Association and Effective Hydrodynamic Thickness of Hydrophobically Associating Polyacrylamide Through Porous Media

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ABSTRACT: This study was aimed at the association and effective hydrodynamic thickness of hydrophobically associating polyacrylamide (HAPAM) through porous media with coreflow experiment. It shows that there is strong hydrophobic association for HAPAM in porous media but not for polyacrylamide (PAM). The resistance factor and effective hydrodynamic thickness of HAPAM are obviously superior to those of PAM. HAPAM exhibits much stronger shear thinning behavior than PAM due to the ability to form transitional network structure. It also indicates that PAM can exhibit a transition from shear thinning behavior to shear thickening behavior at low polymer concentration. © 2008 Wiley Periodicals, Inc. J Appl Polym Sci 110: 1837–1843, 2008

Key words: hydrophobically associating polyacrylamide; association; effective hydrodynamic thickness; coreflow experiment; porous media

INTRODUCTION

Over the past decades, hydrophobically associating polyacrylamides (HAPAM) derived by incorporating a relatively small amount (generally less than 2 mol %) of hydrophobic groups onto a polyacrylamide (PAM) backbone are especially attractive because of their noticeable ability in controlling the viscosity at various shear rates.[1–4] Owing to its excellent viscosity building capacity, this kind of polymers has received a wide application in oilfield exploitations, including drilling, polymer-flooding, chemical flooding and profile modification, etc.[5–13]

Nowadays, numerous researches of HAPAM in this field are focusing on polymerization techniques,[14–20] offering versatility in turning such characteristic parameters of polymer as monomer sequence distribution, characterization,[20–22] and HAPAM solution properties.[4,6,8,10] It is well known that there is intra- and intermolecular interaction of HAPAM due to the nonpolar alky group when dissolved in aqueous solution. When the concentration of HAPAM is above critical associative concentration (CAC), the intermolecular aggregations prevail over intramolecular aggregation, resulting in the formation of the transitional network structure.[4,12,20] This structure could induce a noticeable increase in solution viscosity. However, the applied environment like oil reservoirs is usually complicated.[7,10] If the intermolecular aggregation of HAPAM disappeared in a complicate environment, the excellent viscosity building capacity could not exhibit. Therefore, one of our major tasks is to investigate whether the intermolecular aggregation of HAPAM could take place when applied to oil reservoirs? Further, if this phenomenon exists, could the CAC of HAPAM undergo noticeable changes? On the other hand, when HAPAM is adsorbed on porous sands in oil reservoir, there must be the interaction of fluid flow with adsorbed polymer layer. It is interesting to find out whether the interaction could significantly affect the flow behavior of polymer solution? It is a pity that, up to now, very little work on both theoretical and practical research on these issues have been carried out in recent literatures.[23–26]

In this study, a systematic study of the associative behavior of HAPAM in porous media was made. It is necessary to pointed out that this study was based on the comparison between the behaviors of HAPAM and PAM. The resistance factor was used to reflect the associative behavior. Based on the

TABLE I
The Physical Parameter of the Polymer

	Monomer (observed: mol %)		Intrinsic viscosity (mL/g)
	AM	DM16	
HAPAM	99.0287	0.9713[a]	511[b]
PAM	100	0[a]	502[b]

AM, acrylamide; DM16, 2-(methacryloyloxyl) ethylhexadecyldimethylammonium bromide.

[a] Observed by ion-exchange chromatography.
[b] Measured in formamide.

Poiseuille's law, the effective hydrodynamic thickness was also investigated.

EXPERIMENTAL

Materials

HAPAM and PAM used in this work were synthesized as described previously,[27,28] and the detailed description for them was illustrated in Table I. The purified water (resistivity > 18 MΩ/cm) was distilled for three times. The quartzose sand was purchased from Beibei Reagent (Chongqing, China). The coreflow setup (in Fig. 1) was assembled by Haianhuada petroleum instrument plant (Jiangsu, China). It was very simple in design but capable of very high precision.

