Impact of Internal Structure on Foam Stability in Model Porous Media

Ahmed Zoeir, Alireza Tabatabei Nezhad and Elnaz Khodapanah*

Faculty of Petroleum and Natural Gas Engineering, Sahand University of Technology, Tabriz, Iran

(Received: 04/16/2018, Revised: 06/16/2018, Accepted: 09/08/2018)
[DOI: 10.22059/JCHPE.2018.255950.1228]

Abstract

Application of foam in Enhanced Oil Recovery (EOR) increases macroscopic sweep efficiency via awesome increscent of mobility control. The macroscopic manifestation of foam application performance in porous media is a complex process that involves several interacting microscopic foam events. Stability, as an important factor in foam injection within large reservoirs, depends on several variables, including oil saturation, connate water salinity, and the foam texture. In addition to mentioned parameters, the internal structure is known to affect the foam stability and performance via influencing foam formation and destruction mechanisms within the porous media. In this paper, we mathematically expressed the main mechanism of snap-off for foam generation, mechanisms of capillary suction and diffusion coarsening for foam coalescences in some simplified models. Then we extended the calculations to more realistic 2D spherical models of porous media which were manufactured applying some morphological parameters. Simulation results show that in topologies in which the structure represented a high difference in pore and throat average diameters, foam formation mechanisms were dominant, making foam flow more stable, while conversely when the path tortuosity was high, foam destruction mechanisms overcome and the stability decreased.

Keywords

Foam Stability;
Internal Structure;
Model Porous media;
Rock Topology;
Reservoir Rock

1. Introduction

In upstream oil industry after the primary period in which natural energy of reservoir itself is sufficient to transmit oil and gas to surface facilities, natural or inert gas is injected into the reservoir due to two main reasons, firstly to maintain pressure within the reservoir, and secondly to produce the unswept oil in place. The main advantage of gas injection compared with water flood process is its higher microscopic sweep efficiency that leads to lower residual oil saturation in pores after the process.

Immiscible injection of high permeable fluids like CO_2, N_2, Air, or CH_4 confronts severe fingering and channeling problems that reduce efficiencies within oil extraction processes. In order to overcome these problems, surfactant solutions are

* Corresponding Author.
Tel.: +989143077197
Email: khodapanah@sut.ac.ir (E. Khodapanah)

mixed with injection gas or are co-injected into porous media to form a foam and reduce the mobility of the displacing phase, making injection process more efficient. In porous media, foam phase is considered metastable which means it will decay with time and with respect to the penetration distances.

Several porous media characteristics like temperature and pressure, oil and water saturation, the connate water salinity, and surfactant concentration affect the foam stability and performance. The internal structure of porous media is found to affect foam generation and destruction mechanisms to various extents depending on foam flow texture and the injection rates. Romero and Kantzas experimentally studied the effects of the foam texture and porous media topology on foam sweep efficiencies in several micromodels.

Permeability is considered as a representative parameter to express the different internal structures within the micromodels. It was monitored that foam globules were cracked and reshaped within the porous media [1]. Hirasaki and Khatib studied the effect of average particle sizes on foam stability in porous media. Different quality foams with various flow rates were injected into the sandpack case studies that show various permeabilities. It was also introduced that there are always some critical capillary pressures, subsequently maximum foam qualities to assure the foam stability. In fact, porous media that consist of smaller particles show higher capillary pressures and absorb more fraction of the liquid lamella solution, making the foam unstable [2]. Nguyen and Rossen simulated cases in which various texture foams, range from coarse to intermediate and strong, were injected into a one-dimensional model. Results showed that the foam creation within porous media accelerates, especially at coarse foam texture, as the injection rates increase and significantly affect the foam stability [3]. Radke and Aronson reported the limiting capillary pressure in which accelerated foam coalescence in porous media took place. Several experiments were performed on artificial porous media made up of glass beads with relatively high permeability and outcomes of limiting capillary pressure showed close agreement with the calculated disjoining pressure within foam globules. Results showed that the limiting coalescence capillary pressure was related to average particle sizes within the porous media [4].

Rossen and Alvarez performed simulation and experimental studies to investigate the rock permeability effects on foam stability in porous media. Two types of foam flow regimes were considered, firstly the high-quality foam regime in which the pressure drop along the flow direction is independent of gas flow rate, and secondly the low-quality foam flow regime in which the pressure drop is independent of liquid flow rate. The conclusions showed that at high-quality foams, capillary pressures and coalescence processes were dominant mechanisms that declare the foam stability while in the low-quality foams, foam globules trapping and demobilizations were dominant [5].

