Claims

1. A method of desulfurizing an oil composition, the method comprising:

flowing an oil composition comprising sulfur through a conduit comprising a constricted region, wherein oil-phase bubbles form in the constricted region and collapse in a turbulent zone downstream of the constricted region;

contacting the oil composition with an immiscible deep eutectic solvent in the turbulent zone, thereby extracting at least a portion of the sulfur from the oil composition into association with the deep eutectic solvent; and

separating the deep eutectic solvent and the extracted sulfur from the desulfurized oil composition.

2. The method according to claim 1, wherein contacting the oil composition with the deep eutectic solvent comprises introducing one or more streams of the deep eutectic solvent into the oil composition downstream of the constricted region, preferably by injection directly into the turbulent zone.

3. The method according to claim 2, wherein a flow of the deep eutectic solvent is directed through a flow constriction to produce solvent-phase bubbles in the one or more streams of the deep eutectic solvent introduced into the oil composition, and wherein the solvent-phase bubbles and the oil-phase bubbles collapse coincidentally in the turbulent zone to enhance extraction of the sulfur from the oil composition.

~~4. The method according to claim 3, wherein the solvent-phase bubbles and the oil-phase bubbles collapse coincidentally in the turbulent zone to enhance extraction of the sulfur from the oil composition.~~

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~~5. The method according to any one of claims 2 to 4, wherein the one or more streams of the deep eutectic solvent are introduced into the oil composition by injection counter-current to the flow of the oil composition in the conduit.~~

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~~6.~~4. The method according to any one of claims 1 to ~~5~~3, wherein the deep eutectic solvent comprises a eutectic mixture of a quaternary ammonium salt and a hydrogen bond donor.

~~7.~~5. The method according to claim ~~6~~4, wherein the hydrogen bond donor is a glycol~~, preferably ethylene glycol~~.

~~8. The method according to claim 6 or claim 7, wherein the deep eutectic solvent comprises tetrabutylammonium bromide / ethylene glycol or choline chloride / ethylene glycol.~~

~~9.~~6. The method according to any one of claims 1 to ~~8~~5, further comprising contacting the oil composition with a hydrogen donor in the turbulent zone, wherein the hydrogen donor reduces the viscosity of the desulfurized oil composition**.**

~~10.~~7. The method according to claim ~~9~~6, wherein the hydrogen donor is a hydrocarbon hydrogen donor solvent~~, preferably a refinery distillate~~.

~~11.~~8. The method according to any one of claims 1 to ~~10~~7, further comprising contacting the oil composition with an oxidant in the turbulent zone, wherein the oxidant oxidises sulfur-containing molecules in the oil composition to produce oxidised sulfur species and the oxidised sulfur species are at least partially extracted into the deep eutectic solvent.

~~12. The method according to claim 11, wherein the oxidant is added at a molar ratio of less than 0.5:1 relative to the sulfur in the oil composition, preferably less than 0.3:1 relative to the sulfur in the oil composition.~~

~~13. The method according to claim 11 or claim 12, wherein the oxidant is H_2O_2.~~

~~14.~~9. The method according to any one of claims 1 to ~~13~~8, wherein the deep eutectic solvent is a magnetic deep eutectic solvent.

~~15. The method according to claim 14, wherein the magnetic deep eutectic solvent comprises a eutectic mixture of a quaternary ammonium salt comprising tetrahaloferrate(III) anions and a hydrogen bond donor.~~

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~~16. The method according to claim 14 or claim 15, wherein the magnetic deep eutectic solvent is separated from the desulfurized oil composition by magnetically assisted separation.~~

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~~17. The method according to any one of claims 1 to 16, further comprising stimulating the oil composition with ultrasound in and/or downstream of the turbulent zone, thereby enhancing extraction of the sulfur from the oil composition.~~

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~~18. The method according to any one of claims 1 to 17, further comprising heating the oil composition flowing through the conduit upstream of and/or in the constricted region.~~

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~~19.~~10. The method according to any one of claims 1 to ~~18~~9, wherein the temperature is in the range of 45 to 60°C when contacting the oil composition with the deep eutectic solvent in the turbulent zone.

~~20.~~11. The method according to any one of claims 1 to ~~19~~10, wherein the deep eutectic solvent has a temperature dependent density, wherein the deep eutectic solvent has (i) a density which differs from the density of the desulfurized oil composition by less than 0.08 g/cm^3 when contacting the oil composition with the deep eutectic solvent in the turbulent zone, and (ii) a density which differs from the density of the desulfurized oil composition by more than 0.08 g/cm^3 when separating the deep eutectic solvent and the extracted sulfur from the desulfurized oil composition.

~~21. The method according to claim 20, wherein the deep eutectic solvent has a density which differs from the density of the desulfurized oil composition by less than 0.08 g/cm^3 when contacting the oil composition with the deep eutectic solvent in the turbulent zone.~~

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~~22. The method according to claim 20 or claim 21, wherein the deep eutectic solvent has a density which differs from the density of the desulfurized oil composition by more than 0.08 g/cm^3 when separating the deep eutectic solvent and the extracted sulfur from the desulfurized oil composition.~~

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~~23. The method according to any one of claims 1 to 22, further comprising, before separating the deep eutectic solvent from the desulfurized oil composition, flowing the oil composition through a second constricted region in the conduit and contacting the oil composition with a second portion of immiscible deep eutectic solvent in a second turbulent zone downstream of the second constricted region.~~

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~~24.~~12. The method according to any one of claims 1 to ~~23~~11, wherein flowing the oil composition through the conduit comprises circulating an inventory of the oil composition repeatedly through the conduit.

