Determination of correlation dependences of emulsion viscosity on the concentration of water droplets under non-isothermal conditions

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Abstract. There are several factors that affect the rheological properties of an emulsion. Because heavier oils are highly viscous, determining this property plays a special role in the oil industry. Viscous oils can cause many problems throughout the system and can also cause difficulties in pumping and transportation. In this paper, the experimental values were approximated by an exponential viscosity-temperature relationship in which the empirical coefficients are a function of concentration. At low concentrations, the pre-exponential multiplier is described by the Taylor formula; at concentrations greater than 2.5%, the curve is described by a power function. The dependence of the temperature coefficient of viscosity on concentration is described by a linear function.

Keywords: disperse system, viscosity, emulsion, correlation dependences

Определение корреляционных зависимостей вязкости эмульсии от концентрации капель воды в неизотермических условиях

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Аннотация. Существует несколько факторов, влияющих на реологические свойства эмульсии. Поскольку более тяжелые масла обладают высокой вязкостью, определение этого свойства играет особую роль в нефтяной промышленности. Вязкие масла могут создавать множество проблем во всей системе, а также могут вызывать трудности при перекачке и транспортировке. В настоящей работе экспериментальные значения были аппроксимированы экспоненциальной зависимостью вязкости от температуры. При низких концентрациях предэкспоненциальный множитель описывается формулой Тейлора, при концентрациях более %2,5 кривая описывается степенной функцией. Зависимость температурного коэффициента вязкости от концентрации описывается линейной функцией.

Introduction

Water-in-oil emulsions occur in a variety of natural and industrial systems. In particular, the formation of emulsions causes many serious problems in the oil industry. The presence of emulsions in crude oil causes resistance to flow, especially in arctic thermal conditions, due to rather complex rheology of the fluid [1]. Changes in rheological properties have a significant impact on the entire hydrodynamics of emulsions. For example, the structure of flows during thermal convection of emulsion systems has features that are associated with changes in rheological characteristics during gravitational stratification of the emulsion [2]. In industrial systems, the rheological properties of emulsions are important for modeling energy requirements, process equipment and pipeline design, as well as for assessing flow quality during transportation [3]. Highly efficient computational methods for modeling a large volume of a dispersed system are required to more accurately determine the rheological parameters of such systems based on the calculated properties of its components [4]. There are several factors that influence the rheological properties of emulsions, such as water volume fraction, temperature, shear stress and shear rate. Studying the rheological behavior of emulsions, including their viscosity properties during shear flow, as well as determining the correlation dependences of emulsion viscosity on system parameters is of both theoretical and practical importance.

There are various formulas for calculating the viscosity of disperse systems. In the case of dilute suspensions (particle concentration less than 5%), in which the dispersed phase is particles, the formula published in Einstein's work [5], which started the experimental study of liquids with solid inclusions, can be used to calculate the viscosity:

$$\eta = \eta_c(1 + 2.5C), \tag{1}$$

where η is the viscosity of the suspension, η_c is the viscosity of the dispersion medium, C is the volume content of the dispersed phase.

The expression derived by Einstein is true for spherical particles and can also be used to determine viscosity when droplet deformation is almost non-existent, such as for microemulsions. It is necessary to correct the formula for inclusions of other shapes, for example, flattened or elongated. In order to expand the field of application of the Einstein formula, a different formula for calculating the viscosity of the disperse system was proposed in Taylor's work [6]:

$$\eta = \eta_c\left(1 + 2.5C\left(\frac{\eta_d + 0.4\eta_c}{\eta_d + \eta_c}\right)\right), \tag{2}$$

where η_d is the viscosity of the dispersed phase. Here it is assumed that instead of particles, the inclusions are droplets of another liquid.

