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(54) **ELECTRIC HEATER AND METHOD FOR PROVIDING PROCESS HEAT**

(57) The present invention relates to an electric heater for providing process heat by electrically heating a gaseous fluid stream to a temperature of 1000 °C or more is proposed. The electric heater comprises a heating chamber having a gas inlet configured for providing the gaseous fluid stream to inside the heating chamber and a gas outlet configured for providing the gaseous fluid stream having a temperature of more than 1000 °C to outside the heating chamber. The electric heater further comprises a first heating stage housed in the heating chamber. The first heating stage comprises one or more first active ceramic resistance heating elements that are arranged and configured for generating heat with a first temperature of 1000 °C or more, when applying an electric current to the one or more first active ceramic resistance heating elements. Moreover, the first heating stage comprises at least one passive thermal element that is arranged and configured for passively heating the gaseous fluid stream to the temperature of 1000 °C or more and/or for storing heat generated by the one or more first active ceramic resistance heating elements.

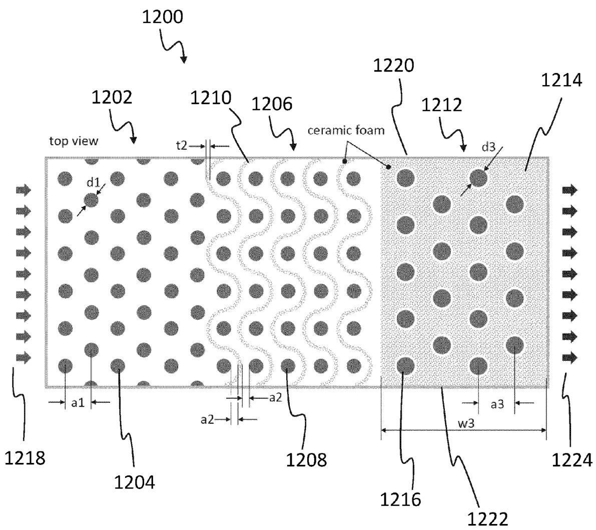

Fig. 12

EP 4 481 293 A1

Description

TECHNICAL FIELD OF THE INVENTION

[0001] The present invention relates to an electric heater configured in a modularway for providing process heat with 200 kilowatts (kW) to 3 megawatts (MW) per unit up to 150 MW in total by electrically heating a gaseous fluid stream to a temperature of 1000 °C or more. Furthermore, the present invention relates to a heating system configured for generating and/or storing process heat. The present invention also relates to a method of providing process heat with an electric heater and to a method of maintenance of an electric heater.

BACKGROUND OF THE INVENTION

[0002] Various different industrial processes require process heat, sometimes also called industrial heat, at MW-scale for the manufacture of an industrial product such as concrete, glass, steel, or paper. Traditionally, providing process heat relies on burning fuels, natural gas or coal. Evidently, the traditional way of providing process heat based on fossil energy leads to the emission of carbon dioxide (CO_2), which in turn increases the earth's natural greenhouse effect causing the global temperature to rise.

[0003] It is thus desirable to provide a system and method for providing process heat at MW-scale for use in industrial processes, which is either carbon neutral or at least causes a significantly reduced emission of CO_2.

SUMMARY OF THE INVENTION

[0004] The present invention is based on the objective of providing an improved electric heater and an improved method for providing process heat. Furthermore, the present invention is based on the objective of providing an improved heating system for generating and/or storing process heat.

[0005] According to the invention, an electric heater for providing process heat by electrically heating a gaseous fluid stream to a temperature of 1000 °C or more is proposed. The electric heater comprises a heating chamber having a gas inlet configured for providing the gaseous fluid stream to inside the heating chamber and a gas outlet configured for providing the gaseous fluid stream having a temperature of more than 1000 °C to outside the heating chamber. The electric heater further comprises a first heating stage housed in the heating chamber. The first heating stage comprises one or more first active ceramic resistance heating elements that are arranged and configured for generating heat with a first temperature of 1000 °C or more, when applying an electric current to the one or more first active ceramic resistance heating elements. Moreover, the first heating stage comprises at least one passive thermal element, preferably, comprising a ceramic material, that is arranged and configured for passively heating the gaseous fluid stream to the temperature of 1000 °C or more and/or for storing heat generated by the one or more first active ceramic resistance heating elements.

[0006] The present invention includes the recognition that the generation of process heat above 1000 °C with known solutions, in general, includes a combustion of natural gas. To avoid CO_2 emission during the generation of process heat above 1000 °C, it is necessary to fully decarbonize high-temperature process heat by replacing natural gas burners by an environmentally friendly solution.

[0007] Process heat of 1000 °C or more is generally difficult to achieve without burning fossil fuels. Therefore, hard-to-abate sectors, like steel and cement, are nowadays responsible for more than 6 % of global COz-emissions. So far, no solution exists that is cost-competitive or easy-to-integrate as burning fossil fuels. In fact, up to now burning fossil fuels was by far the most economical way to generate high-temperature heat. Since in the past, decades of research and optimization were focused on manufacturing processes based on fossil fuels as energy carrier, no easy and fast way to just "switch" to another technology is generally available. With the electric heater according to the present invention, an alternative solution is now available. In particular, the electric heater according to the present invention provides a clean solution which can be operated with no COz-emission in the atmosphere.

[0008] This is because, with the electric heater according to the invention, it is possible to convert electricity, preferably, renewable electricity, into process heat. With the electric heater, this is achieved by employing a first heating stage that comprises one or more first active ceramic resistance heating elements. By applying an electric current to the one or more first active ceramic resistance heating elements, the one or more first active ceramic resistance heating elements generate heat that in turn is used heat a gaseous fluid stream that is flowing from the gas inlet towards the gas outlet. Since one or more first active ceramic resistance heating elements are employed, it is possible to generate heat of 1000 °C or more. In particular, the use of ceramic materials in the one or more first active ceramic resistance heating elements enables the generation of heat of 1000 °C or more. By having one or more passive thermal elements, preferably made of a ceramic material, in addition to the one or more first active ceramic resistance heating elements, it is possible to electrically heat a gaseous fluid stream traversing the heating chamber to a temperature of 1000 °C or more. In particular, using one or more first passive thermal elements in addition to the one or more first active ceramic resistance heating elements has the advantage that the efficiency of the electric heater can be significantly increased and operating costs reduced. This is because active ceramic resistance heating elements, e.g., made of silicon carbide (SiC), may be subject to material oxidation and aging. Passive thermal elements, e.g., made of or comprising a ceramic material such as SiC or the like, in operation, are heated through radiative heat transfer from the active ceramic heating elements. The passive thermal elements are permissible to age, while increasing the active convective heat transfer area to improve the heating of the gaseous fluid stream to a temperature of 1000 °C or more. Moreover, passive thermal elements may contribute beneficially to the operation of the electric heater as air flow guides by guiding the gaseous fluid stream such that turbulence and mixing of the gaseous fluid stream is increased thereby resulting in more homogeneous air outlet temperature.

[0009] With the electric heater according to the invention, it is thus possible to replace fossil fuels in energy-intensive industries by an environmentally friendly and cost-effective solution. For example, off-grid solar or wind electricity can be used for generating the electricity used by the electric heater to generate process heats. The electric heater is comparatively easy to integrate in common existing industrial plants by connecting the gas outlet to a process heat distribution system of the respective industrial plants.

[0010] Preferably, the gaseous fluid is ambient air. Preferably, the electric heater is configured to provide a total mass flow rate of the gaseous fluid stream of at least 2 kilograms per second (approximately 1.5 Nm^3/s) at a temperature of 1000 °C or more, e.g., of 1250 °C or more. Preferably, the electric heater is configured to drive the gaseous fluid stream from the gas inlet to the gas outlet through the heating chamber at an average velocity of 10 m/s up to 60 m/s. Preferably, the electric heater is configured for converting electricity into process heat at a temperature of 1500 °C or more, e.g., 1800 °C or more, e.g., up to 2000 °C.

[0011] Preferably, the gas inlet comprises an air blower fan to suck in ambient air and push it through the heating chamber. Preferably, the gas inlet and in particular, the blower fan, is configured to provide a gaseous fluid stream of at least 2 kilograms per second. For example, the gas inlet may comprise an air blower fan and an upstream filter, which convey the sucked in ambient air directly via a pipe to into the heating chamber. The temperature of the gaseous fluid stream may be measured directly after the gas inlet. To this end, the gas inlet may comprise a gas inlet temperature sensor.

[0012] The gas outlet may be configured as a pipe, which comprises a closing valve, so that if one or more electric heaters, e.g., arranged as an electric heater module in a container, are connected to a common hot air pipe system, e.g., of an industrial plant, individual outlets can be closed when the respective electric heater module is switched off. Preferably, the gas outlet comprises a gas outlet temperature sensor that is arranged and configured to measure the temperature of the gaseous fluid steam at the gas outlet. It is possible that the electric heater only comprises a gas outlet temperature sensor and not a gas inlet temperature sensor and *vice versa.*

[0013] Preferably, the heating chamber is configured as an insulated duct. The duct can be connected at the gas outlet, e.g., to an industrial plant, or to a heat storage device for storing the process heat. For example, an insulation of the heating chamber, e.g., inside the heating chamber may comprise ceramic fibres, firebricks, or fire concrete. Furthermore, an insulation of the heating chamber may comprise alumina-based materials, e.g., alumina silicate, or alumina oxide. Preferably, the heating chamber comprises an outer casing that may be made of or may comprise steel.

[0014] Preferably, the electric heater comprises a control system. The control system, preferably is configured for controlling the amount of the electric current applied to the one or more first active ceramic resistance heating elements. Preferably, the control system is configured to control the electric current applied to the one or more first active ceramic resistance heating elements in at least two groups of first active ceramic resistance heating elements of the one or more first active ceramic resistance heating elements. It is possible that the control system is configured to control the amount of electric current applied to each of the first active ceramic resistance heating elements individually. For controlling the electric current applied to the one or more first active ceramic resistance heating elements, the control system may take into account the gas inlet temperature measured by the gas inlet temperature sensor and the gas outlet temperature measured by the gas outlet temperature sensor. In case, the gas outlet temperature is below or above a predefined target gas outlet temperature, the control system, in operation, may increase or decrease the amount of the electric current applied to the one or more first active ceramic resistance heating elements in order to provide a gaseous fluid stream at the gas outlet with the predefined target gas outlet temperature.

[0015] The control system may also be configured to control the gas inlet, e.g., a blower fan, to increase or decrease the amount of ambient air sucked in the heating chamber in order to provide a gaseous fluid stream of, e.g., at least 2 kilograms per second. For example, one or more fluid flow sensors may be arranged at the gas inlet, within the heating chamber and/or within the gas outlet. The measured fluid flow of the gaseous fluid stream may be measured and the control system may be configured to adjust the operation of the gas inlet, e.g., of the blower fan, in order to increase or decrease the amount of the gaseous fluid stream traversing the heating chamber. For example, at full load, e.g., when considering a 3 MW electric heater and process heat to be applied at 1500 °C, the mass flow rate of the ambient air may be approximately 2 kg/s and the volume flow rate may be 1.5 Nm^3/s.

[0016] Preferably, the electric heater comprises a casing that has an overall size of a typical shipping container, i.e., of about 6 m x 2.5 m x 3 m. In fact, the electric heater may be arranged in a modified shipping container such that the electric heater can be easily transported to an industrial plant and attached to the industrial plant for providing process heat.

[0017] Preferably, the first heating stage has a width of 0.3 m to 1 m, a height of 0.5 m to 1.5 m and a length of 2 m to 3.5 m.

[0018] Preferably, a passive thermal element of the one or more first passive thermal elements is arranged to at least partly enclose one of the first active ceramic resistance heating elements such that when applying an electric current to the first active ceramic resistance heating element, the respective passive thermal element is heated through radiative heat transfer from the encapsulated first active ceramic resistance heating element. A free outer surface of the first active ceramic resistance heating element can be substantially fully covered or encapsulated by the passive thermal element. For example, the passive thermal element may have the shape of a hollow tube and a respective one of the first active ceramic resistance heating element can be arranged at least partly within the hollow interior of the passive thermal element. The cross-section of the passive thermal element can be circular, i.e., the passive thermal element can have the shape of a hollow cylinder. However, also different, non-circular cross-sections are possible. The passive thermal element at least partly enclosing one of the first active ceramic resistance heating elements may function as a convective heating element. The first active ceramic resistance heating elements enclosed by a passive thermal element, respectively, may function as radiative heating elements. Those first active ceramic resistance heating elements that are not enclosed by a passive thermal element may function as convective heating elements.

[0019] For example, a passive thermal element at least partly enclosing one of the first active ceramic resistance heating elements is configured as a heating sleeve that fully surrounds the respective first active ceramic resistance heating element. The heating sleeve may thus be put over a first active ceramic resistance heating element and, in operation, is then heated through radiation. In turn, the gaseous fluid stream may be heated through forced convection by passing over the sleeve area. A further advantage of a heating sleeve is that it also protects the first active ceramic resistance heating element from high flow velocity induced loads thereby reducing or preventing a risk of breakage of the first active ceramic resistance heating element.

[0020] Using a passive thermal element to at least partly enclosing one of the first active ceramic resistance heating elements has the advantage that the total number of first active ceramic resistance heating elements can be reduced and thereby the costs and maintenance associated with the first active ceramic resistance heating elements can be reduced.

[0021] Preferably, a surface area of the passive thermal element at least partly enclosing one of the first active ceramic resistance heating elements is larger than a surface area of the respective enclosed first active ceramic resistance heating element. Preferably, a surface area of the passive thermal element is at least twice as large as a surface area of the enclosed first active ceramic resistance heating element.

[0022] Preferably, the one or more first passive thermal elements are made or comprise a ceramic material such as SiC, Al_2O_3, or Si_3N_4 or the like. Preferably, a passive thermal element of the one or more first passive thermal elements has a cross-section with a circular shape, an elliptic shape or a blade or wing shape. A wing shape has the advantage that a gaseous fluid stream streaming around the wing-shaped passive thermal element is in contact with the passive thermal element for a comparatively longer time longer due to the larger more surface contact along the streaming direction. Thereby, a heat transfer from the wing-shaped passive thermal element to the gaseous fluid stream can be improved. Moreover, a more homogeneous temperature distribution of the gaseous fluid stream may be achieved.

[0023] Preferably, the one or more first active ceramic resistance heating elements are made or comprise a ceramic material such as SiC, SiSiC, molybdenum disilicide ($MoSi_2$), or ZrO_2. Preferably, the one or more first active ceramic resistance heating elements have a diameter of 25 mm to 50 mm, e.g., of 30 mm to 40 mm such as 32 mm or 35 mm. Preferably, the one or more first active ceramic resistance heating elements have a length of 400 mm to 600 mm, e.g., of 450 mm to 550 mm such as 475 mm.

[0024] Preferably, a passive thermal element of the one or more first passive thermal elements has a plurality of burls and/or ribs distributed over its outer surface. Thereby, the outer surface area of the passive thermal element can be increased and convective heating of the gaseous fluid stream can be improved.

[0025] Preferably, a passive thermal element of the one or more first passive thermal elements has a hollow interior and a first active ceramic resistance heating element of the one or more first active ceramic resistance heating elements is arranged within the hollow interior of the passive thermal element.

