid becomes finer, by applying a box-counting algorithm. Suppose that $N(r)$ is the number of boxes of characteristic length r required to cover the set. The foam box-counting dimension is defined as:

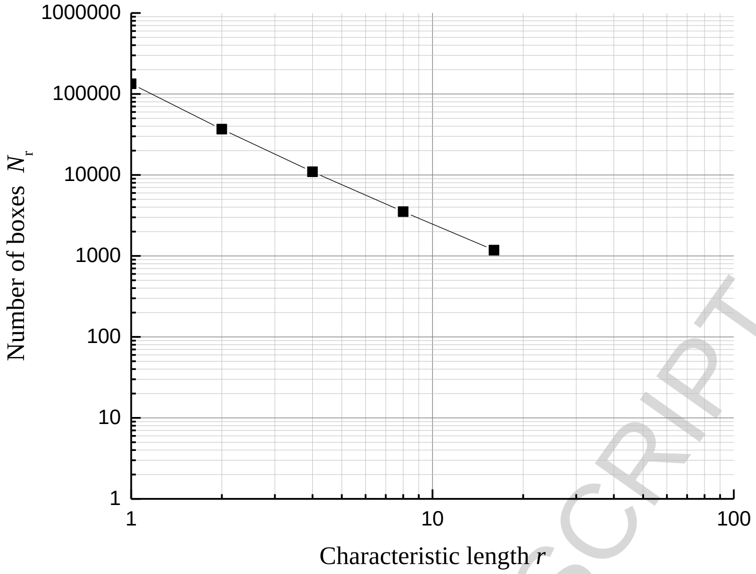
$$D_\mathrm{f} = -\lim_{r\to 0} \mathrm{lg}\, N(r) \,/\, \mathrm{lg}(r) \tag{3.1}$$

Since the characteristic length is a finite quantity, we can compare two basic graphic elements with different characteristic lengths to measure fractal graphics. Two sets of data, r_i and $N_i(r_i)$, can be obtained by changing the characteristic length. Next, two double-logarithmic curves of the number of boxes are plotted as a function of the characteristic length. If the curve is linear, the foam structure possesses fractal characteristics, and the absolute value of the slope obtained by the least square method gives the fractal dimension of the foam. If the curves are not linear, we can conclude that the foam structure does not possess fractal characteristics. A flow chart of the foam fractal dimension calculation process is presented in Fig.S5.

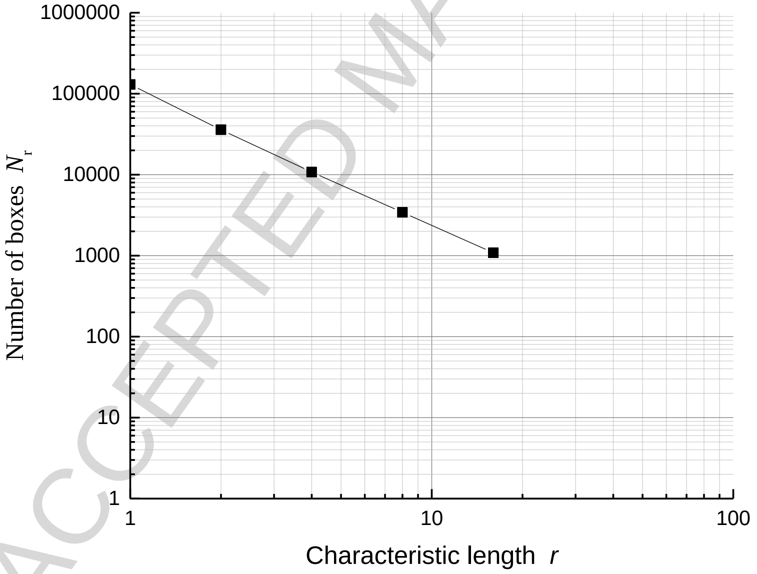
2. Foam Fractal Dimension Calculation and Verification

Fig.2 shows some representative results of fractal dimension calculation of SDS foam (0.3wt %) at different times in porous media (Model 1) using the method described above. From these curves we can see a linear correlation between the number of boxes and the characteristic length and the same results can be obtained in other cases. Accordingly, the foam does have fractal characteristics as we assumed in section 3.1. The calculated fractal dimension at four different times (i.e. the absolute value of the slope) is 1.675, 1.66, 1.672 and 1.681.

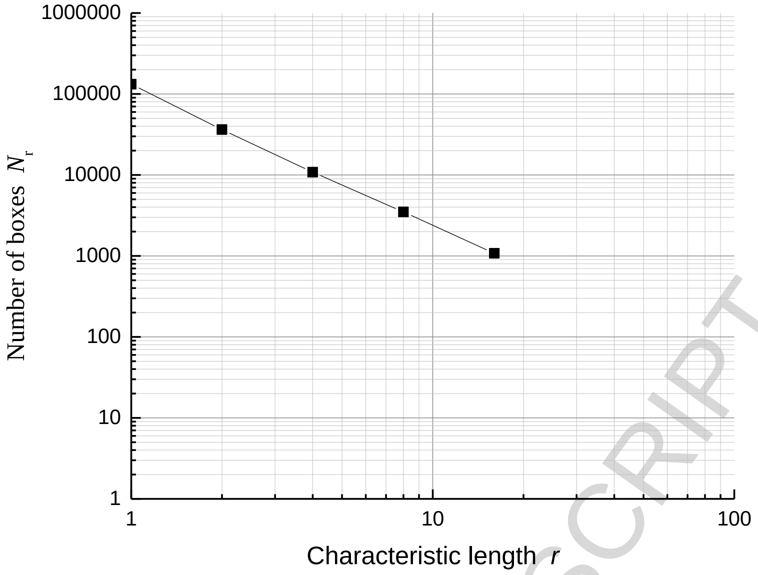
In general, the fractal dimension identifies the amount of space occupied by complex systems and measures their degree of irregularity. Since a foam fluid is a gas-liquid dispersion system, foam fractal dimension can indicate the distribution of gas in a liquid, i.e. a smaller fractal dimension of certain foam indicates a more uniform distribution of bubbles throughout the foam; conversely, the bigger the fractal dimension, the larger the irregularity of the gas distribution. Actually, in porous media, coalescence is the major factor influencing the irregularity of the gas distribution. Therefore, bigger fractal dimension implies a faster coalescence or worse stability of foam.


