

A cooling container

Technical Field

5 This specification relates to a storage vessel or an enclosure for keeping an object in an environment at a temperature lower than the ambient temperature.

Background

Conventional cooling containers maintain a lower temperature than the ambient temperature by passive thermal insulation. Due to imperfect thermal isolation, conventional containers
10 require continued supply of cold material or a cold source to maintain the cold temperature.

Summary

According to an aspect of the present invention, there is provided a cooling container, which comprises: a thermally insulating container comprising a storage space; a radiative cooling
15 portion comprising an internal surface and an external surface. The internal surface faces the storage space and the external surface is exposed to an outside of the cooling container. The radiative cooling portion is configured to dissipate heat from the storage space by emitting a thermal radiation to the outside via the external surface.

In some implementations, the cooling container further comprises a thermal storage medium
20 arranged to be in thermal contact with the internal surface and with the storage space such that heat is dissipated from the storage space and the thermal storage medium by the radiative cooling portion.

In some implementations, the thermal storage medium comprises a sensible heat storage material.

25 In some implementations, the thermal storage medium comprises a latent heat storage material.

In some implementations, the cooling container further comprises a heat siphon structure configured to facilitate a circulation of air inside the storage space when the radiative cooling portion is colder than the storage space.

30 In some implementations, the cooling container further comprises a heat mirror structure configured to reflect and redirect the thermal radiation from the radiative cooling portion within a predetermined solid angle from a normal direction from the external surface.

In some implementations, the heat mirror structure comprises a first opening and a second opening. The heat mirror structure is arranged such that the thermal radiation emitted from
35 the external surface enters the heat mirror structure through the first opening and exits through the second opening.

In some implementations, the cooling container further comprises a convective cover disposed over the external surface and configured to transmit the thermal radiation and to shield the radiative cooling portion from an air flow of the outside of the cooling container.

In some implementations, the convective cover is disposed over the second opening.

- 5 In some implementations, the heat mirror structure comprises a grid structure such that a plurality of channels are formed from the first opening and the second opening. Each of the plurality of channels is configured to reflect and redirect the thermal radiation emitted from the external surface.

- 10 In some implementations, the cooling container further comprises an aperture on the thermally insulating container through which the storage space is exposed to the outside of the cooling container; and a top structure mountable on the aperture to block the aperture and configured to be thermally insulating. The radiative cooling portion is included in the top structure.

- 15 In some implementations, the cooling container further comprises a cap mountable on the thermally insulating container. The cap is configured to be thermally insulating such that the storage space is thermally insulated when the cap is mounted. When the cap is disposed over the radiative cooling portion, the cap is configured to block the thermal radiation emitted from the radiative cooling portion.

- 20 According to another aspect of the present invention, there is provided a structure for covering an aperture of a container, comprising: a radiative cooling portion comprising an internal surface and an external surface; a thermally insulating portion configured to house the radiative cooling portion and to be fitted into the aperture. When the structure is disposed on the container to cover the aperture, the internal surface faces a storage space of the container and the external surface is exposed to an outside of the container. The radiative cooling portion is configured to dissipate heat from the storage space by emitting a thermal radiation to the outside via the external surface.

- 25 In some implementations, the structure further comprises a thermal storage medium arranged to be in thermal contact with the internal surface and such that when the structure is disposed on the container to cover the aperture, the thermal storage medium is in thermal contact with the storage space and such that heat is dissipated from the storage space and the thermal storage medium by the radiative cooling portion.

- 30 In some implementations, the structure further comprises a heat siphon structure configured to facilitate a circulation of air inside the storage space when the radiative cooling portion is colder than the storage space.
- 35

In some implementations, the structure further comprises a heat mirror structure configured to reflect and redirect the thermal radiation from the radiative cooling portion within a predetermined solid angle from a normal direction from the external surface.

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Brief Description of the Drawings

20 Certain embodiments of the present invention will now be described, by way of example, with reference to the accompanying drawings, in which:

FIG. 1 is an exemplary embodiment of a cooling container with a radiative cooling portion.

FIG. 2 is a graph that illustrates exemplary emission spectra of the radiative cooling portion.

FIG. 3a is an exemplary embodiment of the cooling container with a radiative cooling portion.

25 FIG. 3b is an exemplary embodiment of the cooling container with a convective cover disposed over a radiative cooling portion.

FIG. 3c is an exemplary embodiment of the cooling container with a radiative cooling portion and a heat siphon structure.

30 FIG. 3d is an exemplary embodiment of the cooling container with a radiative cooling portion and a thermal storage medium.

FIG. 3e is an exemplary embodiment of the cooling container with an extendable radiative cooling portion.

FIG. 3f is an exemplary embodiment of the cooling container with a radiative cooling portion and a heat mirror structure.

35 FIG. 3g shows exemplary embodiments of the heat mirror structures.

Detailed Description

A cooling container in this specification refers to any structure with an internal storage space which can reduce the transfer of heat to and from the ambient condition such that the storage space is at a temperature lower than the ambient temperature for an extended period of time.

- 5 One of the examples of the cooling container is a portable ice chest, so-called an ice box, or a cooler. The ice box or the cooler refers to a box or a container designed to store food or drink at a temperature that is lower than the ambient temperature so the food or drink stays fresh longer compared to the case the box or the container is not used. The box comprises thermally insulating materials to provide thermal insulation from the ambient condition.
- 10 Other examples include a thermal bag or a cooler bag, which is usually in the form of a flexible pouch. In the case of a vacuum flask, such as a Dewar or a Thermo, the thermal insulation is achieved with two flasks placed on top of one another. The gap between the flask can be evacuated in order to reduce heat transfer by conduction or convection. This provides an extended duration of thermal insulation from the surrounding.
- 15 Further examples of the cooling container include storage tanks embedded in transport vessels such as trucks and ships or storage space where the temperature is regulated inside for the storage of crops and fruits.

These examples of cooling containers often maintain a lower temperature than the ambient temperature by passively maintaining the thermal insulation. To achieve the acceptable

20 temperature range of the storage space initially, and to extend the duration of the acceptable temperature range, a source of coldness or a material to provide coldness, such as an ice pack or a gel pack, is provided within the storage space. Without the continued supply of cold material or a cold source to facilitate the cold temperature, due to imperfect thermal isolation, the temperature within the storage space of the cooling container eventually

25 reaches the ambient temperature. For this reason, conventional cooling containers cannot be used for an extended period exceeding the thermal relaxation time given by the degree of insulation.

For example, the internal temperature of a typical commercial icebox cannot be maintained below ambient temperature for longer than a day or so if the source of coldness is provided

30 only initially. Such containers are often not usable to preserve food or drinks for days in an area without any access to renewed supply of ice packs or gel packs.

This specification relates to a cooling container including a surface capable of radiative cooling. The surface for radiative cooling does not require any electricity or other input of energy but requires direct line of sight access to a clear sky. The surface for radiative cooling

35 is attached, removably or permanently to the cooling container and provides cooling power by emitting infrared thermal radiation into the sky. The surface for radiative cooling is configured such that the storage space within the cooling container reaches a sub-ambient

temperature at least for a duration of time during the day. The lowered temperature inside the storage space can be maintained continuously without use of any electricity and without need to supply any source of coldness within the storage space.

Since the surface for radiative cooling faces the sky, the surface can be heated by the sunlight and by absorbing the emission from the atmosphere, so called “downwelling.” The surface for radiative cooling can also receive heat via conduction, from the material it is in contact with and via convection, from the air circulating around the surface. These factors contribute to reducing the net cooling power and the lowest achievable temperature by radiative cooling. Therefore, the radiative cooling surface and the cooling container can be designed to reduce these sources of heat influx.

Due to the presence of direct sunlight, the achievable steady state temperature by radiative cooling is in general higher during the day than during the night. In case the temperature obtainable by radiative cooling during the day is not low enough for the purpose of the storage space, the coldness obtained during the night can be stored in a thermal storage medium thermally connected to the radiative cooling surface. In case the sunlight during the day is excessive or the line of sight to the clear sky is blocked by excessive clouds, the radiative cooling surface can be covered with a thermally insulating cover or removed from the cooling container.

FIG. 1 shows an exemplary embodiment of a cooling container with a radiative cooling portion.

A left panel 101 shows a cross section view of the cooling container 100 and a right panel 102 shows an exploded view of the cooling container 100. The cooling container 100 includes a main body 110. The main body 110 is configured to provide a storage space 130 and includes an aperture or an opening 111 through which the objects to be stored inside the cooling container 100 can be inserted and taken out.

