This article was downloaded by: [Institute of Mechanics]
On: 02 July 2014, At: 19:17
Publisher: Taylor & Francis
Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK

Journal of Dispersion Science and Technology
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/ldis20

Experimental Investigation on Yield Stress of Water-in-Heavy Crude Oil Emulsions in Order to Improve Pipeline Flow

Jian Zhang [a], Jing-yu Xu [a] & Meng-chen Gao [a]

[a] Key Laboratory for Mechanics in Fluid Solid Coupling Sysytems, Institute of Mechanics, Chinese Academy of Sciences, Beijing, P. R. China

Accepted author version posted online: 22 Jul 2013.Published online: 28 Mar 2014.

To cite this article: Jian Zhang, Jing-yu Xu & Meng-chen Gao (2014) Experimental Investigation on Yield Stress of Water-in-Heavy Crude Oil Emulsions in Order to Improve Pipeline Flow, Journal of Dispersion Science and Technology, 35:4, 593-598, DOI: 10.1080/01932691.2013.811684

To link to this article: http://dx.doi.org/10.1080/01932691.2013.811684

PLEASE SCROLL DOWN FOR ARTICLE

Taylor & Francis makes every effort to ensure the accuracy of all the information (the "Content") contained in the publications on our platform. However, Taylor & Francis, our agents, and our licensors make no representations or warranties whatsoever as to the accuracy, completeness, or suitability for any purpose of the Content. Any opinions and views expressed in this publication are the opinions and views of the authors, and are not the views of or endorsed by Taylor & Francis. The accuracy of the Content should not be relied upon and should be independently verified with primary sources of information. Taylor and Francis shall not be liable for any losses, actions, claims, proceedings, demands, costs, expenses, damages, and other liabilities whatsoever or howsoever caused arising directly or indirectly in connection with, in relation to or arising out of the use of the Content.

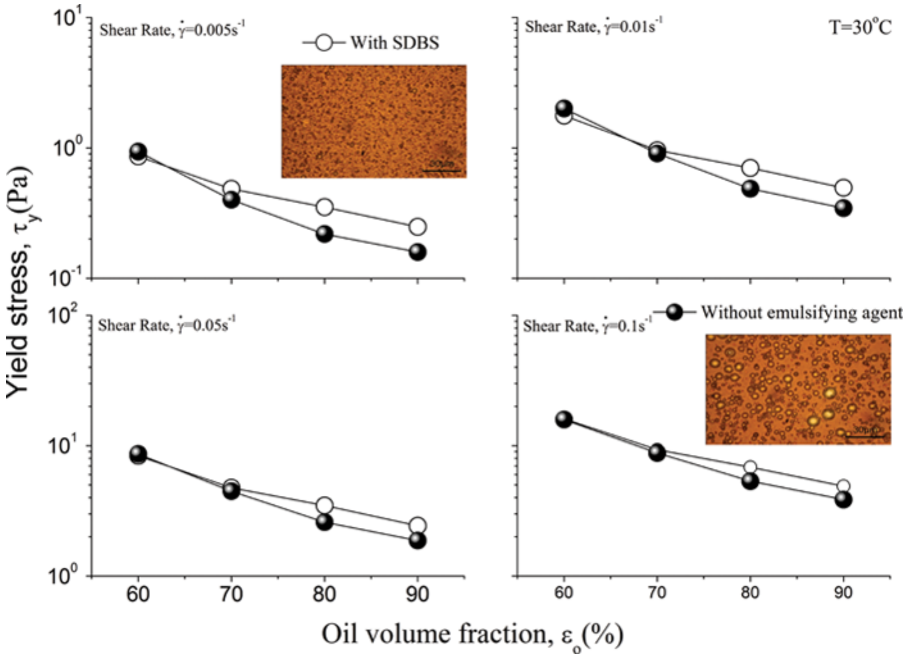
This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden. Terms & Conditions of access and use can be found at http://www.tandfonline.com/page/terms-and-conditions

