the surface) in which depinning of droplets is not easily achievable and, as a result, droplets do not shed easily.

[0007] There is a need for improved articles and methods for manipulating (e.g., promoting or inhibiting) condensation on a surface. For example, there is a need for robust surfaces that promote dropwise condensation with minimal pinning of droplets.

Summary

[0007a] In a first aspect of the present disclosure, there is provided ~~an article~~a condenser comprising a liquid-impregnated surface and a condensing phase that grows on said surface in form of droplets of condensate, the droplets of condensate being shed from said surface ~~configured to promote or inhibit condensation thereupon and/or shedding of condensate thereupon~~, said surface comprising a matrix of features on a solid substrate and an impregnating liquid, said features spaced sufficiently close to stably contain an impregnating liquid therebetween or therewithin, wherein the condensate does not displace the impregnating liquid, and the condensate does not spread on the impregnating liquid in filmwise condensation.

[0007b] In a second aspect of the present disclosure, there is provided a method for ~~enhancing~~ promoting dropwise condensation and~~/or~~ shedding of a condensate (primary liquid) upon a surface of a condenser, the method comprising

selecting an impregnating liquid (secondary liquid) such that the condensate does not displace the impregnating liquid and such that the condensate does not spread on the impregnating liquid in filmwise condensation;

impregnating the surface with ~~an~~ the selected impregnating liquid (secondary liquid), said surface comprising a matrix of features on a solid substrate and the impregnating liquid, said

features spaced sufficiently close to stably contain the impregnating liquid therebetween or therewithin;

exposing the surface to a condensing phase, which forms droplets of the condensate on the surface, and

shedding the droplets of the condensate from the surface.

[0008] The articles and methods described herein provide a way to manipulate condensation on a surface by micro/nano-engineering textures on the surface and filling the spaces between the texture features with an impregnating liquid that is stably held therebetween or therewithin. The articles and methods allow droplets of water, or other condensed phases, e.g., even in the micrometer size range, to easily shed or exude from the surface, thereby enhancing the heat

transfer coefficient of the surface. It has been found that dropwise condensation is enhanced by the use of a surface textured with micro and/or nanostructures and having an impregnating (secondary) liquid with a relatively high surface tension, and, even more preferably, an impregnating liquid with both a high surface tension and a low viscosity.

[0009] Furthermore, in certain embodiments, thermodynamic conditions at which condensation occurs can be manipulated by application of an electric field on the impregnated surface or in the encapsulating secondary liquid.

[0010] The articles and methods have applications in a wide variety of devices that involve condensation, including condensers, aircraft wings, blades, turbines, pipelines, humidifiers, dehumidifiers, fog harvesters and collectors, and the like.

CLAIMS

1. ~~An article~~ A condenser comprising a liquid-impregnated surface and a condensing phase that grows on said surface in form of droplets of condensate, the droplets of condensate being shed from said surface ~~configured to promote or inhibit condensation thereupon and/or shedding of condensate thereupon~~, said surface comprising a matrix of features on a solid substrate and an impregnating liquid, said features spaced sufficiently close to stably contain an impregnating liquid therebetween or therewithin, wherein the condensate does not displace the impregnating liquid, and the condensate does not spread on the impregnating liquid in filmwise condensation.

2. The ~~article~~ condenser of claim 1, wherein the impregnating liquid has a surface tension with respect to air, γ_{oa}, such that:

$$(\gamma_{wa}-\gamma_{ow})<\gamma_{oa}<(\gamma_{wa}+\gamma_{ow})$$

where γ_{wa} is surface tension of the condensate with respect to air or other surrounding gas, γ_{oa} is surface tension of the impregnating liquid with respect to air or other surrounding gas, and γ_{ow} is interfacial tension between the impregnating liquid and the condensate.

3. The ~~article~~ condenser of claim 1 ~~or 2~~, wherein one or more of expressions (a) through (d) holds:

(a) $(\gamma_{wa}-\gamma_{ow})<\gamma_{oa}<(\gamma_{wa}+\gamma_{ow})$;

(b) $\gamma_{os}/\gamma_{ws}<\left[1+(\gamma_{ow}/\gamma_{ws})((r-1)/(r-\phi))\right]$;

(c) $\gamma_{oa}/\gamma_{wa}>\left[1-\gamma_{ow}/\gamma_{wa}\right]$; and

(d) $\gamma_{oa}/\gamma_{wa}<\left[1+\gamma_{ow}/\gamma_{wa}\right]$,

where γ_{wa} is surface tension of the condensate with respect to air or other surrounding gas, γ_{oa} is surface tension of the impregnating liquid with respect to air or other surrounding gas, γ_{ow} is interfacial tension between the impregnating liquid and the condensate, γ_{os} is interfacial tension between the impregnating liquid and the solid substrate, γ_{ws} is interfacial tension between the condensate and the solid substrate, r is ratio of actual surface area of the solid substrate to

projected area of the solid substrate, and ϕ is fraction of the surface area of the solid substrate that touches the condensate.

