New Parameter Derived from the Hansen Solubility Parameter Used to Evaluate the Solubility of Asphaltene in Solvent

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ABSTRACT: In order to determine whether asphaltenes dissolved in certain solvents, the Hansen solubility parameters (HSPs) of asphaltenes and maltenes extracted from SZ36-1 vacuum residual were measured, and a new parameter $\Delta \delta_{tn}$ was obtained by extending the HSP based on the results of asphaltene dissolution experiments. $\Delta \delta_{tn}$ was calculated by the relative differences of the components of HSP between asphaltene and the solvent. The rationality of the $\Delta \delta_{tn}$ was verified from three aspects: the selection of solvent that can dissolve asphaltene, dispersion of asphaltene in various solvents, and compatibility of asphaltenes and maltenes, which further proved that asphaltenes might be dissolved in maltenes. The $\Delta \delta_{tn}$ can be well used to judge whether asphaltene can dissolve in a certain solvent.

1. INTRODUCTION

As a result of the depletion of conventional light crude oil reserves, heavy oil processing is becoming the major focus of refining. Asphaltene, a complex mixture composed of a variety of condensed polyaromatic macromolecules and their non-metallic derivatives, is influenced by its structure and composition as well as the surroundings leading to severe aggregation. Asphaltene aggregation should cause a series of tricky problems in the extraction, transportation, storage, and processing of crude oil, including plugging of oil well, pollution of crude oil pipelines and equipment, coking, and deactivation of the catalyst in oil processing, and so on. Also, the asphaltene aggregation behavior is affected by the pi–pi interaction, dipole interaction, and hydrogen bonding among asphaltenes in a microscopic view. Research on asphaltene aggregation and its influencing factors are critical for the development of heavy oil upgrading processes.

The Hansen solubility parameter (HSP) can be used to evaluate the compatibility or dispersion between substances. The HSP is composed of three sections that are dependent on the intermolecular interactions, including the dispersion force, hydrogen-bonding interaction, and polarity interaction. As a result, the value of HSPs can represent the differences in intermolecular interactions of diverse substances indirectly, and it is appropriate to research the aggregation/dispersion behavior of asphaltene in heavy oil and different solvents using HSPs. Typically, the HSPs of asphaltene are determined by computing and analyzing the Hansen solubility sphere based on the dissolution of asphaltene in various solvents. Sato found that the HSPs of asphaltenes from different sources were affected by H/C, oxygen content, and average molecular weight of asphaltenes; Redelius calculated the HSPs of asphaltenes and maltenes separated from different bitumen, respectively, and concluded that asphaltenes might be dissolved in maltenes; Morimoto investigated the aggregation degree of asphaltene in different solvents within a wide range of concentration by ultraviolet–visible spectrometry and the HSP.

The current study focused on determining the HSPs of asphaltenes and further analyzing their influencing factors. A few studies, however, have been conducted to determine whether asphaltenes are soluble in a solvent merely based on the solvent’s HSPs without conducting solubility experiments in that solvent. Painter derived a guide to the solubility of asphaltenes in several solvents using an association model and the Hildebrand solubility parameter, the origin of the HSP, but it remains to be verified whether the guide is consistent with the actual solubility of asphaltenes. Therefore, by determining and analyzing the actual dissolution of asphaltenes in various溶}
solvents, the relationship between the compatibility and the HSPs of asphaltenes/solvents would be obtained, which can assist gain insights into the aggregation or dispersion behavior of asphaltenes.

In this study, the HSPs of asphaltenes from SZ36-1 vacuum residue were determined, and a new parameter was obtained by extending the HSP, which can be used to evaluate the solubility of asphaltenes in different solvents. In addition, the rationality of the new parameter was verified from three aspects.

2. EXPERIMENTAL SECTION

2.1. Materials and Analysis Methods. The asphaltenes (referred to as SZAsp) and maltenes (referred to as SZMal) used in this study were separated from the SZ36-1 vacuum residue, which was performed as follows: first, 1 g of the vacuum residue was placed in a conical flask and 50 mL of n-heptane was added, and the conical flask was removed and kept in the shade for 1 h after heating and refluxing the mixture of n-heptane and vacuum residue for 0.5 h. Second, the solid–liquid mixture in the conical flask was filtered to obtain n-heptane insoluble asphaltenes and the solution of maltenes/n-heptane. Then, the asphaltenes with a small amount of maltenes on a filter paper were extracted with the solution of maltenes/n-heptane and 60 mL toluene in sequence in a Soxhlet extractor to collect the maltenes and obtain the solution of asphaltenes/toluene. The solution of asphaltenes/toluene and the solution of maltenes/n-heptane were distilled and concentrated and then dried in a vacuum oven at 388 K and 0.01 MPa for 3 h to obtain asphaltenes and maltenes. Figure 1 shows the process of the separation of asphaltenes and maltenes from SZ36-1 vacuum residue. The properties of SZAsp and SZMal are shown in Table 1.

