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DeSteese et al.

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(54) **STRUCTURE AND METHOD FOR CONTROLLING THE THERMAL EMISSIVITY OF A RADIATING OBJECT**

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(51) **Int. Cl.**[7] **G21R 1/00**; F02R 9/64; F28F 13/18; B64G 1/26; H01L 23/36

(52) **U.S. Cl.** **250/505.1**; 250/492.1; 250/493.1; 250/494.1; 250/503.1; 165/133

(58) **Field of Search** 250/492.1, 493.1, 250/494.1, 503.1, 505.1; 165/133, 169, 904; 60/266, 39.5

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Ohnstein, T.R., et al (Tunable IR Filters With Integral Electromagnetic Actuators, Solid State Sensor and Actuator Workshop Proceedings, 1996, pp 196–199, Hilton Head, SC).

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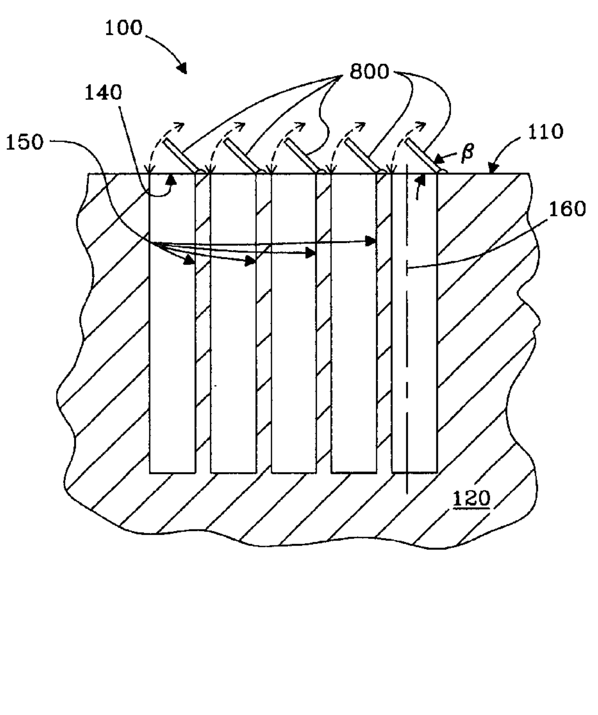
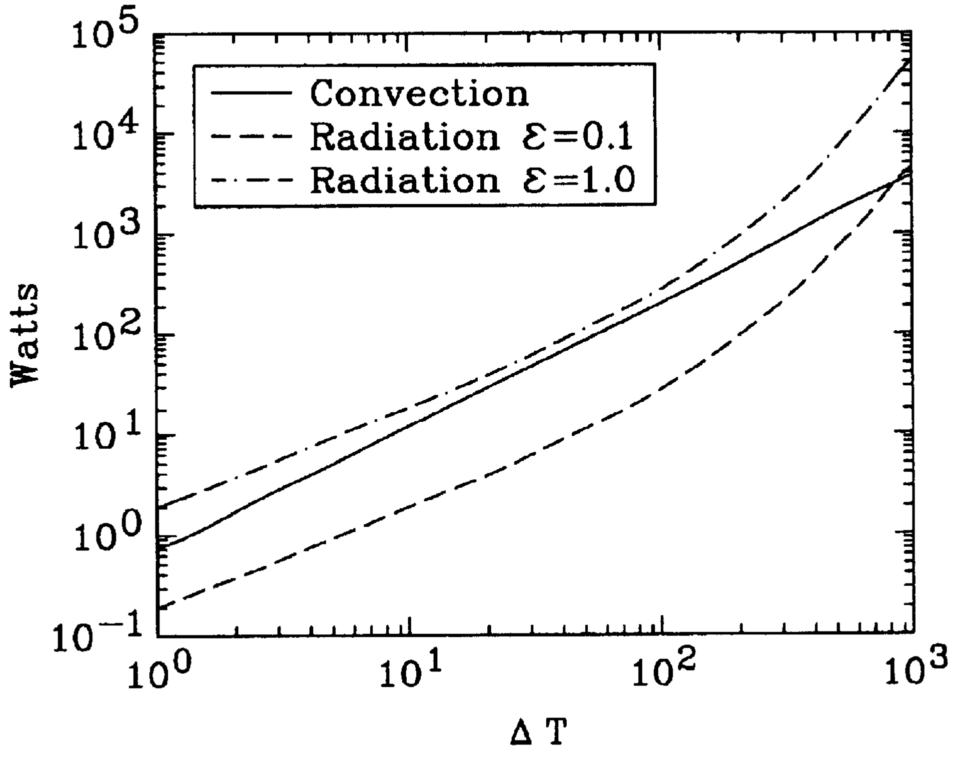
(57) **ABSTRACT**

A structure and method for changing or controlling the thermal emissivity of the surface of an object in situ, and thus, changing or controlling the radiative heat transfer between the object and its environment in situ, is disclosed. Changing or controlling the degree of blackbody behavior of the object is accomplished by changing or controlling certain physical characteristics of a cavity structure on the surface of the object. The cavity structure, defining a plurality of cavities, may be formed by selectively removing material(s) from the surface, selectively adding a material(s) to the surface, or adding an engineered article(s) to the surface to form a new radiative surface. The physical characteristics of the cavity structure that are changed or controlled include cavity area aspect ratio, cavity longitudinal axis orientation, and combinations thereof. Controlling the cavity area aspect ratio may be by controlling the size of the cavity surface area, the size of the cavity aperture area, or a combination thereof. The cavity structure may contain a gas, liquid, or solid that further enhances radiative heat transfer control and/or improves other properties of the object while in service.

35 Claims, 14 Drawing Sheets





Convection
Radiation ε=0.1
Radiation ε=1.0
Watts
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
10^0
10^1
10^2
10^3
Δ T