Journal of Dispersion Science and Technology, 35:593–598, 2014
Copyright © Taylor & Francis Group, LLC
ISSN: 0193-2691 print/1532-2351 online
DOI: 10.1080/01932691.2013.811684

Experimental Investigation on Yield Stress of Water-in-Heavy Crude Oil Emulsions in Order to Improve Pipeline Flow

Jian Zhang, Jing-yu Xu, and Meng-chen Gao
Key Laboratory for Mechanics in Fluid Solid Coupling Sysytems, Institute of Mechanics, Chinese Academy of Sciences, Beijing, P. R. China

GRAPHICAL ABSTRACT



An experimental study on yield stress of water-in-heavy crude oil emulsions has been carried out by using a HAAKE RS6000 Rheometer with a vane-type rotor. Several factors such as oil volume fraction, shear rate, temperature, and emulsifying agent on the yield stress of emulsions were investigated. Zero shear viscosity of heavy crude oil was 6000 mPas at 30°C, with a density 955 kg/m^3. This study shows that the yield stress increases linearly with the increasing shear rate, and displays an exponential decay with increasing the temperature and oil volume fraction. Although the addition of emulsifying agent enhanced the stability of the emulsion, to some extent it also increased the yield stress, especially for the emulsions with high oil volume fractions. Therefore, to reduce the start-up force for the pipeline transport of water-in-heavy crude oil emulsions, the starting rate should be decreased, temperature increased, or oil volume fraction increased. These results are helpful to improve the transportation of water-in-heavy crude oil in pipeline.

Keywords Pipeline flow, water-in-heavy crude oil emulsions, yield stress

1. INTRODUCTION

Heavy crude oil or extra heavy crude oil is any type of crude oil which does not flow easily. The resources of heavy oil in the world are more than twice those of conventional light crude oil. Therefore, the heavy crude oil provides an interesting situation for the economics of petroleum

---

Received 25 May 2013; accepted 2 June 2013.

Address correspondence to Jing-yu Xu, LMFS, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, P. R. China. E-mail: xujingyu@imech.ac.cn

Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/ldis.

development. Generally, the heavy crude oil appears the rheology characteristics of yield stress, thixotropy, viscoelasticity, and so on. The yield stress is one of the most important rheology characteristics since the fluids cannot be transported when external force is less than its yield stress.[1–3] Here, the yield stress can be defined as a limit stress below which the sample behaves like a solid, but above the value of yield stress, the application of stress undergoes unlimited deformation to cause the fluid flow.[4–6] To start the heavy crude oil flow in pipeline, the theoretical minimal pressure drop (ΔP_{min}) could be given by the following correlation[7]:

$$\Delta P_{\min} = \frac{4\tau_y\, L}{D}, \qquad [1]$$

where τ_y is the yield stress of the fluids in *Pa, L* the length of the pipe in *m*, and *D* the inner diameter of the pipe in *m*.

Although the start-up of the heavy crude oil has attracted a lot of considerable attention in the past several decades,[6,8–11] a full picture is still unavailable. As be shown in Equation (1), to gain the minimal pressure drop, the yield stress of fluids have to be known firstly. Thus, a systemic research on the yield stress should be carried out even through some researchers have attempted to investigate the performance of pipeline flow by directly measuring the minimal pressure drop.[12] At present, because of the presence of water in crude oil well or injection of water into the well for increasing crude oil production, the heavy crude oil production frequently results in transportation of water-in-heavy crude oil emulsions in pipeline over long distances. Therefore, study of the effect of the water phase injection with respect to the yield stress is urgent and helpful to provide an accurate design of pipeline transport in the petroleum industry.