[0026] Preferably, a passive thermal element of the one or more first passive thermal elements comprises a bulk material or bulk cargo, preferably, in granular form. The bulk material preferably comprises or is made of a ceramic material. In case the electric heater comprises a passive thermal element in form of bulk material, the electric heater, preferably, comprises, in addition, at least two further first passive thermal elements of the one or more first passive thermal elements that have a plate shape. Preferably, the at least two further passive thermal elements are arranged opposite each other within the heating chamber. Preferably, the bulk material is arranged between the at least two plate-shaped first passive thermal elements. Preferably, the at least two plate-shaped further first passive thermal elements and the passive thermal element in form of bulk material are arranged within the heating chamber such that the passive thermal element in form of bulk material is not in direct contact with the one or more first active ceramic resistance heating elements.

[0027] Thereby, the one or more first active ceramic resistance heating elements can be protected by the at least two plate-shaped further first passive thermal elements from damage through the passive thermal element in form of bulk material.

[0028] The passive thermal element in form of a bulk material can be used as a ceramic heat storage material. The storage material is thus preferably configured as bulk material. Preferably, the passive thermal element in form of a bulk material has a bulk density of up to 2500 kg/m^3 and/or a particle diameter of 2.5 mm to 8 mm, e.g., of 3 mm to 6 mm, e.g., of 5 mm.

[0029] Preferably, the at least two further first passive thermal elements in plate shape between which the bulk material is arranged is made of or comprises a fine porous ceramic foam, e.g., with pores per inch (ppl) of equal to 70 or larger which have a porosity φ of φ<80 %. Preferably, at least two further first passive thermal elements in plate shape are made of or comprise a ceramic material such as SiC, SiSiC or ZrOz. Preferably, the at least two further first passive thermal elements in plate shape have a minimum width of 25 mm. Preferably, the heating elements have a minimum distance from the at least two further first passive thermal elements in plate shape that corresponds diameter of a first active ceramic resistance heating elements of the one or more first active ceramic resistance heating elements.

[0030] Additionally or alternatively, several first active ceramic resistance heating elements of the one or more first active ceramic resistance heating elements may be enclosed by passive thermal elements of the one or more first passive thermal elements, respectively. Preferably, the electric heater comprises a further passive thermal element of the one or more first passive thermal elements that is configured as a bulk material and that is arranged between the passive thermal elements that enclose the several first active ceramic resistance heating elements, respectively. The further passive thermal element of the one or more first passive thermal elements that is configured as a bulk material thus fills the spaces between the passive thermal elements that enclose the several first active ceramic resistance heating elements, respectively. Thereby, direct contact between the further passive thermal element of the one or more first passive thermal elements that is configured as a bulk material and the several first active ceramic resistance heating elements is prevented to protect the several first active ceramic resistance heating elements from damage caused by the bulk material.

[0031] It is thus possible that within the first heating stage with the one or more first active ceramic resistance heating elements, a passive thermal element in bulk material form is used as ceramic heat storage material. It is possible that the spaces between the one or more first active ceramic resistance heating elements enclosed by passive thermal elements in the first heating stage are filled with the further passive thermal element of the one or more first passive thermal elements that is configured as a bulk material. For example, bulk densities of up to 2500 kg/m^3 and a particle diameter of 2.5 mm to 8 mm, e.g., of 3 mm to 6 mm, e.g., of 5 mm can be used for the bulk material. Thereby, the one or more first active ceramic resistance heating elements which may be made of or may comprise SiC or $MoSi_2$, are completely enclosed, e.g., by the heating sleeves as described above, so that there is no physical contact between the one or more first active ceramic resistance heating elements and the bulk material.

[0032] Additionally or alternatively, a thermal passive element of the one or more first passive thermal elements may be configured in form of a block extending between two opposite heating chamber walls and having one or more feedthroughs and wherein one or more first active ceramic resistance heating elements of the one or more first active ceramic resistance heating elements are arranged within the one or more feedthroughs, respectively. Thereby, in the first heating stage, an additional passive heat exchanger is provided, which, in operation, is heated by the thermal radiation of the one or more first active ceramic resistance heating elements arranged in feedthroughs of the thermal passive element in form of a block. The thermal passive element in form of a block may be made of or may comprise a ceramic foam. In operation of the electric heater, thermal passive element in form of a block transfers the heat to the gaseous fluid stream inside the heating chamber via convection. In case the thermal passive element in form of a block is made of or comprises a ceramic foam, the ceramic foam, preferably, is fine-pored with ppl of 70 or larger resulting in a high porosity φ of φ>80 %. The ceramic foam may be made of a ceramic material such as SiC, SiSiC or ZrOz. Preferably, the one or more first active ceramic resistance heating elements that are placed inside the feedthroughs of the ceramic foam have a minimum distance from the ceramic foam that corresponds to one diameter of a first active ceramic resistance heating element of the one or more first active ceramic resistance heating elements.

[0033] Additionally or alternatively, in the electric heater, at least one passive thermal element of the one or more first passive thermal elements may be configured in form of a plate having a wave-like shape that is arranged such that it is or they are wound around respective ones of the one or more first active ceramic resistance heating elements. Within the first heating stage comprising the one or more first active ceramic resistance heating elements thus an additional passive heat exchanger can be comprised that is implemented by at least one passive thermal element in form of a plate having a wave-like shape. In operation, the at least one passive thermal element in form of a plate having a wave-like shape can be heated by the heat radiation of the one or more first active ceramic resistance heating elements and can transfer the heat to the gaseous fluid stream via convection. The at least one passive thermal element in form of a plate having a wave-like shape can be made of or can comprise ceramic foam plates, which have a wave shape. Preferably, a shape of the ceramic foam plates is such that a surface area facing towards respective ones of the semi-enclosed one or more first active ceramic resistance heating elements is maximized while maintaining a minimum distance of one diameter of a first active ceramic resistance heating element between the one or more first active ceramic resistance heating elements and the ceramic foam plates. The ceramic foam plates may be fine-pored with ppl of 70 or larger and with a high porosity φ of φ>80 %. Preferably, the at least one passive thermal element of the one or more first passive thermal elements may be configured in form of a plate having a wave-like shape has a minimum thickness of 20 mm. Preferably, the ceramic foam plates are made of or comprise a ceramic material such as SiC, SiSiC or ZrOz.

[0034] Additionally or alternatively, a passive thermal element of the one or more first passive thermal elements may be configured in form of a plate that has a number of feedthroughs that are arranged to allow the gaseous fluid stream to flow from the gas inlet to the gas outlet. The passive thermal element in form of a plate that has a number of feedthroughs implements a ceramic heat storage material that may be a SiC plate. The passive thermal element in form of a plate has holes in the direction of flow. Preferably, one or more first active ceramic resistance heating elements have a minimum distance from the plates that corresponds to the diameter of a first active ceramic resistance heating element of the one or more first active ceramic resistance heating elements.

[0035] Additionally or alternatively, at least one passive thermal element of the one or more first passive thermal elements may be configured in form of a rod having a plurality of burls and/or ribs distributed over its outer surface and being arranged between the one or more first active ceramic resistance heating elements. The at least one passive thermal element in form of a rod realizes a passive heat exchanger, which, in operation of the heater, is heated by the heat radiation of the one or more first active ceramic resistance heating elements and transfer the heat to the gaseous fluid stream via convection. Preferably, several first passive thermal elements in form of rods are arranged offset to each other within the heating chamber. In operation of the electric heater, the rods may also serve as short-term heat accumulators and thus to introduce inertia into the electric heater, making it easier to regulate the flow of the gaseous fluid stream. Preferably, the least one passive thermal element in form of a rod is made of or comprises a ceramic material such as SiC, SiSiC or ZrOz. Preferably, the rods have a maximum diameter of half the diameter of the one or more first active ceramic resistance heating elements. Preferably, a surface area of the rods is enlarged by dimples or ridges, so that the heat exchange with the gaseous fluid stream is improved.

[0036] In the electric heater, it is generally preferred that at least one passive thermal element of the one or more first passive thermal elements is or comprises a porous ceramic material, preferably, a ceramic foam.

[0037] In a preferred embodiment, both, the one or more first active ceramic resistance heating elements and/or the one or more first passive thermal elements comprise or are made of SiC and/or $MoSi_2$. Preferably, both, the one or more first active ceramic resistance heating elements and/or the one or more first passive thermal elements have a porosity of 5 % or less.

[0038] In particular, in case several first active ceramic resistance heating elements of the one or more first active ceramic resistance heating elements have a rod shape or the form of a plate, e.g., a wave-like-shaped plate, it is preferred that a minimum distance between neighbouring first active ceramic heating elements of the several first active ceramic resistance heating elements is twice the diameter or width of a first active ceramic heating element of the several first active ceramic resistance heating elements. For example, the electric heater may comprise 450 to 720 first active ceramic heating elements in the first heating stage. Preferably, the one or more first active ceramic heating elements are arranged in a regular pattern. Preferably, in case of rod-shaped elements, the one or more first active ceramic heating elements, at least some of the first active ceramic heating elements have six directly neighbouring first active ceramic heating elements.

[0039] Preferably, the electric heater comprises a second heating stage with one or more active metallic resistance heating elements that is arranged closer to the gas inlet than the first heating stage. Preferably, the second heating stage is configured for heating the gaseous fluid stream to a second temperature when providing an electric current to the one or more active metallic resistance heating elements. Preferably, the second temperature is lower than the first temperature of 1000 °C or more.

[0040] In case the electric heater includes a first heating stage and a second heating stage, cascaded heating of the gaseous fluid stream within the heating chamber is possible. With the second heating stage that is closer to the gas inlet, the gaseous fluid stream can be heated to a second temperature that is smaller than the first temperature of 1000 °C or more. In particular, with the second heating stage comprising one or more active metallic resistance heating elements, a low-cost pre-heating technology based on metallic resistance heating elements can be employed for pre-heating of the gaseous fluid stream to the second temperature. The first heating stage comprises higher-cost ceramic heating element, i.e., the one or more first active ceramic resistance heating elements. For example, with SiC first active ceramic resistance heating elements, the gaseous fluid stream can be heated to the first temperature of 1000 °C more, e.g., up to 1500 °C. It is thus preferred that in the heating chamber, the one or more active metallic resistance heating elements are arranged closer to the inlet port than the one or more active first ceramic resistance heating elements. In operation of the heater, the second heating stage may be used for preheating with one or more metallic resistance heating elements to a second temperature and the first heating stage may be used for heating to a first temperature employing the one or more active first ceramic resistance heating elements. Possible materials for the one or more active metallic resistance heating elements are, e.g., an iron-chromium-aluminium alloy, a nickel-chromium alloys, a nickel-iron alloys, or copper-nickel alloys.

[0041] Optionally, the electric heater may comprise a high-temperature blower fan, e.g., arranged between the second heating stage and the first heating stage, for example, at approximately 600 °C fluid stream temperature, to maintain flow velocity of the gaseous fluid stream and/or to overcome the pressure losses of the gaseous fluid stream.

[0042] Preferably, the electric heater may comprise a third heating stage comprising one or more second active ceramic resistance heating elements made of a different ceramic material than the one or more first active ceramic resistance heating elements. The third heating stage, preferably, is configured for heating the gaseous fluid up to a third temperature that is higher than the first temperature when providing an electric current to the one or more second active ceramic resistance heating elements. Thus, in case higher gas outlet temperatures are needed than the first temperature, a third heating stage can be employed. Preferably, the one or more second active ceramic resistance heating elements are made of or may comprise $MoSi_2$ and are thus suitable for achieving a third temperature of up to 1800 °C.

[0043] The electric heater may include only the first heating stage and optionally the second heating stage or the third heating stage or the second heating stage and the third heating stage.

[0044] It is thus possible to implement a cascaded electric heater with up to three heating stages. First, the gaseous fluid stream may be heated up to 1000 °C by a low-cost pre-heating technology based on metallic resistance heating elements with the second heating stage. Second, the air temperature maybe raised up to 1500 °C by a higher-cost ceramic resistance first heating stage, e.g., comprising SiC-based first active ceramic resistance heating elements. Third, in case higher temperatures are required, $MoSi_2$-based second active ceramic resistance heating elements can be employed for achieving gas outlet temperatures of up to 1800 °C or beyond. It is thus preferred that the one or more second active ceramic resistance heating elements comprise or are made of $MoSi_2$. Preferably, the one or more second active ceramic heating elements are arranged closer to the gas outlet than the one or more active first ceramic heating elements. If desired, further heating stages may be added in a modular way.

[0045] In case the electric heater comprises a third heating stage, the at least one of the one or more second active ceramic heating elements, preferably, are at least partly enclosed by a second passive thermal element such that when applying an electric current to the second active ceramic resistance heating element, the second passive thermal element is heated through radiative heat transfer from the encapsulated second active ceramic resistance heating element. Preferably, the second passive thermal element is shaped to extend further towards the outlet port than towards the inlet port with respect to first active ceramic resistance heating element that is enclosed by the second passive thermal element. Preferably, the second passive thermal element are shaped in a way that the passing flow is adjacent, which leads to a larger heat transfer area, more homogeneous heat transfer and temperature distribution. Employing a second passive thermal element yields the advantage that a risk of breakage of the ceramic heating elements due to high flow velocity can be reduced. Moreover, it is possible to improve operating costs of the electric heater by reducing load and thermal stress on active ceramic heating elements. Furthermore, lifetime and durability and of the electric heater can be increased.

[0046] Generally, the one or more second passive thermal elements can be configured the same way as the one or more first passive thermal elements described herein. Accordingly, a second passive thermal elements of the one or more second passive thermal elements can be a bulk material, can be a plate, e.g., made of ceramic foam, can be a plate with a wavy shape, can be a bulk with feedthroughs, etc. The details described herein with respect to the one or more first passive thermal elements may be also applied to the one or more second passive thermal elements. The main difference between the one or more first passive thermal elements and the one or more second passive thermal elements is that the one or more first passive thermal elements are arranged in the first heating stage and the one or more second passive thermal elements are arranged in the third heating stage.

[0047] Optionally, the electric heater comprises one or more passive flow resistance elements that are arranged at a wall of the heating chamber and configured for guiding the fluid stream away from the heating chamber wall.

[0048] The passive flow resistance elements on the wall preferably serve as flow resistors to prevent run-away cold-zones on the heating chamber wall. The active ceramic resistance heating elements preferably maintain a minimum distance from the heating chamber wall. The larger space near the heating chamber wall may ensure that the gaseous fluid stream can stream more quickly at this point and is heated up correspondingly less (the so-called "run-away cold-zones"). In order to achieve a more even heating of the air, preferably, the passive flow resistance elements are integrated on the heating chamber wall, in the same form of the active ceramic resistance heating elements, in order to realize the constant distances between the components arranged within the heating chamber.

[0049] In a preferred embodiment, the one or more first active ceramic resistance heating elements are arranged offset to each other and passive flow resistance elements are arranged on the heating chamber wall to achieve a homogeneous temperature profile of the gaseous fluid stream over the cross-section of the heating chamber. Preferably, the one or more first active ceramic resistance heating elements have a small distance to each, e.g., spaced by a distance that corresponds to the diameter or width of the one or more first active ceramic resistance heating elements to improve the heat transfer and to achieve a high energy transfer density. Thereby, a pressure loss inside the heating chamber can be reduced. Thus, the electric heater has the advantage that parasitic losses related to gas flow through the electric heater are comparatively low, while achieving homogenous heating performance and avoiding run-away cold-zones.

[0050] The present invention also relates to a heating system that is configured for generating and storing process heat. The heating system comprises the electric heater described herein and, in addition, a thermal storage unit operatively connected to the electric heater to receive process heat from the electric heater. The thermal storage unit is configured for storing the process heat provided by the electric heater. For example, the thermal storage unit may comprise a solid material in form of granules, such as sand, gravel, or stones.

