Evaluation of Synthesized Catalytic Complex Structure-Forming Ability during Paraffin Base Tar Upgrade

Alim F. Kemalov 1 , Ruslan A. Kemalov*2, Adiko Serge-Bertrand3

1Kazan Federal University
*Corresponding author E-mail: kemalov.ruslan@gmail.com

Abstract

The combination of the synthesized multicomponent bifunctional catalytic complex (MBC) components with heavy oil residues (HOR) of the paraffin-naphthenic (P-N) base leads to the chemical structuring of the hydrocarbon (HC) segments of the raw material molecules, and the specifics of HOR physicochemical structure, which will be the criteria for the selection of modifiers with a certain chemical nature [1,2,3,4]. It has been established that the introduction of catalytic activators in the tar composition promotes both the intensification of the oxidation process and the production of bituminous insulating material (BIM) with high physicomechanical properties [1,2,4].

Raw materials for the production of special bituminous materials must be highly resinous with a P-HC content of up to 3% by weight. Based on the works by A.S. Kolbanovskaya [6], this is explained by the fact that the dispersed structure of bitumens is significantly dependent on the content of P-HC, since the dispersed phase in the oils is formed by naphthenic (N-) and PN-A-HC at certain temperatures with the side chains of the paraffinic P-HC series. If their content is more than 3% by weight the crystallization skeleton of P-HC is developed, which provides stiffness and reduces the plasticity interval for the system. Together with this, it is known that in the process of HOR oxidation the amount of low-molecular-weight oil A-HC decreases continuously, and the relative amount of PN-HC increases. Due to this, the affinity of the dispersion medium (DM) decreases to asphaltenes [7,8,9], which, moreover, becomes larger, which leads to THE deterioration of the cohesion and adhesion-strength properties of BIM.

Keywords: physico-chemical mechanics, heavy oil residual raw materials, paraffin hydrocarbons, catalytic complexes, pulsed NMR spectroscopy, bituminous insulation materials.

1. Introduction

According to the physico-chemical mechanics of petroleum disperse systems (FCM PDS), the correct understanding of the composition and the structure of HOR raw materials makes it possible to solve the problems of qualitative BIM creation scientifically [1,2,7,8]. Raw materials for insulating bitumen obtaining should be highly resinous with a minimum content of PN-HC. In the process of HOR processing, in particular, the tar of the Elkhovsky NPJSC of PJSC Tatneft or the ENPU, the PN-HC base, it becomes necessary to use such chemically active modifiers which would subject the paraffin chain segments to chemical structuring with the subsequent formation of macromolecular polycyclic naphthenic fragments due to an effective intermolecular diffusion [1, 2,4,5,7].

2 Methods

When they considered the possibilities of HOR processing (Table 1) in the activated state, the chemistry of the oxidation process is based on radical chain reactions of oxidative polymerization [1,2,7,10].

3 Results

<table>
<thead>
<tr>
<th>Indicators</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>density, kg/m³</td>
<td>0.9878</td>
</tr>
<tr>
<td>Assumed viscosity, AV₅₀</td>
<td>51.76</td>
</tr>
</tbody>
</table>

The following measurement modes were used for tar analysis: the starting period $T = 500$ msec - 2 s, the interval between $90^\circ$ and $180^\circ$ pulses $N = 5 - 1000$, the number of accumulations $n = 3 - 50$ [1,2]. The analysis time did not exceed 3 min. In the process of HOR, ENPU tar processing (Table 1), it becomes necessary to use such chemically active modifiers which, due to an effective intermolecular diffusion, would subject the segments of paraffin chains to chemical structuring with the subsequent formation of macromolecular polycyclic naphthenic (PN) fragments. The compounds of the naphthene series in the systems under consideration interact better with P-HC rather than with aromatic (A-) hydrocarbons, which in its turn exhibit weak interaction forces with P-HC. On the basis of this approach, HOR structure should acquire a high-resinous type, and during the structures related to the chemical composition of asphaltenes are formed during oxidation, but it has the physicochemical properties of "heavy" resins [10, 11]. Thus, the obtained sample of special bitumen should be characterized by a rather high content of film former - resins with a small amount of P-HC and asphaltenes.