Rossen and Zhou investigated the foam stability at some limiting capillary pressure conditions. Liquid distribution was considered uniform and constant, independent of changes in gas and liquid flow rate. They also discussed the effects of porous media absolute permeability on capillary curves. In their work, almost all the internal structure characteristics were adjusted in porous media permeability and capillary pressure parameters [6]. Farajzadeh and Lotfollahi experimentally investigated the direct effect of porous media permeability on the critical capillary pressure and its indirect influence on foam stability via studying the effect of these parameters on coefficients that consider the extent to which the abrupt foam coalescence process takes place. Their results showed that the critical foam quality in which coalescence process starts will increase with an increase in permeability values. It was also concluded that the transition zone of the foam quality from completely stabilized conditions to severe coalescence is vaster at higher permeable porous media [7]. Li and Rossen studied several foam generation mechanisms in heterogeneous manufactured sandpacks. Some various texture foams with different injection rates were studied in their work. Reported results showed that foam generation was accelerated at a sharp transition from high to low permeability local regions similarly from throat to pore space [8]. Jimenez and Radke studied the foam flow through the periodically constricted channel and calculated critical capillary pressure above which foam is unstable in various foam injection velocities. It was concluded that the foam coalesces in porous media through capillary suction and diffusion Ostwald ripening. It was also concluded that in high injection rates diffusion was negligible and capillary suction was the dominant process [9]. Ma and Hirasaki estimated the dry out effect parameters that are used in the STARS model via fitting experimental data. The gas and surfactant solution were co-injected into sandpacks at various conditions to find out the critical foam qualities. Steady-state experiments were performed to estimate the reference mobility reduction factor and also the critical water saturation while abruptness factor of the foam dry out effect was estimated from unsteady state experiments [10]. Tanzil and Hirasaki performed some experimental air injections into the sandpack sample which was saturated with surfactant solution. Injection tests were performed to calculate critical velocities and pressure drops. It was concluded that the pressure drop is related to square root of sample permeability. It is noticeable that the foam generation was only monitored at pressures differentials above the critical value [11]. Gauglitz and Rossen investigated the effects of different rock types and properties on the minimum required gaseous phase flow rate for foam generation. Their results showed that the minimum velocity and therefore critical pressure drop was related to the samples permeability in some complex ways. Various samples showed different powers for permeability in their correlation which calculated the pressure drop [12].

Authors think that this shows there are some missing parameters in the literature for investigation of internal structure effects on foam stability and performance. One can express the internal structure of porous media with some more enhanced morphological parameters. Mecke introduced a family of static measures for the description of structure morphology within porous media. The family consisted of four simple parameters, namely covered volume, surface area, integral mean curvature and the Euler characteristic [13]. Arns and Knackstedt generated several artificial porous media models mainly in three different classes using morphological parameters which were extracted from porous media image data files. It was shown that the manufactured models express the original porous media properly [14].

In this paper, we are going to step forward and represent the internal structure of porous media with some more descriptive parameters rather than capillary pressure or permeability. Several artificial porous media models were conducted using MATLAB R2015 software and the foam was simulated to flow through them. Effects of various internal structure parameters on the foam formation and destruction mechanisms were investigated and finally, the decay times were predicted considering some extrapolation methods.

The novelty of this study, in comparison to all previous work in the literature, is that we investigated various internal structure description characteristics while the previous works adjusted all the internal structure effects in only two parameters, the capillary pressure curves, and the absolute permeabilities. In addition, we applied four morphological parameters, namely pore to throat ratio, path tortuosity, integral mean curvature, and surface area to fully depict the porous media internal structure and to investigate the effects of each characteristic separately on mechanisms that influence the foam creation and destruction. Results will aid petroleum investigators to recognize among various porous media types for foam flood experiments and petroleum engineers to know where and how to use different qualities of foam in EOR projects.

2. Methodology

Literature magnifies one main mechanism for foam generation in the porous media, namely snap-off and two main mechanisms for foam decay, namely capillary suction, and the diffusion coarsening coalescences. Other mechanisms like lamella division, leave behind, and pinch-off are known to play a less important role in foam stability in porous media. In this work, first, we expressed a snap-off mechanism, capillary suction and also mass transfer coarsening coalescences in simple situations. Then we extended our formulas to more complex porous media artificial models with various internal structures. Due to the explained forces that affect snap-off mechanism, consider one single foam globule that flows in the pore channel and is just entered one throat, as shown in Fig. 1.