[0051] Optionally, the heating system comprises an electric battery storage operatively connected to the electric heater and being configured for providing an electric current to the heating elements of the first heating stage and, if present of the second and/or third heating stage. The first and/or third heating stage combined with an electric battery storage may serve as a high-temperature booster.

[0052] The present invention also relates to a method of providing process heat with an electric heater as described herein. The method comprises the steps of:

- providing a gaseous fluid stream to inside the heating chamber,
- applying an electric current to the one or more first active ceramic resistance heating elements for generating heat with a first temperature of 1000 °C or more,
- passively heating the gaseous fluid stream to the temperature of 1000 °C or more and/or storing heat generated by the one or more first active ceramic resistance heating elements, and
- providing the gaseous fluid stream having a temperature of more than 1000 °C to outside the heating chamber.

[0053] The present invention also relates to a method of maintenance for the electric heater described herein. The method of maintenance comprises repairing or replacing at least one of the one or more first active ceramic resistance heating elements and/or at least one of the one or more first passive thermal elements.

[0054] It shall be understood that the aspects described above, and specifically the electric heater of claim 1, the system of claim 12 and the method of claim 14 have similar and/or identical preferred embodiments, in particular as defined in the dependent claims.

[0055] It shall be understood that a preferred embodiment of the invention can also be any combination of the dependent claims or above embodiments with the respective independent claim.

[0056] These and other aspects of the invention will be apparent from and elucidated with reference to the embodiments described hereinafter.

BRIEF DESCRIPTION OF THE DRAWINGS

[0057]

Fig. 1 schematically and exemplary shows an electric heater with a first heating stage and a second heating stage arranged in a shipping container;

Fig. 2 schematically and exemplary shows an electric heater with a first heating stage, a second heating stage and a third heating stage connected to an industrial plant;

Fig. 3 schematically and exemplary shows a first heating stage comprising several ceramic foam plates as passive thermal elements and, as a further passive thermal element, a ceramic bulk material arranged between two neighbouring ceramic foam plates, respectively;

Fig. 4 schematically and exemplary shows a first heating stage with several first active ceramic resistance heating elements that are enclosed by respective passive thermal elements, wherein a further passive thermal element is configured as a bulk material and arranged in the spaces between the passive thermal elements enclosing the several first active ceramic resistance heating elements;

Fig. 5 schematically and exemplary shows a first passive thermal element in a cross-sectional view with a corrugated outer surface;

Fig. 6 schematically and exemplary shows a first passive thermal element in a longitudinal-sectional view with ribs arranged on the outer surface;

Fig. 7 schematically and exemplary shows a first passive thermal element in a cross-sectional view with nubs arranged on the outer surface;

Fig. 8 schematically and exemplary shows a first passive thermal element having a wing profile in a cross-sectional view with nubs arranged on the outer surface;

Fig. 9 schematically and exemplary shows the transfer of heat from a first active ceramic resistance heating element to a first passive thermal element and further to the gaseous fluid stream;

Fig. 10 schematically and exemplary shows a first heating stage comprising a first passive thermal elements that is a configured in form of a block having feed-throughs, wherein first active ceramic resistance heating elements are arranged within the feedthroughs;

Fig. 11 schematically and exemplary shows a first heating stage comprising first passive thermal elements that are configured in form of a plate having a wave-like shape that winds around respective ones of the first active ceramic resistance heating elements;

Fig. 12 schematically and exemplary shows a first heating stage comprising in a first section only first active ceramic resistance heating elements, in a second section first active ceramic resistance heating elements and first passive thermal elements in form of a plate having a wave-like shape, and in a third section a further first passive thermal element that is a configured in form of a block having feedthroughs with first active ceramic resistance heating elements being arranged within the feedthroughs;

Fig. 13 schematically and exemplary shows a first heating stage comprising first passive thermal elements in form of plates that each have a number of feed-throughs to allow the gaseous fluid stream to flow from the gas inlet to the gas outlet;

Fig. 14 schematically and exemplary shows a first heating stage comprising a plurality of first passive thermal elements in form of rods and having a plurality of burls and/or ribs distributed over their respective outer surfaces, the rods being arranged between the first active ceramic resistance heating elements;

Fig. 15 schematically and exemplary shows a first passive thermal elements in form of rods in a cross-sectional view and having a plurality of burls and/or ribs distributed over its respective outer surface;

Fig. 16 schematically and exemplary shows a first heating stage comprising first active ceramic resistance heating elements and passive flow resistance elements that are arranged at a wall of the heating chamber;

Fig. 17 schematically and exemplary shows a first heating stage comprising first active ceramic resistance heating elements and passive flow resistance elements that are arranged at a wall of the heating chamber in a 3D-view;

Fig. 18 schematically and exemplary shows a first heating stage comprising first active ceramic resistance heating elements and control scheme of controlling the first active ceramic resistance heating elements in groups;

Fig. 19 schematically and exemplary shows three different first heating stages, wherein the first heating stage on the left comprises first active ceramic resistance heating elements, only, the first heating stage in the middle comprises first active ceramic resistance heating elements and rod-shaped first passive thermal elements, and the first heating stage on the right comprises first active ceramic resistance heating elements and curved-shaped first passive thermal elements;

Fig. 20 schematically and exemplary shows an electric heater system operated in a standard operation mode;

Fig. 21 schematically and exemplary shows an electric heater system operated in an insufficient P_{AC} mode; and

Fig. 22 schematically and exemplary shows an electric heater system operated in storage mode.

DETAILED DESCRIPTION OF EMBODIMENTS

[0058] Figure 1 schematically and exemplary shows an electric heater 100 with a first heating stage 102 and a second heating stage 104 arranged in a shipping container 106. The electric heater comprises a gas inlet 107, with a blower fan 110, and an ambient air filter 108 that is connected to a heating chamber 112, accommodating the first heating stage 102 and a second heating stage 104. The first heating stage 102 comprises first active ceramic resistance heating elements (not shown) that are arranged and configured for generating heat with a first temperature of 1000 °C or more. The second heating stage 104 is arranged closer to the gas inlet 107 and comprises active metallic resistance heating elements for heating a gaseous fluid up to a second temperature when providing an electric current to the one or more active metallic resistance heating elements. The second temperature is lower than the first temperature such that the gaseous fluid is heated in two steps in a cascaded manner. The fluid stream is then provided as process heat via the gas outlet 114 that may be connected to a pipe system of an industrial plant (not shown) for use of the process heat in an industrial process.

[0059] Figure 2 schematically and exemplary shows a 3 to 5 MW electric heater 200 configured in a modular manner with a first heating stage 202, a second heating stage 204 and a third heating stage 206 connected to an industrial plant 208. The electric heater 200 is part of a heating system 209. The electric heater 200 comprises a gas inlet 208 with an air filter 210 and a blower fan 212. The second heating stage 204 comprises active metallic resistance heating elements 214 that are used for preheating of the gaseous fluid. Between the second heating stage 204 and the first heating stage 202, an optional high-temperature blower fan 216 is arranged. The first heating stage 202 comprises first active ceramic resistance heating elements 218, e.g., made of SiC and is configured for heating the gaseous fluid to a temperature of up to 1500 °C. The third heating stage 206 comprises second active ceramic resistance heating elements 220, e.g., made of $MoSi_2$ for heating the gaseous fluid to a temperature of up to 1800 °C. The heated gaseous fluid stream is provided as process heat at the electric heater's outlet 222. The electric heater 200 is arranged in a shipping container 238 with the dimensions 2.4 m x 2.6 m x 6 m.

[0060] For controlling the heating of the gaseous fluid stream inside the heating chamber 224, the electric heater 200 comprises a control system 226, e.g., including power electronics. With the control system 226, the blower fan 212 is controlled to adjust the amount of ambient air that is sucked into the heating chamber 224. Moreover, with the control system 226, the amount of the electric current applied to the active metallic resistance heating elements 214, the first active ceramic resistance heating elements 218 and the second active ceramic resistance heating elements 220 can be controlled. The electric current applied to the active metallic resistance heating elements 214, the first active ceramic resistance heating elements 218 and the second active ceramic resistance heating elements 220 may be generated as renewable electricity 228 by converting wind energy or solar energy into electricity. The heating system 209 comprises an electric battery storage 236 operatively connected to the electric heater 200. With the electric battery storage 236 it is possible to provide an electric current to the heating elements 218 of the first heating stage 202 and the heating elements 214 of the second heating stage 204 and the heating elements 220 of the third heating stage 206. The first and third heating stages 202, 206 combined with the electric battery storage 236 serve as a high-temperature booster.

[0061] The gas outlet 222 may be optionally connected to a thermal storage device 230 for storing the generated process heat. From the thermal storage device 230, process heat may be transported to an air flow management system 232 and onwards to a collecting pipe 234. The collecting pipe 234 may be connected to further electric heaters (not shown) for collecting process heat 240 from several electric heaters. From the collecting pipe 234, process heat is then provided to the industrial plant 208.

[0062] Figure 3 schematically and exemplary shows in a top view a first heating stage 300 comprising several ceramic foam plates 302 as passive thermal elements and, as a further passive thermal element, a ceramic bulk material 304 arranged between two neighbouring ceramic foam plates 302, respectively. The gaseous fluid stream 306 enters the heating chamber 308 and is heated by first active ceramic resistance heating elements 310 that are arranged in rows. The rows of first active ceramic resistance heating elements 310 are separated by the ceramic foam plates 302 and the ceramic bulk material 304 arranged between two adjacent ceramic foam plates 302, respectively. The gaseous fluid stream 306 thus passes rows of first active ceramic resistance heating elements 310 and ceramic foam plates 302 with ceramic bulk material 304 arranged between two adjacent ceramic foam plates 302 in an alternating manner. The ceramic bulk material 304 may have a density of up to 2500 kg/m^3. Moreover, the particles of the ceramic bulk material 304 may have a size of about 5 mm. The ceramic foam plates 302 have a porosity of less than 80 % and may be made of, e.g., SiC, SiSiC or ZrOz. Moreover, the ceramic foam plates 302 have a minimum width of 25 mm. A minimum distance between the first active ceramic resistance heating elements 310 and an adjacent ceramic foam plate 302 corresponds at least to the diameter of a first active ceramic resistance heating element of the first active ceramic resistance heating elements 310. After having traversed the first heating stage 300, the heated gaseous fluid stream 312 is provided either to a third heating stage, if present, or directly to a gas outlet.

[0063] Figure 4 schematically and exemplary shows in a top view a first heating stage 400 with several first active ceramic resistance heating elements 402, e.g., made of SiC or $MoSi_2$, that are enclosed by respective passive thermal elements 404. The passive thermal elements 404 enclosing the several first active ceramic resistance heating elements 402 have a sleeve shape with nubs arranged on their outer surfaces to increase the surface area and to thereby improve convective hating of a gaseous fluid stream 408 entering the first heating stage 400.

[0064] A further passive thermal element 406 is a bulk material and arranged in the spaces between the passive thermal elements 404 enclosing the several first active ceramic resistance heating elements 402. For example, the empty spaces in the first heating stage 400 between the passive thermal elements 404 enclosing the several first active ceramic resistance heating elements 402 may be filled up with the further passive thermal element 406 in bulk form. The ceramic bulk material 406 may have a density of up to 2500 kg/m^3 and may comprise particles with a size of about 5 mm. Due to the passive thermal elements 404 enclosing the several first active ceramic resistance heating elements 402 as heating sleeves, there is not direct contact between the ceramic bulk material 406 and the first active ceramic resistance heating elements 402 to avoid damaging of the first active ceramic resistance heating elements 402 by the ceramic bulk material 406. In operation, the ceramic bulk material 406 may function as a ceramic heat storage material for storing heat provided by the sleeve-shaped passive thermal elements 404 that are heated by radiative heating through the first active ceramic resistance heating elements 402. After having passed the first heating stage 400, the heated fluid stream 410 is provided either to a third heating stage, if present, or directly to a gas outlet.

[0065] Figure 5 schematically and exemplary shows a first passive thermal element 500 in a cross-sectional view with a corrugated outer surface 504. To increase the outer surface area, the corrugated outer surface 504 may comprise fins, pinches, nubs 502 or the like. The first passive thermal element 500 is hollow such that inside the first passive thermal element 500, a first active ceramic resistance heating element can be arranged.

[0066] Figure 6 schematically and exemplary shows a first passive thermal element 600 in a longitudinal-sectional view with ribs 602 arranged on the outer surface 604. Figure 7 schematically and exemplary shows another first passive thermal element 700 in a cross-sectional view with nubs 702 arranged on the outer surface 704. Figure 8 schematically and exemplary shows a first passive thermal element 800 having a wing profile in a cross-sectional view with nubs 802 arranged on the outer surface 804. The first passive thermal element 600, 700, 800 all have an increased surface area to improve the heat transfer to a gaseous fluid stream. In particular, in case the first passive thermal element 800 has a wing profile, the heat transfer to a gaseous fluid stream can be further improved since the gaseous fluid stream is in contact with the first passive thermal element 800 over a longer distance. The first passive thermal element 600, 700, 800 all have a hollow inside such that the first passive thermal element 600, 700, 800 can be sleeved over a respective first active ceramic resistance heating element.

[0067] Figure 9 schematically and exemplary shows the transfer of heat from a first active ceramic resistance heating element 900 to a first passive thermal element 902 and further to the gaseous fluid stream 904. Figure 9 thus illustrates the working principle of convectively heating a gaseous fluid stream by means of a first passive thermal element 902 that is at least part enclosed or even sleeved over the first active ceramic resistance heating element 900. The first active ceramic resistance heating element 900 generates heat when applying an electric current to the first active ceramic resistance heating element 900. For example, the first active ceramic resistance heating element 900 may be made of SiC. The generated heat is transferred as radiate heat 906 to the first passive thermal element 902. The first passive thermal element 902 has a corrugated surface by providing ribs 908 to increase the outer surface of the first passive thermal element 902. The first passive thermal element 902 may be made of SiC, SiSiC, $MoSi_2$ or ZrOz. Within the ceramic material of the first passive thermal element 902, conductive heat transfer 910 occurs. The heat of the first passive thermal element 902 is then provided via convective heat transfer 912 to the gaseous fluid stream 904 passing the first passive thermal element 902.

[0068] Figure 10 schematically and exemplary shows a first heating stage 1000 comprising a first passive thermal element 1002 that is a configured in form of a block having feedthroughs 1004, wherein first active ceramic resistance heating elements 1006 are arranged within the feedthroughs 1004. The first passive thermal element 1002 in form of a block with feedthroughs 1004 is made of a ceramic foam. The block-shaped ceramic foam 1002 implements a passive heat exchanger, which, in operation, is heated by the thermal radiation of the first active ceramic resistance heating elements 1006 are arranged within the feedthroughs 1004. Subsequently, block-shaped ceramic foam 1002 transfers the heat to the fluid stream 1008 via convection. After having traversed the block-shaped ceramic foam 1002, the heated fluid stream 1010 is provided either to a third heating stage, if present, or directly to a gas outlet.

[0069] Figure 11 schematically and exemplary shows in a top view a first heating stage 1100 comprising first passive thermal elements 1102 that are configured in form of a plate having a wave-like shape that winds around respective ones of the first active ceramic resistance heating elements 1104. The wave-like shaped plates 1102 are made of a ceramic material such as SiC, SiSiC or ZrOz with a porosity of 95 %. Alternatively, the wave-like shaped plates 1102 may have a porosity of 80 % or more. Generally, a high porosity is preferred. Moreover, the wave-like shaped plates 1102 have a thickness of 30 mm. Generally, a minimum thickness of 20 mm is preferred.