The carbon, hydrogen, sulfur, and nitrogen contents of asphaltenes and maltenes were measured by an elemental analyzer (Elementar Co. Ltd., Unicube, Germany), and the oxygen content was obtained by the subtraction method. The average molecular weight of asphaltene and maltenes was determined by gel permeation chromatography, or GPC, for short (Waters Co. Ltd., Waters1525, America) using tetrahydrofuran as the mobile phase.

2.2. Experimental Method. In this study, the HSPs of asphaltenes and maltenes were calculated by evaluating the solubility of the above two substances in 27 solvents and constructing the corresponding Hansen solubility spheres.

10 mg of asphaltenes or maltenes was mixed with 10 mL of a selected solvent in a capped cuvette. The mixture was ultrasonicated in the ultrasonic processor (Kunshan Sumei Co. Ltd., KQ-400KDE, China) for 20 min and then left to stand for 24 h. After 24 h of standing, if there was no precipitation at the bottom of the cuvette, the solvent is a good solvent for asphaltenes/maltenes, and on the contrary, the solution is a poor solvent. The HSPs of asphaltenes/maltenes were calculated using HSPiP, which is a powerful software that calculates the HSPs of a substance based on the substance’s solution behavior in a series of solvents and plots the corresponding HSP sphere in a three-dimensional coordinate system.

The particle size distribution of asphaltenes in solvents was measured by a dynamic light scattering (DLS) particle analyzer (Malvern Co. Ltd., Zetasizer Nano ZS90, UK), and the relevant samples were subjected to ultrasonic treatment for 5 min before the measurement.

2.3. Hansen Solubility Parameter and the Hansen Solubility Sphere. Hildebrand proposed the Hildebrand solubility parameter 11 (δt) according to the relationship between the solubility, heat of vaporization, and cohesive energy density. By using this parameter, the compatibility of substances can be predicted to a certain extent, and a proper solvent can be selected for a certain solute. The Hildebrand solubility parameter is defined as follows

$$\delta_t = \left( \frac{CED}{V} \right)^{0.5}$$  \hspace{1cm} (1)
δδδδδδ

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Table 2. Solubility and Related Parameters ofSZAsp in Different Solvents

| solvent               | δd | δp | δh | δf | solution behaviour | Δδsol |
|-----------------------|----|----|----|----|--------------------|--------|
| DMF                   | 17.4 | 13.7 | 11.3 | 24.862 | insoluble | 3.001 |
| DMAC                  | 16.8 | 11.5 | 9.4  | 22.424 | insoluble | 2.222 |
| methanol              | 14.7 | 12.3 | 22.3 | 29.405 | insoluble | 5.455 |
| ethanol               | 15.8 | 8.8  | 19.4 | 26.522 | insoluble | 4.116 |
| pentane               | 15.3 | 0.0  | 0.0  | 15.300 | insoluble | 2.188 |
| N-hexane              | 14.5 | 0.0  | 0.0  | 14.500 | insoluble | 2.231 |
| heptane               | 15.5 | 0.0  | 0.0  | 15.500 | insoluble | 2.178 |
| octane                | 14.9 | 0.0  | 0.0  | 14.900 | insoluble | 2.210 |
| decahydronaphthalene  | 18.0 | 0.0  | 0.0  | 18.000 | insoluble | 2.045 |
| acetonitrile          | 15.3 | 18.0 | 6.1  | 24.399 | insoluble | 6.247 |
| phenethyl alcohol     | 18.3 | 5.6  | 11.2 | 22.174 | insoluble | 1.653 |
| isopropanol           | 15.8 | 6.1  | 16.4 | 23.576 | insoluble | 2.968 |
| dimethyl sulfoxide    | 18.4 | 16.4 | 10.2 | 26.675 | insoluble | 3.153 |
| aniline               | 20.1 | 5.8  | 11.2 | 23.730 | insoluble | 1.656 |
| toluene               | 18.0 | 1.4  | 2.0  | 18.165 | soluble   | 1.348 |
| dimethyl benzene      | 17.8 | 1.0  | 3.1  | 18.096 | soluble   | 1.173 |
| THF                   | 16.8 | 5.7  | 8.0  | 19.461 | soluble   | 0.980 |
| carbon disulphide     | 19.9 | 5.8  | 0.6  | 20.737 | soluble   | 0.933 |
| 1-methylnaphthalene   | 19.7 | 0.8  | 4.7  | 20.269 | soluble   | 0.990 |
| dichloromethane       | 17.0 | 7.3  | 7.1  | 19.814 | soluble   | 0.970 |
| tetrail               | 19.6 | 2.0  | 2.9  | 19.914 | soluble   | 1.034 |
| pyridine              | 19.0 | 8.8  | 5.9  | 21.754 | soluble   | 0.858 |
| quinoline             | 20.5 | 5.6  | 5.7  | 22.002 | soluble   | 0.447 |
| trichloroethylene     | 18.0 | 3.1  | 5.3  | 19.018 | soluble   | 0.737 |
| bromobenzene          | 19.2 | 5.5  | 4.1  | 20.389 | soluble   | 0.142 |
| benzaldehyde          | 19.4 | 7.4  | 5.3  | 21.429 | soluble   | 0.504 |
| nitrobenzene          | 20.0 | 10.6 | 3.1  | 22.847 | soluble   | 1.148 |

