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(54) LOOP HEAT PIPE APPARATUS FOR HEAT TRANSFER AND THERMAL CONTROL

(57) Loop heat pipe apparatus (1) for heat transfer and thermal control, using a two-phase fluid as a working media and comprising:
- at least one evaporator (2) to be connected with a heat source and comprising a thermal stabilization-compensation chamber (10) attached to the at least one evaporator (2) and a secondary capillary pump (40) located inside the thermal stabilization-compensation chamber (10),
- at least one condenser (27) to be connected with a heat sink,
- liquid lines (24) and vapour lines (28) connecting the at least one evaporator (2) and the at least one condenser (27), and
- a remote compensation chamber (20),
wherein the thermal stabilization-compensation chamber (10) comprises a two-phase reservoir (5) and a liquid accumulator reservoir (6) separated by a heat exchange surface (15), such that the remote compensation chamber (20) is hydraulically connected with the two-phase reservoir (5) and the liquid accumulator reservoir (6).

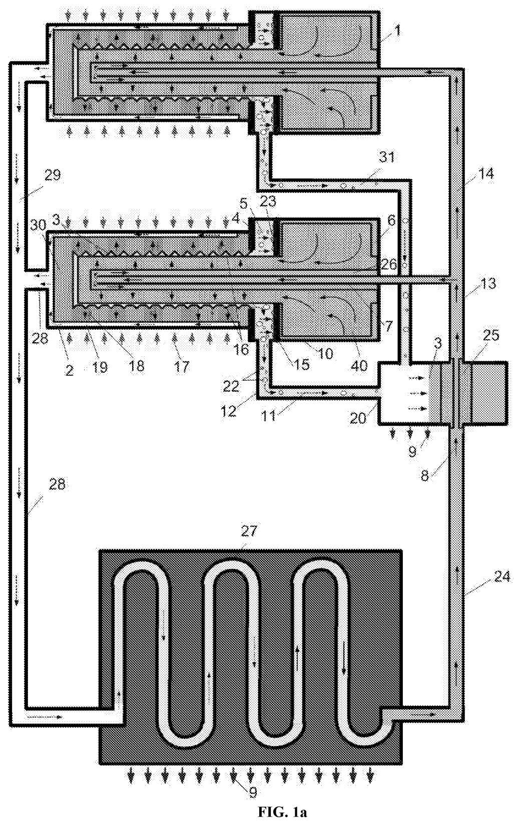

FIG. 1a

EP 2 940 416 A1

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Description

FIELD OF THE INVENTION

[0001] The present invention relates to a heat transfer and thermal control device, in particular for use on a spacecraft, and more particularly the invention is directed to a heat transfer and thermal control device with two-phase capillary driven loops.

BACKGROUND OF THE INVENTION

[0002] Most of the components and subsystems of a spacecraft must operate in restricted temperature ranges. This makes thermal control a key matter in the design and operation of a spacecraft with a significant weight, power and cost impact in the overall spacecraft budget.

[0003] Spacecraft thermal control relies on the global spacecraft thermal balance: the heat loads must be rejected to deep space that works as a thermal sink. Since no matter links this sink and the spacecraft, this rejection is made by thermal radiation through dedicated radiators installed on the satellite external surfaces.

[0004] Spacecraft thermal loads come from the internal spacecraft equipment dissipation and, externally, from the sun and the earth or from the celestial bodies around which the spacecraft orbits. The thermal systems used in spacecrafts must therefore be able to control equipment which operates at a specified range of temperatures and also discontinuously.

[0005] At present, known thermal devices for controlling thermal loads in spacecraft are two phase heat transfer loops which are also known in engineering practice as capillary driven and mechanically pumped loops or heat loops. The purpose of these devices in a spacecraft is to transfer heat between a heat source (for instance, an electronic element) and a heat sink (typically, the space). In two phase heat transfer loops heat is transferred through an evaporation-condensation cycle of a working fluid kept inside a hermetically sealed container. Capillary driven loops have a special porous structure, called capillary pump or wick, serving for working fluid continuous circulation in the system. The wick is always located in the evaporator of the capillary driven loop. The evaporator is attached to a heat source.

[0006] The above-mentioned capillary driven loop technology has found a wide application for thermal control systems in many spacecraft applications, that usually use loops with a single evaporator. However, many applications require thermal control of large thermal contact surface payloads or multiple remotely located heat sources.

[0007] Developers of multiple evaporators and multiple condenser designs of capillary driven loops (known in engineering practice as loop heat pipes (LHPs), capillary pumped loops (CPLs), hybrid two-phase heat loops) intend to create thermal control systems having the following characteristics: optimized functional layout, scalability, expandability, effective heat loads sharing, flexibility in components locations, thermal coupling between separate radiators and minimized mass and volume.

[0008] The LHP technology was initially invented in the Soviet Union, and this technology of a heat transfer apparatus is known as per US 4515209, for example. The first LHP systems were dedicated to terrestrial applications. Later, a capillary link (secondary wick) between the evaporator and the compensation chamber was introduced to provide liquid supply from the compensation chamber to the evaporator primary wick in zero gravity (0-g) conditions.