[0070] In operation, the wave-like shaped plates 1102 serve as a passive heat exchanger that are heated through radiative heat provided by the first active ceramic resistance heating elements 1104 through application of an electric current. To this end, the wave-like shaped plates 1102 preferably have a minimum distance to the next first active ceramic resistance heating elements 1104 that corresponds to the diameter of a first active ceramic resistance heating element of the first active ceramic resistance heating elements 1104. Ambient air 1106 that is entering the first heating stage 1100 passes the wave-like shaped plates 1102 one after another and is thereby heated through convective heating by the wave-like shaped plates 1102 and the first active ceramic resistance heating elements 1104. Eventually, after having passed the first heating stage 1100, the heated fluid stream 1108 is provided either to a third heating stage, if present, or directly to a gas outlet.

[0071] Figure 12 schematically and exemplary shows in a top view a first heating stage 1200 comprising in a first section 1202 only first active ceramic resistance heating elements 1204 and no first passive thermal elements. In a second section 1206, the first heating stage 1200 comprises first active ceramic resistance heating elements 1208 and first passive thermal elements 1210 in form of a plate having a wave-like shape. Moreover, in a third section 1212, the first heating stage 1200 comprises a further first passive thermal element 1214 that is a configured in form of a block extending between opposite walls 1220, 1222 of the heating chamber and having feedthroughs 1216 with first active ceramic resistance heating elements 1216 being arranged within the feedthroughs 1216.

[0072] In operation, a gaseous fluid 1218 entering the first heating stage 1200 is first heated by convective heating through the first active ceramic resistance heating elements 1204. The first active ceramic resistance heating elements 1204 are arranged in a regular pattern such that the first active ceramic resistance heating elements 1204 in the central area have six directly neighbouring first active ceramic resistance heating elements 1204. The distance a1 to the directly neighbouring first active ceramic resistance heating elements 1204 is constant. Moreover, the directly neighbouring first active ceramic resistance heating elements 1204 have a constant diameter d1.

[0073] Having passed the first section 1202, the gaseous fluid stream 1218 enters the second section 1206 where the gaseous fluid stream 1218 is heated by the first active ceramic resistance heating elements 1208 that are configured the same way as the first active ceramic resistance heating elements 1204 of the first section 1202. For example, these first active ceramic resistance heating elements 1204, 1208 may be made of SiC. In the second section 1206, wave-like shaped plates are arranged as first passive thermal elements 1210. In particular, the second section 1206 may be configured the same way as the first heating stage 1100 described with reference to figure 11. The wave-like shaped plates 1210 have a thickness t2 of 20 mm but may also have a larger thickness. The minimum distance a2 between a wave-like shaped plate 1210 and a first active ceramic resistance heating elements 1208 in the second section 1206 corresponds at least to the diameter d1 but may also be larger.

[0074] The third section 1212 may be configured the same way as the first heating stage 1000 described with reference to figure 10. The first passive thermal element 1214 is configured as a block of a ceramic foam material with feedthroughs 1216. As can be seen in figure 12, in the third section 1212, less first active ceramic resistance heating elements 1216 are arranged in a regular pattern that also have a larger diameter d3 compared to the diameter d1 of the first active ceramic resistance heating elements 1204, 1208 of the first section 1202 and the second section 1206, respectively. The block of ceramic foam 1214 has a width w3. In the feedthroughs 1216, the first active ceramic resistance heating elements 1204 are arranged for radiative heating of the block of ceramic foam 1214. For example, the first active ceramic resistance heating elements 1216 of the third section 1212 may be made of a different material as the first active ceramic resistance heating elements 1204, 1208 of the first section 1202 and the second section 1206. For example, the first active ceramic resistance heating elements 1216 of the third section 1212 may be made of $MoSi_2$. After having passed the third section 1212, the heated fluid stream 1224 is provided either to a third heating stage, if present, or directly to a gas outlet.

[0075] Figure 13 schematically and exemplary shows in a top view a first heating stage 1300 comprising first passive thermal elements 1302 in form of plates that each have a number of feedthroughs 1304 to allow the gaseous fluid stream 1306 to flow from the gas inlet to the gas outlet. The plate-shaped first passive thermal elements 1302 may be made of SiC. Between the plate-shaped first passive thermal elements 1302, rows of first active ceramic resistance heating elements 1308 are arranged such the fluid stream is convectively heated in an alternating manner by first active ceramic resistance heating elements 1308 and plate-shaped first passive thermal elements 1302. The plate-shaped first passive thermal elements 1302 may also serve for storing heat radiated by the first active ceramic resistance heating elements 1308. The heated fluid stream 1310 is then provided either to a third heating stage, if present, or directly to a gas outlet.

[0076] Figure 14 schematically and exemplary shows a first heating stage 1400 comprising a plurality of first passive thermal elements 1402 in form of rods as schematically and exemplary shown in figure 15 thus having a plurality of burls and/or ribs 1404 distributed over their respective outer surfaces 1406. The rods 1402 are arranged between the first active ceramic resistance heating elements 1408. In operation, the rods 1402 are thus heated by the first active ceramic resistance heating elements 1408 radiative heat transfer. A gaseous fluid stream 1410 passing the rods 1402 and the first active ceramic resistance heating elements 1408 is then heated via convective heating such that a heated gaseous fluid stream 1410 is provided after having passed the first heating stage 1400.

[0077] Figure 16 schematically and exemplary shows a first heating stage 1600 comprising first active ceramic resistance heating elements 1602 and passive flow resistance elements 1604 that are arranged at a wall 1606 of the heating chamber 1608. The passive flow resistance elements 1604 have a semi-circular shape bur may in other embodiments also have other shapes such as a triangular shape or a rectangular shape. The passive flow resistance elements 1604 serve as flow resistors to prevent run-away cold-zones on the heating chamber wall 1606. Such passive flow resistance elements 1604 may also be employed in the first heating stages described with reference to figures 1 to 15. Passive flow resistance elements 1604 may also be present and useful to avoid run-away cold-zones in a second heating stage and/or a third heating stage, if present.

[0078] Figure 17 schematically and exemplary shows a first heating stage 1700 comprising first active ceramic resistance heating elements 1702 and passive flow resistance elements 1704 that are arranged at a wall 1706 of the heating chamber 1708 in a 3D-view. The first heating stage 1700 may be configured the same way as the first heating stage 1600 described with reference to figure 16. The overall number of first active ceramic resistance heating elements 1702 may be larger than the number of first active ceramic resistance heating elements 1702 as shown in figure 17 and may be in the range of 450 to 720 first active ceramic resistance heating elements. Preferably, the first active ceramic resistance heating elements 1702 are made of SiC. The gaseous fluid stream 1710 may pass through the first heating stage 1700 with a flow rate of 2 to 3.3 kg/s or 1.5 to 2.5 Nm^3/s. The heated fluid stream 1712 may be provided, e.g., to a third heating stage or directly to a gas outlet.

[0079] The first heating stage 1700 has a length 1714 of 2 m to 4 m, a width 1716 of 0.45 m to 0.55 m and a height 1718 of 0.45 m to 1.65 m.

[0080] Figure 18 schematically and exemplary shows a first heating stage 1800 comprising first active ceramic resistance heating elements 1802 made of SiC and control scheme of controlling the first active ceramic resistance heating elements 1802 in groups of 30 to 36 first active ceramic resistance heating elements. As indicated by the straight line 1804. A surface load 1805 is applied linearly between 11 W/cm^3 and 3 W/cm^3 by varying the voltage or current input to the respective groups of first active ceramic resistance heating elements 1802, e.g., using a control system of an electric heater. In particular, the surface load 1805 is altered along the length 1806 of the first heating stage 1800.

[0081] Figure 19 schematically and exemplary shows three different first heating stages 1900, 1910, 1920. The first heating stage 1900 shown on the left comprises first active ceramic resistance heating elements 1902, only. T

[0082] the first heating stage 1910 shown in the middle comprises first active ceramic resistance heating elements 1912 and rod-shaped first passive thermal elements 1914. In particular, in comparison to the first heating stage 1900 shown on the left, in the first heating stage 1910 shown in the middle several of the first active ceramic resistance heating elements have been replaced by rod-shaped first passive thermal elements 1914 such that there is a sequence of rows of first active ceramic resistance heating elements 1912 and rod-shaped first passive thermal elements 1914.

[0083] The first heating stage 1920 shown on the right comprises first active ceramic resistance heating elements 1922 and curved-shaped first passive thermal elements 1924. In the first heating stage 1920 shown on the right, in comparison to the first heating stage 1910 shown in the middle, the rod-shaped first passive thermal elements have been replaced by curved-shaped first passive thermal elements 1924 that may change a direction of a fluid stream locally such that turbulence and mixing of the gaseous fluid stream is increased thereby resulting in more homogeneous fluid stream outlet temperature.

[0084] Figure 20 schematically and exemplary shows an electric heater system 2000 operated in a standard operation mode. The electric heater system comprises a blower fan 2002 for providing ambient air 2003 to one or more electric heaters 2004. For heating the ambient air 2003, power input P_h is provided to the one or more electric heaters 2004. The power input P_h is provided by, e.g., a wind turbine or solar panels 2007, as part of power input P_{AC}. power input P_{AC} further includes excess power P_s that is stored in a thermal storage device 2006. The volume flow rate dV_h/dt of the heated fluid stream is set by a control system to match the power input P_h. The heated fluid stream is then provided to an industrial plant 2008 as process power P_r that is converted into process heat T_{proc}.

[0085] Figure 21 schematically and exemplary shows an electric heater system 2100 operated in an insufficient P_{AC} mode. In the insufficient P_{AC} mode, the power P_h fed into the one or more electric heaters 2104 is not sufficient to provide necessary process power P_r at the required process heat T_{proc}. The volume flow rate dV_h/dt may then be lowered accordingly to match lower power input P_h to still provide T_{proc}. Additional power, i.e., additional volume flow, is drawn from the thermal storage device 2106 to be combined with the power, i.e., the volume flow, from the one or more electric heaters 2104 to deliver the required process power P_r.

[0086] Figure 22 schematically and exemplary shows an electric heater system 2200 operated in storage mode. In the storage mode, no power is provided from the renewable energy plant 2207. Only stored power is available and drawn from the thermal storage device 2206 to provide the required process power P_r.

[0087] In the claims, the word "comprising" does not exclude other elements or steps, and the indefinite article "a" or "an" does not exclude a plurality.

[0088] A single unit or device may fulfil the functions of several items recited in the claims. The mere fact that certain measures are recited in mutually different dependent claims does not indicate that a combination of these measures cannot be used to advantage.

[0089] Any reference signs in the claims should not be construed as limiting the scope.

Claims

1. An electric heater configured for providing process heat at megawatts-scale by electrically heating a gaseous fluid stream to a temperature of 1000 °C or more, wherein the electric heater comprises:

   - a heating chamber having a gas inlet configured for providing the gaseous fluid stream to inside the heating chamber and a gas outlet configured for providing the gaseous fluid stream having a temperature of more than 1000 °C to outside the heating chamber, wherein the heating chamber houses
   - a first heating stage, the first heating stage comprising

     - one or more first active ceramic resistance heating elements that are arranged and configured for generating heat with a first temperature of 1000 °C or more, when applying an electric current to the one or more first active ceramic resistance heating elements, and
     - one or more first passive thermal elements, preferably comprising a ceramic material, that are arranged and configured for passively heating the gaseous fluid stream to the temperature of 1000 °C or more and/or for storing heat generated by the one or more first active ceramic resistance heating elements.

2. The electric heater according to claim 1, wherein at least one of the first passive thermal elements is arranged to at least partly enclose one of the first active ceramic resistance heating elements such that when applying an electric current to the first active ceramic resistance heating element, the respective passive thermal element is heated through radiative heat transfer from the encapsulated first active ceramic resistance heating element.

3. The electric heater of claim 1 or 2, wherein the passive thermal element has a plurality of burls and/or ribs distributed over its outer surface.

4. The electric heater of at least one of the preceding claims, wherein at least one of the first passive thermal elements comprises a bulk material.

5. The electric heater of at least one of the preceding claims, wherein the one or more first active ceramic resistance heating elements are enclosed by a number of first passive thermal elements and wherein a further passive thermal element is configured as a bulk material and arranged between the number of first passive thermal elements enclosing the one or more first active ceramic resistance heating elements.

6. The electric heater of at least one of the preceding claims, wherein at least one of the first passive thermal elements is a configured in form of a block having one or more feedthroughs and wherein one or more of the one or more first active ceramic resistance heating elements are arranged within the one or more feedthroughs, respectively.

7. The electric heater of at least one of the preceding claims, wherein at least one of the first passive thermal elements is a configured in form of a plate having a wave-like shape that is arranged such that it wounds around respective ones of the one or more first active ceramic resistance heating elements.

8. The electric heater of at least one of the preceding claims, wherein at least one of the first passive thermal elements is configured in form of a plate that has a number of feedthroughs that are arranged to allow the gaseous fluid stream to flow from the gas inlet to the gas outlet.

9. The electric heater of at least one of the preceding claims, wherein at least one of the first passive thermal elements is configured in form of a rod having a plurality of burls and/or ribs distributed over its outer surface and being arranged between the one or more first active ceramic resistance heating elements.

10. The electric heater of at least one of the preceding claims, comprising a second heating stage with one or more active metallic resistance heating elements that is arranged closer to the gas inlet than the first heating stage and that is configured for heating the gaseous fluid up to a second temperature when providing an electric current to the one or more active metallic resistance heating elements, the second temperature being lower than the first temperature.

11. The electric heater of at least one of the preceding claims, comprising a third heating stage comprising one or more second active ceramic resistance heating elements made of a different ceramic material than the one or more first active ceramic resistance heating elements configured for heating the gaseous fluid up to a third temperature that is higher than the second temperature when providing an electric current to the one or more second active ceramic resistance heating elements.

12. A heating system configured for generating and storing process heat, the heating system comprising the electric heater according at least one of the preceding claims and a thermal storage unit opera-

tively connected to the electric heater to receive process heat from the electric heater and being configured for storing the process heat provided by the electric heater.

13. The heating system of claim 12, comprising an electric battery storage operatively connected to the electric heater and being configured for providing an electric current to the heating elements of the first heating stage and, if present of the second and/or third heating stage.

14. A method of providing process heat with an electric heater according to at least one of claims 1 to 11, the method comprising the steps of:

- providing a gaseous fluid stream to inside the heating chamber,
- applying an electric current to the one or more first active ceramic resistance heating elements for generating heat with a first temperature of 1000 °C or more,
- passively heating the gaseous fluid stream to the temperature of 1000 °C or more and/or storing heat generated by the one or more first active ceramic resistance heating elements, and
- providing the gaseous fluid stream having a temperature of more than 1000 °C to out-side the heating chamber.

15. A method of maintenance for the electric heater according to at least one of claims 1 to 11, the method comprising repairing or replacing at least one of the one or more first active ceramic resistance heating elements and/or at least one of the one or more first passive thermal elements.