Coreflow experiments

Coreflow experiment is a classical method to test the properties of polymers under simulated conditions of oil reservoirs. The stock solution of HAPAM and PAM were prepared. The standard solutions were prepared daily by serial dilution of stock solution prior to use. A certain amount of quartzose sand was filled in the sand pipes (the diameter of sand pipes is $2R$, and the length is L). One of middle container was filled with water, while the other was filled with either HAPAM or PAM solution. In the first step, the weight (m_1) of sand pipes was measured before the water was allowed to flood though sand pipes with a flux (Q_W) of 20 mL/h. Then the pressure at two different places (P_{2W}, P_{3W}) was recorded when the pressure kept stable (it should be noted that the pressure drop associated with a certain flow rate is measured with a two-fluid U-tube manometer containing water–oil, water–mercury, or water–air, according to the magnitude of the pressure difference to be measured with an accuracy better than 2%.). The pressure difference (ΔP_W) was calculated by eq. (1). Afterward, the weight (m_2) of sand pipes was measured again. In the second step, the polymer solution was allowed to flood through

the sand pipes. The flux is Q_P. Similar with the first step, the pressure of P_{2P} and P_{3P} was recorded. The pressure difference (ΔP_P) was calculated by eq. (2). Here, it is necessary to point out that, in this experiment, the flux Q_P was adjusted firstly from the minimum value to the maximum value (10, 20, 30, 40, 50, and 60 mL/h), and second, from the maximum value back to the minimum value (60, 50, 40, 30, 20, 10, and 5 mL/h). The purpose was to gain a full insight to the hysteresis phenomenon of polymer solutions. The temperature is kept constant at 45°C throughout this work. Except for additional illustrations, all the parallel experiments were repeated for at least three times. And the error bars could be controlled within ±3%.

$$\Delta P_W = P_{2W} - P_{3W} \qquad (1)$$

$$\Delta P_P = P_{2P} - P_{3P} \qquad (2)$$

According to Darcy's law, the permeability (K) of the sand pipes is expressed in terms of Q, μ, L, A, ΔP.

$$K = \frac{Q\mu L}{A\Delta P \times 10} \qquad (3)$$

where Q is the flux of the fluid which flood though the sand pipes, μ is the effective viscosity of the fluid which flood though the sand pipes, A is the cross-sectional of the sand pipes, L is the length of the sand pipes, and ΔP is the pressure difference of the end of the sand pipes. In our experiment, K was tested to be 5.5 ± 0.1 μm^2.

RF represents the resistance factor, which is defined as the ratio of aqueous mobility to polymer solution mobility.[26] It can be expressed as follows:

$$\mathrm{RF} = \frac{\lambda_W}{\lambda_P} = \left(\frac{K_W}{\mu_W}\right) \bigg/ \left(\frac{K_P}{\mu_P}\right) \qquad (4)$$

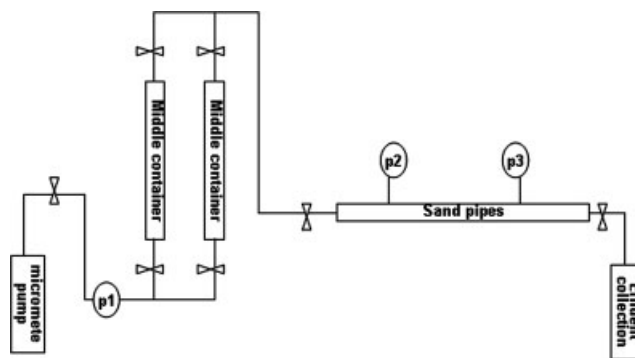Combined with eq. (3), eq. (4) can be changed into:

Figure 1 A typical schematic presentation of coreflow setup.
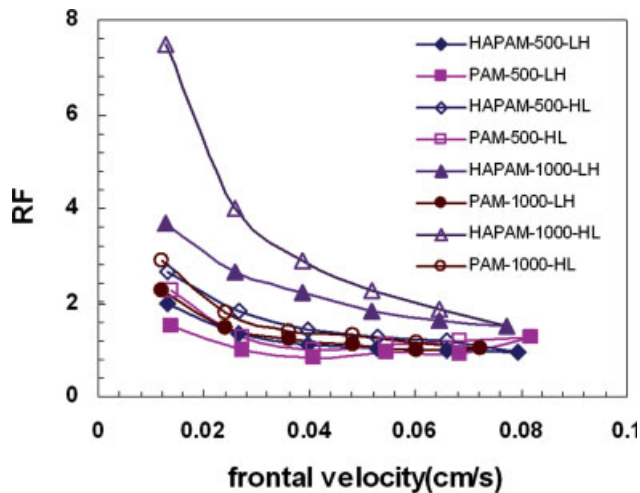
Figure 2 The relationship between frontal velocity and resistance factor. *L-H* indicates that the frontal velocity is varied from the lower (*L*) value to higher (*H*) value, vice versa. 500 represent the polymer concentration of 500 mg/L; 1000 represents the polymer concentration of 1000 mg/L. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

$$RF = \frac{Q_W \times \Delta P_P}{Q_P \times \Delta P_W} \qquad (5)$$

Here, ϕ is the porosity of the sand pipes, which can be calculated by the following equation. In this work, the value of ϕ is about $42 \pm 0.5\%$.