1000000
100000
10000
1000
100
10
1
Number of boxes N_r
1
10
100
Characteristic length r

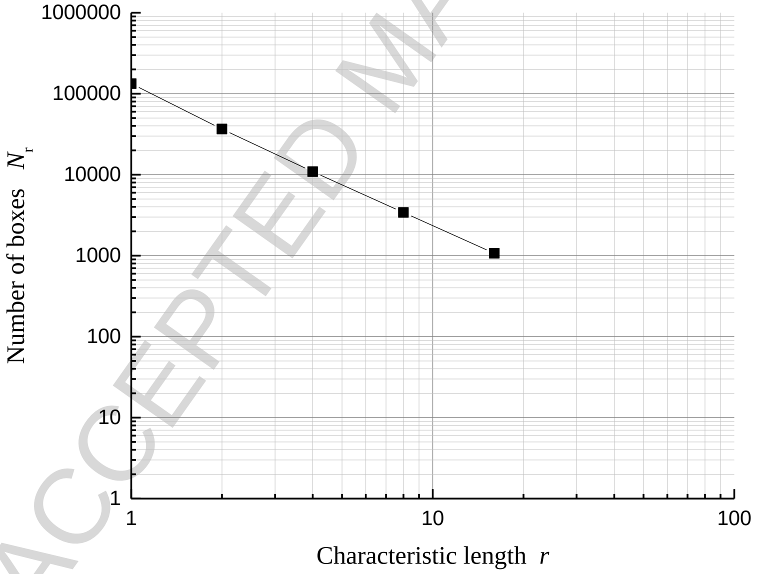
(A)


1000000
100000
10000
1000
100
10
1
Number of boxes N_r
1
10
100
Characteristic length r

(B)



(C)



(D)

Fig.2 Fractal dimension calculation curves of Model 1 at different times.

(A)time=600s;(B)time=1000s;(C)time=1200s;(D)time=1800s.

4 Dynamic Structure Characteristics of Foam Transport in Porous Media

4.1 Fractal Characteristics of Foam Transport in Porous Media

In the previous section, we used the fractal dimension to characterize the structure of foam. The dynamic change of the foam structure can then be simulated by studying the variation of fractal dimension with time.

Fig.3 shows the variation of SDS foam (0.3wt %, 22℃)fractal dimension in about half an hour (Model 1), acquiring the data for the calculations from images, processed as discussed previously. The figure shows that the foam fractal dimension is nearly time-independent (about 1.67 in this case) and the images on the figure show the foam structure at the points marked with circles. Therefore, the fractal dimension of foam remains constant with the change of the foam structure in porous media (i.e. with time), leading to the following equation:

$$D_{\mathrm{f}} = C, \frac{\partial D_{\mathrm{f}}}{\partial t} = 0 \tag{4.1}$$

where D_{f} is the foam fractal dimension, t is the time, C is a constant that related to the properties of aqueous foam and to experimental conditions (discussed next).

This equation can express the characteristics of foam structure during foam transport in porous media under local equilibrium. That is to say, although the foam coalescence or generation appears regularly in the case of micro scale, the foam fractal dimension is almost constant on the whole. In fact, under the experimental conditions, when displacement achieves system stability, foam will be in dynamic equilibrium as a whole. Accordingly, the structural distribution of bubbles varies little with time changing as a whole, so does the foam fractal dimension representing the foam overall structure. At the micro level, foam coalescence and generation reach a stable state, which only changes the local structure and does not change the overall structure. This conclusion also implies that implicit models and population balance models used for foam simulation are equivalent at local equilibrium.

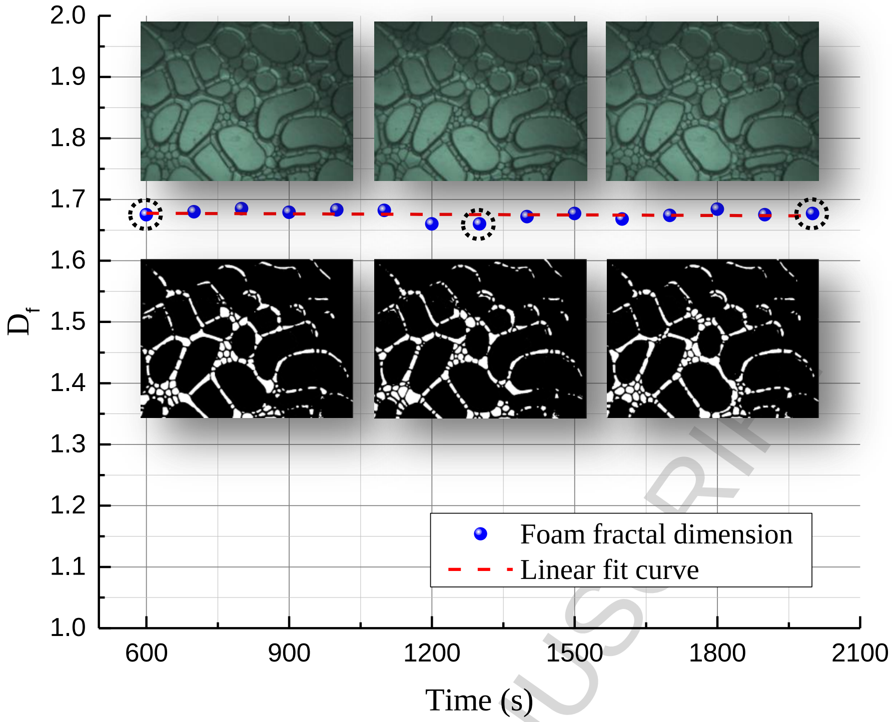


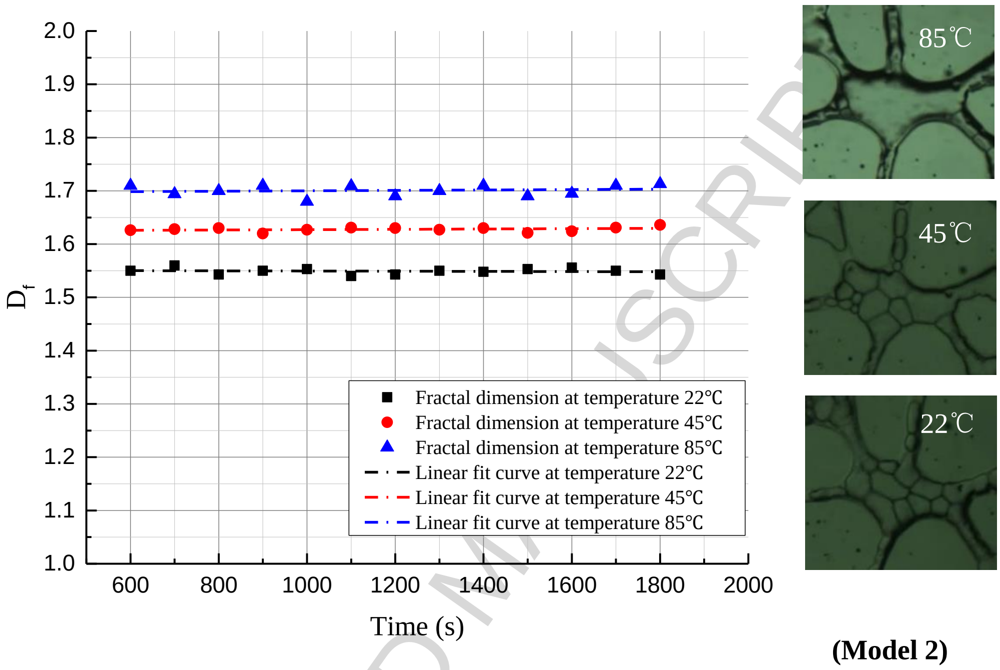
Fig.3 Variation of foam fractal dimension as a function of time

4.2 Major Factors affecting Foam Fractal Dimension in Porous Media

Foam structure is affected by various factors, including the type and concentration of the foaming agent, temperature and pressure. Therefore, more experiments and calculations should be carried out to see if the foam fractal dimension is still constant and how it will change. In this part, we focus on the effects of temperature and concentration first, which are the regular and primary factors influencing the foam structure. Then, pore structure which is an important factor to foam transport in porous media was discussed by changing the micromodel. At last, bubble size was analyzed to give more insight on foam structure distribution and the relationship between fractal dimension and foam structure.

