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Modeling the viscoelasto-plastic behavior of waxy crude

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Abstract: Waxy crude oil exhibits complex rheological behavior below the pour point temperature, such as viscoelasticity, yield stress, and thixotropy, owing to the formation of a three-dimensional spongelike interlock network structure. This viscoelasto-thixotropic behavior is an important rheological behavior of waxy crude oils, determining the flow recovery and safe restart of crude oil pipelines. Up to now, the thixotropic models for waxy crude have been all viscoplastic models, without considering the viscoelastic part before the yield point. In this work, based on analyzing the variation of the elastic stress and viscous stress in the Mujumbar model, a new viscoelasto-plastic model is proposed, whose shear stress is separated into an elastic component and a viscous component. The elastic stress is the product of the shear modulus and elastic strain; the shear modulus is proportional to the structural parameter. For the elastic strain, we followed the line of Zhu and his coauthors and assumed that it may be expressed by an algebraic equation. The model is validated by stepwise shear rate tests and hysteresis loop tests on Daqing and Zhongyuan waxy crude. The results show that the model's fitting and predictive capability is satisfactory.

Key words: Thixotropy, viscoelasticity, viscoelasto-plastic model, thixotropic model, waxy crude

1 Introduction

More than 80% of crude oil produced in China is waxy oil, such as Zhongyuan and Daqing crude oils, with a wax content of 21.5% and 26.3%, respectively. In the past ten years, the output of waxy crude throughout the world has increased significantly. Below the wax appearance temperature (WAT), wax molecules begin to precipitate and form solid wax crystals in crude oil (Rønningsen, 1992). Below the pour point temperature the precipitated wax crystals interlock with each other to form a three-dimensional spongelike network structure, completing the transition of crude oil from sol to colloidal gel (Visintin et al, 2005; Zhu et al, 2007). Consequently the gelled waxy crude oil shows complex rheological behavior, such as viscoelasticity, yield stress, and thixotropy (Zhang and Liu, 2008; Magda et al, 2009). Experimental results show that the mechanical response of a gelled waxy crude is linear viscoelastic at the beginning of deformation (Chang et al, 1998). As the shear strain increases, the three dimensional network composed of loose clusters is disrupted into a small number of relatively large flocs or aggregates, losing the connectivity of the network structure (Chang et al, 1998; Visintin et al, 2005). In this process, the viscoelasticity decays, and the mechanical response gradually transfers from being dominated by the elastic effect to being dominated by the viscous effect. After shearing under some high shear rate for a period of time, the internal network structure is nearly totally destroyed, thus the viscoelastic behavior is very weak and even can be ignored, then the rheological response is mainly thixotropic (Chang et al, 1998).

However, most of the existing thixotropic models for waxy crude are viscoplastic models, utilizing a yield stress to characterize the yielding behavior (Barnes, 1997; Mujumdar et al, 2002; Zhang et al, 2010). The viscoplastic models assume that the material begins to flow only if the shear stress is greater than the yield stress. For this reason, they can only depict the thixotropic behavior after the yield point and cannot account for the initial viscoelastic effect before the yield point (Labanda and Llorens, 2006). In recent years, some scholars attempted to describe both the viscoelastic and thixotropic effects of thixotropic materials with yield stress (Barnes, 1997; Mujumdar et al, 2002; Dullaert and Mewis, 2006; de Souza Mendes, 2009; 2011). To characterize the viscoelastic and thixotropic properties of blood, Fang and Jiang (1998) developed a constitutive equation based on the principle of a mechanical analogy composed of a spring, a dashpot, and a self-developed thixotropic element in parallel. However, the elastic stress of the model increases with the shear strain unbounded in time. To overcome this problem, a modified model was developed (Fang et al, 1999). However,

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