$$\varphi = \frac{m_2 - m_1}{\pi R^2 L} \qquad (6)$$

The slip flow phenomenon is believed to be due to a very thin, low-viscosity region near the pore' wall. Slip effects are usually quantified in terms of the effective frontal velocity (V_f) at the pore wall.[7]

$$V_f = \frac{Q}{\varphi A} \qquad (7)$$

Here, r_P is the average value of the effective rock pore radius. The value of the effective rock pore radius is determined from the capillary model[7,29,30]

$$r_P = (8K/\varphi)^{1/2} \qquad (8)$$

According to Poiseuille's law, the effective hydrodynamic thickness (L_H) of an adsorbed polymer layer can be expressed as follows.[31,32]

$$L_H = r_P \left[1 - \left(\frac{Q_W \times \Delta P_P}{Q_P \times \Delta P_W} \right)^{0.25} \right] \qquad (9)$$

Combined with eq. (5), eq. (9) can be changed into:

$$L_H = r_P(1 - RF^{0.25}) \qquad (10)$$

The effective hydrodynamic thickness is correlated with the wall shear rate, corrected for the effective reduction in the tube radius as suggested by Gramain and Myard.[33] Similarly, for the sand pipes, the value of nominal shear rate has been estimated by fitting the onset of shear rate dependence in both viscometers and porous media flows assuming that[7,34,35]:

$$\gamma_{PT} = 4\alpha V_f / (r_P - L_H) \qquad (11)$$

According to experiences, the value of α, which is minimum in calibrated sphere packs ($\alpha = 1.7$), increase up to 2.5 for sand pipes and reach much higher values in natural heterogeneous media.

RESULTS AND DISCUSSION

Effect of frontal velocity on resistance factor

As shown in Figures 2 and 3, the resistance factor (RF) of HAPAM decreased with the increase in the frontal velocity. However, for PAM with the concentration of 500 mg/L, the RF underwent the first decrease, and then, surprisingly, the new increase with the increase in the frontal velocity. The transition point was observed to be near 0.04 cm/s. Nevertheless, such a phenomenon was not observed when the concentration of PAM was relatively high.
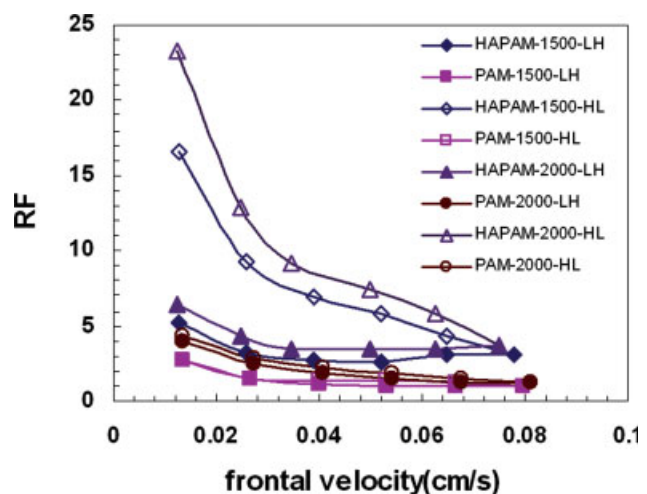