where δd [(MPa^0.5)] is the Hildebrand parameter; CED [J·mol^−1] is the liquid cohesive energy; V [(cm^3·mol^−1)] is the molar volume.

However, the Hildebrand solubility parameter has limitations in describing the solubility of substances with intermolecular hydrogen bonds or polar interactions. Also, the HSPs derived from the Hildebrand solubility parameter removes this limitation and could be intended for polar/associating systems, which are composed of three parts, corresponding to the hydrogen-bonding interactions, dispersion interactions, and dipole interactions, respectively. The HSPs are defined as follows

CED = E_d + E_p + E_h

(2)

δ_d = (E_d/V)^0.5

(3)

δ_p = (E_p/V)^0.5

(3)

δ_h = (δ_d^2 + δ_p^2 + δ_h^2)^0.5

(4)

where δ_d [(MPa^0.5)], δ_p [(MPa^0.5)], δ_h [(MPa^0.5)] are the dispersion component parameter, polar component parameter, and hydrogen bonding component parameter, respectively; E_d [J·mol^−1], E_p [J·mol^−1], E_h [J·mol^−1] are the dispersion energy, polar energy, and hydrogen-bonding energy of cohesion energy, respectively; V [(cm^3·mol^−1)] is the molar volume.\(^8\) R_0 [(MPa^0.5)], which is based on the distance of HSPs for both substances, evaluates the compatibility of the two substances. The RED is defined as follows

R^2 = 4(δ_d1 - δ_d2)^2 + (δ_p1 - δ_p2)^2 + (δ_h1 - δ_h2)^2

(5)

In eq 5, δ_d1 [(MPa^0.5)], δ_p1 [(MPa^0.5)], δ_h1 [(MPa^0.5)] are the HSPs of the solvents, while δ_d2 [(MPa^0.5)], δ_p2 [(MPa^0.5)], δ_h2 [(MPa^0.5)] are the HSPs of the substance to be examined; the smaller value of R^2 means a higher solubility for each other.

For one substance, the solvent that can dissolve the substance is a good solvent for the substance. On the contrary, the solvent that cannot dissolve the substance is a poor solvent.\(^10\) The coordinates, which are obtained with the three components of the HSPs of good/poor solvents for the substance, are plotted in a three-dimensional coordinate system, and then an ellipsoidal boundary between the coordinates corresponding to good and poor solvents can be shown. This ellipsoidal boundary is also known as the HSP sphere, and the coordinates of the good solvent are in the interior of the boundary, while the coordinates of the poor solvent are in the exterior. Furthermore, the center of the sphere corresponds to the substance’s HSPs, and R_0 [(MPa^0.5)] is the radius of the sphere.\(^7\) As a result, the larger the number of solvent coordinates utilized to plot the sphere, the more accurate the HSP of the substance to be examined.

The relative energy difference (RED) is defined as eq 6. When RED is ≤1, the solvent is a good solvent for the substance to be examined, and when RED is > 1, the solvent is a poor solvent. Also, the smaller the RED, the higher the solubility of the substance in the corresponding solvent. Thus, the RED can evaluate the substance solubility in certain solvents more intuitively.