In the example of FIG. 1, the main body 110 may comprise a bottom surface 110-1 of a square shape and four side walls 110-2 attached to the sides of the bottom surface 110-1 such that the storage space 130 is surrounded by five surfaces and the aperture 111 is defined to be the opening formed by the four side walls 110-2 opposing the bottom surface 110-1.

It is understood that the exact shape of the main body 110 is not limited to the example described in FIG. 1. For example, the main body 110 may comprise more or less than five surfaces 110-1, 110-2 as shown in FIG. 1. For another example, the main body 110 may comprise a flexible structure such as a thermal bag, where the storage space 130 is flexibly formed by the presence of the objects to store inside the cooling container 100. In other words, the main body 110 may take on any arbitrary shape as long as it is capable of

providing a storage space 130 and an aperture 111 on the surface of the main body 110. The inventive concepts described below still apply when the shape of the main body 110 deviates from the example of FIG. 1.

The surfaces of the main body 110, for example, the four side walls 110-2 and the bottom surface 110-1 are configured to provide thermal isolation from the surroundings. The main body 110 comprises a thermally insulating material. For example, for outdoor cooler chests, so-called an icebox, the four side walls 110-2 and the bottom surface 110-1 may comprise polyurethane. For another example, for a vacuum flask, such as a Dewar or a Thermo, the surfaces of the main body 110 may be formed by two surfaces interposing an evacuated gap.

In this specification, the phrase “thermally insulating” will be understood to mean that the heat transfer is reduced to meet the purpose of the application. For example, for ice chest, a material with a thermal conductivity less than $0.05 \text{ Wm}^{-1}\text{K}^{-1}$ will be chosen for the surfaces or the walls of the main body 110 and the thickness of the walls of the four side walls 110-2 and the bottom surface 110-1 can be chosen to be at least a few centimeters such that the desired thermal isolation is achieved. For example, in the case of outdoor cooler chests, the thermal isolation performance is often measured in hours it takes for the initial 5 degrees celsius to reach 15 degrees celsius when the cooler chest is disposed at an exemplary ambient temperature, for example 27 degrees celsius. For many commercial cooler chests, it takes at least 15 hours from 5 to 15 degrees celsius. However, it is to be understood that the exact degree of thermal insulation of the main body 110 differs depending on the purpose of the application and the phrases “thermally insulating” or “thermally insulated” are not intended to mean a complete thermal isolation.

In some implementations, the cooling container 100 may further include a cap 150. The cap 150 comprises a thermally insulating material or a thermally insulating structure, as the main body 110, and is configured to close off the storage space 130 and to completely block the aperture 111 such that when the cap 150 blocks the aperture 111, the storage space 130 is thermally insulated from the surroundings.

In some implementations, although not shown in the FIG. 1, the cap 150 may be attached to one of the four side walls 110-2, for example, via one or more hinges or any other means such that the cap 150 can be placed in an open position or in a closed position as desired without being detached from the cooling container 100 or the main body 110. At the closed position, the storage space 130 is sealed off and thermally insulated from the surroundings. In this case, the main body 110 and the cap 150 defines the storage space 130.

The cooling container 100 includes a radiative cooling portion 140. The radiative cooling portion 140 is configured to release heat by emitting IR radiation through the atmosphere into the space.

In some implementations, the radiative cooling portion 140 may be attached to the main body 110. For example, the radiative cooling portion 140 may be permanently attached to the main body 110 without obstructing the aperture 111 of the main body 110. For example, the radiative cooling portion 140 may be permanently attached to one of the side walls 110-2, although not shown in FIG. 1.

In some implementations, the cooling container 100 may further include a top structure 120 and the radiative cooling portion 140 is included in the top structure 120. In this implementation, as shown in FIG. 1, the top structure 120 is configured to fit into the aperture 111. For example, the top structure 120 can be removed for the aperture 111 to be open for access into the storage space 130. When the top structure 120 is at a closed position or fitted into the aperture 111 of the main body 110, the storage space 130 is blocked and surrounded by the walls of the main body 110 and the top structure 120. In some implementations, the top structure 120 may be separate from the main body 110 configured to be detachable from the main body.

In some implementations, although not shown in the FIG. 1, the top structure 120 may be attached to one of the four side walls 110-2, for example, via one or more hinges such that the top structure 120 can be placed in an open position and in a closed position as desired. In this case also, the top structure 120 is to be fitted into the aperture 111.

When both the top structure 120 and the cap 150 are attached to the main body 110, the top structure 120 is placed directly to block the aperture 111 and the cap 150 is placed over the top structure 120, as depicted in FIG. 1. In this case, the cap 150 blocks the top structure 120 from accessing the sky. In this case, the top structure 120 and the main body 110 define the storage space 130 and the cap 150 provides thermal isolation of the storage space 130.

In the implementation where the radiative cooling portion 140 is included in the top structure 120, the radiative cooling portion 140 is arranged to face the external space when the cap 150 is removed or at an open position. The cap 150 is removed to expose the radiative cooling portion 140 to the sky for cooling.

FIG. 1 shows that the top structure 120 including the radiative cooling portion 140 comprise the uppermost surface of the cooling container 100, when the cap 150 is removed such that the radiative cooling portion 140 faces zenith direction. However, the positions of the top structure 120 and the radiative cooling portion 140 are not limited to this example. The position of the radiative cooling portion 140 may be adjusted depending on the surrounding to the cooling container 100.

The cooling container 100 can be positioned for the radiative cooling portion 140 to face the sky. For example, when clouds are directly above the cooling container 100, the cooling

container 100 can be tilted such that the radiative cooling portion 140 faces the portion of the sky with less clouds.

As will be explained in more detail below, if the radiative cooling portion 140 is capable of achieving the desired temperature at all times during the day, the radiative cooling portion

140 can be exposed to face the sky at all times. If the radiative cooling portion 140 is capable of achieving the desired temperature only during limited hours during the day, the radiative cooling portion 140 may be covered by the cap 150 during the hours where the desired temperature is not feasible. In some implementations, the cap 150 for covering the aperture 111 and the cap 150 for covering the radiative cooling portion 140 may be

separately provided.

For the rest of the specification, the examples will be provided with the radiative cooling portion 140 included in the top structure 120. However, the same inventive concepts apply to the embodiments where the radiative cooling portion 140 is built into the main body 110.

FIG. 2 is a graph that illustrates exemplary emission spectra of the radiative cooling portion. A graph 200 shows the emission profile of the radiative cooling portion 140. A horizontal axis 201 represents an emission wavelength in microns. A vertical axis 202 represents the emissivity. The emissivity is the ratio of the thermal radiation of a given object to the thermal radiation of the blackbody of the same temperature. The thermal radiation here is defined as the total power emitted from a surface integrated within the hemisphere. The vertical axis 202 of the graph 200 represents the emissivity of the radiative cooling portion 140.

The radiative cooling portion 140 is configured to release heat by emitting thermal radiation, which is an electromagnetic radiation in the IR wavelength according to the Planck radiation law. In the example of FIG. 2, the wavelength range between only 4 and 30 microns is labelled with a horizontal arrow marked 203. In this specification, a wavelength range for this thermal radiation will be referred to as an IR band 203 or a long wave band 203. The IR band 203 represents the wavelength range covered by IR thermal radiation given by the Blackbody spectrum or Planck spectrum at the given temperature of the radiative cooling portion 140. An appreciable contribution of thermal radiation can be regarded as starting from around 2 to 3 microns wavelength depending on design considerations. For convenience, the IR band 203 in this specification is assumed to start from 4 microns wavelength. However, it is understood that the IR band 203 represents the thermal radiation according to the Planck radiation law.

Importantly, the radiative cooling portion 140 is configured to absorb and radiate efficiently within a wavelength band within the IR band 203, often referred to as a “sky window” or an “atmospheric window.” Within this wavelength band, from 7.9 microns to 13 microns, the atmosphere is significantly more transparent compared to other wavelength bands, thereby

providing a thermal radiation channel between the terrestrial and the space. In this specification, the corresponding wavelength band will be referred to as a sky window. In FIG. 2, the sky window is indicated as a horizontal arrow labelled 204.

Since the peak of the thermal radiation of the ambient temperature, given by the Planck distribution or the blackbody radiation, largely falls within the sky window 204, the thermal emission through the sky window allows for a passive cooling mechanism where a body at ambient temperature on the ground can dissipate heat by radiating emission through the sky window 204 to the outer space. The outer space acts as a heat sink.