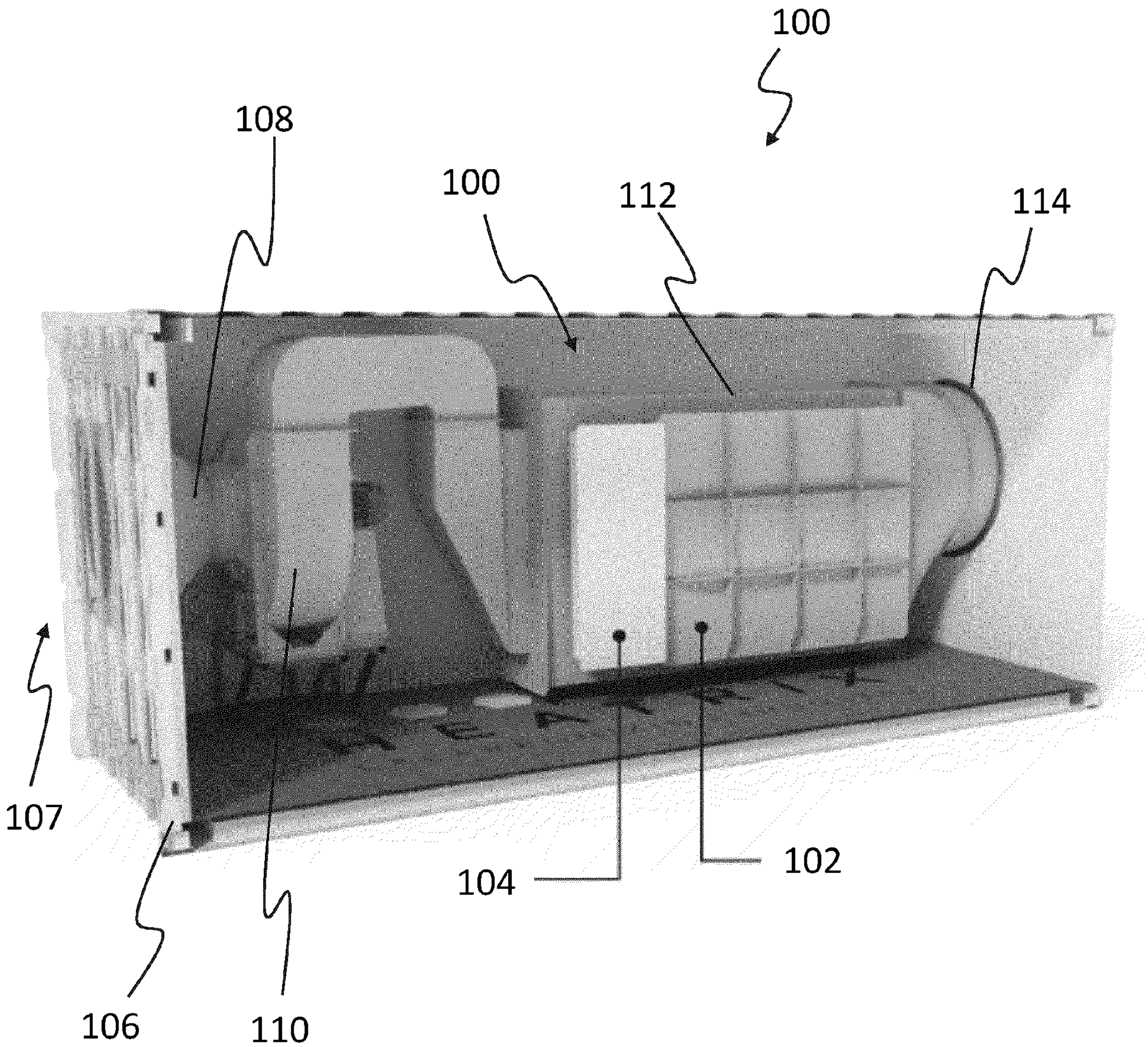

Fig. 1

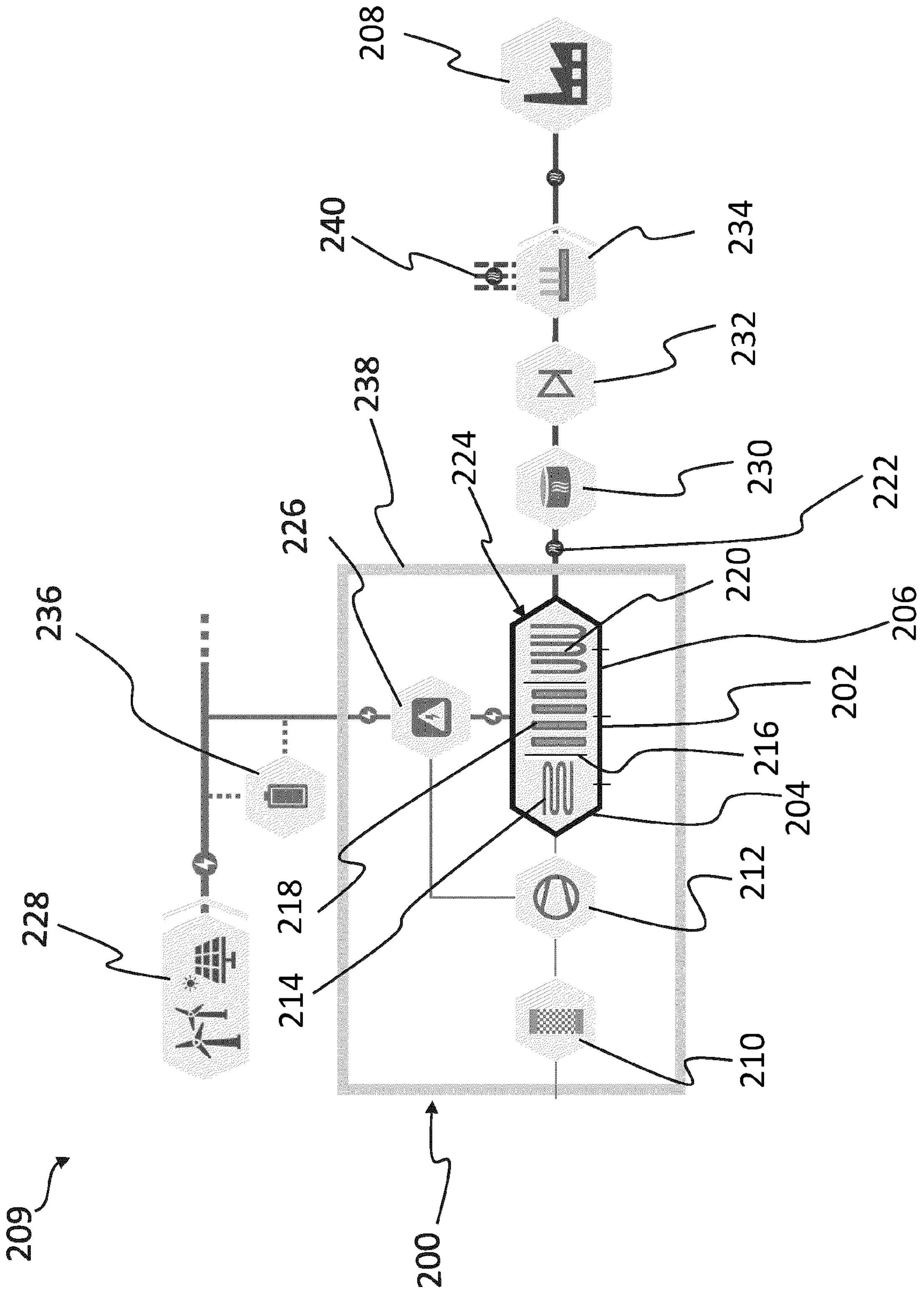
208
240
234
232
238
224
230
222
226
220
206
236
202
216
204
218
212
228
214
210
209
200

