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Monolithic Heat-Transfer Device

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(54) **MONOLITHIC HEAT-TRANSFER DEVICE**

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CPC F28D 15/02; F28D 15/0266; F28D 15/046; F28D 9/0093; F28F 3/086; F28F 21/085; F28F 21/06; F28F 21/02; H01L 23/3121
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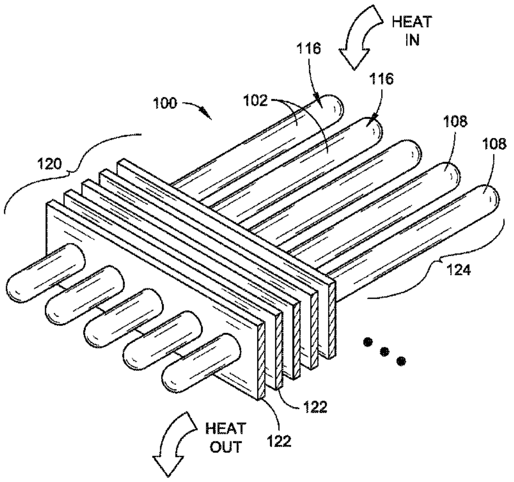
(57) **ABSTRACT**

A monolithic heat-transfer device can include a container wall configured to retain a working fluid, where the container wall is formed of a single material. The container wall also includes an interior surface configured to be in fluid communication with the working fluid. The monolithic heat-transfer device also includes a channel disposed in the interior surface of the container wall, where the channel comprises a microstructure and a nanostructure. The microstructure and the nanostructure are materially contiguous with the single material forming the container wall. In some embodiments, the nanostructure comprises one or more layers of nanoparticles. The monolithic heat-transfer device can be configured as a heat pipe, which can be constructed from the container wall and a second container wall joined together and sealed to one another to contain the working fluid (e.g., using laser welding, electron beam welding (EBW), and so forth).

17 Claims, 3 Drawing Sheets



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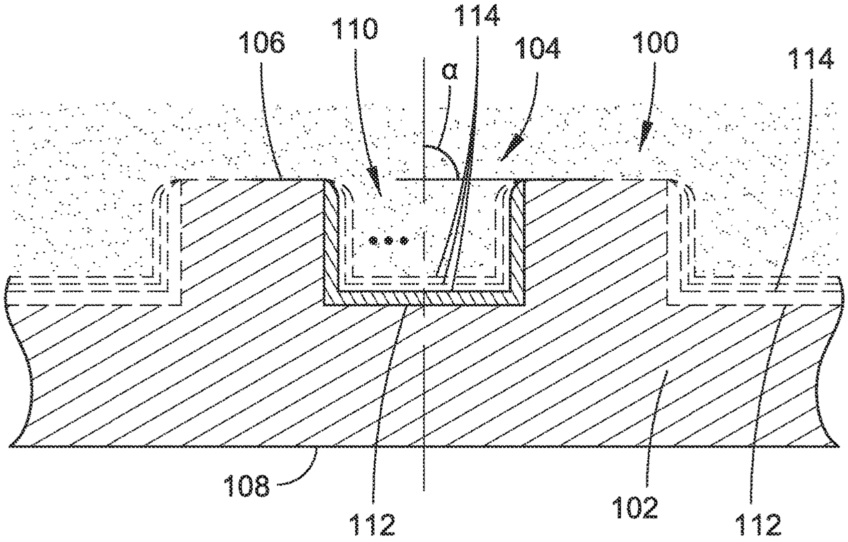
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110
114
α
104
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114
108
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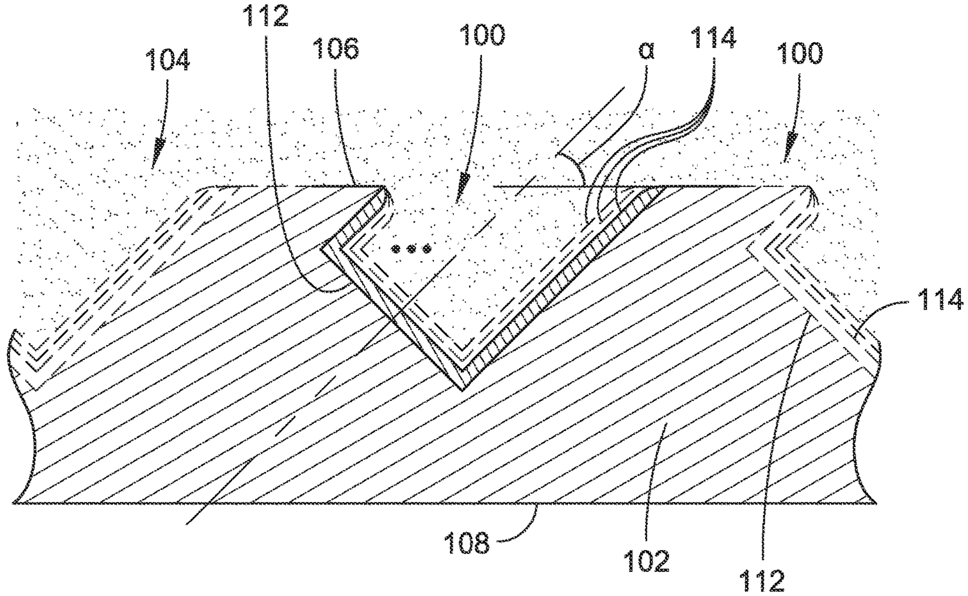
102
112