To improve the pipeline transportation of the watery heavy crude oil, we start this work as the following points. First, our subject for investigation is water-in-heavy crude oil emulsions, for which there are very limited publications devoted to this type fluid. Second, it is considered necessary to carry out a full set of rheological measurements including the effects of shear rate, system temperature and phase volume fraction on the yield stress, in order to obtain the complete rheological characteristics of this type fluids. Third, it seems to be very interesting to make systematic measurements on the emulsions with or without emulsifying agent to determine the effect of microstructure of emulsions on the yield stress. Thus, as a reference we start with the results about the yield stress without emulsifying agent. Thereafter, the influence of emulsifying agent on the yield stress will be presented.

2. EXPERIMENTAL

2.1. Materials

In this study, heavy crude oil used for the preparation of emulsions were obtained from Liaodong bay at Bohai oil field in China. At the temperature of 30°C, the heavy crude oil was characterized by a density of $955\,\mathrm{kg/m^3}$ and the zero shear viscosity of 6000 mPas. Tap water is used as

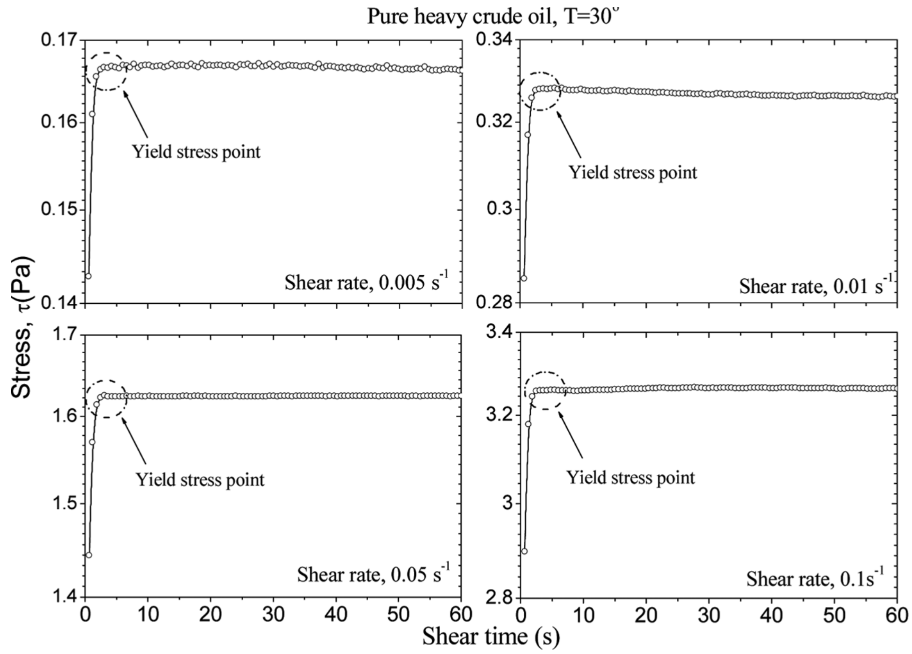


FIG. 1. Yield stress point measurements with a vane-type rotor for pure heavy crude oil at 30°C.

the water phase. The water-in-oil coarse emulsions were prepared with five different oil volume fractions of 60/70/80/90/100 vol%. The homogenization was achieved by stirring the oil and water solutions for 600 seconds, which can promise the similar distribution of pipelines, by using the three-blade stirrer at a fixed speed (1000 r/m). After homogenization, the yield stress of emulsions were measured by exploiting the performance of the rheometer.

2.2. Emulsions Preparation

The samples were prepared in batches of 500 ml and preheated to a fixed test temperature. The steady (fine) emulsions were prepared by adding the emulsifying agent with 1.5 wt% and 600 seconds of stirring. The commercial dodecylbenzene sulfonic acid sodium salt (SDBS) was used as the emulsifying agent supplied by Sinopharm Chemical Reagent Co., Ltd., China.