The viscosity model presented in [10] is applicable to both Newtonian and non-Newtonian fluids:

$$\eta = \eta_c (1 - K_0 K_f(\gamma) C)^{-2.5}, \tag{3}$$

where K_0 is the hydration coefficient, which depends on the nature of the emulsifier, K_f is the flocculation coefficient, which depends on the shear rate and is used only in non-Newtonian fluids.

The formula for emulsion viscosity proposed in [11] is true for any volume concentration of droplets and has the form:

$$\left(\frac{\eta}{\eta_c}\right)^{2/5} \left(\frac{2\eta + 5\eta_d}{2\eta_c + 5\eta_d}\right)^{3/5} = (1 - C)^{-1}. \tag{4}$$

If we take solid particles instead of droplets, i.e. droplet viscosity $\eta_d \to \infty$, we get a formula for the viscosity of a polydisperse system with spherical particles.

Pal has proposed many different formulas in his works, one of them being an extension of the Taylor formula for modeling the viscosity of concentrated emulsions [12]:

$$\left(\frac{\eta}{\eta_c}\right)\left(\frac{2\eta + 5\eta_d}{2\eta_c + 5\eta_d}\right)^{3/2} = \left(1 - \frac{C}{C_{max}}\right)^{-2.5 C_{max}}, \tag{5}$$

where C_{max} is the maximum concentration of droplets.

The author also compared the calculated viscosity according to the formula with the experimental data in his work and obtained a good agreement of the results.

It is necessary to take into account the temperature dependence of viscosity in addition to the dependence of viscosity on concentration when studying the dynamics of emulsion systems under nonisothermal conditions. The present work is devoted to the study of emulsion viscosity changes depending on the temperature and concentration of water droplets in it, as well as to the determination of the correlation dependence.

Materials and Methods

The object of the study in the presented work is water-oil emulsion. Medical Vaseline oil (GOST 3164-78) was used as the dispersed phase. Dispersion medium was deionized water (Milli-Q). Nonionic surfactant sorbitan monooleate (Span 80) was used to obtain a stable emulsion. The manufacturing procedure was as follows: 0.5% Span 80 (by weight) was added to Vaseline oil and stirred for 5 min at 300 rpm using an ES 8300D top drive stirrer (Ecros), then deionized water was added depending on the desired concentration during the stirring process, the water-oil stirring process continued for 5 min. As a result, a stable inverse (water in oil) emulsion was obtained.
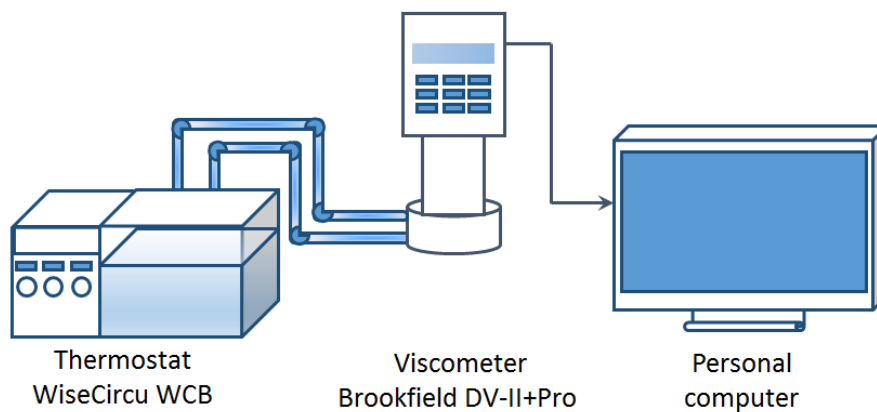

Fig. 1. Schematic of the experimental setup

An experimental setup was assembled, the scheme of which is shown in Fig. 1. The main part of the setup is a Brookfield DV-II+Pro viscometer with a sample bowl, a cone spindle and a thermowell with liquid circulation holes, connected to a WCB (WiseCircu) thermostat. The emulsion to be tested was placed inside the sample bowl in a volume of 0.5 mL.

