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Unifying Viscosity–Temperature Modeling and Thermophysical Equivalence for Heavy Crude Oils

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Abstract:

Understanding the viscosity-temperature behavior of heavy crude oils is essential for viscosity reduction and flow assurance. However, comparative studies across diverse crude oils remain limited. This work experimentally investigates the viscosity-temperature characteristics of 40 representative heavy crude oils from China. A thermophysical equivalence concept is introduced, suggesting that the effect of molecular structure on viscosity-temperature behavior fades at elevated temperatures due to weakened intermolecular interactions. A linear relationship is observed between the viscosity-temperature coefficient (VT_{t-50}) and the viscosity at 50°C (η_{50}) for all samples. The Andrade-Eyring equation accurately describes the measured behavior. The viscous flow activation energy (E_a) and pre-exponential factor (η_a) show logarithmic and exponential correlations, respectively, with the thermal viscosity-retention ratio ($K_{120/50}$). Using the relationship between η_{50} and the viscosity-reduction ratio ($R_{120/50}$), a simple classification method is proposed to group heavy crude oils into three categories. These correlations and the classification scheme provide a practical basis for predicting viscosity-temperature behavior and supporting engineering applications.

Keywords: Viscosity-temperature correlation, Heavy crude oil, Andrade-Eyring equation, Viscosity-temperature coefficient, Thermophysical equivalence

1. Introduction

Global energy demand continues to increase, with crude oil remaining one of the world's primary energy resources. As conventional medium and light crude oil reserves gradually decline, heavy crude oil (HC), owing to its abundant reserves, has become an increasingly important resource for sustaining future energy supply[1, 2]. However, the widespread utilization of HC is severely constrained by its extremely high viscosity, which adversely affects production, transportation, and refining processes[3]. Therefore, understanding the rheological behavior of HC and developing effective viscosity-reduction strategies are essential for its efficient exploitation[4, 5].

Among the available viscosity-reduction technologies, thermal methods, particularly thermal enhanced oil recovery (EOR), are the most widely applied because the viscosity of HC is highly sensitive to temperature. Consequently, accurately describing the viscosity–temperature relationship is fundamental for optimizing thermal recovery processes, transportation conditions, and other engineering operations involving HC[1, 6-8].

Numerous empirical and semi-empirical models have been proposed to describe the viscosity–temperature behavior of crude oils. However, most were developed using limited datasets or specific crude oil systems, making their applicability to chemically diverse heavy crude oils uncertain[9]. Although the principle of corresponding states provides a theoretical framework for generalized fluid-property prediction, its application to heavy crude oils remains limited by molecular complexity, the lack of representative critical properties, and the strong influence of resins, asphaltenes, waxes, and other polar constituents on viscosity[10, 11]. Consequently, existing correlations remain largely empirical and oil-specific, with model parameters lacking clear physical significance or quantitative relationships with intrinsic physicochemical properties. Whether chemically diverse heavy crude oils share common temperature-dependent viscosity responses remains unclear. Resolving this issue is essential for developing more predictive and physically interpretable viscosity–temperature correlations.

To address these issues, the viscosity–temperature behavior of 40 representative

heavy crude oils from China was systematically investigated over a wide viscosity range. Generalized viscosity–temperature correlations applicable to chemically diverse heavy crude oils were developed and rigorously evaluated. Quantitative relationships between model parameters and key physicochemical properties were further established, enhancing both the predictive capability and physical interpretability of the correlations. The results also reveal common temperature-dependent viscosity responses among compositionally diverse heavy crude oils, providing the experimental foundation for a thermophysical equivalence concept and a more generalized framework for describing heavy crude oil viscosity.

2. Experiment

2.1 Samples of heavy crude oils

Forty heavy crude oil samples were collected from typical heavy oil extraction regions in China. Prior to testing, each sample was degassed, desanded, and dehydrated. The samples were numbered HC_1 to HC_{40} in ascending order of viscosity. Detailed information is provided in Table S1.

