EVALUATION OF THIXOTROPIC MODELS FOR WAXY CRUDE OILS BASED ON SHEAR STRESS DECAY AT CONSTANT SHEAR RATES

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ABSTRACT:
Thixotropy is an important rheological behavior of waxy crude oils. The objective of this paper is to demonstrate existing model's abilities to describe shear stress decay behaviors of waxy crude oils at constant shear rates. Seven models specially developed for or currently used to waxy crude oils are reviewed as well as two viscoelastic-thixotropic models for human blood. Stress decay behaviors were measured for four waxy crude oils and at various temperatures. Each of the models was used to fit the stress decay plots at a single shear rate, and at multiple shear rates, respectively. Globally, Zhao's model, a complex viscoplatic model with two structure parameters and twelve physical & fitting parameters, matched the experimental plots better than other compared models. While the three models with viscoelastic backgrounds were not quite successful. For use of models, one may make choice by comprehensively considering a model's complexity in mathematic form and abilities to describe the rheological behaviors.

ZUSAMMENFASSUNG:
Thixotropie stellt eine wichtige Eigenschaft wachsartiger Erdöle dar. Das Ziel dieses Artikels ist zu zeigen, dass existierende Modelle für wachsartige Erdöle den Abfall der Scherspannung bei konstanter Schergeschwindigkeit beschreiben können. Sieben Modelle, die eigens für wachsartige Erdöle entwickelt worden sind, und zwei weitere viskoelastisch-thixotrope Modelle für menschliches Blut werden in dieser Arbeit betrachtet. Der Spannungsabfall wurde für vier wachsartige Öle bei verschiedenen Temperaturen gemessen. Jedes dieser Modelle wurde angewandt, um den Spannungsabfall bei einer einzelnen bzw. mehreren Scherraten zu fitten. Das Modell von Zhao, ein komplexes viskoplastisches Modell mit zwei Strukturparametern und zwölf physikalischen und Fitparametern, beschrieben die experimentellen Daten besser als die anderen Modelle, während die drei Modelle, die auf Viskoelastizität basieren, nicht erfolgreich waren. Bei der Anwendung der Modelle kann man zwischen der mathematischen Komplexität und der Fähigkeit wählen, das rheologische Verhalten zu beschreiben.

RÉSUMÉ:
La thixotropie est un comportement rhéologique important du brut paraffineux. L'objectif de cet article est de démontrer les capacités de modèles thixotropiques existents pour décrire le gradient de contraintes de cisaillement du brut paraffineux en constante vitesse de cisaillement. Sept modèles thixotropiques actuellement utilisés dans le but paraffineux sont discutés ainsi que deux modèles viscoélastique-thixotropique pour le sang humain. Visant les quatre bruts paraffineux, la relaxation de contraintes de cisaillement est mesurée par expérimentation sous les temprératures variées. Chaque de ces modèles mentionnés sont utilisés pour l'ajustement des données de gradient de vitesse de cisaillement respectivement sous la vitesse unitaire de cisaillement et de multiples vitesses de cisaillement. Globalement, le modèle viscoplastique complexe de Zhao avec deux paramètres de structure et douze paramètres d'ajustement s'assortent mieux aux données expérimentales que les autres modèles. L'effet des trois modèles viscoélastiques n'est pas très idéal. Pendant l'application de ces modèles, on peut faire son choix tout en considérant la complexité mathématique et les capacités de la description du comportement rhéologique.