FIG. 1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102
112

FIG. 2

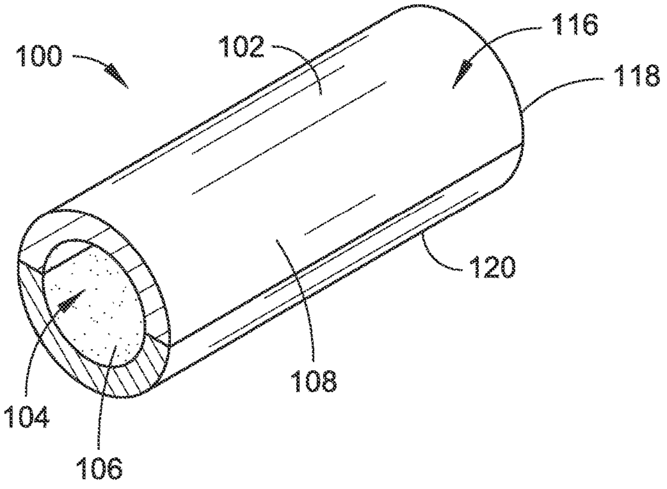
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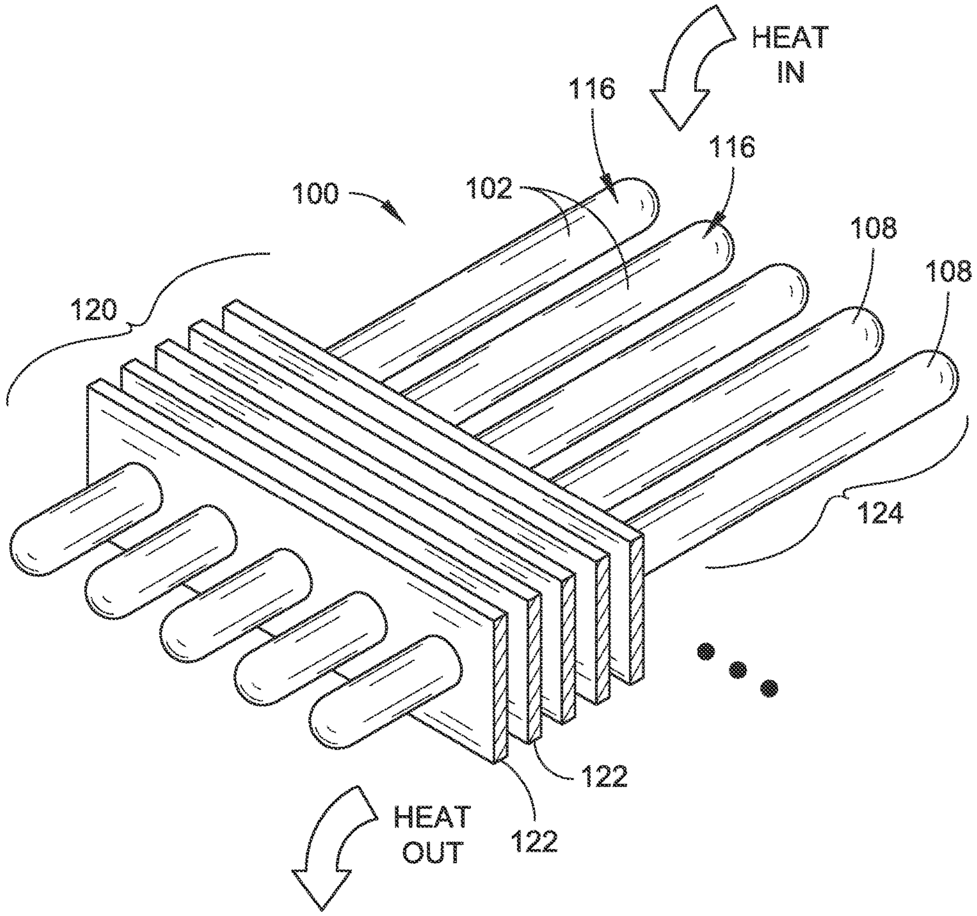
FIG. 3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102
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124
122
122
HEAT OUT