Figure 3 The relationship between frontal velocity and resistance factor. *L-H* indicates that the frontal velocity is varied from the lower (*L*) value to higher (*H*) value, vice versa. 1500 represents the polymer concentration of 1500 mg/L; 2000 represents the polymer concentration of 2000 mg/L. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]
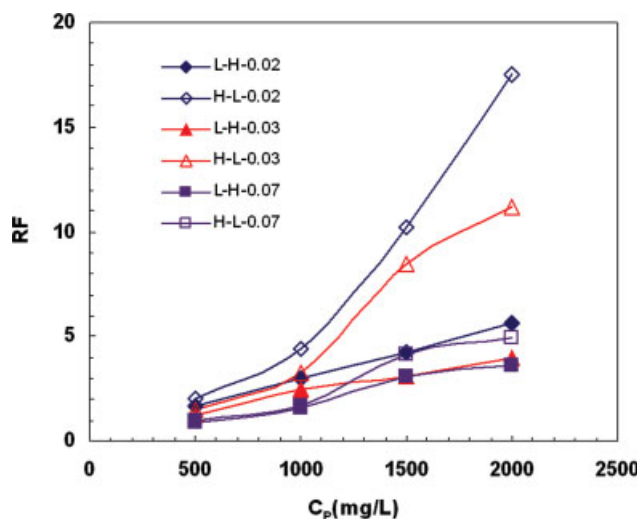
Figure 4 The relationship between polymer concentration and resistance factor for HAPAM. *L-H* indicates that the frontal velocity is varied from the lower (*L*) value to higher (*H*) value, vice versa. 0.02, 0.03, and 0.07 represent the frontal velocity: 0.02, 0.03, and 0.07 cm/s, respectively. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

This suggests a shear thinning behavior and shear thickening behavior for PAM solutions at a lower concentration. A similar result was also reported by Tirrell and coworkers.[34] In their study, the concentration of partial hydrolyzed PAM was 320 ppm, which was quite near to that in our work ($C_P = 500$ mg/L). From these results, a conclusion could be drawn that the shear thinning phenomenon could occur for both HAPAM and PAM solutions, but the shear thickening phenomenon could only occur for PAM solutions. Except for this aspect, no other obvious differences could be observed for the two polymer solutions at a lower concentration.

In the next step, we have found that the concentration of either HAPAM or PAM solutions might exert a subtle influence to the transition of shear thinning to shear thickening. For example, neither HAPAM nor PAM solutions could exhibit the shear thickening phenomenon for a higher concentration, namely 1000, 1500, and 2000 mg/L, respectively. This could be noticed from Figures 2 and 3. The reason why the shear thickening phenomenon only takes place for PAM under a relatively low concentration is, so far, not very clear.[31,34] Apart from this, it could be observed that the hysteresis phenomena became increasingly serious when the concentration of HAPAM solution increased. For example, at a lower concentration of 500 mg/L, ΔRF was no more than 1; but at a concentration of 2000 mg/L, ΔRF could reach far beyond 10. In sharp contrast, this would not happen for PAM solutions. Instead, the hysteresis phenomena became more and more

subtle. The great difference between the behaviors of HAPAM and PAM solutions could be explain as follows: The association between the hydrophobic side chains of HAPAM could be regulated by the shearing force, that is to say, when the frontal velocity of HAPAM solutions changed from higher values to lower values, the network structures of HAPAM could well be recovered. Thus, HAPAM could exhibit the unique fluidic properties when compared with PAM.

Effect of polymer concentration on resistance factor

As shown in Figure 4, the RF of HAPAM increases with the increased in polymer concentration. It could be noticed that there was an abrupt transition for the HAPAMs curve of *H-L*-0.02 and *H-L*-0.03, indicating the strong association formed. The transition point of the concentration was about 900 mg/L, which was very near to the data measured by fluorescence spectroscopy (about 600 mg/L).[27] The RF decreased dramatically with the increase of the frontal velocity, indicating the noticeable shear thinning behavior like hydrophobically associating water-soluble polymer in aqueous media. For PAM (in Fig. 5), however, such a transition point could not be observed. Moreover, the increase of RF of PAM was very modest. By comparison, the reduction of RF for HAPAM with the increase of frontal velocity was more drastic than that of PAM. Because the RF also reflects the change of relative viscosity of polymer in porous media,[23–26,34] this transition could also reflect the relative viscosity transition. From these results, a
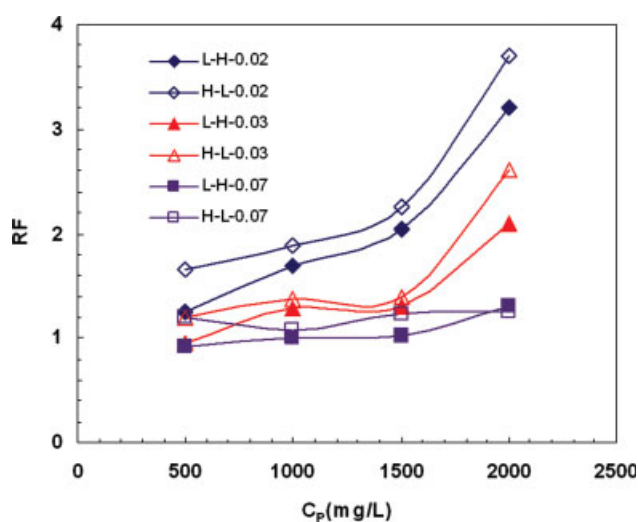