[0009] The development and testing of a LHP with two identical evaporators was first performed by the Institute of Thermal Physics (Russian Academy of Sciences) in the mid-80's. Further developments into a multi-evaporator LHP system, as shown for example in USSR Patent 1395927, were carried out using a LHP with two evaporators and two condensers. The two-evaporator LHPs can efficiently operate at symmetrical and non-symmetrical heat load distributions between the evaporators, and at different temperatures of the condenser(s) cooling. However, shutting down the active cooling of one condenser would result in an abrupt decrease in the maximum transport capability of the device.

[0010] Every evaporator in the typical LHP system has its own compensation chamber, which can be directly connected to the compensation chambers of other evaporators or can have no direct connection with the compensation chambers of other evaporators in the system. In these devices, evaporators are rigidly connected with each other and are at a relatively close distance from each other.

[0011] Despite evident advantages of LHP systems having multiple evaporators designed to operate over a wide temperature range, there exists a limitation on the number of evaporators that can be reasonably used, as each evaporator comprises a compensation chamber. As the minimum operating temperature decreases, the compensation chamber volume increases rapidly when the number of evaporators increases. This leads to a limitation on the number of evaporators that can be used in these systems.

[0012] Besides, certain problems can also exist with the temperature control in multi-evaporator LHP systems: the key components for the LHP temperature control are the compensation chambers. In a two-evaporator installation, the LHP can operate at the desired temperature in most of the cases, as the LHP responds very well to rapid changes of heat load, sink temperature and set point temperature. However, only one of the compensation chambers has a vapor-liquid two-phase condition during the operation regardless of how many are under temperature control.

[0013] The heat, which passed by thermal conduction through the capillary pump wall into the central part of the evaporator, in the direction opposite to the fluid circulation direction, is usually called parasitic heat leak.

Test results showed that when one of the evaporators has a very low heat load, a sudden vapour generation on the inner surface of the capillary pump was observed, stridently increasing the parasitic heat leak to the compensation chamber which results in a higher operational temperature of the loop. This causes a hysteresis control problem for the loop that is hard to predict or prevent. Also, it was found that situations when the liquid distributes itself among the compensation chambers (trying to occupy the lowest pressure spots) can lead to unstable operation of the system. Furthermore, a problem of controllability for multi-evaporator LHP systems arises when the amount of evaporators and compensation chambers increases.

[0014] Therefore, it is possible to conclude that an expandability limitation is the main problem in multi-evaporator LHP systems, as shown in USSR Patent 1395927, such that two evaporators are used or only three evaporators maximum for narrow temperature ranges. A secondary problem presented by these systems too is poor controllability.

[0015] Another type of capillary driven loop is CPL, as for example in documents US 6626231 and US 7118076, typically comprising one or more evaporators, one or more condensers, transport lines, one remote compensation chamber and a sub cooler. Location of compensation chamber is the main distinguishing feature between CPL and LHP designs. LHP compensation chamber(s) is always directly attached to evaporator(s) but CPL has one remote compensation chamber (also known as liquid reservoir), separated from evaporator(s) by small diameter (2-5 mm) connecting tube(s). In CPL, liquid from the condenser and from the remote compensation chamber flows through the sub cooler before reaching the evaporators. The CPL comprising a remote reservoir loses ability for self-start up without special preconditioning. Besides, for any CPL, the tolerance for vapour parasitic heat leak is a significant problem of reliable operability of the system. The growing of a vapour bubble on the inner surface of the capillary pump leads to the pump dry out and, finally, to the failure of CPL operation. In case of LHP, the bubble usually migrates into the compensation chamber (as soon as it is closely attached to the evaporator) and condenses in sub cooled liquid which is always presented in the LHP compensation chamber.

[0016] Continued improvements have been made to the CPLs in the last decades. The two-port evaporator (one liquid inlet and one vapour exit) initially used in CPLs generally experienced dry-out due to the appearance of vapour in the liquid core during start-up and transient regimes. To prevent vapour from blocking liquid return to the wick structure, a three-port capillary evaporator was introduced in the system connecting the remote reservoir line to the liquid core of the evaporator. This configuration allows vapour to expand along the evaporator core and to migrate into the remote reservoir, instead of accumulating in the evaporator core and interfering with liquid returning from the condenser. Initially, three-port capillary pumps were used as starter pumps, and then like the main functional evaporator design. To prevent vapour from depleted evaporators to flow upstream and to block liquid return to operating evaporators, a capillary device, known as a capillary isolator, was introduced, located upstream of the evaporator inlet. Back pressure regulators were also installed in many multiple evaporator CPLs to assist start up. These capillary devices, located in the vapour transport line, redirect vapour initially generated at one evaporator to other inoperative (without heat load) evaporators. This action forces liquid from the vapour lines and improves the chances for a successful start up for all evaporators in the system: it is also helping to promote heat load sharing among evaporators, for instance, when an inoperative evaporator acts as a condenser.