FIG. 4

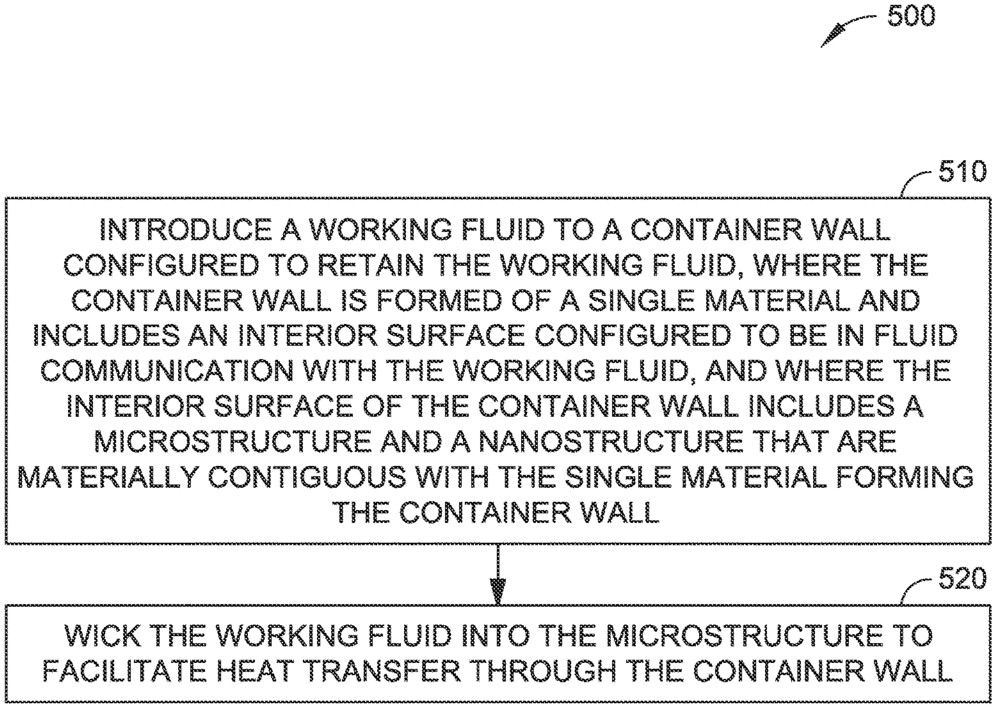
500
510
INTRODUCE A WORKING FLUID TO A CONTAINER WALL CONFIGURED TO RETAIN THE WORKING FLUID, WHERE THE CONTAINER WALL IS FORMED OF A SINGLE MATERIAL AND INCLUDES AN INTERIOR SURFACE CONFIGURED TO BE IN FLUID COMMUNICATION WITH THE WORKING FLUID, AND WHERE THE INTERIOR SURFACE OF THE CONTAINER WALL INCLUDES A MICROSTRUCTURE AND A NANOSTRUCTURE THAT ARE MATERIALLY CONTIGUOUS WITH THE SINGLE MATERIAL FORMING THE CONTAINER WALL
520
WICK THE WORKING FLUID INTO THE MICROSTRUCTURE TO FACILITATE HEAT TRANSFER THROUGH THE CONTAINER WALL

