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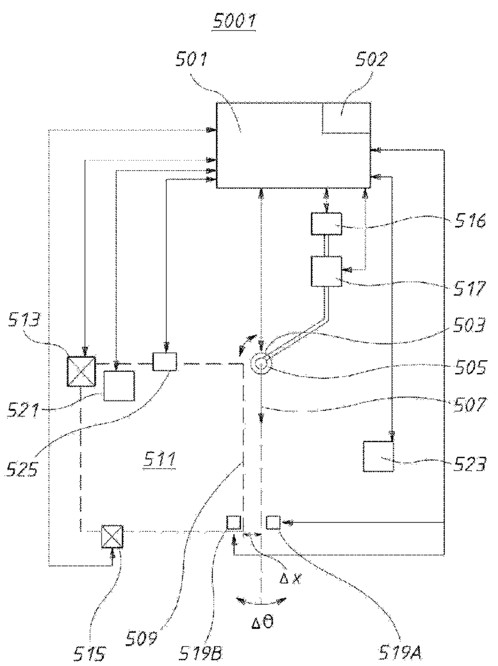

FIG.5

(57) Abstract: An air curtain control system for a solar thermal receiver comprising: at least one air jet (505) arranged to produce a continuous planar air curtain (507) over at least a portion of a receiver aperture 509 of a solar thermal receiver, an air flow control device (517) for controlling a speed of air flow out of the air jet (505), at least one angular control device (503) for controlling an angle of the air curtain (507) relative to the receiver aperture 509, and a system controller (501) arranged to control the air flow control device (517) and angular control device (503) to isolate the receiver aperture (509) from ambient elements external to the receiver aperture (509).

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AIR CURTAIN CONTROL SYSTEM AND METHOD

Technical Field

[0001] The present invention relates generally to an air curtain control system and method and, in particular, to an air curtain control system and method for a solar thermal receiver and a solar thermal receiver.

Background

[0002] Solar thermal receivers are used to collect directed solar radiation from parabolic reflective dishes and heliostat fields. The thermal receivers capture the concentrated solar radiation from the sun through an aperture opening. Typically, fluid inside tubes within the receiver absorbs the heat, which may then be used to generate power. Fig. 1 shows an example of a solar thermal receiver 101 as part of a single dish solar collector 103.

[0003] Various inefficiencies occur with solar thermal receivers including thermal loss at the receiver through conduction, convection and radiation as well as optical losses as the sun light is collected. Fig. 2 shows a conceptual temperature field 201 of a solar thermal receiver 203 losing heat from a receiver aperture 205. As can be seen in Fig. 2, in the absence of an air curtain, significant temperature stratification develops as a stagnant region trapped within the cavity receiver for all angles of inclination slightly greater than 0 degrees.

[0004] Air curtains have generally been available for use in shop front environments to minimise loss of heat from the shop. These types of air curtains use a minimal approach sealing mechanism that is only required to generate an air curtain that extends to the floor. In other words, the floor provides a mechanism for redirecting and containing the air curtain by reducing the vertical component of the flow to zero. Solar thermal receivers do not have the equivalent of a floor to enable an equivalent system to be useful. Further, these types of air curtain are generally limited to reducing heat transfer between horizontally connected volumes. Such units act to suppress the convective exchange of air between a temperature controlled interior environment and an uncontrolled exterior environment.

[0005] Further, air curtains have been used in systems with a falling stream of solid particles being used to absorb thermal energy directly. In these systems, air curtains are directed upwards to help stabilise and confine the stream of particles. However, it is not their purpose to suppress heat loss due to convection from heated surfaces of the thermal receiver.

[0006] In air curtain systems for solar thermal receivers, it is known to have a jet of air being directed towards the aperture of the receiver. However, in these systems the air curtain produced traverses the entire aperture, which may not provide optimum performance. Further, these prior systems do not take into account the pressure distribution within the solar thermal receiver.

Summary

[0007] It is an object of the present invention to substantially overcome, or at least ameliorate, one or more disadvantages of existing arrangements, or to at least provide the public with a useful choice.

[0008] Disclosed are arrangements which seek to address the above problems by controlling an air curtain for a solar thermal receiver in a manner that minimises heat loss.

[0009] According to a first aspect of the present disclosure, there is provided an air curtain control system for a solar thermal receiver comprising: at least one air jet arranged to produce an air curtain over at least a portion of a receiver aperture of a solar thermal receiver, an air flow control device for controlling a speed of air flow out of the air jet, at least one angular control device for controlling an angle of the air curtain relative to the receiver aperture, and a system controller arranged to control the air flow control device to isolate the receiver aperture from ambient elements external to the receiver aperture.

[0010] According to a second aspect of the present disclosure, there is provided an air curtain control method for a solar thermal receiver comprising the steps of: producing an air curtain from at least one air jet over at least a portion of a receiver aperture of a solar thermal receiver, controlling a speed of air flow out of the air jet, controlling an angle of at least one air jet relative to the receiver aperture, wherein the air flow speed and angle of the air curtain are controlled to isolate the receiver aperture from ambient elements external to the receiver aperture.

[0011] According to a further aspect of the present disclosure, there is provided a solar thermal receiver comprising at least one air jet arranged to produce an air curtain over at least a portion of a receiver aperture of a solar thermal receiver, an air extraction device for extracting air out of the receiver aperture and an air injection device for injecting air into the receiver aperture.

[0012] Other aspects of the invention are also disclosed.

Brief Description of the Drawings

[0013] Some aspects of the prior art and at least one embodiment of the present invention will now be described with reference to the drawings and appendices, in which:

[0014] Fig. 1 shows a prior art arrangement for a solar thermal receiver;

[0015] Fig. 2 shows a conceptual temperature field of a solar thermal receiver;

[0016] Fig. 3 shows a representation of a mathematical model of the behaviour of air emitted from an air jet;

[0017] Fig. 4 shows the air curtain effectiveness as a function of air curtain velocity for varying cavity inclinations according to the herein disclosure.

[0018] Fig. 5 shows a schematic diagram of an air curtain control system according to the herein disclosure.

[0019] Fig. 6 shows an example of a solar thermal receiver according to the herein disclosure;

[0020] Fig. 7 shows an example of a solar thermal receiver according to the herein disclosure;

[0021] Fig. 8 shows an example of an air jet module according to the herein disclosure;

[0022] Figs. 9A – 9D show various configurations of an air jet according to the herein disclosure;

[0023] Fig. 10 shows individual jets of air merging to form a planar air curtain according to the herein disclosure;

[0024] Figs. 11A – 11C show further examples of air jet configurations on solar thermal receivers according to the herein disclosure;

[0025] Figs 12A and 12B show a thermal image of a thermal receiver controlled using a first mode of operation according to the herein disclosure;

[0026] Figs 13A and 13B show a thermal image of a thermal receiver controlled using a second mode of operation according to the herein disclosure;

[0027] Figs. 14A -14E show contour plots indicating the effectiveness of two modes of operation of an air curtain system using different configurations according to the herein disclosure;

Detailed Description including Best Mode

[0028] Where reference is made in any one or more of the accompanying drawings to steps and/or features, which have the same reference numerals, those steps and/or features have for the purposes of this description the same function(s) or operation(s), unless the contrary intention appears.

[0029] The high temperatures experienced in cavity receivers result in significant heat loss through conduction, radiation and convection. These heat loss mechanisms are dependent on a variety of factors including operating conditions and the external environment but are always relevant. The different types of receiver technology relate to the different concentrating methods with line receivers relevant in linear Fresnel and trough systems, tower receivers relevant in solar power towers and central cavity receivers relevant in dish concentrator technology.

[0030] Convective heat transfer constitutes any heat transfer occurring between a solid surface and an adjacent body of fluid, such as air. Such heat transfer can be further classified as forced or natural convection. Natural convection refers to a fluid motion occurring as a result of fluid density differences such as those arising from conductive heating of a fluid near receiver surfaces. Forced convection refers to the heat transfer caused by an externally forced flow such as a wind gust.

[0031] Fig. 3 shows a representation of a mathematical model of air jet behaviour which describes in mathematical terms the relationship between the air at the jet outlet (nozzle) 301 and the air a certain distance y away from the jet outlet (nozzle) 303, where the expanding jet corresponds with the air curtain 509. The term air jet is understood to mean in certain examples a single air jet and co-existing nozzle. In other examples, an air jet may incorporate one or more nozzles.

[0032] This is a summary of equations developed for a non-Boussinesq and vertically-directed air-curtain. Horizontal cavity is assumed to be of uniform temperature T_c (density ρ_c) and ambient conditions are uniform temperature T_∞ (density ρ_∞). It should be noted that $\rho_c < \rho_\infty$ for hot cavity. Further it is assumed that the entire flow is nominally at constant (atmospheric) pressure p_a.

[0033] At any height the variables are:

- distance from jet source y
- jet width b
- jet velocity (alongstream) u
- jet density ρ (corresponding to the air temperature T of the jet)
- specific enthalpy h in the jet

[0034] The governing equations may be written in the form:

[0035] 1. Conservation of mass:

$$\frac{d}{dy}(\rho b U) = \alpha(z) U \sqrt{\rho} \left(\sqrt{\rho_\infty} + \sqrt{\rho_c}\right), \qquad (1)$$

[0036] where $\alpha(z)$ describes the entrainment into the turbulent jet; $\alpha(z)$ may take a constant value ≈ 0.08, for example, over the range of heights where the jet entrains, and a negative value over the range of heights where detrainment occurs.

[0037] 2. Conservation of momentum:

$$\frac{d}{dy}(\rho b U^2) = g(\rho - \rho_\infty) b, \qquad (2)$$

[0038] where g is the gravitational acceleration;

[0039] 3. Conservation of energy:

$$\frac{d}{dy}(\rho bUh) = \alpha U\sqrt{\rho}\left(\sqrt{\rho_\infty}h_\infty + \sqrt{\rho_c}h_c\right), \tag{3}$$

[0040] where h_∞ and h_c are the specific enthalpies of the ambient and cavity air, respectively;

[0041] 4. Thermodynamics/ideal gas constraint:

$$\frac{dh}{dy} = -\frac{c_p p_a}{R}\frac{1}{\rho^2}\frac{d\rho}{dy}, \tag{4}$$

[0042] where c_p is specific heat at constant pressure (approximately constant for air) and R is the specific gas constant for air (from ideal gas law $p/\rho = RT$).

[0043] The jet is initialised at $y = 0$ with width b_0, velocity U_0 (positive downwards) and density $\rho_0 = \rho_a$ (corresponding to temperature T_a); the equations need to be integrated downwards ($y > 0$), but are valid only while $U > 0$ (i.e. the jet does not reverse direction).

[0044] The model results compare well with computational fluid dynamics simulations over the initial range of heights where the jet entrains (and the entrainment constant α is known). The model equations need to be generalised both to allow for jets directed initially at an angle to the vertical and to calculate the curved trajectory of jets subjected to transverse forces.

[0045] The inclination of a solar thermal receiver may vary and this variation has an effect on the amount of heat lost from the aperture of the receiver. Fig. 2 shows the modelled temperature field in a thermal receiver that is subject to convective heat loss at an inclination of around 45 degrees.

[0046] The effectiveness ε of the air curtain can be defined as:

$$\varepsilon = 1 - \frac{Q_{ACD}}{Q_C}.$$

[0047] where Q_{ACD} is the heat loss with the air curtain applied and Q_0 is the heat loss without an air curtain for a given angle. The effectiveness as a function of air curtain velocity is shown for each cavity inclination in Fig. 4. From Fig. 4 it can be seen that the horizontal cavity had a maximum effectiveness of 55 - 70%, with an air curtain velocity of 1.4 – 2.2 m/s.

[0048] The air curtain effectiveness reaches a maximum in the range of 30% to 60% when the cavity is inclined between 15° and 75°, which is notably less than that for a horizontal cavity as seen in Fig. 14C. Furthermore the relative effectiveness of the air curtain is demonstrated to become far more sensitive to air curtain velocity as cavity inclination increases.

[0049] Fig. 5 shows a schematic diagram of an air curtain control system 5001. The system has a system controller 501 for controlling a solar thermal receiver 101.

[0050] The system controller 501 may be any suitable electrical or electronic device that may operate to control an electro-mechanical system. For example, the system controller may be a computer system that includes: a computer module; input devices such as a keyboard and a mouse pointer device; and output devices including a display device and loudspeakers. An external Modulator-Demodulator (Modem) transceiver device may be used by the computer module for communicating to and from a communications network via a network connection, such as WAN, LAN or the Internet.

[0051] The computer module typically includes at least one processor unit, and a memory unit 502, such as random access memory (RAM) and read only memory (ROM). The computer module also includes a number of input/output (I/O) interfaces including: an audio-video interface that couples to the video display, loudspeakers and microphone; an I/O interface that couples to the keyboard and mouse; and an interface for an external modem and printer. The computer module may also have a local network interface, which permits coupling of the computer system via a connection to a local-area communications network, known as a Local Area Network (LAN).

[0052] The I/O interfaces may afford either or both of serial and parallel connectivity, the former typically being implemented according to the Universal Serial Bus (USB) standards and having corresponding USB connectors (not illustrated). Storage devices are provided and typically include a hard disk drive (HDD). Other storage devices such as a floppy disk drive and a magnetic tape drive (not illustrated) may also be used. An optical disk drive is typically provided to act as a non-volatile source of data.

[0053] The components of the computer module typically communicate via an interconnected bus and in a manner that results in a conventional mode of operation of the computer system known to those in the relevant art.

[0054] The method of controlling the thermal receiver may be implemented using the computer system, wherein the algorithm may be implemented as one or more software application programs executable within the computer system.

[0055] The software may be stored in a computer readable medium, including the storage devices described below, for example. The software is loaded into the computer system from the computer readable medium, and then executed by the computer system. A computer readable medium having such software or computer program recorded on the computer readable medium is a computer program product.

[0056] The software is typically stored in the HDD or the memory. The software is loaded into the computer system from a computer readable medium, and executed by the computer system. Thus, for example, the software may be stored on an optically readable disk storage medium (e.g., CD-ROM) that is read by the optical disk drive. A computer readable medium having such software or computer program recorded on it is a computer program product.

[0057] The schematic diagram in Fig. 5 shows a single air jet/nozzle 505. However, it will be understood, as explained below, that there may be more than one air jet arranged to produce an air curtain 507. The air curtain may be a planar air curtain where the air curtain is substantially spatially arranged to form a sheet of air. The air curtain may be a non-planar air curtain where the air curtain is shaped according to the arrangement of the air jet(s), such as in a circular or semi-circular manner, for example. The air curtain may be a spatially continuous or spatially semi-continuous air curtain over at least a portion of the air curtain. For example, an initial portion of the air exiting the air jet(s) may not form a spatially continuous air curtain, but may form into a spatially continuous air curtain a distance away from the air jet. Also, the air curtain may be a temporally continuous or temporally semi-continuous air curtain. For example, the air curtain control system may pulse the air coming out of the air jet(s) to produce an intermittent flow of air. The intermittent flow of air may form together to produce a spatially continuous of spatially semi-continuous air curtain. Also, as explained in more detail below, the air curtain 507 is generated so that it covers or encloses at least a portion of the thermal receiver aperture 509. That is, the entire length and width of the aperture of the thermal receiver may be covered by the air curtain, or only a portion of the length and width of the aperture may be covered by the air curtain. It will be understood that the aperture references the aperture plane of the housing of the thermal receiver across the opening at which the air curtain is being generated.

[0058] The angular displacement of the air jet 505 relative to the aperture 509 may be adjusted by an angular control device 503. It will be understood that there may be more than one angular control device. The angular control device controls the angle at the source of the air curtain, i.e., the source angle relative to the aperture of the receiver. It may also control the air curtain, or air jet/nozzle angle, or the direction the air is emitted from the nozzle relative to the aperture of the receiver. The air jet, through adjustment of the air jet or air jet nozzle or housing, may be angularly adjusted so that the air curtain is directed parallel to the aperture 509. Alternatively, the air jet may be angularly adjusted so that the air curtain is directed at a source angle ϴ relative to the aperture 509. It will be understood that the angle ϴ may be a positive or negative value such that the air curtain is directed either towards or away from the thermal receiver (and therefore towards or away from the aperture). The angular control device 503 may, for example, be a motorised device that rotates the air jet 505 according to a control signal generated by the system controller 501. Other suitable angular displacement devices are also envisaged.

