[0006] Another drawback with existing non-wetting surfaces is that they are susceptible to ice formation and adhesion. For example, when frost forms on existing superhydrophobic surfaces, the surfaces become hydrophilic. Under freezing conditions, water droplets can stick to the surface, and ice may accumulate. Removal of the ice can be difficult because the ice may interlock with the textures of the surface. Similarly, when these surfaces are exposed to solutions saturated with salts, for example as in desalination or oil and gas applications, scale builds on surfaces and results in loss of functionality. Similar limitations of existing non-wetting surfaces include problems with hydrate formation, and formation of other organic or inorganic deposits on the surfaces.

[0007] There is a need for non-wetting surfaces (e.g., superhydrophobic surfaces, superoleophobic surfaces, and supermetallophobic surfaces) that are more robust. In particular, there is a need for non-wetting surfaces that resist impalement and ice formation.

Summary

[0007a] In one aspect, the present disclosure refers to an article comprising a liquid-impregnated surface, said surface comprising a plurality of micro-scale and/or nano-scale solid features spaced sufficiently close to stably contain an impregnating liquid therebetween, said surface stably containing said impregnating liquid between said solid features, wherein said impregnating liquid fills the volume between said solid features, wherein said impregnating liquid is held in place between said plurality of features regardless of orientation of said surface, wherein $0 < \phi < 0.5$, where ϕ is the surface area fraction of said surface non-submerged by said impregnating liquid, and wherein said surface is a textured surface and said solid features are engineered protrusions of said textured surface.

[0008] Described herein are non-wetting surfaces that include a liquid impregnated within a matrix of micro/nano-engineered features on the surface, or a liquid filling pores or other tiny wells on the surface. Compared to previous non-wetting surfaces, which include a gas (e.g., air) entrained within the surface textures, these liquid-impregnated surfaces are resistant to impalement and frost formation, and are therefore more robust. The disclosure is fundamental in nature and can be used in any application that benefits from non-wetting surfaces. For example, the methods described herein may be used to reduce viscous drag in oil and gas pipelines, prevent ice formation on aircraft and/or powerlines, and minimize the accumulation of impinging liquids.

[0009] The methods and apparatus described herein have several advantages over existing non-wetting surfaces, referred to herein as gas-impregnated surfaces. For example, compared to gas-impregnated surfaces, liquid-impregnated surfaces have a much higher resistance to impalement. This enables a liquid-impregnated surface to withstand higher pressures (e.g., higher droplet velocities) during liquid impingement. In certain examples, a liquid-impregnated surface resists impalement through the use of micro-scale surface textures, rather than nano-scale textures, as utilized in previous gas-impregnated surface approaches. The use of micro-scale textures, rather than nano-scale textures is extremely advantageous at least because micro-scale features are less expensive and much easier to fabricate.

[0010] Through proper selection of the impregnating liquid, the liquid-impregnated surfaces described herein are easily customizable to suit a wide variety of applications. For example, water drag reduction on a solid surface may be achieved with the use of oil as the impregnating liquid, because water slips readily on oils. The use of oil as the impregnating liquid is also suitable for the prevention of frost and ice formation. In this application, the frost and ice may form only on the peaks of the surface textures, thereby greatly reducing ice formation rates and adhesion strengths.

[0011] In one example, the disclosure is also directed to an article comprising a liquid-impregnated surface, said surface comprising a matrix of features spaced sufficiently close to stably contain a liquid therebetween or therewithin. In certain examples, the liquid has viscosity at room temperature no greater than about 1000 cP (or cSt), no greater than about 100 cP (or cSt), or no greater than about 50 cP (or cSt). In certain examples, the liquid has vapor pressure at room temperature no greater than about 20 mm Hg, no greater than about 1 mm Hg, or no greater than about 0.1 mmHg.

[0012] In certain examples, the features have substantially uniform height and wherein the 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 examples, the features define pores or other wells and the liquid fills the features.

[0013] In certain examples, the liquid has receding contact angle of 0º such that the liquid forms a stable thin film on the top of the features.

[0014] In certain examples, the matrix has a feature-to-feature spacing from about 1 micrometer to about 100 micrometers. In certain examples, the matrix has a feature-to-feature spacing from about 5 nanometers to about 1 micrometer. In certain examples, the matrix comprises hierarchical structures. For example, the hierarchical structures may be micro-scale features that comprise nano-scale features thereupon.

[0015] In certain examples, the features have height no greater than about 100 micrometers. In certain examples, the features are posts. In certain examples, the features include one or more spherical particles, nanoneedles, nanograss, and/or random geometry features that provide surface roughness. In certain examples, the feature comprises one or more pores, cavities, interconnected pores, and/or interconnected cavities. In certain examples, the surface comprises porous media with a plurality of pores having different sizes.

[0016] In certain examples, the liquid comprises a perfluorocarbon liquid, a perfluoroFluorinated vacuum oil (such as Krytox 1506 or Fromblin 06/6), a fluorinated coolant (e.g., perfluoro-tripentylamine sold as FC-70, manufactured by 3M), an ionic liquid, a fluorinated ionic liquid that is immiscible with water, a silicone oil comprising PDMS, a fluorinated silicone oil, a liquid metal, an eletro-rheological fluid, a magneto-rheological fluid, a ferrofluid, a dielectric liquid, a hydrocarbon liquid, a fluorocarbon liquid, a refrigerant, a vacuum oil, a phase-change material, a semi-liquid, grease, synovial fluid, and/or a bodily fluid.