1. Effects of Temperature

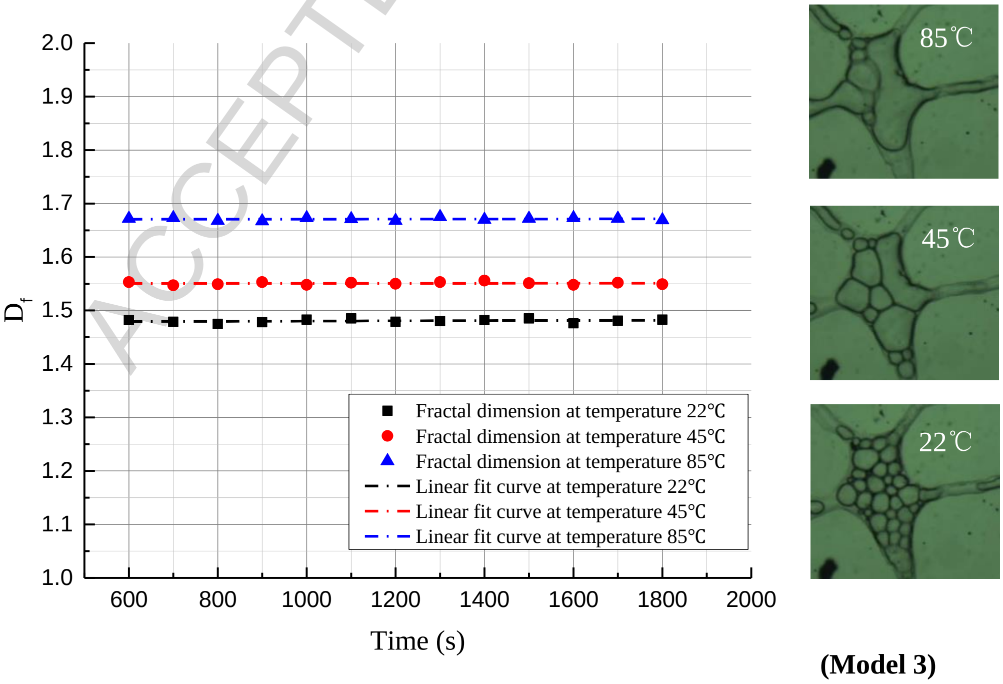
Fig.4a shows the variation of the fractal dimension of SDS foam (0.5wt %) as a function of time in porous media (Model 2), at a temperature of 22℃, 45℃ and 85℃. The trend in fractal dimension was still constant with the changing of time, but the value was different at different temperatures. In fact, the foam fractal dimension was bigger at a temperature of 85℃ (about 1.7)than at 22℃(about 1.55) and between them at temperature 45℃(1.62), because a higher temperature causes a faster movement of molecules in the gas which leads to a worse stability of foam as shown in the images (part of the pore at different temperature) right of Fig.4a. As a result, we may state that variations of temperature only led to changes of the value of foam fractal dimension in porous media but did not change the trend of it with changing time. The same results can be obtained in other models, as shown in Fig.4b (Model 3), and the foam fractal dimension at three different temperature(22℃, 45℃, 85℃) were 1.48, 1.55 and 1.67 respectively.



Part of the pore (Model 2) at different temperature

(Model 2)

Fig.4a Variation of foam fractal dimension as a function of time at different temperatures



Part of the pore (Model 3) at different temperature

(Model 3)

Fig.4b Variation of foam fractal dimension as a function of time at different temperatures

2. Concentration of Foaming Agent

Fig.5a shows the variation of SDS foam(22℃) fractal dimension with time at a foaming agent concentration 0.2wt%, 0.3wt% and 0.5wt%. The fractal dimension in this case was again nearly constant with the changing of time, with different value for different concentrations of the foaming agent. In fact, the fractal dimension was smaller at a concentration of 0.5wt% (about 1.55) than that at 0.2wt% (about 1.69) and between them at a concentration of 0.5wt% (about 1.65), because a higher concentration implies a better stability of foam as shown in the images (part of the pore at different concentration) right of Fig.5a. Therefore, the concentration of the foaming agent also affected the foam structure in porous media, but it did not change the trend of it with changing time too. The same results can be obtained in other models, as shown in Fig.5b (Model 3), and the foam fractal dimension at three different temperature(0.5wt%, 0.3wt%, 0.2wt%) were 1.48, 1.58 and 1.62 respectively.

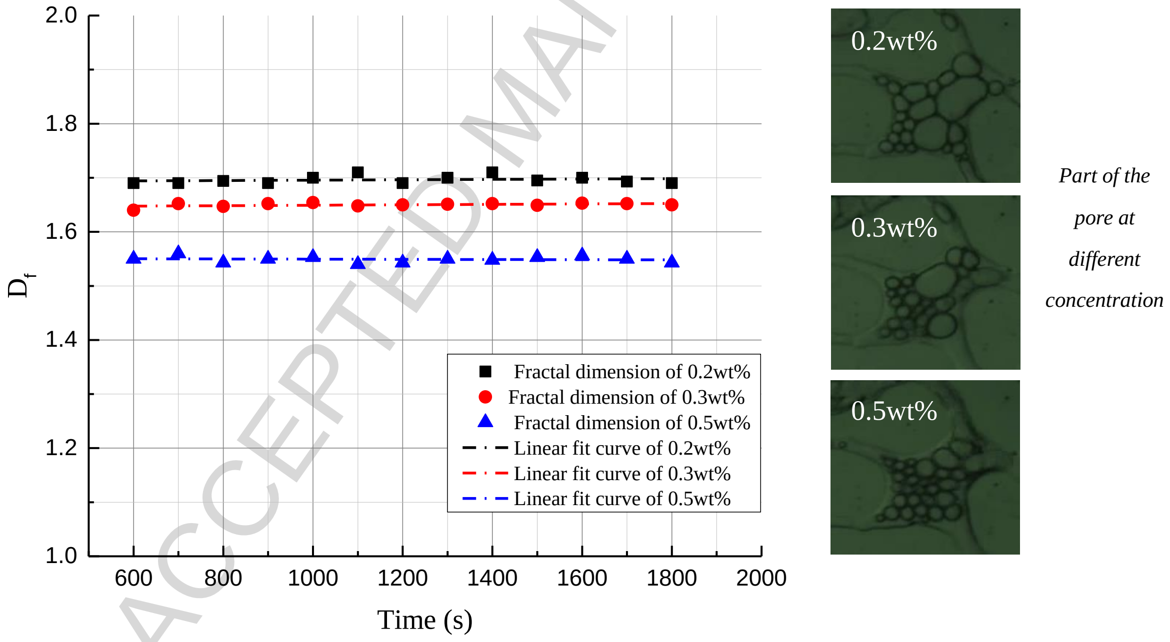


Fig.5a Variation of foam fractal dimension as a function of time for different concentrations (Model 2)