[0059] In addition or alternative to the source angle adjustment, the position of the air jet relative to the aperture may be adjusted or configured depending on the requirements of the system. As shown in Fig. 5, the air jet may be arranged to direct the air curtain from a position located vertically above the receiver aperture. Further, the horizontal positioning of the air jet may be adjusted so that the nozzle of the air jet produces an air curtain that is parallel and coplanar with the aperture 509 of the thermal receiver. Alternatively, the horizontal positioning may be offset by a value Δx so that the nozzle of the air jet produces an air curtain that is parallel and not coplanar with the aperture 509 of the thermal receiver. The positioning of the air jet along the horizontal axis may be fixed, or may be adjusted either manually or by any suitable means. For example, the horizontal position of the air jet may be adjusted by the system controller 501, which outputs a control signal to move a horizontal support upon which the air jet 505 is located. Other suitable horizontal displacement devices are also envisaged.

[0060] It will be understood that the source of the air curtain (i.e., the air jet) and the direction that the air is emitted from the air jet may be modified. For example, the air curtain source may be located vertically above the aperture. Further, the air curtain source may be located anywhere along the x-axis (where the aperture plane is the y-axis) and the angular direction away or towards the aperture plane may be adjusted. Also, the air curtain source may be located in between the upper and lower points of the aperture plane and directed towards the aperture at any angle.

[0061] An air flow generator 516, such as an air fan, provides the air to the air jet 505 via an air flow control device 517 that controls the speed of air flow out of the air jet. It will be understood that the air flow control device 517 and air flow generator 516 may be a single device that combines the two functions. The motion of air generated by the air flow generator passes along a suitable conduit to the air flow control device, and thereon to the air jet 505 via another suitable air conduit.

[0062] One or more pressure sensors (519A and 519B) may be located in, near or around the receiver cavity (or aperture) to measure the air pressure in those locations. Further, one or more temperature sensors 521 may be located within the receiver cavity to measure the temperature in the receiver cavity. Also, one or more ambient wind sensors 523 may be located externally to the receiver cavity to measure ambient wind variables such as temperature, direction and velocity. Each of these sensors (519A, 519B, 521, 523) are in communication with the system controller 501 to send the sensed readings to the controller 501.

[0063] The system controller 501 is arranged to control the air flow control device 517 and the angular control device 503 to generate the air curtain and thus isolate the receiver aperture from ambient elements that are external to the receiver aperture.

[0064] The system controller 501 may be arranged to control the air flow control device 517 and the angular control device 503 by controlling one or more of the speed of air flow and the angle of the air curtain based on a predetermined algorithm. The predetermined algorithm may be stored in a memory module 502 that is in communication with the controller 501.

[0065] The predetermined algorithm may be configured or adjusted based on one or more of the detected temperature(s) in the receiver cavity, the detected inclination of the receiver aperture, one or more computational fluid dynamics models, one or more measured performance characteristics and fundamental flow physics.

[0066] The system controller memory 502 may also incorporate therein a look up table. The look up table may be used by the system controller to adjust one or more of the speed of air flow and the source angle of the air curtain based on an inclination of the receiver aperture. As an alternative, a correlation equation, polynomial expression or any other suitable technique may be used.

[0067] The system controller 501 may be arranged to control the air flow control device 517 and angular control device 503 based on one or more input signals. These input signals may be, for example, one or more of the inclination of the receiver aperture, the temperature(s) in the receiver cavity of the solar thermal receiver, the angle of the air curtain relative to the receiver aperture, the speed of the air flow out of the air jet, ambient wind speed, ambient wind direction, ambient wind temperature and sun position.

[0068] The inclination of the receiver aperture may be detected and sent to the system controller 501 by an inclination module 525. The inclination module may detect the angle of inclination of the solar thermal receiver. Further, the inclination module 525 may also adjust the inclination of the solar thermal receiver.

[0069] The temperature(s) in the receiver cavity of the solar thermal receiver may be detected by a temperature gauge(s) within the cavity of the thermal receiver and sent to the system controller.

[0070] The angle of the air curtain relative to the receiver aperture may be determined by the angular control device and sent to the system controller.

[0071] The speed of the air flow out of the air jet may be determined by the air flow control device and sent to the system controller.

[0072] The ambient wind speed, wind direction and wind temperature may be detected by suitable wind measurement devices positioned externally from the solar thermal receiver aperture.

[0073] As shown in Fig. 5, the system may also include one or more air extraction devices 513 for extracting air out of the solar thermal receiver. Further, the system may include one or more air injection devices 515 for injecting air into the solar thermal receiver. It will be understood that the system may incorporate both air extraction and injection devices. These air extraction and injection devices may be in communication with the controller to receive control signals from the system controller 501 that control how much air is being extracted from or injected into the thermal receiver cavity 511. The adjustment of these air extraction and injection devices may adjust the profile of the air curtain to adjust how much of the receiver aperture is isolated. Further, the air extraction devices 513 and air injection devices 515 may be connected together to enable the air being extracted to be injected. For example, the air may flow from the air extraction devices to the air injection devices via a heat exchanger.

[0074] Therefore, in general, the herein described system generates controlled air flows that are directed so as to partially suppress the convective flows that would otherwise remove thermal energy from the high temperature heat-collecting surface in a concentrating solar thermal receiver. The heat-collecting surface may be recessed to some degree in a housing such as the cavity 511 of Fig. 5 or Fig. 6 or Fig. 7.

[0075] As explained above, the air curtain may be generated and controlled in conjunction with extraction (or injection) of air from (to) the volume trapped in the housing. The system can assist in suppressing thermal losses for receivers that are either fixed in space or inclined at a variety of angles during operation, and/or are exposed to ambient wind and turbulence. Optimum suppression of convective heat loss can be achieved by a control system that can adjust the speed of the air curtain, the angle that the air curtain makes with respect to the aperture plane (i.e. that through which the heated receiver surface is exposed to ambient conditions) and the rate at which air is extracted from (or injected to) the housing.

[0076] Fig. 6 shows a vertical section of a cavity receiver type configuration and Fig. 7 shows a vertical section of a tower receiver type geometry. It will be understood that other types of configuration or geometry may be used in accordance with the herein disclosure. It will also be understood that the receiver shown in Fig. 7 is not required to be positioned vertically as shown in order for it to operate effectively and that any suitable range of inclination angles may be used.+

[0077] A heat collecting surface (601 and 701) consisting of tubes containing working fluid. In each system, a receiver housing (602 and 702) is provided. Air jet nozzle(s) (603 and 703) are provided for directing air over the aperture plane (604 and 704) of the housing. Individual jet(s) of air (605 and 705) exit the air jet nozzle(s). The initial plane (606 and 706) of the air curtain is shown. An extraction valve (607 and 707) shown in one possible position may be used for extracting air from the receiver housing. An injection valve (608 and 708) shown in one possible position may be used for injecting air into the receiver housing. A cavity inclination axis 609 is shown for the cavity receiver type configuration. In each of these examples, incoming solar radiation (610 and 710) is directed and focussed into the cavity (611 and 711) of the receiver to heat the heat collecting surface(s) (601 and 701). A combination of either or both of the air jets (603, 703) and the injection and/or extraction valves (608, 708 and 610,710) are controlled by the system controller 501, which controls the speed and angle of the air jets, as well as the speed of air extraction and injection. The adjustment of one or more of these components may be made based on input variables received as described herein. It will be understood that any combination of air extraction (608, 708), air injection (607, 707), and air-jets (603, 703) may be used at any point in time according the optimal performance settings of the control system.

[0078] Fig. 8 shows an example of an air jet module 801 that could be used with either of the receiver units shown in Fig. 6 and Fig. 7. The air jet module 801 includes a single air jet 803 for generating an air curtain 805. The air flow control device 517 may also form part of the air jet 803, or may be separate and in fluid communication with the air jet 803. The air flow generator 516 may also be part of the air jet 803 or separate from the housing but in fluid communication with the air flow control device 517. As mentioned earlier, the air flow generator and air flow control device may be combined as one unit.

[0079] The angle of the air curtain 805 may be adjusted using the angular control device 503. That is, the entire air jet 801 may be moved to adjust the angle of the air curtain 805, or a nozzle within the air jet 801 may be adjusted. It will be understood that other alternative mechanisms may be used to adjust or control the angle of the air curtain. For example, by locating two air jets close to each other where the air jets operate at different speeds, the differential speed of the two jets may be used to control the angle of the combined air jet. As a further example, a further air jet may be directed into the air curtain, where the air jet is directed perpendicular (or at any other suitable angle) to the main air curtain in order to add lateral momentum.

[0080] Referring to Figs.9A – 9D, various configurations of air jet nozzles as viewed from the jet nozzle orifice end are provided.

[0081] It will be understood that other configurations are also possible such as the use of grille or mesh-like nozzles as outlets for the air jets.

[0082] The generated air curtain is a continuous and approximately planar turbulent jet of air that is formed by the flow of air exiting either a single linear rectangular nozzle or a series of closely spaced nozzles. The nozzles may be, for example, round or rectangular. For example, as shown in Fig. 9A, the air jet nozzle 801 may be a single rectilinear nozzle as shown in Fig. 8.

[0083] Many detailed geometric arrangements of individual jets could be used, such as, for example, a linear or zig-zag arrangement of evenly-spaced individual jets may be provided.

[0084] A series of rectilinear nozzles 901 may be provided as shown in Fig. 9B. In this example, four individual evenly spaced rectilinear air jets (or nozzles) are provided.

[0085] A series of closely-spaced round nozzles 905 may be provided within each air jet 903 as shown in Fig. 9C.

[0086] A zig-zag array of closely-spaced round nozzles 909 in each air jet 907 may be provided as shown in Fig. 9D

[0087] Fig. 10 shows how individual jets of air 1001 from an air jet module 1002 may merge to form a planar air curtain 1003 as viewed normal to the jet of air direction. The spacing d between individual air jets or nozzles should be small enough to allow the jets of air to merge into a continuous planar air curtain by the downstream point where the upper edge of the receiver aperture is first encountered. For example, this may occur by applying a downstream distance of 15x the air jet (or nozzle) spacing as shown in Fig. 10. The nozzle width for an air jet is a function of the receiver operating temperature, the aperture size of the receiver and the jet of air velocity (as described in more detail below). For example, nozzle widths may be in the range of 4-20 mm for smaller receiver apertures of 0.2 m, and up to 0.2-1 m for large apertures of 10 m. Therefore, the width of the one or more nozzles (or air jets as the air leaves the nozzle) may be between 4 mm and 1 m. It will be understood that the technology described herein may be scaled up to apply to cavity receivers of any suitable size.

[0088] It will be understood that various configurations and settings may be used according to the herein disclosure. The following tables provide some specific examples.

[0089] The table below provides some broad operating ranges for air curtain parameters. It should be noted that these ranges are estimates based on nominal operating temperature of 500ºC (ambient temperature ~20ºC), These broad operating ranges would not change by much for temperatures in the range 400-700ºC.

Aperture height H (m)	Air curtain width range b_0 (mm)	Air curtain speed U_0 (m/s)	Jet angle
0.2	4 - 20	0.6 - 12	-20 - +20
0.5	10 – 50	0.9 - 20	-20 - +20
1	20 - 100	1.2 - 28	-20 - +20
4	80 - 400	2.5 - 55	-20 - +20
7	140 - 700	3.3 - 75	-20 - +20
10	200 - 1000	4 - 90	-20 - +20

[0090] The following table provides an example of preferred, close to optimum, operating ranges for air curtain parameters operating according to two different modes.

			First (partially-sealed) mode		Second (fully-sealed) mode	
Aperture height H (m)	Air curtain width b_0 (mm)	Cavity inclination	Air curtain speed U_0 (m/s)	Jet angle	Air curtain speed U_0 (m/s)	Jet angle
0.2	14	0	2.5 – 3.8	-5 - +10	3.4 – 5.1	-15 - -5
		15	1.9 – 3.4	-5 - +10	3.8 – 4.6	-15 - -5
		30	1.4 – 1.9	-5 - +10	2.7 – 3.4	-15 - -5
		45	1 – 1.5	-5 - +10	1.7 – 2.5	-15 - -5
0.5	35	0	4 – 6	-5 - +10	5.4 – 8	-15 - -5
		15	3 – 5.5	-5 - +10	6 – 7.5	-15 - -5
		30	2 - 3	-5 - +10	4.3 – 5.5	-15 - -5
		45	1.5 – 2.5	-5 - +10	2.5 – 4	-15 - -5

1	70	0	5.5 – 8.5	-5 - +10	8 – 12	-15 - -5
		15	4 – 7.5	-5 - +10	8 – 10	-15 - -5
		30	3 – 4.2	-5 - +10	6 – 8	-15 - -5
		45	2.3 – 3.5	-5 - +10	4 – 6	-15 - -5
4	280	0	12 – 17	-5 - +10	15 – 23	-15 - -5
		15	8 – 15	-5 - +10	17 - 21	-15 - -5
		30	6 – 9	-5 - +10	12 – 15	-15 - -5
		45	4 – 7	-5 - +10	8 – 12	-15 - -5
7	500	0	15 – 22	-5 - +10	20 – 30	-15 - -5
		15	11 – 20	-5 - +10	22 – 27	-15 - -5
		30	8 – 11	-5 - +10	16 – 20	-15 - -5
		45	6 - 9	-5 - +10	10 - 15	-15 - -5
10	700	0	18 – 27	-5 - +10	24 – 36	-15 - -5
		15	13 – 24	-5 - +10	27 – 32	-15 - -5
		30	10 -13	-5 - +10	19 – 24	-15 - -5
		45	7 - 11	-5 - +10	12 - 18	-15 - -5

[0091] It will be understood that the air jet (and nozzle) arrangement should preferably collectively span at least the full width/periphery of the aperture through which the heated receiver surface is exposed to ambient conditions.

[0092] Figs. 11A – 11C show further examples of air jet configurations on solar thermal receivers. In Fig. 11B and 11C the air jets are configured into a circumferential arc. In Fig. 11B, the arc of air jets are placed around a circular aperture, as shown facing the aperture. In Fig. 11C, the arc of air jets are placed around the periphery of the housing. It will be understood that in the arrangements described herein the system may be configured so that the flow velocity of the air jets may be controlled locally, i.e. each individual jet is controlled independently.

[0093] In Figs. 11A – 11C, the air jets are shown mounted on axisymmetric cavity receivers. Jet nozzles may be mounted in a linear fashion as shown in Fig. 11A, or a series of linear jet modules mounted to approximate a semi-circular arc as shown in Fig. 11B and 11C. Fig.11A shows a receiver housing 1101, heat collection tubes 1103, jet nozzle module(s) 1105 and an approximately planar air curtain 1107. Fig.11B shows a receiver housing 1109, heat collection tubes 1111, jet nozzle module(s) 1113 and an approximately planar air curtain 1115. Fig. 11C shows a receiver housing 1119, heat collection tubes 1117 in a louvred arrangement, jet nozzle module(s) 1121 and an approximately planar air curtain 1123.

[0094] In each case, the air jet nozzles produce a unidirectional jet of air without radial convergence of flow. The angle of each air jet module (or nozzle) with respect to the aperture plane may be controlled or adjusted by the system controller 501.

[0095] It will be understood that the configuration of the air jets and/or nozzles in Fig. 11C may be adapted for receiver housings 1119 that subtend angles less than 360 degrees in the horizontal plane by adding vertical radial walls (not shown) at the limits of the desired angular extent. Vertical radial “blade-like” walls could also be included to subdivide the receiver into several compartments. For example, the blades may be cooled by incorporating a cooling channel and cooling medium therein.

[0096] The air jets may be supplied with air at an arbitrary temperature. However, as an alternative, the air may be supplied at ambient temperature air. Further, the air jets may be supplied using air extracted from the cavity such that the air is at a non-arbitrary, non-ambient temperature.