The solar radiation spectrum is mostly concentrated within the visible wavelength. In the example of FIG. 2, the wavelength band from 0 to 4 microns is indicated with a horizontal arrow labelled 205. Although most of the solar radiation power is concentrated within the near IR band or below 2 microns wavelength, in this specification, the wavelength band between 0 and 4 microns, will be referred to as a solar radiation band 205 or a short wave band 205.

Since the absorption of the solar radiation in the solar radiation band 205 leads to the heating of the radiative cooling portion 140, the degree to which the solar radiation is reflected by the radiative cooling portion 140 or rejected by other means is one of the main factors in the net cooling rate and the lowest achievable temperature of the radiative cooling portion 140.

Outside the sky window 204 and within the IR band 203, the atmosphere is largely opaque and therefore highly absorptive and highly emissive and the spectrum follows that of the Planck distribution. The solar radiation is absorbed by the constituents of the atmosphere, such as H₂O, CO₂, O₃, CH₄ and N₂O and emitted over the whole range from 4 to 30 microns wavelength. This IR radiation is often referred to as the downwelling. Since the downwelling cancels the effect of the radiative cooling, the degree of the downwelling is another one of the main factors in the efficiency of radiative cooling of the radiative cooling portion 140.

The degree of downwelling depends on several factors. Since gas constituents in the atmosphere more or less uniformly surround around the earth, the degree of downwelling varies decreasingly from the vertical or the zenith direction towards the horizontal direction. The degree of downwelling also depends on the specific regions and weather conditions, especially on the humidity and the carbon dioxide concentration and the presence of clouds. The spectrum of downwelling also depends on the vertical temperature distribution within the atmosphere because the emission spectrum of each gas constituent generally follows the Planck spectrum of the given temperature. For example, the ozone layer, at 15 to 40km height, may be 40 to 70 degrees colder than the ambient temperature at the terrestrial.

According to the Kirchoff's law of thermal radiation, at thermodynamic equilibrium, a high emissivity of a surface leads also to the equally high absorptivity. Therefore, a high emissivity of the radiative cooling portion 140 means equally high degree of absorption of the downwelling.

- 5 The imbalance between emission and absorption can be utilised to overcome the heat gain into the radiative cooling portion 140. Since the sky window 204 is the only wavelength band where downwelling spectrum deviates most strongly from the Blackbody spectrum, to maximise radiative cooling, it is crucial that the emissivity is as close to 1 as possible within the sky window 204.
- 10 If outgoing thermal radiation exceeds the heat gain into the radiative cooling portion 140, a cooling power can be obtained from the radiative cooling portion 140. The heat gain into the radiative cooling portion 140 may originate from the absorption of sunlight and downwelling, the conduction of heat from the surrounding or the convection of air in touch with the external surface of the radiative cooling portion 140.
- 15 The conduction and convection are to be minimised in a given configuration. The spectral profile of the emissivity of the radiative cooling portion 140 can be configured to facilitate a net thermal IR radiation from the radiative cooling portion 140 towards the sky, as described below.

A first curve 210 corresponds to the spectral response or the emissivity of an ideal selective emitter, where the radiative cooling portion 140 has unity emissivity within the sky window 204 and zero emissivity outside the sky window 204. The ideal selective emitter completely reflects the emissions within the solar radiation band 205 and the emissions within the IR band 203 but outside the sky window 204. Therefore, the radiative cooling portion 140 with a spectral response as in the first curve 210 only absorbs and emits within the sky window 204.

In this ideal selective emitter represented by the first curve 210, the heat gain into the radiative cooling portion 140 can only arise from the convection of the ambient air and conduction of the heat towards the radiative cooling portion 140.

The radiative cooling portion 140 with a spectral response represented by the first curve 210 may be used to optimise for the lowest achievable temperature at a steady state, rather than to optimise for a maximum cooling power.

A second curve 220 shows the spectral response or the emissivity of a black body emitter throughout the IR band 203. Therefore, the radiative cooling portion 140 with a spectral response as in the second curve 220 absorbs and emits with unity efficiency throughout the IR band 203 but does not absorb or emit in the solar radiation band 205.

The downwelling within the IR band 203 and outside the sky window 204 may be absorbed by the radiative cooling portion 140 but the radiative cooling portion 140 may also emit throughout the IR band 203.

This configuration may lead to a steady state temperature higher than that of the ideal selective emitter represented by the first curve 210. This is because as the temperature of the radiative cooling portion 140 goes lower, the absorption of the downwelling outside the sky window 204 can offset the net outgoing IR radiation within the sky window 204.

The configuration of the radiative cooling portion 140 represented by the second curve 220 may be used to optimise for the cooling power, rather than the minimum achievable

temperature.

The first curve 210 is configured to suppress the emission and the absorption outside the sky window 204 to maximise the imbalance between the emission and the absorption of downwelling. Since the cooling power, which represents the rate of heat removal, is directly proportional to the area under the first curve 210 and the second curve 220, the selective emitter as in the first curve 210 provides a smaller total cooling power compared to the blackbody emitter case as in the second curve 220. The black body emitter as in the second curve 220 dissipates heat more efficiently than the ideal selective emitter 210 due to the broader spectrum. On the other hand, the selective emitter as in the first curve 210 in general leads to a lower steady state temperature.

The temperature of the blackbody emitter as in the second curve 220 may decrease quicker than the ideal selective emitter as in the first curve 210 but stabilise at a higher temperature than that of the ideal selective emitter as in the first curve 210.

A third curve 230 shows the spectral response or the emissivity of a hypothetical realistic emitter. The radiative cooling portion 140 for the use in the cooling container 100, is

designed to meet at least the following two criteria.

First, the radiative cooling portion 140 is designed or chosen to maximise the emissivity within the sky window 204. As discussed above, the imbalance between the outgoing IR radiation and the downwelling is maximised within the sky window 204. Therefore, the spectral response of the radiative cooling portion 140 is designed or chosen such that the emissivity within the sky window 204 is as close to unity throughout the sky window 204. In some implementations, the radiative cooling portion 140 may comprise a material with average emissivity of at least 0.9 within the sky window 204.

In some implementations, the radiative cooling portion 140 may comprise a material with average emissivity of at least 0.7 within the sky window 204.

In some implementations, the radiative cooling portion 140 may comprise a material with average emissivity of at least 0.9 within the IR band 203.

In some implementations, the radiative cooling portion 140 may comprise a material with average emissivity of at least 0.7 within the IR band 203.

The downwelling spectrum and the degree of downwelling can be directly measured or obtained from atmospheric radiative transfer codes such as MODTRAN or ATRAN. In

particular, the transmissivity of the atmosphere can be estimated depending on the latitude and the climate to estimate the net outgoing IR thermal radiation at a given temperature of the radiative cooling portion 140.

Second, the radiative cooling portion 140 is designed or chosen to minimise the absorption of the solar radiation. The rejection of the solar radiation may be achieved, for example, by arranging the spectral response of the radiative cooling portion 140 such that the solar radiation is selectively reflected while efficiently radiating in the IR band 203. However, as shown in the third curve 240, representing the realistic case, there may be residual finite emissivity, therefore absorption, within the solar radiation band 204.

The spectral response of the radiative cooling portion 140 may be engineered to have a specific spectral response.

In some implementations, the spectral response of the emitter surface 341 may be engineered by continuous variation of the refractive index of the material of the emitter surface 341. In contrast to the case of the multilayer interference filter, where each layer has a fixed refractive index throughout its thickness, the refractive index may be varied continuously.

In some implementations, the emitter surface 341 may have a portion containing multiple layers of constant refractive indices and another portion where the refractive indices are continuously varied.

In some implementations, the spectral response of the emitter surface 341 may be provided by metamaterial microstructure or an electromagnetic metasurface. Sub-wavelength micro- or nano-structures can be deployed in a two-dimensional array within the plane of the surface. In this case, stacking of layers or variation of the refractive indices in the direction normal to the emitter surface 341 is not necessary. Also, separate implementation of the solar reflector part and the IR emitter part is not necessary.

In case the degree of conduction and convection is known and the spectral response of the radiative cooling portion 140 can be designed by iterative processes, the spectrum can be optimised as follows.

Initially, the spectral response of the radiative cooling can be set to be close to the first curve 210, that of an ideal selective emitter. If a temperature lower than the desired temperature can be achieved, the emissivity spectrum can be expanded in the IR band 203 from the sky window 204 to increase the total emissivity, to maximise the cooling power while achieving the desired temperature.

For example, if the minimum achievable temperature of the radiative cooling portion 140 during the daytime is 0 degrees celsius when the spectrum of the radiative cooling portion 140 resembles mostly the first curve 210 and the desired temperature is 10 degrees celsius, the spectrum of the radiative cooling portion 140 may be modified outside the sky window 204 to increase the emissivity outside the sky window 204 within the IR band 203 such that the cooling power is increased at the cost of the achievable minimum temperature. With the modified spectrum, the minimum achievable temperature may be higher but the cooling power may be improved.