2.2 Measurement of Viscosity-Temperature Dependence

HC viscosity as a function of temperature was measured using a rotational rheometer (Kinexus Lab+, Netzsch, Germany) with a 40 mm cone-plate fixture. Apparent dynamic viscosity (η, *simplified as* viscosity) was obtained at a shear rate of 10 s^{-1} at four temperatures (50, 75, 100, and 120 °C), with temperature controlled to ±0.1 °C. All measurements were automatically recorded.

3. Results and Discussion

As temperature increases from t_1 to t_2 °C, the viscosity of heavy crude oil decreases from η_{t1} to η_{t2}. Three composite indicators are used to quantify the viscosity-temperature dependence:

Thermal viscosity-retention ratio $K_{t2/t1} = \eta_{t2}/\eta_{t1}$, representing the retained viscosity fraction;

Thermal viscosity-reduction ratio $R_{t2/t1} = 1 - K_{t2/t1} = (\eta_{t1} - \eta_{t2})/\eta_{t1}$, representing the relative viscosity reduction;

Viscosity-temperature coefficient $VT_{t1\text{-}t2} = (\eta_{t1} - \eta_{t2})/(t_1 - t_2)$, denoting the average rate of viscosity change with temperature (i.e., the mean slope of the viscosity–

temperature curve).

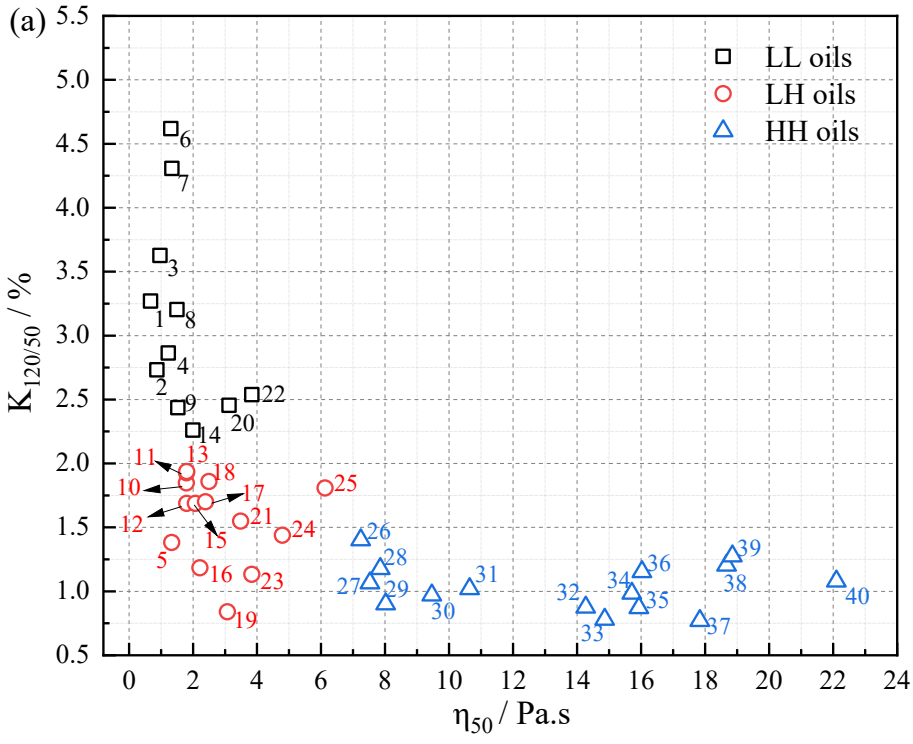
A lower $K_{t2/t1}$ or higher $R_{t2/t1}$ indicates a more effective viscosity reduction over the interval, while a higher $VT_{t1\text{-}t2}$ reflects greater thermosensitivity and improved efficiency of thermophysical viscosity-reduction processes.

Based on the relationships between viscosity at 50 °C (η_{50}) and $K_{120/50}$ or $R_{120/50}$ (Figure 1), the 40 HC samples are classified into three groups using η_{50} as the primary indicator and $R_{120/50}$ as the secondary indicator: HH, LH, and LL. As following:

HH group (blue triangles): high viscosity ($\eta_{50} > 6$ Pa·s) and high thermosensitivity ($R_{120/50} > 98\%$ or $K_{120/50} < 2\%$).