[0097] The continuous and approximately planar jet is directed across the receiver aperture through which the heated receiver surface is exposed to ambient conditions. The plane of the air jet nozzle(s) need not be coincident with the plane of the aperture, but the angle between them (when projected into the vertical plane normal to the aperture) will be typically less than 30° for best suppression of heat loss. The optimum angle for the jet of air depends on the inclination of the aperture plane and the ambient conditions. Typically the ability to suppress heat loss is improved when the vertical component of the jet or air velocity is in the downward rather than upward direction.

[0098] The air curtain control system may operate in two distinct modes to control thermal losses from the heated receiver surface.

[0099] The first mode is termed “partially sealed”, and generates an air curtain that is directed with a component in the downward direction, but with insufficient momentum to fully traverse (and “seal”) the receiver aperture through which the heated receiver surface is exposed to ambient conditions. That is, the system controller is arranged to operate in a first mode of operation where the air jet(s) is arranged to direct the air curtain over less than a full portion of the receiver aperture. One or more of the air flow control device, angular control device, air extraction device and air injection device may be controlled by the system controller based on detected input variables to direct the air curtain over less than a full portion of the receiver aperture.

[00100] The jet nozzle(s) or air jet may be oriented between 0 degrees and 20 degrees, or between 5 degrees and 20 degrees, or between 10 degrees and 20 degrees, or between 15 degrees and 20 degrees, or between 5 degrees and 15 degrees, or between 10 degrees and 15 degrees. Optionally the jet nozzle(s) or air jet may be activated at 5 degrees, 10 degrees, 15 degrees or 20 degrees, either side of the aperture plane (when projected onto the vertical plane normal to the aperture) depending on the operating conditions for the receiver. Directing the air curtain slightly towards the aperture will reduce the jet strength required to maintain optimum conditions. That is, the system controller may operate in the first mode of operation to control the angular control device so the source angle of the air curtain relative to the receiver aperture is any value or range as listed directly above from a plane lying across the receiver aperture. Therefore, in the partial mode of operation, an inwardly angled jet of air (i.e. directed towards the aperture) only partially traverses the aperture.

[00101] According to one example, the system controller may operate in the first mode of operation to control the angular control device so the angle of the air curtain relative to the receiver aperture is substantially 15 degrees from a plane lying across the receiver aperture. The system controller may also be arranged to operate in the first mode of operation using any of the other values or ranges listed directly above. The angle of the air curtain relative to the receiver aperture is either directed away from the solar thermal receiver or towards the solar thermal receiver.

[00102] The second mode is termed “fully sealed”, and employs an air curtain directed with a component in the downward direction, but with greater momentum such that the jet fully traverses the aperture through which the heated receiver surface is exposed to ambient conditions. That is, the system controller is arranged to operate in a second mode of operation where the air jet(s) is arranged to direct the air curtain over a full portion of the receiver aperture. One or more of the air flow control device, angular control device, air extraction device and air injection device may be controlled by the system controller based on detected input variables to direct the air curtain over a full portion of the receiver aperture.

[00103] In this second mode, the system controller controls the air jet and/or nozzle so that the generated air curtain is oriented outwards from the aperture plane, between 0 degrees and 20 degrees, or between 5 degrees and 20 degrees, or between 10 degrees and 20 degrees, or between 15 degrees and 20 degrees, or between 5 degrees and 15 degrees, or between 10 degrees and 15 degrees, when projected onto the vertical plane normal to the aperture, such that the air curtain just returns to the aperture plane after traversing past the heated receiver surface. That is, the system controller is arranged to operate in the second mode of operation to control the angular control device so that the source angle of the air curtain relative to the receiver aperture is any value or range as listed directly above from a plane lying across the receiver aperture and directed away from the solar thermal receiver. That is, according to one example, the system controller may be arranged to operate in the second mode of operation to control the angular control device so that the angle of the air curtain relative to the receiver aperture is between 5 degrees and 15 degrees from a plane lying across the receiver aperture and directed away from the solar thermal receiver. The system controller may also be arranged to operate in the second mode of operation using any of the other values or ranges listed directly above.

[00104] Figs. 12A and 12B show temperature variations for a thermal receiver 1201 within its cavity 1203 as a result of the system controller 501 operating in the partial mode. In this partial

mode, the air curtain 1205 only partially covers the upper portion of the aperture 1207 of the receiver 1201. Fig. 12A shows the receiver at a first inclination of approximately 30 degrees with the velocity of the air emitted from the air jets at 0.8 m/s. Fig. 12B shows the receiver at a second inclination of approximately 60 degrees with the velocity of the air emitted from the air jets at 0.4 m/s. Both Fig. 12A and 12B show the results where the jet width is 5mm and the aperture height is 70 mm.

[00105] The temperatures reached in a solar receiver are typically in the region of 400-900°C, reducing the density of the heated air to between 50 and 25% of that under ambient atmospheric conditions. The density difference across the air curtain plays a significant role in the operational dynamics of this system.

[00106] In the partially-sealed mode, the air curtain entrains a sufficient volume of hot air from the cavity 1203 of the receiver housing that buoyancy acts on the air curtain 1205 to overcome its initial momentum, deflecting the air curtain 1205 away from the aperture plane 1207. This behaviour can be seen in Figs. 12A and 12B where convective losses are suppressed in this partial sealing mode because the air curtain acts like a virtual wall to reduce the size of the aperture through which the heated receiver surface is exposed to ambient temperatures.

[00107] The most effective air curtain strength at a given inclination angle corresponds to the largest stagnant region and a reduction in the convective heat loss (by approximately 40% for a range of inclination angles between 15 degrees and 60 degrees). Figs. 12A and 12B indicate that as cavity inclination is increased, the sealing effect can become detrimental to cavity performance and a reduction in air curtain velocity may be required to maintain effective operation.

[00108] Figs. 13A and 13B show temperature variations for a thermal receiver 1301 within its cavity 1303 as a result of the system controller 501 operating in the fully-sealed mode. In this filly-sealed mode, the air curtain 1305 fully covers the aperture 1307 of the receiver 1301. Fig. 13A shows the receiver at a first inclination of approximately 30 degrees with the air jet pointing away from the aperture at an angle of 10 degrees and with the velocity of the air emitted from the air jets at 2 metres/sec. Fig. 13B shows the receiver at a second inclination of approximately 45 degrees with the air jet pointing away from the aperture at an angle of 10 degrees and the velocity of the air emitted from the air jets at 1.5 metres/second.

[00109] In the fully-sealed mode, the air curtain 1305 acts to largely isolate the volume housing the heated receiver surface from the ambient conditions. The initial momentum of the air curtain generated by the air jet(s) (or nozzle(s)) is not significantly affected by the buoyancy of the hot air that is entrained into the air curtain. This sealing mode works by lowering the pressure in the housing relative to the ambient, drawing the air curtain back to the aperture plane 1307, as seen in Figs. 13A and 13B.

[00110] Both the partial and fully sealed modes may be operated over a wide range of aperture inclinations, typically offering similar reductions in convective loss. Optimum partial-sealing can typically be achieved over a range of initial jet angles and speeds; this range of optimum operating conditions is much narrower for full-sealing, and requires higher initial jet velocities.

[00111] With reference to the tables in paragraphs [0089] and [0090], rough estimates of the operating conditions that are required of jets may be made using the Deflection Modulus (which has formed the basis of work in the area of building ventilation), $D = \rho_a b u^2 / g(\rho_a - \rho_r) H^2$, where ρ_a and ρ_r are the densities of ambient air and air at the heated surface temperature, respectively, b and u are the width and speed of the air curtain, respectively, where it becomes a continuous sheet, g is the gravitational acceleration and H is the size of the aperture housing the section of heated receiver surface. For instance, a receiver operated at approximately 500ºC and with an aperture size to the heated surfaces of order 1 m may be shielded by a linear air curtain generated by a nozzle (or air jet) width 0.07 m and jet of air speeds in the range 1.2-28 m/s. It will be understood that the speed of air from the air jet/nozzle may be based on the orientation of the aperture plane. A large vertical receiver surface of order 10 m, operated at the same temperature, may be shielded by a linear air curtain with nozzle (or air jet) width 0.7 m and jet or air speeds in the range 4-90 m/s. It will be understood that other jet widths and air speed ranges may also be suitable as disclosed herein.

[00112] That is, the system controller may be arranged to control the air flow control device so that the speed of air flow out of the air jet is between 1 and 90 metres per second. Optionally, the system controller may be arranged to control the air flow control device so that the speed of air flow out of the air jet is between 2 and 7 metres per second. As a further option, the system controller may be arranged to control the air flow control device so that the speed of air flow out of the air jet is between 7 and 20 metres per second. Alternatively, the system controller may be arranged to control the air flow control device so that the speed of air flow out of the air jet is within other ranges as disclosed herein.

[00113] The air curtain may be used to shield convective heat loss at the heated receiver surfaces from the ambient wind. The optimum operating conditions for each sealing mode may be modified by the system controller based on one or more of the strength of the ambient wind and its direction. The ambient wind may induce a large-scale pressure distribution around the receiver. For certain wind directions, this will lead to a pressure drop or suction effect that will tend to increase the local convective loss from the receiver surface. Effective shielding of the surface by the air curtain relies on inducing a similar pressure drop in the vicinity of the heated surface, and this can be characterised by the dimensionless parameter $\rho_a U^2 / (p_a - p_r)$, where U is the wind velocity, and $p_a - p_r$ is the maximum pressure difference between the ambient air and that inside the receiver at a given height. Effective shielding may be possible in general for wind speeds up to approximately 40% of the jet speed, and possibly more depending on the orientation of the wind direction with respect to the receiver.

[00114] In addition, operation of these two modes may be assisted by the extraction (and/or injection) of air from (to) the housing surrounding the heat receiver surface using the air extraction device 513 and air injection device 515. Extraction or injection of air from the housing surrounding the heated receiver surfaces can be used in conjunction with the above features to enhance the effectiveness of the air curtain. The process of air extraction or injection modifies the pressure distribution in the housing, and hence the forces acting on the air curtain. It can be used to lower the jet velocities required in either full or partial sealing modes, and may increase the robustness of the air curtain to ambient wind.

[00115] The pressure distribution inside the receiver housing 511 strongly affects the behaviour of the air jets forming the air curtain. It will be understood that the housing may be sealed with the exception of the injection and extraction devices (515 & 513) and the aperture 509. In the fully sealed mode, the air curtain acts to at least partially isolate the receiver interior from the ambient conditions external to the receiver cavity. Much of the interior of the cavity is at a slightly lower pressure than the external pressure. This produces a suction effect that retains the air curtain seal across the aperture. The suction effect also means that the jet turbulence is strong enough to entrain hot air only in the upper part (approximately 20%) of the air curtain. The injection/extraction of air to the receiver housing provides significant ability to control the air curtain seal. This allows sealing modes that operate with reduced jet velocities. The receiver cavity may also be shielded against ambient wind conditions. According to one example, one or more pumps may be coupled to the extraction, injection points or ports. This pump may provide an overpressure or suction in order to produce pressure changes that are comparable to a maximum rated wind speed.

[00116] As a further example, the external pressure outside of the cavity may be tapped to the receiver housing. This may be done, either directly or via the control system, For example, the control system may select the height in the housing at which the tapping could be connected. According to one example, the most suitable tapping may be a surface near to and parallel to the aperture plane. Alternatively, the tapping may be connected to a "stack" acting as a chimney. This arrangement may be used to effectively equalise the ambient pressure and the pressure in the receiver housing, automatically compensating for much of the suction and overpressure effects caused by the ambient wind. It will be understood that such a tapping does not necessarily require a rate of injection and/or extraction to be maintained.

[00117] The air curtain may be driven from an active control system that can respond to the operating conditions to maintain optimum suppression of convective heat loss. The primary inputs to the control system are inclination angle of the aperture plane (for a mobile, sun-tracking receiver), receiver operating temperature and ambient wind strength and direction. The control system may adjust the speed of air forced from the nozzle(s) or air jet(s), the angle that the air curtain produced by the air jet(s) or nozzle(s) makes with the aperture plane, and the rate at which air is extracted from, or injected into, the housing.

[00118] The appropriate air jet/nozzle parameters will may be set by a pre-determined algorithm based on a combination of predictions using fundamental flow physics, (previously conducted) simulations using computational fluid dynamics (CFD) models and measured performance characteristics.

[00119] Fig. 14A shows the effectiveness of the two modes of operation for a range of air curtain angles and speeds. According to this particular example, the cavity is inclined at 45 degrees. It will be understood that other cavity inclinations may be used.

[00120] It can be seen in Fig. 14A that there is increased effectiveness for a partially sealed mode of operation (1401) where the jet velocity is set between 0.5 m/s and 1 m/s, or optionally between 0.6 m/s and 0.9 m/s. For increased effectiveness, the angle of the air window may be directed away from the receiver between 0 and 10 degrees or directed towards the receiver between 0 and 10 degrees. Optionally, the air window may be directed away from the receiver between 0 and 8 degrees or directed towards the receiver between 0 and 8 degrees.

[00121] It can be seen that there is increased effectiveness for a fully sealed mode of operation (1403) where the jet velocity is set between 1 m/s and 1.5 m/s, or optionally between 1.1 m/s

and 1.3 m/s. For increased effectiveness, the angle of the air window may be directed away from the receiver between 5 and 15 degrees. Optionally, the air window may be directed away from the receiver between 8 and 11 degrees.

[00122] Figs 14B-14E show a contour plot of the effectiveness as a function of air speed out of the air jets and the cavity inclination angle for the two modes of operation. Fig. 14B shows a cavity inclination of 0 degrees, Fig. 14C shows a cavity inclination of 15 degrees, Fig, 14D shows a cavity inclination of 30 degrees and Fig. 14E shows a cavity inclination of 45 degrees.

[00123] Each of the values generated for the different configurations and parameters may be recorded in a look up table and retrieved and used by the system controller to effectively control the air curtain system. It will be understood that the invention is not limited to these specific examples and that further set up parameters may be added to the look up table based on further modelling and testing of the air curtain system, for example at different scales.

[00124] It will be understood that these angular and velocity values may be adjusted to counter measured ambient wind effects. For example, with an ambient wind directed towards the chamber of the receiver, the pressure field will force the air curtain to be deflected towards the aperture plane. The angle of the air curtain directed away from the receiver may be increased, along with the jet air velocity to help counteract this effect and thus shield the receiver chamber. Pressure could also be applied to the receiver chamber by injection of air 515. Further, the ambient wind will tend to be accelerated around a receiver or nearby structures, and the associated pressure fields are complicated. As a further example, for orientations where the receiver is exposed to a local pressure drop associated with acceleration of the flow, such as around the flanks of a tower receiver, the air curtain will tend to be drawn out of the aperture plane. The angle of the air curtain directed towards the receiver may be increased, along with the jet air velocity to help counteract this effect. Suction could also be applied to the receiver chamber by extraction of air 513. Therefore, one or more pressure sensors located in, near or around the receiver cavity may provide pressure measurements to the system controller 501.It will be understood that, as an alternative, the system controller may be a mechanical controller that controls the air curtain to a limited extent. For example, a wind-powered ejector may apply control to a pressurised plenum leading to the air curtain jets.

[00125] It will be understood that the term aperture may also be interpreted to include a localised area of a surface in cases where the solar thermal receiver is in a common form such as a solar tower receiver.

[00126] It will be understood that the control system may be configured to control one or more air jets independently. For example, the system may be configured such that one or more air jets are associated with their own air flow generator 516 and/or air flow control device 517.

[00127] It will be understood that the angular control device may be a passive device that is not controlled by the system controller, but is instead fixed in a static position to generate an air curtain that effectively seals or partially seals the cavity as described herein.

Industrial Applicability

[00128] The arrangements described are applicable to the solar thermal energy industries.

[00129] The foregoing describes only some embodiments of the present invention, and modifications and/or changes can be made thereto without departing from the scope and spirit of the invention, the embodiments being illustrative and not restrictive.