FIG. 5

MONOLITHIC HEAT-TRANSFER DEVICE

CROSS-REFERENCE TO RELATED APPLICATIONS

The present application claims the benefit under 35 U.S.C. § 119(e) of U.S. Provisional Application Ser. No. 61/926,440, filed Jan. 13, 2014, and titled "Monolithic Hierarchical Structures Micro Heat Pipe (MHSμHP)," which is herein incorporated by reference in its entirety.

FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

This invention was made with government support under Grant Number FA9451- 12-D-0195 awarded by the Air Force Research Laboratory. The government has certain rights in the invention.

BACKGROUND

The term "heat transfer" is used to describe thermal energy exchanged between physical systems. Thermal energy exchange can be described as heat dissipation that depends on temperature and pressure. Fundamental modes of heat transfer include conduction or diffusion, convection, and radiation. Heat transfer can also be described as an exchange of kinetic energy between particles through a boundary between two systems at different temperatures from one another, or from their surroundings. Thus, heat transfer occurs from a region of high temperature to another region of lower temperature, changing the internal energy of the systems involved.

SUMMARY

A monolithic heat-transfer device can include a container wall configured to retain a working fluid, where the container wall is formed of a single material. The container wall also includes an interior surface configured to be in fluid communication with the working fluid. The monolithic heat-transfer device also includes a channel disposed in the interior surface of the container wall, where the channel comprises a microstructure and a nanostructure. The microstructure and the nanostructure are materially contiguous with the single material forming the container wall. In some embodiments, the nanostructure comprises one or more layers of nanoparticles. The monolithic heat-transfer device can be configured as a heat pipe, which can be constructed from the container wall and a second container wall joined together and sealed to one another to contain the working fluid (e.g., using laser welding, electron beam welding (EBW), and so forth).

This Summary is provided to introduce a selection of concepts in a simplified form that are further described below in the Detailed Description. This Summary is not intended to identify key features or essential features of the claimed subject matter, nor is it intended to be used as an aid in determining the scope of the claimed subject matter.

DRAWINGS

The Detailed Description is described with reference to the accompanying figures. The use of the same reference numbers in different instances in the description and the figures may indicate similar or identical items.

FIG. **1** is a partial cross-sectional side elevation view illustrating a heat-transfer device in accordance with example embodiments of the present disclosure.

FIG. **2** is a partial cross-sectional side elevation view illustrating another heat-transfer device in accordance with example embodiments of the present disclosure.

FIG. **3** is a partial cross-sectional isometric view of a heat-transfer device, such as the heat-transfer device shown in FIG. **1** or the heat-transfer device shown in FIG. **2**, configured as a heat pipe in accordance with an example embodiment of the present disclosure.

FIG. **4** is an isometric view of a heat-transfer device, such as the heat-transfer device shown in FIG. **1** or the heat-transfer device shown in FIG. **2**, configured with multiple heat pipes in accordance with an example embodiment of the present disclosure.

FIG. **5** is a flow diagram illustrating a method of facilitating heat transfer through a container wall in accordance with an example embodiment of the present disclosure.