LL group (black squares): low viscosity ($\eta_{50} < 6$ Pa·s) and low thermosensitivity ($R_{120/50} < 98\%$ or $K_{120/50} > 2\%$).

LH group (red circles): an intermediate category with low viscosity but high thermosensitivity.



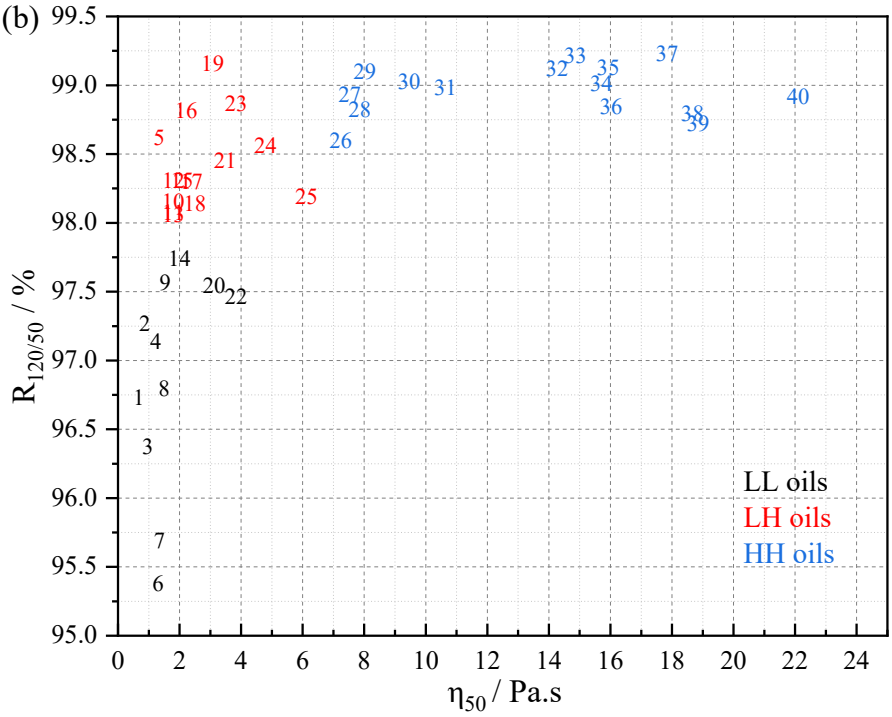


Figure 1. Viscosity at 50 °C (η_{50}) versus (a) thermal viscosity-retention ratio ($K_{120/50}$) and (b) thermal viscosity-reduction ratio ($R_{120/50}$) for 40 heavy crude oils.

Apparent viscosity arises from two contributions: molecular viscosity (Newtonian) and structural viscosity[12]. Molecular viscosity depends primarily on molecular structure and intermolecular interactions, decreasing with increasing molecular mobility. Structural viscosity originates from organized interaction networks or supramolecular structures that hinder molecular motion and contribute additional resistance to flow, and it diminishes as these structures are disrupted upon heating.

The thermal response of heavy crude oils is thus governed by the relative contributions of two factors. Elevated temperatures weaken intermolecular interactions and can progressively break down supramolecular structures, enhancing molecular mobility and reducing structural viscosity. Consequently, viscosity decreases significantly. Comparatively, the apparent viscosity at 50°C (η_{50}) reflects the combined effect of molecular and structural viscosity, whereas the apparent viscosity at elevated temperatures (e.g., η_{120}) is dominated by molecular viscosity, as structural contributions are substantially reduced or eliminated.

Lower $K_{t2/t1}$ or higher $R_{t2/t1}$ typically implies a larger relative contribution of structural viscosity. In Figure 1, the HH group exhibits relatively stable $K_{t2/t1}$ (≈1%) and $R_{t2/t1}$ (≈99%) over a wide η_{50} range, reflecting a consistently high structural contribution in these high-viscosity samples. Conversely, the LL group shows higher and more

scattered $K_{t2/t1}$ values in η_{50}, suggesting a lower and more variable structural contribution among low-viscosity samples.