[00130] In the context of this specification, the word “comprising” means “including principally but not necessarily solely” or “having” or “including”, and not “consisting only of”. Variations of the word "comprising", such as “comprise” and “comprises” have correspondingly varied meanings.

CLAIMS:

1. An air curtain control system for a solar thermal receiver comprising:
at least one air jet arranged to produce an air curtain over at least a portion of a receiver aperture of a solar thermal receiver,
an air flow control device for controlling a speed of air flow out of the air jet,
at least one angular control device for controlling an angle of the air curtain relative to the receiver aperture, and
a system controller arranged to control the air flow control device to isolate the receiver aperture from ambient elements external to the receiver aperture.

2. The air curtain control system of claim 1, wherein the system controller is arranged to control the angular control device to isolate the receiver aperture from ambient elements external to the receiver aperture.

3. The air curtain control system of claim 2, wherein the system controller is arranged to control the air flow control device and angular control device by controlling one or more of the speed of air flow and the angle of the air curtain based on a predetermined algorithm.

4. The air curtain control system of claim 3, wherein the predetermined algorithm is configured based on one or more of a temperature of a receiver cavity of the solar thermal receiver, an inclination of the receiver aperture, pressure in, around or near the receiver cavity computational fluid dynamics models, measured performance characteristics and fundamental flow physics.

5. The air curtain control system of claim 1, wherein the system controller is arranged to control the air flow control device and angular control device based on one or more input signals, wherein the one or more input signals are selected from an inclination of the receiver aperture, temperature(s) in a receiver cavity of the solar thermal receiver, the angle of the air curtain relative to the receiver aperture, the speed of the air flow out of the air jet, ambient wind speed, ambient wind direction, ambient wind temperature and sun position.

6. The air curtain control system of claim 1, wherein the system controller further comprises a memory with a look up table, wherein the look up table is used by the system controller to adjust one or more of the speed of air flow and the angle of the air curtain based on an inclination of the receiver aperture.

7. The air curtain control system of claim 1 wherein the at least one air jet is arranged to direct the air curtain from a position located vertically above the receiver aperture.

8. The air curtain control system of claim 1 wherein the system controller is arranged to operate in a first mode where the at least one air jet is arranged to direct the air curtain over less than a full portion of the receiver aperture.

9. The air curtain control system of claim 8 wherein the system controller is arranged to operate in the first mode and the angular control device is controlled by the system controller so the source angle of the air curtain relative to the receiver aperture is up to 20 degrees from a plane lying across the receiver aperture.

10. The air curtain control system of claim 8 wherein the system controller is arranged to operate in the first mode and the angular control device is controlled by the system controller so the angle of the air curtain relative to the receiver aperture is between 10 degrees and 20 degrees from a plane lying across the receiver aperture.

11. The air curtain control system of claim 9 or 10 wherein the angle of the air curtain relative to the receiver aperture is either directed away from the solar thermal receiver or towards the solar thermal receiver.

12. The air curtain control system of claim 1 wherein the system controller is arranged to operate in a second mode where the at least one air jet is arranged to direct the air curtain over a full portion of the receiver aperture.

13. The air curtain control system of claim 12 wherein the system controller is arranged to operate in the second mode and the angular control device is controlled by the system controller so the angle of the air curtain relative to the receiver aperture is between 0 degrees and 20 degrees from a plane lying across the receiver aperture and directed away from the solar thermal receiver.

14. The air curtain control system of claim 13, wherein the angular control device is controlled by the system controller so that the angle of the air curtain relative to the receiver

aperture is between 5 degrees and 15 degrees from a plane lying across the receiver aperture and directed away from the solar thermal receiver.

15. The air curtain control system of claim 1 further comprising an air extraction device for extracting air out of the solar thermal receiver.

16. The air curtain control system of claim 1 further comprising an air injection device for injecting air into the solar thermal receiver.

17. The air curtain control system of claim 1 further comprising an air extraction device for extracting air out of the solar thermal receiver and an air injection device for injecting air into the solar thermal receiver.

18. The air curtain control system of claim 1 further comprising an air flow generator for generating airflow out of the air jet.

19. The air curtain control system of claim 1 wherein the system controller is arranged to control the air flow control device so that the speed of air flow out of the air jet is between 1 and 27 metres per second.

20. The air curtain control system of claim 1 comprising a single air jet arranged to produce the continuous planar air curtain over at least a portion of the receiver aperture.

21. The air curtain control system of claim 20 wherein the air jet is comprised of a single rectilinear nozzle.

22. The air curtain control system of claim 1 comprising a plurality of air jets arranged to produce the continuous planar air curtain over at least a portion of the receiver aperture.

23. The air curtain control system of claim 22 wherein the air jets are comprised of a series of rectilinear nozzles arranged linearly.

24. The air curtain control system of claim 22 wherein the air jets are comprised of a series of round nozzles arranged linearly.

25. The air curtain control system of claim 22 wherein the air jets are comprised of a series of round nozzles arranged in a zig-zag manner.

26. The air curtain control system of claim 1, wherein the one or more air jets have nozzles with a width between 5 mm and 100 mm.

27. The air curtain control system of claim 1 further comprising a solar thermal receiver comprising the receiver aperture.

28. An air curtain control method for a solar thermal receiver comprising the steps of:
producing an air curtain from at least one air jet over at least a portion of a receiver aperture of a solar thermal receiver,
controlling a speed of air flow out of the air jet,
controlling an angle of the at least one air jet relative to the receiver aperture, wherein the air flow speed and angle of the air curtain are controlled to isolate the receiver aperture from ambient elements external to the receiver aperture.

29. The air curtain control method of claim 28 further comprising the step of controlling one or more of the speed of air flow and the angle of the air curtain based on a predetermined algorithm.

30. The air curtain control method of claim 29, wherein the predetermined algorithm is configured based on one or more of a temperature(s) in a receiver cavity of the solar thermal receiver, an inclination of the receiver aperture, computational fluid dynamics models, measured performance characteristics and fundamental flow physics.

31. The air curtain control method of claim 28, wherein the air flow speed and angle of the air curtain are controlled based on one or more input signals, wherein the one or more input signals are selected from an inclination of the receiver aperture, a temperature(s) in a receiver cavity of the solar thermal receiver, pressure in, around or near the receiver cavity the angle of the air curtain relative to the receiver aperture, the speed of the air flow out of the air jet, ambient wind speed, ambient wind direction, ambient wind temperature and sun position.

32. The air curtain control method of claim 28, further comprising the step of using a look up table to adjust one or more of the speed of air flow and the angle of the air curtain based on an inclination of the receiver aperture.

33. The air curtain control method of claim 28 further comprising the step of directing the air curtain from a position located vertically above the receiver aperture.

34. The air curtain control method of claim 28 further comprising the step of operating in a first mode where the at least one air jet is arranged to direct the air curtain over less than a full portion of the receiver aperture.

35. The air curtain control method of claim 34 wherein the source angle of the air curtain relative to the receiver aperture is up to 20 degrees from a plane lying across the receiver aperture.

36. The air curtain control method of claim 35 wherein the source angle of the air curtain relative to the receiver aperture is between 10 degrees and 20 degrees from a plane lying across the receiver aperture.

37. The air curtain control method of claim 35 or 36 wherein the source angle of the air curtain relative to the receiver aperture is either directed away from the solar thermal receiver or towards the solar thermal receiver.

38. The air curtain control method of claim 28 further comprising the step of operating in a second mode where the at least one air jet is arranged to direct the air curtain over a full portion of the receiver aperture.

39. The air curtain control method of claim 38 wherein the source angle of the air curtain relative to the receiver aperture is between 0 degrees and 20 degrees from a plane lying across the receiver aperture and directed away from the solar thermal receiver.

40. The air curtain control method of claim 39, wherein the source angle of the air curtain relative to the receiver aperture is between 5 degrees and 15 degrees from a plane lying across the receiver aperture and directed away from the solar thermal receiver.

41. The air curtain control method of claim 28 further comprising the step of extracting air out of the solar thermal receiver.

42. The air curtain control method of claim 28 further comprising the step of injecting air into the solar thermal receiver.

43. The air curtain control method of claim 28 further comprising the steps of extracting air out of the solar thermal receiver and injecting air into the solar thermal receiver.

44. The air curtain control method of claim 28 further comprising the step of controlling the speed of air flow out of the air jet to between 1 and 27 metres per second.

45. The air curtain control method of claim 28 further comprising the step of producing the continuous planar air curtain over at least a portion of the receiver aperture.

46. A solar thermal receiver comprising at least one air jet arranged to produce an air curtain over at least a portion of a receiver aperture of a solar thermal receiver, an air extraction device for extracting air out of the receiver aperture and an air injection device for injecting air into the receiver aperture.

