RESEARCH ARTICLE

Effect of Nanomaterials on Improving the Apparent Viscosity of Heavy Oil and the Environmental Evaluation of Reservoir Environment

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Abstract

Heavy oil reservoirs have become an important potential for alleviating energy shortages and supporting economic development. This investigation aims to explore the influence of a nano heavy oil viscosity reducer and reservoir characteristics on crude oil viscosity and flow rate during the underground extraction process, and to reveal the viscosity reduction mechanism of reservoir crude oil. The results indicate that the prepared nano viscosity reducer can significantly weaken oil viscosity compared with the commercial viscosity reducer. Moreover, the nano viscosity reducer NVR (acting as a catalyst) achieves a much higher viscosity reduction performance than the commercial viscosity reducer CVR under the same conditions. Meanwhile, the dosage of nano viscosity reducer NVR shows the greatest impact on the viscosity reduction rate among the investigated factors, whereas the pyrolysis time exhibits the smallest influence. This investigation provides basic data for improving the flowability, mobility, and recovery of reservoir crude oil.

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1 Introduction

Global economic development requires more oil resources, which has exacerbated an energy crisis worldwide [1, 2]. The proportion of heavy oil reservoirs in the world is about 29%, so the development of heavy oil reservoirs has become an important component of supplementing global energy. As an essential measure for reservoir transformation, Heavy oil viscosity reduction can significantly reduce the oil viscosity and rheology partly [3–5]. Reducing the apparent viscosity and viscosity coefficient of heavy oil has become an important data indicator for many petroleum engineers to continuously strive to improve the recovery rate of heavy oil. At present, thermal oil recovery, blending with thin oil, and chemical viscosity reduction are considered as the mainstream measures for reducing the viscosity of heavy oil in reservoirs.

However, although thermal oil recovery showed an excellent oil recovery and viscosity reduction effects, more energy and costs hinders its on-site application [6, 7]. Meanwhile, blending thin oil

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extraction also demonstrates an excellent viscosity reduction effects , but the scarcity of thin oil resources limits the promotion of this measure [8, 9]. A heavy oil viscosity reducer has been considered as an important way to adjust the viscosity of heavy oil due to its extremely low cost. Heavy oil viscosity reducers mainly involve Surfactant, Oil soluble viscosity reducer and Catalytic viscosity reducer [10, 11]. Nevertheless, Surfactant and Oil soluble viscosity reducer are gradually being abandoned due to their extremely low application range. Catalytic viscosity reducer [12, 13] is regarded as an effective viscosity reducer, but its limited viscosity reducing ability still cannot promote the aggregation and recovery of deep ultra-thick shale oil. It has become an important research topic for exploring a shale oil viscosity reducing agent with excellent viscosity reducing effect and no damage to the reservoir.

Herein, a modified nano catalyst is synthesized through nano adsorption and hydrothermal reaction. Furthermore, the effect of reservoir conditions and nano heavy oil viscosity reducer on the crude oil viscosity and flow rate during underground extraction process of crude oil. Then, the mechanism of nanocatalysts in reducing viscosity of heavy oil has also been deeply revealed from a microscopic chemical perspective. In addition, a commercial viscosity reducer is used as a reference material for comparing the viscosity reducing ability of heavy oil. This investigation conducted in the present study could provide theoretical support and basic data for enhancing oil recovery in deep shale oil.

2 Experimental

2.1 Materials

Chemical: Every compound was used without further purification and processing, and more than 99.2% purity is shown in every compound. Vanadyl sulfate, nano-silica(25nm-30nm), carbamide and sodium hydroxide were purchased from China National Pharmaceutical Reagent Co., Ltd. hydrochloric acid and Anhydrous ethanol were provided by Aladdin Industrial Corporation, China. Other compounds such as deionized water, and Triethylenetetramine were obtained from donated by Nanjing Chemical Reagent Co., Ltd. In addition, the heavy oil from shale reservoirs is sourced from the Gulong Block of Daqing Oilfield of China National Petroleum Corporation. The commercially available heavy-oil viscosity reducer used in this study was supplied by Dongying Fukos Petroleum Technology Co., Ltd. The agent is an oil-soluble chemical additive with a flash point exceeding 60.0 °C. Previous studies and product evaluations indicate that this viscosity reducer can effectively dissolve and disperse asphaltenes and resins, thereby significantly reducing heavy-oil viscosity. In addition, it exhibits a pronounced pour-point-depressing effect on waxy heavy oil and is capable of removing stagnant oil in the near-wellbore region, alleviating formation blockage, and improving oil-flow pathways. Owing to its rapid penetration and excellent miscibility with heavy oil, the viscosity reducer achieves an enhanced viscosity-reduction performance. The product is transparent, colorless, and odorless.

Instruments and equipment: Precision and accuracy calibration evaluations are conducted for the pH test paper, HJ-5 magnetic stirrer, HH-W420 constant temperature water bath, UT300 infrared thermometer. In addition, Capillary viscometer used for evaluating the viscosity of crude oil is self-designed by the laboratory.

2.2 Preparation of Nano viscosity reducer

To synthesize the Nano viscosity reducer, the deionized water mixture of 50ml mixed with vanadium oxysulfate (6.3g) was transferred into a two-necked flask (250 ml), and the dispersion process of vanadium sulfate in aqueous solution is carried out at 83 °C for 1h (Figure 1). Thereafter, the ethanol solution containing 21g of nano silica powder was poured into this water mixture at 50 °C for 3h, and a large amount of vanadium sulfate molecules adsorb onto the surface of silica particles. Furthermore, 3.1g of anhydrous urea and slowly pour it into the mixture and reflux at 92 °C for 12 hours. A milky white turbid liquid that undergoes water washing and solid-liquid separation becomes a nano vanadium acid catalyst (NVR).

2.3 Crude oil viscosity reduction performance of catalysts

The crude oil viscosity evaluation system developed in this study comprises four primary components: a heavy-oil delivery module, a heavy-oil viscosity assessment section, a catalyst-injection and mixing unit, and a light-oil viscosity evaluation module. Heavy oil stored in the reservoir tank is first pressurized by transferring it into a secondary steel cylinder using an external pump. The pressurized heavy oil is then injected into a capillary tube via ISCO Pump 1 to determine its viscosity. During this process, the evaluation temperature and pressure