The principle of the rotational viscometer is to measure the torque of the rotor generated by the liquid under test. This measurement is performed by the rotation angle sensor by the twist of the measuring spring.

The cell was heated over a temperature range of 20 to 70°C in 10°C increments. The concentration of water in the emulsion varied from 1 to 20%. All data were acquired with the Rheocalc software, which provides data acquisition and automatic computer control. Shear stresses from the shear rate (torque) of the emulsions at different media temperatures were measured, allowing the viscosity to be further calculated and its dependence on temperature and concentration to be plotted.

Results and Discussion

To determine viscosity values, the experimental shear stress versus shear rate dependencies for an emulsion with a concentration of C = 1−20% in the temperature range 20−70 °C were approximated by the Bingham model, since it includes two components: the Newtonian viscosity takes into account all flow resistance, and the plastic one does not take into account structural strength, but reflects the fracture rate.

According to the results of the experimental studies, the viscosity dependences on the difference of the current and initial temperature for different concentrations were plotted (Fig. 2). It can be seen that as the temperature of the emulsion increases, its viscosity decreases. At the same time, the viscosity dependence on the concentration becomes less noticeable at temperatures above 40 °C.
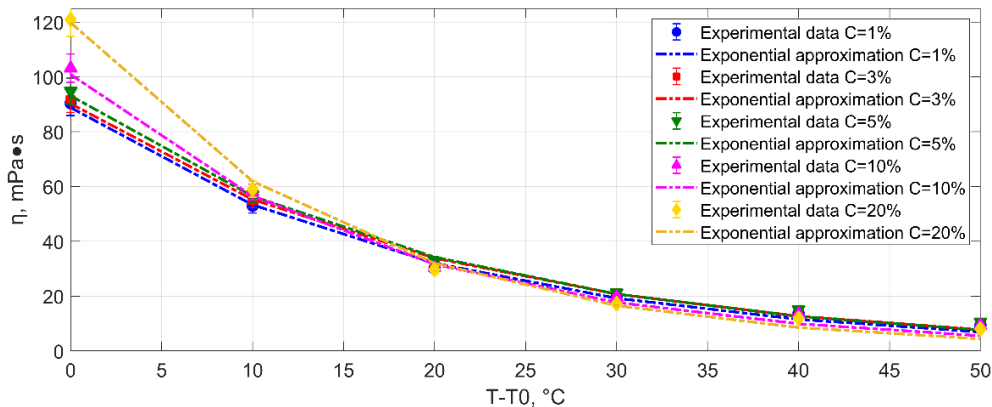

Fig. 2. Experimental dependences of viscosity on temperature
for concentrations C=1, 3, 5, 10 and 20 %

The studies were conducted at different concentrations and temperatures. To obtain an empirical curve, the experimental values were approximated by an exponential relationship in which the empirical coefficients are a function of concentration:

$$\eta = \eta_0(C) \cdot e^{(-\gamma(C) \cdot (T - T_0))}, \qquad (6)$$

where η is the dynamic viscosity of the emulsion at temperature T; $\eta_0(C)$ is the dynamic viscosity of the emulsion at temperature T_0; $\gamma(C)$ is the temperature viscosity coefficient; T, T_0 are the current and initial temperatures of the emulsion.

The dependences of the temperature coefficient of viscosity on the emulsion concentration and the pre-exponent on the emulsion concentration are shown in Table 1.

Table 1

**Dependencies of the emulsion dynamic viscosity at
temperature T_0 and the temperature coefficient of viscosity
on the emulsion concentration**