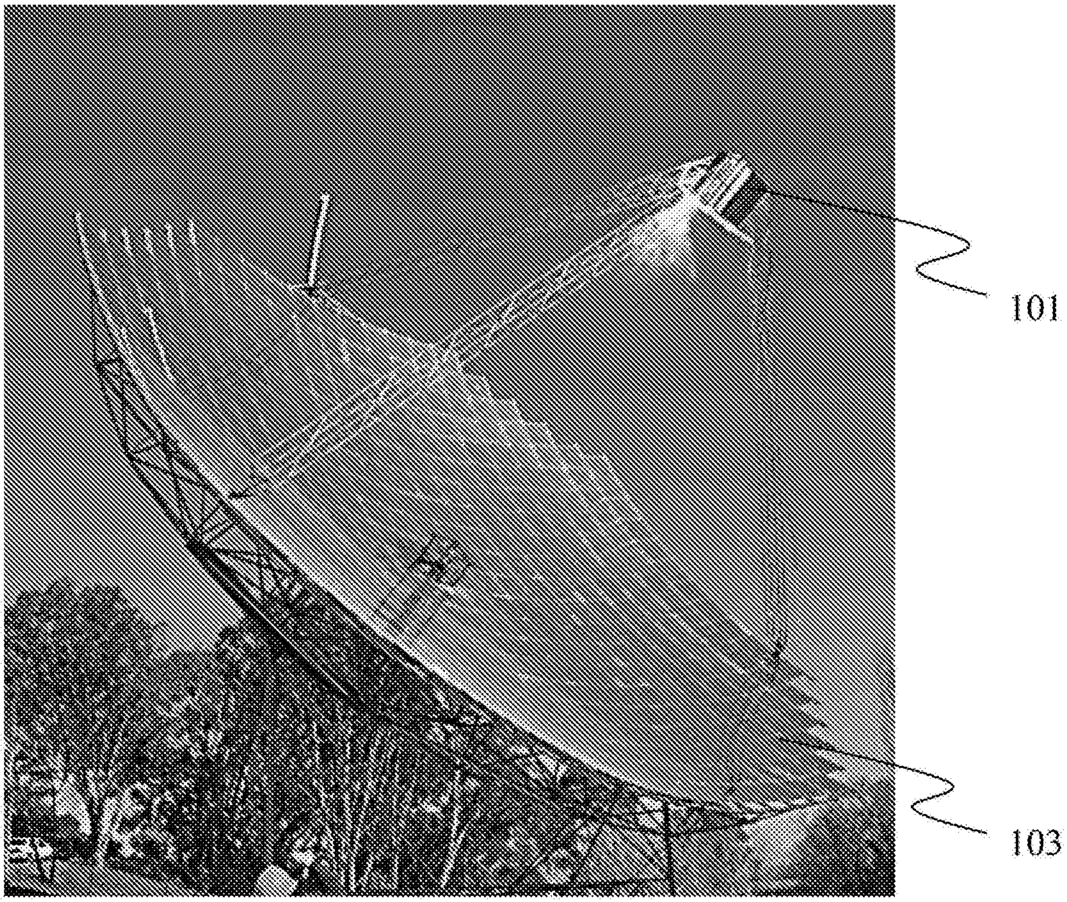


Fig. 1

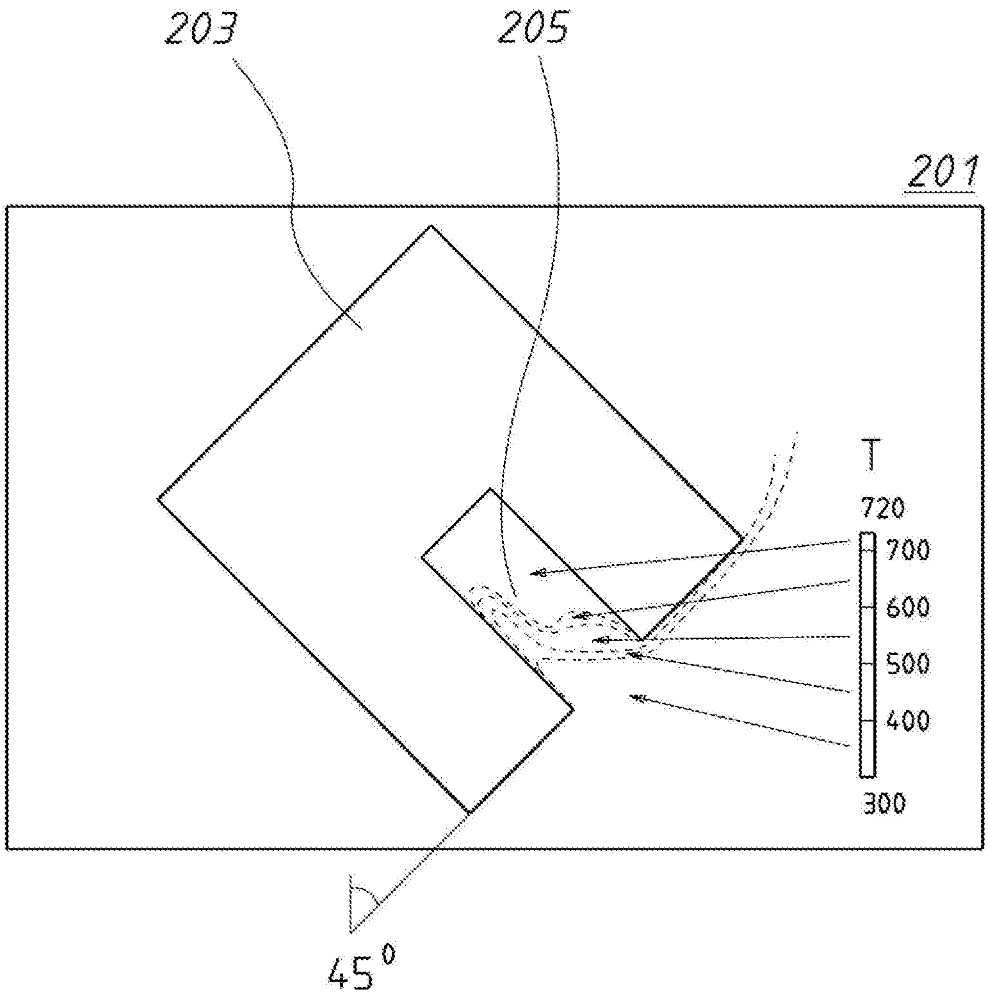


FIG.2

* Physical model

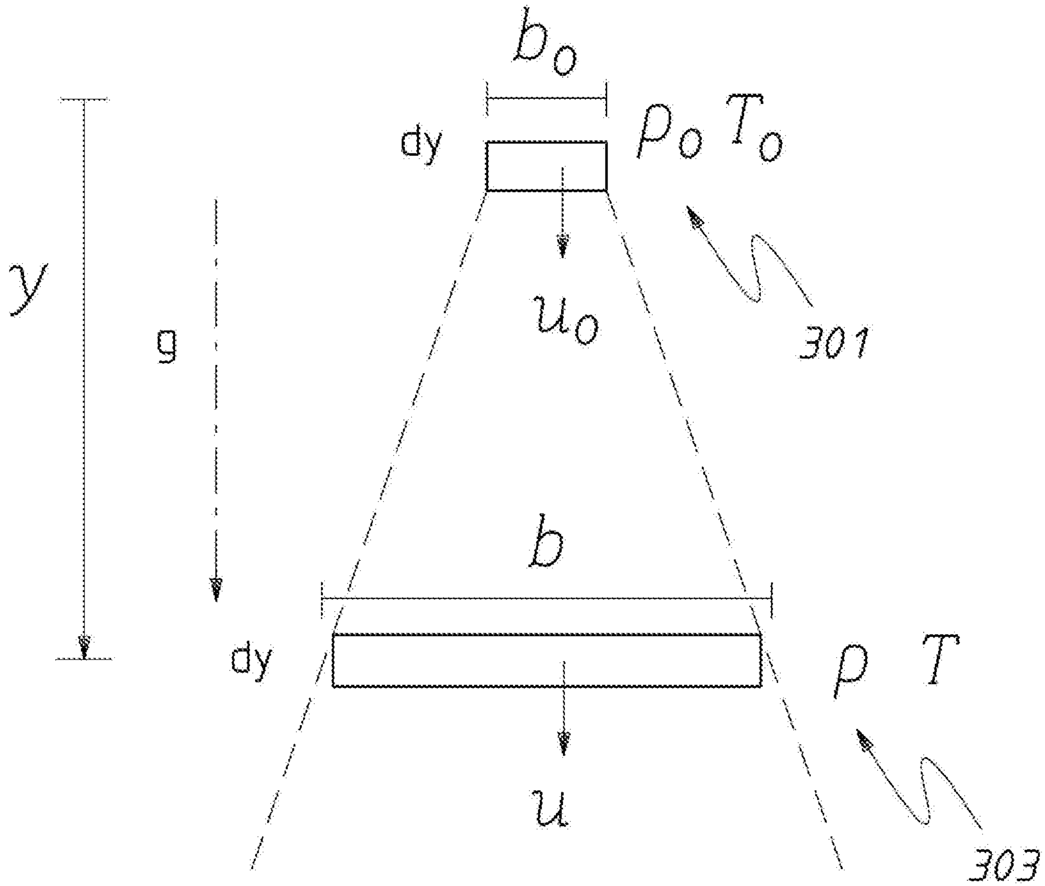


FIG.3

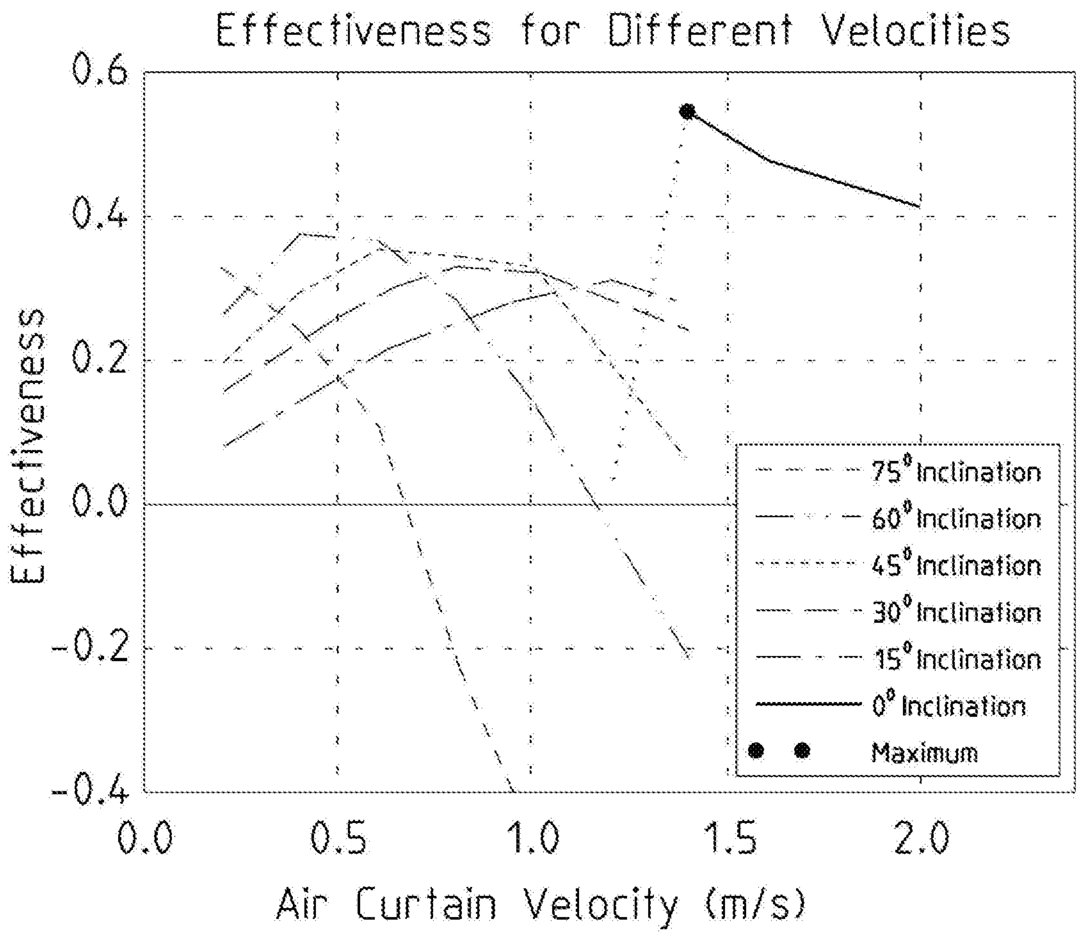

Effectiveness for Different Velocities
Effectiveness
Air Curtain Velocity (m/s)
0.6
0.4
0.2
0.0
-0.2
-0.4
0.0
0.5
1.0
1.5
2.0
75° Inclination
60° Inclination
45° Inclination
30° Inclination
15° Inclination
0° Inclination
Maximum