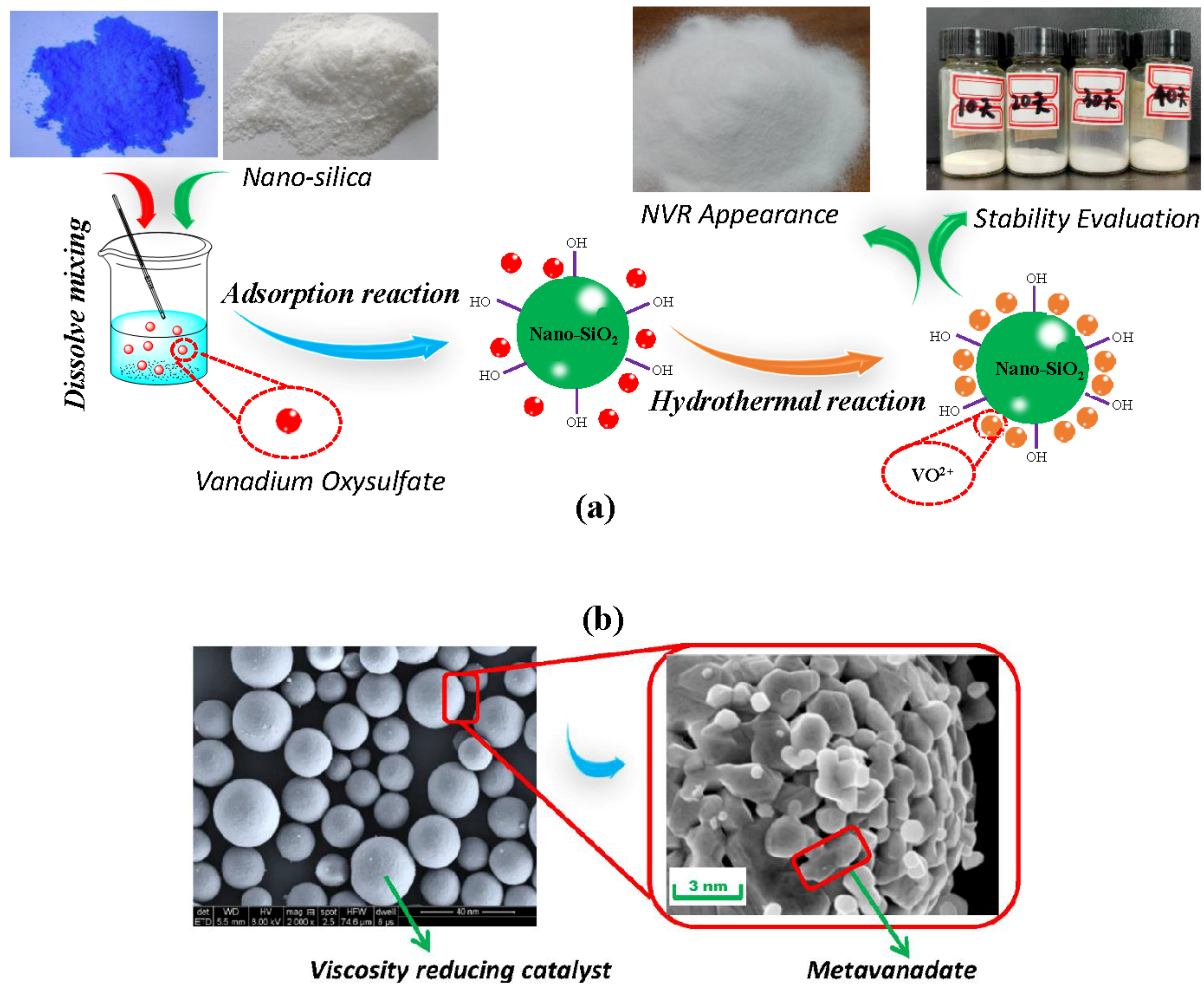

Figure 1. Synthesis of nano vanadium acid catalyst (NVR) and structure characterization.

can be precisely controlled through ISCO Pump 1 and the heating coil wrapped around the capillary tube, thereby enabling accurate simulation of in-situ reservoir thermobaric conditions. Following the initial viscosity measurement, the heavy oil is mixed with the catalyst through a check valve and subsequently enters the second capillary viscometer. The periodic pressure required for this stage is provided by an ISCO pump that displaces heavy-oil components within the pressure-resistant chamber, while the temperature is maintained using the resistance-heating wire surrounding the capillary tube to replicate real-time reservoir temperatures. After completion of the light-oil viscosity assessment, the fluid is routed through a second check valve for recovery and subsequent reuse (Figure 2).

In addition, the apparent viscosity reduction of crude oil can be calculated using Equation 1.

$$\zeta = \frac{\eta_{\text{thin}}}{\eta_{\text{heavy}}} \times 100\% \tag{1}$$

where ζ was apparent viscosity reduction rate of crude oil, %; η_{thin} and η_{heavy} were considered as the viscosity of crude oil respectively, Pa·s.

2.4 Rheology capacity of Crude oil

The capillary viscometer constructed in Figure 2 was used to evaluate the rheological data of fluids such as crude oil and reservoir fluids, and Equation 2 is often regarded as a calculation formula for reservoir fluid viscosity [14, 15].

$$\eta = \frac{D\Delta p}{8v}\frac{4L}{D} = \frac{\Delta p D^2}{32Lv} \tag{2}$$

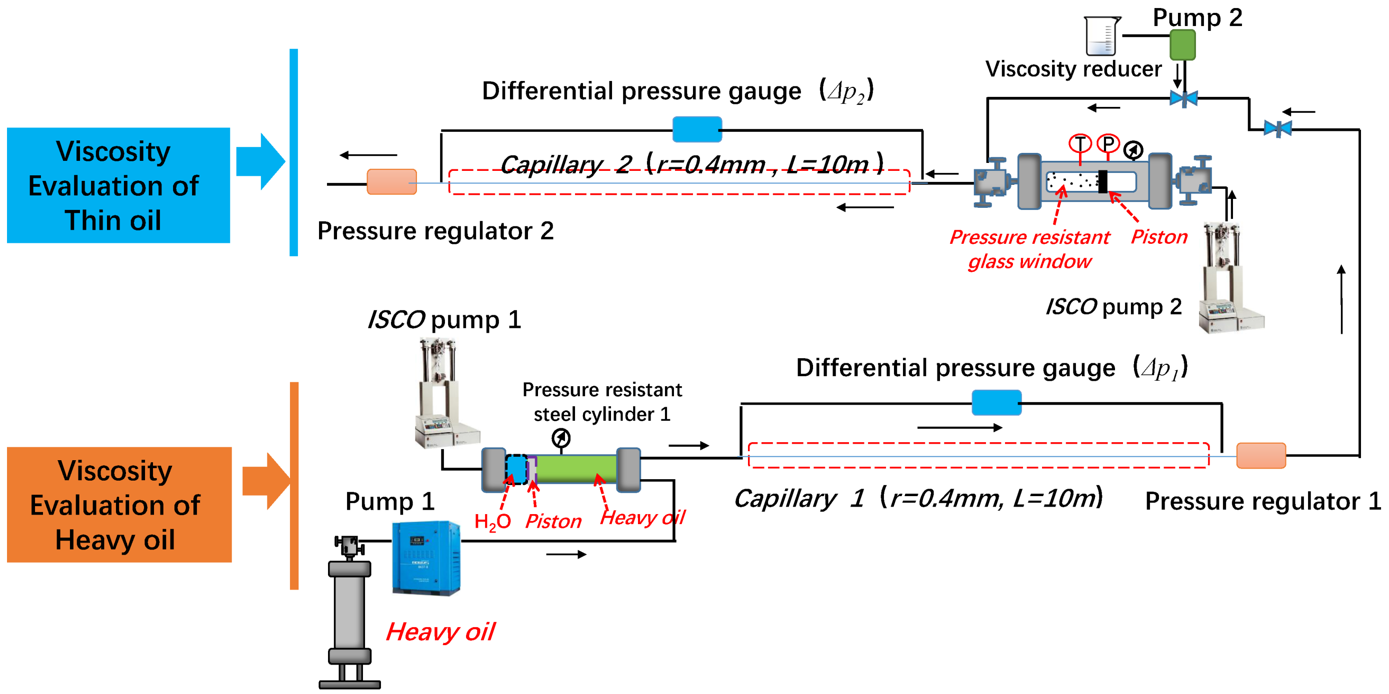

Figure 2. Evaluation equipment for viscosity reduction of heavy oil using catalysts.

where Δp is considered as the pressure difference of capillary or reservoir fractures, MPa; L and D were the capillary length and diameter, m; v is viewed as the flow velocity of crude oil, m·s^{-1}.