[0017] Furthermore, another problem in the known CPL systems is the formation of non-condensable gases in the loop, which can lead to evaporator failure if the non-condensable bubbles reach the evaporator core blocking the liquid return to the evaporators of the CPLs. Since evolution of non-condensable gases over the CPLs lifetime is practically unavoidable, CPLs should be designed to be tolerant to non-condensable gases in one way or another. One of the possible solutions is to implement special traps to collect the bubbles. The traps are usually used for systems with parallel condensers and are placed at the condenser exit where they can also serve as capillary flow regulators (if the trap utilizes a capillary structure to separate gas from liquid). The capillary structure helps to prevent vapour from leaving the condenser. If one of the condensers becomes fully utilized, then this trap can serve to redirect the flow to the other condenser(s).

[0018] The following conclusions summarize the issues related to CPL reliability:

- CPL design should never allow bubbles to form in the liquid side of the loop: a bubble trap should then be provided at the outlet of the sub cooler to prevent convection of non-condensable gases or/and vapour bubbles to the evaporators;
- CPL requires a start up evaporator to clear the vapour channels in the main evaporators before heat is applied to them;
- reducing the diameter of the CPL evaporator elements leads to many unexpected difficulties: the design with thinner capillary pump walls leads to higher probability of vapour bubble formation inside of the liquid core of the evaporator and as consequence to failure of CPL operation;
- it is known in the state of the art, that in order to improve vapour parasitic heat leak tolerance of evaporators, it is preferable to connect these evaporators in series; in this case the first evaporator in series creates sweeping flow for the previous evaporators.

[0019] Another solution is to have several parallel evaporators connected to the same compensation chamber, located at the evaporating part of the loop, and including special long capillary links between the evaporators and the compensation chamber. This system is known as Free Location LHP, as shown for example in documents US 5944092, USRR Patent 1626798 or Russian Patent 2120592. This system was successfully tested on the ground with a favourable gravitational bias of the evaporators relative to the compensation chamber, making it easy for the capillary links to distribute the fluid to each evaporator. Orientation constraint in gravity field is due to limits imposed by the capillary link. The capillary link connecting the evaporators to the compensation chamber limits the separation distance between the evaporators and the compensation chamber. This limitation is similar to the existing in conventional heat pipes. Other significant limitations of this design are complexity and integration difficulties which lead to problems of system expandability, scalability and part standardization. All evaporators have to be below or in the same plane with respect to the plane of the compensation chamber. Since the tube connecting each evaporator to the compensation chamber contains a capillary link inside, the tube internal diameter is typically greater than 4 mm, since it is practically impossible to allocate a capillary structure in smaller diameter tubing. Large diameter connecting tubing leads to inflexible system and high requirements for tolerances for integration purposes. In usual design of a LHP evaporator with a bayonet tube, a capillary link (secondary wick) supplies the primary capillary pump with liquid practically only in transient regimes. However, in this design, the capillary link supplies all amount of liquid that is needed for the evaporator, which leads to significant limitations for rates of change of heat source power or/and heat sink temperature. Other disadvantage of such approach is the low thermal conductance of evaporators due to the permanent presence of vapour phase in the evaporator core.

[0020] An attempt to overcome some of these significant drawbacks led to a so called multi-free LHP CPL known for example per US 5944092, where functional evaporators do not have a capillary link to the compensation chamber, only to the liquid line. Limitations of this design are similar to those of ordinary CPLs with starter pumps. Capillary evaporators linked to the liquid line cannot provide a reliable vapour tolerance and, therefore, this design presents the drawback of the necessity of an additional special evaporator with dedicated power source to provide the loop circulation.

[0021] Further designs were made developing the so called multi-evaporator hybrid LHP, as known for example in documents US 7661464, US 6889754, US 7004240, US 8047268, US 7549461, US 81 09325, US 8066055, US 8047268 or US 7251889, suggesting that a link between evaporators and compensation chamber could itself be a loop and incorporated this idea in a so called advanced CPL, as an attempt to incorporate both the advantages of a robust LHP and the architectural flexibility of a CPL. This system comprises two relatively independently operated loops, a main loop and an auxiliary loop. The main loop is basically a traditional CPL with same as for CPL configuration and operational principles, whose function is to transport the waste heat and reject it to a heat sink via the primary condenser. The auxiliary loop is used to remove vapour bubbles from the core of the CPL evaporators and move them to the compensation chamber. The auxiliary loop contains only one LHP-type evaporator with the attached large compensation chamber. The chamber is only one and it is common for all evaporators: the CPL evaporators in the main loop and the LHP evaporator in the auxiliary loop. In addition, the auxiliary loop is also used to ease the start-up process. In this manner, the auxiliary loop functionally replaces the secondary wick of a conventional LHP. The feasibility of this design was however only achieved when the evaporators were connected in series. This means that liquid consequently goes through the evaporators: flow leaving the first evaporator enters the second one, etc.