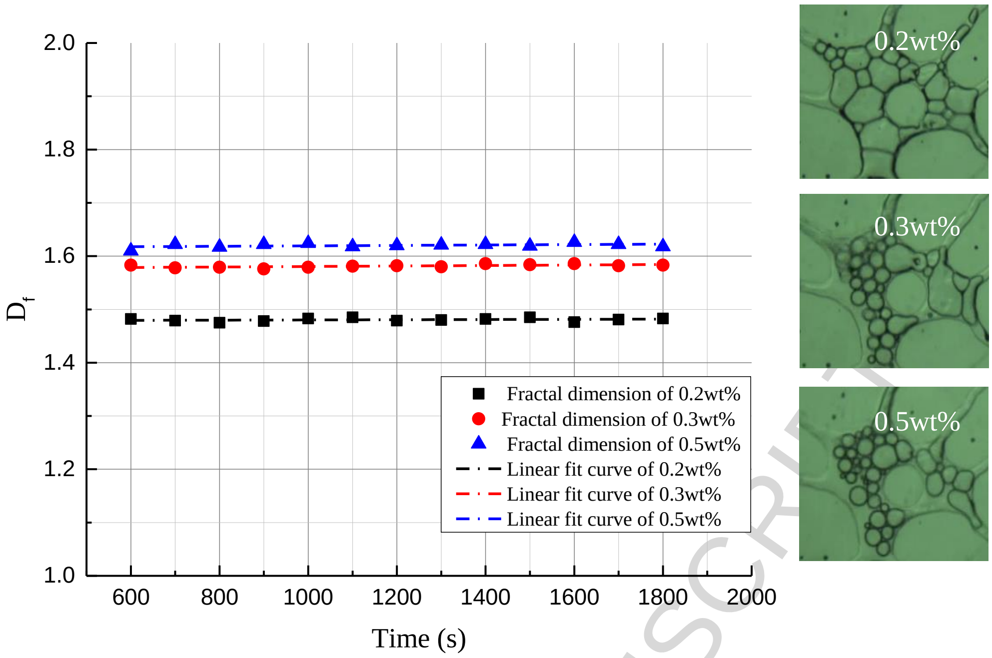
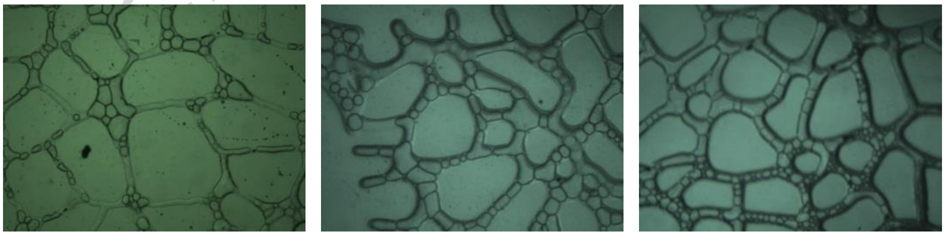


Fig.5b Variation of foam fractal dimension as a function of time for different concentrations (Model 3)

3. Pore Structure

Fig.7 shows the variation of SDS foam fractal dimension with time at different pore structure (Fig.6 Model 3, Model 4 and Model 5). The fractal dimension was still constant with the change of time with different pore structure. In the case of Model 3, the foam fractal dimension was about 1.5; in the case of Model 4, the fractal dimension was about 1.6; in the case of Model 5, the fractal dimension was about 1.72.Therefore, pore structure did not affect the trend of foam fractal dimension or foam structure in porous media too, but it changed the value of it largely.



Model 3 **Model 4** **Model 5**

Fig.6 Different pore structures

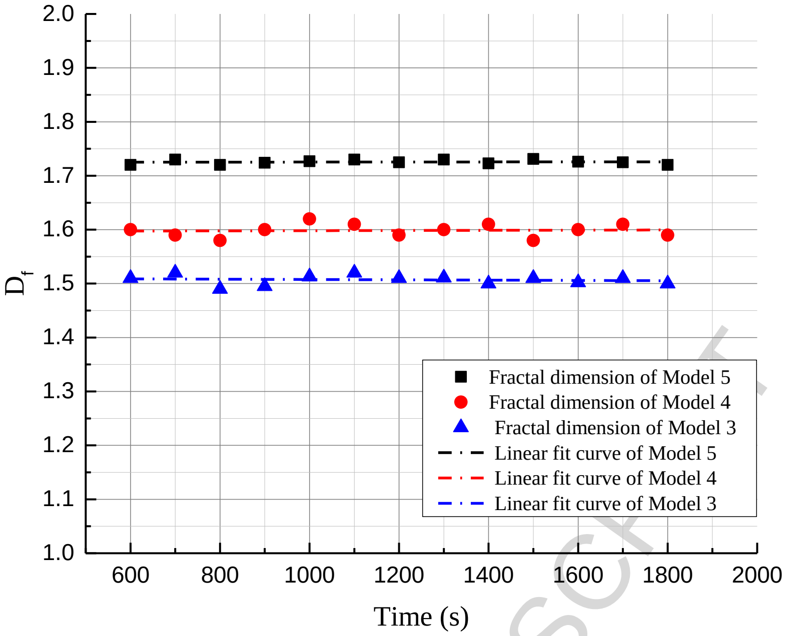


Fig.7 Variation of foam fractal dimension as a function of time at different pore structure

In this part, three major factors affecting foam fractal dimension in porous media were discussed. The foam fractal dimension is still time-independent although we changed these factors. The value of fractal dimension varied with these factors and the pore structure was the largest contributing variable.

Therefore foam fractal dimension can be an important reference index to evaluate the dynamic characteristics of foam fluid in porous media. The relationship between fractal dimension and other normal index, such as resistance factor, can be established. Besides, foam fractal dimension can be introduced in simulation models to replace some empirical parameters.

4. Bubble size

The foam stability has a significant relationship with the bubble size distribution. In this part, we analyze the bubble size distribution and the relationship between bubble size and fractal dimension using CSA (cell size analysis) option of Foamscan as showed in Fig.8.