Thus, Equation 1 could be corrected to the following equation according to Equation 2 [16].

$$\zeta = \frac{\eta_{\text{thin}}}{\eta_{\text{heavy}}} \times 100\% = \frac{\Delta p_{\text{thin}}}{\Delta p_{\text{heavy}}} \times 100\% \tag{3}$$

In addition, Consistency coefficient K and rheological index n are often used to analyze the rheological capacity of reservoir fluids, and the calculation formula can be described as Equation 4 [17, 18].

$$\lg \tau_w = \lg K \left(\frac{3n+1}{4n}\right)^n + n \lg \left(\frac{8v}{D}\right) \tag{4}$$

where τ_w was a wall shear stress, Pa. Equation 4 could be considered as a straight line for the specific capillary, and the slope of a straight line can be expressed in rheological index n.

2.5 Reservoir environmental evaluation

Earlier research has shown that the injection of oilfield chemicals into formations can result in high reservoir development efficiency. Nevertheless, associated drawbacks such as fracture clogging and reservoir contamination are currently considered to be significant obstacles to the widespread adoption of oilfield chemicals, including heavy oil viscosity reducers. This study investigates the fracture sealing and reservoir damage capabilities of oilfield chemicals, with a focus on the reduction of heavy oil viscosity under specific reservoir conditions. The analysis is conducted by measuring the adsorption of substances onto reservoir rock and the changes in fracture permeability. The quantification of reservoir damage is achieved through the implementation of Equation 5, while the evaluation of adsorption performance is facilitated by attenuated total reflectance infrared spectroscopy, as previously elucidated in extant research [19].

$$\vartheta = \frac{K_1 - K_2}{K_1} \times 100\% \tag{5}$$

where ϑ is the rock damage rate of the geological reservoir, %. K_1 and K_2 presented the permeability of the reservoir rock before and after the viscosity reduction of heavy oil, m^2.

3 Results and Discussion

3.1 Chemical Characterization of Nano viscosity reducer

Scanning electron microscope (SEM) showed in Figure 1(b) indicated that Nano viscosity reducer has been synthesized. In addition, it can be observed from

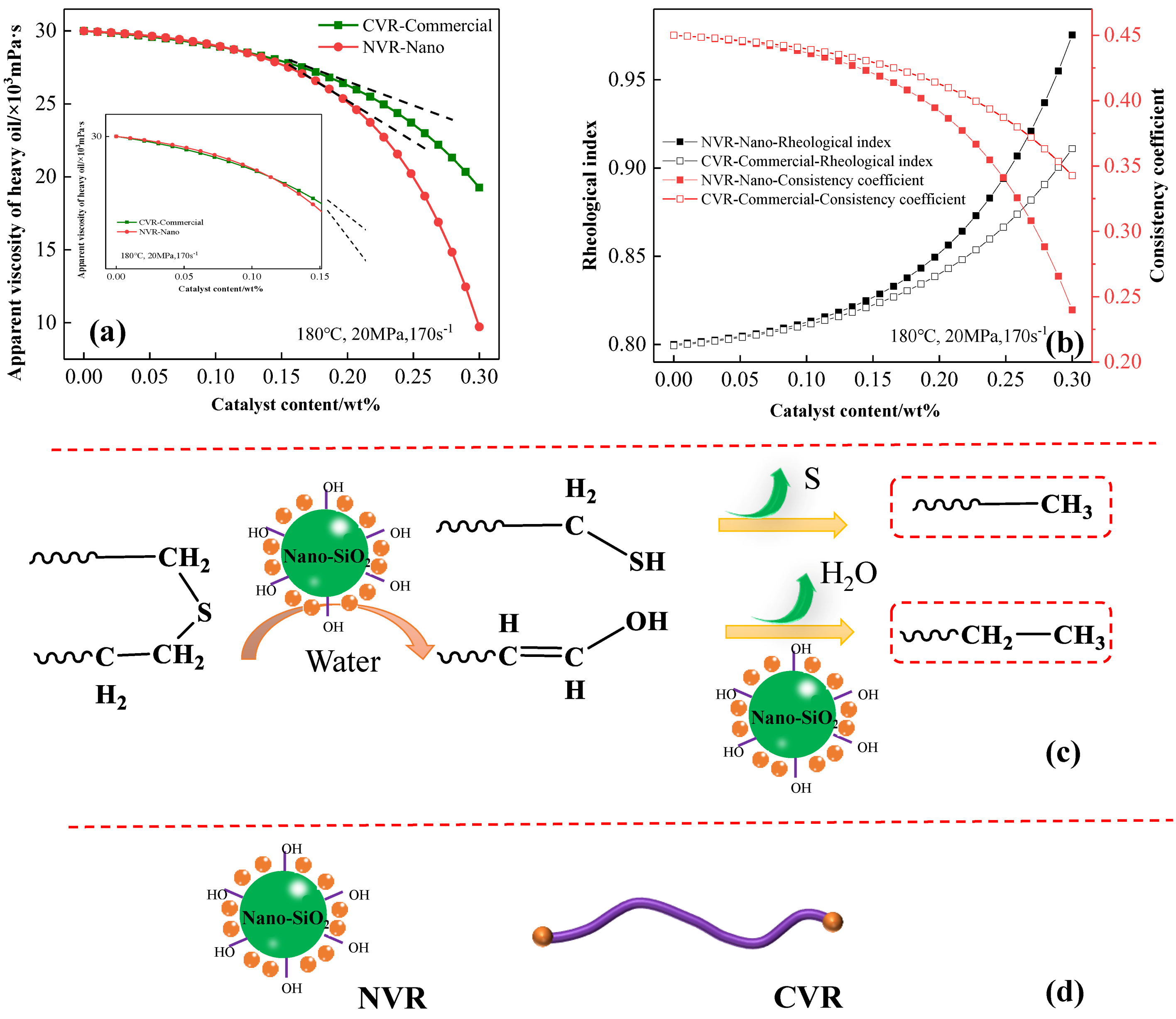

Figure 3. Effect of catalyst content on oil viscosity and rheological parameters.

Figure 3 that a large amount of vanadate and acid ions are adsorbed on the surface of nano silica, and The tiny protrusions on the particle surface are caused by a large number of active groups gathered on the surface of the nanoparticles. Meanwhile, the particle diameter is also distributed between 25-35nm, the specific surface area of extremely small spherical nanoparticles is significantly enhanced, facilitating the aggregation of active groups on their surface and thereby enhancing the catalytic effect.

3.2 Effects of viscosity reducer on the rheological capacity

As we all know, the extreme viscous resistance from the reservoir crude oil hinders its aggregation in the production well, which reduces the oil washing efficiency and crude oil recovery [20]. Accordingly, this investigation first analyzed the viscosity reduction rate and rheological properties of heavy oil with different catalyst contents, and explored the excellent viscosity reduction and reservoir protection capabilities of NVR compared to the commercially available viscosity reducer CVR.

It can be seen from Figure 3(a) that high content catalyst exhibited an excellent viscosity reduction capability compared to a low content. 0.3wt% NVR reduces the apparent viscosity of crude oil to 11×10^3 mPa·s, while the initial viscosity of crude oil (0.0wt% NVR) is as high as 30×10^3 mPa·s. However, the same amount of commercially available catalyst CVR only reduced the apparent viscosity of crude oil by 20×10^3 mPa·s , which is lower than the viscosity reduction of NVR. 60% viscosity reduction caused by 0.3wt% NVR , indicating that, Nano-catalysts NVR contributed to promote the rheological ability of crude oil. Apart from the apparent viscosity, the rheological index and consistency coefficient in Figure 3(b) are also used to evaluate the viscosity reducing ability of the catalyst on crude oil [26]. As shown in Figure 3(b), the consistency coefficient exhibits a similar trend to the apparent viscosity, which is mainly based on the fact that both parameters are proportional to the pressure difference (Δp) at both ends of the capillary. Additionally, the rheological index shows a decreasing trend with increasing catalyst content, which represents that an excellent rheological improvement abilityfor heavy oil was displayed in the the catalyst.