Fig. 2

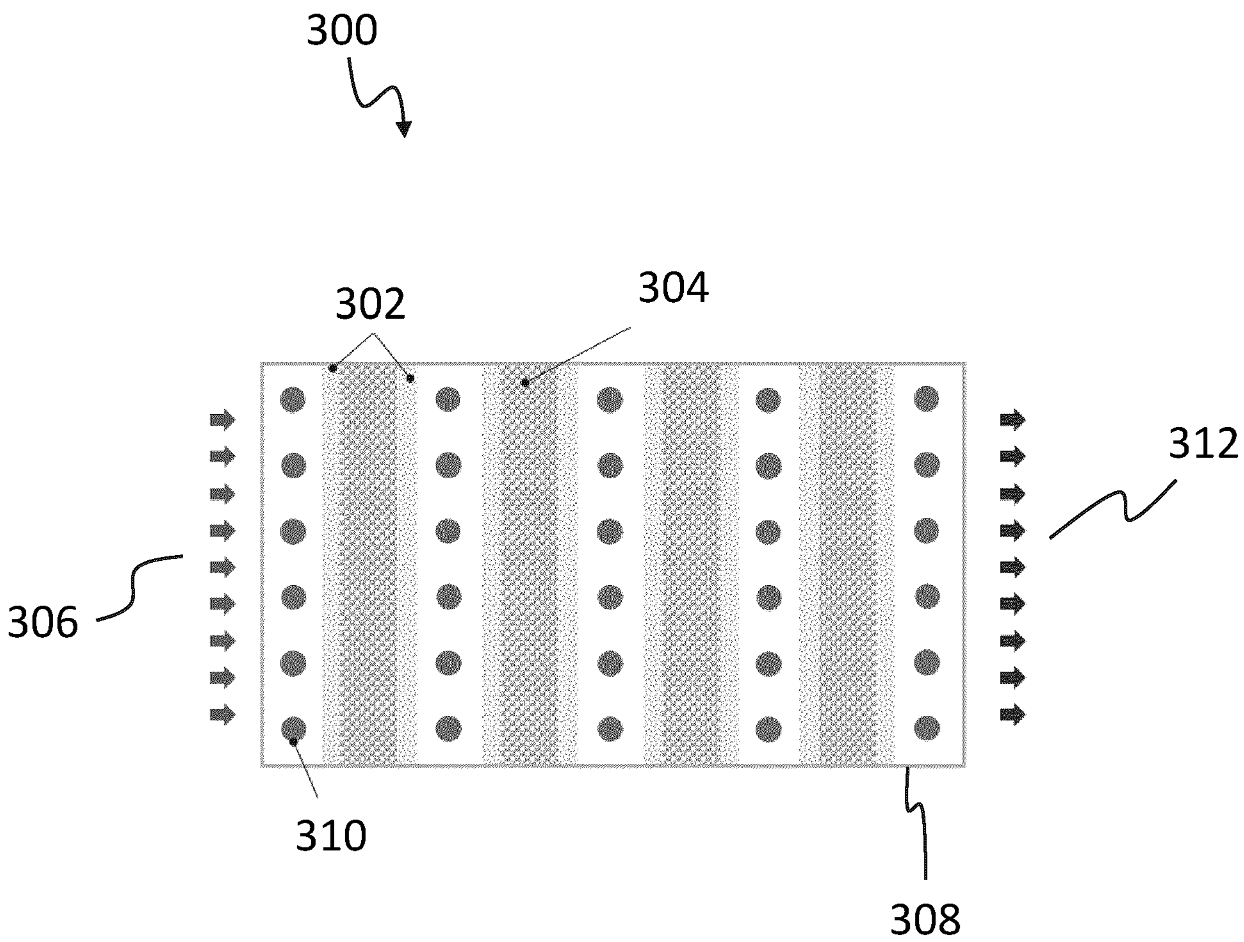

Fig. 3

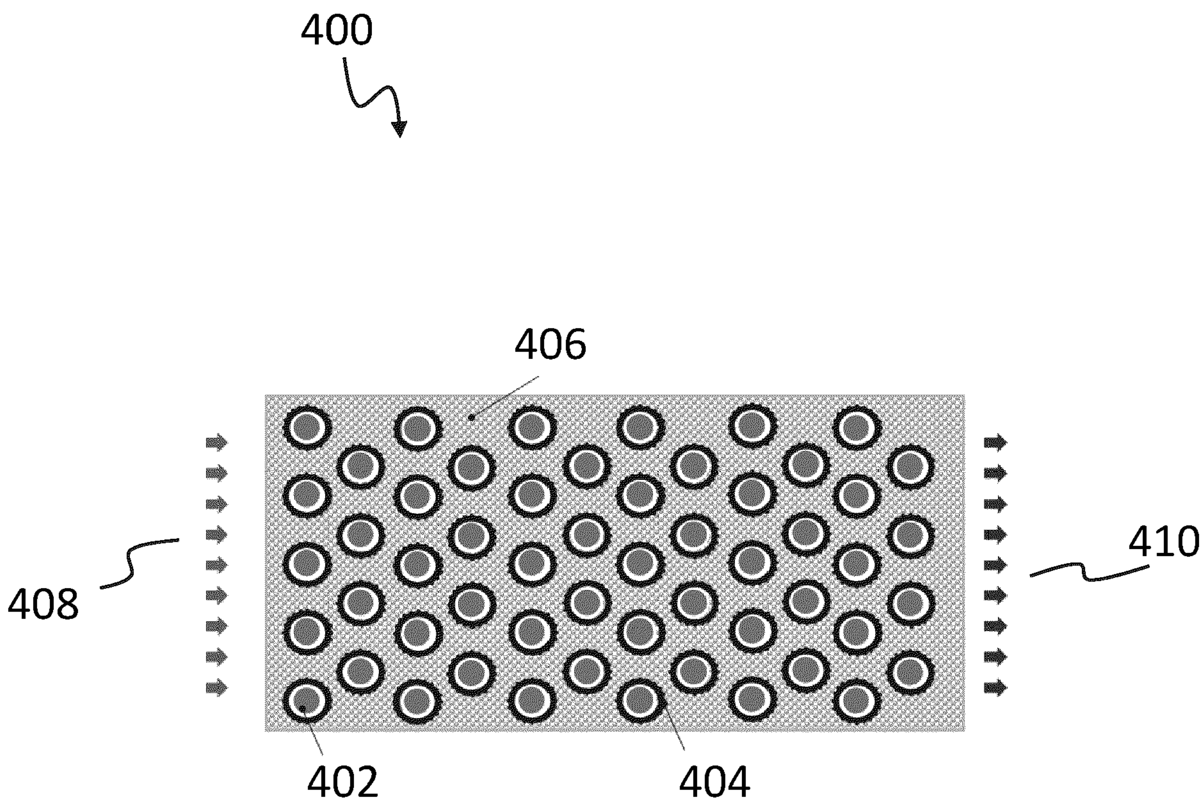

Fig. 4

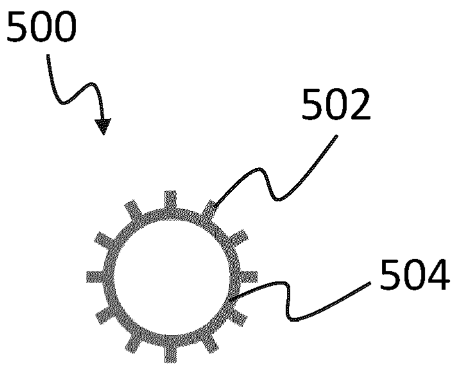

Fig. 5

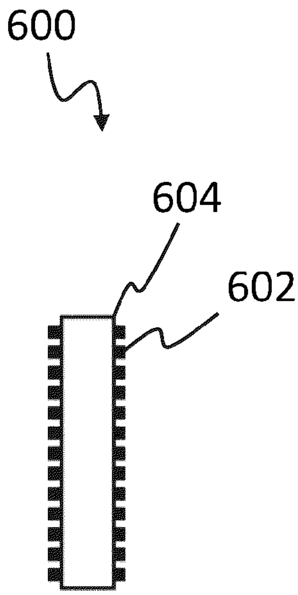

Fig. 6

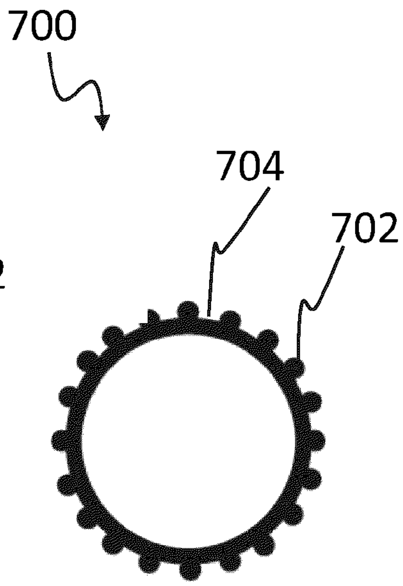

Fig. 7

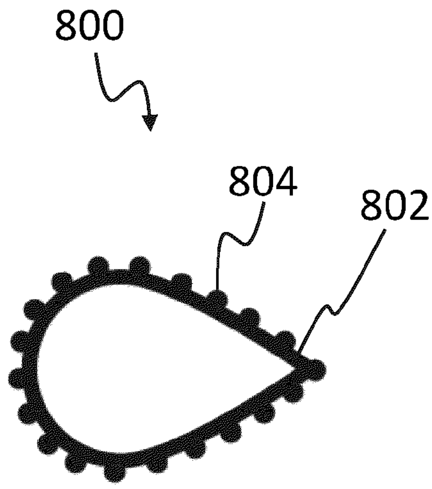

Fig. 8

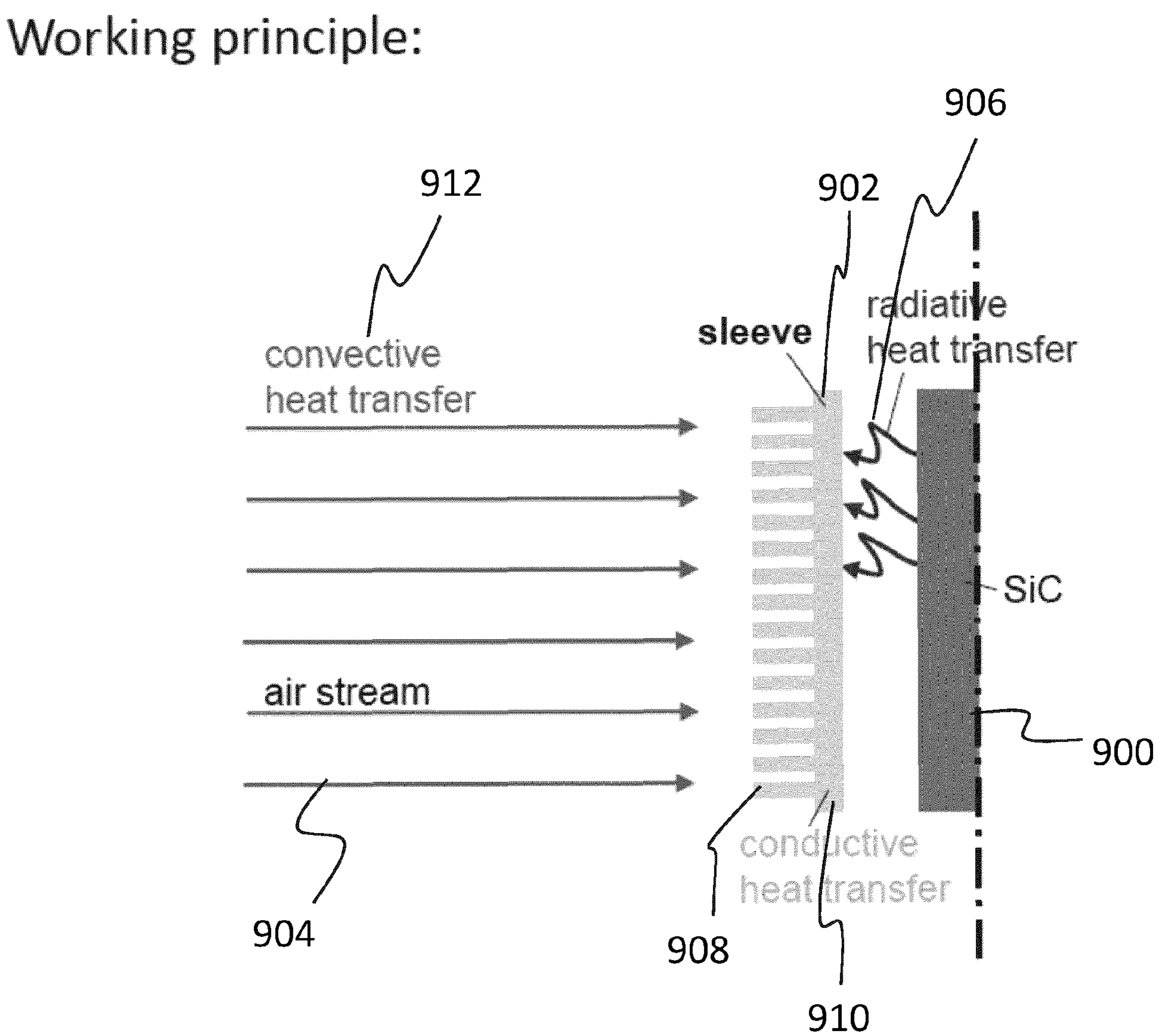
Working principle:
906
912
902
radiative
heat transfer
sleeve
convective
heat transfer
SiC
air stream
900
conductive
heat transfer
904
908
910

Fig. 9

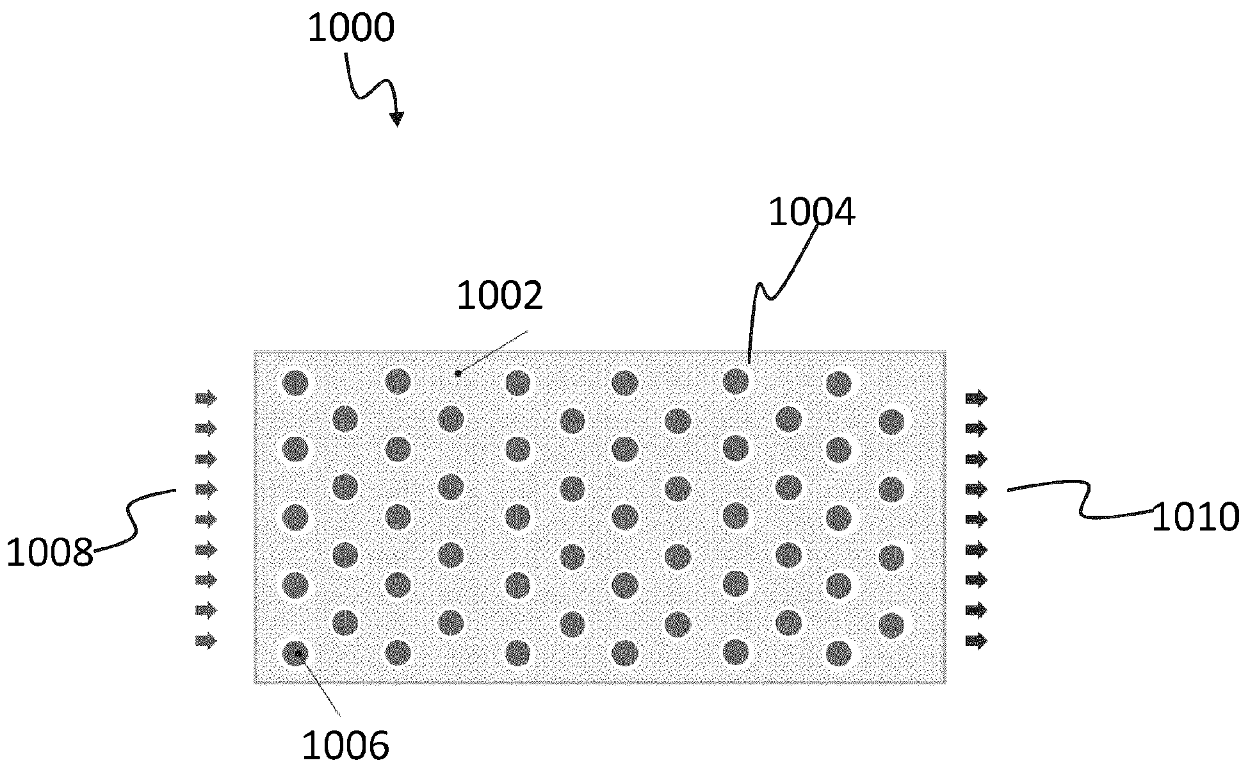

Fig. 10

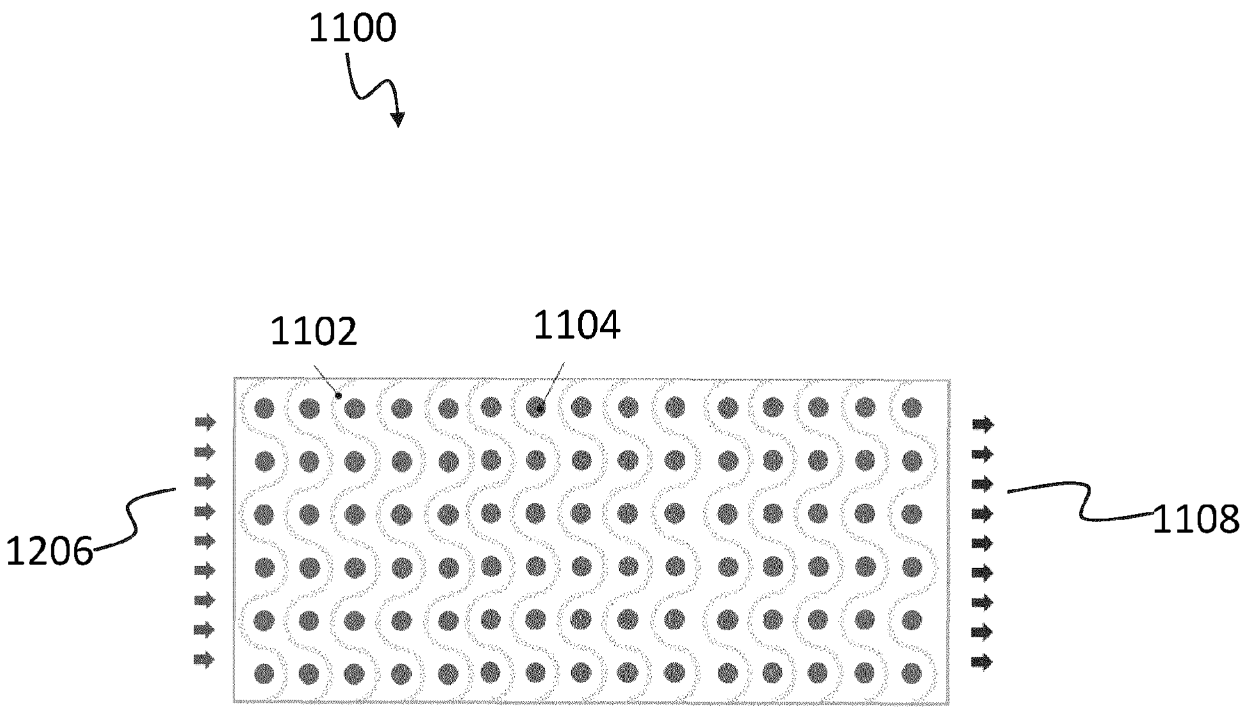

Fig. 11

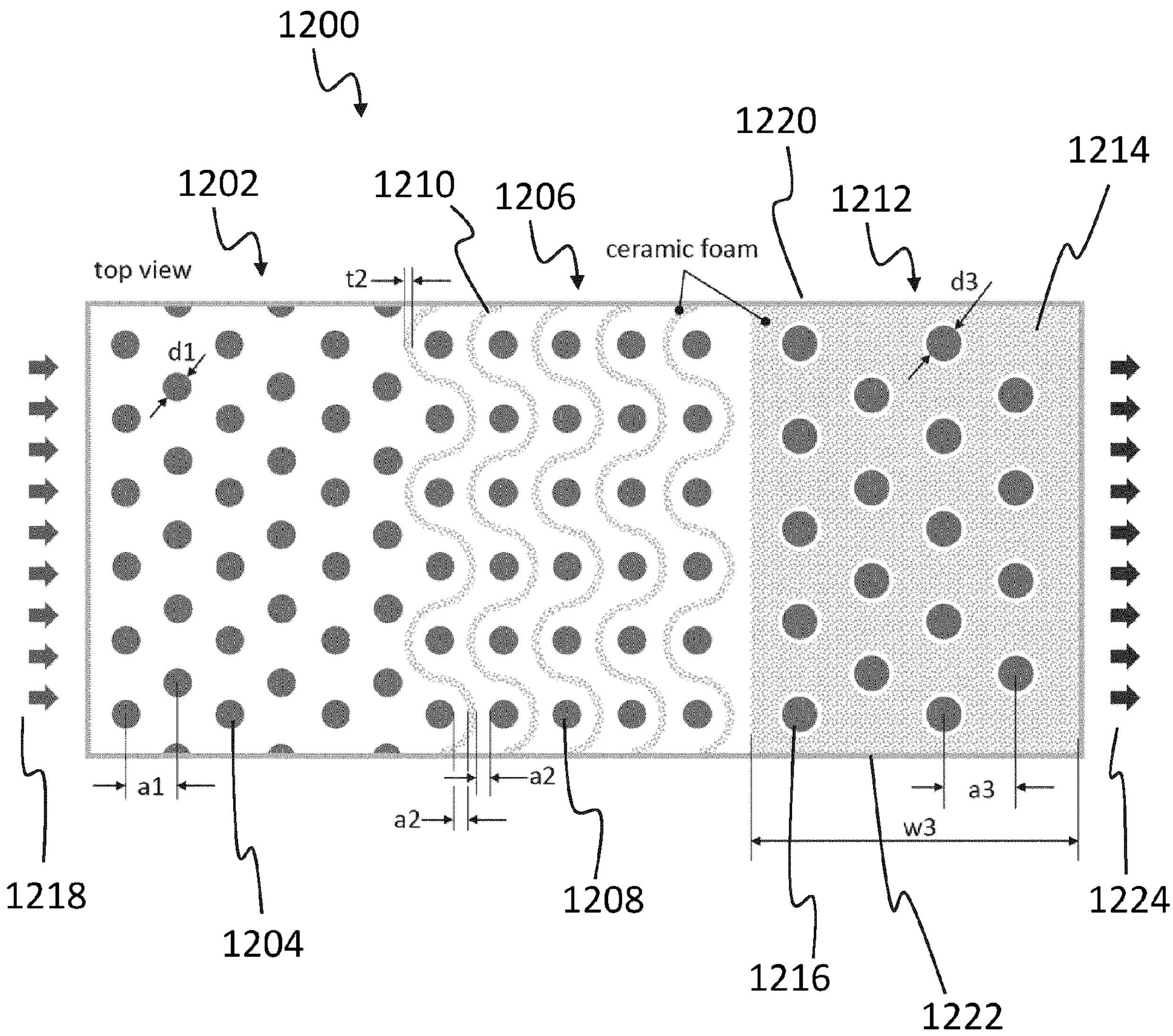
1200
1202
1210
1206
ceramic foam
1220
1212
1214
top view
t2
d1
d3
a1
a2
a2
a3
w3
1218
1204
1208
1216
1222
1224