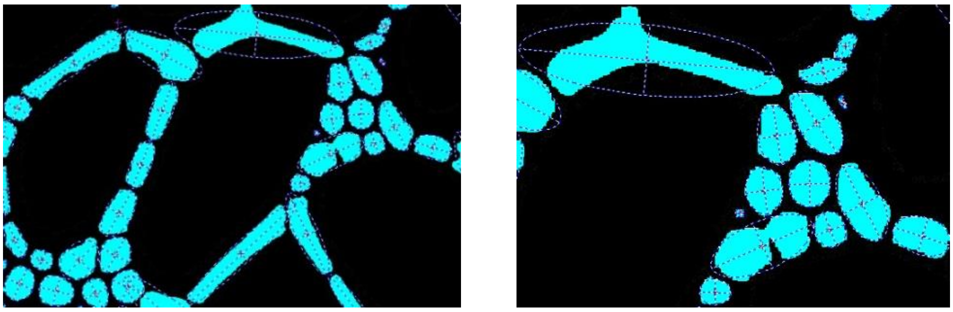


Fig.8 Measurement of bubble size using CSA option of Foamscan

Fig.9 shows the variation of bubble size dimension as a function of time in porous media (Model 1), at a temperature of 22℃. From the curves we can see that mean of bubble size and standard deviation of bubble size changed in a very small range. In other words, the numbers of foam and the difference of bubble size changed a little with the changing of time. This conclusion was in accord with the result that the foam fractal dimension is almost constant on the whole discussed before.

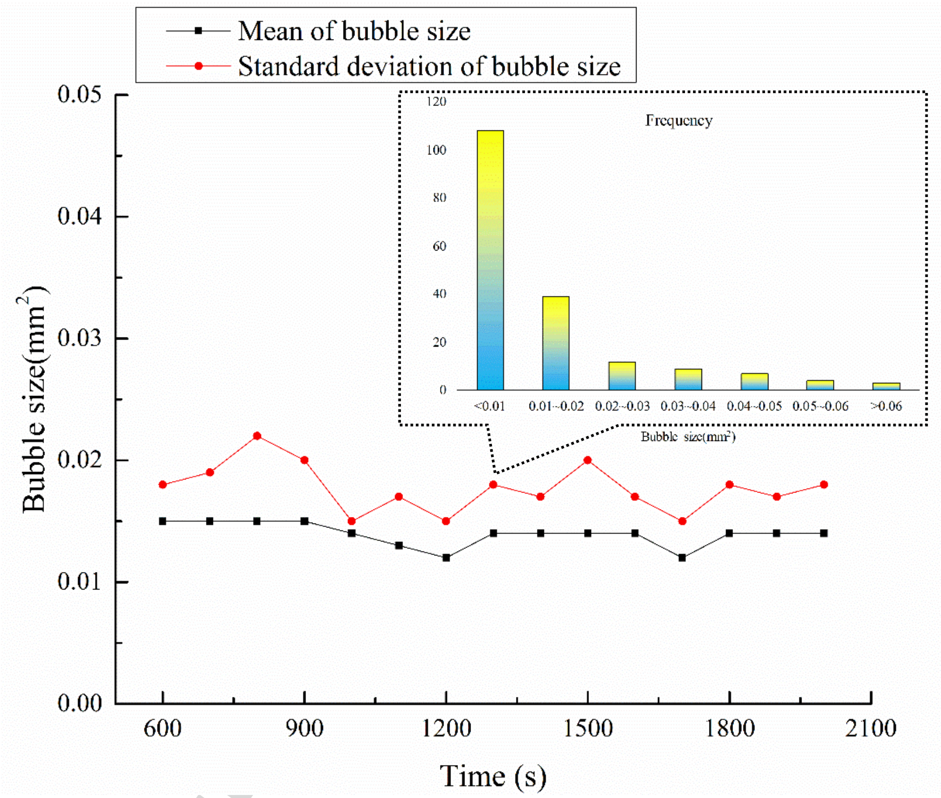


Fig.9 Variation of bubble size dimension as a function of time (Model 1)

Fig.10 show the bubble-size distribution at different temperature (22℃,45℃,85℃) corresponding to different fractal dimension(1.48,1,55,1.67). The total number of foams changed a little, but the number of foams with smaller bubble size decreased with temperature increasing and the number of foams with lager bubble size increased with temperature increasing. In summary, a higher temperature causes a faster coalescence rate of foam which leads to a lager ratio of big bubble.

Fig.11 shows the relationship between bubble size and foam fractal dimension corresponding to Fig.10. From the curves we can see that mean of bubble size and standard deviation of bubble size increased with fractal dimension increasing. Combined with Fig.10 analysis, higher temperature (bigger fractal dimension) causes a more number of big bubbles and a lager difference of bubble size. In other words, a smaller fractal dimension of certain foam indicates a more uniform distribution of bubbles throughout the foam.