The above experimental results are attributed to the catalyst density per unit volume of heavy oil. As given in Figure 3(c), the sulfur (S) element contained in the heavy oil molecule can be stimulated and excited by catalyst molecules (NVR or CVR), and C-S bond can be quickly attacked and broken according to the extremely weak C-S bond energy [21, 22]. The longer molecular chains of heavy oil become shorter, which directly results in a decrease in the molecular weight and entanglement of the molecular chains of heavy oil. The shortening of molecular chains directly forms a low molecular chain entanglement and sparse micro-grid, a lower viscosity of heavy oil is exhibited [23, 24]. Immediately, a smaller grid density is displayed with increasing the catalyst content, resulting in weaker macroscopic apparent viscosity and better fluidity. In addition, catalyst content below 0.15% that cannot be filled with every corner of heavy oil to appear an almost constant fluid viscosity. Conversely, the catalyst molecules (>0.15 wt%) can fill the entire heavy oil system, which is enough to cleave more C-S bonds. A rapidly decreasing apparent viscosity and rapidly increasing rheological parameters are shown in Figures 4(a) and 4b after 0.15 wt% of catalyst content.

Moreover, It can be obtained from the data analysis of Figure 3(a) and Figure 3(b) that NVR exhibits better viscosity reducing ability than CVR at the same content. Large amounts of vanadium acid, adsorbed on the surface of chemical NVR nanoparticles, can more efficiently act on the S-C bonds of long-chain heavy oil molecules of large molecules. Nevertheless, the very few pantothenic acid targets in CVR reduce the probability and ability of S-C bonds acting on heavy oil molecules (Figure 3(d)).

3.3 Effects of reservoir temperature on the rheological capacity

Geological reservoirs are often accompanied by high-temperature environments, and the rising temperature trend is displayed with increasing the stratum depth. Figure 4 shows the effects of different reservoir temperature on the apparent viscosity and rheological coefficient of heavy oil. As displayed in Figure 4, an apparent viscosity of 17×10^3 mPas was presented on the heavy oil (containing 0.3wt% NVR) at 100 °C, but 180 °C of reservoir temperature could decreased the apparent viscosity to 11×10^3 mPa·s, indicating that, reservoir temperature is conducive to alleviate the apparent viscosity of heavy oil [25]. Meanwhile, the variation of rheological index with reservoir temperature also reflects the above viewpoint. A definite proportional relationship is presented between the rheological index and reservoir temperature, that is, the rheological index increases with the increase of reservoir temperature [25, 26]. The rheological index of heavy oil with 0.3 wt% NVR was only 0.92 at 100°C of reservoir temperature, but a 0.98 of rheological index of heavy oil was expressed when reservoir temperature increased to 180 °C.

Similarly, Figure 4 also shows the temperature rheological effect curve consistent with CVR and NVR. As can be illustrated from Figure 4, the increase in reservoir temperature shows a greater reduction in the viscosity of heavy oil containing CVR than that of NVR. 0.3 wt% CVR can increase the apparent viscosity of heavy oil from 24 ×10^3 mPa·s to 20 ×10^3 mPa·s when the reservoir temperature increases from 100 °C to 180 °C, the decreasing trend of apparent viscosity of 5 ×10^3 mPa·s is shown in the heavy oil system containing 0.3 wt% CVR. However, the same amount of NVR actually reduces the apparent viscosity of heavy oil by 7 ×10^3 mPa·s with decreasing the reservoir temperature from 100 °C to 180 °C. Additionally, the similar effect of reservoir temperature on the rheological index of heavy oil is presented between CVR and NVR, but the rheological index of heavy oil (0.3wt% CVR) has increased from 0.87 of 100 °C to 0.91 of 180 °C.

As can be seen in Figure 4(b) and Figure 4(c), two microscopic reasons dictate the data analysis that showed in Figure 4(a): (1) Arrhenius equation, a description of the relationship between temperature and molecular activity, was used to analyze the effect of reservoir temperature on the viscosity of heavy oil

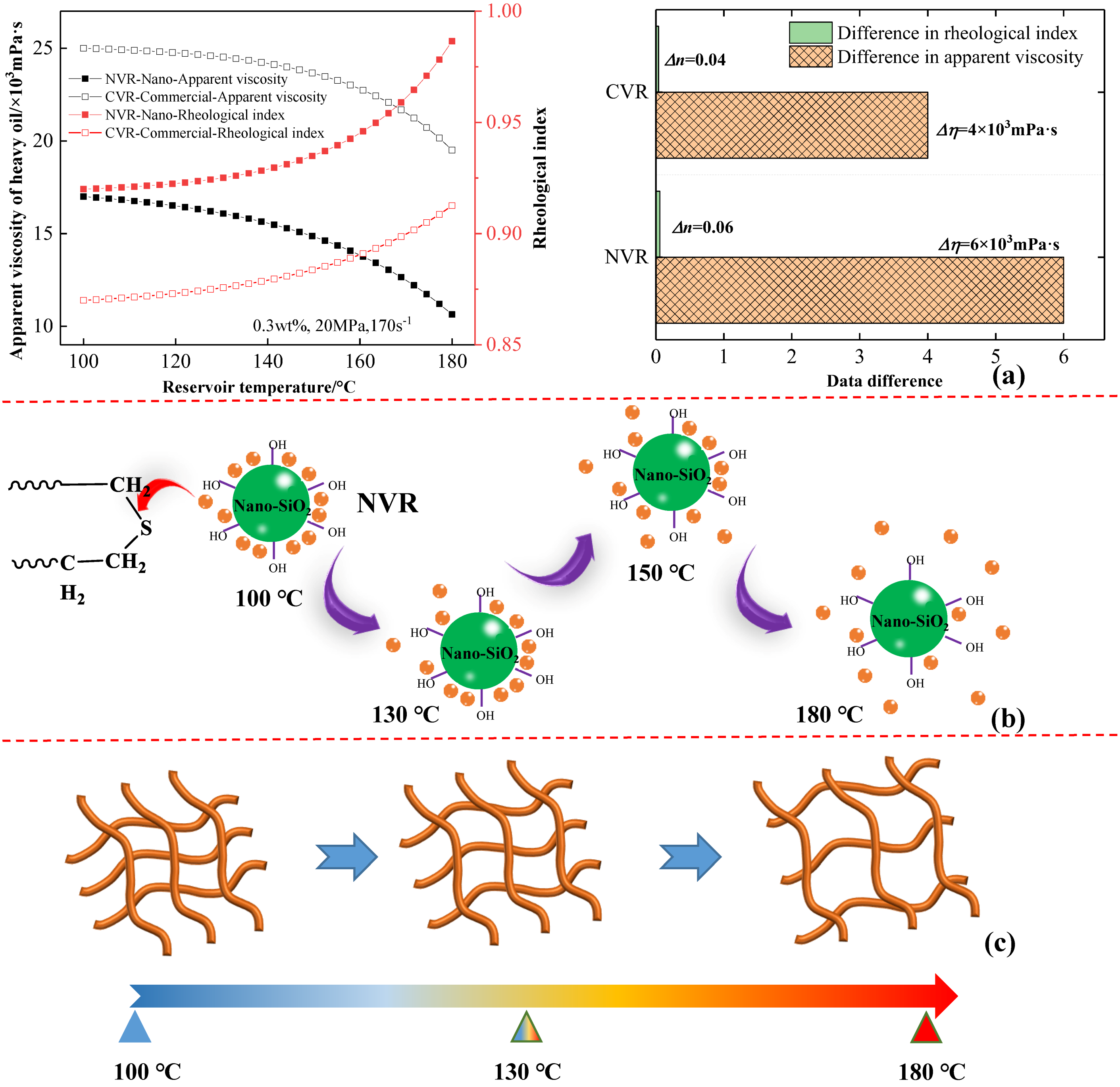

Figure 4. Effect of reservoir temperature on oil viscosity and rheological parameters.