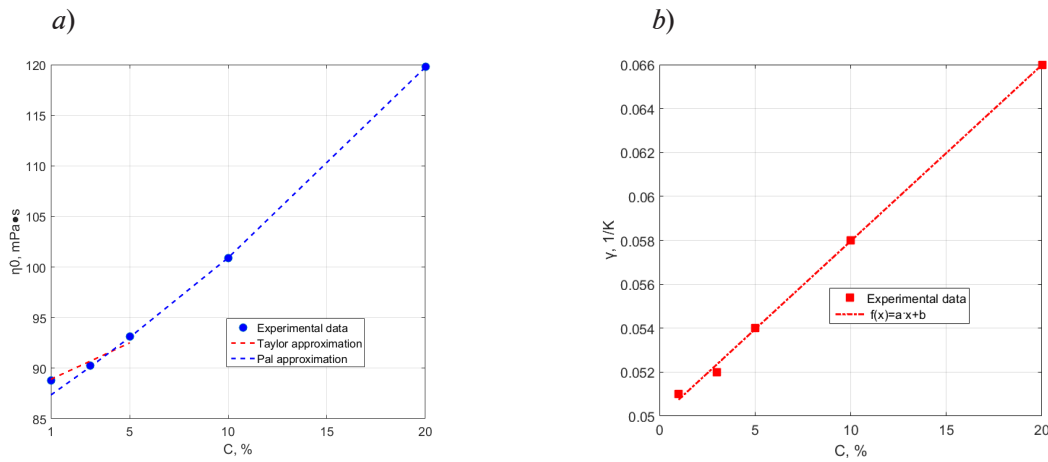| C, %	η_0, mPa·s	γ
1	88.8	0.051
3	90.23	0.052
5	93.12	0.054
10	100.9	0.058
20	119.8	0.066

a)　　　　　　　　　　　　　　　　　b)

Fig. 3. Experimental concentration dependences of emulsion dynamic viscosity
at temperature T_0 (*a*); temperature viscosity coefficient (*b*)

The dependence of emulsion viscosity on concentration at temperature T_0 obtained during the experiments (Table 1) was analyzed by means of empirical dependences (2) and (3). It was obtained that at low concentrations (less than 5%), the results agreed well with the Taylor formula (red curve in Fig. 3,*a*, η_{c1} = 88 mPa·s. At concentrations over 2.5%, the curve is described by function (3) with coefficient $K_0 K_f$ = 0.62 (blue curve in Fig. 3, *a*), η_{c2} = 86 mPa·s. A weak dependence of the temperature coefficient of viscosity on concentration was observed. The dependence has a linear character and is described by the equation $\gamma(C) = \gamma_0 + \alpha \cdot C$, where $\gamma_0 = 0.04994$ 1/K, $\alpha = 8 \cdot 10^{-4}$ 1/K (Fig. 3,*b*).

Finally, we obtain an empirical relationship for the viscosity of the water in vaseline oil emulsion:

$$\eta = \eta_0(C) \cdot e^{(-\gamma(C) \cdot (T - T_0))}, \ 20°C \le T \le 70°C,$$

$$\eta_0(C) = \begin{cases} \eta_{c1}\left(1 + 2.5C\left(\dfrac{\eta_d + 0.4\eta_{c1}}{\eta_d + \eta_{c1}}\right)\right), 0 \le C \le C_s, \\ \eta_{c2}\left(1 - K_0 K_f C\right)^{-2.5}, C_s < C \le 20\%, \end{cases}$$

$$\gamma(C) = \gamma_0 + \alpha \cdot C.$$

(7)

Dependence (7) is valid for concentrations from 0 to 20% and for temperatures from 20 to 70 °C. It can be used, for example, to estimate the viscosity of emulsions in process systems, as well as in the simulation of processes related to heating and stratification of concentrated emulsions.

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Conclusion

Experimental studies of the viscosity of water-in-oil emulsion as a function of temperature and concentration of water droplets in it using a Brookfield DV-II+Pro viscometer were conducted. The experimental values are approximated by an exponential dependence of viscosity on temperature, in which the empirical coefficients are a function of concentration. At low concentrations, the pre-exponential multiplier is described by the Taylor formula; at concentrations over 2.5%, the curve is described by a power function. The dependence of the temperature coefficient of viscosity on concentration is described by a linear function

Acknowledgments

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