RED = R^2 / R_0^2

(6)
3. RESULTS AND DISCUSSION

3.1. HSPs of Asphaltene. The solubility of asphaltenes in the different solvents is shown in Table 2. The HSP sphere of asphaltene (SZAsp) constructed using HSPiP is shown in Figure 2. The HSPs of SZAsp are as follow: \( \delta_d = 18.85 \pm 0.1 \text{ MPa}^{0.5} \), \( \delta_p = 5.89 \pm 0.1 \text{ MPa}^{0.5} \), \( \delta_t = 4.35 \pm 0.1 \text{ MPa}^{0.5} \), and \( \delta_h = 20.20 \pm 0.1 \text{ MPa}^{0.5} \), \( R_0 = 5.50 \text{ MPa}^{0.5} \).

Without the solubility experiment of asphaltene, Painter\(^5\) predicted the solubility of asphaltenes in various solvents by combining the association model and the Hildebrand solubility parameter to guide the selection of asphaltene solvents. Also, the solubility of SZAsp in each solvent is consistent with that predicted by Painter\(^5\) to a certain extent; as demonstrated in Table 2, the asphaltenes (SZAsp) in this study were indeed not dissolved in DMAC, a strong polarity solvent, and the SZAsp (δ) has a range of 0.142 to 1.348, whereas the range of \( \Delta \delta_{tn} \) for good solvents of asphaltenes is 0.142 to 1.348, whereas the range of \( \Delta \delta_{tn} \) for poor solvents of asphaltenes is 1.653 to 5.435. There is no overlap between the two ranges, so it is speculated that there should be a threshold of \( \Delta \delta_{tn} \) between the good solvents and poor solvents of asphaltenes. When a solvent’s \( \Delta \delta_{tn} \) is less than the threshold, it can dissolve the asphaltenes, and conversely, when the \( \Delta \delta_{tn} \) of a solvent is more than the threshold, asphaltenes cannot be dissolved in the solvent.

In order to investigate the rationality of the new parameter from more aspects, this study continues with the asphaltenes (SZAsp) and the corresponding maltenes (SZMal) as the experimental raw material. The rationality of \( \Delta \delta_{tn} \) could be verified by three aspects as follows.

3.2.1. Guiding the Selection of the Asphaltene Solvent. Some solvents (except for the above 27 solvents) were selected according to the \( \Delta \delta_{tn} \) that can dissolve asphaltenes (SZAsp), which include acetophenone, bromotrichloromethane, phenetole, and 1,4-dichlorobutane. According to the method in Section 2.2, the SZAsp were dispersed in a selected solvent to prepare the solutions with an asphaltene concentration of 0.001 g/mL, and the results are shown in Table 3.

As shown in Table 3, all the \( \Delta \delta_{tn} \) of selected solvents are in the range of 0.142 to 1.348, and the SZAsp can dissolve in all the selected solvents. At the same time, the RED of the above solvents is smaller than 1, which is consistent with the fact that the asphaltenes were dissolved in the above solvents, indicating that both the \( \Delta \delta_{tn} \) and the RED can determine whether a substance can be dissolved in a certain solvent. As a result, the \( \Delta \delta_{tn} \) can guide the selection of solvents capable of dissolving asphaltene, which has a practical significance.

3.2.2. Evaluating Asphaltene Dispersibility in Solvent. The better the asphaltenes dissolved or dispersed in the solvent, the smaller the average particle size should be. The \( \Delta \delta_{tn} \) and the

![Image](https://doi.org/10.1021/acsomega.2c00018)

Table 3. Solubility of SZAsp in Selected Solvents According to \( \Delta \delta_{tn} \) and Related Parameters

| solvent           | \( \delta_d \) | \( \delta_p \) | \( \delta_t \) | \( \delta_h \) | solubility parameter (MPa^{0.5}) | solution behaviour | \( \Delta \delta_{tn} \) | RED  |
|-------------------|----------------|----------------|----------------|----------------|-------------------------------|-------------------|-------------------|------|
| acetophenone      | 18.0           | 8.1            | 4.0            | 20.18          | soluble                       | 0.654             | 0.648             |      |
| bromotrichloromethane | 18.3          | 8.1            | 6.0            | 20.893         | soluble                       | 0.784             | 0.540             | 0.308 |
| phenetole         | 18.4           | 4.5            | 4.0            | 19.360         | soluble                       | 0.340             | 0.308             |      |
| 1,4-dichlorobutane | 18.3           | 7.7            | 2.8            | 20.050         | soluble                       | 0.693             | 0.477             |      |
RED values represent the differences in the HSPs between asphaltene and the solvent, so they could reflect the dispersibility of asphaltene in the solvent to some extent. The accuracy of $\Delta \delta_{tn}$ and RED in evaluating the dispersion of a substance in a certain solvent, on the other hand, must be compared.