Figure 5 The relationship between polymer concentration and resistance factor for PAM. *L-H* indicatEs that the frontal velocity is varied from the lower (*L*) value to higher (*H*) value, vice versa. 0.02, 0.03, and 0.07 represent the frontal velocity: 0.02, 0.03, and 0.07 cm/s, respectively. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]
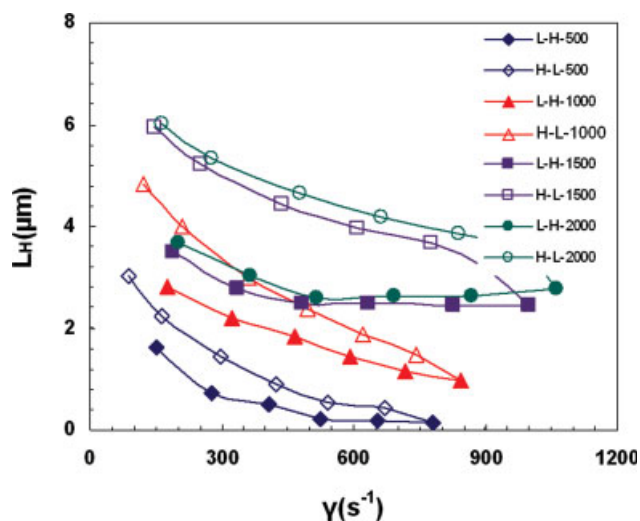
Figure 6 The relationship between nominal shear rate and effective hydrodynamic thickness for HAPAM. *L-H* indicates that the nominal shear rate is varied from the lower (L) value to higher (L) value, vice versa. 500, 1000, 1500, and 2000 represent the polymer concentration: 500, 1000, 1500, and 2000 mg/L, respectively. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

conclusion could be drawn that HAPAM can also exhibit hydrophobic association in porous media. This conclusion could be responsible for the noticeable shear thinning behavior of HAPAM in porous media, because HAPAM could usually exhibit noticeable shear thinning behaviors in noumenal aqueous solution. Owing to the lack of hydrophobic side chains, the hydrophobic association phenomena did not occur in porous media for PAM. On the basis of the above discussion, one can safely say that HAPAMs hydrophobic association interaction still exists in porous media, just like the environment of oil reservoir. And the concentration of association point in porous media was quite near to that in aqueous media.

Effect of shear rate on effective hydrodynamic thickness

As shown in Figures 6 and 7, the effective hydrodynamic thickness of HAPAM decreased with the increase of nominal shear rate. However, for *L-H*-500 of PAM, there was a little transition point, as was first reported by Cohen.[31] It suggests that PAM can exhibits both shear thinning behavior and shear thickening behavior. As shown in Figure 7, the transition point was gradually replaced by the plateau region when PAM solutions' concentration increased. It is speculated that the transition point is correlated with polymer solutions' concentration, because the condition of transition occurrence (namely, shear thinning to shear thickness behavior)

in our experiments was very similar with the reported work by Cohen[31] and Tirrell and coworkers.[34] For higher PAM solutions' concentration, no shear thickness behavior was observed. Till now, the reasons for such phenomena were still unclear. For HAPAM, the plateau could only be observed in higher polymer concentration. It is obvious that the effective hydrodynamic thickness of HAPAM is larger than PAM when the polymer concentration was above 1000 mg/L. It suggests that the ability to change the effective pore size for HAPAM is greater than PAM. This ability can be attributed to the existence of hydrophobic association among polymer molecules. Besides, there was an obvious hysteresis of effective hydrodynamic thickness, and the hysteresis of HAPAM become more dramatic than that of PAM with the increase of polymer concentration. This could be explained as follows: the transitional network structure formed from hydrophobic association could be reinforced with the increase in polymer concentration. When the shear rate varies from higher to lower values, the transitional network could be adjusted automatically, resulting in the formation of better transitional network. This could in turn contribute to the increase of the effective hydrodynamic thickness. Therefore, the ability of HAPAM to resist shear rate is enhanced, which could be responsible for the noticeable hysteresis phenomena of HAPAM. Perhaps, it may be the association interactions between HAPAMs that resisted the transition from shear thickening to shear thinning phenomena.
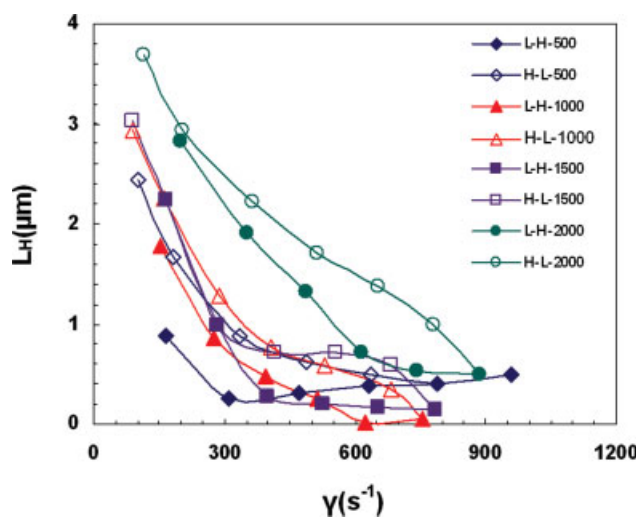