2.3. Equipment and Measurement

So far, several methods have been suggested to measure the yield stress of fluids including squeeze flow and rotational rheometer with different modes and rotors.[13–17] The rotational rheometer with a vane rotor, controlled by CR or CS mode, has become one of the most popular equipment for measuring the yield stress of non-Newtonian fluids in the past decades, since its ability to remove wall slip effects and disturb minimally to the microstructure of complex fluids.[18,19] Thus, in the following study, the yield stress were obtained on a HAAKE RS6000 Rheometer with a vane-type rotor (FL22, diameter = 40 mm, four vanes, gap width = 1.5 mm) by measuring the stress versus time at a given shear rate. A variety of temperature control units was also available to reliably and accurately handle temperatures ranging from −40°C to 140°C. After positioning the sample on the sensor system, the corresponding measurement was started after one minute and three replicates of each test were performed. Furthermore, the microstructure of emulsions was obtained by using the equipment of microscope (Olympus BX43) and CCD imaging system (ProgRes C5 cool).

3. YIELD STRESS OF HEAVY CRUDE OIL

In order to simulate the start-up rate, four different shear rates, that is, 0.005 s^{-1}, 0.01 s^{-1}, 0.05 s^{-1}, and 0.1 s^{-1}, have been selected to measure the yield stress. Figure 1 gives the resulting shear stress plotted versus test time. At an initial stage, the shear stress increases rapidly and passes through a peak, and thereafter decreases slightly and maintains an approximate constant value with the time. In the present study, the peak value can be said as the yield point according to the suggestion by Schramm,[20] after that the fluids will star to flow.

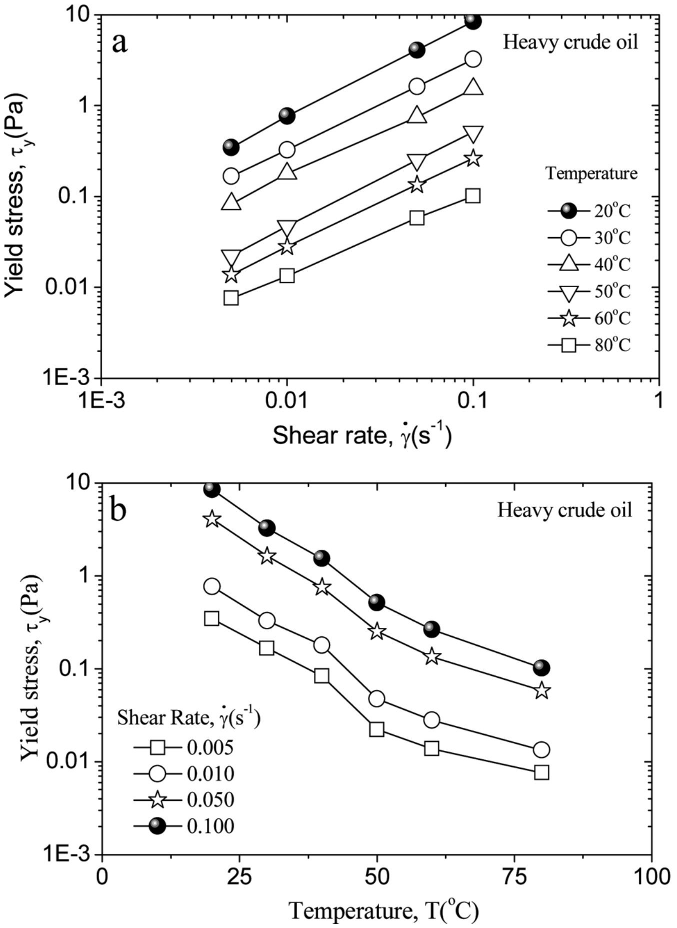


FIG. 2. Effects of shear rate and system temperature on the yield stress for pure heavy crude oil.

Figure 2a depicts the variation of the yield stress in a function of shear rate under six different temperatures. Generally, with the increases of the shear rate the yield stress become lager. The curve shows an approximately linear relationship with the shear rate at a fixed temperature. It is also observed in Figure 2b that the effect of shear rate on the yield stress becomes smaller with increases of temperature. The changes of the yield stress under four given shear rates show a similar trend. Generally, the yield stress follows an approximate exponential decay as the increasing temperatures.