For another example, if the spectrum of the radiative cooling portion 140 resembles the second curve 220 with a near-blackbody spectrum and is capable of achieving the desired temperature within the storage space 130, this is an optimal situation in that the cooling power is maximised while the desired temperature is achieved.

In some implementations, the design or the choice of the spectrum of the radiative cooling portion 140 may be such that it is close to the ideal selective emitter as represented in the first curve 210 and the area of the radiative cooling portion 140 may be extended by using multiple units of the radiative cooling portion 140 in parallel, as will be discussed later in FIG. 3e.

In some implementations, the rejection of the solar radiation may also be aided by physically blocking the direct sunlight via an additional reflection or blocking structure in the vicinity of the radiative cooling portion 140. This can alleviate the effect of finite emissivity in the solar radiation band 205.

In some implementations, the radiative cooling portion 140 may be designed considering only the emissivity within IR band 203. Depending on the circumstances such as geographical location and the properties for the material available to the user, the sub-ambient cooling may not be feasible during the day, and only night time cooling may be possible. In this case, the direct incidence of the solar radiation may not be considered in the design of the spectrum of the radiative cooling portion 140. In other words, the spectrum of the radiative cooling portion 140 may be designed or chosen to efficiently absorb and emit within the sky window 204 and to achieve the desired temperature while maximising cooling power within the IR band 203.

In this case, during the daytime, in presence of solar radiation, the radiative cooling portion 140 may be covered with the cap 150 or any other thermally isolating component to prevent the radiative cooling portion 140 from receiving heat by absorbing sunlight. The coolness can be stored for use during the daytime, as will be discussed later.

For example, black paint, such as carbon black, painted on aluminium or silver surface as the radiative cooling portion 140 would act as an efficient blackbody emitter at night, although during the day the black paint would absorb the solar radiation strongly. During the day, the radiative cooling portion 140 may be covered with the cap 150 to avoid absorbing the solar radiation.

In some implementations, two or more layers of materials with known spectral response can be chosen and overlaid on top of each other or mixed to provide a desired spectral response. For example, the radiative cooling portion 140 may be a combination of two components, a IR radiation portion and a solar reflection portion. For example, a polymeric layer, with a high emissivity in the sky window 204 or in the IR band 203, can be disposed over a metallic layer, suitable for reflecting solar radiation in the solar radiation band 205. For another example, nanoparticles which reflect solar radiation can be doped in a polymer film. For another example, metal flakes which can reflect solar radiation can be deposited on a surface and a transparent overcoat with a high emissivity may be deposited to embed the metal flakes. For another example, anodised metals such as anodised aluminium may be used.

The examples of the materials which can be used for IR radiation in the sky window 204 or in the IR band 203 include polymers such as polyvinyl-fluoride polymer film (TEDLAR), polyvinylchloride (PVC), poly (4-methylpentene) (TPX) and inorganic material such as silicon nitride (Si_3N_4) or silicon oxide (SiO), magnesium oxide (MgO), lithium fluoride (LiF), silicon carbide (SiC) and silica nanoparticles.

The examples of the materials which can be used for IR radiation in the sky window 204 or in the IR band 203 further include gas such as ethylene (C_2H_2), ammonia (NH_3) and ethylene oxide ($\text{C}_2\text{H}_4\text{O}$). In this case, the encapsulation of the gas is achieved with a container with a material with a high transmissivity in the IR band 203.

The solar radiation reflection portion includes silver surface and polished aluminium surface and aluminium flakes and tin oxide (TiO_2) nanoparticles, barium sulphate (Ba_2SO_4) particles.

FIGS. 3a to 3f present exemplary embodiments of the cooling container with a radiative cooling portion.

The features of the cooling container 100 in the example of FIG. 1 are included in the cooling container 300 in FIGS. 3a to 3f, unless otherwise noted. The cooling container 100, 300 includes a main body 110, 310 and the top structure 120, 320. The top structure 120, 320 is configured to be fitted into the aperture 111, 311 and to hold the radiative cooling portion 340. The top structure 120, 320 comprises a thermally insulating material around the

radiative cooling portion 340 to reduce heat conduction into the radiative cooling portion 340 via the surrounding material of the top structure 120, 320.

The radiative cooling portion 140, 340 is configured such that when exposed to the sky, the temperature of the radiative cooling portion 140, 340 decreases as a result. As explained in FIG. 2, the radiative cooling portion 140, 340 is designed or chosen to efficiently absorb and emit within the wavelength band of the sky window 204. In some implementations, the radiative cooling portion 140, 340 is designed or chosen also to efficiently reflect the solar radiation in the solar radiation band 205.

The features in the embodiments in FIGS. 3a to 3f are not to be regarded as mutually exclusive alternatives and can be included in combination in the cooling container 300 unless otherwise noted.

FIG. 3a shows an exemplary embodiment of the cooling container with a radiative cooling portion.

The radiative cooling portion 340 includes an external surface 340-1 and an internal surface 340-2.

The external surface 340-1, when the top structure 320 is fitted into the aperture 311, is arranged to be directed to the outside of the cooling container 300 such that IR radiation can be emitted from the external surface 340-1 towards the sky. In case part of the view of the sky is blocked or clouds are directly above the cooling container 300, the cooling container 300 with the top structure 320 can be tilted such that the direction normal to the external surface 340-1 points to the clearest possible portion of the sky.

The internal surface 340-2, when the top structure 320 is mounted on the cooling container 300 and fitted into the aperture 311, is arranged to face the storage space 330. The air and the contents in the storage space 330 come in thermal contact with the internal surface 340-2. When the temperature of the radiative cooling portion 340 lowers, the air and the contents in the storage space 330 are thermalised with the internal surface 340-2 to reach a steady state temperature. The air and the contents in the storage space 330 act as thermal load. When the steady state temperature becomes sufficiently low, sources of coldness, such as ice cubes or cooling gels do not need to be provided to the cooling container 300. Even when the achievable steady state temperature is higher than the desired temperature and sources of coldness, such as ice cubes or cooling gels need to be provided initially to the storage space 330, the radiative cooling portion 340 can aid in slowing down the increase of the temperature in the storage space 330.

In some implementations, the external surface 340-1 of the radiative cooling portion 340 may be directly exposed to the surrounding of the cooling container 300, as shown in FIG. 3a,

without any protection between the external surface 340-1 and the air outside the cooling container 300.

In some implementations, the internal surface 340-2 of the radiative cooling portion 340 may be directly exposed to the storage space 330, also as shown in FIG. 3a. As the radiative cooling portion 340 cools down, the temperature of the internal surface 340-2 is lowered.

Then the air inside the storage space 330, directly exposed to and in direct thermal contact with the internal surface 340-2, is thermalised with the internal surface 340-2 of the radiative cooling portion 340. As a result, the temperature of the storage space is lowered.

In some implementations, the internal surface 340-2 may comprise a metallic layer. The metallic layer has a high thermal conductivity and therefore thermalises fast with the air in the storage space 330 or any heat exchange medium between the internal surface 340-2 and the air in the storage space 330. For example, the internal surface 340-2 may be the polished surface of an aluminium substrate and the external surface 340-1 may be a polymeric layer, such as PDMS layer, disposed on the aluminium substrate.

In some implementations, the internal surface 340-2 comprises a blackbody radiator. Since the blackbody radiator absorbs and emits the IR radiation efficiently, the radiative transfer of heat to and from the internal surface 340-2 can be more efficient. For example, the internal surface may be painted with carbon black.

In some implementations, the internal surface 340-2 comprises a metallic layer with a thin layer of blackbody radiator. For example, the internal surface 340-2 may be a polished aluminium surface painted with carbon black. This is to enhance the heat transfer from the internal surface 340-2 to the storage space 330 both via conduction and thermal radiation. For the reasons explained in FIG. 2, the net cooling power and the minimum achievable temperature of the radiative cooling portion 340 may be different at different times of the day.

For example, the net cooling power in the presence of the solar radiation is less than the cooling power in absence of the solar radiation. The net cooling power and the minimum achievable temperature of the radiative cooling portion 340 also depend on the weather conditions such as humidity and the amount of sunlight. For example, in the tropical regions with high humidity, the degree of downwelling is higher than that of the dry regions.

Depending on the weather conditions and the region, at least for some hours each day, the minimum achievable temperature of the radiative cooling portion 340 may be higher than the desired temperature of the storage space 330. For example, the desired temperature in the storage space 330 may be at least 15 degrees celsius or lower. However, during the day, the radiative cooling portion 340 may not be able to reach a temperature lower than 15 degrees.