(Equation 6) [12, 13, 27, 28].

$$\eta = A_v \exp\left(\frac{E_f}{R_g T}\right) \tag{6}$$

where A_v and R_g are often seen as constants, which means that the above two parameters will not change due to temperature changes. In addition, E_f and T are the molecular activation energy and reservoir temperature, respectively. Gradually increasing reservoir temperature will reduce the activation energy of molecules. The lower molecular activation energy at high temperature promotes the catalyst molecules to present an excited state, which is conducive to the Brownian motion of catalyst molecules and collision with heavy oil molecules [29, 30].

Catalyst molecules have more opportunities to touch the S–C bond of heavy oil molecules, which can achieve chain breaking of heavy oil molecules. The entanglement of longer oil molecular chains can form a larger apparent viscosity, but the breaking of molecular chains reduces the mutual entanglement of crude oil molecules and improves the fluidity of heavy oil.

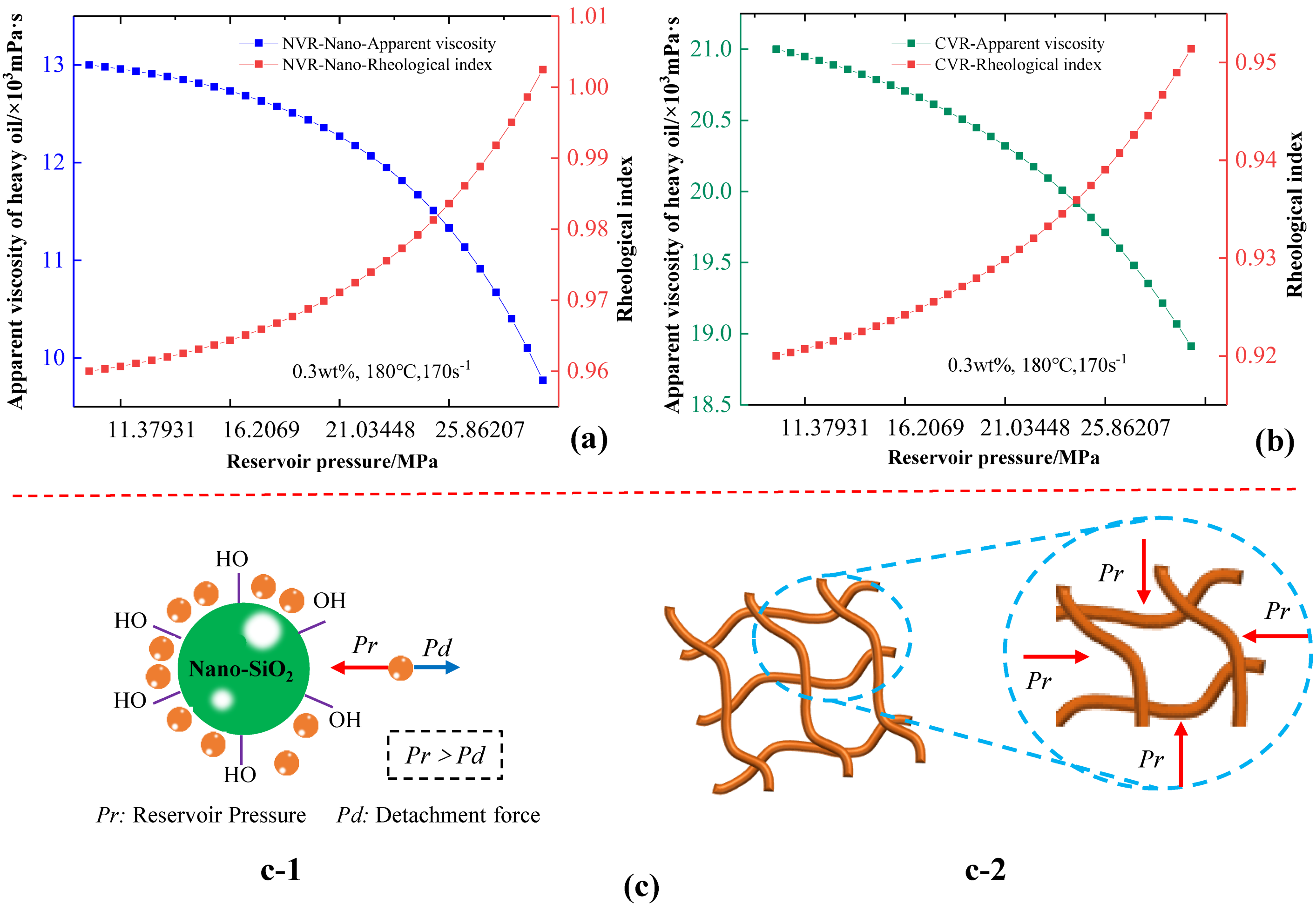

Figure 5. Effect of reservoir pressure on oil viscosity and rheological parameters.

The vitality of larger crude oil molecules caused by the increase in temperature promotes the rapid movement of oil molecules, which also triggers the previously entangled molecules quickly breaking free and separating. In summary, the micro grid density of the heavy oil system exhibits a decrease in fluid viscosity macroscopically because of the elevated reservoir temperature [31, 32]. In addition, the effect of reservoir temperature on the viscosity reduction of NVR is greater than that of CVR, because more targets on NVR are dispersed onto the S-C bonds of heavy oil molecules according to the more strongly active pantothenic acid.

3.4 Effects of reservoir pressure on the rheological capacity

The heavy oil in shale reservoirs exhibits different reservoir pressure environments at different depths, and reservoir pressure has also become an important factor that seriously affects the viscosity and recovery efficiency of heavy oil [33, 34]. As given in Figure 5(a), a comparative lower apparent viscosity of heavy oil and higher rheological index were demonstrated with an elevated reservoir pressure. Namely, the increase in formation pressure promotes the flow of heavy oil, which contributed to enhance oil recovery partly. 13×10^3 mPa·s of apparent viscosity and 0.96 of rheological index of heavy oil were estimated at geological pressure of 10 MPa, yet a high-pressure reservoir of 30 MPa would result in a 10×10^3 mPa·s of apparent viscosity and 1.00 of rheological index. A clear inverse relationship was illustrated between formation pressure and oil viscosity, but rheological index of heavy oil could be magnified effectively with an increasing in the reservoir pressure.