DETAILED DESCRIPTION

Heat-transfer devices are described herein. In some embodiments, a heat-transfer device can be configured as a monolithic hierarchical structures micro heat pipe (MHSμHP). For example, a heat pipe comprises metallic microchannels having interior surfaces that include microstructures and nanostructures from the same base substrate metal. In this manner, the metallic microchannels, microstructures, and nanoparticles can be one piece (e.g., monolithic hierarchical structures) from the same base material. As described herein, heat-transfer devices with surfaces configured in accordance with the present disclosure can provide exceptional superwicking abilities, e.g., resulting from the presence of nanoparticles on top of microstructures. For instance, capillary flow of liquid material proximate to the surface of a heat-transfer device is enhanced by the presence of one or more nanoparticle layers, which can wick the liquid material deep into crevices in the surface of the heat-transfer device.

Referring generally to FIGS. **1** through **4**, monolithic heat-transfer devices **100** are described. A heat-transfer device **100** comprises a substrate (e.g., a container wall **102**) configured to contain a working fluid **104**, where the container wall **102** is formed of a single material and includes an interior surface **106** and an exterior surface **108**. The inner surface **106** is configured to be in fluid communication with the working fluid **104**. The heat-transfer device **100** also includes one or more channels **110** disposed in the interior surface **106** of the container wall **102**. In embodiments of the disclosure, each channel **110** can include one or more microstructures **112** and one or more nanostructures **114**. As described herein, the microstructures **112** and the nanostructures **114** are materially contiguous with the material forming the container wall **102**. Nanoparticles of the nanostructures **114** allow the working fluid **104** to wick deep into the microstructures **112** (e.g., into the interior surface **106** of the heat-transfer device **100**). Further, the microstructures **112** can provide enhanced single-phase and/or two-phase heat transfer (e.g., facilitating change of phase of the working fluid **104**). For example, in some embodiments, the microstructures **112** can provide an increase in the surface area of the interior surface **106** of the heat-transfer device **100** of about five (5) to seven (7) times (e.g., when compared to a heat-transfer device that does not use microstructures).

In embodiments of the disclosure, the microstructures **112** can have various cross-sectional shapes, including, but not necessarily limited to: square, semi-circular, semi-elliptical, triangular, and so forth. Further, the microstructures **112** can be fabricated at various angles a, ranging from at least approximately normal to the interior surface **106** at zero degrees)(0°) (e.g., as shown in FIG. **1**) to other angles from normal to the interior surface **106** (e.g., as shown in FIG. **2**). In some embodiments, a can range up to at least approximately seventy degrees)(70°) from normal to the interior surface **106**. However, it should be noted that an angle of seventy degrees)(70°) is provided by way of example and is not meant to limit the present disclosure. In other embodiments, a can be greater than seventy degrees)(70°) from normal to the interior surface **106**.

In embodiments of the disclosure, the microstructures **112** can be fabricated with different aspect ratios and/or heights. As used herein, the term "aspect ratio" can refer to the ratio of, for example, the height (e.g., depth) of a microstructure **112** to the width of the microstructure **112**. For example, the depth of a microstructure **112** can be equal to or less than at least approximately one hundred micrometers (100 μm). Further, the width of a microstructure **112** can range from about three-tenths of a micrometer (3/10 μm) to about one micrometer (1 μm) or more (e.g., depending on the spot size of a laser focused on the interior surface **106** to fabricate a microstructure **112**). In some embodiments, a microstructure **112** can be several millimeters or more in width. In some embodiments, the thickness of a nanostructure **114** (e.g., the total thickness of one or more layers of nanoparticles) can be equal to or less than at least approximately ten micrometers (10 μm). However, these characteristic dimensions are provided by way of example and are not meant to limit the present disclosure. In other embodiments, the microstructures **112** can have different characteristic depths (e.g., greater than one hundred micrometers (100 μm)), the nanostructures **114** can have different characteristic thicknesses (e.g., greater than ten micrometers (10 μm)), and so forth.