The main forces that affect the foam globules prior to their entrance into the throats are momentum force due to foam flow and capillary force difference among the pores and throats. Globules will enter throats only if momentum forces overcome the capillary difference forces. This shows why the required minimum gas flow rate was recognized earlier in the literature for the snap-off process to take place. immediately after their entrance, two forces, namely momentum and the capillary differences, try to split right part of the globule from the original volume, while surface tension force that is applied to that narrow throat surface occupied with gas, impedes this splitting process. If splitting forces overcome surface tension, part of the globule will set apart from the original volume and the snap-off process takes place. Momentum force due to fluid flow increase while right part of the globule grows:

$$F_{\text{Gas Momentum}} = \int_0^{\text{Right Part}} \frac{\rho_{\text{Gas}}\, {Q_{\text{Gas}}}^2}{2\, {A_{\text{Right Part}}}^2}\, dA \tag{1}$$

Capillary difference force is applied from throat with smaller diameter toward side pores with larger diameters, trying to split the foam:

$$F_{\text{Capillary Difference}} = 2\,\sigma \cos\theta\, A_{\text{throat}} \times \left(\frac{1}{R_{\text{throat}}} - \frac{1}{R_{\text{pore}}}\right) \tag{2}$$

Surface tension as a single force that impedes split process is applied to the perimeter of the foam inside the throat, one can suppose globule to fully occupy throat cross section:

$$F_{\text{Surface Tension}} = \int_0^{\text{throat Perimeter}} \sigma \cos\theta\, dL \tag{3}$$

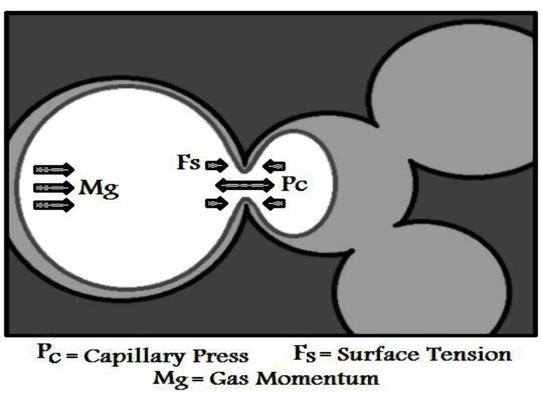

Figure 1. Schematic Representation of Snap-Off Mechanism and the Effective Forces

As foam globule passes through the throat, its right part area increases continuously making the momentum force more effective while at the same time, surface tension and capillary difference forces remain constant. The snap-off process takes place just after the momentum force exceeds the sum of the two other forces. Thus the size of the newly born foam globule is calculated with respect to explained forces. Generation of new foam globules competes for the foam destruction mechanisms and delays the foam decay in porous media. One of the most important decay mechanisms within foam flow in porous media is the diffusion coarsening coalescence in which the mass transfer takes place from the smaller foam globules to the larger ones. In foam flow through the pore channels, smaller diameter globules exhibit relatively higher pressures according to the Young-Laplace equation. Thus some local concentration difference appears among the globules and gas mass transfer takes place from the smaller toward the larger foam globules (Fig. 2.).

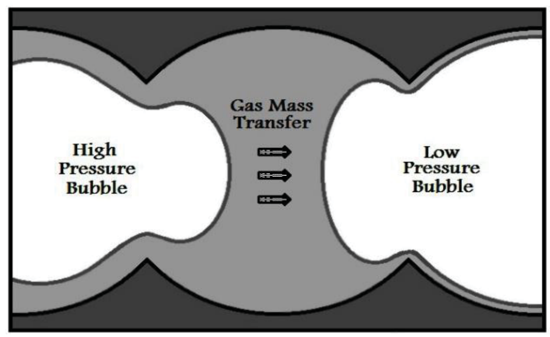

Figure 2. Schematic Representation of Mass Transfer Coarsening Coalescence Process

Diffusion mass transfers are always slow processes especially in those porous media with high tortuosities. It must be noticed while the foam flow is itself a slow phenomena, mass transfer destruction mechanism can play an important role in determining foam stability, especially at temperatures largely higher than ambient temperature. Calculation of mass transfer within porous media is complex, mainly due to internal structure complexity of the media. Theoretically, each foam globule can exchange gas via mass transfer with all the other existing foam globules. But practically chains of foam globules flow through every pore channels and each globule can only exchange gas in significant amounts, with previous and next one in the same chain. In addition, lamella thicknesses are always very thin in high-quality foams making the mass transfer decay mechanism more effective. When the lamella thickness is very thin, we can neglect its curvature and simplify the mass transfer equation:

$$J_{\text{Diffusion}} = \int_0^{\text{Lamella Area}} \frac{D(P_{\text{small}} - P_{\text{Large}})}{W_{\text{Lamella}}} dA \tag{4}$$