4. YIELD STRESS OF EMULSIONS

4.1. Effect of Oil Volume Fraction

Based on the experimental observation and previous studies,[21,22] the apparent viscosity of oil and water emulsions has a maximum around an oil volume fraction of 0.6 regardless of the changes of the shear rates. At this point the interaction between oil-continuous regions and

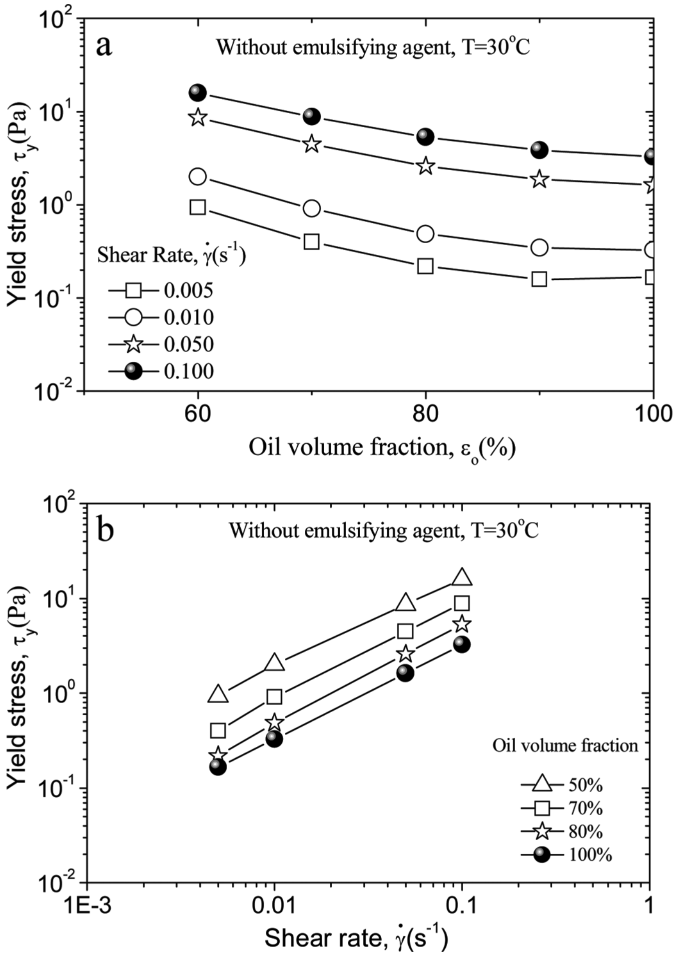


FIG. 3. Effects of oil volume fraction and shear rate on the yield stress for water-in-heavy crude oil emulsions.

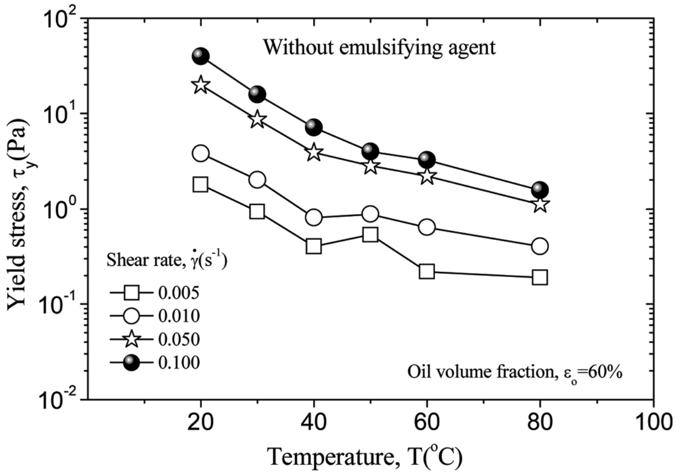


FIG. 4. Effects of system temperature on the yield stress for water-in-heavy crude oil emulsions at 60% oil volume fraction.