In some embodiments, a laser process can be used to fabricate the microstructures **112** and the nanostructures **114** in the channels **110** in the substrate. For example, femtosecond laser surface processing (FLSP) laser pulses can be used to form a microstructure **112** with a nanostructure **114** (e.g., one or more layers of nanoparticles) sintered at the Gaussian edge of the laser pulse. Thus, in some embodiments, a nanostructure **114** can comprise metal oxides of a metallic base substrate material sintered by a laser pulse or laser pulses. For example, a nanostructure **114** comprising nickel oxide nanoparticles is generated when a microstructure **114** is formed in a nickel container wall **102**. Other materials for constructing container walls **102** can include, but are not necessarily limited to: gold; steel alloys (e.g., stainless steel); titanium; aluminum; copper; zirconium alloys; silicon carbide; nickel-based, precipitation hardenable superalloys; silicon; germanium; various combinations of these materials; and so forth. In some embodiments, laser sintering can be used to control the thickness (e.g., layer density) of the nanostructures **114** (e.g., where a desired thickness is determined based upon, for example, wicking properties of the working fluid **104**). However, it should be noted that laser sintering is provided by way of example and is not meant to limit the present disclosure. Thus, in other embodiments, the microstructures **112** and/or the nanostructures **114** can be formed using other processing techniques, including laser processes that do not involve sintering.

In implementations, the microstructures **112** and the nanostructures **114** in the channels **110** in the substrate can be formed using FLSP, which can develop the nanostructures **114** on the interior surface **106** through a combination of growth mechanisms, including, but not necessarily limited to: preferential ablation, capillary flow of laser-induced melt layers, and redeposition of ablated surface features. In implementations, the size and density of both micrometer and nanometer-scale surface features can be tailored by controlling FLSP conditions, such as laser fluence, incident pulse count, polarization, and incident angle, to thereby produce a multiscale metallic surface, which can affect heat transfer associated with, inter alia, change of phase of materials (see, e.g., Kruse et al., "Extraordinary Shifts of the Leidenfrost Temperature from Multiscale Micro/Nanostructured Surfaces," Langmuir, 29, 9798-9806 (2013); Zuhlke, "Control and Understanding of the Formation of Micro/Nanostructured Metal Surfaces Using Femtosecond Laser Pulses," UMI Number: 3546643; Zuhlke et al.,

"Comparison of the structural and chemical composition of two unique micro/nanostructures produced by femtosecond laser interactions on nickel," Appl. Phys. Lett. 103, 121603 (2013); Zuhlke et al., "Fundamentals of layered nanoparticle covered pyramidal structures formed on nickel during femtosecond laser surface interactions," Applied Surface Science 283 (2013), 648-653, which are incorporated herein by reference).

In some embodiments, a heat-transfer device **100** can be configured as a heat pipe **116**, which can be used to manage heat transfer between two or more interfaces. For example, a heat pipe **116** includes one or more container walls **102** configured to retain working fluid **104**, examples of which can include, but are not necessarily limited to: ammonia, alcohol (e.g., methanol, ethanol, etc.), water, refrigerants, liquid helium, mercury, cesium, potassium, sodium, indium, and so forth. The container wall **102** or container walls **102** can be sealed to contain the working fluid **104** (e.g., forming an envelope). In some embodiments, the working fluid **104** mass is chosen so that the heat pipe **116** can contain the working fluid **104** as both vapor and liquid (e.g., over the operating temperature range of the heat pipe **116**).

In some embodiments, two halves **118** and **120** of metallic hypodermic tubes and/or milled slabs of metallic material (e.g., each comprising a container wall **102**) are joined together, e.g., laser welded, electron beam welded (EBW), and so forth, to contain working fluid **104**. In these embodiments, enhanced functionalized surfaces comprising microstructures **112** and nanostructures **114** can be fabricated on the interior surfaces **106** of the container walls **102** before adding the working fluid **104**, and then the two halves **118** and **120** can be joined together and sealed to one another to contain the working fluid **104**. Depending on the desired diameter, the interior surfaces **106** of the container walls **102** can be fabricated by laser processing (e.g., as previously described) and/or other processing. In this manner, the heat-transfer devices and techniques described herein can facilitate ease of assembly and/or a large range of microchannel dimensions.