Fig. 1

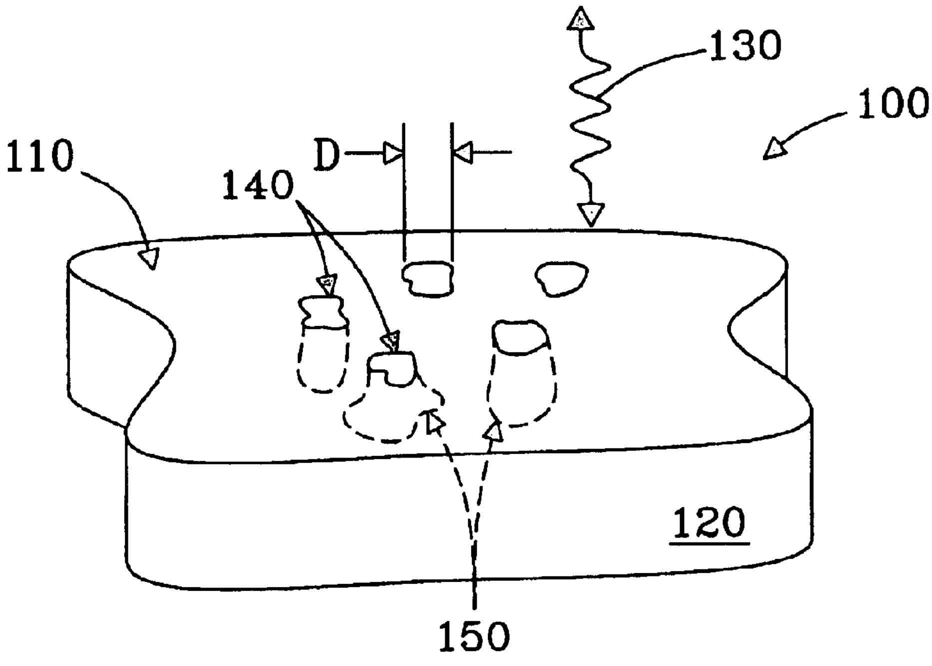


Fig. 2

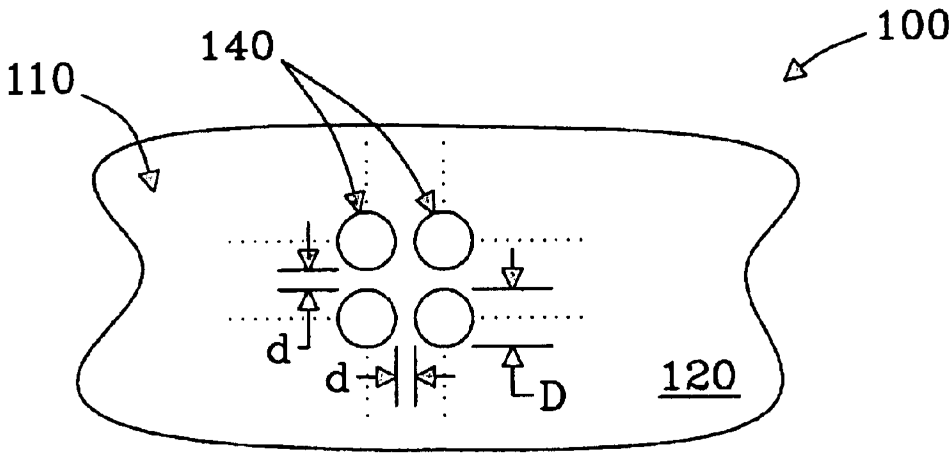


Fig. 3

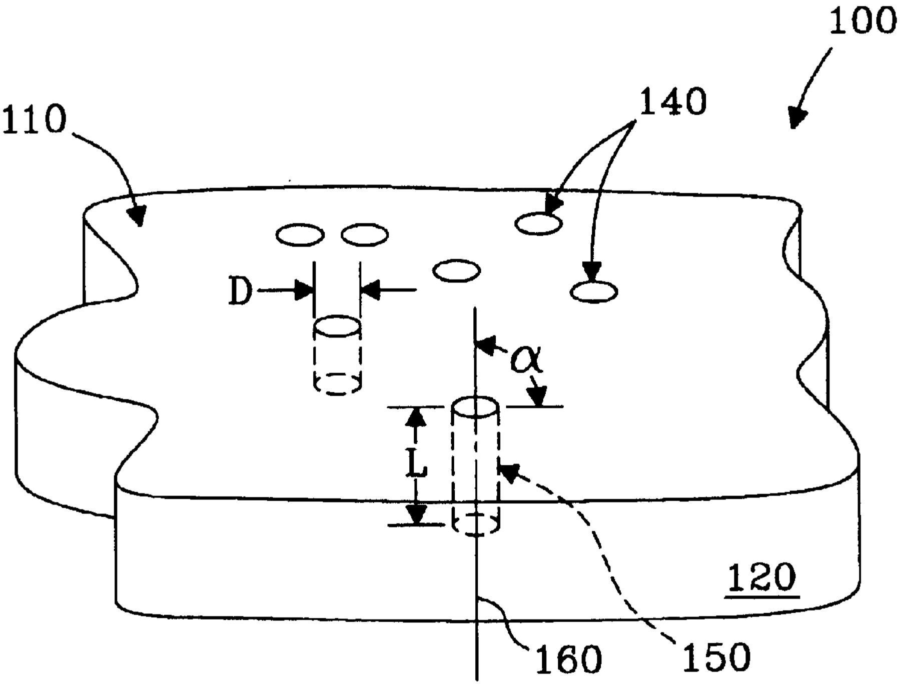


Fig. 4a

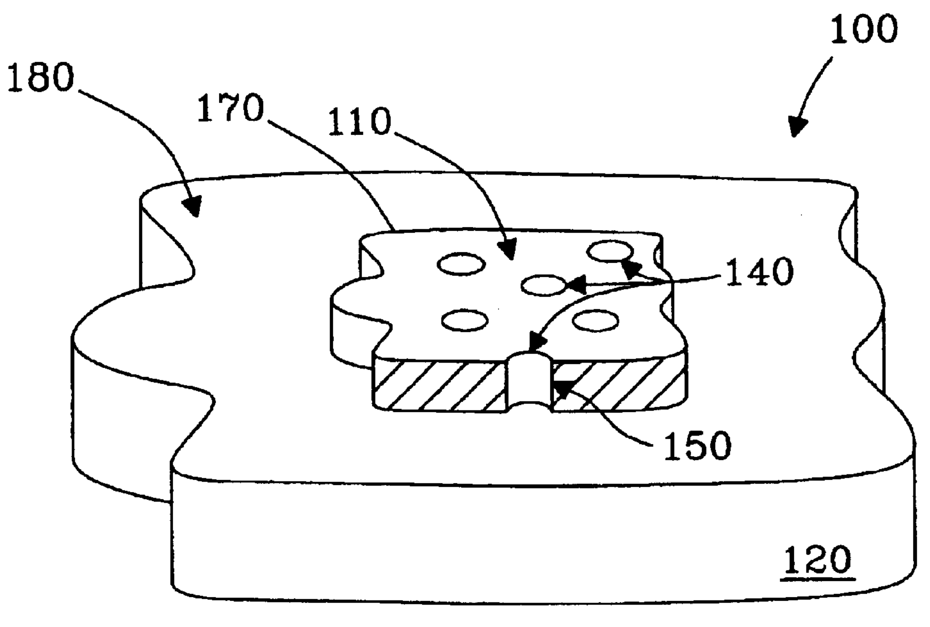
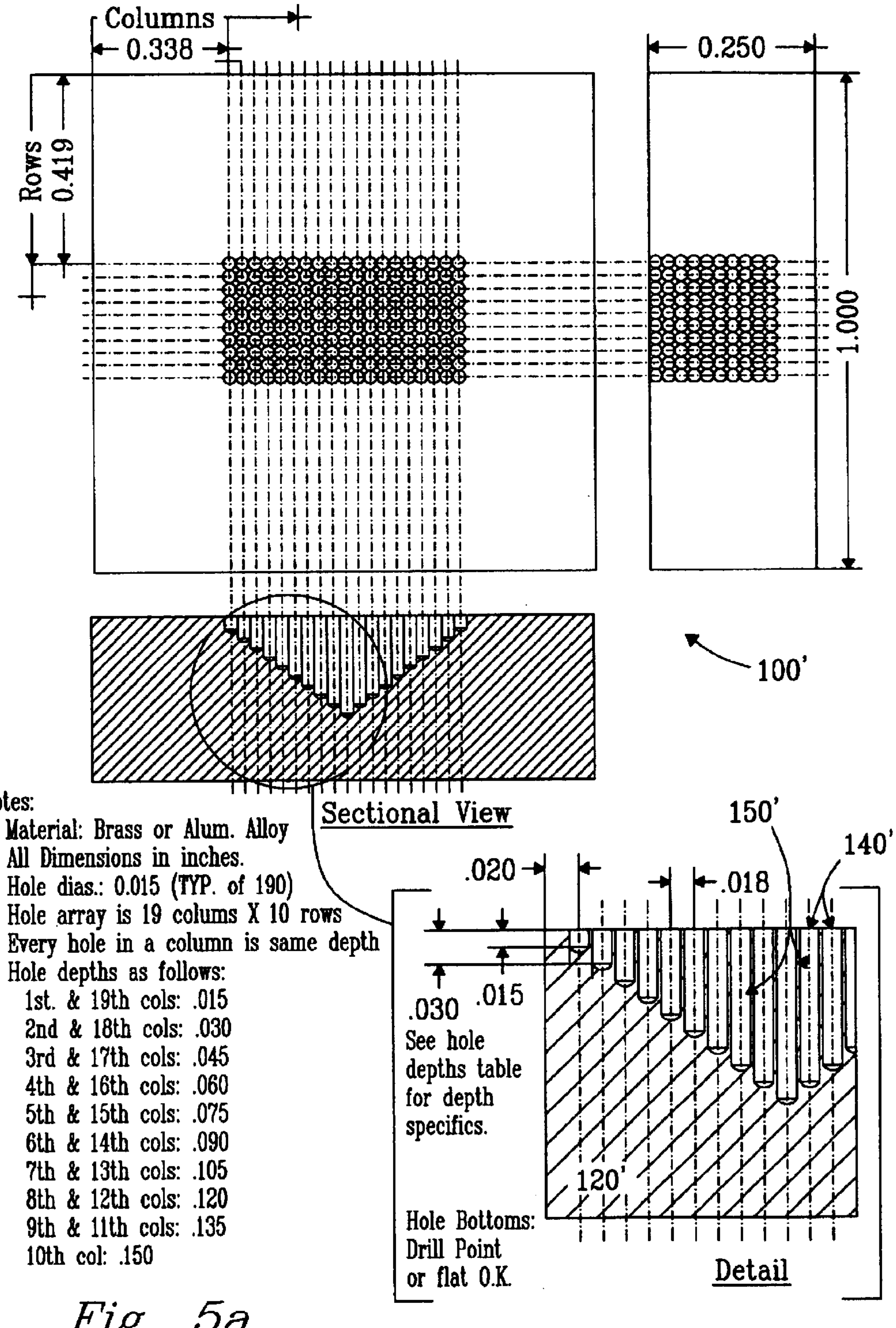


Fig. 4b



Notes:
1. Material: Brass or Alum. Alloy
2. All Dimensions in inches.
3. Hole dias.: 0.015 (TYP. of 190)
4. Hole array is 19 colums X 10 rows
5. Every hole in a column is same depth
6. Hole depths as follows:
   - 1st. & 19th cols: .015
   - 2nd & 18th cols: .030
   - 3rd & 17th cols: .045
   - 4th & 16th cols: .060
   - 5th & 15th cols: .075
   - 6th & 14th cols: .090
   - 7th & 13th cols: .105
   - 8th & 12th cols: .120
   - 9th & 11th cols: .135
   - 10th col: .150

Fig. 5a

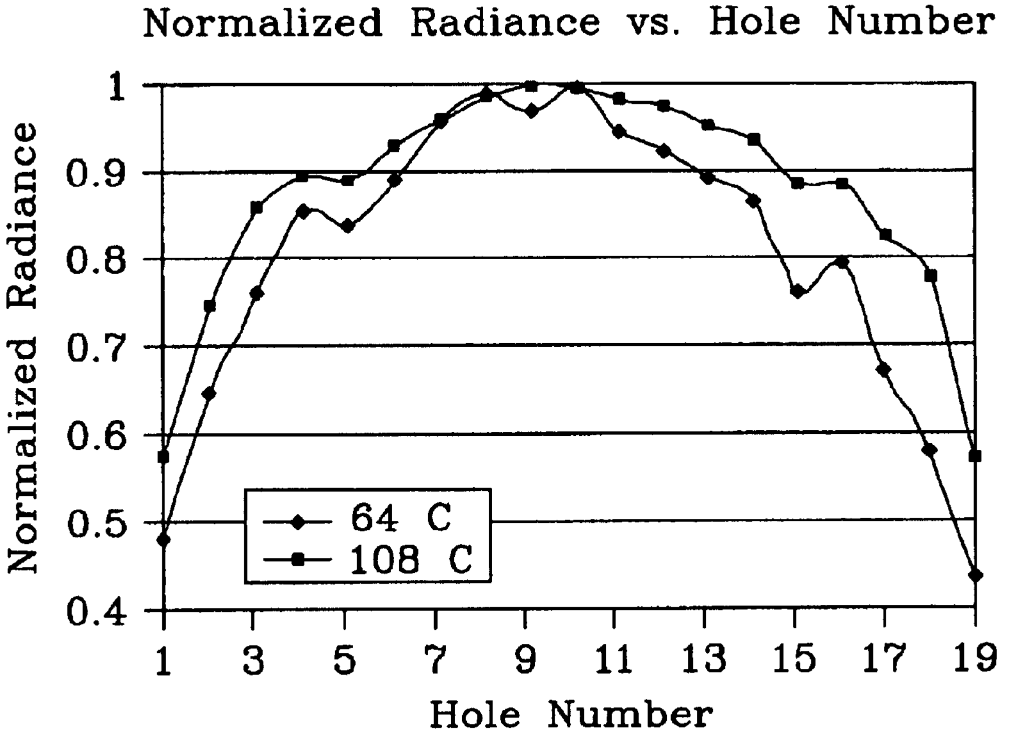
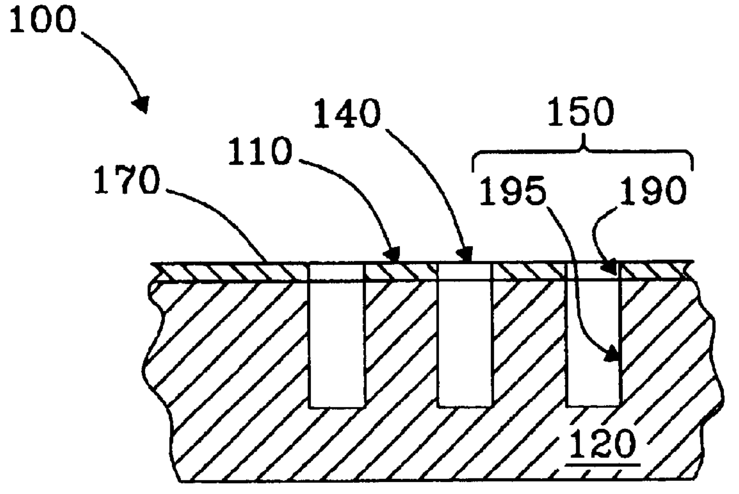
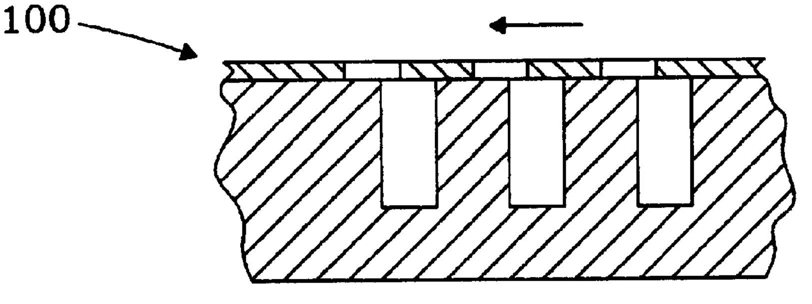

Normalized Radiance vs. Hole Number
Normalized Radiance
1
0.9
0.8
0.7
0.6
0.5
0.4
1 3 5 7 9 11 13 15 17 19
Hole Number
64 C
108 C