Figure 7 The relationship between nominal shear rate and effective hydrodynamic thickness for PAM. *L-H* indicates that the nominal shear rate is varied from the lower (L) value to higher (L) value, vice versa. 500, 1000, 1500, and 2000 represent the polymer concentration: 500, 1000, 1500, and 2000, respectively. [Color figure can be viewed in the online issue, which is available at www. interscience.wiley.com.]

Effect of polymer concentration on effective hydrodynamic thickness

As shown in Figure 8, the effective hydrodynamic thickness of HAPAM dramatically increased with the increase of polymer concentration. With the increase of nominal shear rate, the effective hydrodynamic thickness of HAPAM decreased correspondingly. And the reduction of effective hydrodynamic thickness for HAPAM was drastic, indicating the strong dependence of nominal shear rate (Fig 9). As far as the PAM is concerned, the effective hydrodynamic thickness increased with the increase of polymer concentration when the nominal shear rate is 200 s^{-1}. But for the higher nominal shear rate, an obvious transition of effective hydrodynamic thickness for PAM occurred. It indicates that the increase of HAPAM concentration could contribute to control the permeability of oil reservoirs, while the increase of PAM concentration does not absolutely reduce the permeability of oil reservoir. Besides, the hysteresis of effective hydrodynamic thickness for HAPAM is more serious than that for PAM when the nominal shear rate increases from 200 to 700 s^{-1}. Ye and coworkers has concluded that the hydrophobically associating water-soluble polymers may usually exhibit obvious shear hysteresis properties.[25] On the basis of our experimental findings, we could speculate that such kind of a hystereous phenomenon could be attributed to the fact that the associating interactions between
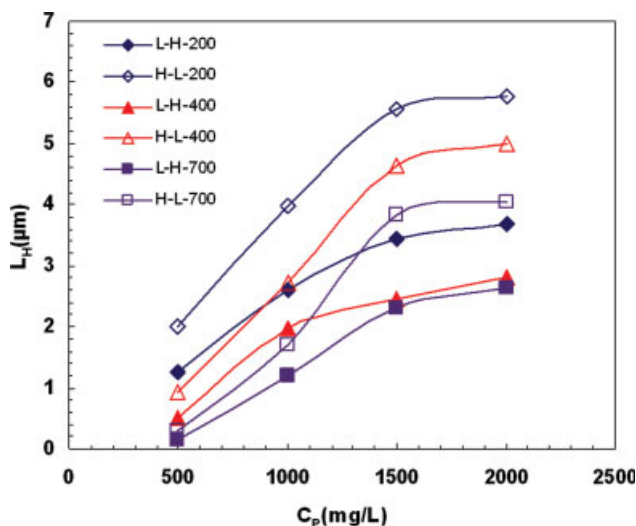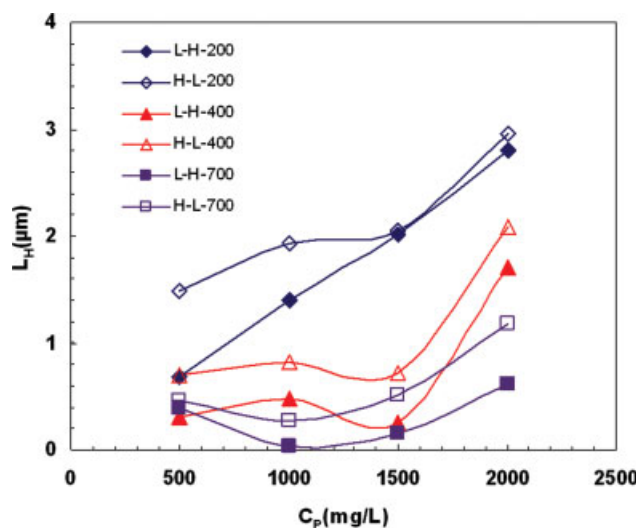