Whenever the desired temperature in the storage space 330 is not obtainable by the radiative cooling portion 340, the cap 150 can be mounted on the main body 310 over the top structure 320. Then the radiative cooling portion 340 is blocked from being exposed to the surroundings by the cap 150 and the storage space 330 is thermally insulated from the surroundings.

Alternatively, in some implementations, when the desired temperature in the storage space 330 is not obtainable by the radiative cooling portion 340, the top structure 320 may be removed from the cooling container 300 and the cap 150 may be mounted to seal the storage space 330.

For example, if the desired temperature is 10 degrees celsius and if during the night for several hours, the radiative cooling portion 340 may be able to reach a temperature below 10 degrees celsius, the top structure 320 including the radiative cooling portion 340 is mounted only during those hours.

In some implementations, the top structure 320 may be removed from the cooling container 300 and the temperature of the radiative cooling portion 340 can be monitored before being mounted on the cooling container 300.

When to fit the top structure 320 on can be decided by monitoring the temperature of the radiative cooling portion 340. For example, the top structure 320 can be disposed separate from the cooling container 300 to be directed to clear sky. As soon as the temperature of the internal surface 340-2 is within the target level, the top structure 320 can be mounted. This reduces the interval of time where the storage space 330 and the contents are exposed to a surface with a temperature higher than the desired temperature.

Although not shown in FIG. 3a, in some implementations, the top structure 320 may comprise a temperature sensor and a readout monitoring the temperature of the internal surface 340-2. For example, the digital readout can be implemented with a solar powered battery, also mounted on the top structure 320. Alternatively, in case the radiative cooling portion 340 is fixed in the main body 310, the temperature sensor and the readout may be also mounted on the main body 310.

In some implementations, the main body 310 may comprise a temperature sensor and a readout monitoring the temperature of the storage space 330. For example, the digital readout can be implemented with a solar powered battery, also mounted on one of the walls of the main body 310. This enables the user to determine whether to mount the top structure including the radiative cooling portion 340 or to further introduce sources of coldness.

FIG. 3b shows an exemplary embodiment of the cooling container with a convective cover disposed over a radiative cooling portion.

In some implementations, the cooling container 300 may further include a convection cover 360.

As the temperature of the external surface 340-1 of the radiative cooling portion 340 becomes lower than the ambient temperature, the temperature gradient generates the movement of air, convection, around the external surface 340-1 and the convection continues until the radiative cooling portion 340 is thermalised with the ambient air.

Therefore, the convection contributes as heat gain into the radiative cooling portion 340. In some cases, when the wind speed is high, it may not be possible to achieve a temperature lower than the ambient temperature due to convection.

In order to prevent the flow of air into the external surface 340-1 and/or prevents dew and first formation, the convection cover 360 can be disposed between the ambient air and the external surface 340-1 of the radiative cooling portion 340 to prevent the convection while transmitting the IR radiation in the IR band 203. With the convection cover 360, a temperature lower than the ambient temperature can be facilitated at the radiative cooling portion 340.

The transparency band of the convection cover 360 is configured to cover the emission spectrum of the radiative cooling portion 340. The convection cover 360 is configured to efficiently transmit the IR radiation at least within the wavelength range where the emission from the radiative cooling portion 340 exceeds the absorption of downwelling.

For example, when the emissivity spectrum of the radiative cooling portion 340 is designed to be a selective emitter, close to the first curve 210 in FIG. 2, the convection cover 360 may be configured to be transparent at least within the sky window 204. When the emissivity spectrum of the radiative cooling portion 340 is designed to be a blackbody emitter, close to the second curve 220 in FIG. 2, the convection cover 360 may be configured to be transparent throughout the IR band 203.

In some implementations, when the cooling container 300 includes the top structure 320 and the top structure 320 includes the radiative cooling portion 340, the convection cover 360 is included in the top structure 320, placed above the radiative cooling portion 340, as depicted in FIG. 3b.

The examples of the convection cover 360 includes polyethylene film ranging from 10 to 500 microns thickness. In this case, a thinner thickness leads to a higher transmission, therefore a higher efficiency of radiative cooling but at the cost of a lower mechanical strength. For example, 10 micron thickness of polyethylene film provides 90% transmission in the sky window 204.

Other examples of the convection cover 360 includes polypropylene in sheet, foil or fabric form, or other inorganic materials such as zinc sulfide (ZnS) and cadmium telluride (CdTe) thin film. The examples are not limited to these examples.

In some implementations, the convection cover 360 is also configured to efficiently reflect the solar radiation in the solar radiation band 205. The convection cover 360 optimised for IR transmission can be doped with particles which reflects solar radiation.

For example, a polyethylene film can be doped with one or more of titanium oxide (TiO₂) white pigments and carbon black particles, zinc sulfide (ZnS) particles, zinc selenide (ZnSe) particles. For another example, a polyethylene film can be coated with lead sulfide (PbS) or lead selenide (PbSe) thin films. This prevents the convection cover 360 from heating up by absorbing solar radiation.

A gap 361 between the external surface 340-1 and the convection cover acts as a thermal insulation between the ambient air and the radiative cooling portion 340.

In some implementations, the top structure 320, the radiative cooling portion 340 and the convective cover 360 form an airtight structure. In some implementations, the gap 361 may be under negative pressure.

In some implementations, the top structure 320 may further comprise one or more spacers 362. In case the convective cover 360 is not a rigid material, the spacer 362 comprising a thermally insulating material may be disposed within the gap to maintain the space between the radiative cooling portion 340 and the convective cover 360.

For example, when the convective cover 360 is a polymer film, the spacer 362 may be in the form of a grid such that the convective cover 360 in the form of a film is supported at a regular interval across the area of the external surface 340-1. The low density polyethylene film, for example a food wrap, can be a good convective cover 360 considering that the thickness is around 15 microns. In case the low density polyethylene film is used as convective cover 360, the convective cover 360 can be replaced regularly by the user to ensure mechanical stability.

In some implementations, the spacer 362 may comprise a material with low emissivity in IR band 203. The spacer 362 in this case may act as a heat mirror which efficiently reflects the thermal IR radiation in the IR band 203. The height of the spacer 362 may be configured to direct the emission from the radiative cooling portion 340 towards the zenith or into a predetermined solid angle around the zenith direction and to reflect the downwelling outside that solid angle. This will be discussed in more detail in FIG. 3g.

FIG. 3c shows an exemplary embodiment of the cooling container with a radiative cooling portion and a heat siphon structure.

The cooling container 300 depicted in FIG. 3c may include any of the features discussed in FIGs. 3a and 3b. For example, the cooling container 300 may include a convective cover 360 and spacers 362.

In some implementations, the cooling container 300 may include a heat siphon structure 321 or a thermosiphon structure 321. In case the cooling container 300 includes a top structure 320, the heat siphon structure 321 may be included in the top structure 320.

In FIG. 3c, the cross section of the heat siphon structure 321 is illustrated with the cross section of the top structure 320 in the yz-plane. In case the heat siphon structure 321 is included in the top structure 320, the heat siphon structure 321 may be formed integrally within the top structure by forming an air channel at the periphery of the top structure 320. The air channel is formed such that only the portion of the air within the storage space 330 which reached the highest point near the wall of the main body 310 is let into the air channel. This way, only the warmest portion of the air, which travelled upwards within the storage space 330, is introduced into the top structure 320. Once in the air channel, the warm air is guided into the internal surface 340-2. The heat siphon structure 321 includes a hole 322 formed to expose at least part of the internal surface 340-2 of the radiative cooling portion 340 to the storage space 330. The air is cooled down by being in contact with the internal space 340-2 as the temperature decreases. The cooled down air, with a higher density than the vicinity, descends through the hole 322 into the storage space 330.

An exemplary movement of air within the storage space 330 around the heat siphon structure 321 is depicted as a solid arrow labelled 323 in FIG. 3c. A warmer portion of the air inside the storage portion 330, directed upwards, enters the thermosiphon structure 321 at the periphery near the wall of the main body 310 and is guided by the thermosiphon structure 320-1 to travel in the transverse direction, the y-direction in the example of FIG. 3c, towards the centre of the internal surface 340-2. The portion of the air in contact with the internal surface 340-2 is cooled and subsequently travels downwards in the opening 322 of the thermal siphon structure 321 near the centre of the internal surface 340-2.

