NANOPARTICLE ASSISTED GEMINI SURFACTANT AS WAX DEPOSITION SUPPRESSANT IN MALAYSIAN CRUDE OIL USING EXPERIMENTAL AND MOLECULAR DYNAMICS SIMULATION

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I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

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ABSTRAK

Pengendapan lilin boleh menyebabkan operasi menjadi perlahan atau terhenti dengan menghadkan aliran minyak mentah disebabkan lilin yang tersumbat dan mencetuskan ketidakaturan tekanan. Perencat kimia berinteraksi dengan molekul lilin dalam minyak mentah dan mencegah molekul lilin yang besar daripada melekat bersama. Penggunaan Gemini surfactant dan nanopartikel untuk mengelakkan pemendapan lilin masih tidak menyeluruh. Dalam tesis ini, kecekapan Gemini surfactant 2,5,8,11 Tetramethyl 6 dodecyn-5,8 Diol Ethoxylate (GS), tiga nanopartikel yang berbeza: silikon dioksida (NP1),timah oksida (NP2) dan nikel (III) oksida (NP3) dan campuran antara keduanya dinilai pada keadaan operasi yang berbeza bagi mengkaji pengaruh terhadap kelikatan minyak mentah menggunakan DV-III Brookfield viskometer dan perencatan lilin menggunakan analisis jari sejuk. Sebagai tambahan, simulasi model dinamik (MD) digunakan untuk menganalisa interaksi intermolekular diantara molekul lilin (n-icosane) dengan perencat menggunakan Accelrys Material Studio 8. Interaksi molekul lilin dengan perencat dianalisis menggunakan nilai fungsi taburan jejarian (*rdf*). Penggunaan GS dan nanopartikel secara berasingan dapat mengurangkan kelikatan minyak mentah dan pengendapan lilin dengan ketara. Walau bagaimanapun, prestasi yang lebih baik dapat dilihat dengan menggabungkan GS dan nanopartikel berbanding dengan penggunaan secara penggunaan tunggal untuk kelikatan dan analisis jari sejuk. Secara keseluruhannya, kelikatan minyak mentah berkurang sebanyak 85-92% pada suhu 10°C dengan penambahan GS dan nanopartikel. Pengurangan kelikatan tertinggi yang diperolehi adalah sebanyak 92.8% menggunakan campuran GS dan NP1. Penambahan nanopartikel kepada GS meningkatkan kecekapan perencatan dengan meningkatkan kadar penyebaran. Namun begitu, penggunaan GS dan nanopartikel secara tunggal mencapai kecekapan perencatan paraffin (PIE) sebanyak 45-48%. PIE tertinggi iaitu 61.63% telah dicapai bagi campuran GS/NP3 manakala yang terendah adalah 45.3% dengan menggunakan NP1 secara tunggal. Bagi keputusan MD, campuran GS/NP3 menunjukkan interaksi intermolekular yang paling lemah bersama n-icosane dengan nilai rdf tertinggi iaitu 5.25Å. Campuran GS/NP3 mempunyai interaksi van der Waals (vdW) yang kuat bersama atom hidrogen didalam n-icosane berbanding dengan sistem penggunaan tunggal GS dan NP3 yang berasingan. Ini disebabkan oleh kehadiran kumpulan O karbonyl didalam GS dan NP3, yang mana ia memperkukuhkan bilangan ikatan hidrogen yang lebih banyak. Oleh itu, perencatan lilin dalam n-icosane adalah lebih tinggi dalam campuran GS/NP3 berbanding dengan sistem penggunaan tunggal GS dan NP3. Ujikaji melalui analisis jari sejuk mengesahkan keputusan simulasi yang membuktikan bahawa gabungan GS/NP3 dapat mengurangkan pembentukan lilin dengan ketara sebanyak 61.6%. Sebagai perbandingan, penggunaan GS dan NP3 secara tunggal dapat mengurangkan pembentukan lilin masing-masing sebanyak 46.5% dan 47.7%. Secara keseluruhan, gabungan GS dan NP3 menunjukkan kecekapan tertinggi dalam perencatan lilin melalui analisis jari sejuk dan kebolehlarutan lilin tertinggi melalui analisis rdf. Oleh itu, campuran GS/NP3 adalah perencat terbaik berbanding dengan kombinasi perencat yang lain bagi menghalang perencatan lilin dalam minyak mentah Malaysia.

ABSTRACT

Wax deposition can cause a slowdown or halt in operation by restricting crude oil flow in the pipeline due to the wax blockage and triggering pressure irregularities. Chemical inhibitors interact with the wax molecule in crude oil and prevent large wax molecules from attach. The use of Gemini surfactant and nanoparticles to prevent wax deposition is still in its infancy. In this thesis, the efficiency of Gemini surfactant 2,5,8,11 Tetramethyl 6 dodecyn-5,8 Diol Ethoxylate (GS), three different nanoparticles: silicon dioxide (NP1), tin oxide (NP2) and nickel (III) oxide (NP3) and their blends at different operating conditions are assessed to study their influence on the crude oil viscosity using Brookfield DV-III viscometer and wax inhibition using cold finger analysis. In addition, molecular dynamics modeling (MD) is used to analyze the intermolecular interaction between a wax molecule (n-icosane) with inhibitors using Accelrys Material Studio 8. The interaction of wax molecules with inhibitors were analysed through radial distribution function (rdf) value. The separate use of GS and nanoparticles significantly reduced crude oil viscosity and wax deposition. However, combining the GS and nanoparticles showed better performance than their corresponding individual use in viscosity and cold finger analysis. Overall, the viscosity of crude oil was reduced by about 85-92% at 10°C with the addition of GS and nanoparticles. The highest viscosity reduction obtained was 92.8% using the blend of GS and NP1. The addition of nanoparticles to GS improved their inhibition efficiency by providing dispersion. Nevertheless, the use of GS and nanoparticles individually achieved a paraffin inhibition efficiency (PIE) of 45-48%. The highest PIE of 61.6% was achieved by GS/NP3 blend while the lowest was 45.3% with NP1 individual used. For the MD results, GS/NP3 blend shows the weakest wax-wax intermolecular interaction with n-icosane, indicating higher wax solubility with the highest radial distribution function (rdf) value of 5.25 Å. Also, the GS/NP3 blend has the stronger van der Waals (vdW) interaction with a hydrogen atom in n-icosane compared to the individual systems of GS and NP3 separately. This can be due to the presence of the O carbonyl group in both GS and NP3, which can establish a higher number of bonds. Therefore, wax inhibition in n-icosane is higher in GS/NP3 blend compared to the individual system of GS and NP3. An experimental study through cold finger analysis validated simulation result which proved that the GS/NP3 blend significantly reduced the wax formation by 61.6%. In comparison, the individuals of GS and NP3 reduced wax formation by 46.5% and 47.7% respectively. Overall, the combination of GS and NP3 has shown highest efficiency in wax inhibition through cold finger analysis and highest wax solubility in rdf analysis. Thus, GS/NP3 blend is the best inhibitor among tested inhibitor combinations in inhibiting wax in Malaysian crude oil.