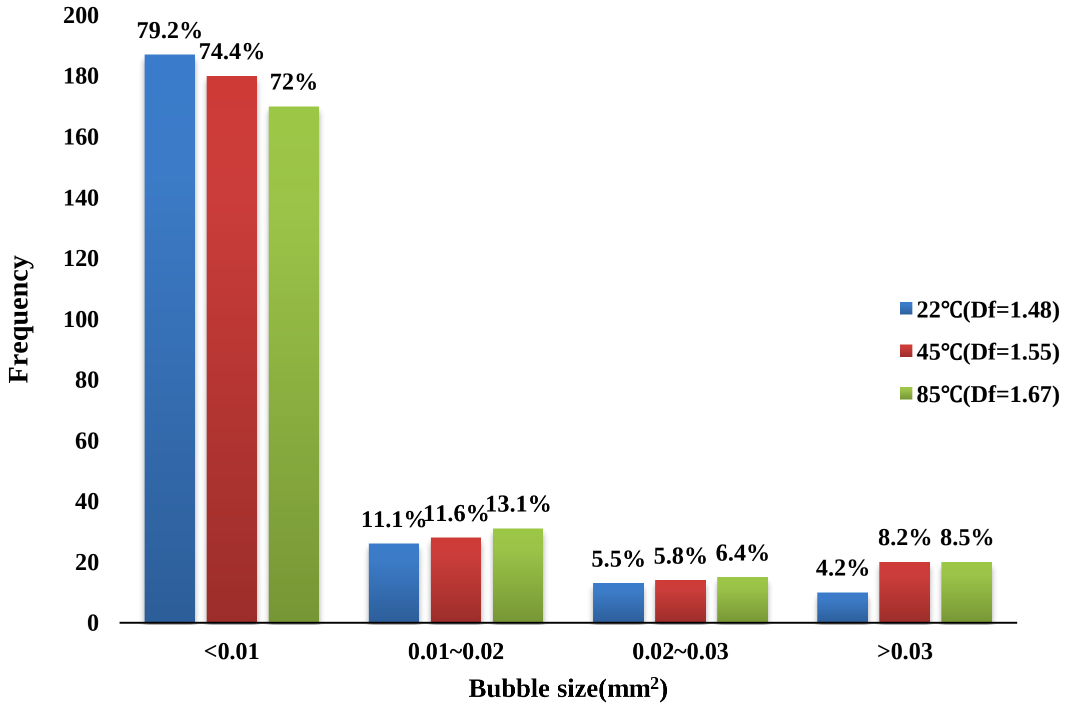


Fig.10 Bubble-size distribution at different temperature

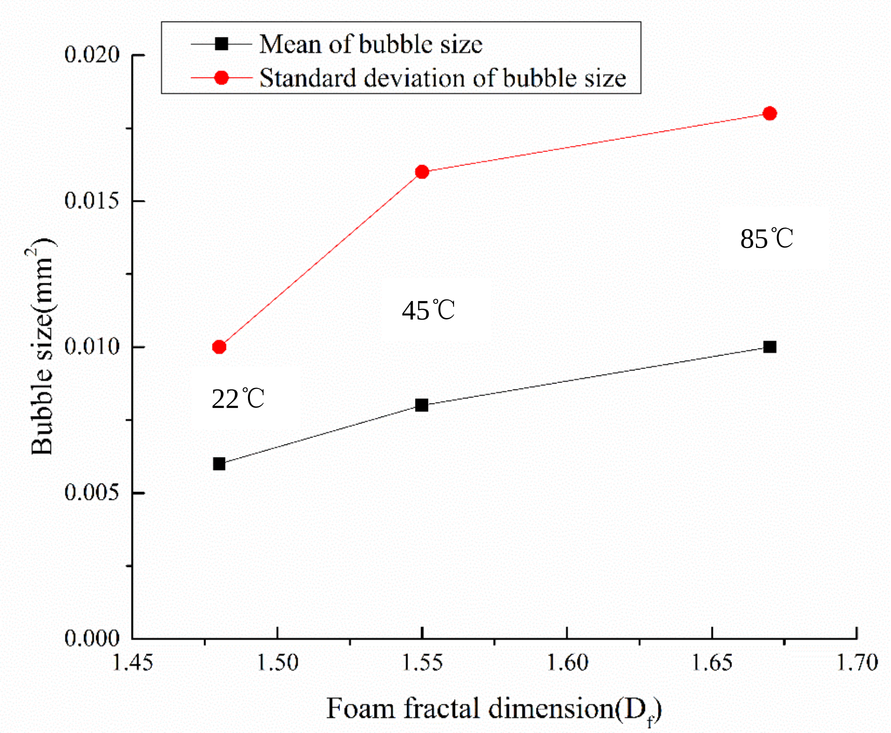


Fig.11 Relationship between bubble size and foam fractal dimension (Model 2)

5 Conclusions

(1) In this work, we demonstrated that foam fluids have fractal characteristics in porous media, exhibiting a box-counting fractal dimension between 1 and 2 based on 2-dimensional images.

(2) The fractal dimension of aqueous foam is nearly time-independent during displacement.

(3) Three factors affecting the foam structure, namely temperature, concentration and pore structure were separately analyzed. The results show that the trend in fractal dimension was still constant with the changing of time, but the value was different at different conditions.

(4) Analyses of bubble size illustrated that a smaller foam fractal dimension indicates a more uniform distribution of bubbles throughout the foam.

Acknowledgements

This work was financially supported by National Natural Science Foundation of China (51274228) and the Fundamental Research Funds for the Central Universities (15CX06032A). We sincerely thank other persons in the Foam Research Center in China University of Petroleum (East China) for helping with the experimental research.

Appendix A. Supplementary data

Fig. S1 to S5 are given as supplementary information.