Since the air inside the storage space 330 is directly exposed to the internal surface 340-2 of the radiative cooling portion 340, the heat exchange medium is the air inside the storage space 330. The thermosiphon structure 320-1 passively circulates the air and enhances the circulation of the air inside the storage portion 330 by convection. The enhanced circulation arises especially when the temperature difference between the internal surface 340-2 and the storage space 330 is large.

The heat siphon structure 321 renders the airflow within the storage space 330 more efficient such that the thermalisation with the internal surface 340-2 is achieved quicker and in a more uniform fashion.

FIG. 3d shows an exemplary embodiment of the cooling container with a radiative cooling portion and a thermal storage medium.

The top structure 320 depicted in FIG. 3d may include any of the features discussed in FIGs.

5 3a to 3c. For example, the top structure 320 may include a convective cover 360 and the spacers 362.

In some implementations, the cooling container 300 may include a thermal storage medium 370. When the cooling container 300 includes the top structure 320, the thermal storage medium 370 may be included in the top structure 320. The thermal storage medium 370 is
10 disposed in the vicinity of or in physical contact with the internal surface 340-2 such that coldness can be transferred from the radiative cooling portion 340 to the thermal storage medium 370 via conduction.

The thermal storage medium 370 may be disposed to face the storage space 330. At least a surface of the thermal storage medium 370 may be exposed to the storage space 330 such
15 that the air and the contents within the storage space 330 are thermalised with the thermal storage medium 370.

The thermal storage medium 370 includes a thermal storage enclosure 371 and a thermal storage material 372. The thermal storage material 372 is enclosed in a thermal storage enclosure 371. A lower surface 371-1 of the thermal storage enclosure faces the storage
20 space 330 and in direct contact with the air in the storage space 330. The thermal storage medium 370 acts as a heat exchange medium between the radiative cooling portion 340 and the contents and the air of the storage space 330.

In some implementations, a surface of the thermal storage enclosure 371 is in contact with the internal surface 340-2 of the radiative cooling portion 340 or integrally formed with the
25 radiative cooling portion 340 such that the thermal storage material 372 is directly in contact with the internal surface 340-2 of the radiative cooling portion 340. The thermal storage medium 370 effectively increases the thermal mass or heat capacity of the radiative cooling portion 340.

In some implementations, the thermal storage enclosure 371 is separate from the radiative
30 cooling portion 340 and an efficient heat transfer is facilitated from the radiative cooling portion 340 via a thermal contact. In this case, an efficient thermal contact is to be implemented, for example, using thermal paste between the internal surface 340-2 and the thermal storage enclosure 371.

Alternatively, in some implementations, the internal surface 340-2 and the thermal storage
35 enclosure 372 are integrally formed such that the thermal storage material 372 is enclosed by the thermal storage enclosure 372 and the internal surface 340-2 of the radiative cooling portion 340. In this case, shown in FIG. 3d, the thermal storage material 372 is in direct

contact with the internal surface 340-2 although it is in thermal contact with the storage space 330 via the thermal storage enclosure 372.

The material and the thickness of the thermal storage enclosure 371 are chosen such that the heat transfer coefficient or the thermal resistance is kept at a minimum while ensuring necessary mechanical strength. The thermal storage enclosure 371 may comprise a material with a thermal conductivity larger than $0.1 \text{ Wm}^{-1}\text{K}^{-1}$.

For example, when a commercial ice gel pack can be used as the thermal storage medium 370 and attached to the internal surface 340-2, the thermal enclosure 371 may be plastic casing with a few hundred microns thickness. Other examples of the thermal enclosure 371 includes fibreglass, or glass-lined steel containers.

In some implementations, the lower surface 371-1 of the thermal enclosure 371 comprises a metallic layer. Compared to plastic or other dielectric material, the metallic layer has a higher thermal conductivity and therefore may thermalise faster with the air in the storage space 330. For example, the lower surface 371-1 may be the polished surface of an aluminium.

In some implementations, the lower surface 371-1 comprises a blackbody radiator. Since the blackbody radiator absorbs and emits the IR radiation efficiently, the radiative transfer of heat to and from the lower surface 371-1 can be rendered more efficient. For example, the lower surface 371-1 may be painted with carbon black.

In some implementations, the lower surface 371-1 comprises a metallic layer with a thin layer of blackbody radiator. For example, the lower surface 371-1 may be a polished aluminium surface painted with carbon black. This is to enhance the heat transfer from the lower surface 371-1 to the storage space 330 both via conduction and thermal radiation.

In some implementations, the thermal storage material 372 comprises a sensible heat storage medium. The sensible heat storage medium, either liquid or solid, can store coldness obtained from the radiative cooling portion 340 by lowering the temperature of the heat storage medium. A material with a high specific heat or a large heat capacity can be chosen for the thermal storage material 372 for sensible heat storage.

For example, the thermal storage material 372 for sensible heat storage can be water, in case the desired temperature in the storage space 330 is above zero degree celsius. Water has low cost and relatively high specific heat and is safe.

In some implementations, the thermal enclosure 371 may comprise an sealable opening configured such that the thermal storage material 372, for example water, can be replenished or exchanged.

In some implementations, the thermal storage material 372 comprises a latent heat storage medium. The latent heat storage medium can store coldness obtained from the radiative cooling portion 340 both by lowering the temperature and by releasing heat when the latent heat storage medium undergoes a phase change. A material with a high specific heat or a

large heat capacity, a high phase transition latent heat, and a melting temperature within the operating range can be chosen for the thermal storage material 372.

For example, when the operating temperature range includes zero degree celsius, water can be the thermal storage material 372 for latent heat storage and the coldness is stored as water is freezed to ice.

Other examples of the thermal storage material for latent heat storage include the phase change material (PCM) such as salt hydrates, eutectic salt or paraffin.

Considering the operation near ambient temperature or food storage temperature, the examples of salt hydrates include Lithium Chlorate Trihydrate ($\text{LiClO}_3 \cdot 3\text{H}_2\text{O}$, 8),

Dipotassium Hydrogen Phosphate Hexahydrate ($\text{K}_2\text{HPO}_4 \cdot 6\text{H}_2\text{O}$, 14) and Potassium Fluoride Tetrahydrate ($\text{KF} \cdot 4\text{H}_2\text{O}$, 18.5). The parentheses indicate molecular formula and approximate melting temperature in degrees celsius.

The examples of eutectic salt include 45% $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ + 55% $\text{CaBr}_2 \cdot 6\text{H}_2\text{O}$ with 14.7 degree celsius melting temperature.

The examples of paraffins include n-tetradecane (6), n-pentadecane (10), n-hexadecane (18) and n-heptadecane (22). The parentheses indicate approximate melting temperature in degree celsius.

The coldness can be stored in the thermal storage medium 370 during the efficient hours when the minimum achievable temperature of the radiative cooling portion 340 is far lower than the desired temperature.

During less efficient hours, when the minimum achievable temperature is higher than the desired temperature, the storage space 330 can be kept cold by the thermal storage medium 370 and the thermal isolation of the main body 310 and the cap 150. In some implementations, the cap 150 can be mounted on the cooling container 300 to cover the radiative cooling portion 340 and the storage space 330. Alternatively, in some implementations, the cap 150 can be mounted on the cooling container 300 and the radiative cooling portion can be removed.

With thermal storage medium 370, without any renewed supply of ice packs or any source of coolness, the storage space 330 can be kept within the desired temperature range longer than the thermal relaxation period defined by the thermal isolation of the main body 310 and the cap 150 and longer than the case where only the radiative cooling portion 340 is used without the thermal storage medium 370.

In addition to acting as a heat sink to store the coldness, the thermal storage medium 370 also may act as a thermal mass. The temperature fluctuation of the radiative cooling portion 340 during a day cycle will be reduced and the total cooling power will be increased.

According to the Stefan-Boltzmann law, as the temperature decreases, the cooling rate also

decreases, vice versa. The thermal storage medium 370 at a higher temperature for a longer duration leads to a higher cooling rate for a longer duration of time.

In addition to acting as a heat sink and a thermal mass, the thermal storage medium 370 can also prevent excessive cooling and therefore provides temperature regulation. For example, in case the contents in the storage space 330 should be kept above the zero degree celsius and the radiative cooling portion 340 is capable of going below zero degree celsius for some hours during the night, water can be used as the thermal storage material 372 and the amount of water can be determined such that any further cooling below zero degree celsius can be prevented.

The top structure 320 depicted in FIG. 3d may include the heat siphon structure 321 discussed in FIG. 3c. In this case, the heat siphon structure 321 depicted in FIG. 3c is positioned below the thermal storage medium 370. The description of the heat siphon structure 321 with respect to the internal surface 340-2 can be replaced with that with respect to the lower surface 371-1.