TABLE OF CONTENT

REFERENCES

Adam, F., Siti Hana, A. B., Yusoff, M. M., & Tajuddin, S. N. (2014). Molecular dynamic simulation of the patchouli oil extraction process. *Journal of Chemical and Engineering Data*, *59*(2), 183–188. https://doi.org/10.1021/je3013292

Adams, J. J., Tort, F., Schabron, J. F., Loveridge, J. L., Rovani, J., & Baig, K. (2018). Evaluation of Wax Inhibitor Performance through Various Techniques. *Energy and Fuels*, *32*(12), 12151–12165. https://doi.org/10.1021/acs.energyfuels.8b02693

Adeyanju, O. A., & Oyekunle, L. O. (2019). Experimental study of water-in-oil emulsion flow on wax deposition in subsea pipelines. *Journal of Petroleum Science and Engineering*, *182*(July), 106294. https://doi.org/10.1016/j.petrol.2019.106294

Afdhol, M. K., Abdurrahman, M., Hidayat, F., Chong, F. K., & Mohd Zaid, H. F. (2019). Review of solvents based on biomass for mitigation of wax paraffin in Indonesian oilfield. *Applied Sciences (Switzerland)*, *9*(24). https://doi.org/10.3390/app9245499

Ahn, S., Wang, K. S., Shuler, P. J., Creek, J. L., & Tang, Y. (2005). Paraffin crystal and deposition control by emulsification. *Proceedings - SPE International Symposium on Oilfield Chemistry*, 601–609. https://doi.org/10.2523/93357-ms

Akinyemi, O. P., Udonne, J. D., & Oyedeko, K. F. (2018). Study of effects of blend of plant seed oils on wax deposition tendencies of Nigerian waxy crude oil. *Journal of Petroleum Science and Engineering*, *161*(December 2017), 551–558. https://doi.org/10.1016/j.petrol.2017.12.017

Akmaz, S., Iscan, O., Gurkaynak, M. A., & Yasar, M. (2011). The structural characterization of saturate, aromatic, resin, and asphaltene fractions of Batiraman crude oil. *Petroleum Science and Technology*, *29*(2), 160–171. https://doi.org/10.1080/10916460903330361

Al-Adwani, H., & Al-Mulla, A. (2019). The analysis of drag reduction in Kuwaiti crude oil samples using surfactants and polyacrylamide. *Journal of Petroleum Exploration and Production Technology*, *9*(3), 2235–2245. https://doi.org/10.1007/s13202-018-0590-9

Al-Ruqeishi, M. S., Mohiuddin, T., & Al-Saadi, L. K. (2019). Green synthesis of iron oxide nanorods from deciduous Omani mango tree leaves for heavy oil viscosity treatment. *Arabian Journal of Chemistry*, *12*(8), 4084–4090. https://doi.org/10.1016/j.arabjc.2016.04.003

Al-Sabagh, A. M., Betiha, M. A., Osman, D. I., Hashim, A. I., El-Sukkary, M. M., & Mahmoud, T. (2016a). A new covalent strategy for functionalized montmorillonite-poly(methyl methacrylate) for improving the flowability of crude oil. *RSC Advances*, *6*(111), 109460–109472. https://doi.org/10.1039/c6ra21319g

Al-Sabagh, A. M., Betiha, M. A., Osman, D. I., Hashim, A. I., El-Sukkary, M. M., & Mahmoud, T. (2016b). Preparation and Evaluation of Poly(methyl methacrylate)-

Graphene Oxide Nanohybrid Polymers as Pour Point Depressants and Flow Improvers for Waxy Crude Oil. *Energy and Fuels*, *30*(9), 7610–7621. https://doi.org/10.1021/acs.energyfuels.6b01105

Al-Yaari, M. (2013). Paraffin wax deposition: Mitigation & removal techniques. *Society of Petroleum Engineers - Saudi Arabia Section Young Professionals Technical Symposium 2011*, *March*, 35–44.

Almahfood, M., & Bai, B. (2018). The synergistic effects of nanoparticle-surfactant nanofluids in EOR applications. *Journal of Petroleum Science and Engineering*, *171*(May), 196–210. https://doi.org/10.1016/j.petrol.2018.07.030

Alnaimat, F., & Ziauddin, M. (2020). Wax deposition and prediction in petroleum pipelines. *Journal of Petroleum Science and Engineering*, *184*(August), 106385. https://doi.org/10.1016/j.petrol.2019.106385

Andreozzi, P., Pons, R., Pérez, L., Infante, M. R., Muzzalupo, R., Suber, L., & La Mesa, C. (2008). Gemini surfactant binding onto hydrophobically modified silica nanoparticles. *Journal of Physical Chemistry C*, *112*(32), 12142–12148. https://doi.org/10.1021/jp8026989

Anisuzzaman, S. M., Abang, S., Bono, A., Krishnaiah, D., Karali, R., & Safuan, M. K. (2017). Wax inhibitor based on ethylene vinyl acetate with methyl methacrylate and diethanolamine for crude oil pipeline. *IOP Conference Series: Materials Science and Engineering*, *206*(1). https://doi.org/10.1088/1757-899X/206/1/012074

Anto, R., Deshmukh, S., Sanyal, S., & Bhui, U. K. (2020). Nanoparticles as flow improver of petroleum crudes: Study on temperature-dependent steady-state and dynamic rheological behavior of crude oils. *Fuel*, *275*(December 2019), 117873. https://doi.org/10.1016/j.fuel.2020.117873

Aristizábal-Fontal, J. E., Cortés, F. B., & Franco, C. A. (2018). Viscosity reduction of extra heavy crude oil by magnetite nanoparticle-based ferrofluids. *Adsorption Science and Technology*, *36*(1–2), 23–45. https://doi.org/10.1177/0263617417704309

Ashoori, S., Sharifi, M., Masoumi, M., & Mohammad Salehi, M. (2017a). The relationship between SARA fractions and crude oil stability. In *Egyptian Journal of Petroleum* (Vol. 26, Issue 1, pp. 209–213). https://doi.org/10.1016/j.ejpe.2016.04.002

Ashoori, S., Sharifi, M., Masoumi, M., & Mohammad Salehi, M. (2017b). The relationship between SARA fractions and crude oil stability. *Egyptian Journal of Petroleum*, *26*(1), 209–213. https://doi.org/10.1016/j.ejpe.2016.04.002

Atta, A. M., El-Ghazawy, R. A., Morsy, F. A., Hebishy, A. M. S., & Elmorsy, A. (2015). Adsorption of Polymeric Additives Based on Vinyl Acetate Copolymers as Wax Dispersant and Its Relevance to Polymer Crystallization Mechanisms. *Journal of Chemistry*, *2015*. https://doi.org/10.1155/2015/683109

Basin, J. (2000). *Waxes and Asphaltenes - Their Chemistry , Analysis and Relevance to*

Production Problems. 1–4.