Fig. 12

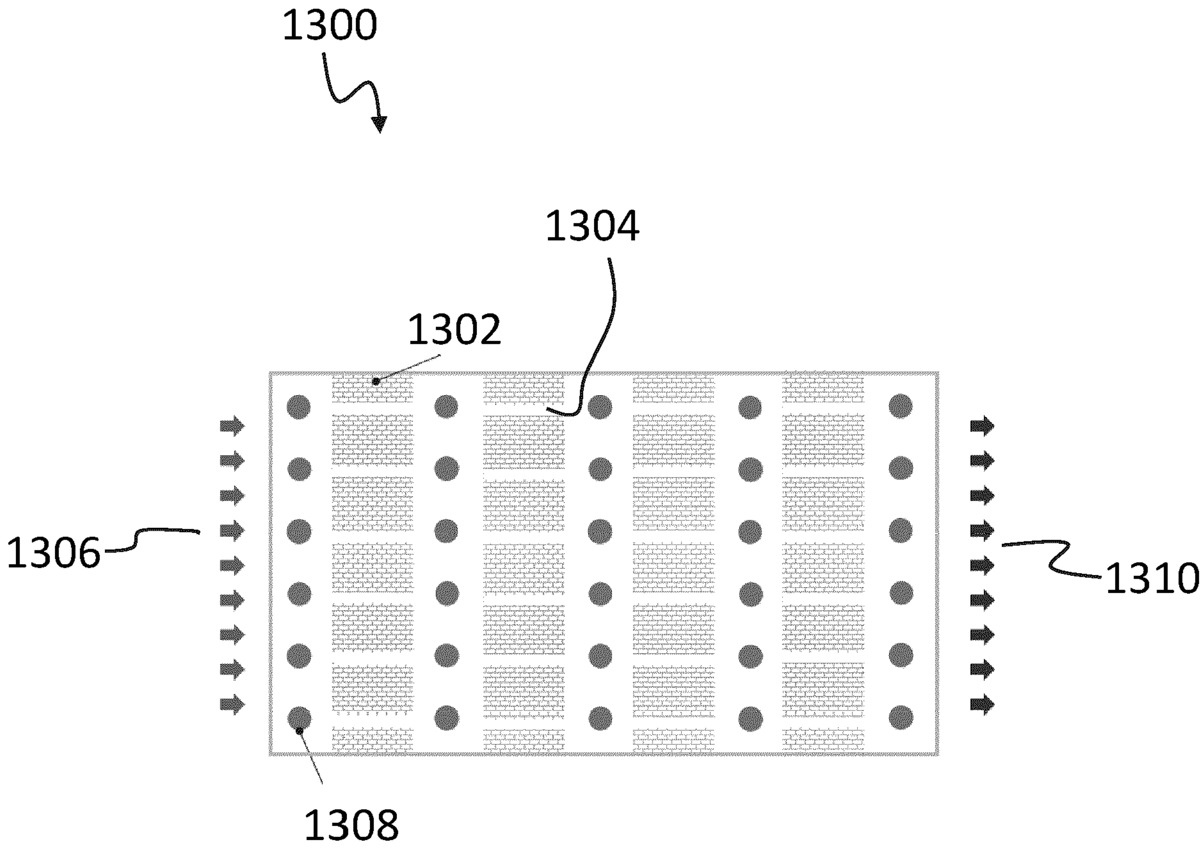

Fig. 13

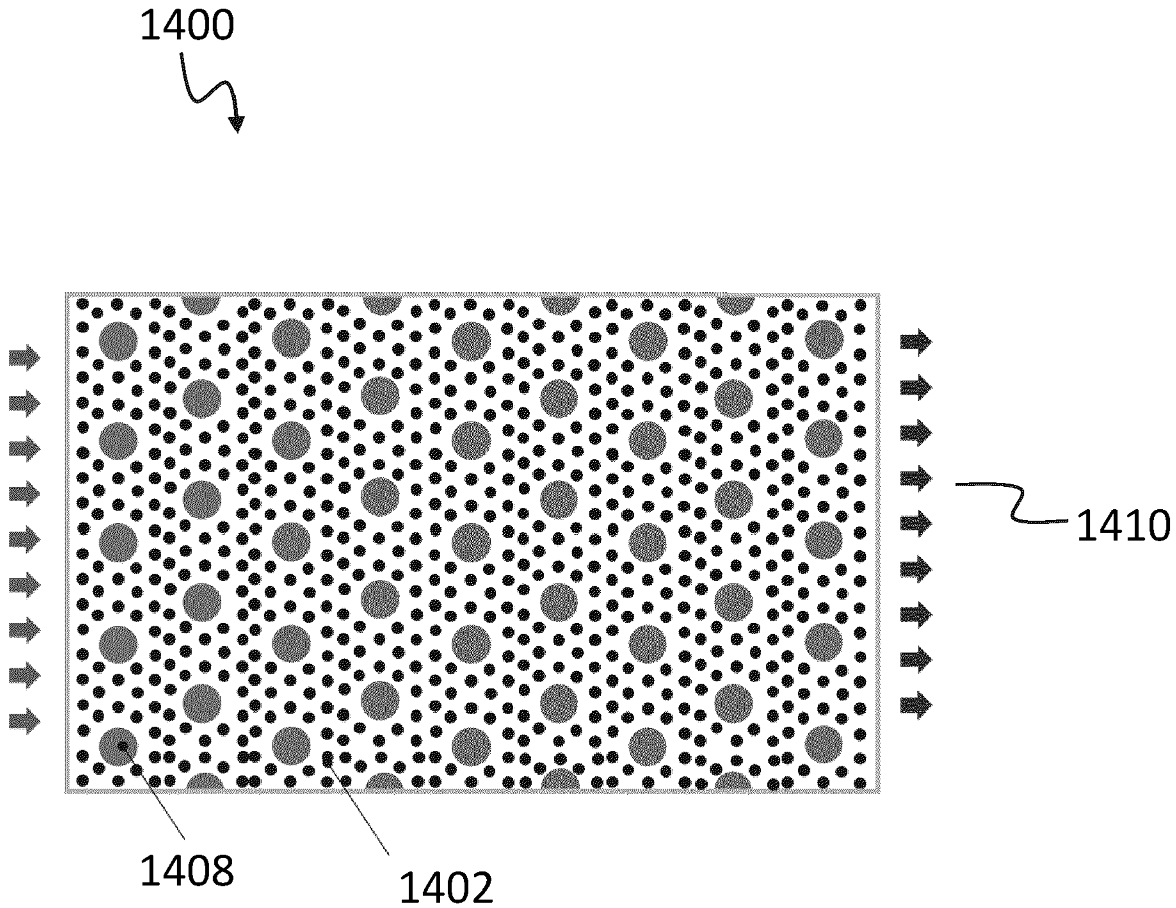

Fig. 14

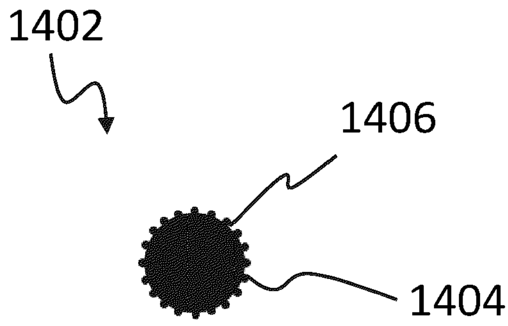

Fig. 15

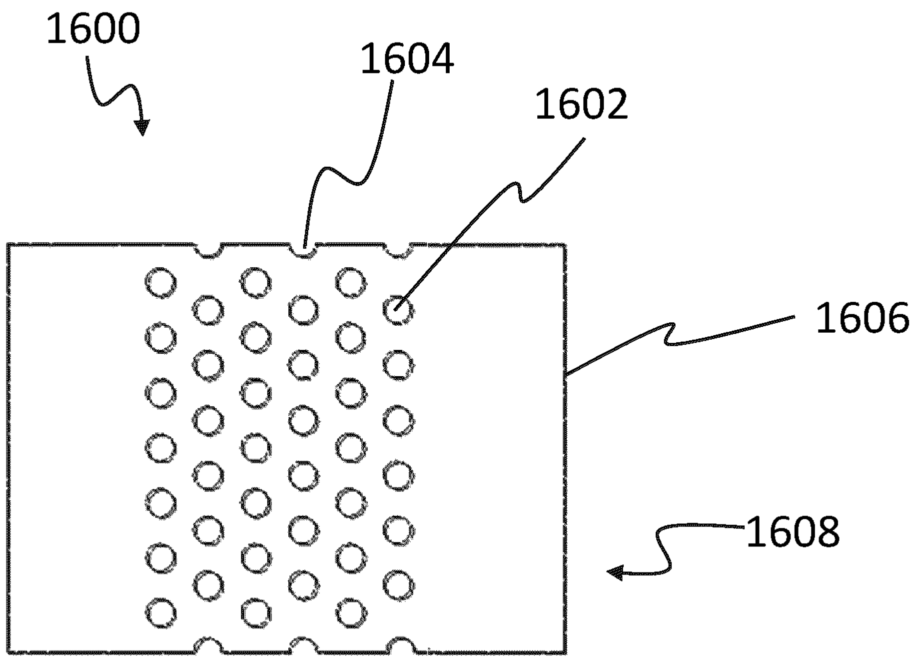

Fig. 16

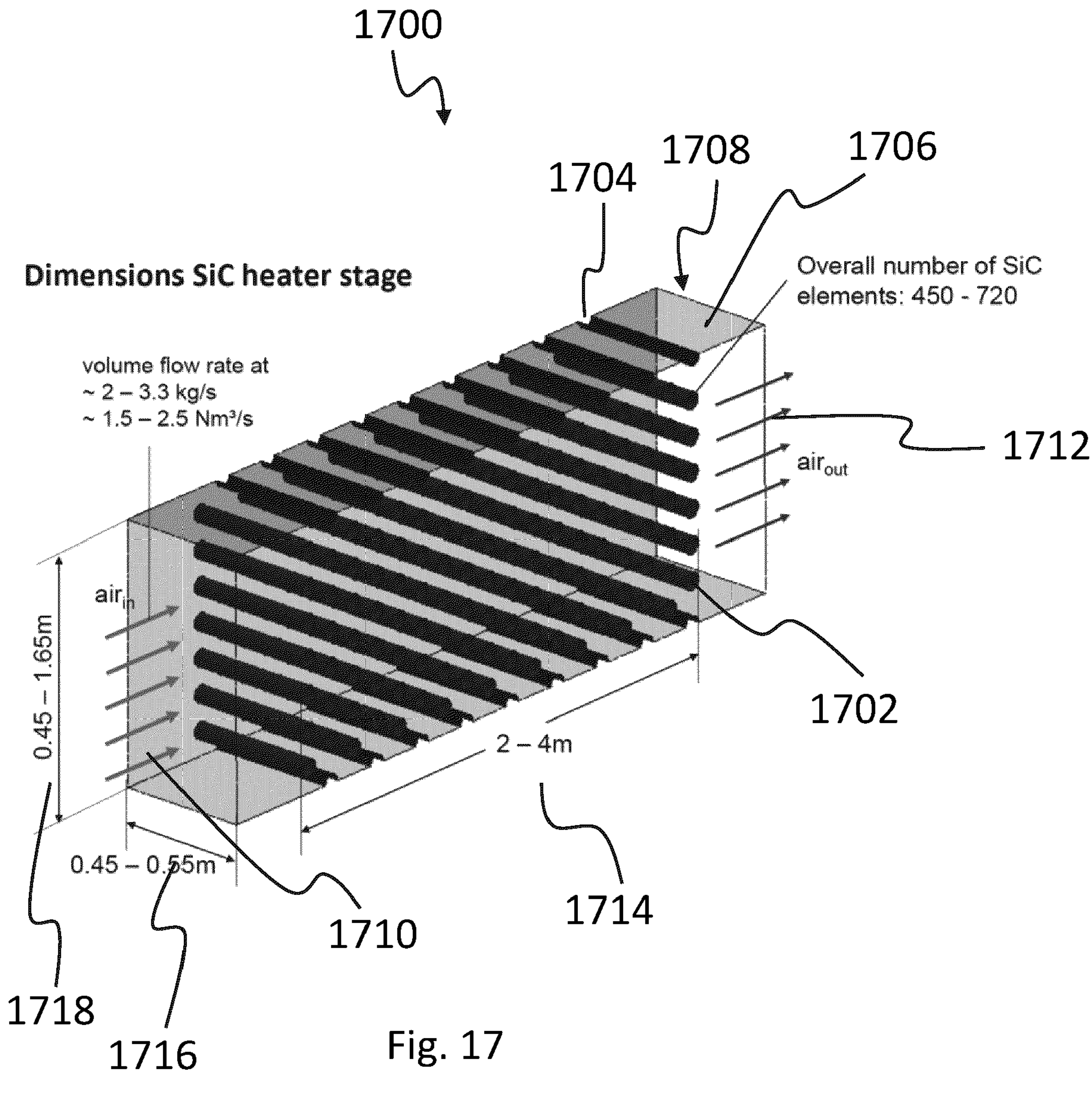
1700
1704
1708
1706
Dimensions SiC heater stage
Overall number of SiC elements: 450 - 720
volume flow rate at
~ 2 – 3.3 kg/s
~ 1.5 – 2.5 Nm³/s
1712
air$_{out}$
air$_{in}$
0.45 – 1.65m
1702
2 – 4m
0.45 – 0.55m
1710
1714
1718
1716

Fig. 17

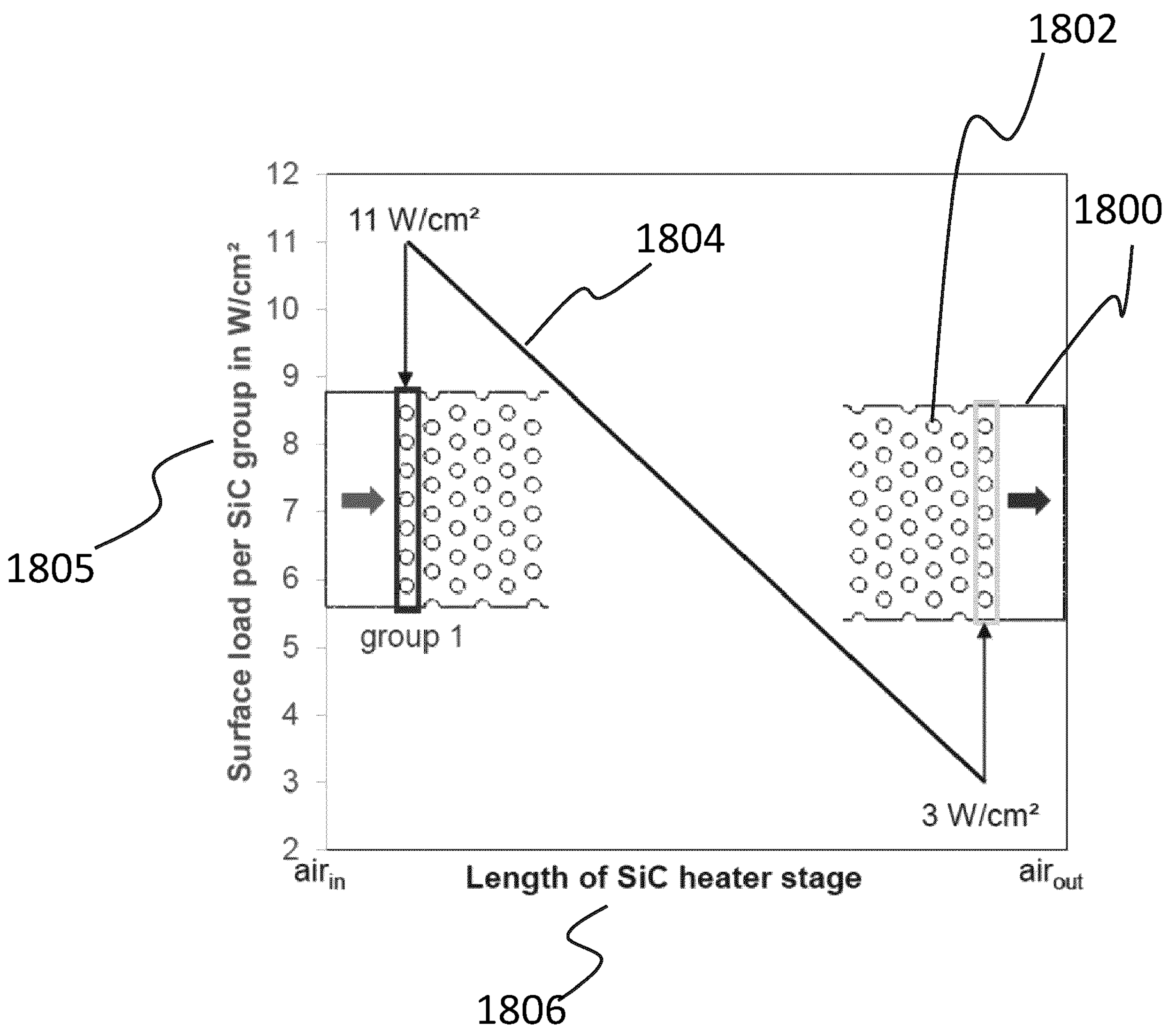
1802
1800
1804
11 W/cm²
12
11
10
9
8
7
6
5
4
3
2
Surface load per SiC group in W/cm²
1805
group 1
3 W/cm²
air$_{in}$
Length of SiC heater stage
air$_{out}$
1806