Fig. 5b



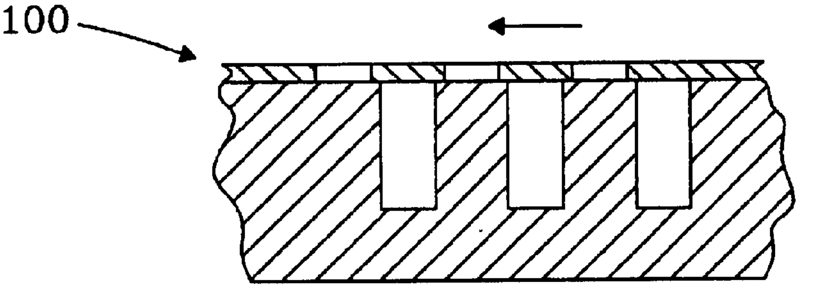
High Emissivity State

Fig. 6a



Intermediate Emissivity State

Fig. 6b



Low Emissivity State

Fig. 6c

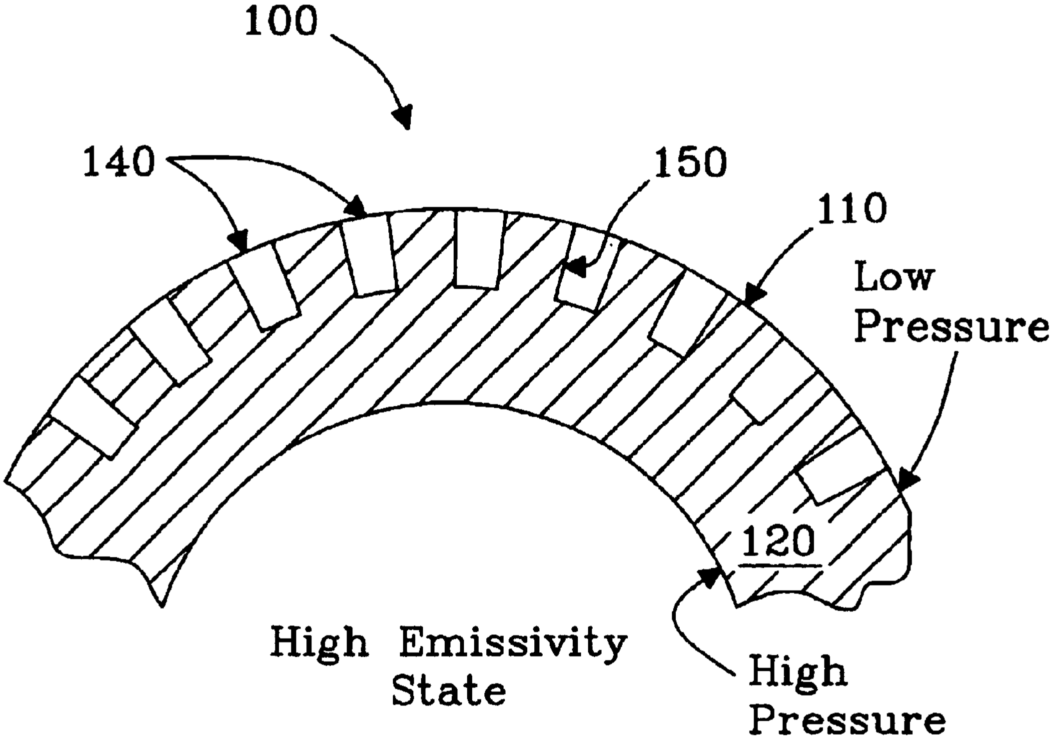

100
140
150
110
Low
Pressure
120
High Emissivity
State
High
Pressure

Fig. 7a

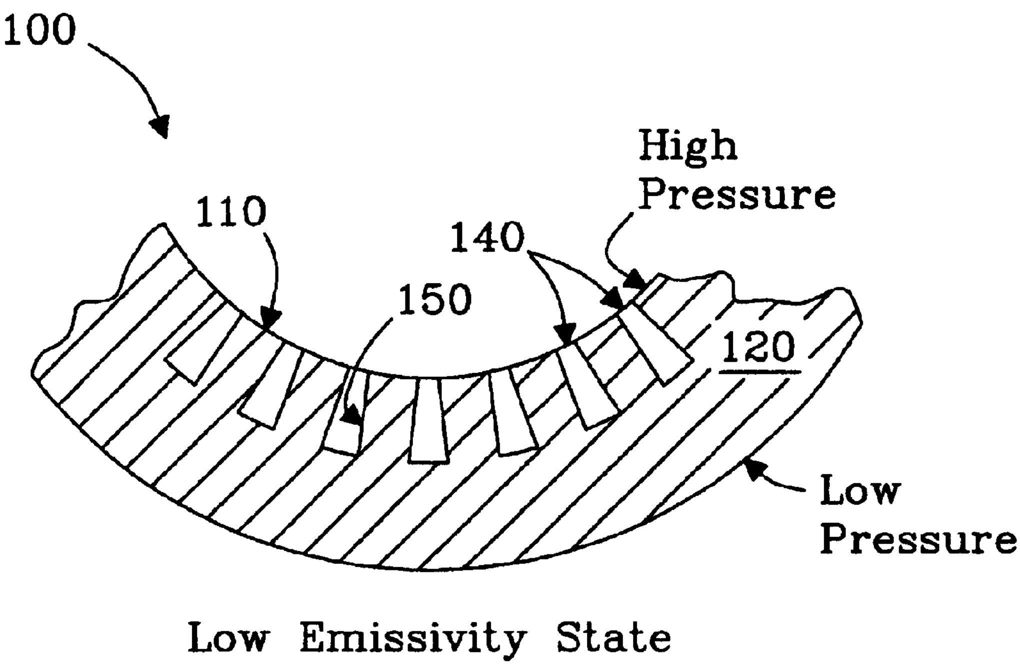

100
High
Pressure
110
140
150
120
Low
Pressure
Low Emissivity State

Fig. 7b

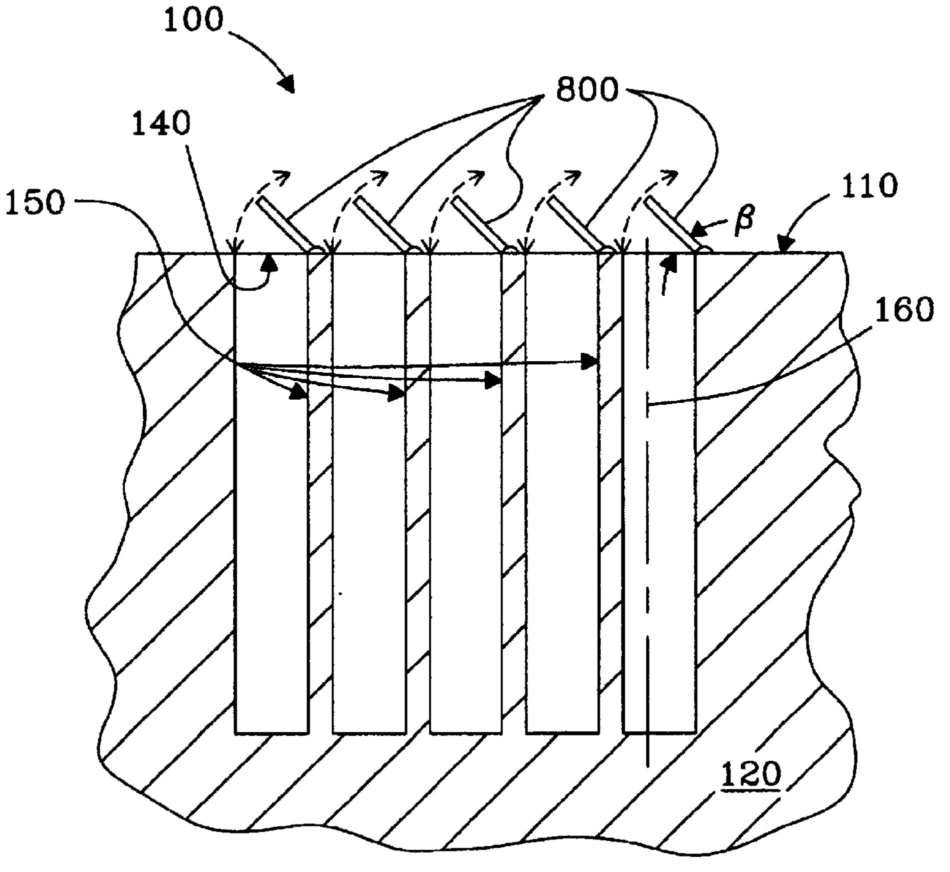


Fig. 8a

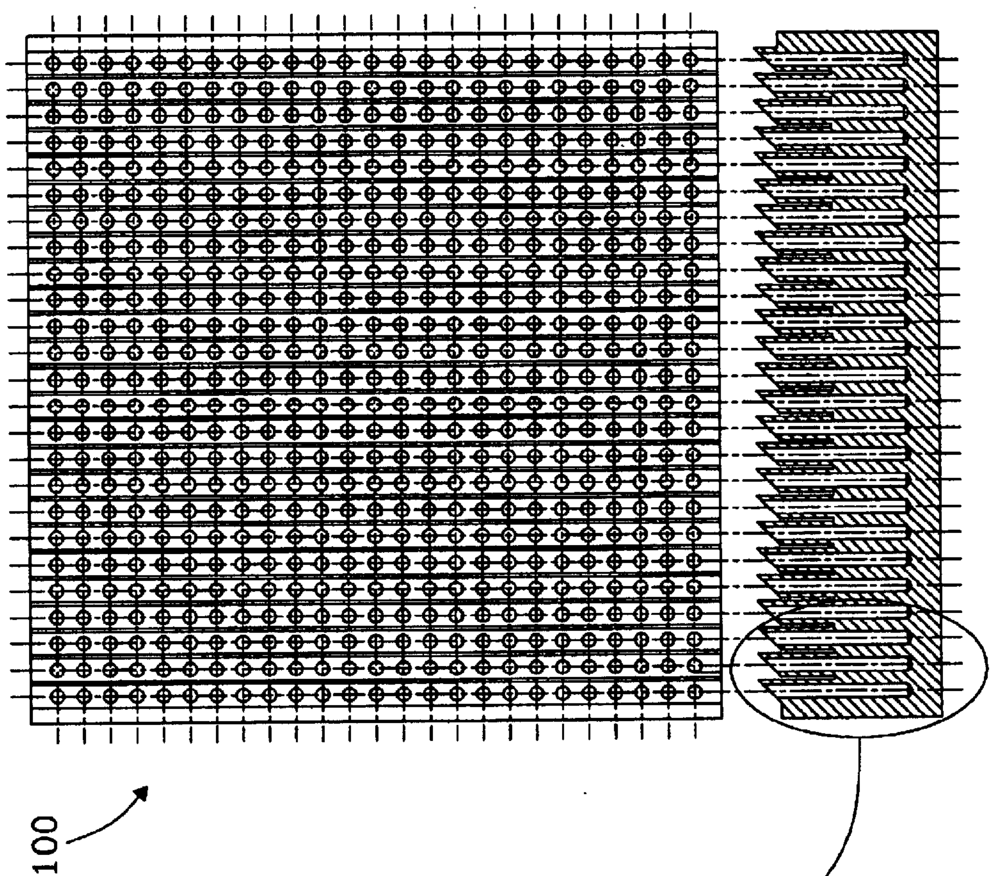


Fig. 8b

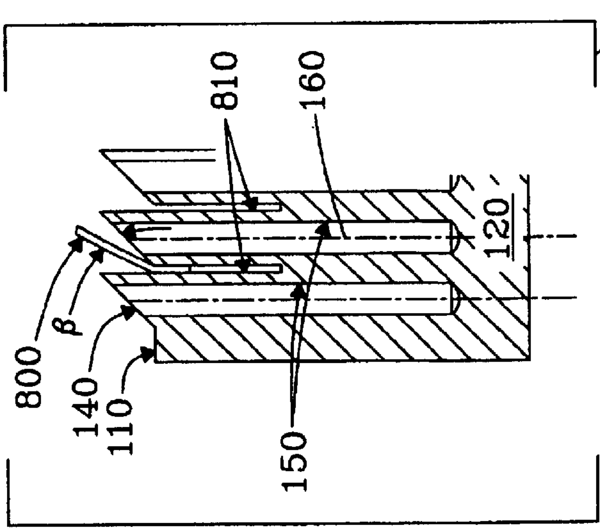
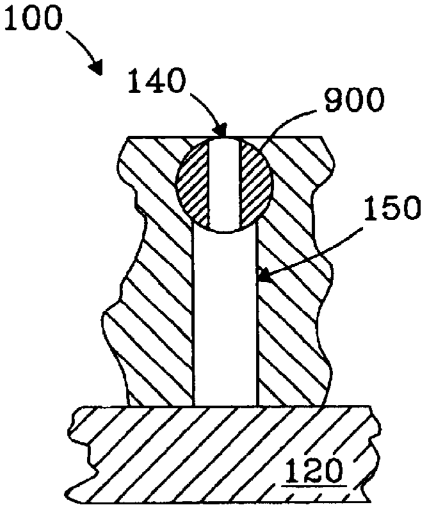
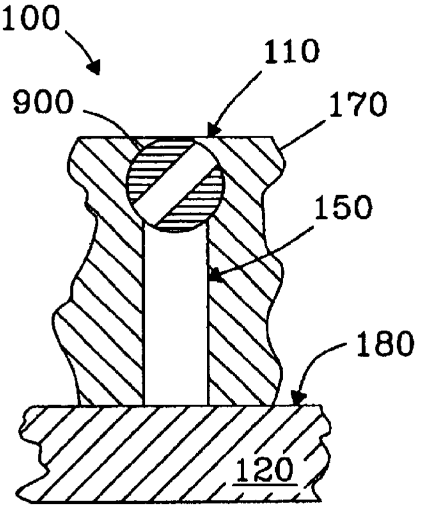