The profound mechanism by the geological pressure was conducive to alleviate the oil viscosity and rheology attributed to two aspects: (1). The entanglement between heavy oil molecules is a microscopic reason why heavy oil exhibits apparent viscosity under natural conditions [35]. The entanglement grid density formed by molecular compression under low pressure is relatively low, which magnifies the macroscopic fluid viscosity. Nevertheless, the increase in reservoir pressure also increases the compression of external pressure around the grid, The grid composed of heavy oil molecules gradually decreases in area due to the increasing pressure difference between the inside and outside (Figure 5(c)). The continuously decreasing micro grid area also triggers an increase in grid density, which is manifested at the macro level as an increase in apparent viscosity [36, 37]. (2). In typical circumstances, the catalyst adsorbed on nano-SiO_2 can expeditiously release and attack the S-H bonds of heavy oil molecules. The process of breaking down the molecular chains of heavy oil has been shown to have a significant impact on the viscosity of the fluid, with a concomitant improvement in its rheological properties. Consequently, the elevated reservoir pressure exerts a reciprocating force on the catalyst in all directions, propelling it towards the nanospheres. This process facilitates the desorption of the catalyst from the nano-SiO_2, thereby enabling enhanced interaction with heavy oil macromolecules. Consequently, pantothenic acid molecules exhibit minimal desorption under low pressure, thereby impeding the catalytic cracking of the S-C bonds in heavy oil molecules and directly hindering the flow and accumulation of heavy oil in reservoir fractures. However, under conditions of elevated pressure, the catalyst pantothenic acid can achieve enhanced contact with macromolecules and facilitate the rupture of S-H bonds. The presence of fluid reservoir heavy oil, characterised by its reduced fluid viscosity, has been demonstrated to enhance reservoir recovery.

The viscosity and rheological parameter of heavy oil (containing 0.3wt% commercial CVR) under different pressures also exhibit similar trends to those of NVR (Figure 5(b)). However, a minimal range of decrease in apparent viscosity and increase in rheological index is expressed when reservoir pressure increases from 10 MPa to 30 MPa. the viscosity of heavy oil decreased from 21×10^3 mPa·s to 19×10^3 mPa·s, and the rheological index increased from 0.92 to 0.95. The main reason why the reservoir pressure affected the rheological properties of heavy oil is the compression of micro grids by reservoir pressure, but the lack of CVR desorption from the nanoparticles slows down the decrease in apparent viscosity of heavy oil. It is also an important reason why pressure has a lower impact on NVR viscosity reduction than CVR. The above data indicates that the increase in geological pressure can achieve effective extraction of heavy oil.

3.5 Effects of shear rate on the rheological capacity

The shear effect generated by the oil flow in reservoir fractures can greatly alter the hydrodynamic parameters of crude oil fluids, and Figure 6 shows the changes in viscosity and rheological index of heavy oil under different shear rates. It can be seen from Figure 6 that the increase in shear rate leads to a continuous decrease in the viscosity of heavy oil, and low shear rates will result in a lower rate of decrease in oil viscosity. In other words, increasing from $100s^{-1}$ to $140s^{-1}$ only reduced the apparent viscosity by 0.5 $\times$ 10^3 mPa·s, but the viscosity of heavy oil containing 0.3 wt% NVR decreased from 12 $\times$ 10^3 mPas to 11$\times$ 10^3 mPa·s while changing the shear rate from $140s^{-1}$ to $180s^{-1}$. When the shear rate increased from $100s^{-1}$ to $180s^{-1}$, the rheological index increased from 0.97 to 0.99. The rheological index of heavy oil is mainly affected by the apparent viscosity of the fluid, and micro grid density is the underlying cause of macro viscosity [38, 39]. The heavy oil flowing through reservoir fractures is sheared or dispersed due to shear action, resulting in the original grid of heavy oil molecules being cut off or dispersed. The increase in shear rate and shear force also accelerates the rate of grid fracture Immediately, which is manifested as a rapid decrease in crude oil viscosity. In addition, the shear action also desorbs vanadate on the surface of nano SiO_2 particles, which quickly acts and breaks heavy oil molecules. And high shear rate exhibits greater vanadium acid desorption ability than low shear rate, which also helps to accelerate the rate of viscosity reduction of heavy oil.

Nevertheless, However, commercial CVR exhibits a slightly smaller decrease in fluid viscosity compared to NVR in the presence of shear rate. 100 s^{-1} only increased the viscosity of heavy oil containing 0.3wt% CVR to 21.2$\times$ 10^3 mPas, but the shear rate of 140 s^{-1} resulted in a small decrease in apparent viscosity by 0.3$\times$ 10^3 mPas. In addition, a viscosity decrease amplitude of 1$\times$ 10^3 mPas is shown when the shear rate increases from 140 s^{-1} to 180 s^{-1}. The difference in shear rate between CVR and NVR is mainly attributed to the absence of shear induced pantothenic acid desorption in CVR molecules, and the decrease in viscosity of heavy oil containing 0.3 wt% CVR is mainly due to the shear effect on grid failure and the decrease in grid density. Thus, shear action is conducive to achieve fracture flow of heavy oil, and NVR exhibits an excellent viscosity reduction ability than that of CVR.

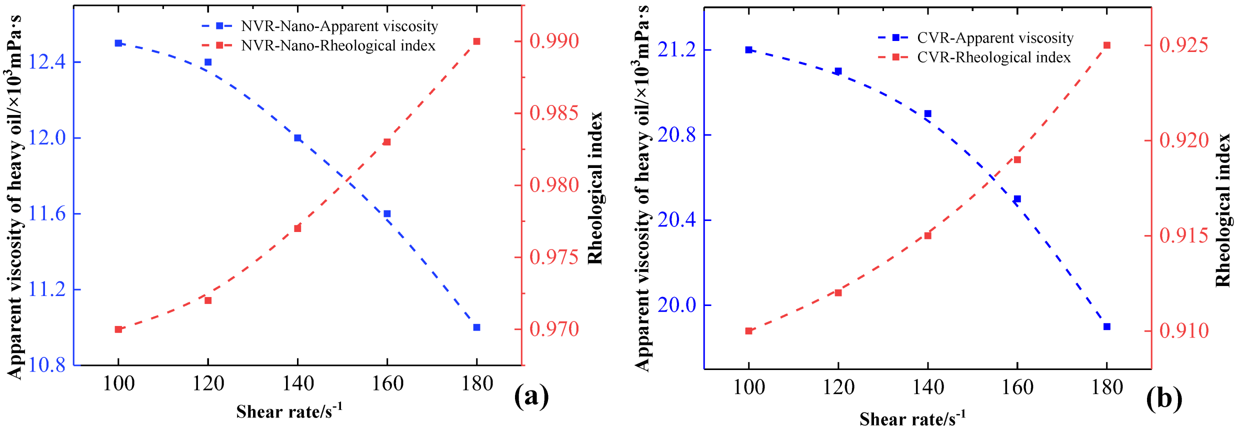

Figure 6. Effect of shear rate on oil viscosity and rheological parameters.

Table 1. The distribution of horizontal values and corresponding values of factors.

Factors	1	2	3	4	5	Data range
Centent, wt%	0	0.05	0.1	0.2	0.3	0-0.3
Temperature, °C	100	120	140	160	180	100-180
Pressure, MPa	10	15	20	25	30	10-30
Shear rate, s^{-1}	100	120	140	160	180	100-180

3.6 Analysis of Enhanced oil recovery

As an important evaluation indicator of crude oil recovery rate, fluid mechanics parameters such as apparent viscosity play an important role in enhancing oil recovery [40, 41]. As illustrated in Figure 7(a) and Table 1, significant differences of four factors affecting the recovery rate of heavy oil reservoirs was displayed. In terms of subdivision, 0.00 wt% NVR only achieves 8% of heavy oil recovery, but 0.03% NVR enhanced heavy oil recovery from 8% to 25%. However, the heavy oil recovery changed from 8% to 19% when CVR content increased to 0.3 wt% NVR not only has a greater improvement effect on the rheological capacity of heavy oil, but also significantly improves oil recovery efficiency. Besides, a minimal impact was shown between reservoir pressure on the improvement of heavy oil recovery, and geological temperature is considered as the second influencing factor on reservoir recovery rate. A 23% of heavy oil recovery was illustrated with increasing the geological temperature from 100 °C to 180 °C. The recovery curve is basically consistent with the fluid viscosity curve, because high viscosity fluids reduce the flow rate and also increase the frictional resistance of fractures.