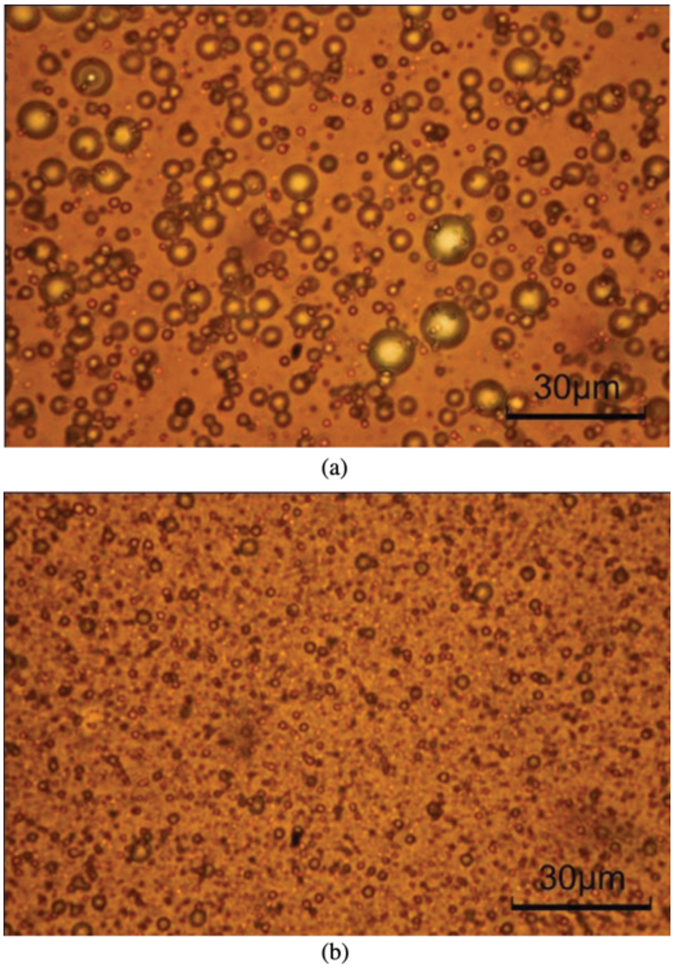


FIG. 5. Microstructure of oil-water emulsion at oil volume fraction (ε_o) = 90%. (a) Without emulsifying agent and (b) with SDRS.

water-continuous regions is the strongest. Thus, in the following study, when the oil volume fraction is above 0.6, the heavy crude oil is considered as the continuous phase and the solution is the water-in-heavy crude oil emulsion.

Figure 3 presents the results of measurement for the emulsions with different oil volume fractions at 30°C. Generally, the yield stress decreases as the oil volume fraction increasing. The value of 60% oil volume fraction is approximate 5 times than that of pure heavy crude oil at a fixed shear rate. Therefore, it means that the fluids need a greater force to start the pipeline transport due to the joining of water. It can be also seen in Figure 3b that the increases of the yield stress in an approximate linear with the shear rate increasing over a wide range of she shear stress rates from $0.005\,s^{-1}$ to $0.1\,s^{-1}$.

4.2. Effect of System Temperature

It is well known that the system temperance has an important effect on the rheology characteristics of emulsions. For