[0017] In certain examples, the article is a steam turbine part, a gas turbine part, an aircraft part, or a wind turbine part, and the liquid-impregnated surface is configured to repel impinging liquid. In certain examples, the article is eyeglasses, goggles, a ski mask, a helmet, a helmet face shield, or a mirror, and the liquid-impregnated surface is configured to inhibit fogging thereupon. In certain examples, the article is an aircraft part, a wind turbine part, a power transmission line, or a windshield, and the liquid-impregnated surface is configured to inhibit formation of ice thereupon. In certain examples, the article is a pipeline (or a part or coating thereof), and the liquid-impregnated surface is configured to inhibit the formation of hydrate thereupon and/or enhance the slippage (reduce drag) of fluid flowing thereupon (or therethrough). In certain examples, the article is a heat exchanger part or an oil or gas pipeline (or a part or coating thereof), and the liquid-impregnated surface is configured to inhibit the formation and/or adhesion of salt thereupon. In certain examples, the liquid-impregnated surface is configured to inhibit corrosion.

[0018] In certain examples, the article is an artificial joint and the liquid-impregnated surface is configured to reduce friction between mating surfaces and/or provide long-lasting lubrication of the joint. In certain examples, the article is an engine part (e.g., piston or cylinder), and the liquid-impregnated surface is configured to provide long-lasting lubrication of the part. In certain examples, the liquid-impregnated surface is configured to release liquid from the surface over time, thereby providing lubrication over time.

[0019] In certain examples, the liquid-impregnated surface is an anti-fouling surface configured to resist adsorption of debris thereupon. In certain examples, the article is a heat exchanger part, and the liquid-impregnated surface is configured to facilitate shedding of condensate thereupon, thereby enhancing condensation heat transfer.

What is claimed is:

1. An article comprising a liquid-impregnated surface, said surface comprising a plurality of micro-scale and/or nano-scale solid features spaced sufficiently close to stably contain an impregnating liquid therebetween, said surface stably containing said impregnating liquid between said solid features, wherein said impregnating liquid fills the volume between said solid features, wherein said impregnating liquid is held in place between said plurality of features regardless of orientation of said surface, wherein $0 < \phi < 0.5$, where ϕ is the surface area fraction of said surface non-submerged by said impregnating liquid, and wherein said surface is a textured surface and said solid features are engineered protrusions of said textured surface.

2. The article of claim 1, wherein said impregnating liquid has viscosity at room temperature no greater than about 1000 cP.

3. The article of claim 1, wherein said impregnating liquid has vapor pressure at room temperature no greater than about 20 mm Hg.

4. The article of claim 2, wherein said impregnating liquid has a viscosity at room temperature on the order of 10 cSt or less.

5. The article of claim 1, wherein the plurality of solid features has a feature-to-feature spacing from about 1 micrometer to about 100 micrometers.

6. The article of claim 1, wherein the plurality of solid features has a feature-to-feature spacing from about 5 nanometers to about 1 micrometer.

7. The article of claim 1, wherein the plurality of solid features comprises hierarchical structures.

8. The article of claim 7, wherein the hierarchical structures are micro-scale features that comprise nano-scale features thereupon.

9. The article of claim 1, wherein the solid features have height no greater than about 100 micrometers.

10. The article of claim 1, wherein the solid features comprise at least one member selected from the group consisting of a spherical particle, a nanoneedle, a nanograss, and a random geometry feature that provides surface roughness.

11. The article of claim 1, wherein the impregnating liquid comprises a member selected from the group consisting of silicone oil, a perfluorocarbon liquid, a perfluoroFluorinated vacuum oil, a fluorinated coolant, an ionic liquid, a fluorinated ionic liquid that is immiscible with water, a silicone oil comprising PDMS, a fluorinated silicone oil, a liquid metal, an eletro-rheological fluid, a magneto-rheological fluid, a ferrofluid, a dielectric liquid, a hydrocarbon liquid, a fluorocarbon liquid, a refrigerant, a vacuum oil, a phase-change material, a semi-liquid, grease, synovial fluid, bodily fluid.

12. The article of claim 1, wherein the article is a part of or coating of a pipeline, and wherein the liquid-impregnated surface inhibits the formation of hydrate thereupon and/or enhances the slippage of fluid flowing thereupon.

13. The article of claim 1, wherein the liquid-impregnated surface inhibits corrosion.

14. The article of claim 1, wherein the liquid-impregnated surface is an anti-fouling surface that resists adsorption of debris thereupon.

15. The article of claim 1, wherein $0 < \phi \leq 0.25$.

16. The article of claim 1, wherein said impregnating liquid is held in place within said plurality of solid features regardless of contact of said liquid-impregnated surface with a liquid different from said impregnating liquid.

17. The article of claim 1, wherein the plurality of micro-scale and/or nano-scale solid features comprises randomly-spaced features.

18. The article of claim 1, wherein the plurality of micro-scale and/or nano-scale solid features are evenly spaced.