The material of the container walls **102** can be selected based upon the working fluid **104**. For example, a copper container wall **102** envelope can be used with water working fluid **104**. In another example, a copper and/or steel container wall **102** envelope can be used with a refrigerant working fluid **104**. In a further example, an aluminum container wall **102** envelope can be used with ammonia working fluid **104**. In another example, a superalloy container wall **102** envelope can be used with an alkali metal working fluid **104** (e.g., cesium, potassium, sodium, and so forth). In this manner, the heat pipes **116** described herein can be used for various applications, including, but not necessarily limited to: electronics cooling applications; heating, ventilating, and air conditioning (HVAC) applications (e.g., for energy recovery); thermal control applications; temperature measurement device calibration applications; and so forth.

However, these container wall materials, working fluids **104**, and applications are provided by way of example and are not meant to limit the present disclosure. Thus, in other embodiments, different materials for the container walls **102** and/or the working fluids **104** can be used, including, but not necessarily limited to: a stainless steel container wall **102** envelope with nitrogen, oxygen, neon, hydrogen, or helium working fluid **104**; a copper container wall **102** envelope with methanol working fluid **104**; an aluminum container wall **102** envelope with ethane working fluid **104**; a refractory metal container wall **102** envelope with lithium working fluid **104**; and so on. Further, heat pipes **116** as described herein can be configured as constant conductance heat pipes (CCHPs), vapor chambers (e.g., flat heat pipes), variable conductance heat pipes (VCHPs), diode heat pipes, loop heat pipes (e.g., micro loop heat pipes), and so forth.

In some embodiments, a heat-transfer device **100** can comprise a single heat pipe **116** (e.g., as shown in FIG. **3**). In other embodiments, a heat-transfer device **100** can comprise multiple heat pipes **116**, which can be mechanically and/or thermally connected together (e.g., without necessarily connecting the working fluids **104** in the various heat pipes **116**). For example, as shown in FIG. **4**, a heat-transfer device **100** includes an array of heat pipes **116** that form a condenser **120**, where pipe ends can be connected together using, for instance, heat dissipation fins **122**. The heat-transfer device **100** also includes an evaporator **124**. As shown, heat flows from the evaporator **124** to the condenser **120** as the working fluid **104** moves from one end of the heat pipes **116** at the evaporator **124** to the other end of the heat pipes **116** at the condenser **120**, and then back to the evaporator **124**. However, it should be noted that the heat pipes **116** shown are provided by way of example and are not meant to limit the present disclosure. Thus, heat-transfer devices **100** can be configured for other various applications that use thermal management, including thermal management for microelectronics, nanoelectronics, laser diodes, energy conversion systems, and so forth.

The following discussion describes example techniques for facilitating heat transfer through a container wall. FIG. **5** depicts a procedure **500**, in example embodiments, in which heat transfer is facilitated through a container wall by introducing a working fluid to the container wall, where the container wall includes one or more microstructures and one or more nanostructures formed on the interior surface of the container wall. In the procedure **500** illustrated, a working fluid is introduced to a container wall configured to retain the working fluid, where the container wall is formed of a single material and includes an interior surface configured to be in fluid communication with the working fluid, and where the interior surface of the container wall includes a microstructure and a nanostructure that are materially contiguous with the single material forming the container wall (Block **510**). For example, with reference to FIGS. **1** and **2**, working fluid **104** is introduced to container wall **102**, which includes interior surface **106** with microstructures **112** and nanostructures **114** formed on the interior surface **106**. Then, the working fluid is wicked into the microstructure to facilitate heat transfer through the container wall (Block **520**). For instance, with reference to FIGS. **1** and **2**, the working fluid **104** is wicked into the microstructure **112**.

Although the subject matter has been described in language specific to structural features and/or process operations, it is to be understood that the subject matter defined in the appended claims is not necessarily limited to the specific features or acts described above. Rather, the specific features and acts described above are disclosed as example forms of implementing the claims.