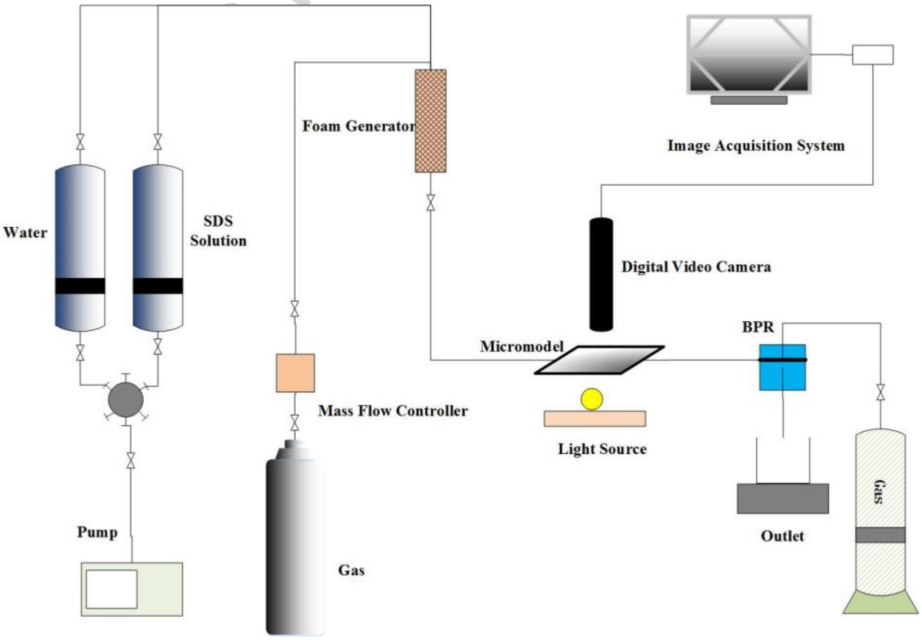


Fig.S1 Schematic of the microscopic experimental apparatus

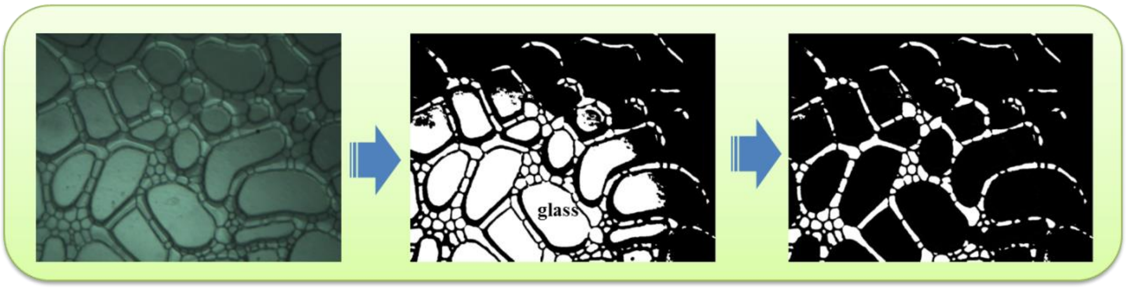


Fig.S2 Images of foam before and after image processing

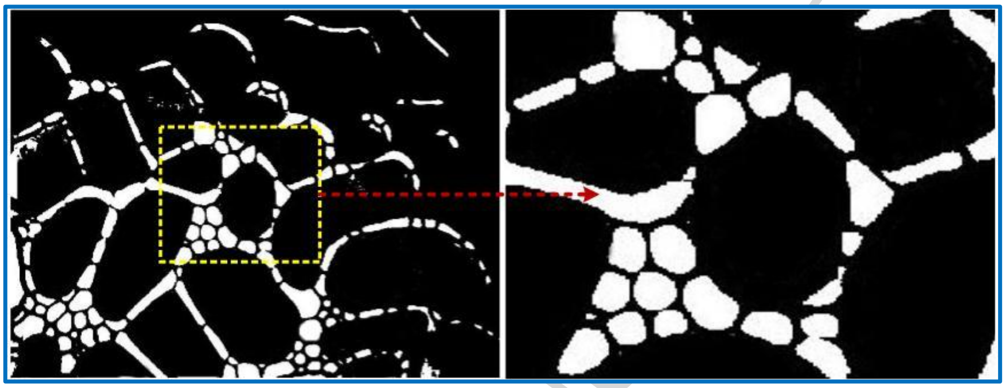


Fig.S3 Self-similarity of the part and the whole in foams

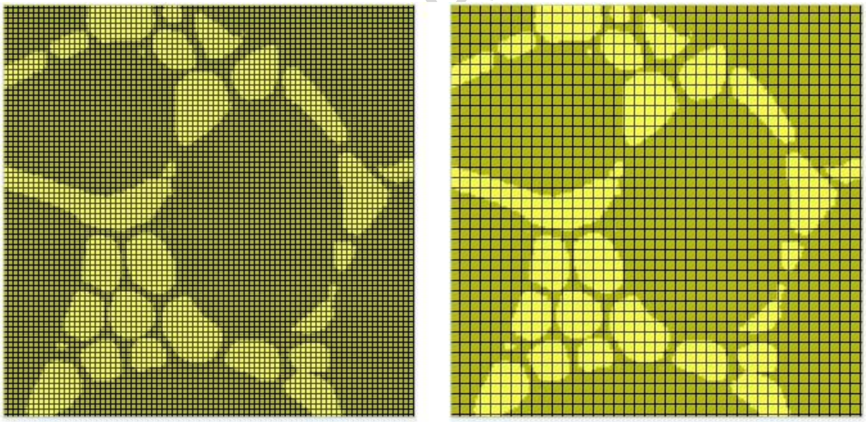


Fig.S4 Sketch map of two grid divisions for the box-counting dimension process with different characteristic length

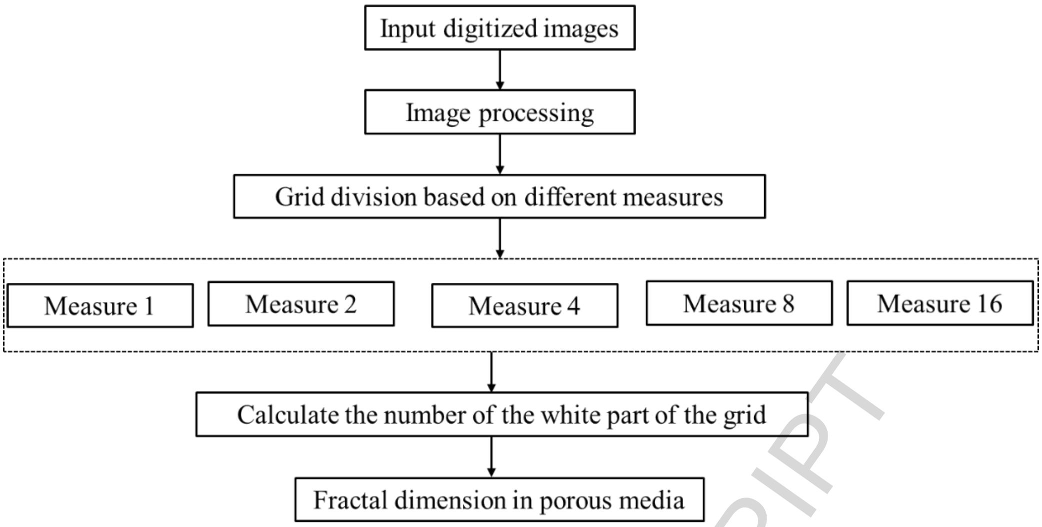


Fig.S5 Flow chart of fractal dimension calculation

References

[1] Z.L.Li, W.D.Qian, Survey on the application of foam fluid in China oil field, Drilling Fluid & Completion Fluid, 1994, 11(1):1-5.

[2] W.R. Rossen, M.W. Wang. Modeling Foams for Acid Diversion. SPE Journal, 1999, 4: 92-100.

[3] Kennedy D. K., Kitziger F. W., Hall B. E. Case study on the effectiveness of nitrogen foams and water-zone diverting agents in multistage matrix acid treatments [J]. SPE Production Engineering. 1992, 7(2): 203-211 (SPE 20621)

[4] Songyan Li, Zhaomin Li, Riyi Lin, et al. Research and Application of Mathematical Model for Foam Diversion Acidizing [C]. Presented at the 2008 SPE Western Regional and Pacific Section AAPG Joint Meeting held in Bakersfield, California, U.S.A., 31 March–2 April, SPE 114003

[5] Sun Q, Li Z, Li S, et al. Utilization of surfactant-stabilized foam for enhanced oil recovery by adding nanoparticles [J]. Energy & Fuels, 2014, 28(4): 2384-2394.

[6] Sun Q, Li Z, Wang J, et al. Aqueous foam stabilized by partially hydrophobic nanoparticles in the presence of surfactant [J]. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 2015, 471: 54-64.

[7] Sun Q, Li Z, Wang J, et al. Properties of multi-phase foam and its flow behavior in porous media [J]. RSC Advances, 2015, 5(83): 67676-67689.

[8] Bernard G. G., Holm L. W., Jacobs W. L. Effective of foam on trapped gas saturation and

on permeability of porous media to water [J]. SPE Journal. 1965, 5(4): 295-300.

[9] Friedmann F., Jensen J. A. Some parameters influencing the formation and propagation of foams in porous media [C]. SPE 15087, 1986.

[10] Huh D. G., Handy L. Comparison of steady- and unsteady-state flow of gas and foaming solution in Porous media [J]. SPE Reservoir Engineering, 1989, 4(1): 77-84.

[11] Sanchez J. M., Schechter R. S. Surfactant effects on the two-phase flow of steam-water and nitrogen-water through permeable media [J]. Journal of Petroleum Science & Engineering. 1989, 3(1-2): 185-199.

[12] Bretherton F. P. The motion of long bubbles in tubes [J]. Journal of Fluid Mechanics, 1961, 10: 166-188.

[13] Xu Q., Rossen W. R. Effective viscosity of foam in periodically constricted tubes [J]. Colloids Surfaces, 2003:175-194.

[14] Gillis J. V., Radke C. J. A dual-gas tracer technique for determining trapped gas saturation during steady foam flow in porous media [C]. SPE 20519, 1990.

[15] Saye R I, Sethian J A. Multiscale modeling of membrane rearrangement, drainage, and rupture in evolving foams [J]. Science, 2013, 340(6133): 720-724.

[16] Jian Hou, Qingjun Du, Zhenquan Li, et al. Experiments on foam texture under high pressure in porous media. Flow Measurement and Instrumentation, 2013(33):68-76.

[17] Zhen Li, William R.Rossen, Quoc P.Nguyen. Three-Dimensional Modeling of Tracer Experiments to Determine Gas Trapping in Foam in Porous Media. Energy &Fuels, 2010(24):3239-3250.

[18] Kun Ma, Jose L. Lopez-Salinas, Maura C. Puerto, et al. Estimation of Parameters for the Simulation of Foam Flow through Porous Media. Part 1: The Dry-Out Effect. Energy &Fuels, 2013(27):2363-2375.