Five solvents (bromobenzene, benzaldehyde, tetralin, nitrobenzene, toluene) were selected, and solutions were prepared with asphaltene at the concentration of 0.0001 g/mL, according to the method in Section 2.2, respectively. The $\Delta \delta_{tn}$ and the RED of the above solvents are shown in Table 4. The particle size distribution of SZAsp in each solvent was tested by DLS after 5 min of ultrasonic treatment. The results are shown in Figure 3.

Figure 3 shows that asphaltenes have a larger particle size in solvents with a larger $\Delta \delta_{tn}$. In other words, asphaltenes disperse better in solvents with a smaller $\Delta \delta_{tn}$. The RED of toluene is smaller than the RED of nitrobenzene, yet asphaltenes have the largest particle size in toluene, demonstrating that the $\Delta \delta_{tn}$ is more accurate than RED in evaluating the dispersion of asphaltene in a certain solvent. Therefore, when additives were selected to improve the reaction performance of feedstocks containing asphaltenes, the additives with $\Delta \delta_{tn}$ value as small as possible can be selected to reduce the problems caused by asphaltene aggregation.

### 3.2.3. HSPs of SZMal and $\Delta \delta_{tn}$

To further verify the rationality of $\Delta \delta_{tn}$ in the actual system, the HSPs of SZMal were determined under the same conditions as those of SZAsp. The solubility of SZMal in the different solvents is shown in Table 5, and the HSP sphere of SZMal is shown in Figure 4.

The HSPs of SZMal are as follow: $\delta_d = 17.22 \pm 0.1 \text{ MPa}^{0.5}$, $\delta_p = 5.33 \pm 0.1 \text{ MPa}^{0.5}$, $\delta_h = 1.54 \pm 0.1 \text{ MPa}^{0.5}$, $\delta_t = 18.10 \pm 0.1 \text{ MPa}^{0.5}$.

Compared with SZAsp, SZMal can be dissolved in solvents with a strong dispersion, weak hydrogen bonds, and a weak polarity, such as $n$-alkanes and decahydronaphthalene. It may be due to the lower heteroatom content of SZMal compared to SZAsp, which leads to a weaker strength of hydrogen-bonding interactions and dipole interactions between S7ZMal and the solvent. According to the HSPs of SZMal, the $\Delta \delta_{tn}$ value of SZMal relative to SZAsp was calculated to be 0.805, which is in the range of 0.142 to 1.348 (range of $\Delta \delta_{tn}$ for good solvents).

### Table 4. $\Delta \delta_{tn}$ and RED of Selected Solvents

| solvent       | $\Delta \delta_{tn}$ | RED   |
|---------------|----------------------|-------|
| bromobenzene  | 0.142                | 0.153 |
| benzaldehyde  | 0.504                | 0.381 |
| tetralin      | 1.034                | 0.803 |
| nitrobenzene  | 1.148                | 0.981 |
| toluene       | 1.348                | 0.971 |