Summation of all diffusion rates will give the amount of the total mass transfer from an initial condition to the disappearance of the smaller globule.

$$N_{\text{Mass Transfer}} = \int_{\text{Globule Volume}}^{0} J_{\text{Diffusion}} dv \tag{5}$$

During mass transfer the mean curvature of the lamella surface around the larger globule decreases while at the same time, the mean curvature of smaller globule increases. Thus the pressure within larger globule decreases while the pressure in the smaller one increases and therefore the pressure difference among the neighbor globules in the chain, as the mass transfer driving force, increases. Lamella contact area of two neighbor globules decreases as their size change from the original state, making mass transfer process weaker. Anyway, this process always continues until two neighbor globules in the chain merge together. One other important destruction mechanism within foam flow in porous media is the capillary suction coalescence in which the pressure in lamella is higher than the pressure in plateau due to local curvature, according to the Young-Laplace equation. While at most only one foam globule fully occupies one individual pore within the connected network, the generation of smaller foam globules during the snap-off process will create situations in which some globules coexist in one pore, as shown in Fig. 3.

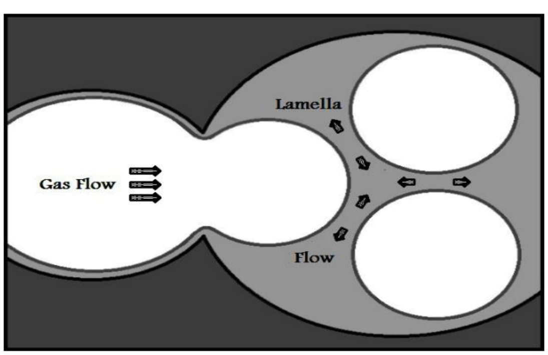

Figure 3. Schematic Representation of Capillary Suction Coalescence Process

Capillary suction coalescence is negligible when only two foam globules are in contact, mainly due to the small difference in lamella curvatures along their contact surface. Conversely, it is even more important than diffusion process in foam destruction at conditions in which some foam globules meet each other. The flow of the surfactant solution from the lamella center toward the plateau region continues until the lamella layer that separates the two globules disappear and two globules merge together, reducing the foam strength. Since there is no contact with the solid phase in capillary suction coalescence, inviscid flow is in progress toward the plateau. Euler equation calculates the flow velocity within the process.

$$\frac{\partial V_{\text{Suction}}}{\partial t} = \int_0^{\text{Lamella width}} \frac{(P_{\text{Lamella}} - P_{\text{Plateau}})}{\rho_{Lamella}} dw \tag{6}$$

Lamella thinning continues until its thickness reaches zero and then two foam globules will merge. In this process, surface tension forces do not resist the lamella destruction due to the fact that lamella forms extremely thin film at late times in the process. The literature demonstrates that the capillary suction process plays a second important role in foam destabilization in porous materials. In fact, its cooperation with diffusion mechanism accelerates the foam destruction and contrast snap-off generation mechanism. After the mathematic representation of significant mechanisms that affect foam generation and destruction within porous media, we used MATLAB R2015 software to define some artificial porous media models with different internal structures.

In order to perform this task, four morphological parameters, sensitive to the explained topology, were used to describe internal structure within artificial models. Parameters were intrinsically volumetric and easily evaluated with single sweep within the artificial models. Four different spatial characteristics were used, namely pore to throat ratio, integral mean curvature, tortuosity, and surface area.

Pore to throat ratio, as one important internal structure characteristic, influences the snap-off and capillary suction coalescence. Larger pore to throat ratios will increase capillary difference forces that are applied to globules when they are passing through the throats. Also, larger pore to throat ratios decreases the surface tension forces that resist the snap-off. So the larger pore to throat ratios will accelerate the snap-off process, generating newly born globules and therefore will delay the foam decay in porous media. The integral mean curvature is another morphological parameter which declares average pore and throat sizes. Larger integral mean values also indicate that the pore and throat surfaces have more roughness. From an overall point of view, smaller values of integral mean curvature will decelerate or even totally stop the snap-off process due to large throat diameters, while at the same time accelerates the capillary suction coalescence. The net effect is that smaller integral mean curvatures will accelerate the foam decay in porous media. Tortuosity explains path longitude of the foam flow through porous media. Larger in size tortuosities give more time for the diffusion process to take place while do not affect the snap-off mechanism significantly. Thus the net tortuosity effect is that its larger values accelerate the foam decay. Surface area among pore channels and solid grains which is indirectly relevant to porosity gives also some senses to porous media permeability. One can expect that higher surface areas introduce smaller diameter channels. In this work, MATLAB R2015 software is used to produce artificial models with various morphologies. Two different realization samples of the artificial models are illustrated in Fig. 4.