4. The ~~article~~ condenser of ~~any one of the preceding claims~~claim 3, wherein all of (a), (b), (c), and (d) holds such that the impregnating liquid does not spread on the condensate, the condensate does not displace the impregnating liquid, and the condensate does not spread on the impregnating liquid in filmwise condensation.

5. The ~~article~~ condenser of any one of ~~the preceding~~ claims 1 to 4, wherein the surface is configured to promote condensation and/or shedding of condensate thereupon, and wherein the impregnating liquid has a surface tension from ~~about~~ 30% to ~~about~~ 95%, or 33% to 67% of the surface tension of the condensate.

~~6. The article of claim 5, wherein the impregnating liquid has a surface tension from about 33% to about 67% of the surface tension of the condensate.~~

~~7~~6. The ~~article~~ condenser of any one of ~~the preceding~~ claims 1 to 5, wherein the condensate is water.

~~8~~7. The ~~article~~ condenser of claim ~~7~~6, wherein the surface tension of the impregnating liquid is from about 24 dynes/cm to about 49 dynes/cm.

~~9~~8. The ~~article~~ condenser of any one of ~~the preceding~~ claims 1 to 7, wherein the impregnating liquid comprises at least one member selected from the group consisting of Krytox-1506, ionic liquid

(e.g., BMI-IM), tetradecane, pentadecane, cis-decalin, alpha-bromonaphthalene, , alpha-chloronapthalene, diiodomethane, Ethyl Oleate, o-bromotoluene, diiodomethane, tribromohydrin, Phenyl Mustard Oil, Acetylene tetrabromide, and EMI-Im ($C_8H_{11}F_6N_3O_4S_2$).

~~10~~9. The ~~article~~ condenser of any one of ~~the preceding~~ claims 1 to 8, wherein the impregnating liquid has viscosity no greater than ~~about~~ 500 cP or no greater than 100 cP or no greater than 50 cP or wherein the impregnating liquid has vapor pressure at room temperature no greater than about 20 mm Hg.

~~11. The article of claim 10, wherein the impregnating liquid has viscosity no greater than about 100 cP.~~

~~12. The article of claim 11, wherein the impregnating liquid has viscosity no greater than about 50 cP.~~

~~13. The article of any one of the preceding claims, wherein the impregnating liquid has vapor pressure at room temperature no greater than about 20 mm Hg.~~

~~14~~10. The ~~article~~ condenser of any one of ~~the preceding~~ claims 1 to 9, wherein the matrix of features comprises hierarchical structures.

~~15~~11. The ~~article~~ condenser of claim ~~14~~10, wherein the hierarchical structures are micro-scale features that comprise nano-scale features thereupon.

~~16~~12. The ~~article~~ condenser of any one of ~~the preceding~~ claims 1 to 11, wherein the features have substantially uniform height and wherein the impregnating liquid fills space between the features and coats the features with a layer at least about 5 nm in thickness over the top of the features.

~~17~~13. The ~~article~~ condenser of any one of ~~the preceding~~ claims 1 to 12, wherein the features define pores or other wells and wherein the impregnating liquid fills the features.

~~18~~14. The ~~article~~ condenser of any one of ~~the preceding~~ claims 1 to 13, wherein the impregnating liquid forms a stable thin film on top of the features.

~~19~~15. The ~~article~~ condenser of any one of ~~the preceding~~ claims 1 to 14, wherein the matrix has a feature-to-feature spacing from about 1 micrometer to about 100 micrometers.

~~20~~16. The ~~article~~ condenser of any one of ~~the preceding~~ claims 1 to 15, wherein the features comprise at least one member selected from the group consisting of posts, particles, nanoneedles, nanograss, and random geometry features.

~~21~~17. The ~~article~~ condenser of any one of ~~the preceding~~ claims 1 to 16, wherein the ~~article~~ condenser comprises a plurality of spaced-apart electrodes configured for imposing an electric field or an electric flux to the liquid-impregnated surface.

~~22. The article of claim 21, wherein the article is a condenser.~~

~~23~~18. The ~~article~~ condenser of any one of ~~the preceding~~ claims 1 to 17, wherein the solid substrate comprises one or more members selected from the group consisting of a hydrocarbon, a polymer, a fluoropolymer, a ceramic, glass, fiberglass, and a metal.