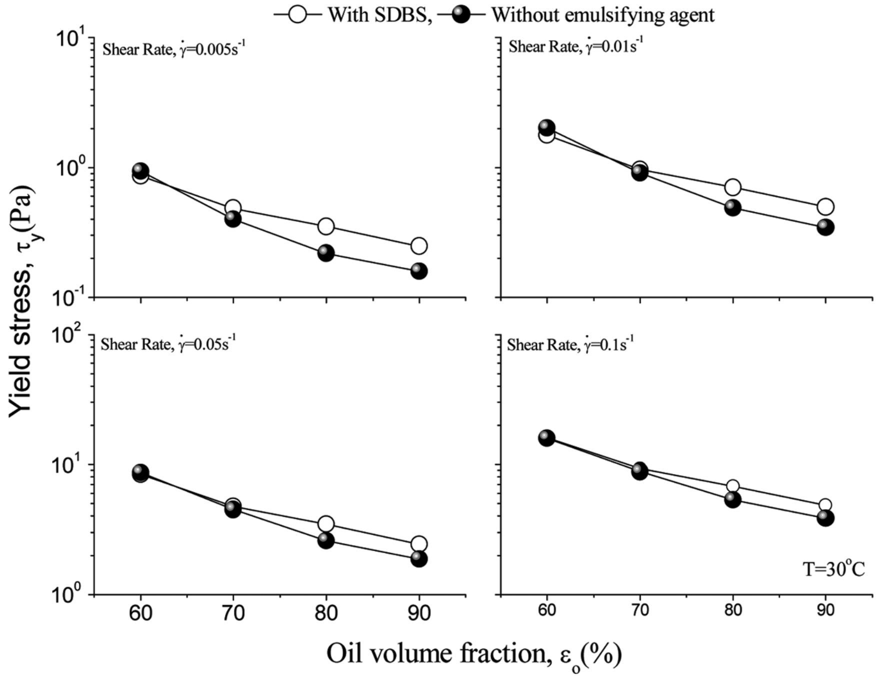


FIG. 6. Effects of emulsifying agent on the yield stress for water-in-heavy crude oil emulsions at fixed shear rates.

instance, a reduction of temperature causes a remarkable increase in the viscosity of continuous phase. Figure 4 shows that the effects of system temperance on the yield stress for water-in-heavy crude oil emulsions at four different shear rates ($\varepsilon - 0.6$). Generally, the increases of temperance reduce the yield stress of emulsions, especially for the emulsions with high shear rate. By comparing Figure 4 with Figure 2, it can be found that there is a similar tendency with the system of pure heavy crude oil and but the yield stress for emulsions is bigger than that for pure heavy crude oil at a given shear rate.

4.3. Effect of Emulsifying Agent

An emulsifying agent has two important functions for oil-water emulsions, namely: (a) to reduce the interfacial tension between oil and water and thereby enabling easier formation of the emulsions, and (b) to stabilize the dispersed phase against coalescence once it is formed.[23] Figure 5 gives the microstructure of water-in-heavy crude oil emulsions with or without emulsifying agent at oil volume fraction of 90%, respectively. As be shown, the droplet sizes of the emulsions with emulsifying agent are much smaller than those without emulsifying agent. Also, the fine emulsion with emulsifying agent appears to have a narrow distribution of droplet sizes and exhibits a greater tendency to flocculate. Therefore, it should be exerted a greater force to make it flow. In the figure, the approximate values of volume average droplet sizes of emulsions are 10 μm and 3 μm, respectively.

Figure 6 show that the effects of emulsifying agent on the yield stress for four different shear rates. In general, the emulsifying agent strengthens the yield stress of emulsions and with the increase of oil volume fraction, the degree of impact become larger. With the increase of the oil volume fractions, the yield stress of emulsions with emulsifying agent become higher than those without emulsifying agent, and show an approximately linear relationship in a linear-log coordinate system, that is, exponential decay in a log-log coordinate system.

5. CONCLUSION

To understand the start-up condition of water-in-heavy crude oil emulsions flowing in pipes, the yield stress is investigated by using a HAAKE RS6000 Rheometer with a vane rotor. The factors, including oil volume fraction, shear rate, temperature, and emulsifying agent, are concerned in this study. Based on the experimental results and analysis, the following conclusions can be obtained:

- The yield stresses of water-in-heavy crude oil emulsions are significantly influenced by shear rate, system temperature and oil volume fraction.
- The yield stress increases linearly as the increasing shear rate, and displays an exponential decay with the increasing temperature and oil volume fraction.