Fig. 4b shows that pore connected network exhibits a high value of tortuosity while its pore to throat ratio is low. In such circumstances, diffusion mass transfer coalescence is large due to long foam flow paths while the snap-off process is very weak. Conversely, Fig. 4a shows that pore to throat ratio is high, making the snap-off process more effective. It could be expected that foam remains more stable for longer times in such realizations compared with others. In order to generate realizations of porous media artificial models, firstly we considered one cube with constant side length as the porous space. Then we started to generate weighted random spherical pores within the assumed porous space. Initially, the porosity of space was zero and during pore generation procedure, generated pores were placed into the cubic lattice and its porosity was increased.

Originally four independent modified random numbers specify the center and the radius of each generated pore. The modification to fourth random number is that it was multiplied with upper minus lower assumed pore diameter limits and was added to the lower limit, to give one in range diameter for each generated pore. Furthermore, the selected morphological parameters were used to weight the other random pore creator function and provide our favorite internal structure in each artificial model. In order to apply our first morphological parameter, namely pore to throat ratio, into the artificial models, some fixed limits for pore to throat ratios was imposed for each model. Then the random pore generation procedure was started while the newly generated pore centers were prevented to place in locuses that make the created throat diameter to exceed the desired limits. After that, the tortuosity was applied as another parameter in some other artificial models somehow that the generated pores were prevented to neighbor previously existing pores in the supposed flow direction. In this way, we could provide models with high tortuosity values. The integral mean curvature is another selected morphological parameter that specifies the throat and pores absolute diameters and will fully describe the pore channel properties in cooperation with previously specified pore to throat ratios. Surface area among the pore channels and solid grains, as our fourth selected parameter, is not an independent parameter and specifies with respect to other parameters.

a

b

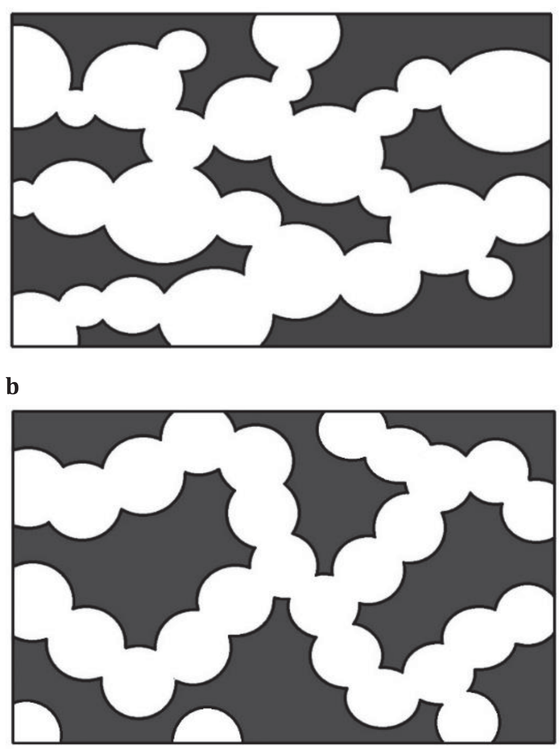

Figure 4. Two Different Realizations of Generated Artificial Spherical Models via MATLAB R2015

3. Result and Discussion

In order to investigate the impact of the porous media internal structure on foam generation and destruction mechanisms, several two-dimensional spherical pore models were manufactured using MATLAB R2015 software. Various morphological parameter values were assigned to weight the Poisson process functions and create four major types of artificial porous media, named Severe, Tortuous, Junction and Routine. In statistics, the Poisson process expresses that the events occur at known constant rate and time independent of each other since the last event [15]. In the family of realizations that called Severe, first selected morphological parameter, the pore to throat ratio, was defined high enough to magnify the snap-off mechanism while the second morphological parameter, namely the path tortuosity was adjusted small. Conversely, in the Tortuous family of realizations, path tortuosity value was assigned large enough in order to magnify the diffusion coalescence mechanism. In the family of realizations called Junction, channels meet each other in many connections while the first morphological parameter is still kept high. The integral mean curvature was considered slightly higher than Severe family. Finally, some midway parameter values were assigned to Routine realization family, as shown in Table 1.