[0022] Initially, the multi-evaporator hybrid LHP included three evaporators, one of which was a standard LHP evaporator directly attached to the common system's compensation chamber, and two traditional three-port CPL evaporators. Tests indicated that the system was not very reliable during power cycling. The sensitivity to power cycle was attributed to the expansion of vapour bubbles in the evaporator core. Heat conduction through the wall of the evaporator capillary pump made it relatively easy to nucleate vapour in the evaporator core. In case of steady state operation, these bubbles were swept from the core of functional evaporators by forward flow of the liquid to the capillary pump. However, as the functional evaporators input power decreased, liquid movement forced by capillary action on the auxiliary evaporator was not enough to efficiently remove all vapour bubbles from the evaporator core to prevent vapour blockage of the capillary pump (dry-out) after sudden increase of the evaporator power. On the other hand, sudden power reduction leads to temporary fluid flow break in the condenser until new stable temperature/pressure equilibrium was established in the system. This flow break therefore required a net flow mass displacement from the evaporator and the compensation chamber to the condenser. As a result, nominal forward direction flow was disrupted. During this reversal flow, vapour bubbles could then accumulate or even expand in the evaporator capillary pump core, therefore causing evaporator dry-out and failure of the system.

[0023] To improve vapour tolerance, the internal design of the evaporators was modified to include a special phase separation wick, designed to provide better control of the two phases vapour/liquid distribution in the core of the pumps. The design modifications were intended to extend the phase control provided by the secondary wick in the traditional LHP evaporator to the CPL evaporators. Despite general successful results obtained during testing, the operation was verified in relatively limited conditions: mostly in horizontal orientation, evaporators were located close to each other, and therefore with similar hydraulic resistance of lines. Therefore, such configuration was not representative of the conditions of potential spacecraft thermal control application when evaporators and remote reservoir are spatially separated, and the rate of evaporators response on variations of the input power and heat sink conditions depend on the length of the lines connecting these elements. Therefore, the ability for temperature control was not properly verified.

[0024] Also known in the art are *hybrid cooling loop technology,* as those shown for example in documents US6990816 and US6948556, which combine the active liquid pumping with the passive capillary liquid management in the wick structure of the evaporator and its liquid/vapour separation. The hybrid cooling loop consists of an evaporator, a condenser, a liquid compensation chamber and a pump as the simplest design. Because of the active amplificatory pumping system, the hybrid loop system could manage different multiple evaporator designs. Despite certain advantages, the necessity of the supplementary loop circulation means can be considered as a drawback because of the active character of critical design components which reduces the reliability and life time of the system.

[0025] Another known system developed is the so called advanced LHP which is a LHP with two evaporators: main (functional) and secondary (auxiliary) evaporators, as per document US6810946 B2, for example, incorporating a secondary evaporator to the conventional LHP design. The secondary evaporator is located in a cold-biased environment to ensure that its capillary pump is always primed. Electrical heaters are attached to this evaporator to provide the necessary thermal power for its functioning. With the secondary pump operating, it actively removes the vapour that is accumulated in the compensation chamber by the parasitic heat leaks to the compensation chamber of the main evaporator and to the liquid line. This design considers only a single main evaporator LHP. The main drawback of this approach is the existence of the additional evaporator and its active character. In fact, this solution is needed only for a LHP with not properly designed secondary pump.

[0026] Further, an evaporator with attached compensation chamber was proposed to use in a capillary driven loop, known for example per documents US7061446, US7268744 or US7841 392. The undivided large capillary wick is used in the evaporator portion and in the compensation chamber. The wick has greater transverse size in the compensation chamber than in the evaporator portion. There are no means to guarantee vapour tolerance of the evaporators.

[0027] Thus, as a summary, it is possible to conclude that the main and the most critical element in a capillary driven loop is the evaporator. The vapour and non-condensable gases intolerance, which can lead to total failure of the system in heat transfer, is the main problem in the development of capillary driven multi-evaporator two phase thermal control systems. Various methods have been proposed and investigated to solve the problem; however, the existing technical solutions still cannot guarantee reliable and stable performance in different actual thermal conditions of spacecraft operation.

[0028] The present invention is therefore oriented towards these needs.

SUMMARY OF THE INVENTION

[0029] The present invention therefore provides a heat transfer and thermal control system, in particular, a two-phase capillary driven LHP system.

[0030] An object of the invention is to provide a two-phase capillary driven LHP system having reliable operation at a wide range of operation conditions, providing at the same time vapour parasitic heat leak tolerance means for the evaporator and design flexibility by implementation of remote compensation chamber.

[0031] Another object of the present invention is to provide a two-phase capillary driven LHP system that can be expanded, that is, that can vary the number of its evaporators and/or its condensers.

[0032] Other objects of the two-phase capillary driven LHP system of the invention are the following:

- *scalability*: the size (both diameter and length) of the evaporators can vary in a wide range and can be adjusted for any particular application needed;
- *controllability:* possibility to control the operating temperature of the system by thermal control of the remote compensation chamber;
- *capability of heat load sharing* when the two-phase capillary driven LHP system comprises multiple evaporators: power ranges can be different for each evaporator, such that some evaporators can have the maximum heat load while others have no power application;
- *configuration flexibility:* theoretically, an unlimited number of evaporators/condensers can be used; the distance between evaporators and compensation chamber can be up to several meters; evaporators, condensers and remote compensation chamber can be located in gravity field at various levels with elevation difference up to 1-3 m taking into account only capillary potential of evaporators secondary pumps;
- *functional flexibility:* there exists a wide range of heat input powers for the entire system and for every evaporator; resistance to rapid change of power inputs or/and condenser temperatures occurs (related to the main objective of the invention: vapour parasitic heat leak tolerance);
- *integration flexibility:* small diameter (1-2 mm) tubing connecting evaporators with remote compensation chamber allows easy installation of the system on the satellite level; also, flexible inserts such as tube coils or/and flexible hoses can be used for better

integration of the system;