Behbahani, T. J., Dahaghin, A., & Kashefi, K. (2011). Effect of solvent on rheological behavior of Iranian waxy crude oil. *Petroleum Science and Technology*, *29*(9), 933–941. https://doi.org/10.1080/10916460903502548

Bello, O., Fasesan, S., Teodoriu, C., & Reinicke, K. (2006). An evaluation of the performance of selected wax inhibitors on paraffin deposition of Nigerian crude oils. *Petroleum Science and Technology*, *24*(2), 195–206. https://doi.org/10.1081/LFT-200044504

Benziane, M. M., & Liazid, A. (2011). *Crude-Oil Flow Modelling in Pipeline Conditions*. 275–284. https://doi.org/10.1007/978-94-007-0588-3_17

Chala, G. T., Sulaiman, S. A., Japper-Jaafar, A., Kamil Wan Abdullah, W. A., & Mior Mokhtar, M. M. (2014). Gas void formation in statically cooled waxy crude oil. *International Journal of Thermal Sciences*, *86*, 41–47. https://doi.org/10.1016/j.ijthermalsci.2014.06.034

Chen, H., Han, L., Luo, P., & Ye, Z. (2005). The ultralow interfacial tensions between crude oils and gemini surfactant solutions. *Journal of Colloid and Interface Science*, *285*(2), 872–874. https://doi.org/10.1016/j.jcis.2004.11.066

Chi, Y., Daraboina, N., & Sarica, C. (2017). Effect of the Flow Field on the Wax Deposition and Performance of Wax Inhibitors: Cold Finger and Flow Loop Testing. *Energy and Fuels*, *31*(5), 4915–4924. https://doi.org/10.1021/acs.energyfuels.7b00253

De Castro Machado, A. L., & Lucas, E. F. (1999). Poly(ethylene-co-vinyl acetate) (EVA) copolymers as modifiers of oil wax crystallization. *Petroleum Science and Technology*, *17*(9), 1029–1041. https://doi.org/10.1080/10916469908949763

Deshmukh, S., & Bharambe, D. P. (2012). Wax dispersant additives for improving the low temperature flow behavior of Waxy crude oil. *Energy Sources, Part A: Recovery, Utilization and Environmental Effects*, *34*(12), 1121–1129. https://doi.org/10.1080/15567031003753587

dos Santos, J. da S. T., Fernandes, A. C., & Giulietti, M. (2004). Study of the paraffin deposit formation using the cold finger methodology for Brazilian crude oils. *Journal of Petroleum Science and Engineering*, *45*(1–2), 47–60. https://doi.org/10.1016/j.petrol.2004.05.003

Duffy, D. M., & Rodger, P. M. (2002). Modeling the activity of wax inhibitors: A case study of poly(octadecyl acrylate). *Journal of Physical Chemistry B*, *106*(43), 11210–11217. https://doi.org/10.1021/jp026501j

Edholm, O., & Jähnig, F. (1992). *Molecular Dynamics Simulations of Bacteriorhodopsin*. *December*, 47–60. https://doi.org/10.1007/978-94-011-2718-9_5

Ehsani, S., Haj-Shafiei, S., & Mehrotra, A. K. (2019). Experiments and modeling for investigating the effect of suspended wax crystals on deposition from ‘waxy’

mixtures under cold flow conditions. *Fuel*, *243*(November 2018), 610–621. https://doi.org/10.1016/j.fuel.2019.01.089

El-Ghazawy, R. A., Atta, A. M., & Kabel, K. I. (2014). Modified maleic anhydride-co-octadecene copolymers as flow improver for waxy Egyptian crude oil. *Journal of Petroleum Science and Engineering*, *122*, 411–419. https://doi.org/10.1016/j.petrol.2014.07.040

Elbanna, S. A., Abd El Rhman, A. M. M., Al-Hussaini, A. S., & Khalil, S. A. (2017). Synthesis and characterization of polymeric additives based on A-Olefin as pour point depressant for Egyptian waxy crude oil. *Petroleum Science and Technology*, *35*(10), 1047–1054. https://doi.org/10.1080/10916466.2017.1307852

Elsharkawy, A. M., Al-Sahhaf, T. A., & Fahim, M. A. (2000). Wax deposition from Middle East crudes. *Fuel*, *79*(9), 1047–1055. https://doi.org/10.1016/S0016-2361(99)00235-5

Ermilova, I., & Swenson, J. (2020). DOPC: Versus DOPE as a helper lipid for gene-therapies: Molecular dynamics simulations with DLin-MC3-DMA. *Physical Chemistry Chemical Physics*, *22*(48), 28256–28268. https://doi.org/10.1039/d0cp05111j

Fan, T., Wang, J., & Buckley, J. S. (2002). Evaluating Crude Oils by SARA Analysis. *Proceedings - SPE Symposium on Improved Oil Recovery*, 883–889. https://doi.org/10.2118/75228-ms

Fang, L., Zhang, X., Ma, J., & Zhang, B. (2012). Investigation into a pour point depressant for shengli crude oil. *Industrial and Engineering Chemistry Research*, *51*(36), 11605–11612. https://doi.org/10.1021/ie301018r

Farag, R. K. (2008). Poly(cinnamoyloxy ethyl methacrylate-co-octadecyl acrylate) as flow improver for egyptian waxy crude oils. *International Journal of Polymeric Materials and Polymeric Biomaterials*, *57*(3), 189–202. https://doi.org/10.1080/00914030701486211

Feng, H., Hou, J., Ma, T., Meng, Z., Wu, H., Yang, H., & Kang, W. (2018). The ultra-low interfacial tension behavior of the combined cationic/anionic-nonionic gemini surfactants system for chemical flooding. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, *554*(June), 74–80. https://doi.org/10.1016/j.colsurfa.2018.06.028

Fereidooni Moghadam, T., Azizian, S., & Wettig, S. (2015). Synergistic behaviour of ZnO nanoparticles and gemini surfactants on the dynamic and equilibrium oil/water interfacial tension. *Physical Chemistry Chemical Physics*, *17*(11), 7122–7129. https://doi.org/10.1039/c5cp00510h

Fernandes, F. M. S. S., & Cabral, B. (2014). *Modified Ewald Sum and NVT Ensemble in Molecular Dynamics of an Ionic System*. *May*.