[19] Chi U.Ikoku, Henry J.Ramey. Flow of Foam in Porous Media. SPE 7192.

[20] C.H.Marfoe, H.Kazemi. Numerical Simulation of Foam Flow in Porous Media. SPE 16709.

[21] A.H.Falls, G.J.Hirasakl, T.W.Patzek, et al. Development of a Mechanistic Foam Simulator: The Population Balance and Generation by Snap-Off. SPE 14961.

[22] A.W.Fisher, R.W.S.Foulser. Mathematical Modeling of Foam Flooding. SPE 20195.

[23] S.I.Chou. Percolation Theory of Foam in Porous Media. SPE 20239.

[24] Francols Friedmann, W.H.Chem, P.A.Gauglltz. Experimental and Simulation Study of High-Temperature Foam Displacement in Porous Media. SPE 17357.

[25] A.R.Kovscek, T.W.Patzek, C.J.Radke. Simulation of Foam Transport in Porous Media. SPE 26402.

[26] A.R.Kovscek, T.W.Patzek, C.J.Radke. A Mechanistic Population Balance Model for Transient and Steady-State Foam Flow in Boise Sandstone. Chemical Engineering Science, 1995(23):3783-3799.

[27] W.R.Rossen, S.C.Zeilinger, Jianxin Shi, et al. Simplified Mechanistic Simulation of Foam Processes in Porous Media. SPE 57678.

[28] W.R.Rossen, Z.H.Zhou. Modeling Foam Mobility at the “Limiting Capillary Pressure”. SPE 22627.

[29] Z.H.Zhou, W.R.Rossen. Applying Fractional-Flow Theory to Foam Processes at the “Limiting Capillary Pressure”. SPE 24180.

[30] Z.H.Zhou, W.R.Rossen. Applying Fractional-Flow Theory to Foams for Diversion in Matrix Acidization. SPE 24660.

[31] J.A.Robert, M.G.Mack. Foam Diversion Modeling and Simulation. SPE 29676.

[32] Anthony R. Kovscek, Tadeusz W.Patzek, Clayton J.Radke. Mechanistic Foam Flow Simulation in Heterogeneous and Multidimensional Porous Media. SPE 39102.

[33] J.X.Shi,W.R.Rossen. Simulation of Gravity Override in Foam Processes in Porous Media. SPE 35166.

[34] H.J.Bertin, M.Y.Quintard, L.M.Castanier. Development of a Bubble-Population Correlation for Foam-Flow Modeling in Porous Media. SPE 52596.

[35] L.Cheng, A.B.Reme,D.Shan, et al. Simulating Foam Processes at High and Low Foam Qualities.SPE59287.

[36] L.Cheng, S.I.Kam,M.Delshad, et al. Simulation of Dynamic Foam-Acid Diversion Processes. SPE 68916.

[37] L.Cheng, S.I.Kam,M.Delshad, et al. Simulation of Dynamic Foam-Acid Diversion Processes. SPE 79639.

[38] Pacellil.J.Zitha. Foam Drainage in Porous Media. Transport in Porous Media,

2003(52):1-16.

[39] S.I.Kam, W.R.Rossen. A Model for Foam Generation in Homogeneous Media. SPE 87334.

[40] S.I.Kam, Q.P.Nguyen, Q.Li, et al. Dynamic Simulations with an Improved Model for Foam Generation. SPE 90938.

[41] P. A. Gauglitz a, F. Friedmann, S.I.Kam, et al. Foam generation in homogeneous porous media. Chemical Engineering Science, 2002(57): 4037-4052.

[42] Z.F. Dholkawala, H.K. Sarma, S.I. Kam. Application of fractional flow theory to foams in porous media. Journal of Petroleum Science and Engineering, 2007(57):152-165.

[43] Q.Chen, M.G.Gerritsen, A.R.Kovscek. Modeling Foam Displacement with the Local-Equilibrium Approximation: Theory and Experimental Verification. SPE 116735.

[44] R. Farajzadeh, B.M. Wassing, P.M. Boerrigter. Foam assisted gas-oil graity drainage in naturally-fractured reservoirs. Journal of Petroleum Science and Engineering, 2012(94-95):112-122.

[45] E. Ashoori, D. Marchesin b, W.R. Rossen. Dynamic foam behavior in the entrance region of a porous medium. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 2011(377):217-227.

[46] Huseyin O. Balan, Matthew T. Balhoff, Quoc P.Nguyen, et al. Network Modeling of Gas Trapping and Mobility in Foam Enhanced Oil Recovery. Energy & Fuels, 2011(25):3974-3987.

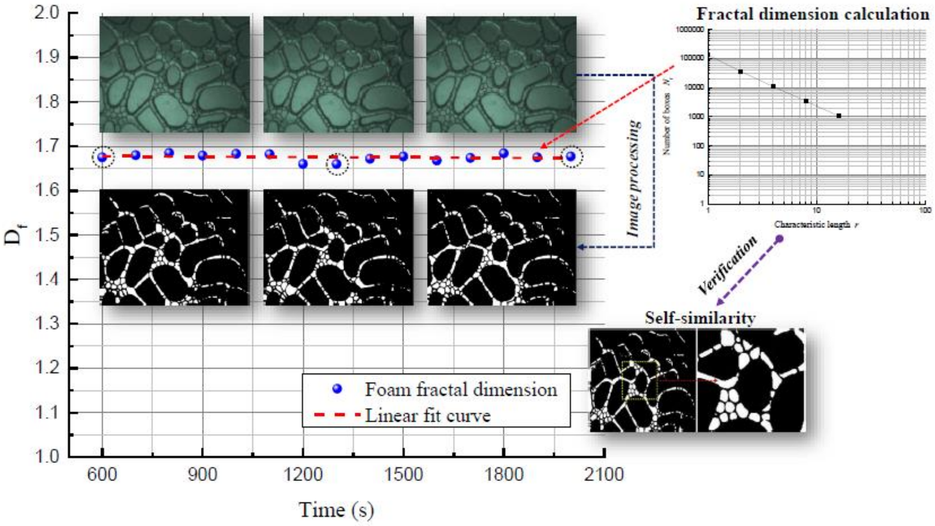
[47] A.R.Edrisi, S.I.Kam. A New Foam Model in Pipes for Drilling and Fracturing Applications.SPE162709.

[48] Kun Ma, Guangwei Ren, Khalid Mateen, et al. Modeling Techniques for Foam Flow in Porous Media. SPE 169104.

[49] B. B. Mandelbrot. How long is the coast of Britain? Statistical self-similarity and fractional dimension. Science, 1967(156):636-638.

[50] B. B. Mandelbrot. Self-Affine Fractals and Fractal Dimension. Physica Scripta, 2006, 32(4):257-260.

[51] N Sarkar, BB Chaudhuri. An efficient differential box-counting approach to compute fractal dimension of image. IEEE Transactions on Systems Man & Cybernetics, 1994, 24(1):115-120.



Graphical abstract

Highlights

- Fractal theory was used for evaluation of aqueous foam in porous media.
- A concise relation was established by calculating the foam fractal dimension.
- Multiple major factors affecting foam structure were discussed.