FIG.4

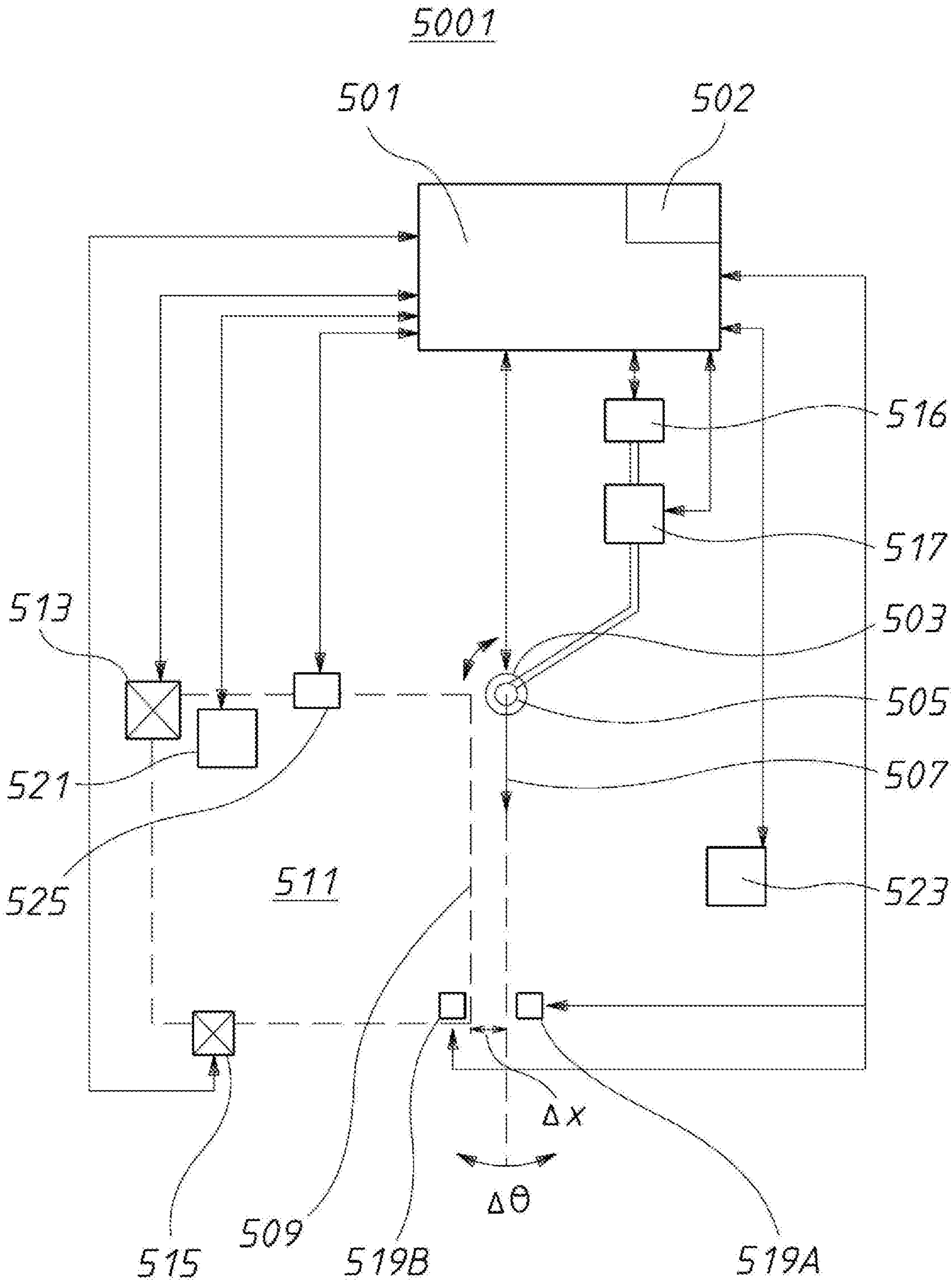

5001
501
502
516
517
503
505
507
513
521
525
511
523
515
509
519B
519A
Δx
Δθ

FIG.5

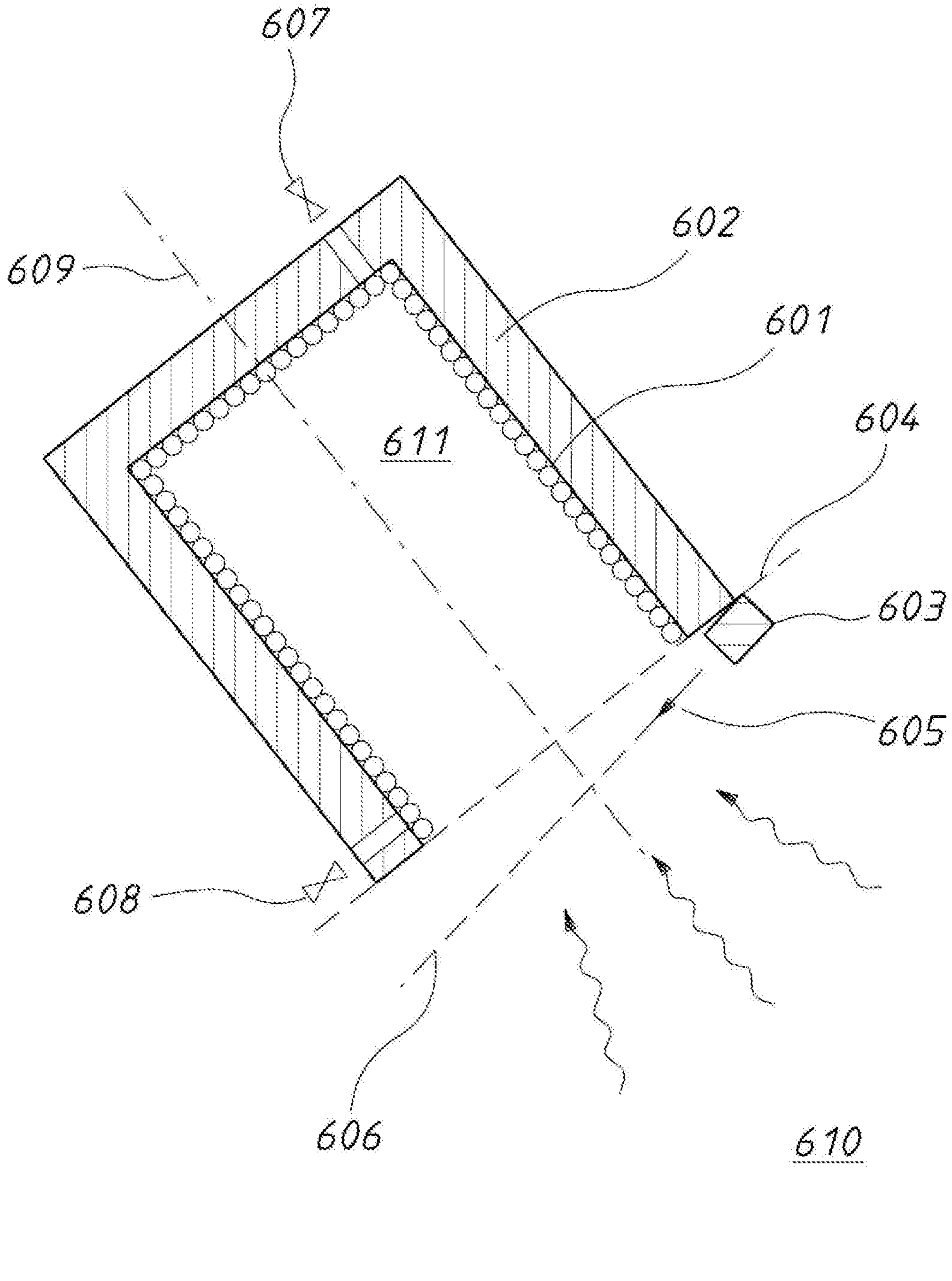


FIG.6

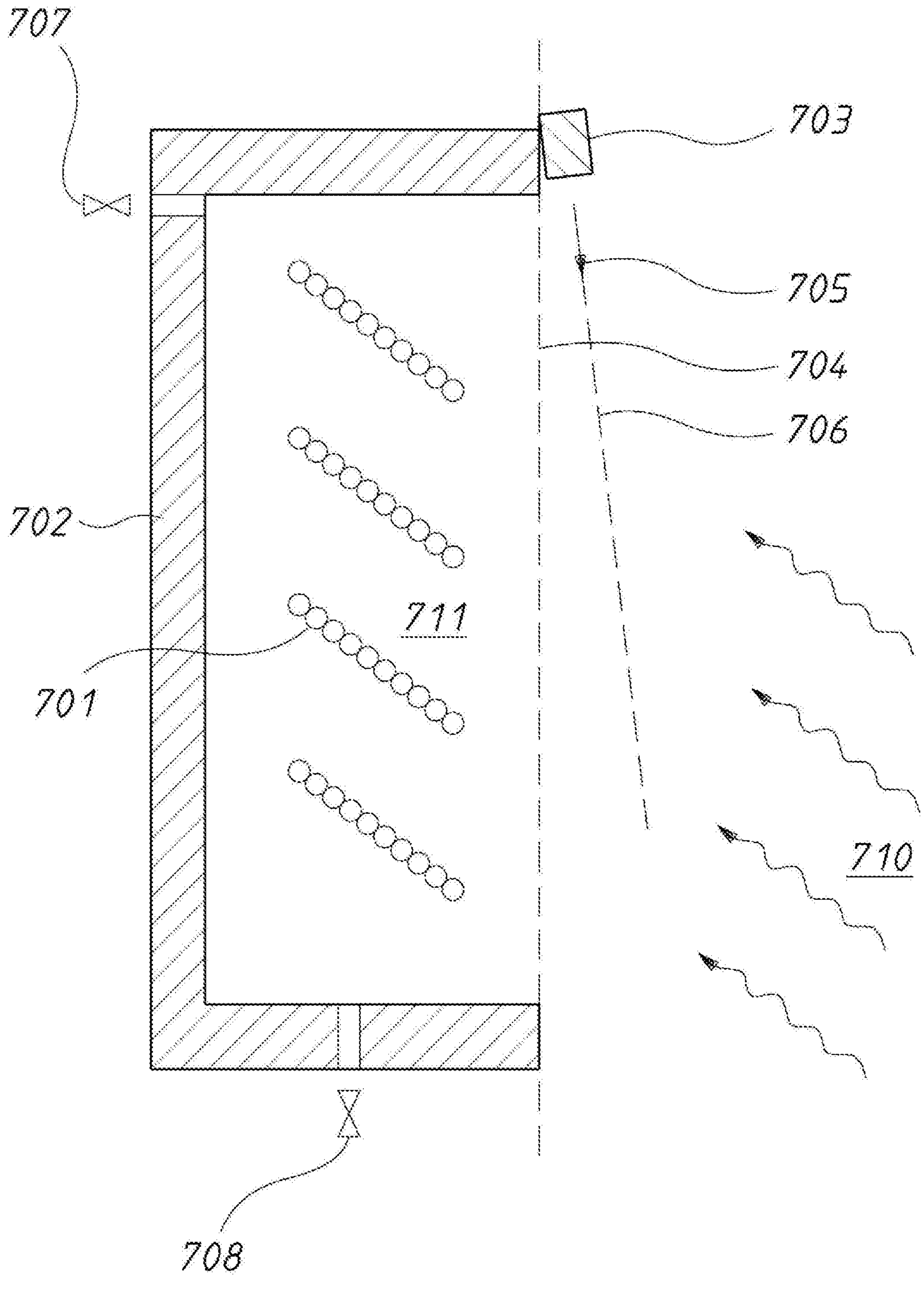


FIG.7

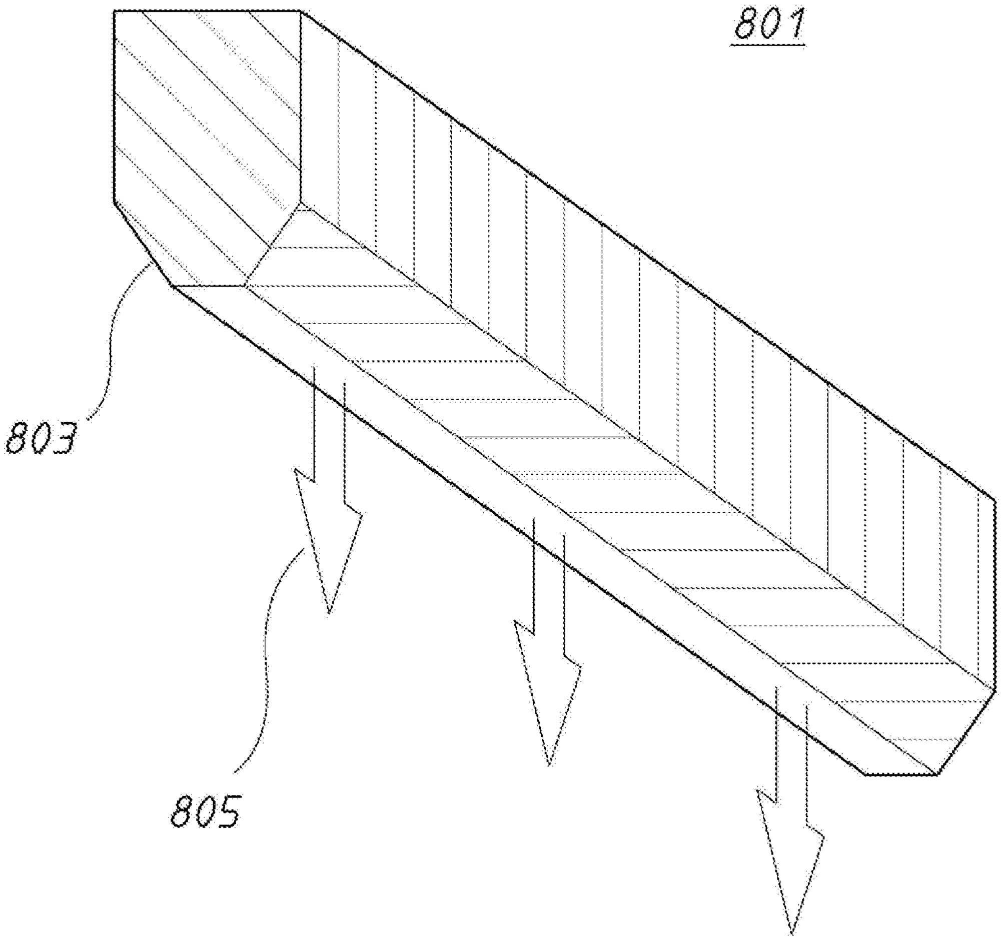


FIG.8

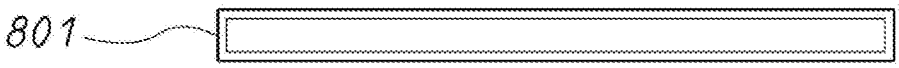


FIG.9A

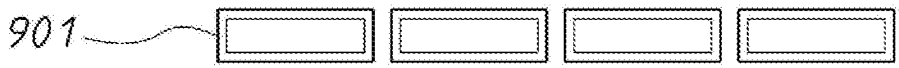


FIG.9B

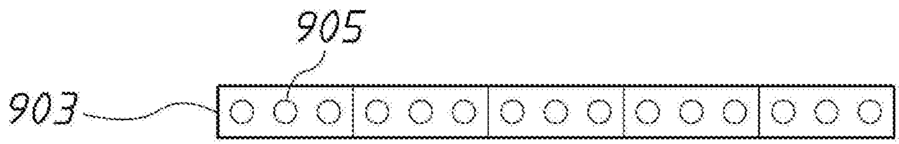


FIG.9C

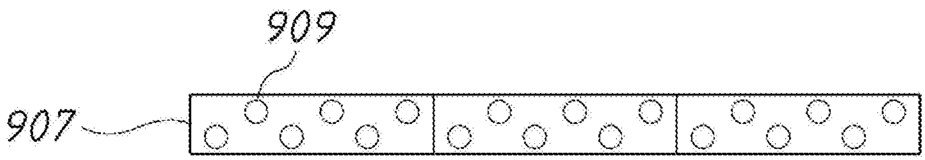


FIG.9D

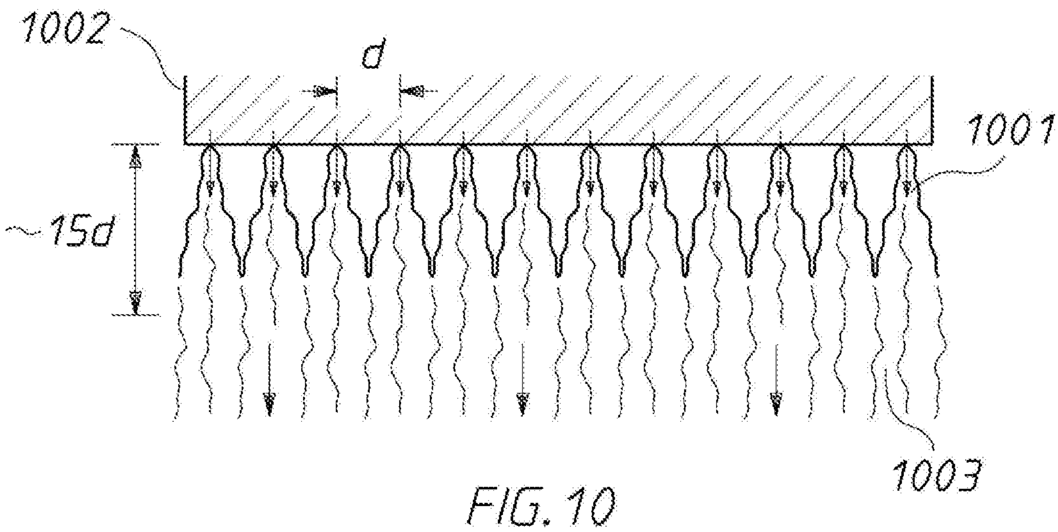


FIG.10

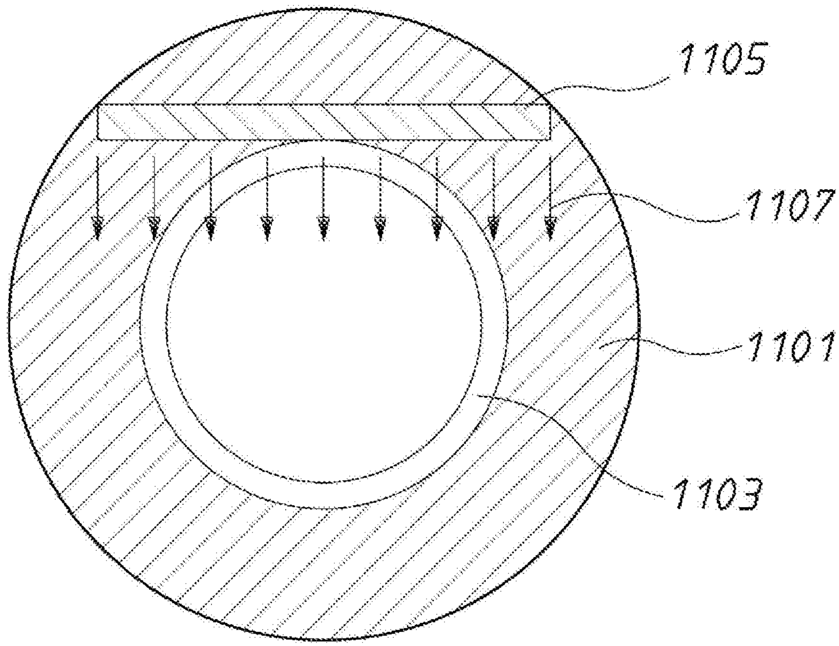


FIG. 11A

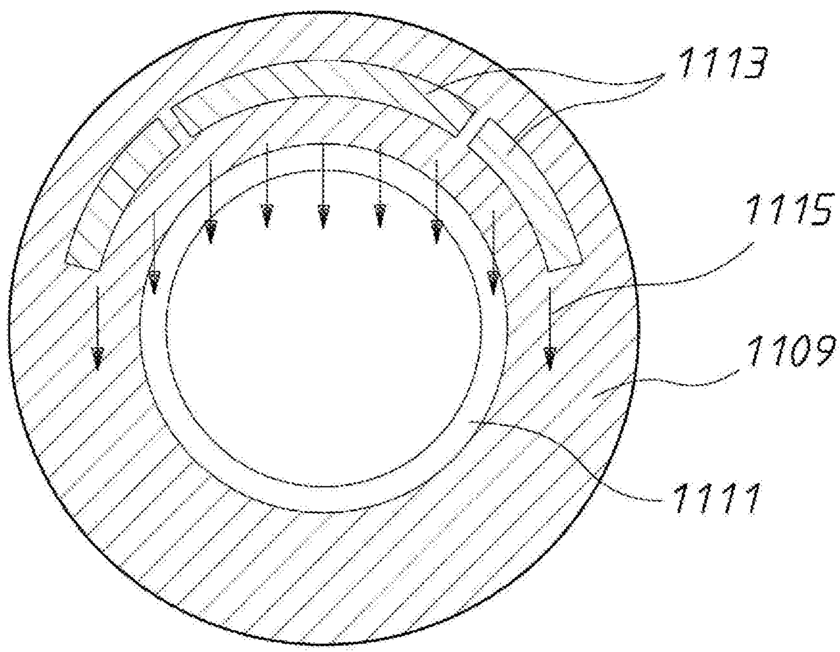


FIG. 11B

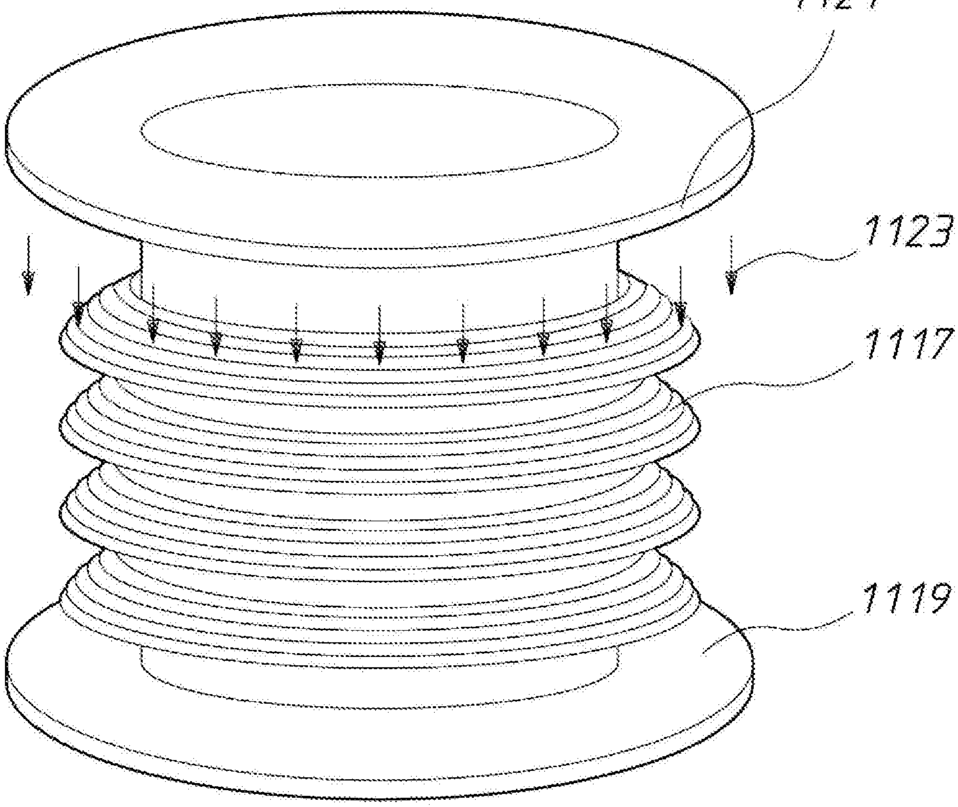


FIG. 11C

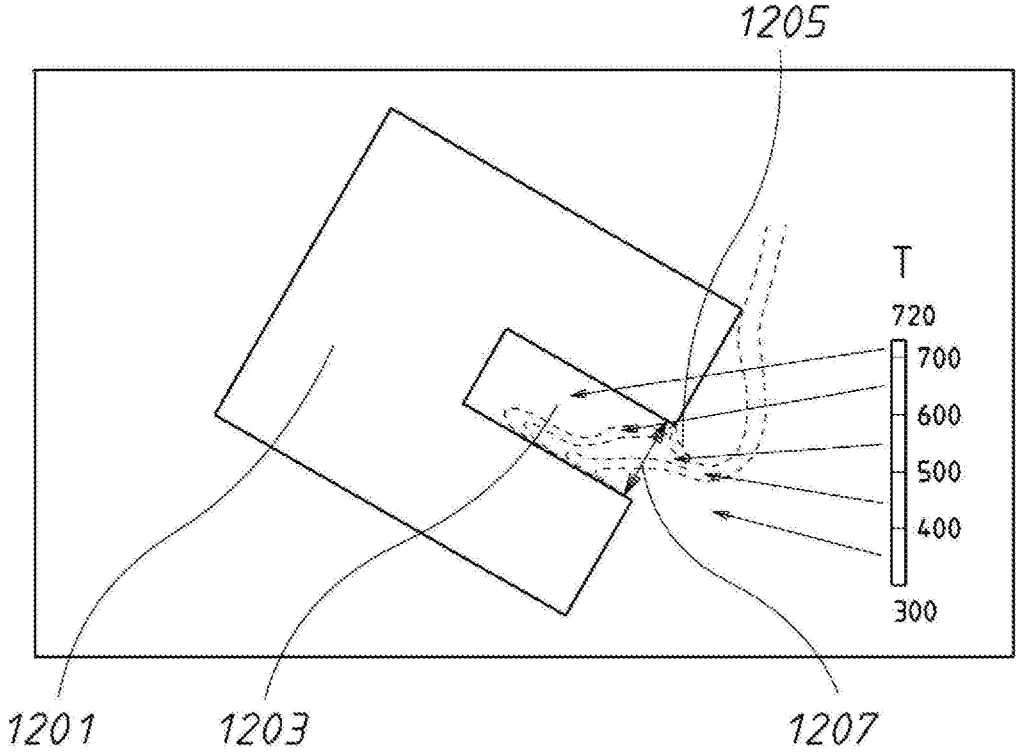


FIG. 12A

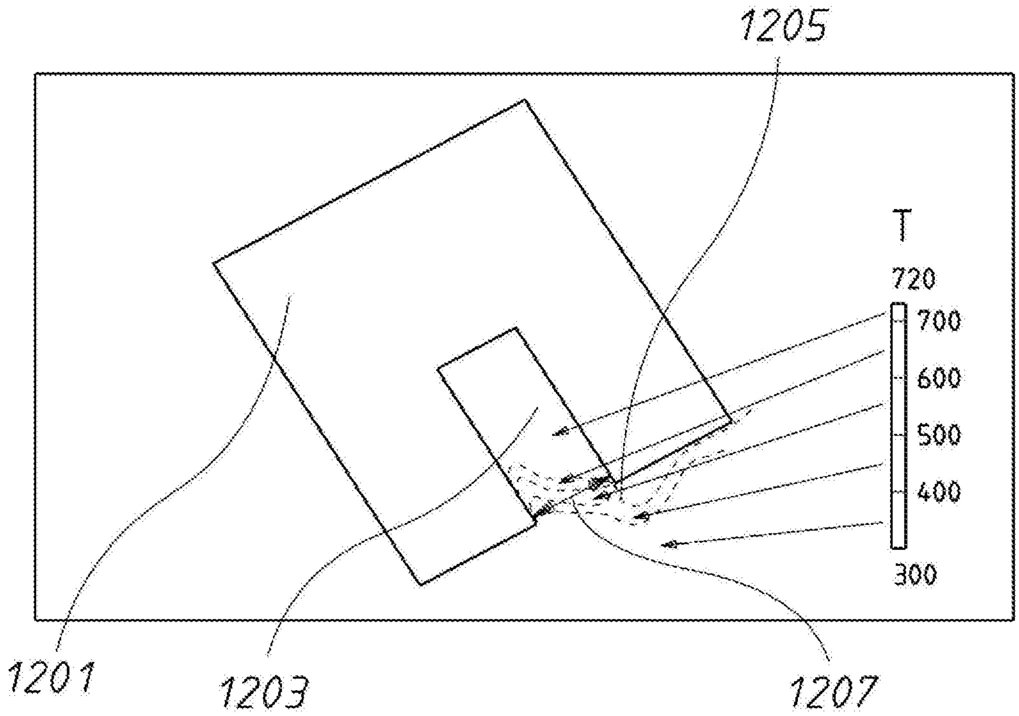


FIG. 12B

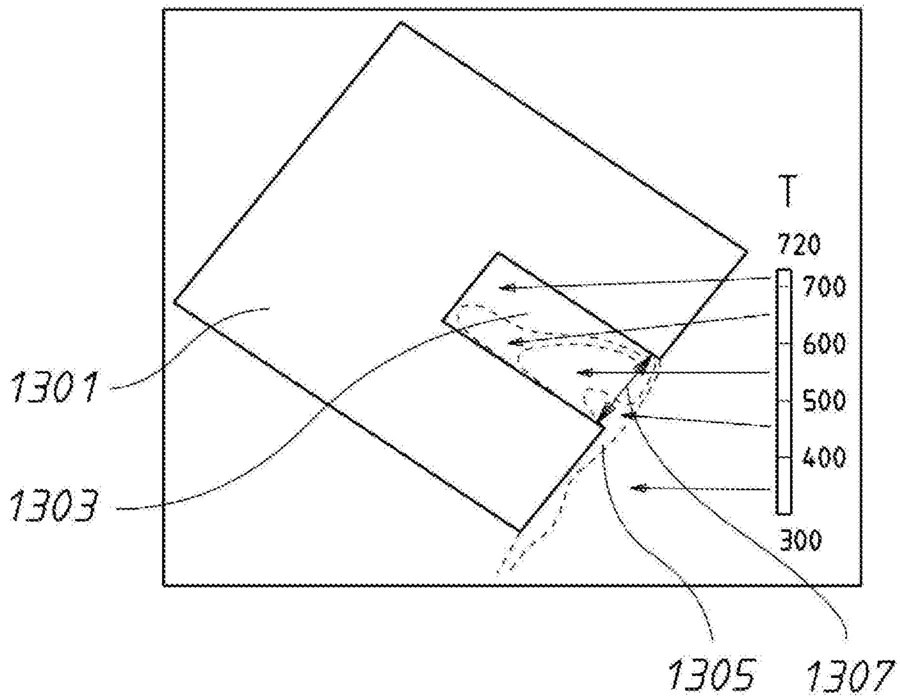


FIG. 13A