Franco, C. A., Nassar, N. N., Ruiz, M. A., Pereira-Almao, P., & Cortés, F. B. (2013). Nanoparticles for inhibition of asphaltenes damage: Adsorption study and displacement test on porous media. *Energy and Fuels*, *27*(6), 2899–2907.

https://doi.org/10.1021/ef4000825

Frigaard, I. A., Paso, K. G., & de Souza Mendes, P. R. (2017). Bingham's model in the oil and gas industry. *Rheologica Acta*, *56*(3), 259–282. https://doi.org/10.1007/s00397-017-0999-y

Fung, G., Backhaus, W. P., McDaniel, S., & Erdogmus, M. (2006). To pig or not to pig: The Marlin experience with stuck pig. *Offshore Technology Conference 2006: New Depths. New Horizons*, *3*, 2009–2015. https://doi.org/10.4043/18387-ms

Ghannam, M. T., Hasan, S. W., Abu-Jdayil, B., & Esmail, N. (2012a). Rheological properties of heavy & light crude oil mixtures for improving flowability. *Journal of Petroleum Science and Engineering*, *81*, 122–128. https://doi.org/10.1016/j.petrol.2011.12.024

Ghannam, M. T., Hasan, S. W., Abu-Jdayil, B., & Esmail, N. (2012b). Rheological properties of heavy & light crude oil mixtures for improving flowability. *Journal of Petroleum Science and Engineering*, *81*, 122–128. https://doi.org/10.1016/j.petrol.2011.12.024

Giri, A. M., & Rabah, A. A. (2018). Rheological Behavior of Waxy Crude Oils under Oscillatory Shear and Effect of Plant Seed Oil. *International Journal of Engineering Trends and Technology*, *58*(4), 165–176. https://doi.org/10.14445/22315381/ijett-v58p231

Gu, X., Zhang, F., Li, Y., Zhang, J., Chen, S., Qu, C., & Chen, G. (2018). Investigation of cationic surfactants as clean flow improvers for crude oil and a mechanism study. *Journal of Petroleum Science and Engineering*, *164*(January), 87–90. https://doi.org/10.1016/j.petrol.2018.01.045

Hafiz, A. A., & Khidr, T. T. (2007). Hexa-triethanolamine oleate esters as pour point depressant for waxy crude oils. *Journal of Petroleum Science and Engineering*, *56*(4), 296–302. https://doi.org/10.1016/j.petrol.2006.10.003

Hait, S. K., & Moulik, S. P. (2002). Gemini surfactants: A distinct class of self-assembling molecules. *Current Science*, *82*(9), 1101–1111.

Hao, L. Z., Al-Salim, H. S., & Ridzuan, N. (2019). A review of the mechanism and role of wax inhibitors in the wax deposition and precipitation. *Pertanika Journal of Science and Technology*, *27*(1), 499–526.

He, C., Ding, Y., Chen, J., Wang, F., Gao, C., Zhang, S., & Yang, M. (2016). Influence of the nano-hybrid pour point depressant on flow properties of waxy crude oil. *Fuel*, *167*, 40–48. https://doi.org/10.1016/j.fuel.2015.11.031

Hejazi, I., Seyfi, J., Sadeghi, G. M. M., & Davachi, S. M. (2011). Assessment of rheological and mechanical properties of nanostructured materials based on thermoplastic olefin blend and organoclay. *Materials and Design*, *32*(2), 649–655. https://doi.org/10.1016/j.matdes.2010.08.009

Hemeida, A. M. (1990). Rheological Behavior of Saudi Crude Oils. *Journal of King Saud University - Engineering Sciences*, *2*(1), 181–193.

https://doi.org/10.1016/S1018-3639(18)30886-9

Hou, B., Jia, R., Fu, M., Wang, Y., Ma, C., Jiang, C., & Yang, B. (2019). A novel high temperature tolerant and high salinity resistant gemini surfactant for enhanced oil recovery. *Journal of Molecular Liquids*, *296*, 112114. https://doi.org/10.1016/j.molliq.2019.112114

Ibrahim, R. I., Oudah, M. K., & Hassan, A. F. (2017). Viscosity reduction for flowability enhancement in Iraqi crude oil pipelines using novel capacitor and locally prepared nanosilica. *Journal of Petroleum Science and Engineering*, *156*(December 2016), 356–365. https://doi.org/10.1016/j.petrol.2017.05.028

Jafari Behbahani, T., Beigi, A. A. M., Taheri, Z., & Ghanbari, B. (2015). Investigation of wax precipitation in crude oil: Experimental and modeling. *Petroleum*, *1*(3), 223–230. https://doi.org/10.1016/j.petlm.2015.07.007

Jang, S. S., Shiang-Tai, L., Maiti, P. K., Blanco, M., Goddard, W. A., Shuler, P., & Tang, Y. (2004). Molecular dynamics study of a surfactant-mediated decane-water interface: Effect of molecular architecture of alkyl benzene sulfonate. *Journal of Physical Chemistry B*, *108*(32), 12130–12140. https://doi.org/10.1021/jp048773n

Jang, Y. H., Blanco, M., Creek, J., Tang, Y., & Goddard, W. A. (2007). : Support of the incorporation- perturbation mechanism from molecular dynamics simulations. *Journal of Physical Chemistry B*, *111*(46), 13173–13179. https://doi.org/10.1021/jp072792q

Jennings, D. W., & Breitigam, J. (2010). Paraffin inhibitor formulations for different application environments: From heated injection in the desert to extreme cold arctic temperatures. *Energy and Fuels*, *24*(4), 2337–2349. https://doi.org/10.1021/ef900972u

Jennings, D. W., & Weispfennig, K. (2005). Effects of shear and temperature on wax deposition: Coldfinger investigation with a Gulf of Mexico crude oil. *Energy and Fuels*, *19*(4), 1376–1386. https://doi.org/10.1021/ef049784i

Jia, H., Liu, P. G., Pu, W. F., Ma, X. P., Zhang, J., & Gan, L. (2016). In situ catalytic upgrading of heavy crude oil through low-temperature oxidation. *Petroleum Science*, *13*(3), 476–488. https://doi.org/10.1007/s12182-016-0113-6