Fig. 8c



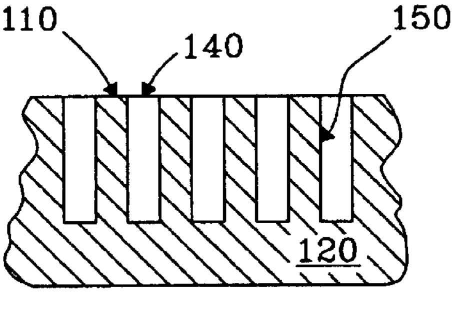
High Emissivity State

Fig. 9a



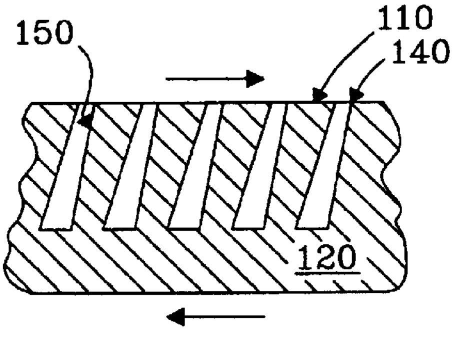
Low Emissivity State

Fig. 9b



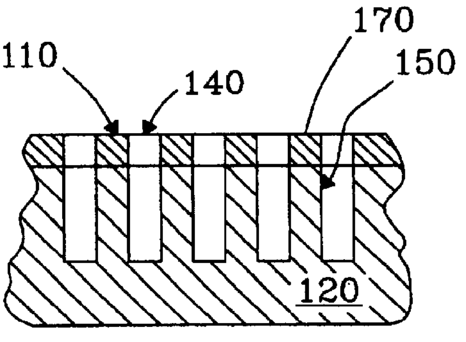
High Emissivity State

Fig. 10a



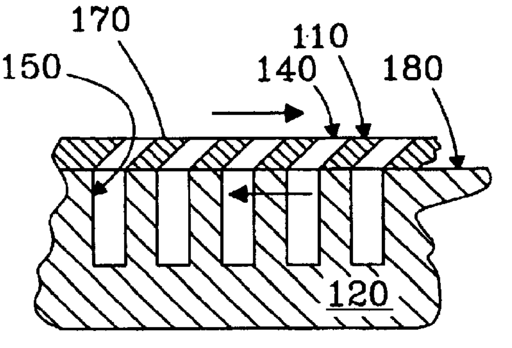
Low Emissivity State

Fig. 10b



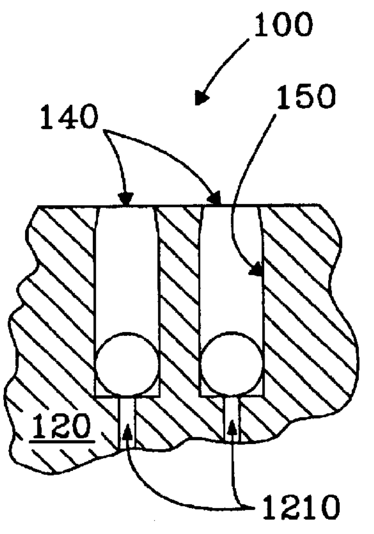
High Emissivity State

Fig. 11a



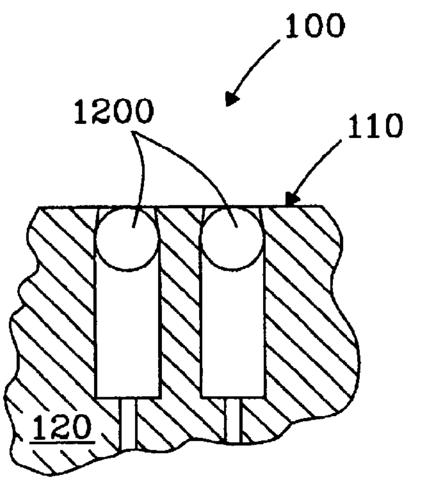
Low Emissivity State

Fig. 11b



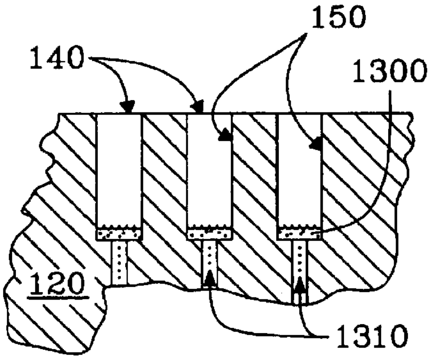
High Emissivity State

Fig. 12a



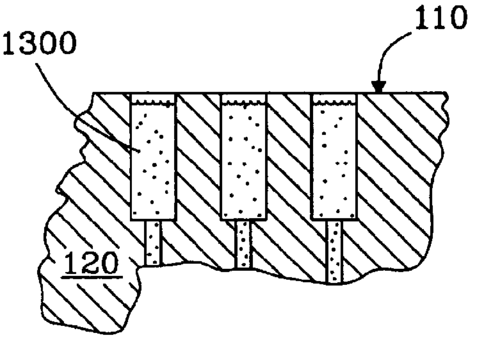
Low Emissivity State

Fig. 12b



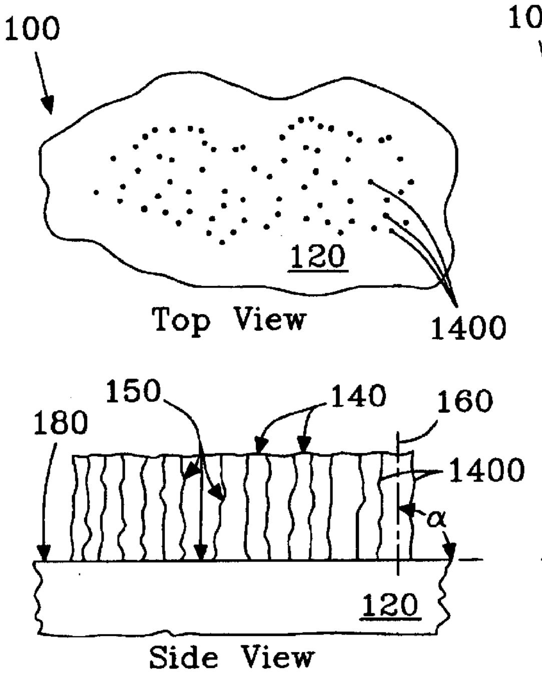
High Emissivity State

Fig. 13a



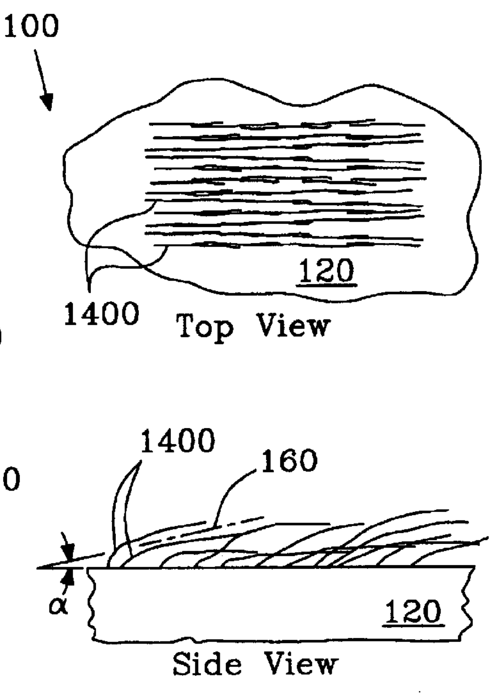
Low Emissivity State

Fig. 13b



High Emissivity State

Fig. 14a



Low Emissivity State

Fig. 14b

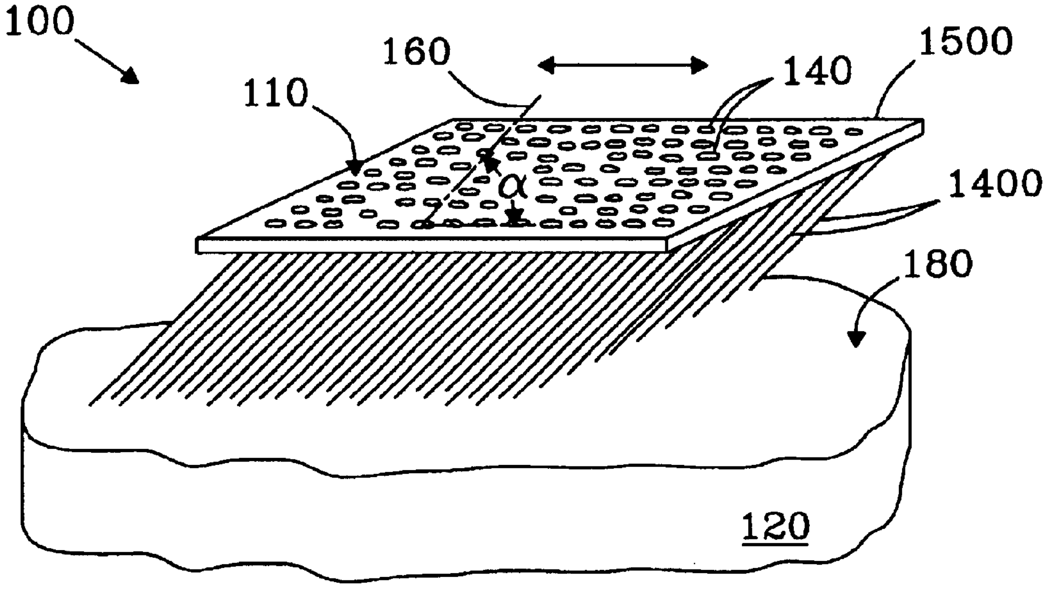
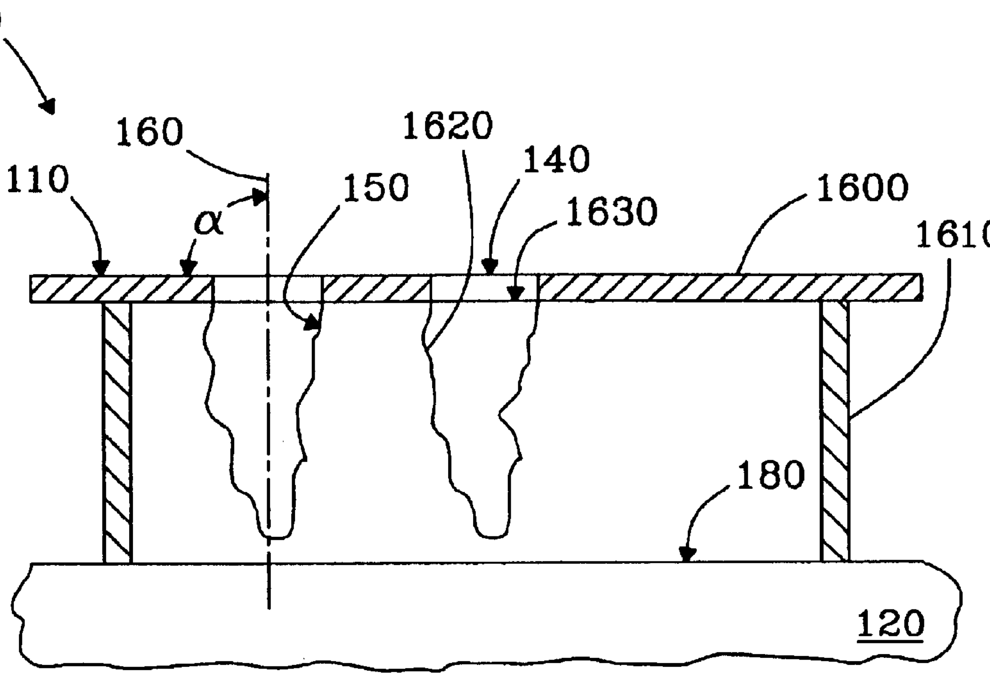
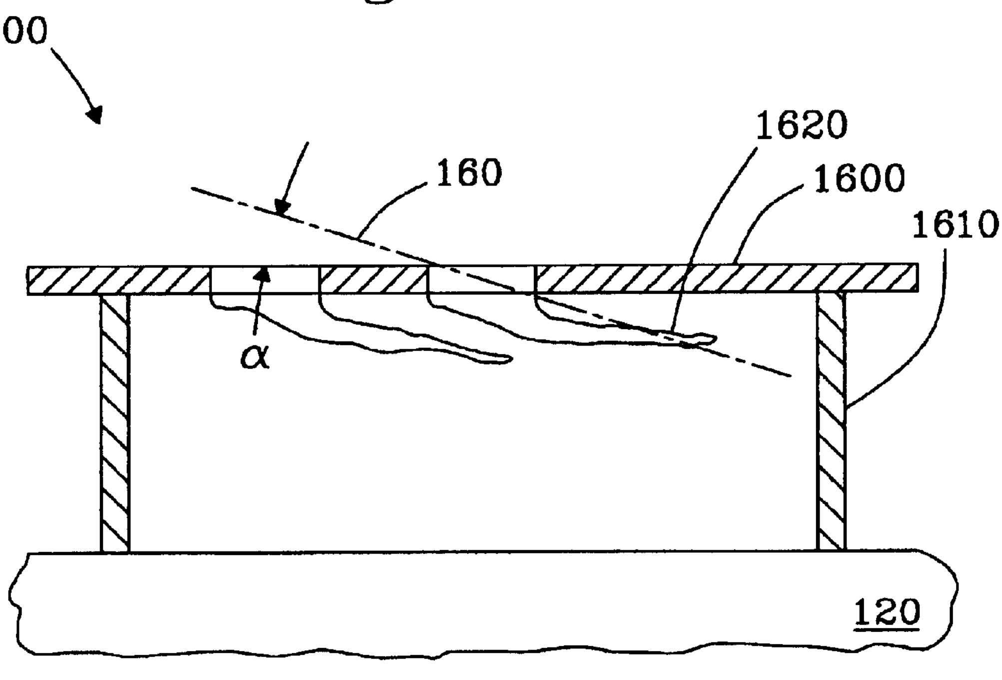


Fig. 15



High Emissivity State

Fig. 16a



Low Emissivity State

Fig. 16b

STRUCTURE AND METHOD FOR CONTROLLING THE THERMAL EMISSIVITY OF A RADIATING OBJECT

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

This invention was made with Government support under Contract DE-AC0676RLO1830 awarded by the U.S. Department of Energy. The Government has certain rights in the invention.

FIELD OF THE INVENTION

The present invention relates to a structure and method for changing or controlling the thermal emissivity of the surface of a radiating object in situ, and thus, for changing or controlling the radiative heat transfer between the object and its environment in situ. More particularly, changing or controlling the degree of blackbody behavior of the object is accomplished by changing or controlling certain physical characteristics of a structure defining a plurality of cavities on the surface of the object. As described herein, this cavity structure may be integral to the radiating object or added to the surface of the object to form a new radiating surface.

BACKGROUND OF THE INVENTION

Heat transfer between an object and its environment is achieved by up to three main processes: conduction, convection, and radiation. While conduction occurs at solid/solid and solid/fluid interfaces, the principal means of transferring heat into or out of many systems is by a combination of convective media and radiation. Terrestrial system designs typically exploit both convective and radiative heat transfer, however, heat management in many space (i.e., extraterrestrial) systems relies essentially on radiation because of the lack of a convective medium.

Convective heat transfer is provided by the natural or forced flow of a fluid over the surface of an object and can be controlled by changing parameters such as the fluid medium and/or its physical properties, flow rate, and surface roughness. In contrast, radiative heat transfer depends on the degree of blackbody behavior exhibited by the surface and the fourth power of surface temperature. Thermal energy radiated by a surface is expressed by the Stefan-Boltzmann equation:

$$Q_{rad}=A\sigma\epsilon(T_b^4-T_a^4) \tag{1}$$

where

Q_{rad}=thermal power radiated (W)

A=area of radiating surface (m^2)

σ=the Stefan-Boltzmann Constant ($5.67\times10^{-8}W/m^2/K^4$)

ε=thermal emissivity factor of radiating surface

T_b=temperature of the radiating surface (K)

T_a=ambient temperature (K)

The thermal emissivity factor (ε) is the ratio of an object's radiative emission efficiency to that of a perfect radiator, also called a blackbody. The thermal emissivity factor of most materials ranges between 0.05 and 0.95 and is relatively constant over a significant temperature range. Therefore, the radiative heat transfer capability of an object is typically a predetermined, monotonic function of its temperature raised to the fourth power.

The following example illustrates the expected impact of changing the thermal emissivity, or degree of blackbody behavior, of an object that is transferring heat by free

convection and radiation. In this example, the reference object is a horizontal cylinder 1 m long with a 10 cm outer diameter, rejecting heat to a 300K environment through free convection and radiation. A simplified equation for the laminar flow convective heat transfer coefficient, h, for the object is:

$$h=1.32(\Delta T/D_c)^{0.25} \tag{2}$$

(Holman, J. P., Heat Transfer, Sixth Edition, McGraw-Hill) where

ΔT=temperature difference between surface and ambient (K)

D_c=diameter of cylinder (m)

Heat transferred by convection (Q_{conv}) is expressed by:

$$Q_{conv}=hA(T_b-T_a) \tag{3}$$

where A, T_b, and T_a are the same variables as in Equation 1.

FIG. **1** shows the amount of heat rejected from the reference object by convection and radiation using Equations 1 and 3, respectively, over a ΔT range of 1–1000 K, which covers a principal range of engineering interest. This figure shows the convection term (Q_{conv}) to be approximately an order of magnitude larger than radiation (Q_{rad}) from a surface with ε=0.1 for ΔT up to about 100 K. Beyond this temperature, the T^4 dependence of radiation increases more rapidly, making the two modes of heat transfer approximately equal when ΔT approaches 1000 K. In contrast, radiation from a surface exhibiting ideal blackbody behavior (i.e., ε=1.0) is always greater than convection and is at least an order of magnitude larger when ΔT is near or above 1000 K. More importantly, FIG. **1** illustrates the potential impact on the heat transfer capability of the reference object as the thermal emissivity of its surface changes, by changing the thermal emissivity factor from ε=1.0 to ε=0.1, and vice versa.