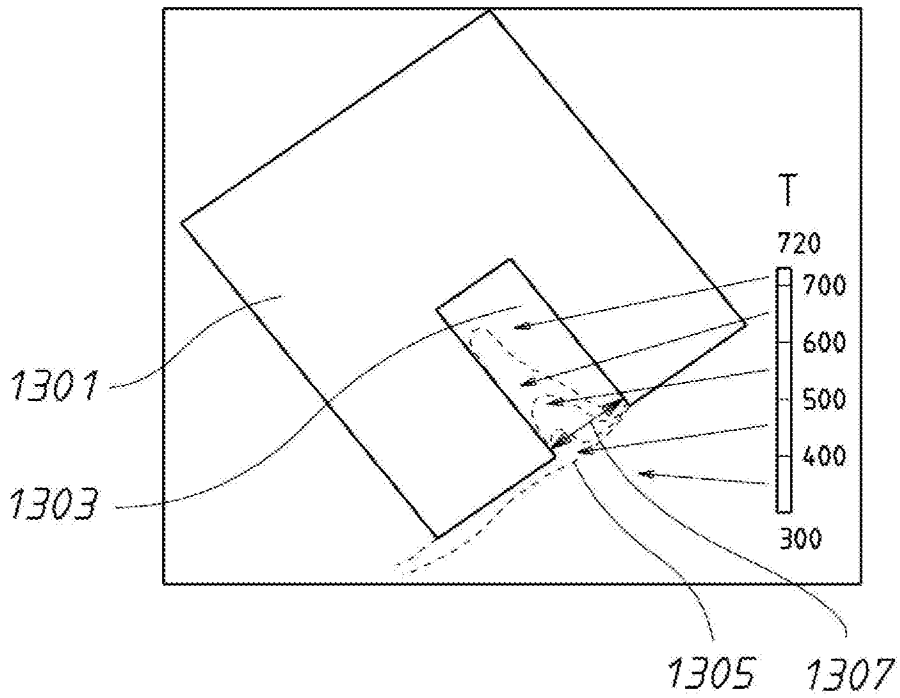
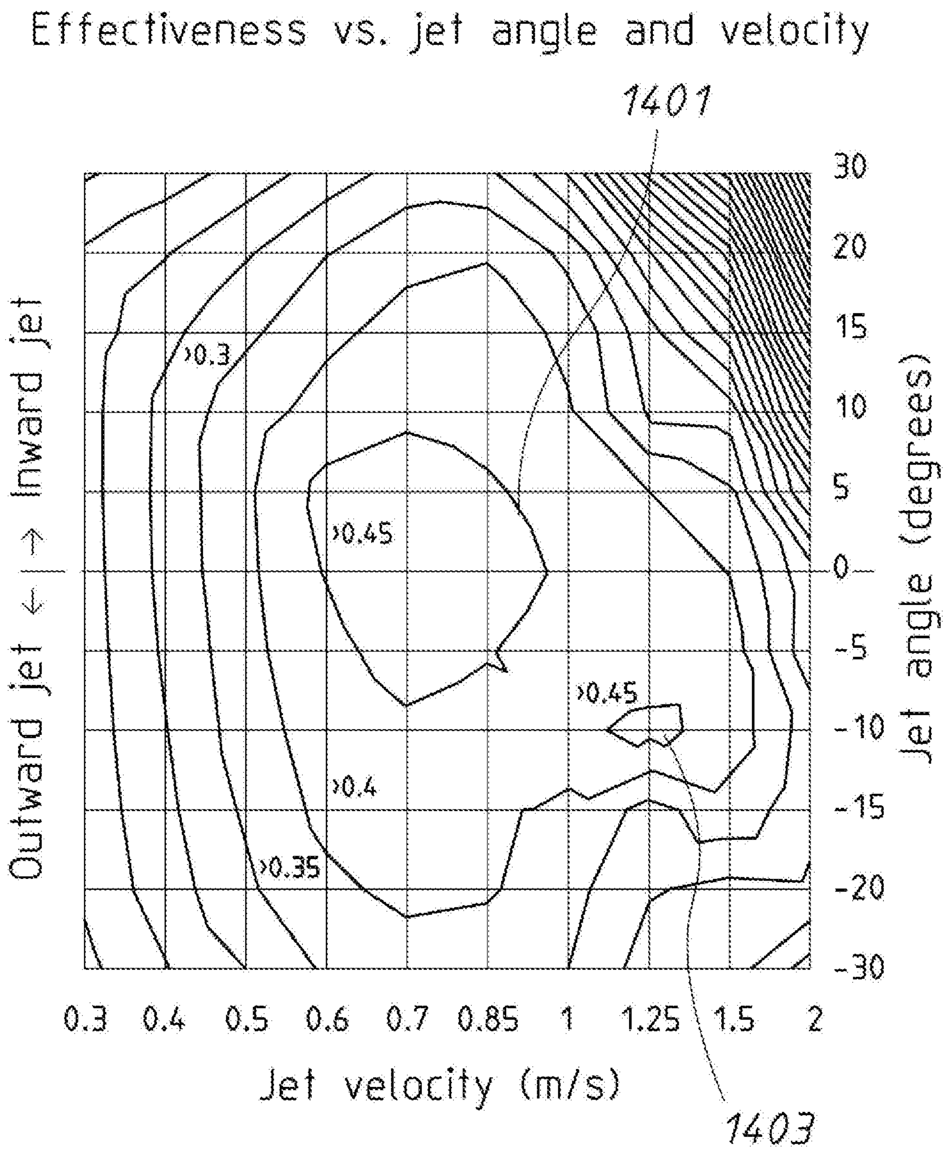


FIG. 13B



Effectiveness vs. jet angle and velocity
1401
>0.3
>0.45
>0.45
>0.4
>0.35
Outward jet ← | → Inward jet
Jet angle (degrees)
30
20
15
10
5
0
-5
-10
-15
-20
-30
0.3 0.4 0.5 0.6 0.7 0.85 1 1.25 1.5 2
Jet velocity (m/s)
1403

FIG. 14A

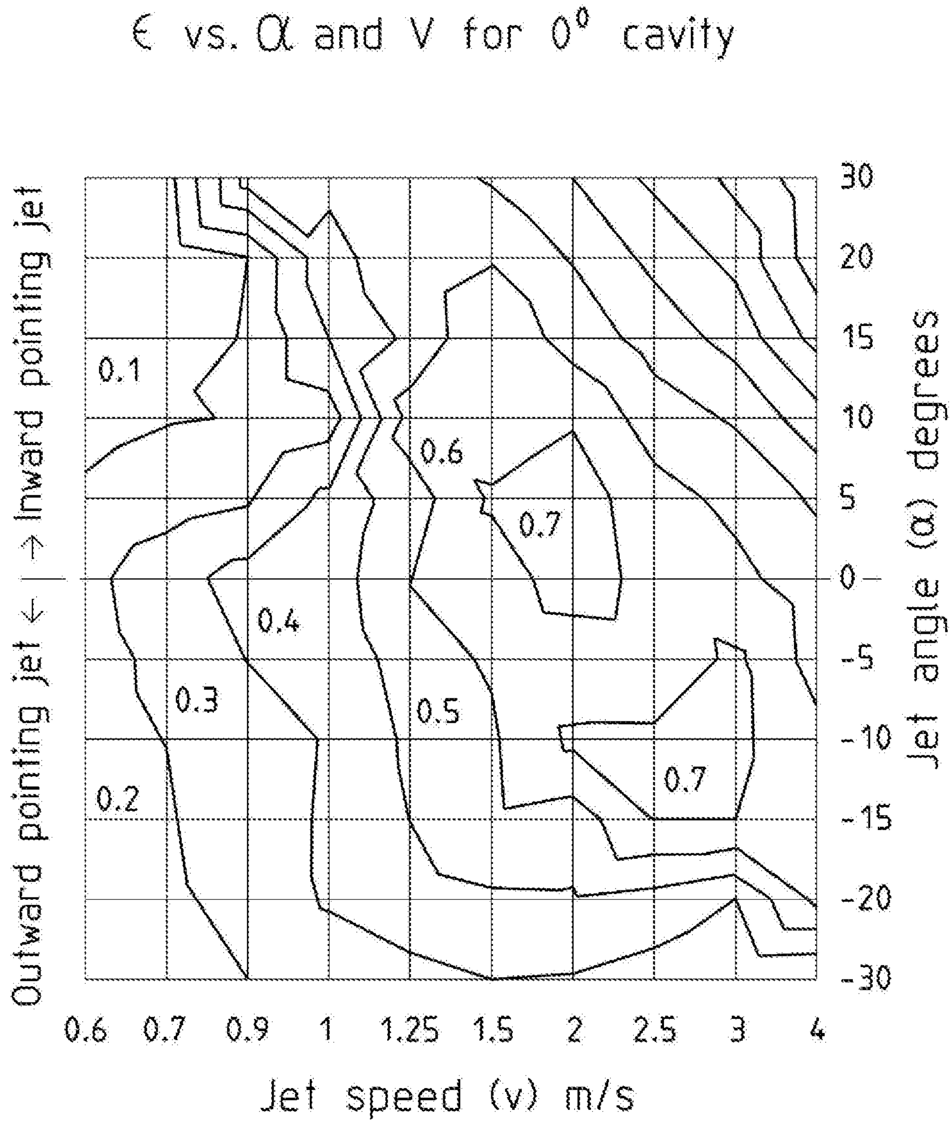

ε vs. α and V for 0° cavity
Outward pointing jet ← | → Inward pointing jet
Jet angle (α) degrees
30
20
15
10
5
0
-5
-10
-15
-20
-30
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.7
0.6
0.7
0.9
1
1.25
1.5
2
2.5
3
4
Jet speed (v) m/s

FIG. 14B

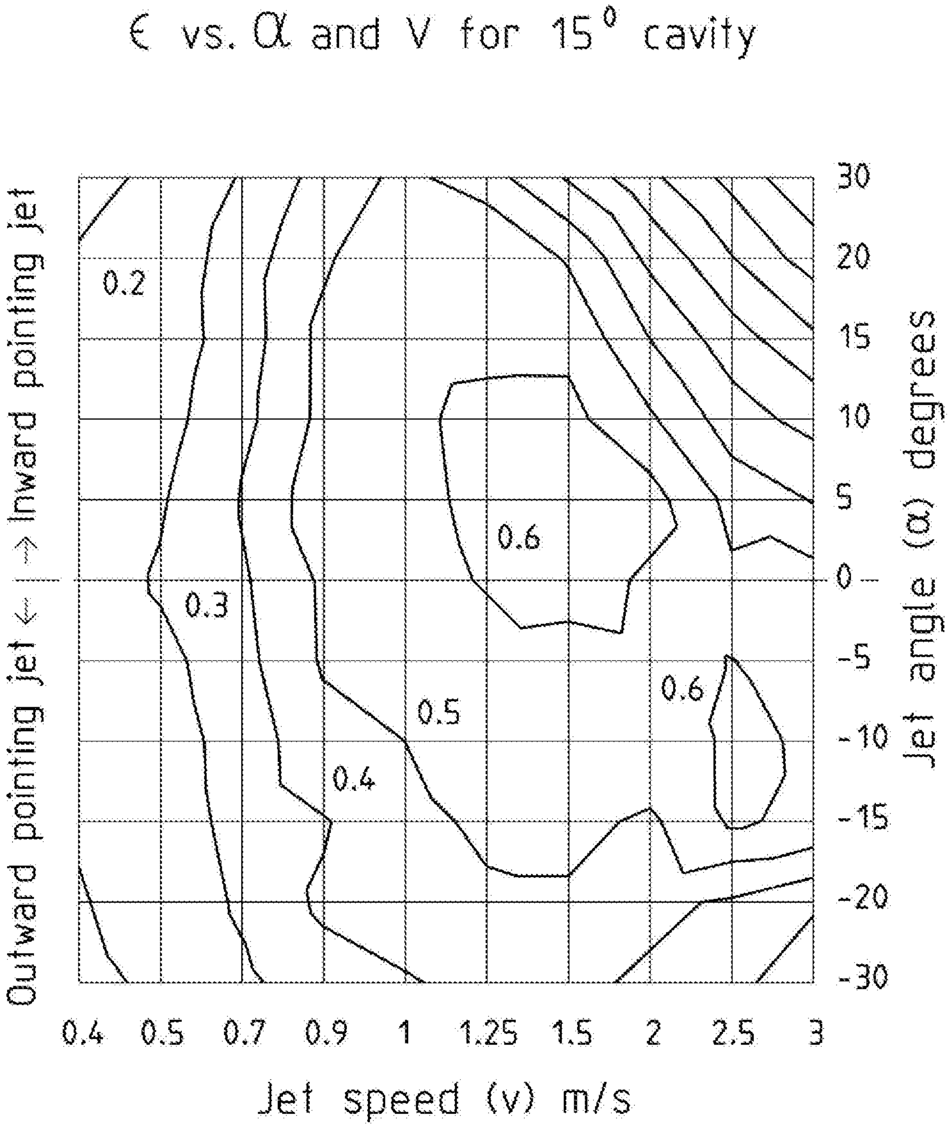

∈ vs. α and V for 15° cavity
0.2
0.3
0.4
0.5
0.6
0.6
30
20
15
10
5
0
-5
-10
-15
-20
-30
0.4
0.5
0.7
0.9
1
1.25
1.5
2
2.5
3
Jet speed (v) m/s
Jet angle (α) degrees
Outward pointing jet ← → Inward pointing jet