Table 1: Physicochemical properties of ENPU tar oil

Copyright © 2018 Authors. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.
Content, % weight:

- SAV 28.23
- sulfur 0.887
- paraffins 15
- Asphaltenes/resins 0.45

**Picture 1:** The change in the relaxation times $T_i$ as a function of temperature.

**Picture 2:** Dependence of the populations of protons of oil tar - byproduct from temperature.
Relaxation times $T_i$, ms.

Temperature $10^3/T$, $\text{K}$

- $T_{2a}$
- $T_{2b}$
- $T_{2c}$

- $T_{1a}$
- $T_{1b}$
- $T_{1c}$

---

Picture 3: Changing the relaxation times oil - byproduct - KPSO depending on temperature

---

Population of protons $P_{2i}$, % mas

Temperature $10^3/T$, $\text{K}$

- $P_{2a}$
- $P_{2b}$
- $P_{2c}$

- $P_{1a}$
- $P_{1b}$
- $P_{1c}$

---

Picture 4: Dependence of the populations of protons of oil - byproduct - KPSO from temperature

- $a$ - spin spin system
- $b$ - spin-lattice system
The high degree of HOR structuring is confirmed by the fact that (Fig. 5) at 50 °C (3,096K) > T_{exp} > 24°C (3,367K) CCE in the structural-dynamic analysis (SDA) is a single phase, then in the interval 89°C (2,762K) > T_{exp} > 50°C (3,096K) two phases are shown - oily and resinous-asphaltene. Small differences in the molecular mobility of phase B and C also determine their high degree of chemical affinity.
4. Discussion

The regulation of oxidized bitumen properties was carried out in accordance with the main provisions of FCM [1,2,7,8,9,12] by directional regulation of their spatial DS through the change of dispersed phase (DP) particle size by the introduction of MBC into the process of joint oxidation. Bifunctionality (Fig. 7, 8) consists both in HRO oxidation time reduction, and in the necessary improvement of the basic physico-mechanical properties obtained at its BIM. The following components were used as MBK components: the byproduct process component, the synthetic oil production component (KPSO) and the metallized DM complex.

It was established that the byproduct provides a light oxidizability for coatings, since it contains the components actively interacting with air oxygen, namely unsaturated acids, mixed with resin acids. To ensure that both the total ether and the acid were involved in the subsequent film formation of the bitumen solution in various media, KPSO and byproduct were introduced into the tar with an intensive stirring and the temperatures up to 180 °C, since it is known that unsaturated acids are not able to form a solid film as the result of oxidative polymerization. The violation of the technological process of component combination (temperature increase) or a change of additive introduction stages led both to the course of DM reaction decomposition, and to the deterioration of the physico-mechanical properties of BIM in the future. The acknowledgment of the theoretical prerequisites for the chemical activity of MBC was the study of the structural-dynamic states of HOR of paraffin base by the NMR method when it was combined with MBC components [1,2,13,14,15].

During the analysis of Fig. 1, it should be noted that for the compared systems tar and by-product phase A and C are detected at the same TEXP. So for tar at TEXP = 31.87 °C, the spin-spin relaxation time T2B is 2.5 ms, and for the tar-by-product system at TEXP = 31 °C T2A is 2.26 ms. The detection of phase C for tar systems and tar-by-product occurs at TEXP 49.58 and 50 °C with spin-spin relaxation times T2C of 0.8 and 0.77 ms, respectively.

The presence of T2C minimum 0.3 ms at 2.85 K for tar is explained by the conformational difficulties of the spatial arrangements of paraffin-naphthenic chains in the molecules of asphaltites. In the future, with the growth of Texp, the values of the relaxation times T2A and T2C for the considered SDS are completely convergent. The studies of T2B dependences on TEXP (Fig. 1) show that phases B are detected for the following systems: tar at 47.51 °C, tar-byproduct at 31 °C, where T2B makes 1 and 0.54 ms. At the same time tar-by-product shows a slight increase of T2B at TEXP ≥ 90 °C.