Overall, this dual-indicator classification effectively captures structural viscosity effects alongside viscosity level and thermophysical response, offering a robust framework for describing viscosity–temperature behavior.

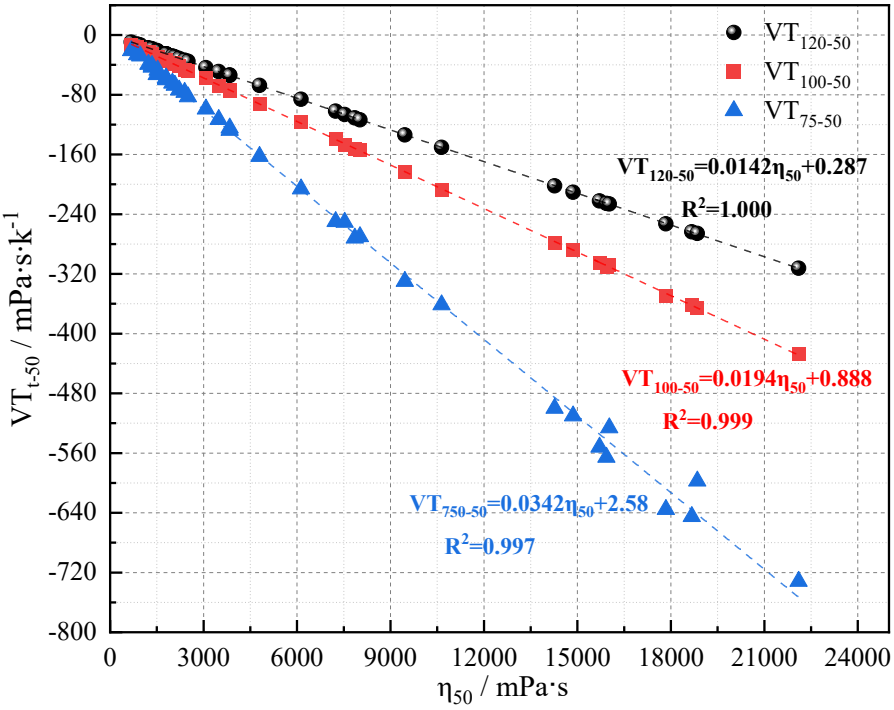


Figure 2. Correlation between the viscosity-temperature coefficient (VT_{t-50}) and the viscosity at 50 °C (η_{50}) for 40 heavy crude oils.

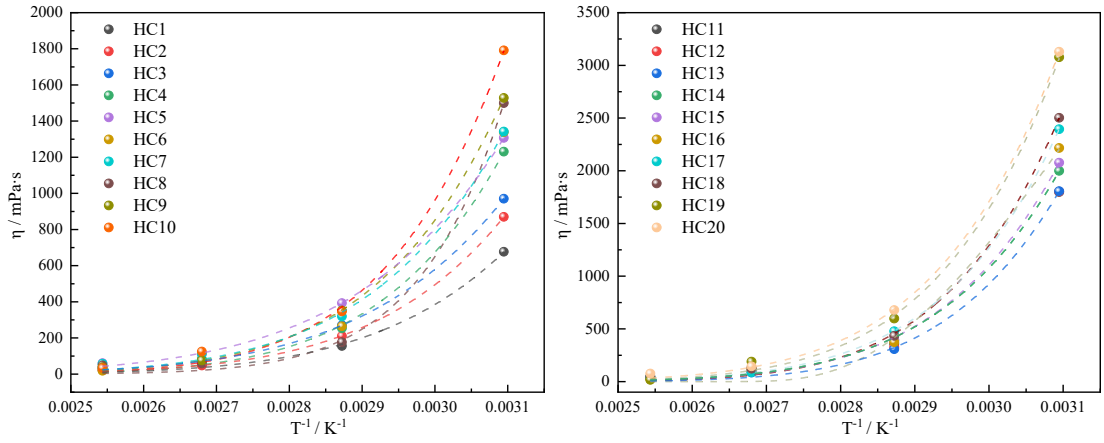
Figure 2 presents the relationships between the viscosity–temperature coefficients (VT_{t-50}) and the viscosity at 50°C (η_{50}) for heavy crude oils over three temperature intervals: 50-75°C, 50-100°C, and 50-120°C. All datasets exhibit excellent linear correlations with coefficients of determination $R^2 \geq 0.997$, indicating a strong linear dependence.