KEY WORDS: waxy crude oil, thixotropy, shear stress decay, model, evaluation

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Oil	Shear rate [1/s]	Average AADs of various model [%]								
		Houska	Zhao	Chen	Hou	Liu	Fang-1	Fang-2	Cast-1	Cast-2
1	1	5.3	0.9	4.1	0.6	11.4	8.9	10.8	12.6	5.8
	2	6.9	1.0	2.7	0.3	12.9	13.3	13.1	13.2	4.6
	4	9.4	1.4	2.7	0.8	9.7	8.8	8.3	12.2	4.5
	8	11.0	3.0	1.0	0.9	10.0	10.2	7.2	11.6	6.4
	average	8.1	1.6	2.6	0.6	11.0	10.3	9.8	12.4	5.3
2	1	5.1	0.8	3.2	0.5	9.2	9.1	9.3	10.1	3.8
	2	7.6	0.9	3.3	0.3	10.4	10.8	10.5	11.2	4.3
	4	10.7	2.5	2.5	0.6	10.9	10.8	10.9	10.3	5.7
	8	9.3	2.4	2.2	0.7	10.8	7.0	4.3	9.4	6.3
	average	8.2	1.7	2.8	0.5	10.3	9.4	8.8	10.35	5.0
3	1	2.9	0.6	1.6	0.5	9.7	6.9	9.2	11.1	3.5
	2	2.3	0.5	1.4	0.4	10.2	5.9	8.2	10.6	3.8
	4	3.6	0.4	1.6	0.3	8.7	6.7	10.4	9.4	3.4
	8	5.6	0.7	1.6	0.1	7.0	6.4	8.0	7.8	3.1
	average	3.6	0.6	1.6	0.3	8.9	6.5	8.9	9.8	3.5
4	1	4.7	1.0	3.4	0.8	8.1	3.9	3.9	8.7	3.4
	2	9.1	1.8	2.8	0.6	9.2	8.9	9.2	9.3	4.4
	4	6.0	1.7	2.4	0.2	6.7	4.5	4.0	7.2	3.3
	8	4.5	1.3	1.5	0.8	4.7	4.2	3.5	5.1	2.5
	average	6.1	1.4	2.5	0.8	7.2	5.4	5.1	7.6	3.4
	overall average	6.5	1.3	2.4	0.6	9.3	7.9	8.2	10.0	4.3

Oil	Temperature [°C]	Average AADs of various model [%]								
		Houska	Zhao	Chen	Hou	Liu	Fang-1	Fang-2	Cast-1	Cast-2
1	32	15.9	3.8	12.0	12.2	20.9	23.9	16.1	21.4	14.9
	33	12.4	3.6	11.1	8.8	18.3	19.1	12.6	20.4	14.5
	34	8.1	2.6	5.0	7.2	15.1	13.7	8.1	13.4	9.2
	35	5.2	2.4	3.5	5.2	13.3	12.5	5.3	13.4	9.8
	36	4.6	1.6	2.1	4.0	6.3	6.5	4.0	7.8	5.9
	average	9.3	2.8	6.7	7.5	14.8	15.1	9.2	15.3	10.8
2	32	13.6	3.2	5.0	10.4	16.8	16.0	13.8	22.8	17.4
	33	11.9	3.4	7.9	9.8	15.3	14.9	11.8	22.2	17.1
	34	11.3	4.0	9.0	8.7	16.8	15.2	11.9	20.2	15.7
	35	7.1	3.3	4.0	6.0	12.2	12.0	6.8	17. 8	14.2
	36	5.3	2.4	3.6	5.9	10.9	9.9	5.8	14.5	11.2
	average	9.8	3.3	5.9	8.1	14.4	13.6	10.0	19.5	15.1
3	38	10.6	1.8	2.5	5.6	19.3	13.9	10.9	16.9	12.3
	39	9.8	2.7	5.8	6.6	17.9	12.4	11.6	15.7	12.0
	40	7.3	5.0	6.3	7.1	12.8	10.6	8.3	12.7	9.2
	average	9.2	3.2	4.9	6.4	16.7	12.3	10.3	15.1	11.2
4	28	14.1	4.3	4.2	9.9	17.4	19.9	14.1	23.4	17.5
	29	13.4	3.3	3.5	11.7	18.5	16.1	13.4	22.4	17.1
	30	9.7	3.2	5.1	7.4	14.8	13.9	9.8	21.0	16.5
	31	7.3	3.3	4.5	7.0	13.0	11.0	7.5	17.3	13.6
	32	5.8	3.3	3.7	5.8	10.1	8.5	6.8	14.3	11. 1
	average	10.1	3.5	4.2	8.4	14.8	13.9	10.3	19.7	15.2
	overall average	6.5	1.3	2.4	0.6	9.3	7.9	8.2	10.0	4.3

Table 2 (above): The average absolute deviations of fittings to single shear rate data.

Table 3: The average absolute deviations of fittings to multiple shear rate data.

generally doubled or even more, with more than half of them above 10% and some even above 20%. Besides, the AADs show clear tendency of increase with decreasing temperature. This indicates that change of oil temperature indeed impacts model's abilities to match experimental data. However, it is in this case that Zhao's model undoubtedly shows exceptional abilities to describe the shear stress decay behaviors for all four oils and at all test temperatures, with a maximum of average AAD of only 5%.