The limited extent of the under calculation porous media artificial patterns restricted us to use mechanistic methods for the description of foam flow in porous media. Creation of foam globules occurred independent of the pattern extent, in every narrow throat in which the summation of momentum and capillary forces overcome the surface tension forces applied on phase interfaces. Conversely, mass transfer coalescence process that made smaller globules disappear or capillary suction process which vanished the lamella layer, needed time or pattern extent to proceed. So it is impossible to calculate the rate of foam destruction only with accounting for disappearances in limited extent realizations. Instead, the coalescence advancements were represented with respect to the amount of lamella thickness reductions and change in globules diameters while foam flows through each artificial model. Foam quality is assumed fixed, containing spherical slugs that comply the Poisson curve over the ranged diameters and flows from one side of the artificial realizations to another. Within this work, the extents were chosen small enough to reduce the system requirements, RAM and CPU, while at the same time, they were larger than the REV of porous media characteristics. Effects of the foam creator mechanism and also the foam coalescence mechanisms are calculated as the percent of the advancement in such processes after one pore volume foam injection. The internal structure of porous media was found to have various influences with respect to injection foam superficial velocities, as shown in Table 2.

In a Severe family of realizations in which the first selected morphological parameter was high, the snap-off process was the dominant mechanism. As foam superficial velocity increased, the momentum forces increase tended to enlargement of the creation process and thus the foam creation rate overcome coalescence rate, making foam completely stable for infinite times. Conversely, in a Tortuous family of realizations, the second morphological parameter value was high while the first selected morphological parameter was low. In such circumstances, mass transfer coalescence was the dominant mechanism, mainly due to longer channels for the foam to travel in, that gave the mass transfer process more time to take place. As foam superficial velocity increased in Tortuous realization family, the mass transfer mechanism was weakened and foam decay was delayed to longer times. It was observed that the suction coalescence effects increased whenever an increase in the snap-off process took place. This was due to this fact that the situations in which several gaseous slugs met together always appeared after throats. Both higher foam momentum force and higher foam superficial velocities resulted in much larger capillary suction coalescence effects. In Junction family, several connections appeared in artificial realizations making the long path effects less influencing while the first morphological parameter was slightly lower that Severe family. This made both foam creation and the destruction mechanisms weak. In such circumstances, results show that the rate of creation was never increased too much to overcome decay mechanisms and foam will decay with more foam invasion into porous media. As foam superficial velocity increased, the difference in destruction and creation mechanisms decreased and foam will not decay for longer times. In addition to the effects of foam superficial velocities, internal structure was found to have various influences on foam stability at different injection foam textures, as demonstrated in Table 3.

While globule sizes within the injection foam increased the flow was more prone to snap-off process. Forces that affect the foam creation mechanism do not differ with a change in globule sizes, instead larger in size globules created smaller globules while passing through throats.

Table 1. Selected Morphological Parameter Values for Severe, Tortuous, Junction and Routine Realization Families

Artificial Models		Morpholgical Parameters			
		Pore to Throat Ratio	Path Tortuousity	Integral Mean Curvatutre	Surface Area
Sever	Target Value	4.5	1.3	15	-
(Al haddad)	From Realizations	4.2	1.2	13	335
Tortuous	Target Value	2	3	12	-
(Al Tawil)	From Realizations	1.9	2.8	10	285
Junction	Target Value	3.5	1.1	18	-
(Al Faraa)	From Realizations	3.3	1.1	16	315
Routine	Target Value	3	1.5	10	-
(Al Aadi)	From Realizations	2.8	1.4	10	305

Table 2. The effectiveness of Each Mechanism under Different Flow Rates

Artificial Models	Superficial Velocity	Generation/Destruction Mechanisms		
		Snap-Off Separation	Diffusion Coalescence	Suction Coalescence
Severe (Al Haad)	1 ft/Day	0.6 %	0.4 %	0.3 %
	2 ft/Day	0.8 %	0.3 %	0.4 %
	3 ft/Day	0.9 %	0.2 %	0.5 %
Tortuous (Al Tawil)	1 ft/Day	0.0 %	0.9 %	0.2 %
	2 ft/Day	0.1 %	0.7 %	0.3 %
	3 ft/Day	0.2 %	0.5 %	0.4 %
Junction (Al Faraa)	1 ft/Day	0.5 %	0.5 %	0.3 %
	2 ft/Day	0.6 %	0.4 %	0.4 %
	3 ft/Day	0.7 %	0.3 %	0.5 %
Routine (Al Aadi)	1 ft/Day	0.2 %	0.6 %	0.4 %
	2 ft/Day	0.4 %	0.5 %	0.5 %
	3 ft/Day	0.6 %	0.4 %	0.6 %