VT_{t-50} increases linearly with η_{50}, implying that higher-viscosity oils are more temperature-sensitive. This trend suggests that both molecular and structural viscosity contributions scale proportionally with η_{50} during thermophysical viscosity reduction. As the upper temperature limit increases, the slope of the fitted line decreases, reflecting a reduced contribution of structural viscosity at elevated temperatures. This linear relationship is practically useful for predicting viscosity at different temperatures and

assessing viscosity-reduction performance. However, increasing the endpoint temperature yields diminishing returns in viscosity reduction when considering energy consumption and equipment costs.

Based on these observations, we propose a concept of thermophysical equivalence: at elevated temperatures, the influence of molecular structure on viscosity-temperature behavior gradually diminishes due to weakened intermolecular interactions. Consequently, different heavy crude oils tend to converge in their viscosity-temperature response under strong thermophysical effects. Within this framework, molecular and structural viscosity contribute comparably (though not necessarily equally) to the temperature-dependent viscosity variation.

From an engineering perspective, heating reduces viscosity through the combined attenuation of molecular and structural viscosity. Nevertheless, oils rich in structural components (e.g., polar compounds or species prone to forming colloidal or gel-like networks) may respond more favorably to viscosity-reduction treatments[13]. Given the diminishing efficiency of high-temperature processes, integrated approaches such as moderate thermal methods combined with chemical additives (thermochemical strategies) are likely to achieve improved performance, particularly for structure-rich heavy crude oils.



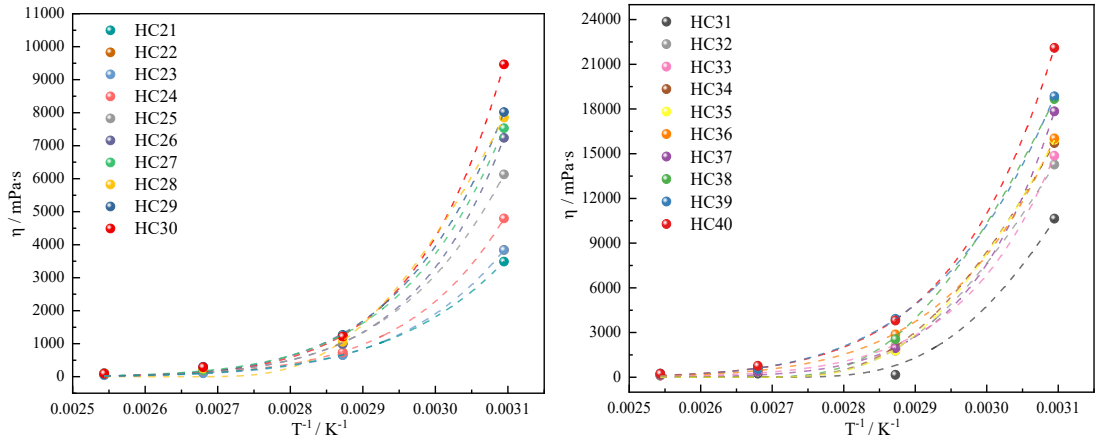


Figure 3. Viscosity (η) as a function of reciprocal reciprocal of Kelvin temperature (1/T) for 40 heavy crude oils. Colored dashed lines represent fits to the Andrade–Eyring equation.

As illustrated in Figure 3, the viscosity-temperature relationship of all 40 heavy crude oils follows the Andrade-Eyring equation, with coefficients of determination R^2>0.99 for the fitting equations. The fitting parameters were listed in Table S1. Andrade-Eyring equation, similar in form to but distinct from the Arrhenius equation, is expressed as follows:

$$\eta = \eta_A \cdot e^{\frac{E_a}{RT}}$$

Note: η: Apparent viscosity, mPa·s; η_A: Pre-exponential factor; T: Thermodynamic temperature, K; Ea: Viscous-flow activation energy, J·mol^{-1}; R: Molar gas constant, J·mol^{-1}·K^{-1}.