What is claimed is:

1. A monolithic heat-transfer device comprising a container wall configured to retain a working fluid;
- wherein the container wall comprises an interior surface configured to be in fluid communication with the working fluid;
- wherein at least one channel is disposed in the interior surface of the container wall, the channel including a functionalized surface comprising a plurality of microstructures and a plurality of nanostructures;
- wherein the container wall is formed of a base material and the microstructures and the nanostructures are formed of a sintered oxide of the base material;
- wherein the microstructures and the nanostructures are materially contiguous with the base material forming the container wall;
- wherein the monolithic heat-transfer device comprises a heat pipe; and
- wherein the heat pipe is constructed from the container wall and a second container wall joined together and sealed to one another to contain the working fluid.

2. The monolithic heat-transfer device as recited in claim **1**, wherein at least one nanostructure comprises at least one layer of nanoparticles.

3. The monolithic heat-transfer device as recited in claim **1**, wherein the microstructures are less than at least approximately one hundred micrometers (100 μm) in depth.

4. The monolithic heat-transfer device as recited in claim **1**, wherein the nanostructures are less than at least approximately ten micrometers (10 μm) in total thickness.

5. The monolithic heat-transfer device as recited in claim **1**, wherein the container wall and the second container wall are joined together with at least one of laser welding or electron beam welding (EBW).

6. The monolithic heat-transfer device of claim **1**, wherein the at least one channel protrudes into the interior surface of the container wall.

7. A monolithic heat pipe comprising a container wall configured to retain a working fluid;
- wherein the container wall comprises an interior surface configured to be in fluid communication with the working fluid;
- wherein at least one channel is disposed in the container wall interior surface, and formed at an angle from the interior surface, the channel including a functionalized surface comprising a plurality of microstructures and nanostructures;
- wherein the container wall is formed of a base material and the microstructures and the nanostructures are formed of a sintered oxide of the base material;
- wherein the microstructures and the nanostructures are materially contiguous with the base material forming the container wall; and
- wherein the heat pipe is constructed from the container wall and a second container wall joined together and sealed to one another to contain the working fluid.

8. The monolithic heat pipe as recited in claim **7**, wherein at least one nanostructure comprises at least one layer of nanoparticles.

9. The monolithic heat pipe as recited in claim **7**, wherein the microstructures are less than at least approximately one hundred micrometers (100 μm) in depth.

10. The monolithic heat pipe as recited in claim **7**, wherein the nanostructures are less than at least approximately ten micrometers (10 μm) in total thickness.

11. The monolithic heat pipe as recited in claim **7**, wherein the container wall and the second container wall are joined together with at least one of laser welding or electron beam welding (EBW).

12. The monolithic heat pipe of claim **7**, wherein the at least one channel protrudes into the interior surface of the container wall.

13. A monolithic heat-transfer structure configured to retain a working fluid, wherein the monolithic structure comprises:

an interior surface configured to be in fluid communication with the working fluid; and

one or more channels disposed in, and protruding into, the interior surface of the monolithic structure, the one or more channels each including a functionalized surface comprising a plurality of microstructures and a plurality of nanostructures;

wherein the monolithic structure comprises a base material and the plurality of microstructures and the plurality of nanostructures comprise a sintered oxide of the base material; and

wherein the plurality of microstructures and the plurality of nanostructures are materially contiguous with the base material of the monolithic structure.

14. The monolithic heat-transfer structure of claim **13**, wherein at least one of the one or more channels protrudes into the interior surface angled relative to a normal to the interior surface.

15. The monolithic heat-transfer structure of claim **13**, wherein at least one nanostructure of the plurality of nanostructures in at least one channel comprises at least one layer of nanoparticles.

16. The monolithic heat-transfer structure of claim **13**, wherein the plurality of microstructures in each of the one or more channels are each less than at least approximately one hundred micrometers (100 μm) in depth.

17. The monolithic heat-transfer structure of claim **13**, wherein the plurality of nanostructures in each of the one or more channels are each less than at least approximately ten micrometers (10 μm) in total thickness.

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