Fig. 18

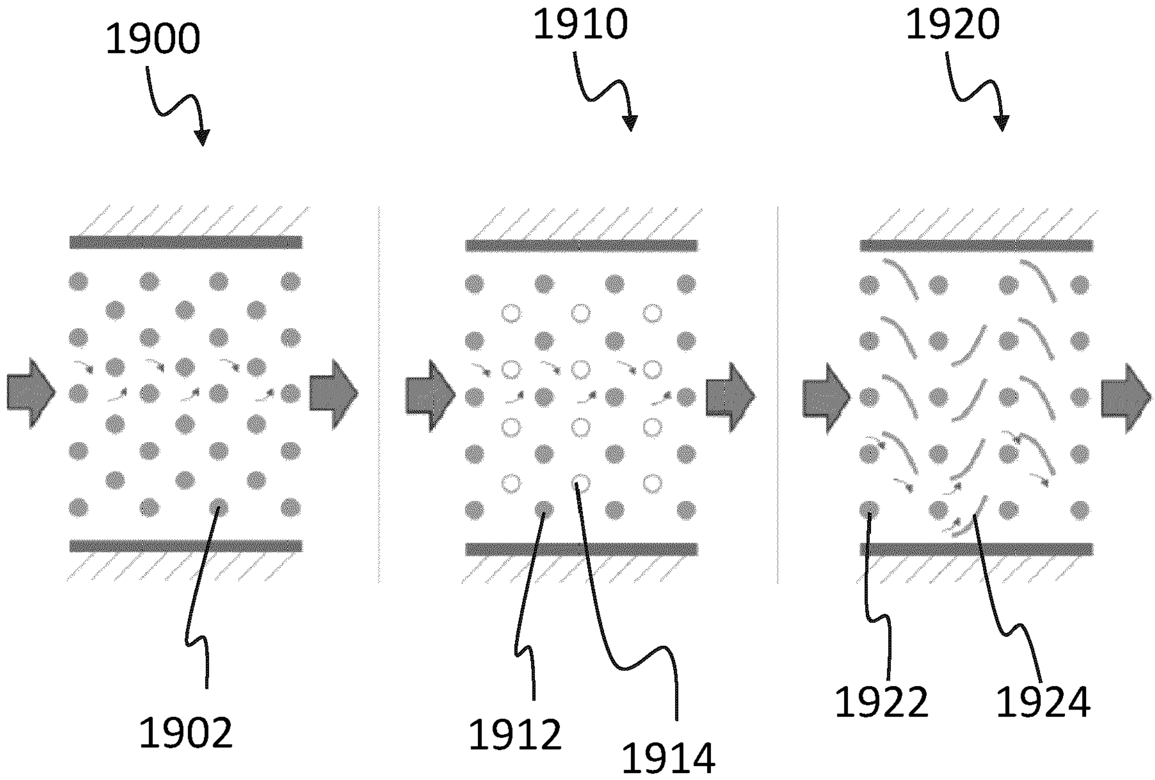

Fig. 19

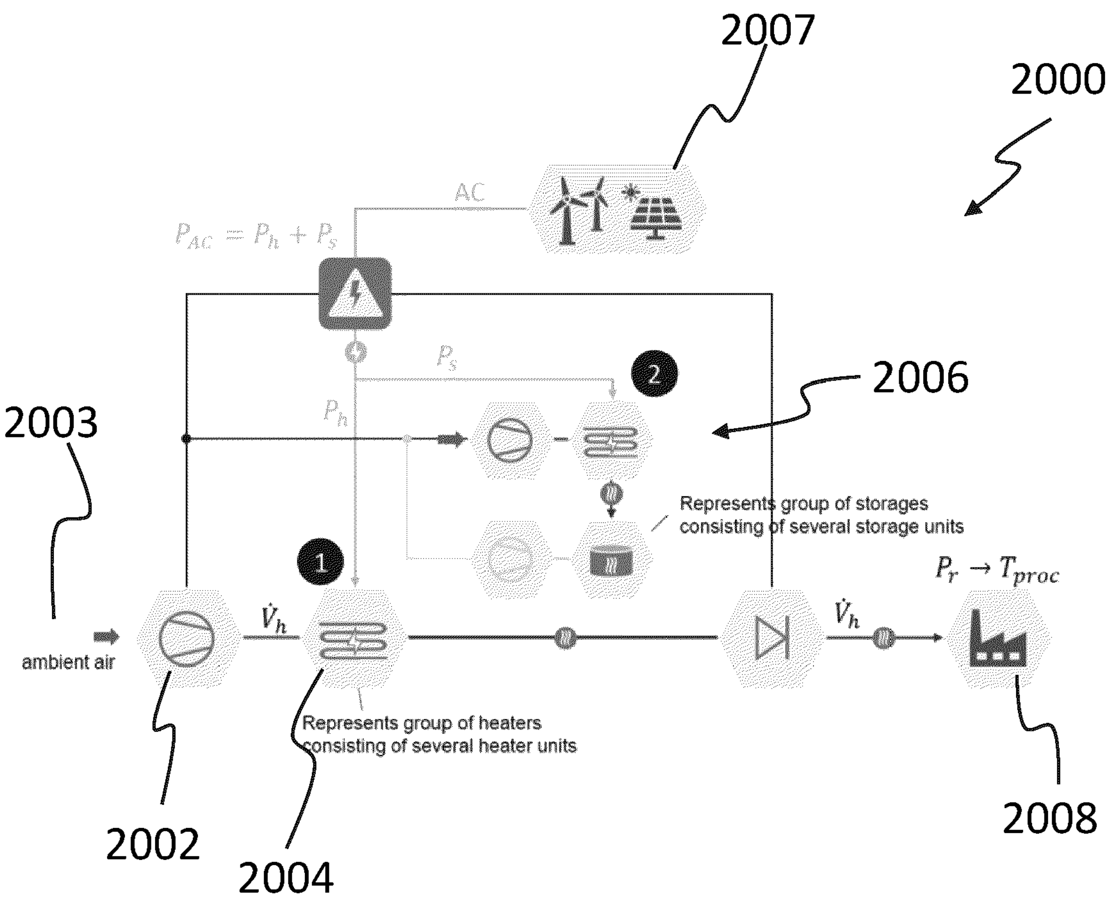
2007
2000
AC
$P_{AC} = P_h + P_s$
P_s
2
2006
P_h
2003
Represents group of storages consisting of several storage units
1
$P_r \rightarrow T_{proc}$
$\dot{V}_h$
$\dot{V}_h$
ambient air
Represents group of heaters consisting of several heater units
2008
2002
2004

Fig. 20

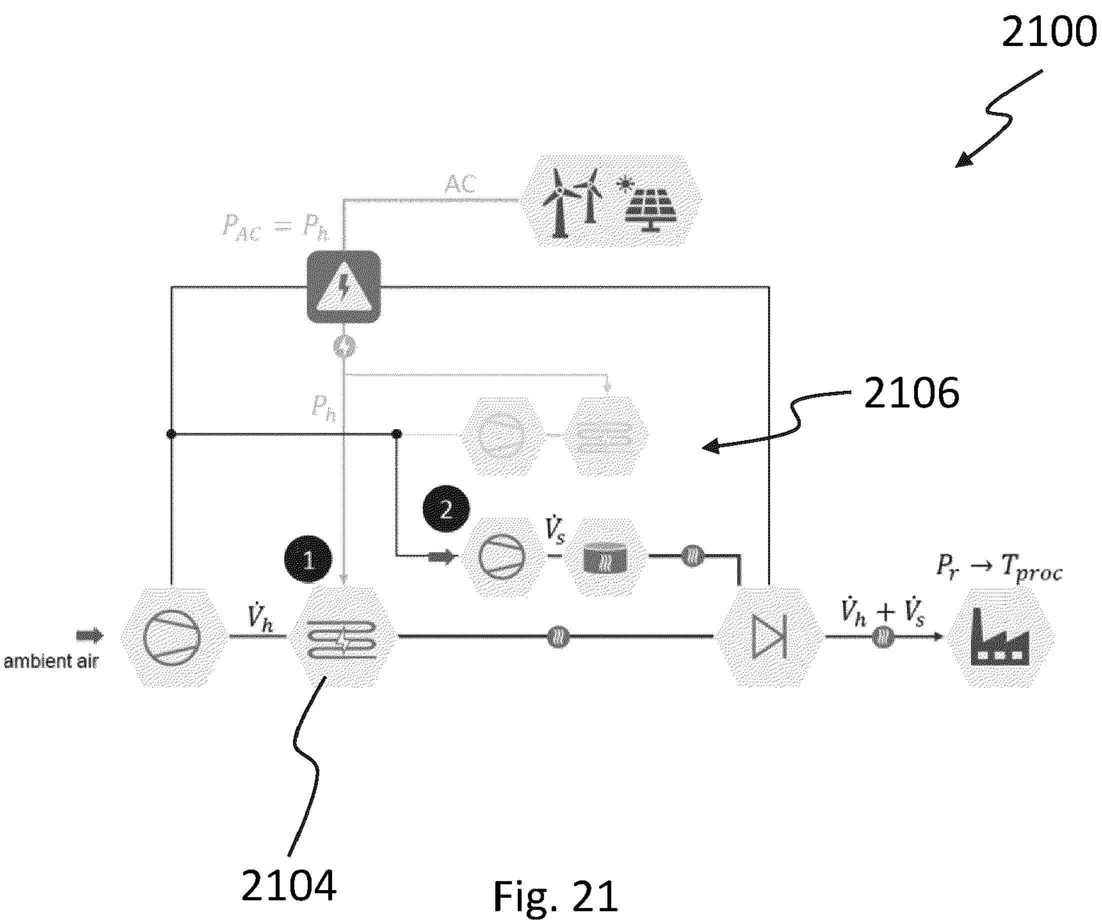
2100
AC
$P_{AC} = P_h$
P_h
2106
2
1
$\dot{V}_s$
$P_r \rightarrow T_{proc}$
$\dot{V}_h$
$\dot{V}_h + \dot{V}_s$
ambient air
2104

Fig. 21

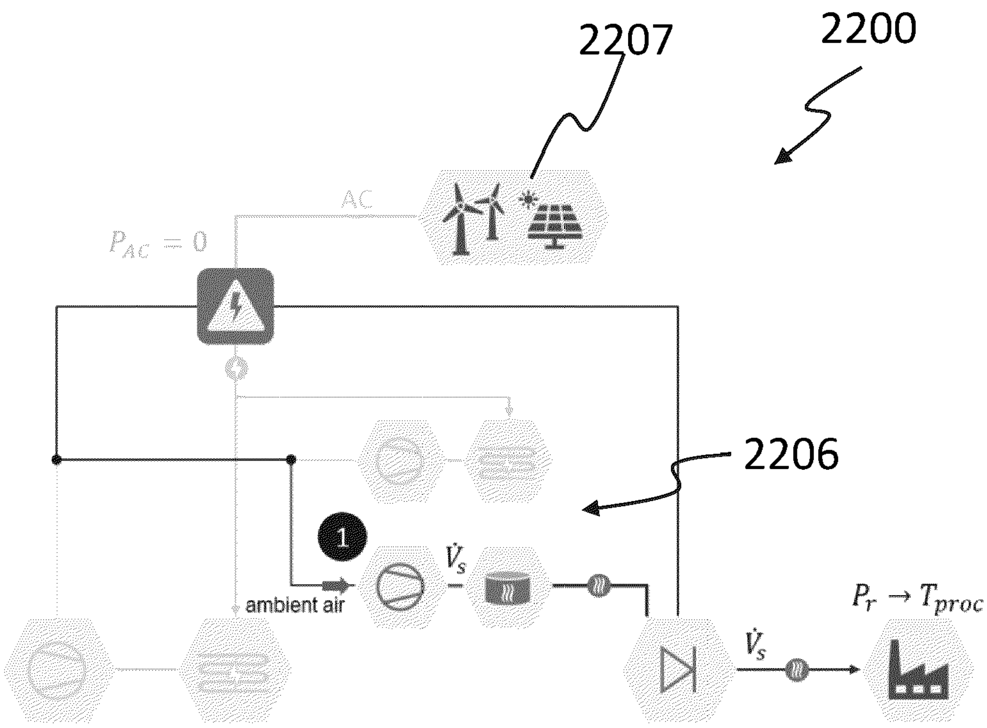
2207
2200
AC
$P_{AC} = 0$
2206
1
$\dot{V}_s$
ambient air
$\dot{V}_s$
$P_r \rightarrow T_{proc}$

Fig. 22

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EUROPEAN SEARCH REPORT

Application Number
EP 23 17 9961

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
E	WO 2023/177669 A1 (LUMMUS TECHNOLOGY INC [US]) 21 September 2023 (2023-09-21) * paragraphs [0019], [0022], [0024], [0026], [0036], [0038], [0040] - [0042], [0045] - [0049]; claims 13,18,20; figure 4 *	1-3,9,14	INV. F24H3/04 F24H3/08 F24H7/04 F24H9/00 F24H9/1863 H05B3/14
A	WO 2023/104746 A1 (KANTHAL GMBH [DE]) 15 June 2023 (2023-06-15) * page 3, line 15 - page 4, line 9; figures 1-6 *	1-15	
A	US 11 603 776 B2 (RONDO ENERGY INC [US]) 14 March 2023 (2023-03-14) * figure 2 *	12	
			TECHNICAL FIELDS SEARCHED (IPC)
			F24H H05B

The present search report has been drawn up for all claims

1

Place of search	Date of completion of the search	Examiner
Munich	20 November 2023	García Moncayo, O

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
Y : particularly relevant if combined with another document of the same category
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L : document cited for other reasons

& : member of the same patent family, corresponding document

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The members are as contained in the European Patent Office EDP file on
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20-11-2023

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		US 2022259987 A1	18-08-2022
		US 2022259988 A1	18-08-2022
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		US 2022268181 A1	25-08-2022
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		US 2023250736 A1	10-08-2023
		WO 2022115721 A2	02-06-2022

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