Jiang, B., Zhang, R., Yang, N., Zhang, L., Sun, Y., Jian, C., Liu, L., & Xu, Z. (2019). Molecular mechanisms of suppressing asphaltene aggregation and flocculation by dodecylbenzenesulfonic acid probed by molecular dynamics simulations. *Energy and Fuels*, *33*(6), 5067–5080. https://doi.org/10.1021/acs.energyfuels.9b00821

Joonaki, E., & Ghanaatian, S. (2014). The application of nanofluids for enhanced oil recovery: Effects on interfacial tension and coreflooding process. *Petroleum Science and Technology*, *32*(21), 2599–2607. https://doi.org/10.1080/10916466.2013.855228

Kamal, M. S., Adewunmi, A. A., Sultan, A. S., Al-Hamad, M. F., & Mehmood, U. (2017). Recent advances in nanoparticles enhanced oil recovery: Rheology, interfacial tension, oil recovery, and wettability alteration. *Journal of*

Nanomaterials, *2017*. https://doi.org/10.1155/2017/2473175

Kelechukwu, E. M., Al Salim, H. S. S., & Yassin, A. A. M. (2010). Influencing factors governing paraffin wax deposition during crude production. *International Journal of Physical Sciences*, *5*(15), 2351–2362.

Kumar, R., Banerjee, S., Kumar, N., Mandal, A., & Kumar Naiya, T. (2015). Comparative Studies on Synthetic and Naturally Extracted Surfactant for Improving Rheology of Heavy Crude Oil. *Petroleum Science and Technology*, *33*(10), 1101–1109. https://doi.org/10.1080/10916466.2015.1044612

Kumar, Ravindra, Banerjee, S., Mandal, A., & Kumar Naiya, T. (2017a). Flow improvement of heavy crude oil through pipelines using surfactant extracted from soapnuts. *Journal of Petroleum Science and Engineering*, *152*, 353–360. https://doi.org/10.1016/j.petrol.2017.02.010

Kumar, Ravindra, Banerjee, S., Mandal, A., & Kumar Naiya, T. (2017b). Flow improvement of heavy crude oil through pipelines using surfactant extracted from soapnuts. *Journal of Petroleum Science and Engineering*, *152*(January 2016), 353–360. https://doi.org/10.1016/j.petrol.2017.02.010

Kumar, S., & Mahto, V. (2016). Emulsification of Indian heavy crude oil in water for its efficient transportation through offshore pipelines. *Chemical Engineering Research and Design*, *115*, 34–43. https://doi.org/10.1016/j.cherd.2016.09.017

Lashkarbolooki, M., Esmaeilzadeh, F., & Mowla, D. (2011). Mitigation of wax deposition by wax-crystal modifier for Kermanshah crude oil. *Journal of Dispersion Science and Technology*, *32*(7), 975–985. https://doi.org/10.1080/01932691.2010.488514

Lashkarbolooki, M., Seyfaee, A., Esmaeilzadeh, F., & Mowla, D. (2010). Experimental investigation of wax deposition in Kermanshah crude oil through a monitored flow loop apparatus. *Energy and Fuels*, *24*(2), 1234–1241. https://doi.org/10.1021/ef9010687

Lee, H. S. (2008). *Computational and Rheological Study of Wax Deposition and Gelation in Subsea Pipelines*. 127.

Lei, S., Xu, L., Qu, C., & Jiao, H. (2016). Influence of Gemini Surfactant with Modified TiO2 Nanoparticles on the Interfacial Tension of Oil/Water. *Journal of Dispersion Science and Technology*, *37*(10), 1494–1501. https://doi.org/10.1080/01932691.2015.1015076

Li, B., Liu, X., Zhang, X., & Chai, W. (2015). Stainless steel mesh coated with silica for oil-water separation. *European Polymer Journal*, *73*, 374–379. https://doi.org/10.1016/j.eurpolymj.2015.10.031

Li, H., & Zhang, J. (2014). Viscosity prediction of non-Newtonian waxy crude heated at various temperatures. *Petroleum Science and Technology*, *32*(5), 521–526. https://doi.org/10.1080/10916466.2011.596886

Li, N., Mao, G., & Liu, Y. (2018). Effect of the Evaluation and Mechanism Analysis of

a Novel Nanohybrid Pour Point Depressant on Facilitating Flow Properties of Crude Oil. *Energy and Fuels*, *32*(10), 10563–10570. https://doi.org/10.1021/acs.energyfuels.8b02371

Li, P., Guo, Y., Lu, Z., Zhang, W., & Hou, L. (2019). Syntheses, surface activities and aggregation morphologies of a series of novel itaconic acid based asymmetrical gemini surfactants. *Journal of Molecular Liquids*, *290*, 111218. https://doi.org/10.1016/j.molliq.2019.111218

Li, Q., Deng, X., Liu, Y., Cheng, Q., & Liu, C. (2021). Gelation of waxy crude oil system with ethylene-vinyl acetate on solid surface: A molecular dynamics study. *Journal of Molecular Liquids*, *331*, 115816. https://doi.org/10.1016/j.molliq.2021.115816

Lim, Z. H., Al Salim, H. S., Hasiholan, B., & Ridzuan, N. (2019). Evaluation of silane-based surfactant nanohybrid as flow improver in a Malaysian light crude oil. *IOP Conference Series: Materials Science and Engineering*, *469*(1). https://doi.org/10.1088/1757-899X/469/1/012001

Lim, Zhen Hao, Al Salim, H. S., Ridzuan, N., Nguele, R., & Sasaki, K. (2018). Effect of surfactants and their blend with silica nanoparticles on wax deposition in a Malaysian crude oil. *Petroleum Science*, *15*(3), 577–590. https://doi.org/10.1007/s12182-018-0241-2

Liu, T., Fang, L., Liu, X., & Zhang, X. (2015). Preparation of a kind of reactive pour point depressant and its action mechanism. *Fuel*, *143*, 448–454. https://doi.org/10.1016/j.fuel.2014.11.094

Lucas, E. F., & Machado, A. L. de C. (1999). Poly (ethylene-co-vinyl acetate)(EVA) Copolymers as Modifiers of Oil Wax. *Petroleum Science and Technology*, *17*(9&10), 1029–1041.