- *evaporators standardization:* possibility of using compensation chambers attached to the evaporators, having standardized dimensions without the need of effecting any re-qualification of the evaporators for every configuration and size of the system; this is especially important for the improvement of the mechanical viability of the two-phase capillary driven LHP system during vibration, as every evaporator of the system has relatively small standardized individual compensation chamber (simpler mechanical design as for the evaporators with the large chambers) and can be mechanically designed and qualified individually only one time.

[0033] These objectives are achieved with a two-phase capillary driven LHP system, effecting heat transfer and thermal control applications with a two-phase fluid as a working media. The system of the invention comprises at least one evaporator, comprising a thermal stabilization-compensation chamber attached to it, at least one condenser, liquid and vapour lines, and a single remote compensation chamber, the thermal stabilization-compensation chamber comprising two-phase and hydro accumulator reservoirs. The remote compensation chamber is hydraulically connected with the two-phase and hydro accumulator reservoirs of the thermal stabilization-compensation chamber. The evaporator comprises a primary capillary pump which serves to absorb heat from the equipment, which has to be cooled, and to provide fluid heat continuous circulation between the evaporator, which is connected to the heat source, and the condenser, which is connected to the heat sink. A secondary capillary pump is located inside the primary wick and inside of the thermal stabilization-compensation chamber and serves to supply the primary wick with liquid, and to provide fluid/heat intermittent circulation in transient regimes of operation of the system, between the inner part of the primary wick and the thermally controlled remote compensation chamber. In steady state regimes of operation of the system, the thermal stabilization-compensation chamber serves to remove internal heat leak through a primary capillary pump by convection and condensation on the heat exchanger surface, which separates the two-phase and hydro accumulator reservoirs in the thermal stabilization-compensation chamber.

[0034] Other features and advantages of the present invention will be disclosed in the following detailed description of illustrative embodiments of its object in relation to the attached figures.

DESCRIPTION OF THE DRAWINGS

[0035] The features, objects and advantages of the invention will become apparent by reading this description in conjunction with the accompanying drawings, in which:

Figures 1 a, 1b and 1 c show schematic views of the LHP device of the invention having a remote compensation chamber and two evaporators.

Figure 2 shows a general view of the LHP device of the invention having multiple evaporators (4 units) and multiple condensers (2 units).

DETAILED DESCRIPTION OF THE INVENTION

[0036] The present invention relates to a LHP device 1 comprising evaporator 2 containing a stabilization-compensation chamber 10, a combination of a primary capillary pump 30 and a secondary capillary pump 40, together with the corresponding plumbing components of the LHP device 1. The primary capillary pump 30 serves for pumping fluid in the LHP device 1, the evaporation of which absorbs heat from the system that has to be cooled. The secondary capillary pump 40 serves for supplying liquid to the primary capillary pump 30 and, together with the stabilization-compensation chamber 10 and the remote compensation chamber 20, for providing means to remove the vapour that is formed by internal parasitic heat leak of the at least one evaporator 2.

[0037] The present invention relates to a LHP device 1, which can be of the type single evaporator-condenser or multiple evaporators (and /or condensers) embodiments, as shown in Figures 1a, 1b, 1c. The LHP device 1 of the invention comprises the following components:

- at least one evaporator 2: the evaporator 2 comprises stabilization-compensation chamber 10, a combination of a primary capillary pump 30 and a secondary capillary pump 40. The primary capillary pump 30 serves for pumping fluid in the LHP device 1, the evaporation of which absorbs heat from the equipment that has to be cooled. The secondary capillary pump 40 serves for supplying liquid to the primary capillary pump 30 and, together with the stabilization-compensation chamber 10 and the remote compensation chamber 20, for providing means to remove the vapour that is formed by internal parasitic heat leak 18 of the at least one evaporator 2;
- one remote compensation chamber 20 in two-phase condition for temperature control functions and for managing changes of liquid phase volume together with excessive vapour parasitic heat leaks in the LHP transient regimes of operation, providing compact standardized design of evaporator 2 and expandability in the embodiment having multiple evaporators 2; there is no need of the stabilization-compensation chambers 14 having large volumes, depending on total volume of the LHP device 1, as they can have minimal unified volumes, enough to manage and ensure vapour/non-condensable gases tolerance in steady state regimes;
- at least one condenser 27;
- vapour line 28 and liquid line 24.

