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 ~~of the Invention~~

[0007a] In a first aspect of the present disclosure, there is provided an article comprising a liquid-impregnated 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.

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

[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.

[0011] Referring to FIG. 1c, in certain embodiments, the articles and methods manipulate condensation on a surface by including a secondary liquid 106 impregnated within (i.e., encapsulating) the surface textures. The secondary liquid encapsulates the surface textures, thereby preventing a condensed phase from attaining the Wenzel state. Since liquids, unlike gases, are incompressible over a large range of pressures, impalement of a condensed phase can be prevented even with relatively large microtextures, without requiring nano-scale textures, as utilized with previous, non-encapsulated or non-impregnated surfaces. In addition, the secondary layer greatly increases droplet mobility of the condensed phase. The increased mobility of condensed droplets on the secondary liquid allows the droplets to shed easily from the surface. Unlike previous superhydrophobic surfaces, which require high droplet contact angles, the high droplet mobility achieved with the surfaces described herein is independent of the droplet contact angle. Furthermore, in various embodiments, the temperature at which the condensed phase may form on the surface is manipulated by application of an electric field on the impregnated surface or in the encapsulating secondary liquid. As a result, dropwise condensation can be induced at temperatures above saturation temperature for a given pressure, and the rate of dropwise condensation and/or droplet shedding can be enhanced significantly at a given subcooling temperature.

[0012] In one ~~aspect~~embodiment, the ~~invention~~ present disclosure is directed to an article including a liquid-impregnated surface configured to promote or inhibit condensation thereupon and/or shedding of condensate thereupon, said surface including a matrix of features and an impregnating liquid, said features spaced sufficiently close to stably contain an impregnating liquid therebetween or therewithin. In one embodiment, the surface tension of impregnating (secondary) liquid is such that the impregnating liquid does not spread on the condensing phase (primary liquid, i.e., condensate)

hereto, are, in certain embodiments, additionally included in the liquid-impregnated surfaces of the articles above.

[0014] In another ~~aspect~~embodiment, the ~~invention~~ present disclosure is directed to a method for enhancing condensation and/or shedding of a condensate upon a surface, the method including impregnating the surface with an impregnating liquid, said surface including a matrix of features and an impregnating liquid, said features spaced sufficiently close to stably contain the impregnating liquid therebetween or therewithin. In certain embodiments, the method further includes applying an electric field or electric flux to at least a portion of the surface to enhance condensation and/or shedding of condensate. In certain embodiments, the surface is one of the liquid-impregnated surfaces described above.

[0015] In another ~~aspect~~embodiment, the ~~invention~~ present disclosure is directed to an article including a liquid-impregnated surface configured to promote or inhibit condensation thereupon and/or shedding of condensate thereupon, said surface including 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, in any orientation. In certain embodiments, 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. In certain embodiments, one or more of expressions (a) through (d) holds:

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

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

viscosity no greater than about 100 cP. In certain embodiments, the impregnating liquid has viscosity no greater than about 50 cP. In certain embodiments, the impregnating liquid has vapor pressure at room temperature no greater than about 20 mm Hg. In certain embodiments, the matrix of features comprises hierarchical structures. In certain embodiments, the hierarchical structures are micro-scale features that comprise nano-scale features thereupon. In certain embodiments, 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. In certain embodiments, the features define pores or other wells and wherein the impregnating liquid fills the features. In certain embodiments, the impregnating liquid forms a stable thin film on top of the features. In certain embodiments, the matrix has a feature-to-feature spacing from about 1 micrometer to about 100 micrometers. In certain embodiments, the features comprise at least one member selected from the group consisting of posts, particles, nanoneedles, nanograss, and random geometry features. In certain embodiments, the article comprises a plurality of spaced-apart electrodes configured for imposing an electric field or an electric flux to the liquid-impregnated surface. In certain embodiments, the article is a condenser. In certain embodiments, 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. In certain embodiments, the solid substrate is a coating. In certain embodiments, the solid substrate is intrinsically hydrophobic.

[0016] In another ~~aspect~~embodiment, the present disclosure ~~invention~~ is directed to a method for enhancing condensation and/or shedding of a condensate (primary liquid) upon a surface, the method including impregnating the surface with an impregnating liquid (secondary liquid), said surface including a matrix of features on a solid substrate and the impregnating liquid, said features spaced

liquid has partial miscibility with the primary liquid such that the surface tension of a primary phase consisting essentially of the primary liquid is reduced and the spreading cofficient S is negative. In certain embodiments, the method further includes applying an electric field or electric flux to at least a portion of the surface. In certain embodiments, the method includes 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. In certain embodiments, the surface is the liquid-impregnated surface of the article of any one of the above-described embodiments.

[0017] Elements of embodiments described with respect to a given aspect of the ~~invention~~ present disclosure may be used in various embodiments of another aspect of the present disclosure~~invention~~. For example, it is contemplated that features of dependent claims depending from one independent claim can be used in apparatus and/or methods of any of the other independent claims.

Brief Description of the Drawings

[0018] The objects and features of the invention can be better understood with reference to the drawing described below, and the claims.

[0019] FIG. 1a is a schematic view of a primary liquid (e.g., a condensed phase) on a solid surface (e.g., a superhydrophobic surface) in a Cassie state in which the primary liquid sits on top of microstructures, according to an illustrative embodiment of the invention.

[0020] FIG. 1b is a schematic view of a primary liquid (e.g., a condensed phase) on a solid surface (e.g., a superhydrophobic surface) in a Wenzel state in which liquid may nucleate substantially everywhere on the surface and a large droplet remains in an impaled state, according to an illustrative embodiment of the invention.

Equivalents

[0084] While the invention has been particularly shown and described with reference to specific preferred embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the appended claims.

~~[0085] What is claimed is:~~

CLAIMS

1. An article comprising a liquid-impregnated 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.

2. The article 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 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