Although the addition of emulsifying agent enhances the stability of the emulsion, to some extent it also increases the yield stress, especially for the emulsions with high oil volume fractions. Therefore, to reduce the start-up force for the pipeline transport of water-in-heavy crude oil emulsions, the starting rate should be decreased, temperature increased or oil volume fraction increased. Such studies should be helpful to improve the transportation of watery heavy crude oil in pipeline.

FUNDING

The authors gratefully acknowledge that the work described here is financially supported by the Special Development of National Key Scientific Instruments in China (2011YQ120048-02) and the Outstanding Young Talent Incubation Program at Institute of Mechanics, Chinese Academy of Sciences.

REFERENCES

[1] Cheng, D.C.H. (1986) *Rheol. Acta*, 25: 542–554.
[2] Chang, C., Boger, D.V., and Nguyen, Q.D. (1998) *Ind. Eng. Chem. Res.*, 37: 1551–1559.
[3] Rensing, P.J., Liberatore, M.W., Sum, A.K., Koh, C.A., and Sloan, E.D. (2011) *J. Non-Newton Fluid Mech.*, 166: 859–866.
[4] Wardhaugh, L.T. and Boger, D.V. (1987) *Chem. Eng. Res. Des.*, 65: 74–83.
[5] Hou, L. and Zhang, J.J. (2007) *J. Oil & Gas Tech.*, 29: 99–102.
[6] Mendes, P.R.S., Soares, F.S.A., Ziglio, C.M., and Goncalves, M. (2012) *J. Non-Newtonian Fluid Mech.*, 179–180: 23–31.
[7] Wachsa, A., Vinaya, G., and Frigaardb, I. (2009) *J Non-Newtonian Fluid Mech.*, 159: 81–94.
[8] Cawkwell, M.G. and Charles, M.E. (1987) *J. Pipelines*, 7: 41–52.
[9] Sestak, J., Charles, M.E., Cawkwell, M.G., and Houska, M. (1987) *J. Pipelines*, 6: 15–24.
[10] Webber, R.M. (1999) *J. Rheol.*, 43: 911–931.
[11] Taghavi, S.M., Alba, K., Monyers-Gonzalez, M., and Frigaard, I.A. (2012) *J Non-Newton Fluid Mech.*, 167–168: 59–74.
[12] Madjid, M.B., Sabah, A.A., Mohamed, B., and Mansour, B. (2012) *Fuel*, 95: 97–107.
[13] Keentok, M. (1982) *Rheol. Acta*, 21: 325–332.
[14] Kim, Y.D. and Kee, D.D. (2008) *Rheol. Acta*, 47: 105–110.
[15] Rabideau, B.D., Lanos, C., and Coussot, P. (2009) *Rheol. Acta*, 48: 517–526.
[16] Meeten, G.H. (2010) *Rheol. Acta*, 49: 45–52.
[17] Pérez-González, J., López-Durán, J.J., Marín-Santibáñez, B.M., and Rodríguez-González, F. (2012) *Rheol. Acta*, 51: 937–946.
[18] Liddell, P.V. and Boger, D.V. (1996) *J. Non-Newton Fluid Mech.*, 63: 235–261.
[19] Barnes, H.A. and Nguyen, Q.D. (2001) *J. Non-Newton Fluid Mech.*, 98: 1–14.
[20] Schramm, G. (2000) In *A Practical Approach to Rheology and Rheometry*; 2nd ed., edited by G. Schramm; Gebrueder: HAAKE GmbH; pp. 210–214.
[21] Miñana-Perez, M., Jarry, P., Pérez-Sánchez, M., Ramirez-Gouveia, M., and Salager, J.L. (1986) *J. Dispersion Sci. Technol.*, 7: 331–343.
[22] Zhang, J., Xu, J., Gao, M., and Wu, Y. (2013) *J. Dispersion Sci. Technol.*, 34: 1148–1160.
[23] Pal, R. (1996) *AIChE J.*, 42: 3181–3190.