[0038] Figures 1 a, 1b and 1 c show different schemes of an embodiment of the invention, showing a LHP device 1 having an arrangement of a remote compensation chamber 20 and evaporators 2, such that:

- Figure 1 a shows the remote compensation chamber 20 being connected to a two-phase reservoir 5 of the stabilization-compensation chamber 10 by a two-phase line 12, the liquid accumulator reservoir 6 of the stabilization-compensation chamber 10 being connected to the remote compensation chamber 20 by a liquid line 13. The returned liquid from the condenser is always passed through remote compensation chamber 20 before to arrive to evaporators 2.
- Figure 1 b shows the remote compensation chamber 20 being connected to the two-phase reservoir 5 of the stabilization-compensation chamber 10 by a two-phase line 12, the liquid line 13 being directly connected to the liquid line 24 returning liquid to a bayonet tube 7 at the entrance of the evaporator 2 from the condenser 27. Via lines 13 and 24 the remote compensation chamber 20 has a hydraulic link with the liquid accumulator reservoir 6 of the stabilization-compensation chamber 10.
- Figure 1 c shows the remote compensation chamber 20 being connected to the two-phase reservoir 5 of the stabilization-compensation chamber 10 by a two-phase line 12, the stabilization-compensation chamber 10 also comprising a liquid accumulator reservoir 6 directly connected to the remote compensation chamber 20 by a liquid return line 13.

[0039] The three presented cases illustrate different variants of the remote compensation chamber 20 designs and different ways of layout in the LHP device 1. The two-phase port of the remote compensation chamber 20 is always connected via line 12 with the stabilization-compensation chamber 10. However liquid port(s) of the remote compensation chamber can be connected to stabilization-compensation chamber 10 in 3 different manners: directly (Fig 2c), through liquid line 24 in series (Fig. 2a) and in parallel (Fig 2b). Two is the minimum amount of fluid ports (one is for two-phase line 12 and second for liquid return line 13 (see Fig. 2b). The maximum quantity of fluid ports for remote compensation chamber 20 can be calculated by multiplying the number of evaporators by two and adding the number of condensers: in this case every evaporator has two individual lines 12 and 13 joining the stabilization-compensation chamber 10 with remote compensation chamber 20 and the remote compensation chamber 20 has additional liquid lines 24 connected with the condenser. Different combinations between maximum and minimum amount of ports are possible and it also provides flexibility in the system design.

[0040] The numerals shown in Figures 1a-1b-1c and 2a-2b-2c represent the following:

1 LHP device
2 Evaporator
3 Vapour-liquid interface
4 Separator of low and high pressure sides of the primary capillary pump 30
5 Two-phase reservoir linked to the internal core of the primary capillary pump 30
6 Liquid accumulator reservoir
7 Bayonet tube, liquid transport line entrance from condenser 27
8 Liquid flow direction
9 Heat sink
10 Stabilization-compensation chamber
11 Vapour flow direction
12 Two phase line to the remote compensation chamber 20
13 Liquid return line of the remote compensation chamber 20
14 Fluid in liquid state
15 Heat exchanger (heat exchange surface) - separator of low (liquid) and high (two-phase) pressure sides of the secondary capillary pump 40
16 Vapour-removing channels inside the primary capillary pump 30 (evaporator core)
17 Heat input
18 Parasitic heat leak into the central core of the primary capillary pump 30
19 Vapour-removing channels outside the primary capillary pump 30
20 Remote compensation chamber
21 LHP device 1 vapour line inlet
22 Vapour bubbles
23 Liquid drops
24 Liquid transport line
25 Porous wick inside the remote compensation chamber 20
26 Liquid channel
27 Condenser
28 Vapour line
29 Fluid in vapour state
30 Primary capillary pump
31 Fluid in two-phase state
40 Secondary capillary pump

[0041] The evaporator 2 comprises a small stabilization-compensation chamber 10 containing a secondary capillary pump 40, designed in such a way that it efficiently manages the vapour flow due to the parasitic heat leak 18 into the central core of the primary capillary pump 30.

[0042] The evaporator 2 design comprises a primary capillary pump 30 with external vapour-removing channels 19 outside the primary capillary pump 30, a secondary capillary pump 40 and a stabilization-compensation chamber 10 which comprises two chambers, a two-phase reservoir 5 and a liquid accumulator reservoir 6. The primary capillary pump 30 also comprises internal vapour-removing channels 16 in the evaporator 2 core, to remove the vapour that forms due to the heat leak through the primary capillary pump 30. These vapour-removing channels 16 are connected with the small two-phase reservoir 5 close to the vapour-removing channels 16 outlets. This two-phase reservoir 5 comprises a heat exchanger 15 (heat exchange surface) between the two-phase reservoir 5 and the liquid accumulator reservoir 6 of the stabilization-compensation chamber 10. The liquid accumulator reservoir 6 and the two-phase reservoir 5 with the heat exchange surface 15 can be called as stabilization-compensation chamber 10. The secondary capillary pump 40 is located inside of the primary capillary pump 30 and the stabilization-compensation chamber 10. A porous wick 25 is installed inside of the remote compensation chamber 20 to manage fluid distribution in micro gravity conditions. The porous wick 25 prevents also vapour or non condensable gas bubbles penetration to the liquid line 13 as well as to the liquid accumulator reservoir 6.

[0043] Working fluid exists in three states inside of the LHP device 1 of the invention: vapour 29, liquid 14 and two-phase 31 states.