Ma, T., Feng, H., Wu, H., Li, Z., Jiang, J., Xu, D., Meng, Z., & Kang, W. (2019). Property evaluation of synthesized anionic-nonionic gemini surfactants for chemical enhanced oil recovery. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, *581*(66), 123800. https://doi.org/10.1016/j.colsurfa.2019.123800

Machado, A. L. C., Lucas, E. F., & González, G. (2001). Poly(ethylene-co-vinyl acetate) (EVA) as wax inhibitor of a Brazilian crude oil: Oil viscosity, pour point and phase behavior of organic solutions. *Journal of Petroleum Science and Engineering*, *32*(2–4), 159–165. https://doi.org/10.1016/S0920-4105(01)00158-9

Maithufi, M. N., Joubert, D. J., & Klumperman, B. (2011). Application of gemini surfactants as diesel fuel wax dispersants. *Energy and Fuels*, *25*(1), 162–171. https://doi.org/10.1021/ef1006287

Mansourpoor, M., Azin, R., Osfouri, S., & Izadpanah, A. A. (2018). Effect of DSO, EVA, and SiO2 and clay nanohybrids on rheological properties of waxy oil mixtures. *Materials Research Express*, *5*(9). https://doi.org/10.1088/2053-1591/aad858

Mansourpoor, M., Azin, R., Osfouri, S., & Izadpanah, A. A. (2019). Experimental investigation of wax deposition from waxy oil mixtures. *Applied Petrochemical Research*, *9*(2), 77–90. https://doi.org/10.1007/s13203-019-0228-y

Manzhai, V. N., Monkam Monkam, C. L. G., & Terre, D. A. (2016). Rheological properties of crude oils in Yaregskoye and Yaraktinskoye oil fields. *IOP Conference Series: Earth and Environmental Science*, *43*(1). https://doi.org/10.1088/1755-1315/43/1/012018

Mendes, R. (2015). *Rheological behavior and modeling of waxy crude oils in transient flows*. 174.

Meriem-Benziane, M., Abdul-Wahab, S. A., Benaicha, M., & Belhadri, M. (2012). Investigating the rheological properties of light crude oil and the characteristics of its emulsions in order to improve pipeline flow. *Fuel*, *95*, 97–107. https://doi.org/10.1016/j.fuel.2011.10.007

Mohammadi, M., Dadvar, M., & Dabir, B. (2017). TiO2/SiO2 nanofluids as novel inhibitors for the stability of asphaltene particles in crude oil: Mechanistic understanding, screening, modeling, and optimization. *Journal of Molecular Liquids*, *238*, 326–340. https://doi.org/10.1016/j.molliq.2017.05.014

Montes, D., Taborda, E. A., Minale, M., Cortés, F. B., & Franco, C. A. (2019). Effect of the NiO/SiO2 Nanoparticles-Assisted Ultrasound Cavitation Process on the Rheological Properties of Heavy Crude Oil: Steady State Rheometry and Oscillatory Tests. *Energy and Fuels*, *33*(10), 9671–9680. https://doi.org/10.1021/acs.energyfuels.9b02288

Moradi, B., Pourafshary, P., Jalali, F., Mohammadi, M., & Emadi, M. A. (2015). Experimental study of water-based nanofluid alternating gas injection as a novel enhanced oil-recovery method in oil-wet carbonate reservoirs. *Journal of Natural Gas Science and Engineering*, *27*, 64–73. https://doi.org/10.1016/j.jngse.2015.07.009

Mpelwa, M., Tang, S., Jin, L., Hu, R., Wang, C., & Hu, Y. (2020). The study on the properties of the newly extended Gemini surfactants and their application potentials in the petroleum industry. *Journal of Petroleum Science and Engineering*, *186*(December 2019), 106799. https://doi.org/10.1016/j.petrol.2019.106799

Njuguna, J., Vanli, O. A., & Liang, R. (2015). A Review of Spectral Methods for Dispersion Characterization of Carbon Nanotubes in Aqueous Suspensions. *Journal of Spectroscopy*, *2015*. https://doi.org/10.1155/2015/463156

Norrman, J., Solberg, A., Sjöblom, J., & Paso, K. (2016). Nanoparticles for Waxy Crudes: Effect of Polymer Coverage and the Effect on Wax Crystallization. *Energy and Fuels*, *30*(6), 5108–5114. https://doi.org/10.1021/acs.energyfuels.6b00286

Pal, N., Kumar, N., Saw, R. K., & Mandal, A. (2019). Gemini surfactant/polymer/silica stabilized oil-in-water nanoemulsions: Design and physicochemical characterization for enhanced oil recovery. *Journal of Petroleum Science and Engineering*, *183*(September), 106464.

https://doi.org/10.1016/j.petrol.2019.106464

Pal, N., Kumar, N., Verma, A., Ojha, K., & Mandal, A. (2018). Performance Evaluation of Novel Sunflower Oil-Based Gemini Surfactant(s) with Different Spacer Lengths: Application in Enhanced Oil Recovery. *Energy and Fuels*, *32*(11), 11344–11361. https://doi.org/10.1021/acs.energyfuels.8b02744

Pal, N., Saxena, N., & Mandal, A. (2018). Studies on the physicochemical properties of synthesized tailor-made gemini surfactants for application in enhanced oil recovery. *Journal of Molecular Liquids*, *258*, 211–224. https://doi.org/10.1016/j.molliq.2018.03.037

Paramashivaiah, B. M., & Rajashekhar, C. R. (2016). Studies on effect of various surfactants on stable dispersion of graphene nano particles in simarouba biodiesel. *IOP Conference Series: Materials Science and Engineering*, *149*(1). https://doi.org/10.1088/1757-899X/149/1/012083

Park, S. J., & Ali mansoori, G. (1988). Aggregation and deposition of heavy organics in petroleum crudes. *Energy Sources*, *10*(2), 109–125. https://doi.org/10.1080/00908318808908921

Patel, H., Shah, S., Ahmed, R., & Ucan, S. (2018). Effects of nanoparticles and temperature on heavy oil viscosity. *Journal of Petroleum Science and Engineering*, *167*(May), 819–828. https://doi.org/10.1016/j.petrol.2018.04.069

Pedersen, K. S., & Rønningsen, H. P. (2003). Influence of wax inhibitors on wax appearance temperature, pour point, and viscosity of waxy crude oils. *Energy and Fuels*, *17*(2), 321–328. https://doi.org/10.1021/ef020142+

Quan, Q., Gong, J., Wang, W., & Wang, P. (2015). The influence of operating temperatures on wax deposition during cold flow and hot flow of crude oil. *Petroleum Science and Technology*, *33*(3), 272–277. https://doi.org/10.1080/10916466.2014.948120

Quan, Q., Wang, W., Wang, P., Duan, J., Yang, J., Yao, H., & Gong, J. (2015). Wax deposition from emulsion-water in stratified flow. *Petroleum Science and Technology*, *33*(6), 749–755. https://doi.org/10.1080/10916466.2015.1007381

Ragunathan, T., Husin, H., & Wood, C. D. (2020a). Inhibiting wax deposition using palm oil additives. *Offshore Technology Conference Asia 2020, OTCA 2020*, 1–25. https://doi.org/10.4043/30079-ms