Table 3. The effectiveness of Each Mechanism in Various Globule Sizes

Artificial Models	Globules Average Diameter	Generation/Destruction Mechanisms		
		Snap-Off Separation	Diffusion Coalescence	Suction Coalescence
Severe (Al Haad)	10±5 m inch	0.6 %	0.4 %	0.3 %
	20±5 m inch	1.0 %	0.4 %	0.6 %
	10±8 m inch	0.8 %	0.6 %	0.4 %
Tortuous (Al Tawil)	10±5 m inch	0.1 %	0.8 %	0.3 %
	20±5 m inch	0.3 %	0.8 %	0.6 %
	10±8 m inch	0.2 %	1.3 %	0.4 %
Junction (Al Faraa)	10±5 m inch	0.5 %	0.5 %	0.3 %
	20±5 m inch	0.8 %	0.5 %	0.5 %
	10±8 m inch	0.6 %	0.6 %	0.3 %
Routine (Al Aadi)	10±5 m inch	0.3 %	0.6 %	0.4 %
	20±5 m inch	0.7 %	0.6 %	0.7 %
	10±8 m inch	0.5 %	0.8 %	0.4 %

In addition to that, when globule size dispersion was wider, more globules existed in larger sizes, so the flowing foam was slightly more prone to creation mechanism. Conversely, an increase in foam globule sizes within injection flow had no effect on mass transfer coalescence.

All the realization families showed the same trend in which the effects of average globule size on foam destruction via mass transfer process was negligible.

Conversely, wider dispersion of globule sizes will increase the mass transfer from smaller globules to larger ones. It was observed that the mass transfer effects could increase significantly when flow contains highly variable size globules. Whenever more newly born foam globules appeared in the flow due to advancement in the snap-off process, capillary suction coalescence accelerated. It was concluded from the results that an increase in inlet foam globule sizes or an increase in dispersion limits within the inlet globule sizes, also accelerated the capillary suction coalescence process. Foam creation mechanism was affected significantly, in Severe and Junction families of realizations, mainly due to the high value of the first selected morphological parameter within them. Conversely, at conditions of wider globule dispersions, the Tortuous family was more affected with the mass transfer coalescence process, due to longer traveling distances for foam flow.

Table 4 shows the average calculated foam stability time in various simulated situations via extrapolation. Foam flow with various textures always had the longest life in the Severe family of realizations in which the first selected morphological parameter, namely pore to throat ratio was high. As foam globules enlarged, or injection rates increased, foam was more prone to snap-off process and thus, the foam formation mechanisms overcome destruction ones making the foam unlimitedly stable for long times.

Conversely, it could be apperceived that there is no difference in stability life of the Tortuous path family at various foam textures. Instead, as the injection flow rates increased foam formation mechanisms was invigorated making the flow more stable.

Also, it must notice there is a difference in foam stability life of the Severe family and Tortuous family of realizations. While the same texture foam was assumed to flow through each series, foam stability life in the Severe family was about ten times larger than the Tortuous family. This shows the significant impact of the internal structure on foam stability and performance.

In the Junction family of realizations in which several channel connections make the path tortuosity small while the first selected morphological parameter is still high, longer foam stability times was apperceived compared with Tortuous family. Again one can expect longer times with an increase in flow velocities and average globule sizes. As the injection velocities increased within Junction family, the foam stability times were calculated to increase twice or even triple. It was concluded that the first morphological parameter, namely pore to throat ratio had the most important effect on foam decay time while the path tortuosity took the second place in this classification. Integral mean curvature specifies the pore channel average diameters directly affecting the porous media permeability which was previously considered in the literature. Authors propose that the foam experimental models like CMG STARS must include more characteristic parameters of internal structure and topology of porous media into account for foam application simulations.

Table 4. Predicted Decay Time using Extrapolation Methods

Artificial Models	Globules Average Diameter	Foam Superficial Velocity in Porous Media		
		1 foot/Day	2 feet/Day	3 feet/Day
Severe	10±5 m inch	1000	∞	∞
(Al Haad)	20±5 m inch	∞	∞	∞
Tortuous	10±5 m inch	90.9	111.1	142.8
(Al Tawil)	20±5 m inch	90.9	111.1	142.8
Junction	10±5 m inch	333.3	500.0	1000
(Al Faraa)	20±5 m inch	500.0	750.0	1500
Routine	10±5 m inch	125.0	166.7	250.0
(Al Aadi)	20±5 m inch	150.0	200.0	300.0

4. Conclusions

Several key finding of the present paper can be summarized as follows:

- Several more influencing porous media descriptive characteristics including pore to throat ratio, the path tortuosity, and integral mean curvature, impact on foam stability rather than capillary pressure curves and permeabilities.
- Internal structures with a sharp transition from large pores to small throats and vice versa are more prone to foam formation mechanisms, making long delays in foam decay, increasing foam stability in porous media.
- Structures which represent higher path tortuosities, give the foam coalescence mechanisms, slow mass transfer, and capillary suction processes, more time to take place, and make the foam flow in porous media fewer stability times.
- In order to understand the direct effect of internal structure on foam stability, the independent topological parameters like pore to throat ratios and path tortuosities must take into account. Permeabilities and capillary pressure curves are not very descriptive.
- In order to understand the topology and internal structure of core samples, one can use digital core analysis methods and feed the extracted parameters into foam stability calculations.
- The commercial foam simulators like CMG STARS, Eclipse or MoReS software which applies experimental models to simulate foam flow in porous media currently are not considering internal structure impact on the foam flow stability.

References

[1] Romero-Zeron, L. and Kantzas, A. (2003). “Effects of Porous Media Topology on Foamed Gel Performance as Demonstrated by Flow Visualization Studies”, In Canadian International Petroleum Conference. Petroleum Society of Canada, Calgary, Alberta.

[2] Khatib, Z. I., Hirasaki, G. J. and Falls, A. H. (1988). “Effects of Capillary Pressure on Coalescence and Phase Mobilities in Foams Flowing Through Porous Media.” *SPE Reservoir Engineering*, Vol 3. No. 3pp. 919-926.

[3] Kam, S. I., Nguyen, Q. P., Li, Q. and Rossen, W. R. (2007) “Dynamic Simulations With an Improved Model for Foam Generation”, *Society of Petroleum Engineers Journal*, Vol. 12, No. 01, pp.35-48.

[4] Aronson, A. S., Bergeron, V., Fagan, M. E. and Radke C.J. (1994). “The Influence of Disjoining Pressure on Foam Stability and Flow in Porous Media”, *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, Vol. 83, No. 2, pp. 109-120.

[5] ALvarez, J. M., Rivas, H. J. and Rossen, W. R. (2001). “Unified Model for Steady-State Foam Behaviour at High and Low Foam Qualities.” *Society of Petroleum Engineers Journal*, Vol. 6, No. 3, pp. 325-333.

[6] Rossen, W. R. and Zhou, Z. H. (1995). “Modeling Foam Mobility at the Limiting Capillary Pressure.” *SPE Advanced Technology Series*, Vol. 3, No. 1, pp. 146-153.

[7] Farajzadeh, R., Lotfollahi, M., Eftekhari, A. A., Rossen, W. R. and Hirasaki, G. J. (2015). “Effect of Permeability on Implicit-Texture Foam Model Parameters and the Limiting Capillary Pressure.” *Energy & Fuels*. Vol. 29, No. 5, pp. 3011-3018.

[8] Li, Q., Rossen and W. R., (2005). “Injection Strategies for Foam Generation in Homogeneous and Layered Porous Media.” SPE 96116, Annual Technical Conference and Exhibition, Dallas, Texas, USA.

[9] Jimenez, A. I., Radke, C. J., (1989). “Dynamic Stability of Foam Lamella Flowing Trough Periodically Constricted Pore.” *ACS Symposium Series*, Vol. 396, pp. 460-479.

[10] Ma, K., Lopez-Salinas, J. L., Puerto, M. C., Miller, C. A., Biswal, S. L. and Hirasaki, G. J. (2013). “Estimation of Parameters for the Simulation of Foam Flow through Porous Media Part1: The Dry-Out Effect.” *Energy & Fuels*, Vol. 27, No. 5, pp. 2363-2375.

[11] Tanzil, D., Hirasaki, G. J., Miller, C. A., (2002). “Conditions for Foam Generation in Homogeneous Porous Media”, SPE 75176, *SPE/DOE Improved Oil Recovery Symposium*, Tulsa, Oklahoma.

[12] Gauglitz, P. A., Friedmann, F., Kam, S. I. and Rossen, W.R. (2002). "Foam Generation in Homogeneous Porous Media." *Chemical Engineering Science*, Vol. 57, No. 19, pp. 4037-4052.

[13] Mecke, K. R. (1998). "Integral Geometry in Statistical Physics." *International Journal of Modern Physics B*, Vol. 12, No. 09, pp. 861-899.

[14] Arns, C. H., Knackstedt, M. A. and Mecke, K. R. (2004). "Characterization of Irregular Spatial Structures by Parallel Sets and Integral Geometric Measures." *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, Vol. 241, No. 1-3, pp. 351-372.

[15] Haight, F. A., (1967). *Handbook of the Poisson Distribution*, John Wiley & Sons, Inc., New York.