4 CONCLUDING REMARKS

Thixotropic models for waxy crude oils are reviewed. By using experimental data of four waxy crude oils at various temperatures, nine models are evaluated for their abilities to match shear stress decay data at constant shear rates. It is found that all studied models may fairly predict the shear stress decay behaviors if fittings are made on single shear rate basis. However, if fittings are made on multiple shear rates basis, deviations understandably become larger. This paper provides information of every model's abilities to describe shear stress decay behavior at constant shear rate. Among all studied models, Zhao's model undoubtedly shows exceptional abilities to match the shear stress decay data for all four oils and at all test temperatures even in the case of multiple shear rate fittings.

However, Zhao's model is more complicated than the currently-used Houska model that is already thought to be too much complex. Therefore, from practical point of view, if a thixotropic model is required, say, for numerical simulation of the transient flow of the thixotropic waxy crude oil, one may choose a less complex but acceptably accurate model. In other words, development of thixotropic models with simpler mathematic form but better accuracy is remained to be a task for future studies. Besides, the three models with viscoelastic background are found not to be quite successful in describing the shear stress decay of waxy crude oils at constant shear rates, indicating that further studies are necessary to develop viscoelastic-thixotropic models that may better characterize the thixotropic behaviors from rheological point of view. Finally, many other materials such as cement pastes [28, 29] and sludge [30] may also exhibit thixotropic behaviors. Therefore, thixotropic models developed for waxy crude oils may be considered for their fitness to these materials as well.

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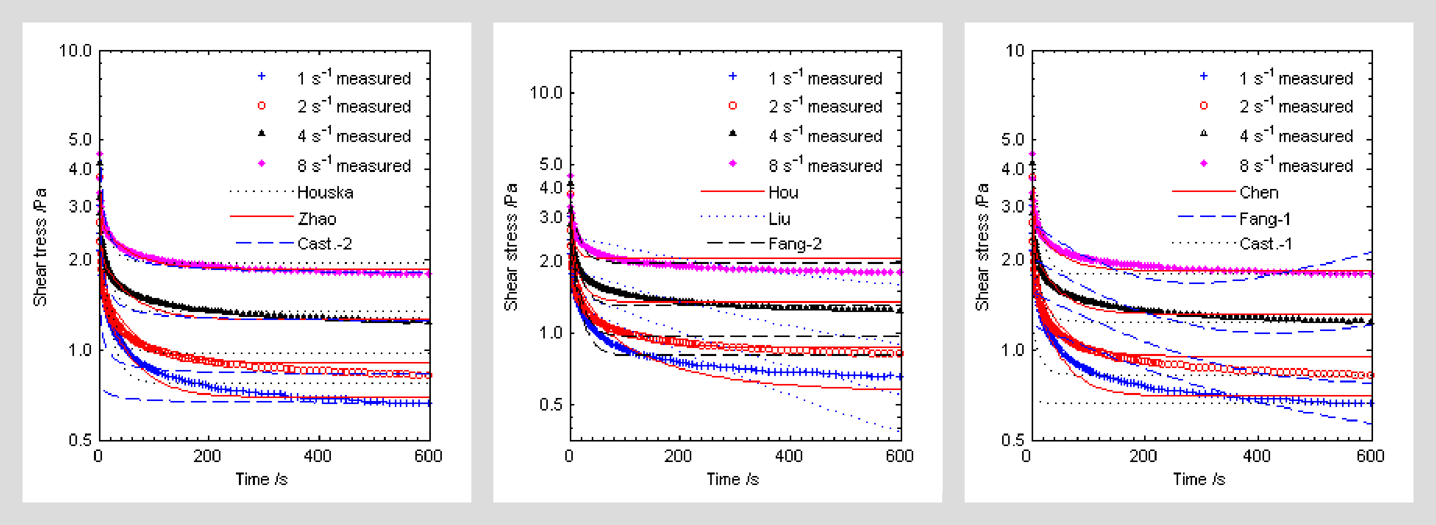

Figure 4: Fittings of models to measured data for oil 4 at 31°C.

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