FIG. 3e shows an exemplary embodiment of the cooling container with an extendable radiative cooling portion.

The cooling container 300 depicted in FIG. 3e may include any of the features discussed in FIGs. 3a to 3d. For example, the top structure 320 may include the thermal storage medium 370, although not shown in FIG. 3e.

In some implementations, the radiative cooling portion 340 may include a main radiative cooling portion 340a and an auxiliary radiative cooling portion 340b or side radiative cooling portion 340b attached sideways to the main radiative cooling portion 340a.

One or more auxiliary radiative cooling portions 340b are attached laterally to the main radiative cooling portion 340a, in the xy-plane in FIG. 3e such that the total area of the radiative cooling portion 340 is enlarged, thereby increasing the net cooling power.

In some implementations, the cooling container 300 includes a main convective cover 360a, and an auxiliary convective cover 360b. The main convective cover 360a and the auxiliary convective cover 360b are disposed directly over the main radiative cooling portion 340a and the auxiliary cooling portion 340b, respectively. In some implementations, the cooling container 300 may further comprise the spacer 362a, 362b between the main radiative cooling portion 340a and the main convective cover 360a and/or between the auxiliary radiative cooling portion 340b and the auxiliary convective cover 360b, as shown in FIG. 3e.

In some implementations, the cooling container 300 may comprise the top structure 320 and the main convective cover 360a and the auxiliary convective cover 360b may be included in the top structure.

In some implementations, the one or more auxiliary radiative cooling portions 340b may
5 comprise add-on structures separate from the main radiative cooling portion 340a. In this case, the auxiliary radiative cooling portions 340b can be attached to the top structure 320 when they are needed. For example, although not shown in FIG. 3e, the top structure 320 and the one or more auxiliary radiative cooling portion 340b may comprise mutually matching insertion structures such that the one or more auxiliary radiative cooling portions
10 340b can be fitted onto the top structure 320.

In some implementations, the one or more auxiliary radiative cooling portions 340b are attached to the main radiative cooling portions 340a via one or more hinges 341. When not used, the one or more auxiliary radiative cooling portions 340b can be folded on top of the main radiative cooling portion 340a using the one or more hinges 341.

15 When the main radiative cooling portion 340a is included in the top structure 320, the one or more hinges 341 may be included in the top structure 320. With the one or more hinges 341 included in the top structure 320, the volume occupied by the top structure 320 can be minimised and the top structure 320 can be rendered more portable.

The external surface 340-1 of the radiative cooling portion 340, directed towards outside of
20 the cooling container 300, may comprise a main portion 340-1a of the main radiative cooling portion 340a and one or more side portions or auxiliary portion or extended portion 340-1b included in the auxiliary radiative cooling portion 340b. For radiative cooling, the side portions 340b can be disposed such that the external surface 340-1b is directed towards the outside of the cooling container 300 and to the sky.

25 When the side radiative cooling portions 340b are in an open position or deploying position to be used for radiative cooling, the side radiative cooling portions 340b are thermally connected to an internal surface 340-2a of the main radiative cooling portion 340a such that the thermal radiation emitted at the side portions 340-1b of the external surface 340-1 therefore contributes to the cooling of the storage space 330.

30 In some implementations, the thermal contact between the side radiative cooling portions 340b and the internal surface 340-2a of the main radiative cooling portion 340a is facilitated via mechanical contact between the side surfaces of the side radiative cooling portions 340b and the opposing side surfaces of the main radiative cooling portion 340a.

In some implementations, the thermal contact between the side radiative cooling portions
35 340b and the internal surface 340-2a of the main radiative cooling portion 340a is facilitated via heat conduction at the one or more hinges 341.

The internal surface 340-2a of the main radiative cooling portion corresponds to the internal surface 340-2 of the radiative cooling portion 340 described earlier in this specification.

In some implementations, the radiative cooling portion 340 may further comprise insulating layer 342 deposited on parts of the one or more side radiative cooling portions 340b.

5 The insulating layer 342 may be deposited to cover the parts of the side radiative cooling portions 340b which are not configured to emit IR radiation towards the sky and the parts which are not configured to be thermally connected to the storage space 330. This is to prevent unnecessary thermal loss via conduction or convection from the radiative cooling portion 340.

10 As shown in FIG. 3e, parts of the side radiative cooling portion 340b which extends outside of the footprints or the area occupied by the cooling container 300 can be covered with the thermal insulation 342.

The area enlarged by the addition of the side radiative cooling portions 340b contributes to increased cooling capacity, therefore extended duration of storage time. For example, if an

15 average of 50 W/m² of net cooling power is obtained for seven hours a day with the chosen material of the radiative cooling portion 340, the main radiative cooling portion 340a with the external surface 340-1a of 30cm by 45cm area can provide an cooling energy of 170100J, which is equivalent to heat absorbed in melting around 500 grams of ice. By using additional auxiliary radiative cooling portions 340b with twice the area of the external surface 340-1b,
20 the cooling power can be three times, corresponding to melting 1.5kg of ice.

In a commercial ice chest, the performance is often tested by measuring the time duration for the temperature to change from 5 degrees celsius to 15 degrees when 1.5kg of ice is provided within the storage space 330. The performance of the cooling container 300 with the radiative cooling portion 340 can be comparable to the performance of the commercial
25 ice chest starting with 1.5kg ice as the cold source.

According to this estimation, the cooling container 300, whose performance is comparable to the commercial ice chest, with the radiative cooling portin with an area of 0.4m², can be left overnight to expose the radiative cooling portion 340 towards the sky to store the coldness in the thermal storage medium 370. The stored coldness can be used during the day with the
30 cap 150 on over the main body 310. The cooling container 300 can be used continuously without supplying any ice.

Depending on the climate, the 50W/m² cooling power for seven hours, the assumption for the estimation above, may be regarded as conservative. For example, in a climate where daytime radiative cooling is feasible, a comparable cooling power can be achieved for a
35 larger number of hours and the use of the auxiliary radiative cooling portions 340b may not be necessary.

FIG. 3f shows an exemplary embodiment of the cooling container with a radiative cooling portion and a heat mirror structure.

The cooling container 300 depicted in FIG. 3f may include any of the features discussed in FIGS. 3a to 3e. For example, the cooling container 300 may include a convective cover 360 and thermal storage medium 370, although not shown in FIG. 3f.

In some implementations, the cooling container 300 further includes a heat mirror structure 380. The heat mirror structure 380 comprises a heat mirror 381.

In some implementations, the cooling container 300 may comprise a top structure 320 and the heat mirror structure 380 may be mounted on the top structure 320.

The heat mirror 381 comprises a surface with an average emissivity less than 0.1 in the sky window 204. The material for the heat mirror 381 is chosen to have minimum possible emissivity such that both the absorption and the emission of the IR radiation in the IR band 203 are minimised. The heat mirror 381 may comprise a metallised surface, for example, bare polished aluminium surface or metallised silver surface with a thin oxide protective layer.

The heat mirror structure 380 can be mounted around or on the radiative cooling portion 340 but not to completely obstruct the line of sight towards the sky from the external surface 340-1. For example, the heat mirror structure 380 can form a fence around the radiative cooling portion 340 with a finite height such that the incidence angle into the external surface 340-1 is limited outside a certain angle from the zenith direction, or the direction normal to the external surface 340-1 when the cooling container 300 stands upright.

In some implementations, the heat mirror structure 380 may be formed as a tubular structure, wherein the heat mirror structure 380 comprises a first opening and a second opening. The heat mirror structure 380 is arranged such that the thermal radiation emitted from the external surface 340-1 enters the heat mirror structure through the first opening and exits through the second opening.

As discussed above, the degree of downwelling varies decreasingly from the vertical or the zenith direction towards the horizontal direction. Therefore, the transparency of the sky window 204 depends on the direction and is most transparent in the zenith direction. For example, at an incidence angle near to the horizontal direction, the downwelling contribution within the sky window 204 almost follows that of the blackbody radiation. In other words, the sky window 204 is “closed” and the heat transfer by IR thermal radiation from the radiative cooling portion 340 to the sky is largely offset by the downwelling. Therefore, if the radiative cooling portion 340 is arranged to only accept within a limited solid angle around the zenith direction, the outgoing IR radiation at large angles can be redirected into the direction near the zenith, whereas the downwelling contribution at large angles can be rejected. Therefore, the performance of the radiative cooling portion 340 can be enhanced.