The analysis of the thermodynamic features of spin-lattice changes with the increase of TEXP (Fig. 1b) shows the presence of characteristic extrema for T1A and T1B, which can be expressed by steric hindrance during the segmental mobility of the newly formed system. At that it should be noted that the introduction of byproduct into tar does not fundamentally affect the thermodynamic stability of the SDS as a whole, since the relaxation times T1A, T1B for the HOR under study are in the same range of values.

Taking into account the fact that during the thermal treatment at T ≥ 250-280 °C the polymeric sugar inhibitors break down and the transition of isolated double bonds in the acyl residues to the more active conjugate state occurs, it should be noted that analogous chemical transformations occur in byproduct, but with slightly lower reaction rates. This is explained by the fact that byproduct refers to the group of saturated film-forming systems (ICHPPO = 4,3664). The reaction of isomerization during heat treatment is based, first of all, on partial transitions of isolated double bonds into a more active state, respectively, and the structuring of HOR with the introduction of byproduct occurs insignificantly. However, byproduct use is advantageous by the fact that low isomerization rates, low polymerization rates are observed during the thermophysical alignment with HOR. This fact, in its turn, plays an important role in the storage of HOR, since in this case there will be no sharp increase of acid numbers (AN), viscosity, specific weight with a simultaneous IN decrease, which will subsequently deactivate MDC for HOR.

The pronounced ordering of HOR chemical structure, which is the system of tar-byproduct, is observed when it is combined with KPSO (Fig. 1b, 2-4).

According to the comparative analysis of the structural-dynamic parameters of Fig. 1-4 it follows that the branched structure of the KPSO molecule has a structuring effect aimed at the isomerization of PN-HC structure of the most mobile phases A and B. This is confirmed by the data (Fig. 3, 4a) of the spin-spin relaxation T2A,B and P2A,B, where the decrease of T2A,B values and the increase of protons P2A,B populations are observed as compared with the values for tar - byproduct (Fig. 1b). The study of the experimental data characterizing the change of proton P2 populations with TEXP (Fig. 4a) increase the tar-byproduct - KPSO shows the symbiosis of P2A and P2B and the antinature of P2A,B values from P2A,B. This is explained by the fact that the macromolecular mobility of the terminal groups of the structured phase A increases to a certain P2A limit with the growth of TEXP, and then, as the result of their proximity to the segmental part of the kinetic chains of phase B, the T2B precession frequency increases (Fig. 3) and, thus, the growth of P2B is observed (Fig. 4a).

Due to the affinity of chemical structures of byproduct and tar maltens, interfacial diffusion of the components takes place. We believe that when KPSO is combined with HOR PN-HC base at 80-100 °C, the physico-chemical structure is already changing by macromolecular isomerism of P-HC structures into polycyclic naphthenic ones with a high degree of the carbon chain isostructure, i.e. by the content of methyl and ethyl end groups. The presence of C = C double bonds in the composition of byproduct is apparently expressed by the extremes of T2A and P2i values, which show their activity at TEXP above 80 °C, since they are in the newly formed PCN-HC structures. At the same time, the contained double bonds in byproduct pass into the PCN-HC structures, which are within some limits of TEXP to P2B or to P2C during P2i measurement. Subsequently, during the oxidizing of HOR, we believe, they are transformed without any special difficulties into the PCN-A-HC of the asphaltene system, or remain in the original state, initiating a spin-lattice system to create related resinous structures. The last type of chemical structuring is most acceptable, because localized C = C double bonds in H-HC structures are affected to spatial structuring only in the case of intense oxidation, which is ensured only after the application and the evaporation of solvent and the shrinkage of BIM on the substrate, where it proceeds at high velocities due to the small thickness of BIM (30-50 μm) and the maximum contact of a small BIM area with air oxygen. This statement is based on the fact that liquid-phase high-temperature oxidation causes an incomplete use of oxygen supplied to the reactor (up to 50% by weight), and, thus, thermal destruction over structuring predominates in the process. These assumptions are confirmed by high physico-mechanical properties of BIM, associated with a high degree of film-forming material oxidation, the result of which are newly formed (at the physical mixing of KPSO with tar-byproduct) NA-HC structures and C = C double bonds of byproduct.