In this equation, the pre-exponential factor η_A is a sensitivity factor related to the molecular structure and intermolecular interaction. A higher η_A value indicates a greater frequency or number of relative displacement events of flow units under the measurement conditions[14]. The viscous-flow activation energy Ea, interpreted via Eyring's free-space model of liquid structure, represents the energy barrier that heavy oil molecules must overcome to create voids that facilitate molecular motion. It characterizes the extent of intermolecular entanglement and frictional resistance within the oil. As T→ 0 K, $\eta \to \infty$, reflecting a "solid-like" structure where intermolecular interactions immobilize the molecular system. At extremely high temperatures, $\eta \to \eta_A$ (a very small value at high-temperature) rather than zero, implying that ultra-high temperature can nearly eliminate intermolecular forces, approaching the directional motion of free molecules under fluid flow conditions. At such high temperatures,

viscosity is determined solely by the thermal resistance to directional molecular motion, representing the lower limit of viscosity [1].

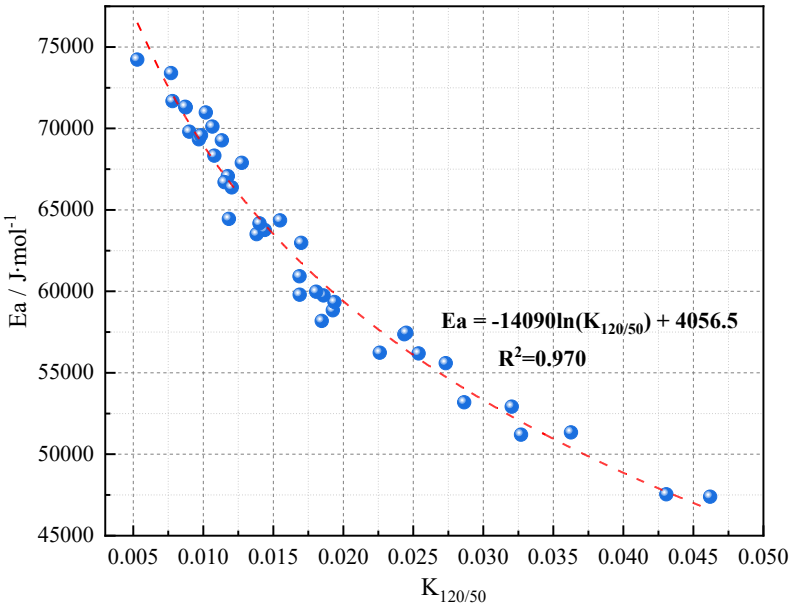


Figure 4. Correlation between viscous-flow activation energy (E_a) from the Andrade–Eyring equation and the thermal viscosity-retention ratio ($K_{120/50}$). The red dashed line represents a logarithmic fit, with the fitting equation shown in the figure.

To further understand the viscosity-temperature behavior of heavy crude oils, correlations were examined between the Andrade-Eyring fitting parameters (Ea and η_A) and the thermal viscosity-retention ratio ($K_{120/50}$). As shown in Figure 4, Ea decreases linearly with ln($K_{120/50}$): a higher $K_{120/50}$ corresponds to a lower Ea. Figure 5 reveals a strong exponential relationship between η_A and $K_{120/50}$, with η_A increasing exponentially as $K_{120/50}$ rises.