[0044] When heat 17 is supplied to the evaporator 2 by the heat releasing equipment or heat source, the heat evaporates working liquid. Vapour goes from the evaporator 2 to the condenser 27 through the vapour transport line 28, where it is condensed. After that, the working liquid returns to the stabilization-compensation chamber 10 and to the evaporator 2 through the liquid transport line 24, to be again evaporated in the primary capillary pump 30 of the evaporator 2. Unlike ordinary LHP systems, the proposed LHP device 1 of the invention is controlled by the remote compensation chamber 20, as two-phases are always present in this chamber.

[0045] The link of the secondary capillary pump 40 and the stabilization-compensation chamber 10 provides the following functions:

- redistributes and supplies liquid from the bayonet tube 7 and internal liquid channel 26, supplying it to the primary capillary pump 30 (mainly in steady state regimes);
- transports liquid from the remote compensation chamber 20 through the liquid accumulator reservoir 6, supplying it to the primary capillary pump 30 (mainly in transient regimes);
- together with the stabilization-compensation chamber 10 and remote compensation chamber 20, it provides vapour parasitic heat leak tolerance passive means individually for every evaporator 2 (of multi-evaporator design).

[0046] The LHP device 1 can contain several evaporators 2 and several condensers 27 (Figures 1, 2). It is provided the opportunity that the evaporators 2 can collect the power from different heat sources, which could be located far one from the others thanks to the flexibility/adaptability provided by the LHP device 1 concept:

[0047] Various embodiments of present invention regarding the power rejection are possible. Even for single-evaporator LHP device 1, several condensers 27 can be placed in different locations to take advantage of the most favourable conditions of sink depending on the position along the orbit (for space applications of the LHP device 1), for example, two parallel condensers 27 can be located in opposite faces (Fig. 2).

[0048] Several means of vapour tolerance management are designed for compensating primary heat leak penetrating through the primary capillary pump 30 to the evaporator 2 core and for compensating secondary parasitic heat leak penetrating through the secondary capillary pump 40 (which is significantly, in order of magnitude lower than the primary parasitic heat leak):

- the heat exchanger 15 in the stabilization-compensation chamber 10 provides the possibility to cool and condense vapour generated by the main (primary) parasitic heat leak 18; the cold sub-cooled liquid in the liquid accumulator reservoir 6 cools and condenses vapour bubbles 22 when liquid exists in the two-phase reservoir 5 or condenses vapour with forming drops of liquid 23 on the heat exchange surface 15, the heat exchanger 15 being designed having a surface area calculated to condensate vapour corresponding to 10-15% of the evaporator input heat load 17 (maximum possible values of the heat leak), so that the two-phase line 12 is usually filled with liquid, which is the nominal regime of the LHP operation in steady state conditions, the heat exchanger 15 being the main means of vapour parasitic heat leak tolerance;
- a self-induced *"core sweepage"* mechanism to ensure compensation of the parasitic heat leak during transient regimes, such that the secondary capillary pump 40 guarantees the removal of vapour from the evaporator core 16 to the remote compensation chamber 20 and the liquid return 13 to the stabilization-compensation chamber 10, which is especially important during transient operation regimes (change of input heat 17 or/and condenser temperature) with elevated heat leak;
- design of the stabilization-compensation chamber 10 as a cold liquid accumulator, providing effective compensation of secondary parasitic heat leak through secondary capillary pump 40.

[0049] Thus, the main vapour / non-condensable gases tolerance means are located in maximum proximity to the evaporators 2. Moreover, not only the liquid flowing from the condenser 27 reaches the evaporator 2, but also liquid storage in the liquid accumulator reservoir 6 can be supplied to the evaporator 2 when required (mainly in transient regimes), providing additional reliability for the system. Besides, several additional redundant means can be considered: auxiliary LHP and / or thermal electrical cooler, for example.

[0050] Vapour generated by internal heat leak 18 in the evaporator core moving to the two-phase reservoir 5 is condensed by the heat exchanger 15 (nominal case operation). Therefore the two-phase line 12 connecting the two-phase reservoir 5 and the remote compensation chamber 20 is usually filled with liquid.

[0051] During the most unfavourable transient regimes part of vapour 11, which could not be condensed completely on the heat exchange surface 15 in the stabilization-compensation chamber 10, can go to the remote compensation chamber 20 to condensate there. The rest of heat leak (secondary leak penetrating to the liquid channel through the secondary capillary pump 40 will be compensated with condensation in the liquid accumulator reservoir 6 in the stabilization-compensation chamber 10 by sub-cooled liquid.

[0052] Presence of the remote compensation chamber 20 gives the opportunity to manage non-condensable gas inside of the LHP. In typical LHP, non-condensable gas is located in the compensation chamber 10 in proximity of the evaporator 2 and can penetrate to the evaporator core 16 and thus influence more significantly the evaporator 2 and therefore, the LHP operation, In the proposed design according to the invention, non-condensable gas will move to the remote compensation chamber 20 and it will accumulate non-condensable gas preventing negative impact on LHP operation.