Thus, the ability to change or control the degree of blackbody behavior of a radiating object, while it is in service (i.e., in situ), analogous to changing or controlling the convective term in a fluid system during operation by altering the flow rate of the fluid, would enable a remarkable improvement in the thermal design and control of many systems where radiative heat transfer is important. For example, the surface of an object or system with controllable thermal emissivity could be activated at some limiting temperature as a thermal safety valve. In this mode of operation, the surface would be triggered to switch to a higher thermal emissivity that, in turn, radiates more heat to prevent the temperature of the object or system increasing above safe limits. Similarly, switching thermal emissivity to a lower value could protect against a system operating at less than a desirable temperature limit.

In addition, changing the thermal emissivity of an object will effectively change its thermal, or infrared (IR), signature. This is especially important in detection, recognition, and camouflage applications. For example, the ability to change or control the thermal emissivity of an object provides an opportunity for an object to match its thermal emission characteristics with those of other objects or structures in its vicinity, thereby enabling an IR camouflage effect.

In current systems where radiative heat transfer is important, the surface material and/or surface preparation of a radiating object is carefully selected to obtain the desired fixed thermal emissivity and resulting radiative heat transfer characteristic. Typical surface preparations include a variety of coating, etching, and polishing techniques. Etching techniques are also being used to create fixed surface textures for spectroscopic applications. For example, Ion Optics Inc. (Waltham, Mass.) has developed tuned infrared sources using ion beam etching processes that create a random fixed surface texture consisting of sub-micron rods and cones (http://www.ion-optics.com). Such a surface texture has a high emissivity over a narrow band of wavelengths and low emissivity in other bands and is an attractive alternative to IR light-emitting diodes.

Applying the emerging field of solid state microelectromechanical technology, tunable IR filters for IR spectral analysis are also being developed. An example of such a device is reported by Ohnstein, T. R., et al ("Tunable IR Filters With Integral Electromagnetic Actuators," Solid State Sensor and Actuator Workshop Proceedings, 1996, pp 196–199, Hilton Head, S.C.). Such tunable IR filters comprise arrays of waveguides whose transmittance can be varied by changing the spacing between them using linear actuators. The wavelength cutoff range from 8 μm to 32 μm achieved by Ohnstein et al with this technology is typical of its narrowband selectivity. Such IR spectral analysis devices, like the devices developed by Ion Optics, Inc., are purposely designed with surface microstructures having dimensions comparable to specific wavelengths in the electromagnetic spectrum to be effective at wavelengths that are discrete or in narrow bandwidths. Consequently, these devices are ineffective for applications which require the changing or controlling of broader ranges of wavelengths important in radiative heat transfer.

Accordingly, there is a need for a capability to change or control broadband radiative heat transfer between an object and its environment while the object is in service.

BRIEF SUMMARY OF THE INVENTION

The present invention provides a structure and method for changing or controlling the thermal emissivity of the surface of an object in situ, and thus, changing or controlling the radiative heat transfer between the object and its environment in situ. Changing or controlling the degree of blackbody behavior of the object is accomplished by changing or controlling certain physical characteristics of a cavity structure on the surface of the object. The cavity structure, defining a plurality of cavities, may be formed by selectively removing material(s) from the surface, selectively adding a material(s) to the surface, or adding an engineered article(s) to the surface to form a new radiative surface.

The physical characteristics of the cavity structure that are changed or controlled in accordance with the present invention include cavity area aspect ratio, cavity longitudinal axis orientation, and combinations thereof. Controlling the cavity area aspect ratio may be performed by controlling the size of the cavity surface area, the size of the cavity aperture area, or a combination thereof. As described herein, the cavity structure may contain a gas, liquid, or solid that further enhances radiative heat transfer control and/or improves other properties of the object, for example surface finish, while in service.