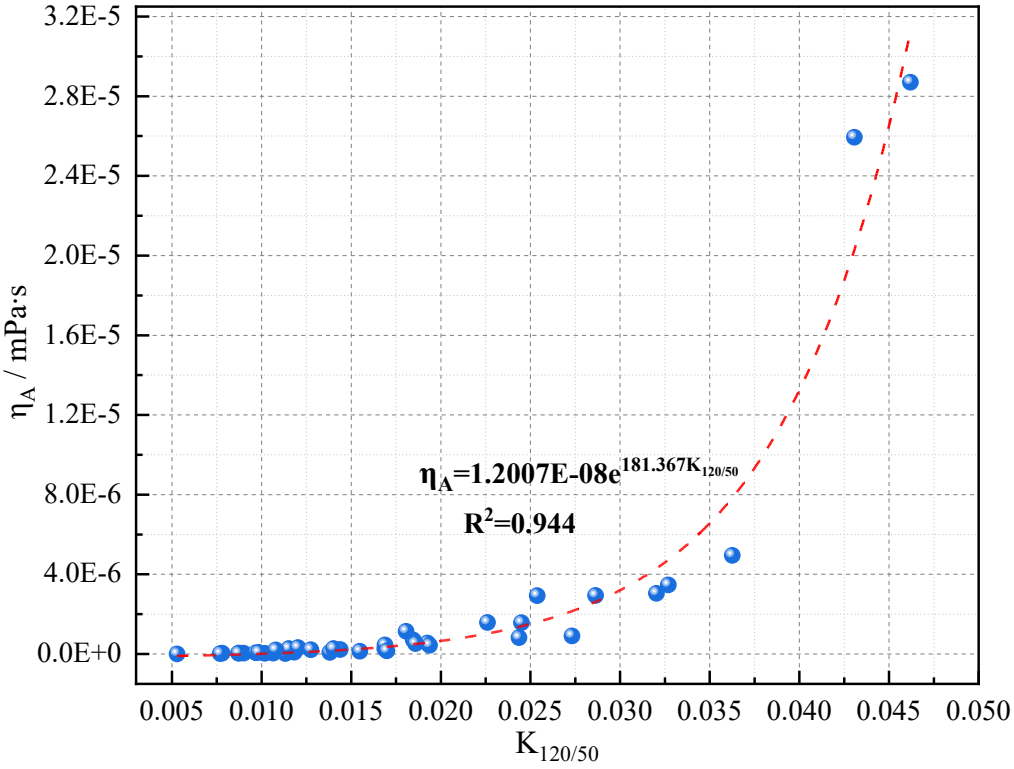


Figure 5. Correlation between the pre-exponential factor (η_a) from the Andrade–Eyring equation and the thermal viscosity-retention ratio ($K_{120/50}$). The red dashed line represents an exponential fit, with the fitting equation shown in the figure.

In summary, for the China's heavy crude oils studied, *Ea* depends logarithmically and η_A exponentially on $K_{120/50}$ (and similarly on $R_{120/50}$). In contrast, no functional relationship was found between either *Ea* or η_A and η_{50} (see Supporting Material).

3. Conclusions

Based on a detailed investigation of the viscosity-temperature behavior of forty representative heavy crude oils (HC) from major producing regions in China, the following conclusions are drawn:

(1) Thermophysical effects are equivalent across all HC samples. Consequently, all samples exhibit a linear relationship between the viscosity–temperature coefficient ($VT_{t\text{-}50}$) and the viscosity at 50 °C (η_{50}).

(2) Using η_{50} as the primary indicator and the thermal viscosity-reduction ratio ($R_{120/50}$) as the secondary indicator, a simple classification strategy is proposed. Heavy crude oils are classified into three groups: High-viscosity and High-thermosensitivity oil (HH), Low-viscosity and High-thermosensitivity oil (LH), and Low-viscosity and

Low-thermosensitivity oil (LL).

(3) The viscosity-temperature relationship of all HC samples follows the Andrade-Eyring equation. It is observed for the first time that the viscous-flow activation energy (E_a) depends exponentially, and the pre-exponential factor (η_A) depends logarithmically, on the thermal viscosity-retention ratio ($K_{120/50}$). These correlations between fitting parameters and physical properties may facilitate a broader and more unified understanding of the thermal response mechanisms across different types of heavy crude oils.

Supporting Material

The sources, viscosity ratios, fitting parameters, and some of the relationship graphs for the heavy oil samples are presented in the Supporting Material.

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