3.7 Reservoir damage caused by chemicals

Reservoir pollution and damage are critical issues that require close attention and urgent solutions in the current reservoir renovation process. As shown in Figure 7(b), the effects of various parameters on reservoir damage for the two chemicals (NVR and CVR) are illustrated. Without any viscosity reducer (0 wt% NVR), the reservoir damage rate is approximately 10% (calculated via Equation 5). Adding NVR up to 0.3 wt% results in a slight increase in the damage rate, reflecting its minimal impact on reservoir integrity. In contrast, CVR at the same content (0.3 wt%) causes significantly greater reservoir damage than NVR, as evidenced by higher adsorption and fracture-sealing tendencies. After releasing the vanadium acid groups, the remaining long chains in CVR gradually condense into clusters, leading to temporary sealing of reservoir fractures. However, the lack of such long chains in NVR, combined with the inability of smaller nano-SiO_2 particles to settle rapidly at fast flow rates, minimizes blockage and reduces overall damage.

The impact of varying levels and types of heavy oil viscosity reducers on fracture permeability and reservoir sealing in geological reservoirs can be elucidated through differences in chemical adsorption on rock surfaces. In order to achieve a comprehensive understanding of the issue, it is necessary to conduct a thorough investigation into the presence of reservoir residues, the occurrence of which is attributable to both physical and chemical adsorption. As illustrated in Figure 8, microscopic images of the adsorption of different heavy oil viscosity reducers on rock surfaces in geological reservoirs are presented. The varying adsorption amounts and adsorption data demonstrate their potential for reservoir contamination and damage. Heavy oil viscosity reducers prepared with the same chemical content exhibit weaker reservoir adsorption than commercially available chemicals, as reflected in the reservoir damage rate in Figure 8. Moreover, an increase in chemical content is inevitably accompanied by an increase in adsorption on rock surfaces in

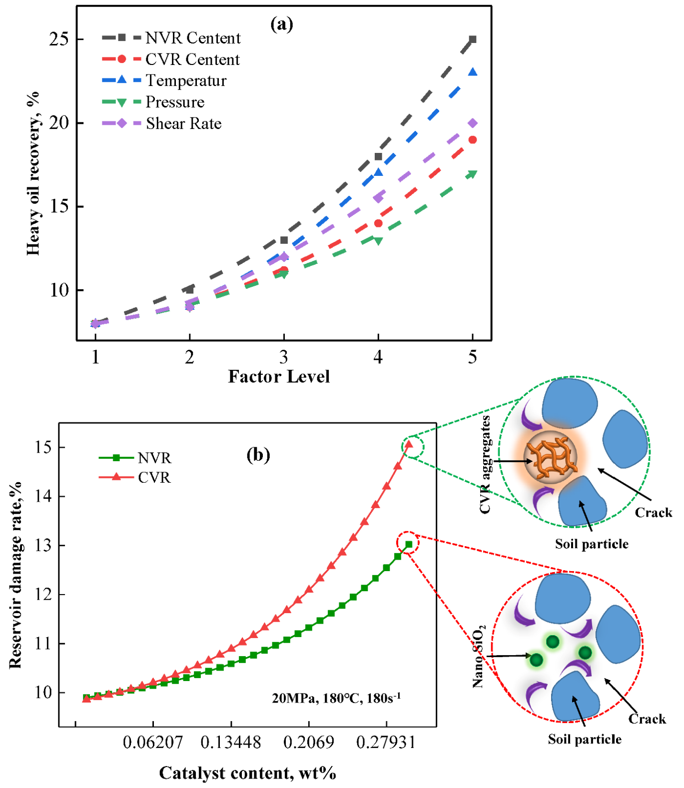

Figure 7. The influence of different factors on heavy oil recovery (a) and reservoir damage (b).

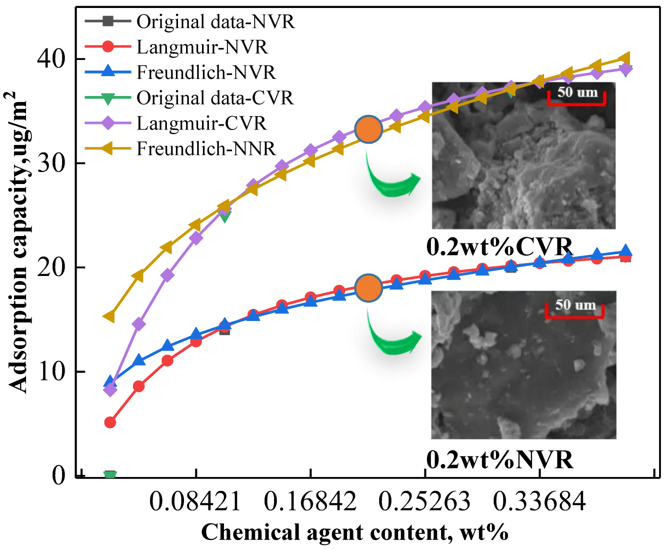

Figure 8. Microscopic images and adsorption trend of different chemicals on the reservoir rock surface.

Table 2. Adsorption of two chemicals on the reservoir rock surface and changes in chemical bond parameters.

Reservoir temperature, °C	100	120	140	160	180
NVR adsorption capacity, ug/m^2	21	20	18	15	11
Chemical bond length of NVR, nm	106	108	111	117	125
Chemical bond energy of NVR, J/mol	42	41	39	35	30
CVR adsorption capacity, ug/m^2	35	34.5	33.5	32	29
Chemical bond length of CVR, nm	48	49	51	54	59
Chemical bond energy of CVR, J/mol	67	66	64	61	58

geological reservoirs, thereby exacerbating reservoir contamination.

Figure 8 demonstrates that differences in surface adsorption of the two compounds on reservoir rock directly lead to variations in reservoir damage efficiency, primarily due to their distinct capacities to seal fractures. These differences in adsorption and consequent damage are fundamentally governed by the chemical structures of the compounds. Variations in molecular configurations and functional groups generate diverse attractive and repulsive forces, which directly influence the extent of reservoir impairment.

The synthetic compound, containing a high density of polar groups (e.g., hydroxyl groups), exhibits strong repulsive interactions with polar organic moieties and metal sites on the rock surface. This repulsion increases the separation distance between the compound and the reservoir rock, thereby reducing adsorption. Moreover, the inherent three-dimensional spherical structure of the synthetic compound exposes a greater number of polar groups, intensifying repulsive forces with the rock surface and further diminishing adsorption and fracture-sealing capacity.

Table 2 presents the adsorption characteristics and microscopic parameters of the synthetic compound at varying reservoir temperatures, revealing a pronounced decline in adsorption with increasing temperature. This inverse correlation can be explained by molecular dynamics simulations of bond parameters between polar groups on the compound and the rock surface. At lower temperatures, molecular interactions are characterized by shorter bond lengths and higher bond energies, promoting stronger adsorption and enhanced fracture blockage. By contrast, elevated reservoir temperatures enhance molecular mobility and random motion, reducing bond energy and length, which weakens adsorption. As a result, more molecules migrate away from the rock surface, thereby mitigating fracture sealing, minimizing reservoir damage, and preserving permeability.