Ragunathan, T., Husin, H., & Wood, C. D. (2020b). Wax formation mechanisms, wax chemical inhibitors and factors affecting chemical inhibition. *Applied Sciences (Switzerland)*, *10*(2), 1–18. https://doi.org/10.3390/app10020479

Rakhmatullin, I. Z., Efimov, S. V., Tyurin, V. A., Al-Muntaser, A. A., Klimovitskii, A. E., Varfolomeev, M. A., & Klochkov, V. V. (2018). Application of high resolution NMR (1H and 13C) and FTIR spectroscopy for characterization of light and heavy crude oils. *Journal of Petroleum Science and Engineering*, *168*(January), 256–262. https://doi.org/10.1016/j.petrol.2018.05.011

Rashidi, M., Mombekov, B., & Marhamati, M. (2016). A study of a novel inter pipe coating material for paraffin wax deposition control and comparison of the results with current mitigation technique in oil and gas industry. *Offshore Technology Conference Asia 2016, OTCA 2016*, *April*, 4163–4169.

Ridzuan, N., Adam, F., & Yaacob, Z. (2014). Molecular recognition of wax inhibitor through Pour Point Depressant type inhibitor. *Society of Petroleum Engineers - International Petroleum Technology Conference 2014, IPTC 2014 - Innovation and Collaboration: Keys to Affordable Energy*, *2*, 1649–1657. https://doi.org/10.2523/iptc-17883-ms

Ridzuan, N., Adam, F., & Yaacob, Z. (2015). Effects of shear rate and inhibitors on wax deposition of Malaysian crude oil. *Oriental Journal of Chemistry*, *31*(4), 1999–2004. https://doi.org/10.13005/ojc/310417

Ridzuan, N., Adam, F., & Yaacob, Z. (2016a). Evaluation of the inhibitor selection on wax deposition for Malaysian crude oil. *Petroleum Science and Technology*, *34*(4), 366–371. https://doi.org/10.1080/10916466.2015.1127971

Ridzuan, N., Adam, F., & Yaacob, Z. (2016b). Screening of factor influencing wax deposition using full factorial experimental design. *Petroleum Science and Technology*, *34*(1), 84–90. https://doi.org/10.1080/10916466.2015.1122625

Ridzuan, N., & Al-Mahfadi, M. (2017). Evaluation on the effects of wax inhibitor and optimization of operating parameters for wax deposition in Malaysian crude oil. *Petroleum Science and Technology*, *35*(20), 1945–1950. https://doi.org/10.1080/10916466.2017.1373128

Ruwoldt, J., Humborstad Sørland, G., Simon, S., Oschmann, H. J., & Sjöblom, J. (2019). Inhibitor-wax interactions and PPD effect on wax crystallization: New approaches for GC/MS and NMR, and comparison with DSC, CPM, and rheometry. *Journal of Petroleum Science and Engineering*, *177*(February), 53–68. https://doi.org/10.1016/j.petrol.2019.02.046

Safaei-Naeini, Y., Aminzare, M., Golestani-Fard, F., Khorasanizadeh, F., & Salahi, E. (2012). Suspension stability of Titania nanoparticles studied by UV-VIS spectroscopy method. *Iranian Journal of Materials Science and Engineering*, *9*(1), 62–68.

Sahai, M., Singh, R. K., Kukrety, A., Kumar, A., Ray, S. S., Chhibber, V. K., & Kumar, S. (2018). Application of Triazine-Based Gemini Surfactants as Viscosity Reducing Agents of Tar Sand Derived Bituminous Crude. *Energy and Fuels*, *32*(3), 3031–3038. https://doi.org/10.1021/acs.energyfuels.7b03596

Sanchez-Minero, F., Ancheyta, J., Silva-Oliver, G., & Flores-Valle, S. (2013). Predicting SARA composition of crude oil by means of NMR. *Fuel*, *110*, 318–321. https://doi.org/10.1016/j.fuel.2012.10.027

Sekhon, B. S. (2004). Gemini (dimeric) surfactants The Two-Faced Molecules. *Resonance*, 42–49. https://doi.org/10.1016/S1359-0294(96)80093-8

Shokrlu, Y. H., & Babadagli, T. (2014). Viscosity reduction of heavy oil/bitumen using

micro- and nano-metal particles during aqueous and non-aqueous thermal applications. *Journal of Petroleum Science and Engineering*, *119*, 210–220. https://doi.org/10.1016/j.petrol.2014.05.012

Singh, P., Venkatesan, R., Fogler, H. S., & Nagarajan, N. (2000). Formation and aging of incipient thin film wax-oil gels. *AIChE Journal*, *46*(5), 1059–1074. https://doi.org/10.1002/aic.690460517

Song, X., Yin, H., Feng, Y., Zhang, S., & Wang, Y. (2016). Effect of SiO2 Nanoparticles on Wax Crystallization and Flow Behavior of Model Crude Oil. *Industrial and Engineering Chemistry Research*, *55*(23), 6563–6568. https://doi.org/10.1021/acs.iecr.6b00836

Sousa, A. L., Matos, H. A., & Guerreiro, L. P. (2019). Preventing and removing wax deposition inside vertical wells: a review. *Journal of Petroleum Exploration and Production Technology*, *9*(3), 2091–2107. https://doi.org/10.1007/s13202-019-0609-x

Straub, T. J., Autry, S. W., & King, G. E. (1989). *An Investigation Into Practical Removal of Downhole Paraffin by Thermal Methods and Chemical Solvents*. https://doi.org/10.2118/18889-ms

Subramanie, P. A. P., Padhi, A., Ridzuan, N., & Adam, F. (2020). Experimental study on the effect of wax inhibitor and nanoparticles on rheology of Malaysian crude oil. *Journal of King Saud University - Engineering Sciences*, *32*(8), 479–483. https://doi.org/10.1016/j.jksues.2019.05.003

Sulaimon, A. A., & Yusoff, M. H. (2015). Icipeg 2014. *Icipeg 2014*. https://doi.org/10.1007/978-981-287-368-2

Taborda, E. A., Franco, C. A., Ruiz, M. A., Alvarado, V., & Cortés, F. B. (2017). Experimental and Theoretical Study of Viscosity Reduction in Heavy Crude Oils by Addition of Nanoparticles. *Energy and Fuels*, *31*(2), 1329–1338. https://doi.org/10.1021/acs.energyfuels.6b02686

Taheri-Shakib, J., Shekarifard, A., Kazemzadeh, E., Naderi, H., & Rajabi-Kochi, M. (2020). Characterization of the wax precipitation in Iranian crude oil based on wax appearance temperature (WAT): The influence of ultrasonic waves. *Journal of Molecular Structure*, *1202*, 127239. https://doi.org/10.1016/j.molstruc.2019.127239