The subject matter of the present invention is particularly disclosed and distinctly claimed in the concluding portion of this specification. However, both the organization and method of operation, together with further advantages and objects thereof, may best be understood by reference to the following description and examples taken in connection with accompanying drawings wherein like reference characters refer to like elements.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** illustrates the temperature dependence of convective and radiative heat transfer at two extreme values of the thermal emissivity factor at temperatures between 1 and 1000 K;

FIG. **2** illustrates a simplified representation of a cavity structure;

FIG. **3** shows the top view of one example of a cavity structure defining a plurality of cavities and a geometric array of cavity apertures with circular shapes;

FIG. **4***a* illustrates an example of a cavity structure defining a plurality of cylindrically-shaped cavity surfaces having cavity longitudinal axes oriented relative to the radiative surface;

FIG. **4***b* illustrates an alternative mode of obtaining a cavity structure, similar to that of FIG. **4***a*, by the addition of a cavity article on the surface of the object;

FIG. **5***a* illustrates a test cavity structure used to determine the effect of cavity area aspect ratio on radiative heat transfer from the structure;

FIG. **5***b* graphically depicts the radiance as a function of hole number (i.e., cavity area aspect ratio) in the test cavity structure of FIG. **5***a* at two operating temperatures;

FIGS. **6***a*–**6***c* illustrate an embodiment of the present invention whereby the degree of blackbody behavior (i.e., thermal emissivity) of the cavity structure is changed from a high emissivity state (FIG. **6***a*), to an intermediate emissivity state (FIG. **6***b*), and then to a low emissivity state (FIG. **6***c*), by changing the cavity area aspect ratio (i.e., by changing A_a) by translational movement of a cavity article relative to the object;

FIGS. **7***a*–**7***b* illustrate an embodiment of the present invention whereby the degree of blackbody behavior (i.e., thermal emissivity) of the cavity structure is changed from a high emissivity state (FIG. **7***a*) to a low emissivity state (FIG. **7***b*) by changing the cavity area aspect ratio (i.e., by changing A_a) by the application of tensile or compressive forces resulting from pressure differences across the object;

FIG. **8***a* illustrates another embodiment of the present invention whereby the degree of blackbody behavior (i.e., thermal emissivity) of the cavity structure is changed by changing the cavity area aspect ratio (i.e., by changing A_a) by the movement of caps over the cavity apertures;

FIGS. **8***b*–**8***c* illustrate another embodiment of the present invention, similar to that of FIG. **8***a*, whereby the caps and cavity structure are designed so as to produce thermal emissivity changes with less cap movement than that of the embodiment shown in FIG. **8***a;*

FIGS. **9***a*–**9***b* illustrate another embodiment of the present invention whereby the degree of blackbody behavior (i.e., thermal emissivity) of the cavity structure is changed from high emissivity state (FIG. **9***a*) to a low emissivity state (FIG. **9***b*) by changing the cavity area aspect ratio (i.e., by changing A_a) by the rotation of a shutter;

FIGS. **10***a*–**10***b* illustrate another embodiment of the present invention whereby the degree of blackbody behavior (i.e., thermal emissivity) of the cavity structure is changed from a high emissivity state (FIG. **10***a*) to a low emissivity state (FIG. **10***b*) by changing the cavity area aspect ratio (i.e., by changing A_a) by the application of a shear force on the object;

FIGS. **11***a*–**11***b* illustrate another embodiment of the present invention whereby the degree of blackbody behavior (i.e., thermal emissivity) of the cavity structure is changed from a high emissivity state (FIG. **11***a*) to a low emissivity state (FIG. **11***b*) by changing the cavity area aspect ratio (i.e., by changing A_a) by the application of a shear force on a cavity article rigidly attached to the surface of the object;

FIGS. **12***a*–**12***b* illustrate another embodiment of the present invention whereby the degree of blackbody behavior (i.e., thermal emissivity) of the cavity structure is changed from a high emissivity state (FIG. **12***a*) to a low emissivity state (FIG. **12***b*) by changing the cavity area aspect ratio (i.e., by changing A_c) by the movement of a block within the cavity structure;

FIGS. **13***a*–**13***b* illustrate another embodiment of the present invention whereby the degree of blackbody behavior (i.e., thermal emissivity) of the cavity structure is changed from a high emissivity state (FIG. **13***a*) to a low emissivity state (FIG. **13***b*) by changing the cavity area aspect ratio (i.e., by changing A_c) by the raising of the level of a selector within the cavity structure;

FIGS. **14***a*–**14***b* illustrate another embodiment of the present invention whereby the cavity structure is a fiber mat and the degree of blackbody behavior (i.e., thermal emissivity) of the cavity structure is changed from a high emissivity state (FIG. **14***a*) to a low emissivity state (FIG. **14***b*) by changing the orientation of the cavity longitudinal axes;

FIG. **15** illustrates another mode of changing the orientation of the cavity longitudinal axes of a cavity structure similar to that of FIGS. **14***a*–**14***b*; and

FIGS. **16***a*–**16***b* illustrate another embodiment of the present invention whereby the cavity structure comprises bladders and the degree of blackbody behavior (i.e., thermal emissivity) of the cavity structure is changed from a high emissivity state (FIG. **16***a*) to a low emissivity state (FIG. **16***b*) by changing the orientation of the cavity longitudinal axes.

DETAILED DESCRIPTION OF THE INVENTION

An aspect of the present invention is a structure on the surface of an object wherein the structure defines a geometric or random array of cavities open to the environment, for example pits, thru-holes, closed-end holes, and the like. The structure may be formed by selectively removing material(s) from the surface, selectively adding a material(s) to the surface, or adding an engineered article(s) to the surface to form a new radiative surface. The structure may be similar to closed-cell or open-cell foams in the regard that the cavities may be physically separated from other cavities or may be interconnected with one or more other cavities. The structure may be formed by a suitable mechanical, chemical, electrical, or biological process including but not limited to drilling, pressing, coining, etching, lithography, irradiation, laser ablation, vapor deposition, explosive forming, spallation, bacterial, enzyme and viral action, and combinations thereof. It is to be understood that this list of processes, and others disclosed herein, are exemplary only and that those skilled in this art will appreciate that the present invention is not limited to a particular method of forming a structure defining a plurality of cavities.

A purpose of the following FIGS. **2**–**5** is to provide a basis for terminology used herein to describe the structure defining a plurality of cavities. FIGS. **6**–**16** illustrate various embodiments of the present invention whereby the degree of blackbody behavior of an object (i.e., thermal emissivity) can be changed or controlled using such a structure.

FIG. **2** illustrates a simplified representation of a cavity structure **100** comprising a radiative surface **110** of an object **120** wherein the cavity structure **100** defines a plurality of cavities open to the environment with which the object **120** is transferring radiant energy **130**. In particular, the cavity structure **100** defines a plurality of cavity apertures **140** at the radiative surface **110**, each with a cross-sectional area A_a and an effective diameter D equal to $2\times(A_a/\pi)^{1/2}$, and a plurality of cavity surfaces **150**, each with a cavity surface area A_c. The cavity area aspect ratio R is defined as A_c/A_a. The cavity apertures **140** (and cavity surfaces **150**) are not necessarily the same size and shape for a given cavity structure **100**. As is known to those skilled in the art, the cavity apertures **140** and cavity surfaces **150** may be any size and shape, including those that define slots, consistent with (1) the theory behind blackbody behavior of cavities (e.g., Chapter 3 of Wolfe, W. L., 1965, Handbook of Military Infrared Technology, Office of Naval Research, Department of the Navy, Washington, D.C.), (2) the desired range of thermal emissivity control of the cavity structure **100**, and (3) other desired surface properties of the cavity structure **100**, for example surface finish or roughness.

The number and density of cavity apertures **140** and cavity surfaces **150** are variable and depends on the desired degree of blackbody behavior of the cavity structure **100** and desired degree of radiative control. Measurable thermal emissivity changes were obtained with the present invention when the cumulative sum of the cross-section areas of the cavity apertures **140** (i.e., ΣA_a) was as low as 20% of the object's surface (i.e., the ratio of total cavity aperture area, ΣA_a, to the area of the radiative surface **110** was 1:4). In most engineered systems, however, it is typically desirable to have a higher percentage of the object's surface occupied by cavity apertures **140** and cavity surfaces **150** so that a larger range of radiative control is obtained.

FIG. **3** shows the top view of an example of a cavity structure **100**, comprising the radiative surface **110** of an object **120**, and defining a dense array of cavity apertures **140** with circular shapes (the cavity surfaces **150** below the cavity apertures **140** are not shown for clarity). In this example, the cavity apertures **140** have an effective diameter D (equal to the diameter of the cavity apertures **140**) centered on a square pitch array with the thinnest section of wall of the cavity structure **100** between adjacent cavity apertures **140** designated by the minimum wall thickness d. Choosing a minimum wall thickness d equal to about 0.08D provides the following ratio of total cavity aperture area, ΣA_a, to the area of the radiative surface **110** (i.e., surface area unoccupied by cavity apertures **140** and excluding ΣA_c):

$$0.25\pi D^2:[(1.08D)^2-0.257\pi D^2]\cong 2:1$$

The cavity structure **100** in FIG. **3** will increase the radiative heat transfer capability of the object **120** (relative to an unaltered object surface) proportional to the sum of the respective $A\epsilon$ terms in Equation 1. In this example, if $\epsilon=0.1$ for the radiative surface **110** (i.e., the object surface unoccupied by cavity apertures) and the cavities represent blackbodies (i.e., $\epsilon=1.0$), the cavity structure **100** enhances the radiative power of the object **120** by a factor of:

$$(2\times 1+1\times 0.1)/((2+1)\times 0.1)=7$$

The ultimate potential enhancement of radiative power by this means can closely approach that of the whole surface of the object **120** acting as a single blackbody. Both larger and smaller radiation enhancement factors will be achieved with different minimum wall thicknesses d and different emissivities of the radiative surface **110**. For example, if the cavities represent blackbodies, d=0.08, and $\epsilon=0.05$ for the radiative surface **110**, there is the potential of a nearly 15-fold enhancement, whereas having $\epsilon=0.2$ allows only a 3-fold enhancement. As will be described later, such a cavity structure **100** can be physically altered in situ to reduce the degree of blackbody behavior (and then physically altered again in situ to increase the degree of blackbody behavior) so that a range of radiative control is obtained.

The shape of the cavity aperture **140** may be any regular shape (e.g., circular, elliptical, rectangular, quadrilateral, and other polygonal shapes) or any irregular shape, although the shape will typically be limited by manufacturing and economic constraints. Effective diameters of the cavity apertures **140** in the range from about 1 μm to several 1000 μm are practical and provide the principal benefits of the present invention for most engineered systems. Larger effective diameters may be optimal for very large systems. Smaller effective diameters may be optimal for systems operating at very high temperatures. As is evident to those skilled in the art, the range of radiative heat transfer control depends upon the radiation bandwidth emitted by the object **120**. Consequently, it is preferred that the size of the cavity apertures **140** be chosen to achieve an acceptable amount of radiative heat transfer control by virtue of the temperature of the object **120**. In most applications, it is preferred that the average effective diameter of the plurality of cavity apertures **140** is at least 10 μm.

FIG. **4***a* illustrates an example of a cavity structure **100** defining a plurality of cylindrical cavity surfaces **150** (and circular cavity apertures **140**) with an effective diameter of D (equal to the diameter of the cylinder) and a depth/length of L. In this example, the cavity area aspect ratio R equals $A_c/A_a=(\pi DL+\pi D^2/4)/\pi D^2/4=4L/D+1$. When the cavity structure **110** defines closed-end holes made by drilling or boring, the bottom of the cavity surfaces **150** will typically have a shape that conforms to the machine tool used to form the cavities (e.g., a taper produced by a standard drill bit). In cases whereby the shape of the cavity surface **150** has a longitudinal axis (as conventionally defined) the orientation of such a cavity longitudinal axis **160**, relative to the radiative surface **110**, is measured by the angle α as shown in FIG. **4***a*.