~~24~~19. The ~~article~~ condenser of any one of ~~the preceding~~ claims 1 to 18, wherein the solid substrate is a coating.

~~25~~20. The ~~article~~ condenser of any one of ~~the preceding~~ claims 1 to 19, wherein the solid substrate is intrinsically hydrophobic.

~~26~~21. A method for ~~enhancing~~ promoting dropwise condensation and~~/or~~ shedding of a condensate (primary liquid) upon a surface of a condenser, the method comprising

selecting an impregnating liquid (secondary liquid) such that the condensate does not displace the impregnating liquid and such that the condensate does not spread on the impregnating liquid in filmwise condensation;

impregnating the surface with ~~an~~ the selected impregnating liquid (secondary liquid), said surface comprising a matrix of features on a solid substrate and the impregnating liquid, said features spaced sufficiently close to stably contain the impregnating liquid therebetween or therewithin;

exposing the surface to a condensing phase, which forms droplets of the condensate on the surface, and

shedding the droplets of the condensate from the surface.

~~27~~22. The method of claim ~~26~~21, wherein the surface is configured and/or the impregnating liquid is chosen such that one or more of expressions (a) through (d) holds:

(a) $(\gamma_{wa}-\gamma_{ow})<\gamma_{oa}<(\gamma_{wa}+\gamma_{ow})$;

(b) $\gamma_{os}/\gamma_{ws}<\left[1+(\gamma_{ow}/\gamma_{ws})((r-1)/(r-\phi))\right]$;

(c) $\gamma_{oa}/\gamma_{wa}>\left[1-\gamma_{ow}/\gamma_{wa}\right]$; and

(d) $\gamma_{oa}/\gamma_{wa}<\left[1+\gamma_{ow}/\gamma_{wa}\right]$,

where γ_{wa} is surface tension of the condensate with respect to air or other surrounding gas, γ_{oa} is surface tension of the impregnating liquid with respect to air or other surrounding gas, γ_{ow} is interfacial tension between the impregnating liquid and the condensate, γ_{os} is interfacial tension between the impregnating liquid and the solid substrate, γ_{ws} is interfacial tension between the condensate and the solid substrate, r is ratio of actual surface area of the solid substrate to projected area of the solid substrate, and ϕ is fraction of the surface area of the solid substrate that touches the condensate.

~~28~~23. The method of claim ~~27~~22, wherein all of (a), (b), (c), and (d) holds such that the secondary liquid does not spread on the primary liquid, the primary liquid does not displace the secondary liquid, and the primary liquid does not spread on the secondary liquid in filmwise condensation.

~~29~~24. The method of any one of claims ~~26~~21 to ~~28~~23, wherein the impregnating liquid (the secondary liquid) is ~~chosen~~ selected such that the spreading coefficient S of the ~~secondary~~ impregnating liquid on the ~~primary liquid~~condensate is negative~~.~~, where $S = \gamma_{wa} - \gamma_{oa} - \gamma_{ow}$, where γ_{wa} is surface tension of the condensate with respect to air or other surrounding gas, γ_{oa} is surface tension of the impregnating liquid with respect to air or other surrounding gas, and γ_{ow} is interfacial tension between the impregnating liquid and the condensate.

~~30~~25. The method of claim ~~29~~24, wherein the ~~secondary~~ impregnating liquid is chosen such that the ~~secondary~~ impregnating liquid has partial miscibility with the ~~primary liquid~~condensate such that the surface tension of a primary phase consisting essentially of the ~~primary liquid~~condensate is reduced and the spreading cofficient S is negative.

~~31~~26. The method of any one of claims ~~26~~ 21 to ~~30~~25, further comprising applying an electric field or electric flux to at least a portion of the surface.

~~32~~27. The method of claim ~~31~~26, comprising applying the electric field or electric flux via a plurality of spaced-apart electrodes, wherein the electrodes are spread apart to disseminate a charge throughout the impregnating liquid.

~~33~~28. The method of any one of claims ~~26~~ 21 to ~~32~~27, wherein the surface is the liquid-impregnated surface of the ~~article~~ condenser of any one of claims 1-~~25~~ to 20.

29. The condenser of any one of claims 1 to 20, wherein a spreading coefficient S of the impregnating liquid on the condensate is negative, where $S = \gamma_{wa} - \gamma_{oa} - \gamma_{ow}$, where γ_{wa} is surface tension of the condensate with respect to air or other surrounding gas, γ_{oa} is surface tension of the impregnating liquid with respect to air or other surrounding gas, and γ_{ow} is interfacial tension between the impregnating liquid and the condensate,

wherein the impregnating liquid has partial miscibility with the condensate such that the surface tension of a primary phase consisting essentially of the condensate is reduced and the spreading coefficient S is negative.