In some implementations, the heat mirror structure 380 may include an insertion structure 382, which fits into a insertion groove 323 on the main body 310. In some implementations, when the heat mirror structure 380 is mounted on the top structure 320, the insertion groove 323 is included in the top structure 320. The heat mirror structure 380 can be an add-on structure which can be mounted only when needed. When the insertion structure 382 is inserted into the insertion groove 323, the heat mirror structure 380 is fixed to the top structure 320 and the acceptance solid angle with respect to the normal direction of the external surface 341-1 of the radiative cooling portion 340 is limited to a predetermined value.

FIG. 3g shows exemplary embodiments of the heat mirror structures.

The panels 380-1, 380-2, 380-3 show three examples of the geometry of the heat mirror structure 380. The heat mirror structure 380 comprises one or more channels with at least two openings on each side. One of the openings is arranged to at least partially enclose the radiative cooling portion 380. The other of the openings is, when mounted on the cooling container 300, arranged to face the sky, in the zenith direction or towards the clear part of the sky.

In some implementations, the heat mirror structure 380 comprises a frustum or a truncated structure. For example, the first panel 380-1 shows a heat mirror structure 380-1 in the form of a truncated pyramidal structure or a trapezoidal prism. For another example, the second panel 380-2 shows a heat mirror structure 380-2 in the form of a truncated cone with the two truncated planes, top and bottom or a truncated paraboloid surface.

The first panel 380-1 shows that the heat mirror structure 380-1 comprises four pieces of the heat mirror 381-1, forming side surfaces of a trapezoidal prism. The side of the heat mirror 380-1 towards the smaller opening or the smaller truncated plane, is connected to the insertion structure 382. When installed on the cooling container 300 or the top structure 320, the external surface 340-1 of the radiative cooling portion 340 is exposed through the smaller opening of the truncated planes.

The second panel 380-2 shows that the heat mirror 381-2 comprises a truncated cone shape or a truncated paraboloid shape. The side of the heat mirror 381-2 with the smaller opening comprises the insertion structure 382 to be attached to the top structure 320 via the insertion groove 323. When installed on the top structure 320, the external surface 340-1 of the radiative cooling portion 340 coincides with the plane of the smaller opening. In some implementations, when the heat mirror 381 comprises a truncated paraboloid shape, the external surface 340-1 traverses the foci of the parabola such that the emission from the

radiative cooling portion 340 is emitted normal to the external surface 340-1. The side of the heat mirror 380 towards the smaller opening or the smaller truncated plane, is connected to the insertion structure 382.

In some implementations, as shown in the third panel 380-3, the heat mirror structure 380-3 comprises a plurality of walls of heat mirror 381-3 and grid structure 384 included within the plurality of walls. The grid structure 384 comprises a plurality of planes arranged to intersect with each other, dividing the space within the four parallel walls of the heat mirror 381 into a plurality of elongated channels. The planes of the grid structure also comprises low emissivity material or the same material as the heat mirror 381-3.

For example, the heat mirror structure 380-3 in the third panel 380-3 comprises four walls and the grid structure 384 comprises a plurality of planes, each plane being parallel to two of the walls, dividing the space within the walls into a plurality of cuboid shape channels. The insertion structure 382, is disposed around the opening arranged to expose the radiative cooling portion 340 when mounted on the cooling container 300.

In some implementations, when the heat mirror structure 380 is mounted on the cooling container 300, the convective cover 360 may be placed on the top opening of the heat mirror structure 380, opposite the bottom opening near the radiative cooling portion 340.

As discussed in FIG. 3b, when the convective cover 360 comprises a material of low mechanical stability such as low density polyethylene film, the spacer 362 may be disposed to provide extra mechanical support. In the heat mirror structure in the third panel 380-3, the grid structure 384 corresponds to the spacer 362 in the description of FIG. 3b. The height of the planes of the grid structure 384 may be configured to direct the emission from the radiative cooling portion 340 towards the zenith or into a predetermined solid angle around the zenith direction and to reflect the downwelling outside that solid angle.

The embodiments of the invention shown in the drawings and described above are exemplary embodiments only and are not intended to limit the scope of the invention, which is defined by the claims hereafter. It is intended that any combination of non-mutually exclusive features described herein are within the scope of the present invention.

Claims

1. a cooling container, comprising:
a thermally insulating container comprising a storage space;
5 a radiative cooling portion comprising an internal surface and an external surface,
wherein the internal surface faces the storage space and the external surface is
exposed to an outside of the cooling container, and
wherein the radiative cooling portion is configured to dissipate heat from the storage
space by emitting a thermal radiation to the outside via the external surface.
10
2. the cooling container of claim 1, further comprising:
a thermal storage medium arranged to be in thermal contact with the internal surface
and with the storage space such that heat is dissipated from the storage space and the
thermal storage medium by the radiative cooling portion.
15
3. the cooling container of claim 2,
wherein the thermal storage medium comprises a sensible heat storage material.
4. The cooling container of claim 2,
20 wherein the thermal storage medium comprises a latent heat storage material.
5. the cooling container of any preceding claim, further comprising:
a heat siphon structure configured to facilitate a circulation of air inside the storage
space when the radiative cooling portion is colder than the storage space.
25
6. the cooling container of any preceding claim, further comprising:
a heat mirror structure configured to reflect and redirect the thermal radiation from
the radiative cooling portion within a predetermined solid angle from a normal direction from
the external surface.
30
7. the cooling container of claim 6,
wherein the heat mirror structure comprises a first opening and a second opening,
and
wherein the heat mirror structure is arranged such that the thermal radiation emitted
35 from the external surface enters the heat mirror structure through the first opening and exits
through the second opening.

8. the cooling container of any preceding claim, further comprising:
a convective cover disposed over the external surface and configured to transmit the thermal radiation and to shield the radiative cooling portion from an air flow of the outside of the cooling container.
9. the cooling container of claim 8 as dependent on claim 7,
wherein the convective cover is disposed over the second opening.
10. the cooling container of any one of claims 6 to 9,
wherein the heat mirror structure comprises a grid structure such that a plurality of channels are formed from the first opening and the second opening, and
wherein each of the plurality of channels is configured to reflect and redirect the thermal radiation emitted from the external surface.
11. the cooling container of any preceding claim, further comprising:
an aperture on the thermally insulating container through which the storage space is exposed to the outside of the cooling container; and
a top structure mountable on the aperture to block the aperture and configured to be thermally insulating,
wherein the radiative cooling portion is included in the top structure.
12. the cooling container of any preceding claim, further comprising:
a cap mountable on the thermally insulating container,
wherein the cap is configured to be thermally insulating such that the storage space is thermally insulated when the cap is mounted, and
wherein when the cap is disposed over the radiative cooling portion, the cap is configured to block the thermal radiation emitted from the radiative cooling portion.
13. a structure for covering an aperture of a container, comprising:
a radiative cooling portion comprising an internal surface and an external surface;
a thermally insulating portion configured to house the radiative cooling portion and to be fitted into the aperture,
wherein when the structure is disposed on the container to cover the aperture, the internal surface faces a storage space of the container and the external surface is exposed to an outside of the container, and

wherein the radiative cooling portion is configured to dissipate heat from the storage space by emitting a thermal radiation to the outside via the external surface.

14. the structure of claim 13,

5 a thermal storage medium arranged to be in thermal contact with the internal surface and such that when the structure is disposed on the container to cover the aperture, the thermal storage medium is in thermal contact with the storage space and such that heat is dissipated from the storage space and the thermal storage medium by the radiative cooling portion.

10 15. the structure of claim 13 or 14, further comprising:

a heat siphon structure configured to facilitate a circulation of air inside the storage space when the radiative cooling portion is colder than the storage space.

15 16. the structure of any one of claims 13 to 15, further comprising:

a heat mirror structure configured to reflect and redirect the thermal radiation from the radiative cooling portion within a predetermined solid angle from a normal direction from the external surface.

20 17. the cooling container of claim 16,

wherein the heat mirror structure comprises a first opening and a second opening, and

wherein the heat mirror structure is arranged such that the thermal radiation emitted from the external surface enters the heat mirror structure through the first opening and exits
25 through the second opening.

18. the structure of any one of claims 13 to 17, further comprising:

a convective cover disposed over the external surface and configured to transmit the thermal radiation and to shield the radiative cooling portion from an air flow of the outside of
30 the cooling container.

19. the cooling container of claim 18 as dependent on claim 17,

wherein the convective cover is disposed over the second opening.

35 20. the cooling container of any one of claims 16 to 19,

wherein the heat mirror structure comprises a grid structure such that a plurality of channels are formed from the first opening and the second opening, and

wherein each of the plurality of channels is configured to reflect and redirect the thermal radiation emitted from the external surface.