FIG. **4***b* illustrates another example of a cavity structure **100**, similar to that of FIG. **4***a*, except that the cavity structure **100** in FIG. **4***b* is formed by the addition, or deposition, of a cavity article **170** to the surface **180** of the object **120** to form a new radiative surface **110**. As is evident to those skilled in the art, the cavity article **170** would typically be in contact with the object **120** in a manner to assure a good thermal bond. The cavity article **170** may be formed by a variety of material deposition techniques, including those used in semiconductor manufacture, or may comprise a separately manufactured component (e.g., a perforated plate, screen, mesh, fiber mat) that is in contact with the object **120**. Furthermore, the cavity structure **100** may be formed by combining the cavity structure **100** shown in FIG. **4***a* with the cavity article **170** shown in FIG. **4***b* such that the cavity surface **150** resides in both the object **120** and the cavity article **170**. This may be advantageous from a manufacturing perspective since boring cavities deep enough to act as blackbodies may be difficult in some sizes, materials and/or configurations. Furthermore, such a shared arrangement also provides another mode of thermal emissivity control as explained in more detail below.

As is evident from the previous discussion, the amount of radiative control of an object **120** depends upon the amount by which its thermal emissivity can be changed. For maximum radiative control, the thermal emissivity factor should be capable of being changed from a value of near 0 to near 1 and vice versa. In accordance with the present invention, a cavity structure **100** having an average cavity area aspect ratio of approximately 8 or greater provides a means by which the thermal emissivity of an object's surface can be significantly increased. This is illustrated in FIGS. **5***a*–**5***b* whereby a test cavity structure **100'**, defining **190** cavity apertures **140'** and cavity surfaces **150'**, has variable cavity area aspect ratios ranging between 5 and 41 ($1^{st}/19^{th}$ holes and 10^{th} hole, respectively). FIG. **5***b* shows the measured normalized radiance of each cavity (i.e., hole) which is proportional to its thermal emissivity. The 1^{st} and 19^{th} holes, each with a depth to diameter ratio of 1:1 (i.e., a cavity area aspect ratio of 5) have a radiance close to that of the unmodified surface of the test object **120'**. The 2^{nd} and 18^{th} holes, each with a depth to diameter ratio of 2:1 (i.e., a cavity area aspect ratio of 9) show an onset of increased radiance, and hence increased thermal emissivity. Holes with higher depth to diameter ratios show the expected higher radiance. As is evident to those skilled in the art, the aforementioned cavity area aspect ratio range of approximately 8 or greater would also be expected to be suitable for a cavity structure **100** defining a plurality of cavities whereby one or more of the cavities are backfilled with a material that is substantially transparent to incident and emitted radiation. Such backfilling would be advantageous, for example, in applications whereby the object **120** requires a smooth surface finish.

Embodiments Whereby ϵ is Changed by Changing R

An embodiment of the present invention is a cavity structure **100** for an object **120** whereby the radiative heat transfer between the object **120** and its environment is controlled in situ by controlling the cavity area aspect ratio R of the cavity structure **100** in situ (in some circumstances, changing the cavity area aspect ratio R also changes the ratio of total cavity aperture area to surface area unoccupied by cavity apertures **140**). Controlling the cavity area aspect ratio R may be implemented by controlling the effective size of the cavity aperture area A_a, the effective size of the cavity surface area A_c, or a combination thereof. The controlling may be by passive means, active means, or a combination thereof (e.g., spontaneous or externally applied stimuli such as temperature, chemistry, biology, humidity, pressure, electrical current or field, voltage, magnetic field, electromagnetic radiation, particle radiation, mechanical force, and combinations thereof).

FIGS. **6**–**13** illustrate specific embodiments of the present invention whereby thermal emissivity control is obtained by varying the cavity area aspect ratio R. In these figures, the control systems and actuators are not shown because it is evident to those skilled in the art that a variety of control systems and actuators could be utilized and interfaced with the cavity structure **100** without undue experimentation.

FIGS. **6***a*–**6***c* illustrate an embodiment of the present invention comprising a cavity article(s) **170** that is a perforated plate/sheet, sleeve, screen, or mesh. The cavity surface **150** defining the combination of thru-hole surfaces **190** in the cavity article **170** and the hole surfaces **195** in the object **120**. The array of perforations in the cavity article **170** dimensionally match the array of holes in object **120** so that when the thru-hole surfaces **190** are aligned in full coincidence with the hole surfaces **195**, the thermal emissivity of the resulting cavity is at a maximum (FIG. **6***a*). As the cavity article(s) **170** is translated relative to the object **120**, the effective size of the aperture area A_a is changed such that the thermal emissivity of the cavity structure **100** is controlled over a range of different values (FIG. **6***b*). A minimum thermal emissivity is obtained when there is no coincidence between the thru-hole surfaces **190** and hole surfaces **195** (FIG. **6***c*). Relative movement between the cavity article(s) **170** and the object **120** may be by passive means, active means, or a combination thereof including mechanical, thermal, electrical, magnetic, and chemical means (e.g., the cavity article(s) **170** may be moved by a solenoid, motor, bimetallic actuator, piezoelectric element, etc. (not shown) that is connected to a control system (not shown)).

FIGS. **7***a*–**7***b* illustrate a further embodiment of the present invention whereby the cavity area aspect ratio is changed (i.e., by changing the area of the cavity aperture **140**) by applying tensile or compressive forces to the radiative surface **110** of the object **120** (e.g., by applying a differential pressure across the object **120** as shown FIGS. **7***a*–**7***b*). Similar cavity aspect ratio changes can be induced by exposing a cavity structure **100** that is made of a hydrophilic, or hydrophobic, material to water. The present invention anticipates all means of swelling, shrinking, deforming, exposing, or obscuring single or multiple cavity apertures **140** to change the effective aperture area A_a, and thus cavity area aspect ratio R.

FIG. **8***a* illustrates a further embodiment of the present invention whereby the size of the cavity apertures **140** is controlled by controlling the movement of caps **800** positioned proximate the cavity apertures **140**. The caps **800** are attached (e.g., by fasteners, hinges, welding, soldering, adhesives, slide rails) to the radiative surface **110** to allow angular movement of the caps **800** through an angle β (up to 90° in this embodiment) relative to the radiative surface **110**. In another embodiment, the movement of the caps **800** may be in the same plane as the radiative surface **110** (e.g., a cap **800** that slides across the radiative surface **110** along rails, not shown). The caps **800** may be moved relative to the radiative surface **110** individually, or in sets, by incorporating into the caps **800** active elements such as bimetallic, shape memory, piezoelectric, magnetic, magnetostrictive, and combinations thereof and then activating the caps **800** by the application of heat/cold, voltage, magnetic field, etc. Such activation causes the caps **800** to bend or otherwise move to change the size of the cavity apertures **140**. The caps **800** may also be moved individually or in sets by mechanical means (e.g., a stepping motor). Furthermore, it is anticipated that an individual cap **800** may be sized such that it changes the size of more than one aperture **140** at one time upon its movement. In the embodiment shown in FIG. **8***a*, the cavity longitudinal axes **160** are approximately perpendicular to the plane of the cavity apertures **140**, but the present invention is not limited to such an orientation.

For example, FIGS. **8***b*–**8***c* illustrate a further embodiment of the present invention, similar to that shown in FIG. **8***a*, except that the cavity longitudinal axis **160** is not perpendicular to the plane of the cavity apertures **140**, and slots **810** are incorporated in the cavity structure **100**. Such a cavity longitudinal axis **160** orientation reduces the amount of cap **800** angular movement (as indicated by the angle β) required for a given change in the size of the cavity aperture **140** (and thus, thermal emissivity). The slots **810** facilitate the attachment of the caps **800** to the cavity structure **100** (e.g., by using the slots **810** as a sliding track for the caps **800**, or using the slots **810** as a means to press-fit or weld the caps **800** to the cavity structure **100**).

FIGS. **9***a*–**9***b* show a further embodiment of the present invention whereby the size of the cavity aperture **140** is changed by the rotation of a shutter **900** located proximate to the cavity aperture **140** in a cavity article **170**. The shutter **900** is penetrated by a hole such that by rotating the shutter **900** (e.g., by magnetic, electrical, pressure, or mechanical means), the effective size of the cavity aperture **140** is increased (FIG. **9***a*) or decreased (FIG. **9***b*). The hole in the shutter **900** can be any size or shape, depending upon the degree of radiative control desired.

FIGS. **10***a*–**10***b* show a further embodiment of the present invention whereby the size of the cavity aperture **140** is changed by mechanical deformation of the radiative surface **110** by shear force. FIGS. **11***a*–**11***b* show a further embodiment of the present invention, similar to the embodiment shown in FIGS. **10***a*–**10***b*, whereby the cavity surfaces **150** are shared between the cavity article **170** and the object **120**. In this embodiment, the cavity article **170** would typically be rigidly fixed to the object surface **180**. The cavity article **170** may be manufactured from a material different from that of the object **120** and which has desirable shear deformation properties.

FIGS. **12***a*–**12***b* illustrate a further embodiment of the present invention whereby the effective cavity surface area A_c is changed by the movement of a block **1200** relative to the cavity surface **150**. In this embodiment, if the shape of the cavity surface **150** is cylindrical, the block **1200** may be cylindrical or spherical in shape (similar configuration to that of a ball valve). The block **1200** may be moved by pressure differences across the block **1200** (e.g., by pneumatic or hydraulic means via channel **1210**) or by magnetic, electrical, or mechanical means.

FIGS. **13***a*–**13***b* illustrate a further embodiment of the present invention whereby the cavity structure **100** defines a plurality of cavities whereby one or more of the cavities are backfilled with a selector **1300**. The selector **1300** may be a liquid, solid, condensable gas, or a combination thereof. In applications whereby the selector **1300** is fluid, the cavity surface area A_c may be changed by the raising or lowering of the level of the selector **1300** using a feed/drain channel **1310**. Furthermore, the cavity surface area A_c may be changed by eliminating the feed/drain channel and relying on the evaporation, sublimation, or condensation of the selector **1300** to effect a change in the level of the selector **1300**.

The thermal emissivity of a cavity structure **100** can further be changed or controlled by backfilling the cavities in the cavity structure **100** with a selector **1300** and then changing the radiative characteristics (e.g., reflectivity, transmissivity, and absorptivity) of the selector **1300** by the application of physical and/or environmental stimuli to the selector **1300**. For example, the selector **1300** may be a luminescent material, liquid crystal, photochrome, electrochrome, or a combination thereof. Backfilling cavities with a selector **1300** that is reflective and/or opaque to incident radiation while transparent to emitted radiation or vice versa will have the character of a thermal diode. This is a further modification of the present invention that increases the ability to thermally engineer and independently control the radiative heat transfer properties of an object **120**. This control approach can be designed to modify both emitted and absorbed radiation to effect thermal control of the object **120**.

Activation of the selector **1300** by physical means and/or environmental stimuli provides a broad range of IR detection, recognition and tagging possibilities. For example, the cavity structure **100** of the present invention provides reservoirs for a variety of selectors **1300** to aid detection, inspection, tracking and tracing activities commonly practiced in law-enforcement, customs and excise, brand and fraud verification, etc. Selectors contained in cavity structures **100** having a high average cavity area aspect ratio will be superior to surface-applied taggants in resisting wear, erasure or alteration. Thermal or other means of activating the cavity structure **100** could dispense new selector **1300** to the radiative surface **110** to restore the desired IR signature of the surface and replace surface-active material that may have been removed or obscured.