Figure 9 The relationship between polymer concentration and effective hydrodynamic thickness for PAM. *L-H* indicates that the nominal shear rate is varied from the lower (*L*) value to higher (*L*) value, vice versa. 200, 400, and 700 represent the nominal shear rate: 200, 400, and 700 s^{-1}, respectively. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

HAPAM in porous media could still exist.[25,26] In general, all these behaviors could be attributed to the existence of hydrophobic association interaction of HAPAM in porous media. Because the physical crosslinking points which resulted in the transitional net-structure of HAPAM solution were formed by hydrophobic microdomain, which was the aggregation of hydrophobic side unite, the effective hydrodynamic thickness exhibited changeability.

Grattonin thought that the formation of thick PAM layer could correspond to adsorption-entanglement mechanism, which is essentially an adhering of the polymer, forming a network on the pore surface that is constantly replenished from the flowing polymer solution.[36] At the beginning stage of the increase of pressure, polymers (HAPAM or PAM) may gradually adsorb onto the sands' surface. This process will continue until the pressure reaches constant, suggesting that the equilibrium of adsorption and desorption of polymers on the sands' surface is established. As for the difference between the adsorption behaviors of PAM and HAPAM, we think that HAPAM is characterized by a larger adsorption amount than PAM because of the inter-molecule interactions, i.e., the hydrophobic associating interactions. And based on this point, the formed multilayers of HAPAM on the sands' surface may improve HAPAMs effective hydrodynamic thickness and stability. But for PAM, the intermolecular interaction may appear weak due to the absence of hydrophobic association interaction, resulting in the thin effective hydrodynamic thickness. It is the

Figure 8 The relationship between polymer concentration and effective hydrodynamic thickness for HAPAM. *L-H* indicates that the nominal shear rate is varied from the lower (*L*) value to higher (*L*) value, vice versa. 200, 400, and 700 represent the nominal shear rate: 200, 400, and 700 s^{-1}, respectively. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

reversible transitional network that makes the HAPAM to exhibit a special behavior.

CONCLUSIONS

This study has shown that HAPAM can exhibit strong hydrophobic association in porous media, but with the exception for PAM. HAPAM possesses a strong ability to increase RF than PAM. It has been observed that 500 mg/L PAM aqueous solution could present both shear thinning behavior and shear thickening behavior. Moreover, for high PAM concentration, the appearance of transition may correlate with the polymer concentration. For HAPAM, there is no transition like PAM in all cases. With the increase of polymer concentration, HAPAM exhibited much stronger shear thinning behavior than PAM. At the same time, the RF increased drastically with the increase of HAPAM concentration. However, PAM did not behave so. Last but not least, the hysteresis of HAPAM is more serious than PAM.

The effective hydrodynamic thickness of HAPAM was test to be obviously superior to PAM, suggesting that HAPAM could exhibit ideal performance in porous media. Absorbed PAM could still exhibit shear thinning behavior and shear thickening behavior at low polymer concentration, indicating that the transition of effective hydrodynamic thickness is related with polymer concentration. However, the mechanisms for these phenomena are still unclear due to the lack of related researches. For HAPAM, because of the strong hydrophobic association interaction, the transition was not observed during our experimental condition. It was the hydrophobic association interaction that increases the effective hydrodynamic thickness. It is believed that all these helpful information gained in our work could help a better control of the permeability of polymers in oil reservoirs.