However, the relatively low number of polar groups in the molecular structure of commercially available chemicals does not generate significant repulsion against the polar groups on the reservoir rock surface, resulting in stronger adsorption compared with synthetic chemicals. In addition, the planar, two-dimensional configuration of commercially

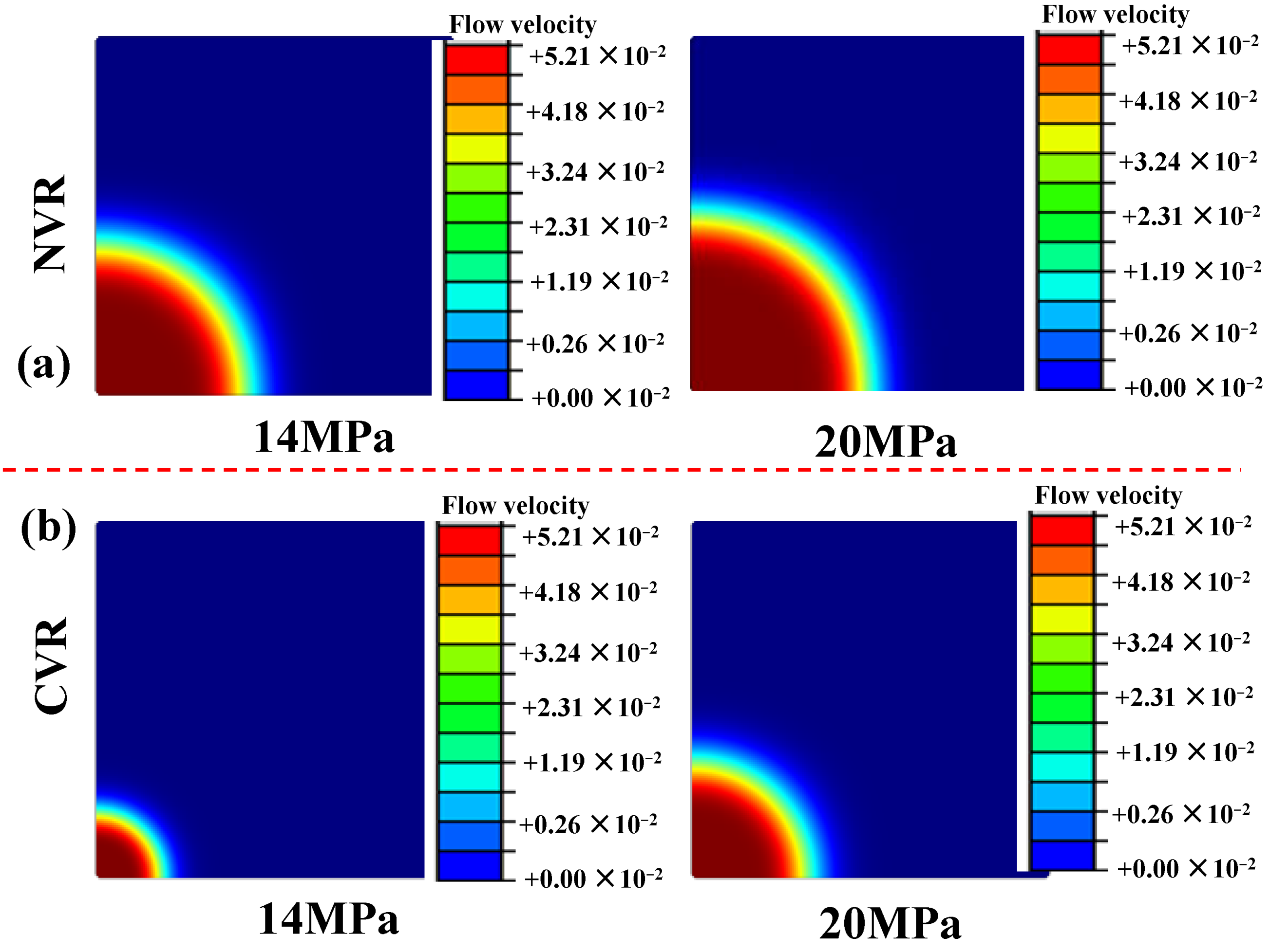

Figure 9. Comparison of oil displacement efficiency of different heavy oil viscosity reducers under pressure changes.

available chemicals reduces steric hindrance and limits unfavorable interactions between their polar groups and the rock surface, thereby further enhancing adsorption and aggravating fracture clogging.

As illustrated in Figure 2, the adsorption of commercially available chemicals on reservoir rock substantiates these differences, which can be quantitatively explained by variations in bond energy and bond length. Under identical temperature and concentration conditions, the bond energy between commercially available chemicals and reservoir rock is significantly higher, while the corresponding bond length is shorter, compared with synthetic chemicals. Consequently, beyond their role in improving the rheological performance of high-viscosity crude oil, synthetic chemicals—with their optimized molecular structures—also markedly reduce reservoir damage and mitigate fracture clogging.

3.8 Evaluation of Heavy Oil Extraction Efficiency

Viscosity reduction of heavy oil has demonstrated significant advantages in enhanced oil recovery (EOR) as an effective reservoir stimulation strategy. Accordingly, this study further investigates the oil displacement efficiency of reservoir cores following heavy-oil viscosity reduction. Shale cores with a length of 20 cm, a diameter of 5 cm, and a porosity of 9.5% were employed to quantitatively evaluate the oil displacement efficiency before and after viscosity reduction. Figure 9 presents the oil displacement efficiency of viscosity-reduced heavy oil under reservoir pressure conditions. The results indicate that increasing reservoir pressure markedly enhances the displacement efficiency of viscosity-reduced heavy oil. This positive correlation is primarily attributed to the intensified interactions between the catalyst and heavy-oil molecules at elevated pressures, which effectively reduce the apparent viscosity of the oil. Under high-pressure conditions, crude oil exhibiting a higher rheological index demonstrates improved flow capacity, thereby contributing to enhanced oil displacement efficiency. Furthermore, commercially available viscosity reducers exhibit trends in oil displacement efficiency similar to those of synthetic viscosity reducers, confirming the reliability of the evaluation methodology and the validity of the observed patterns. Nevertheless, under identical experimental conditions, the oil displacement efficiency achieved using commercially available viscosity reducers is significantly lower than that obtained with synthetic viscosity reducers. This disparity is likely due to the ability of synthetic viscosity reducers to achieve a higher rheological index under comparable conditions, resulting in reduced flow resistance. Consequently, the oil displacement experiments demonstrate that synthetic viscosity reducers offer superior displacement performance for highly viscous heavy oil, thereby facilitating more efficient energy recovery from geological reservoirs.

4 Conclusion

To ameliorate the mobility of heavy oil in reservoir fractures and the residual chemicals in the reservoir, a Nano pantothenic acid catalyst named NVR was synthesized and used for improving the apparent viscosity of heavy oil. A significant inverse relationship was shown between NVR content and heavy oil viscosity, which is much more significant than commercially available CVR. In addition, rheological index and oil recovery increased with increasing the catalyst content, especially NVR. The large amount of pantothenic acid distributed on the surface of nanospheres in NVR molecules is considered an important reason for significantly improving the rheological properties of heavy oil. Besides, Nano pantothenic acid catalysts were provided with less reservoir damage ability than commercially available catalysts, which mainly was decided by the extremely small nano size of NVR. Long chains in commercial CVR molecules will entangle and block the reservoir fractures in clusters.

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

Yanling Wang served as an Editorial Board Member of the *Reservoir Science* at the time of manuscript submission. To ensure the integrity of the peer-review process, Yanling Wang was not involved in the editorial handling, peer review, or decision-making process for this manuscript, which was handled independently by another editor. The remaining authors declare no conflicts of interest.

AI Use Statement

The authors declare that no generative AI was used in the preparation of this manuscript.

Ethical Approval and Consent to Participate

Not applicable.

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