Embodiments Whereby ϵ is Changed by Changing α

Another embodiment of the present invention is a cavity structure **100** for an object **120** whereby the radiative heat transfer between the object **120** and its environment is controlled in situ by controlling the orientation of the cavity longitudinal axes **160** in the cavity structure **100** relative to the radiative surface **110**. The controlling may be by passive means, active means, or combinations thereof (e.g., spontaneous or externally applied stimuli such as temperature, chemistry, biology, humidity, pressure, electrical current or field, voltage, magnetic field, electromagnetic radiation, particle radiation, mechanical force, and combinations thereof).

FIGS. **14–16** illustrate specific embodiments of the present invention whereby thermal emissivity control is obtained by varying the orientation of the cavity longitudinal axis **160** (measured by the angle α). In these figures, the control systems and actuators are again not shown because it is evident to those skilled in the art that a variety of control systems and actuators could be utilized and interfaced with the cavity structure **100** without undue experimentation.

FIGS. **14***a*–**14***b* illustrate a further embodiment of the present invention whereby the cavity structure **100** comprises a plurality of filaments **1400** whereby each end of a filament **1400** is attached to the object surface **180** to form a mat of filaments **1400** approximately parallel with one another. The mat may comprise, for example, 5–10 μm diameter filaments **1400** that are synthetic, ceramic, metal, or combinations thereof and typically would have a high surface reflectivity. The filaments **1400** may be solid or hollow and may be coated with a metal. For example, hollow filaments could be incorporated as micro heat pipes containing a working fluid. Such an arrangement would deploy in the high emissivity condition when the working fluid pressure reaches some design value as a consequence of heating. Such a cavity structure **100** has an array of interconnected cavity surfaces **150** and interconnected cavity apertures **140**. The filaments **1400**, oriented approximately perpendicular to the object surface **180** (i.e., $\alpha \cong 90°$), presents a maximum thermal emissivity configuration (FIG. **14***a*) while the filaments **1400** oriented approximately parallel to the object surface **180** (i.e., $\alpha \cong 0°$) presents a minimum thermal emissivity configuration (FIG. **14***b*). Maximum and minimum thermal emissivity configurations of the filaments **1400** may be obtained, for example, by applying a electrostatic charge to the filaments and grounding the filaments, respectively. An alternative embodiment of the present invention includes selective treating or coating of the filaments **1400** to obtain selective electrostatic behavior. Another means by which the orientation of the filaments **1400** may be changed is by attaching a substantial number of the free ends of the filaments **1400** to a perforated sheet **1500** as shown in FIG. **15** to form the cavity structure **100**. As shown in FIG. **15**, low and high thermal emissivity configurations may be obtained by translating the perforated sheet **1500** relative, and parallel, to the object surface **180**. Relative movement between the perforated sheet **1500** and object **120** may be accomplished by a variety of means including, mechanical, thermal, electrical, magnetic, and chemical.

FIGS. **16***a*–**16***b* illustrate a further embodiment of the present invention whereby the cavity structure **100** comprises a perforated membrane **1600** defining a plurality of cavity apertures **140**. The perforated membrane **1600** may be a perforated plate/sheet, mesh, or screen. The perforated membrane **1600** is typically thermally bonded to the object **120** by one or more connecting members **1610**. The cavity structure **100** further comprises a plurality of inflatable and/or deflatable bladders **1620** that have an open end **1630** attached to the perforated membrane **1600** at the cavity aperture **140**. As shown in FIGS. **16***a*–**16***b*, high and low thermal emissivity configurations may be obtained by inflating or deflating the bladder **1620**, effectively changing the orientation of the cavity longitudinal axis **160** relative to the radiative surface **110**. Such inflation/deflation may be accomplished by such means as mechanical suction, pressurization through heating, and mechanical expansion.

As is evident from the foregoing, another embodiment of the present invention is a cavity structure **100** for an object **120** whereby the radiative heat transfer between the object **120** and its environment is controlled in situ by controlling the cavity area aspect ratio R and orientation of the cavity longitudinal axis **160** in combination.

The present invention has extremely broad and diverse applications with the potential of providing preset or dynamic control of temperature and heat transfer in objects as diverse as automobiles, machinery, buildings, power generation equipment, and military and space systems. Cavity structures **100** used in the manner disclosed herein enable a variety of components (e.g., engines, exhaust components, transmission lines, reactors) to run cooler, thereby reducing the size and power requirements of the conventional cooling system, increasing safety, and extending component life. Furthermore, the cavities in the cavity structures **100** can be backfilled with a material (e.g., glass, polymer), that is substantially transparent to the incident and emitted radiation, to restore the original surface smoothness and prevent the cavities from being filled with dirt or other undesirable materials.

The present invention also offers the potential of controlling the sizes of individual, or groups, of cavity apertures **140**, cavity surfaces **150**, or combinations thereof, to effect local control of thermal zones on an object **120**. Among many possible uses, the ability to program individual or groups of cavity apertures **140**, cavity surfaces **150**, or combinations thereof, with a different thermal emissivity could be used to disguise or randomize the IR signature of objects **120** so that they escape detection by IR cameras or sensors. Such an arrangement could provide thermal camouflage of objects **120** having, for example, military or law-enforcement significance. Furthermore, actively controlled cavity structures **100** could enable a programmable identification friend or foe (IFF) capability necessary in warfare and law-enforcement. IFF signatures expressed by patterns of open and closed cavity apertures **140** would be detectable by IR cameras or sensors. These patterns could be reprogrammed frequently to avoid recognition or use by an enemy. Another application is maintaining optical precision in relatively large structures such as telescopes. With computer control of a cavity structure **100** in the base of a large mirror system, for example, thermal emissivity could be manipulated to provide a means of ultrafine-tuning the mirror's shape by local thermally-induced contractions and expansions of the structure.

CLOSURE

While numerous embodiments of the present invention have been shown and described, it will be apparent to those skilled in the art that many changes and modifications may be made without departing from the invention in its broader aspects. The appended claims are therefore intended to cover all such changes and modifications as fall within the true spirit and scope of the invention.

What is claimed is:

1. A method of increasing the thermal emissivity of a surface of an object comprising the step of:

forming a cavity structure on the surface defining a plurality of cavities, said cavity structure further defining a plurality of cavity apertures and cavity surfaces, wherein said cavity structure has an average cavity area aspect ratio of at least 8.

2. The method of claim 1, wherein said forming comprises selectively removing material from the surface of the object.

3. The method of claim 1, wherein said forming comprises selectively adding material to the surface of the object.

4. The method of claim 1, wherein the ratio of the cumulative cross-sectional area of said plurality of cavity apertures to surface area that is not occupied by said plurality of cavity apertures is greater than about 1:4.

5. The method of claim 4, wherein the ratio of the cumulative cross-sectional area of said plurality of cavity apertures to surface area that is not occupied by said plurality of cavity apertures is greater than about 2:1.

6. The method of claim 1, wherein said plurality of cavity apertures form a geometric array on the surface of the object.

7. The method of claim 1, wherein said plurality of cavity apertures are circular in shape.

8. The method of claim 7, wherein said plurality of cavity apertures have approximately the same diameter.

9. The method of claim 1, wherein the average effective diameter of said plurality of cavity apertures is at least 10 μm.

10. The method of claim 1, further comprising the step of backfilling at least a portion of said plurality of cavities in said cavity structure with a material that is substantially transparent to incident and emitted radiation.

11. A method of controlling the amount of radiation transferred between a surface of an object and its environment in situ, comprising the steps of:

forming a cavity structure on the surface defining a plurality of cavities, said cavity structure further defining a plurality of cavity apertures and cavity surfaces, wherein said cavity structure has an average cavity area aspect ratio of at least 8; and

changing the degree of blackbody behavior of the surface by changing a physical characteristic of said cavity structure in situ.

12. The method of claim 11, wherein said physical characteristic is selected from the group consisting of cavity area aspect ratio, cavity longitudinal axis orientation, and combinations thereof.

13. The method of claim 12, wherein changing the cavity area aspect ratio is by changing the area of at least a portion of said plurality of cavity apertures.

14. The method of claim 13, wherein changing the area of at least a portion of said plurality of cavity apertures is by moving at least one cap proximate said portion of cavity apertures.

15. The method of claim 14, wherein said at least one cap incorporates an activate element selected from the group consisting of bimetallic, shape memory, piezoelectric, magnetic, magnetostrictive, and combinations thereof.

16. The method of claim 13, wherein changing the area of at least a portion of said plurality of cavity apertures is by deforming said portion of cavity apertures.

17. The method of claim 12, wherein changing the cavity area aspect ratio is by changing the area of at least a portion of said plurality of cavity surfaces.

18. The method of claim 17, wherein changing the area of at least a portion of said plurality of cavity surfaces is by changing the level of a selector contained in said portion of said plurality of cavities.

19. The method of claim 11, further comprising the step of backfilling at least a portion of said plurality of cavities in said cavity structure with a selector, wherein said selector is selected from the group consisting of luminescent materials, liquid crystals, photochromes, electrochromes, and combinations thereof.

20. The method of claim 11, wherein changing said physical characteristic is caused by a stimulus selected from the group consisting of temperature, chemistry, biology, humidity, pressure, electrical current, electric field, voltage, magnetic field, electromagnetic radiation, particle radiation, mechanical force, and combinations thereof.

21. The method of claim 11, wherein the average effective diameter of said plurality of cavity apertures is at least 10 μm.

22. A surface structure that increases the thermal emissivity of a surface of an object, comprising:

a cavity structure defining a plurality of cavities, said cavity structure further defining a plurality of cavity apertures and cavity surfaces, wherein said cavity structure has an average cavity area aspect ratio of at least 8.

23. The surface structure of claim 22, wherein the ratio of the cumulative cross-sectional area of said plurality of cavity apertures to surface area that is not occupied by said plurality of cavity apertures is greater than about 1:4.

24. The surface structure of claim 23, wherein the ratio of the cumulative cross-sectional area of said plurality of cavity apertures to surface area that is not occupied by said plurality of cavity apertures is greater than about 2:1.

25. The surface structure of claim 22, wherein said plurality of cavity apertures form a geometric array on the surface.

26. The surface structure of claim 22, wherein said plurality of cavity apertures are circular in shape.

27. The surface structure of claim 26, wherein said plurality of cavity apertures have approximately the same diameter.

28. The surface structure of claim 22, wherein the average effective diameter of said plurality of cavity apertures is at least 10 μm.

29. The surface structure of claim 22, further comprising a material that backfills at least a portion of said plurality of cavities in said cavity structure, said material substantially transparent to incident and emitted radiation.

30. A controllable surface structure for controlling the amount of radiation transferred between a surface of an object and its environment in situ, comprising:

a cavity structure defining a plurality of cavities, said cavity structure further defining a plurality of cavity apertures and cavity surfaces, wherein said cavity structure has an average cavity area aspect ratio of at least 8; and

a means to change a physical characteristic of said cavity structure in situ to control the degree of blackbody behavior of the surface.

31. The controllable surface structure of claim 30, wherein said physical characteristic is selected from the group consisting of cavity area aspect ratio, cavity longitudinal axis orientation, and combinations thereof.

32. The controllable surface structure of claim 30, wherein said means is selected from the group consisting of electrical, mechanical, and combinations thereof.

33. The controllable surface structure of claim 30, wherein the average effective diameter of said plurality of cavity apertures is at least 10 μm.

34. The controllable surface structure of claim 30, further comprising a selector in at least a portion of said plurality of cavities.

35. The controllable surface structure of claim 34, wherein said selector is selected from the group consisting of luminescent materials, liquid crystals, photochromes, electrochromes, and combinations thereof.

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