### Table 5. Solubility and Related Parameters of SZMal in Different Solvents

| solvent          | solubility parameter (MPa$^{0.5}$) | solution behaviour |
|------------------|------------------------------------|--------------------|
| DMF              | 17.4                               | 13.7               | 11.3               | 24.862   | insoluble |
| DMAC             | 16.8                               | 11.5               | 9.4                | 22.424   | insoluble |
| methanol         | 14.7                               | 12.3               | 22.3               | 29.405   | insoluble |
| ethanol          | 15.8                               | 8.8                | 19.4               | 26.522   | insoluble |
| pentane          | 15.3                               | 0.0                | 0.0                | 15.300   | soluble  |
| N-hexane         | 14.5                               | 0.0                | 0.0                | 14.500   | soluble  |
| heptane          | 15.5                               | 0.0                | 0.0                | 15.500   | soluble  |
| octane           | 14.9                               | 0.0                | 0.0                | 14.900   | soluble  |
| decahydrodiphenyl | 18.0                               | 0.0                | 0.0                | 18.000   | soluble  |
| acetonitrile     | 15.3                               | 18.0               | 6.1                | 24.399   | soluble  |
| phenylethyl alcohol | 18.3                           | 5.6                | 11.2               | 22.174   | soluble  |
| isopropanol      | 15.8                               | 6.1                | 16.4               | 23.576   | soluble  |
| dimethyl sulfoxide | 18.4                           | 16.4               | 10.2               | 26.675   | soluble  |
| aniline          | 20.1                               | 5.8                | 11.2               | 23.730   | soluble  |
| toluene          | 18.0                               | 1.4                | 2.0                | 18.165   | soluble  |
| dimethyl benzene | 17.8                               | 1.0                | 3.1                | 18.096   | soluble  |
| THF              | 16.8                               | 5.7                | 8.0                | 19.461   | soluble  |
| carbon disulphide | 19.9                           | 5.8                | 0.6                | 20.737   | soluble  |
| 1-methylphenol    | 19.7                               | 0.8                | 4.7                | 20.269   | soluble  |
| dichloromethane  | 17.0                               | 7.3                | 7.1                | 19.817   | soluble  |
| tetralin         | 19.6                               | 2.0                | 2.9                | 19.914   | soluble  |
| pyridine         | 19.0                               | 8.8                | 5.9                | 21.754   | soluble  |
| quinoline        | 20.5                               | 5.6                | 5.7                | 22.082   | soluble  |
| trichloroethylene | 18.0                           | 3.1                | 5.3                | 19.018   | soluble  |
| bromobenzene     | 19.2                               | 5.5                | 4.1                | 20.389   | soluble  |
| benzaldehyde     | 19.4                               | 7.4                | 5.3                | 21.429   | soluble  |
| nitrobenzene     | 20.0                               | 10.6               | 3.1                | 22.847   | soluble  |

Figure 4. HSP sphere (green●) of SZMal in the three-dimensional coordinate system. red■—poor solvents for SZMal; blue●—good solvents for SZMal.
In addition, the HSP coordinates of both SZAsp and SZMal are in the interior of each other’s HSP spheres, as seen in Figure 5. Both of the above indicated that SZAsp might be soluble in SZMal, which is consistent with Redelius’s conclusion\textsuperscript{10} and the fact that the residual oil system is relatively stable in actual conditions. However, the dispersion system obtained by dissolving asphaltenes in these solvents, including the maltenes, is a colloidal system but not a solution, according to the particle size distribution of asphaltenes in different solvents determined in the previous section.

4. CONCLUSIONS

The HSPs of SZAsp and SZMal from the SZ36-1 vacuum residue were determined. The HSPs of SZAsp were as follows: $\delta_d = 18.85 \pm 0.1 \text{ MPa}^{0.5}$, $\delta_p = 5.89 \pm 0.1 \text{ MPa}^{0.5}$, $\delta_h = 4.35 \pm 0.1 \text{ MPa}^{0.5}$, $\delta_f = 20.20 \pm 0.1 \text{ MPa}^{0.5}$. Also, the HSPs of SZMal were as follows: $\delta_d = 17.22 \pm 0.1 \text{ MPa}^{0.5}$, $\delta_p = 5.33 \pm 0.1 \text{ MPa}^{0.5}$, $\delta_h = 1.54 \pm 0.1 \text{ MPa}^{0.5}$, $\delta_f = 18.10 \pm 0.1 \text{ MPa}^{0.5}$.

The new parameter $\Delta \delta_m$ derived from HSP was obtained based on the solubility experiments of SZAsp, and the rationality of $\Delta \delta_m$ was verified by the solvent selection of asphaltenes, dispersion of asphaltenes in solvents with different $\Delta \delta_m$, and compatibility of asphaltenes with maltenes, respectively. Furthermore, the determination experiment of the particle size proved that the $\Delta \delta_m$ is more accurate than the RED in evaluating the dispersion behavior of a substance in a certain solvent. It was also proved that SZAsp might be dissolved in SZMal by using $\Delta \delta_m$.

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Figure 5. HSP sphere of SZMal (green●) and SZAsp (yellow●): red●—the sphere center of SZMal’s solubility parameter sphere; ○—the sphere center of SZAsp’s solubility parameter sphere.

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Notes

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■ ABBREVIATIONS

DMF $N,N$-dimethylformamide

DMAC $N,N$-dimethylacetamide

THF tetrahydrofuran

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