Taraneh, J. B., Rahmatollah, G., Hassan, A., & Alireza, D. (2008). Effect of wax inhibitors on pour point and rheological properties of Iranian waxy crude oil. *Fuel Processing Technology*, *89*(10), 973–977. https://doi.org/10.1016/j.fuproc.2008.03.013

Theyab, M. A. (2018). Wax deposition process: mechanisms, affecting factors and mitigation methods. *Open Access Journal of Science*, *2*(2), 109–115. https://doi.org/10.15406/oajs.2018.02.00054

Theyab, M. A., & Yahya, S. Y. (2018). Introduction to Wax Deposition. *International Journal of Petrochemistry and Research*, *2*(1), 126–131.

https://doi.org/10.18689/ijpr-1000122

Theyab, M., & Diaz, P. (2016). Experimental Study on the Effect of Inhibitors on Wax Deposition. *Journal of Petroleum & Environmental Biotechnology*, *07*(06). https://doi.org/10.4172/2157-7463.1000310

Tinsley, J. F., & Prud'homme, R. K. (2010). Deposition apparatus to study the effects of polymers and asphaltenes upon wax deposition. *Journal of Petroleum Science and Engineering*, *72*(1–2), 166–174. https://doi.org/10.1016/j.petrol.2010.03.014

Tung, N. P., Phong, N. T. P., Long, B. Q. K., Thuc, P. D., & Son, T. C. (2001). Studying the Mechanisms of Crude Oil Pour Point and Viscosity Reductions when Developing Chemical Additives with the Use of Advanced Analytical Tools. *Proceedings - SPE International Symposium on Oilfield Chemistry*, 383–394. https://doi.org/10.2118/65024-ms

Ungerer, P., Lachet, V., & Tavitian, B. (2006). Applications of molecular simulation in oil and gas production and processing. *Oil and Gas Science and Technology*, *61*(3), 387–403. https://doi.org/10.2516/ogst:2006040a

Wang, D. X., Chen, S. Sen, Jin, S. H., Shu, Q. H., Jiang, Z. M., Shang, F. Q., & Li, J. X. (2016). Investigation into the Coating and Desensitization Effect on HNIW of Paraffin Wax/Stearic Acid Composite System. *Journal of Energetic Materials*, *34*(1), 26–37. https://doi.org/10.1080/07370652.2014.993049

Wang, F., Zhang, D. M., Ding, Y. F., Zhang, L. X., Yang, M. S., Jiang, B. L., Zhang, S. M., Ai, M. Y., Liu, G. W., Zhi, S. J., Huo, L. F., Ouyang, X., & Li, L. (2011). The effect of nanohybrid materials on the pour-point and viscosity depressing of waxy crude oil. *Chinese Science Bulletin*, *56*(1), 14–17. https://doi.org/10.1007/s11434-010-4174-4

Wang, Z., Yu, X., Li, J., Wang, J., & Zhang, L. (2016). The use of biobased surfactant obtained by enzymatic syntheses forwax deposition inhibition and drag reduction in crude oil pipelines. *Catalysts*, *6*(5). https://doi.org/10.3390/catal6050061

Wei, B. (2015). Recent advances on mitigating wax problem using polymeric wax crystal modifier. *Journal of Petroleum Exploration and Production Technology*, *5*(4), 391–401. https://doi.org/10.1007/s13202-014-0146-6

Wu, C., Zhang, J. L., Li, W., & Wu, N. (2005). Molecular dynamics simulation guiding the improvement of EVA-type pour point depressant. *Fuel*, *84*(16), 2039–2047. https://doi.org/10.1016/j.fuel.2004.12.009

Yan, M., Li, G., & Li, X. (2018). Study on the Effect of Crude Oil Composition on Waxing Characteristics of Waxy Crude Oil. *IOP Conference Series: Materials Science and Engineering*, *452*(3). https://doi.org/10.1088/1757-899X/452/3/032018

Yang, F., Paso, K., Norrman, J., Li, C., Oschmann, H., & Sjöblom, J. (2015). Hydrophilic nanoparticles facilitate wax inhibition. *Energy and Fuels*, *29*(3), 1368–1374. https://doi.org/10.1021/ef502392g

Yang, F., Yao, B., Li, C., Shi, X., Sun, G., & Ma, X. (2017). Performance improvement of the ethylene-vinyl acetate copolymer (EVA) pour point depressant by small dosages of the polymethylsilsesquioxane (PMSQ) microsphere: An experimental study. *Fuel*, *207*, 204–213. https://doi.org/10.1016/j.fuel.2017.06.083

Yang, F., Yao, B., Li, C., Sun, G., & Ma, X. (2017). Oil dispersible polymethylsilsesquioxane (PMSQ) microspheres improve the flow behavior of waxy crude oil through spacial hindrance effect. *Fuel*, *199*, 4–13. https://doi.org/10.1016/j.fuel.2017.02.062

Yang, Y. I., Shao, Q., Zhang, J., Yang, L., & Gao, Y. Q. (2019). Enhanced sampling in molecular dynamics. *Journal of Chemical Physics*, *151*(7). https://doi.org/10.1063/1.5109531

Yao, B., Li, C., Yang, F., Zhang, Y., Xiao, Z., & Sun, G. (2016). Structural properties of gelled Changqing waxy crude oil benefitted with nanocomposite pour point depressant. *Fuel*, *184*, 544–554. https://doi.org/10.1016/j.fuel.2016.07.056

Yu, J., Grossiord, N., Koning, C. E., & Loos, J. (2007). Controlling the dispersion of multi-wall carbon nanotubes in aqueous surfactant solution. *Carbon*, *45*(3), 618–623. https://doi.org/10.1016/j.carbon.2006.10.010

Yu, W., & Xie, H. (2012). A review on nanofluids: Preparation, stability mechanisms, and applications. *Journal of Nanomaterials*, *2012*. https://doi.org/10.1155/2012/435873

Zhang, J., Zhang, M., Wan, J., & Li, W. (2008). Theoretical study of the prohibited mechanism for ethylene/vinyl acetate co-polymers to the wax crystal growth. *Journal of Physical Chemistry B*, *112*(1), 36–43. https://doi.org/10.1021/jp073052k

Zhao, Z., Xue, Y., Xu, G., Zhou, J., Lian, X., Liu, P., Chen, D., Han, S., & Lin, H. (2017). Effect of the nano-hybrid pour point depressants on the cold flow properties of diesel fuel. *Fuel*, *193*, 65–71. https://doi.org/10.1016/j.fuel.2016.12.020