The comparative analysis of the thermodynamic states of the spin-lattice systems of tar-byproduct and tar-byproduct - KPSO (Fig. 1b, 2-4) shows that the introduction of KPSO enhances the structuring effect of byproduct, with the same extreme structural-dynamic states at identical TEXP, but even at smaller TEXP. Fig. 2b and 4b show that due to the symbiosis of the phases B and C, the chemical inhomogeneity of the maltens is observed. Due to the fact that some part of HOR system, mainly the phases A and B, as well as alkyl substituents of phase C, tend to ordering, i.e. to the creation of PCN-HC structures, then for TDO, expressed by the increase of P2B, the PCN-HC and the isomers of P-HC
structures are responsible that predominate in the maltenes of the newly formed system. Thus, from Fig. 3 and 4 and it can be seen that in the temperature range of 83.5 °C (2.805 K) > T exp > 45 °C (3,145 K) there is a single resinous-asphaltene phase P_{2B} = 44.4-53%, i.e. the sum of the phases B and C; and at T exp above 83.5 °C the phase C is manifested, at that the quantitative content of phase B decreases, and the quantitative content of phase A increases, i.e. P_{2A} = 51%, P_{2B} = 34%, P_{2C} = 15%. In this regard, the generalization of the most mobile phases A and B - “maltenes” in NMR relaxometry does not agree with the ongoing studies of HOR chemical structure. Since at initial or final T exp the phase C falls out from the structural-dynamic analysis of HOR, due to the chemical affinity and molecular mobility of resin and asphaltene components, and when the phase C response takes place, the characteristic decrease in P_{2B} is observed, so the generalization must be made between the phases B and C - resinous-asphaltene phase.

The reaction of macromolecular structuring of byproduct, KPSO and tar components introduced into HOR composition of the catalyst leads to the newly formed SDS and CCE, respectively, to the state of thermodynamic equilibrium, which is expressed by the decrease of the spin SDS system relaxation times of SDS in comparison with the previously studied HOR with the participation of tar and stepwise introduced modifiers (Fig. 1, 3, 5).

An important distinctive feature of the studied HOR is the disappearance of the spin-lattice relaxation times of T_{1}(Fig. 5) and, accordingly, the population of P_{1C} protons (Fig. 6b). This is explained by the initiation of deep interphase structuring reactions, directed, in our opinion, to the isomerization of long-chain P-HC fragments in maltenes and substituted aliphatic chains in asphaltenes with a small degree of branching.

5 Conclusions

It is determined that during the introduction of byproduct into tar, the structuring of the most mobile phases A and B takes place, expressed by the decrease of their segmental mobility, that is:

a) due to an insignificant decrease of T_{2A} at 68 (2.933) > T_{exp} > 31 °C (3,289K). At T_{exp} > 68 °C in tar - byproduct T_{2A} 8 ms is less than T_{2A} 8.5 ms for tar, which is obviously associated with steric hindrance of the molecular mobility of alkyl segments in paraffin-naphthenic structures;

b) due to the mutual diffusion and the affinity of byproduct and tar components, minor differences are observed during proton relaxation T_{2B}, where the values of T_{2B} for tar are to a lesser degree exceed those for tar - byproduct, which reflects the ordering of HOR chemical structure.

At the stage of physical combination of byproduct and tar at 80-100 °C, the initial stage of the polymerization reaction takes place (with an insignificant access of atmospheric oxygen), which subsequently proceeds with the thermo-oxidative degradation of HOR and ends on the substrate directly.

6. Summary

Ultimately, based on small values of the spin system molecular mobility (Fig. 5), with a simultaneous absence of extrema T_{2A,B} and the disappearance of the phase C of the spin-lattice system T_{1C} with T_{exp} increase, it can be concluded that the predominant fragmentary structure of the newly formed system tar - byproduct - KPSO - DM is a naphthenic with a developed substitution system by alkyl chains, which is proved (Fig. 6) by the presence of extremes P_{2B} and P_{2B}. Thus, (Fig. 7, 8) the introduction of activators into the composition of tar makes it possible to intensify the oxidation process and to obtain BIM with high physical and mechanical properties.

Acknowledgements

The work is performed according to the Russian Government Program of Competitive Growth of Kazan Federal University.

References