References

1. Bock, J.; Valint, P. L., Jr.; Pace, S. J.; Siano, D. B.; Schulz, D. N.; Turner, S. R. In Water-Soluble Polymers for Petroleum Recovery; Stahl, G. A., Schulz, D. N., Eds.; Plenum Press: New York, 1988; p 147.
2. Bock, J.; Varadaraj, R.; Schulz, D. N.; Maurer, J. J. In Macromolecular Complexes in Chemistry and Biology; Dubin, P., Bock, J., Davies, R. M., Schulz, D. N., Ties, C., Eds.; Springer: Berlin, 1994; p 33.
3. Glass, J. E.; Karunasena, A. Polym Mater Sci Eng 1989, 61, 145.
4. Glass, J. E. Associative Polymers in Aqueous Media (ACS Symposium Series); Washington, DC: American Chemical Society, 1991.
5. Glass, J. E. Hydrophilic Polymers: Performance with Environmental Acceptability (Advances in Chemistry Series); Washington, DC: American Chemical Society, 1996.
6. Glass, J. E. Polymers in Aqueous Media: Performance Through Association (Advances in Chemistry Series); Washington, DC: American Chemical Society, 1989.
7. Glass, J. E. Water-Soluble Polymers: Beauty with Performance (Advances in Chemistry Series); Washington, DC: American Chemical Society, 1986.
8. Schulz, D. N.; Bock, J. J Macromol Sci Chem A 1991, 28, 1235.
9. Schulz, D. N.; Bock, J.; Valint, P. L., Jr. In Dubin, P., Bock, J., Davies, R. M., Schulz, D. N., Ties, C., Eds.; Macromolecular Complexes in Chemistry and Biology; Springer: Berlin, 1994; p 3.
10. Shalaby, S. W.; McCormick, C. L.; Butler, G. B. Water-Soluble Polymers: Synthesis, Solution Properties and Applications (ACS Symposium Series); Washington, DC: American Chemical Society, 1991.
11. Schulz, D. N.; Glass, J. E. Polymers as Rheology Modifiers (ACS Symposium Series); Washington, DC: American Chemical Society, 1991.
12. Wang, T. K.; Iliopoulos, I.; Audibert, R. Polym Bull 1988, 20, 577.
13. Candau, F.; Selb, J. Adv Colloid Interface Sci 1999, 79, 149.
14. Bastiat, G.; Grassl, B.; François, J. Polym Int 2002, 51, 958.
15. Candau, F.; Pabon, M.; Anquetil, J. Y. Colloids Surf A 1999, 53, 47.
16. Schulz, D. N.; Kaladas, J. J.; Maurer, J. J.; Bock, J. Polymer 1987, 28, 2110.
17. Yahaya, G. O.; Ahdab, A. A.; Ali, S. A.; Abu-Sharkh, B. F.; Hamad, E. Z. Polymer 2002, 42, 3363.
18. Pabon, M.; Corpart, J. M.; Selb, J.; Candau, F. J Appl Polym Sci 2004, 91, 916.
19. Magny, B.; Lafuma, F.; Ilipoulous, I. Polymer 1992, 33, 3151.
20. Feng, Y.; Billon, L.; Grassl, B.; Khoukh, A.; Francois, J. Polymer 2002, 43, 2055.
21. Kujawa, P.; Audibert-Hayet, A.; Selb, J.; Candau, F. J Polym Sci Part A: Polym Chem 2004, 41, 3261.
22. Zhong, C.; Luo, P. J Polym Sci Part B: Polym Phys 2007, 45, 826.
23. Zhang, J.; Ye, Z. Xinjiang Petroleum Geol 2004, 25, 6.
24. Han, L.; Luo, P.; Ye, Z. Natural Gas Industry 2004, 24, 119.
25. Shi, L.; Ye, Z.; Luo, P. Natural Gas Exploration Exploitation 2004, 27, 4.
26. Ji, Z. PhD Thesis, Southwest Petroleum University, Chengdu, 2006.
27. Lu, H; Feng, Y. e-Polymers 2007, 099.
28. Lu, H.; Feng, Y. Presented at the National Macromolecular Conference, China, 2007.
29. Zaitoun, A.; Chauveteau, G. Paper Soc Pet Eng 1998, 39674.
30. Denys, K.; Fichen, C. ; Zaitoun, A. Paper Soc Pet Eng 2001, 64984.
31. Cohen, Y. Macromolecules 1988, 21, 494.
32. Cohen, Y.; Metzner, A. Macromolecules 1982, 15, 1425.
33. Gramain, Ph.; Myard, Ph. Macromolecules 1981, 14, 180.
34. Bagassi, M.; Chauveteau, G.; Lecourtier, J.; Englert, J.; Tirrell, M. Macromolecules 1989, 22, 262.
35. Chauveteau, G. J Rheol 1982, 26, 111.
36. Grattonia, C. A.; Luckhamb, P. F.; Jinga, X. D.; Normanc, L.; Zimmerman, R. W. J Petrol Sci Eng 2004, 45, 233.