FIG. 14C

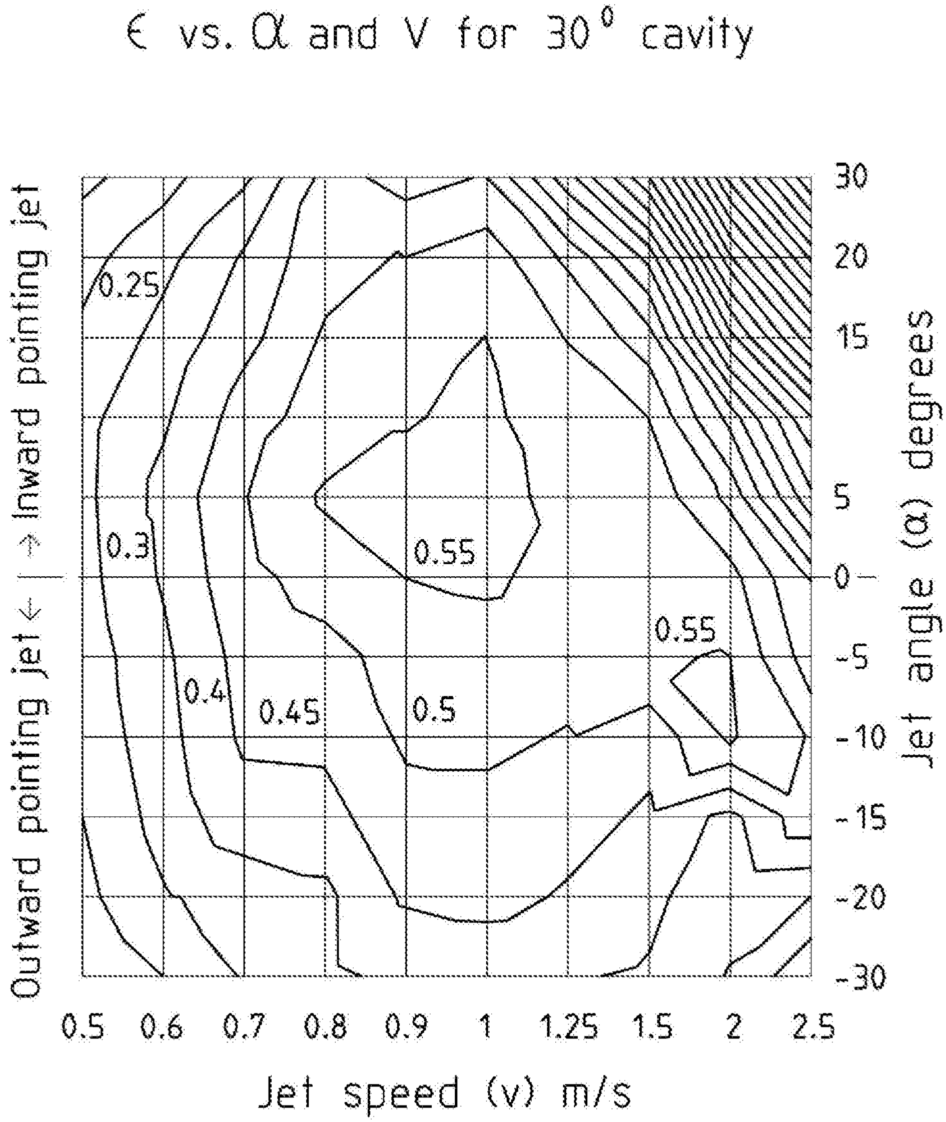
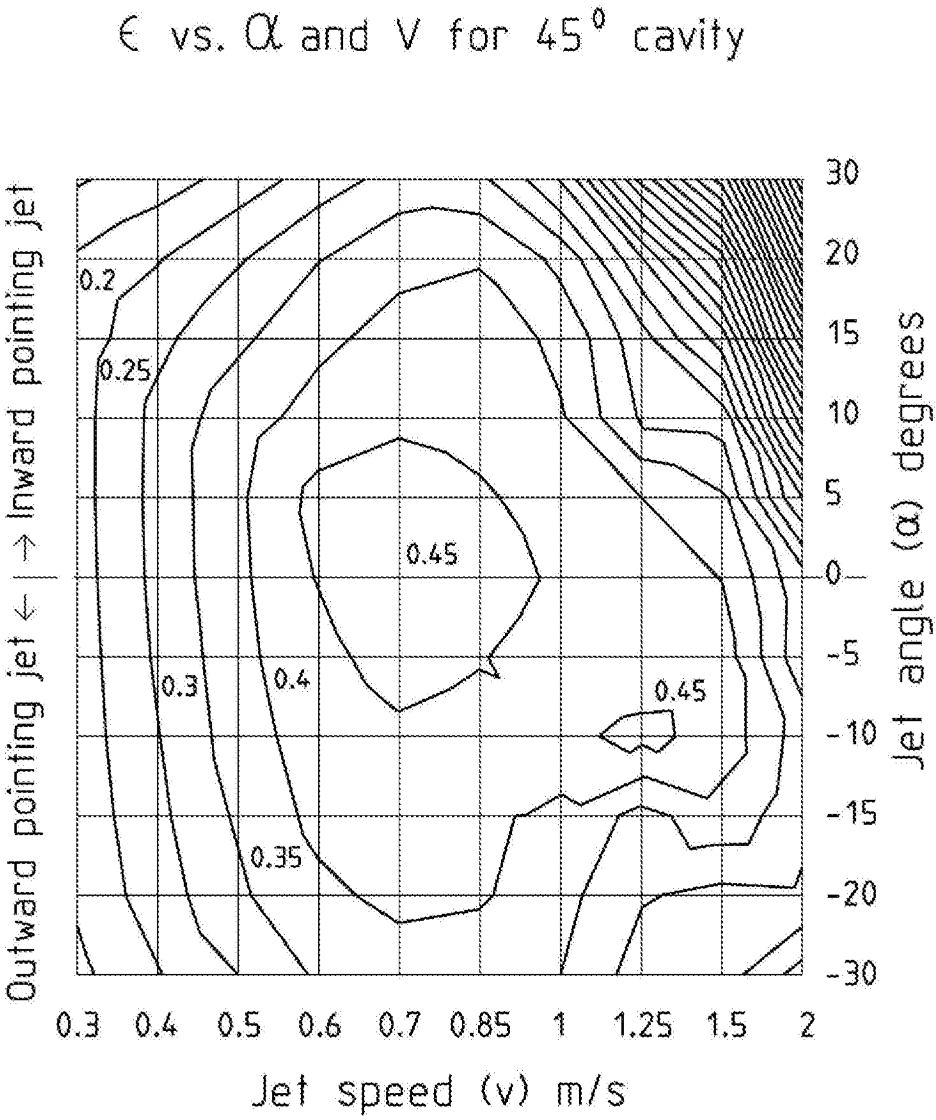

∈ vs. α and V for 30° cavity
0.25
0.3
0.4
0.45
0.5
0.55
0.55
30
20
15
5
0
-5
-10
-15
-20
-30
0.5
0.6
0.7
0.8
0.9
1
1.25
1.5
2
2.5
Jet speed (v) m/s
Jet angle (α) degrees
Outward pointing jet ← | → Inward pointing jet

FIG. 14D



ϵ vs. α and V for 45° cavity
Outward pointing jet ← | → Inward pointing jet
Jet angle (α) degrees
30
20
15
10
5
0
-5
-10
-15
-20
-30
0.3
0.4
0.5
0.6
0.7
0.85
1
1.25
1.5
2
Jet speed (v) m/s
0.2
0.25
0.3
0.35
0.4
0.45
0.45

FIG. 14E

INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU2015/000742

A. CLASSIFICATION OF SUBJECT MATTER

F24J 2/04 (2006.01) F24J 2/40 (2006.01) F24J 2/46 (2006.01) F24J 2/00 (2014.01)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPOQUENET (WPIP, EPODOC databases): Keywords and (IPC & CPC) indexing marks used such as: CONCENTRAT+ OR FOCUS+ OR FOCAL+; (CURTAIN+ OR SHIELD+ OR WALL OR SHEET?) 3D AIR; TILT+ OR ANGUL+ OR ANGL+ OR SLANT+ OR SLOP+ OR INCLIN+; /IC/CC(F24J2/00 OR F24J2/04 OR F24J2/06 OR F24J2/07 OR F24J2/46 OR F24J2/52 OR F24J40 OR F24J2/10 OR F24J2/4638 OR F24J2/4609 OR F24J2/4605 OR Y02E10/40 OR Y02E10/41 OR Y02E10/45); and similar terms/indexing marks searched. **Esp@cenet; Google Scholar; Google Patents; General Internet Keyword Search; USPTO Patent Database/s:**Search terms used such as: solar; receiver; tilt; slope; angle; jet; nozzles; curtain; air; wall; sheet; inject; and similar terms used. **Applicant(s)/Inventor(s) Search:** Applicants: ANU; Australian National University; and Inventor names: PYE, John Downing ; HUGHES, Graham Owen searched through Esp@cenet; AUSPAT; USPTO; and internal databases provided by IP Australia.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
	Documents are listed in the continuation of Box C	

[X] Further documents are listed in the continuation of Box C   [X] See patent family annex

* Special categories of cited documents:

"A"	document defining the general state of the art which is not considered to be of particular relevance	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"E"	earlier application or patent but published on or after the international filing date	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O"	document referring to an oral disclosure, use, exhibition or other means	"&"	document member of the same patent family
"P"	document published prior to the international filing date but later than the priority date claimed		

Date of the actual completion of the international search	Date of mailing of the international search report
21 April 2016	21 April 2016
Name and mailing address of the ISA/AU	**Authorised officer**
AUSTRALIAN PATENT OFFICE PO BOX 200, WODEN ACT 2606, AUSTRALIA Email address: pct@ipaustralia.gov.au	Peter Ellis AUSTRALIAN PATENT OFFICE (ISO 9001 Quality Certified Service) Telephone No. 02 6225 6106

INTERNATIONAL SEARCH REPORT	International application No.
C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT	**PCT/AU2015/000742**

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 4913129 A (KELLY et al.) 03 April 1990 See whole document, most notably abstract; figures 1 to 6; column 2, lines 41- 52; column 3, lines 4-10; column 6, lines 59-64; column 7, lines 18- 31; and claims.	1 to 46
A	US 4777934 A (DE LAQUIL, III) 18 October 1988 See whole document.	1 to 46
A	WO 2014/177740 A1 (TERMO FLUIDS S.L. [ES]) 06 November 2014 See whole document.	1 to 46
A	US 8109265 B1 (KOLB) 07 February 2012 See whole document.	1 to 46
A	DE 2948355 A1 (KRAFTWERK UNION AG [DE] et al.) 04 June 1981 See Esp@cenet English Translation of the German Language Document.	1 to 46
A	US 4321324 A1 (ROSS et al.) 26 January 1982 See whole document.	1 to 46

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:

   because they relate to subject matter not required to be searched by this Authority, namely:

   the subject matter listed in Rule 39 on which, under Article 17(2)(a)(i), an international search is not required to be carried out, including

2. ☐ Claims Nos.:

   because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos:

   because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a)

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

See Supplemental Box for Details

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☒ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

Supplemental Box

Continuation of: **Box III**
This International Application does not comply with the requirements of unity of invention because it does not relate to one invention or to a group of inventions so linked as to form a single general inventive concept.

This Authority has found that there are different inventions based on the following features that separate the claims into distinct groups:

• **Claims 1 to 45** are directed to an air curtain control system (and method of control) for a solar thermal receiver comprising: at least one air jet arranged to produce an air curtain over at least a portion of a receiver aperture of a solar thermal receiver, an air flow control device for controlling a speed of air flow out of the air jet, at least one angular control device for controlling an angle of the air curtain relative to the receiver aperture, and a system controller arranged to control the air flow control device to isolate the receiver aperture from ambient elements external to the receiver aperture. The feature of an air curtain control system (and method of control) for a solar thermal receiver is specific to this group of claims.

• **Claim 46** is directed to a solar thermal receiver comprising at least one air jet arranged to produce an air curtain over at least a portion of a receiver aperture of a solar thermal receiver, an air extraction device for extracting air out of the receiver aperture and an air injection device for injecting air into the receiver aperture. The feature of an air extraction device for extracting air out of the receiver aperture and an air injection device for injecting air into the receiver aperture is specific to this group of claims.

PCT Rule 13.2, first sentence, states that unity of invention is only fulfilled when there is a technical relationship among the claimed inventions involving one or more of the same or corresponding special technical features. PCT Rule 13.2, second sentence, defines a special technical feature as a feature which makes a contribution over the prior art.

When there is no special technical feature common to all the claimed inventions there is no unity of invention.

In the above groups of claims, the identified features may have the potential to make a contribution over the prior art but are not common to all the claimed inventions and therefore cannot provide the required technical relationship. The only feature common to all of the claimed inventions and which provides a technical relationship among them is a solar thermal receiver comprising at least one air jet arranged to produce an air curtain over at least a portion of a receiver aperture of a solar thermal receiver. However this feature does not make a contribution over the prior art because it is disclosed in:

US 4913129 A (KELLY et al.) 3 April 1990.

Therefore in the light of this document this common feature cannot be a special technical feature. Therefore there is no special technical feature common to all the claimed inventions and the requirements for unity of invention are consequently not satisfied a posteriori.

INTERNATIONAL SEARCH REPORT Information on patent family members	International application No. **PCT/AU2015/000742**

This Annex lists known patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document/s Cited in Search Report		**Patent Family Member/s**	
Publication Number	**Publication Date**	**Publication Number**	**Publication Date**
US 4913129 A	03 April 1990	US 4913129 A	03 Apr 1990
		EP 0399381 A1	28 Nov 1990
		EP 0399381 B1	24 Feb 1993
US 4777934 A	18 October 1988	US 4777934 A	18 Oct 1988
WO 2014/177740 A1	06 November 2014	WO 2014177740 A1	06 Nov 2014
		CN 105283716 A	27 Jan 2016
		EP 2993425 A1	09 Mar 2016
		ES 2525196 A1	18 Dec 2014
		ES 2525196 B1	26 Feb 2016
		US 2016076791 A1	17 Mar 2016
US 8109265 B1	07 February 2012	US 8109265 B1	07 Feb 2012
DE 2948355 A1	04 June 1981	DE 2948355 A1	04 Jun 1981
US 4321324 A1	26 January 1982	None	

End of Annex

Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.