~~25. The method according to claim 24, wherein the volume of oil composition in the turbulent zone of the conduit is less than 1% of the volume of the inventory.~~

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~~26.~~13. The method according to any one of claims 1 to ~~25~~12, wherein the oil composition is a fuel oil and wherein the desulfurized oil composition has a sulfur content of no more than 1.97 wt.%~~, preferably no more than 1.47 wt.%, more preferably no more than 0.97 wt.%~~.

~~27. The method according to any one of claims 1 to 25, further comprising extracting at least one further component selected from nitrogen-containing species, metals such as vanadium, nickel and iron, and residual catalyst fines from the oil composition into association with the deep eutectic solvent.~~

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~~28.~~14. A two-stage process for desulfurizing an oil composition, comprising:

in a first stage, desulfurizing an oil composition by a method according to any one of claims 1 to ~~27~~ 13 to produce a first desulfurized oil composition; and

in a second stage, desulfurizing the first desulfurized oil composition by a method according to any one of claims 1 to ~~27~~ 13 to produce a second desulfurized oil composition.

~~29. The two-stage process according to claim 28, wherein a hydrogen donor is added in the second stage for contact with the first desulfurized oil composition in the turbulent zone, wherein the hydrogen donor reduces the viscosity of the second desulfurized oil composition.~~

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~~30. The two-stage process according to claim 28, wherein an oxidant is added in the second stage for contact with the first desulfurized oil composition in the turbulent zone.~~

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~~31. The two-stage process according to any one of claims 28 to 30, wherein the deep eutectic solvent in the second stage is tetrabutylammonium bromide / sulfolane.~~

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~~32.~~15. A system for desulfurizing an oil composition, the system comprising:

a conduit comprising a constricted region;

a pump for flowing an oil composition comprising sulfur through the conduit; and

one or more injection ports for introducing a stream of deep eutectic solvent to the conduit;

wherein the system is operable to:

(i) flow the oil composition through the conduit such that oil-phase bubbles form in the constricted region and collapse in a turbulent zone downstream of the constricted region; and

(ii) contact the oil composition with the deep eutectic solvent in the turbulent zone, thereby extracting at least a portion of the sulfur from the oil composition into association with the deep eutectic solvent.

~~33.~~16. The system according to claim ~~32~~15, wherein the injection ports introduce the stream of deep eutectic solvent to the conduit downstream of the constricted region~~, preferably~~ by injection directly into the turbulent zone.

~~34.~~17. The system according to claim ~~33~~16, wherein at least one~~, and preferably each,~~ of the injection ports comprises a flow constriction configured to produce solvent-phase bubbles in the stream of deep eutectic solvent introduced into the conduit.

~~35. The system according to claim 34, wherein the injection ports are configured such that the solvent-phase bubbles and the oil-phase bubbles collapse coincidentally in the turbulent zone.~~

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~~36. The system according to any one of claims 32 to 35, further comprising one or more inlets for introducing an oxidant or a hydrogen donor to contact the oil composition in the turbulent zone.~~

~~37. The system according to any one of claims 32 to 36, further comprising one or more ultrasonicator devices for stimulating the oil composition with ultrasound in and/or downstream of the turbulent zone.~~

~~38. The system according to any one of claims 32 to 37, further comprising a heater for heating the oil composition flowing through the conduit upstream of and/or in the constricted region.~~

~~39. The system according to any one of claims 32 to 38, wherein an internal diameter of the constricted region is adjustable to control the size and/or distribution of the oil-phase bubbles.~~

~~40.~~18. The system according to any one of claims ~~32~~ 15 to ~~39~~17, further comprising a separator for separating the deep eutectic solvent and the extracted sulfur from the desulfurized oil composition.

~~41.~~19. The system according to claim ~~40~~18, wherein the separator is selected from a magnetic separator and a triphase liquid-liquid separator for separating a phase rich in desulfurized oil composition, a phase rich in deep eutectic solvent, and a phase rich in sulfur-containing compounds.

~~42. The system according to claim 40 or claim 41, wherein the separator is a triphase liquid-liquid separator for separating a phase rich in desulfurized oil composition, a phase rich in deep eutectic solvent, and a phase rich in sulfur-containing compounds.~~

~~43. The system according to any one of claims 32 to 42, further comprising a second constricted region in the conduit downstream of the turbulent zone.~~

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~~44. The system according to claim 43, further comprising one or more second injection ports for introducing a stream of deep eutectic solvent to the conduit downstream of the second constricted region.~~

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~~45.~~20. The system according to any one of claims ~~32~~ 15 to ~~44~~19, further comprising a reservoir for holding an inventory of the oil composition to be flowed, by the pump, through the conduit, wherein the system is configured to circulate the inventory of the oil composition repeatedly through the conduit.

~~46. The system according to claim 45, configured to circulate the inventory of the oil composition repeatedly through the conduit.~~

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