[0053] Such scheme guarantees vapour / non-condensable gases tolerance of the LHP device 1 and system reliability (especially in transient regimes) individually, passively and automatically for every evaporator 2 (of multiple evaporator option), without the necessity of having an active control. This design is a simpler and more robust alternative to the active external "forced pumping" designs of known technical solutions in the prior art equipped with remote auxiliary capillary or mechanically pumped loops for the entire system. The secondary capillary pump 40 is working as a capillary pump of the secondary loop with remote compensation chamber 20 as a condenser to absorb heat leak through the primary capillary pump 30. Thus, the secondary capillary pump 40 has similar function as a remote auxiliary capillary or mechanically pumped loop in known designs.

[0054] A remote compensation chamber 20 (common for all evaporators 2 of multiple evaporator option) included in the proposed design serves to accumulate liquid and to compensate the liquid volume changes during the LHP device 1 operation. This large reservoir helps to avoid the obligation of designing a large volume compensation chamber for the individual evaporators in the multiple evaporator option (in ordinary LHPs with multiple evaporators their volumes depend strongly on the total number of evaporators 2 in the system). Therefore, this configuration allows having a scalable design which can be fitted easier to the required number of evaporators 2 and the specific requirements of each application, because evaporators 2 will have same design independently on the design and volume of the lines, condensers 27, total number of evaporators 2, etc. Only the volume of the remote compensation chamber 20 has to be adjusted for specific requirements.

[0055] The design and location of the remote compensation chamber 20 can be selected depending on the functional purposes and the geometrical constraints. However, it is recommendable to control the temperature of the remote compensation chamber 20. For these purposes, several options can be considered and the best solution can be selected depending on each application requirements:

- to have an active control by using a heater or thermal electrical cooler, to control the temperature and facilitate the priming of the loop prior to the start up;
- to have a heat link with the environment to maintain its temperature in a certain range.

[0056] The LHP device 1 of the invention can comprise several optional additional elements, such as:

- a subcooler located between the condenser 27 and the outlet of the liquid line 24;
- a capillary blocker can be installed at the outlet of parallel condensers 27 for a better vapour distribution between them;
- additional capillary blockers could be also introduced at the outlets of the liquid lines 24 of multiple evaporators 2 to prevent the liquid line 24 and the evaporators 2 to experience pressure drops.

[0057] The LHP device 1 of the invention may further comprise external auxiliary means such as cold bias links or thermal electric coolers for subcooling the liquid inside the liquid accumulator reservoirs 6 in the stabilization-compensation chambers 10.

[0058] There also exist other auxiliary elements to provide subcooling to the liquid accumulator reservoirs 6 in the stabilization-compensation chamber 10: this cooling is settled mainly as additional means to remove the back conduction of the evaporators 2 and parasitic heat leak to the liquid line 24. Thus, several options are considered:

- cold bias links;
- thermal electric coolers located on the stabilization-compensation chamber 10.

[0059] All the above-mentioned options should be carefully evaluated for every particular case depending on the operational conditions desired for the LHP device 1.

[0060] Although the present invention has been fully described in connection with preferred embodiments, it is evident that modifications may be introduced within the scope thereof, not considering this as limited by these embodiments, but by the contents of the following claims.

Claims

1. Loop heat pipe apparatus (1) for heat transfer and thermal control, using a two-phase fluid as a working media and comprising:

   - at least one evaporator (2) to be connected with a heat source and comprising a thermal stabilization-compensation chamber (10) attached to the at least one evaporator (2) and a secondary capillary pump (40) located inside the thermal stabilization-compensation chamber (10),
   - at least one condenser (27) to be connected with a heat sink,
   - liquid lines (24) and vapour lines (28) connecting the at least one evaporator (2) and the at least one condenser (27), and
   - a remote compensation chamber (20),

   characterized in that the thermal stabilization-compensation chamber (10) comprises a two-phase reservoir (5) and a liquid accumulator reservoir (6) separated by a heat exchange surface (15), such that the remote compensation chamber (20) is hydraulically connected with the two-phase reservoir (5) and the liquid accumulator reservoir (6).

2. Loop heat pipe apparatus (1) for heat transfer and thermal control, according to claim 1, wherein the primary capillary pump (30) comprises outer vapour channels (19) to collect and remove heat from a cooled device and inner vapour channels (16) to collect and remove vapour produced by parasitic heat leak penetrating through the primary capillary pump (30).

3. Loop heat pipe apparatus (1) for heat transfer and thermal control, according to claim 2, wherein the inner vapour channels (16) are linked with the two-phase reservoir (5) of the stabilization-compensation chamber (10) where the removed vapour generated due to parasitic heat leak is condensed on the dedicated heat exchange surface (15).

4. Loop heat pipe apparatus (1) for heat transfer and thermal control, according to any of the preceding claims, wherein the secondary capillary pump (40) contains an inner liquid channel (26) with a bayonet tube (7) for liquid returned from the condenser (27) and the remote compensation chamber (20)

5. Loop heat pipe apparatus (1) for heat transfer and thermal control, according to any of the preceding claims, wherein the remote compensation chamber (20) has an internal capillary structure which separates the liquid return line (13) from entire volume of the remote compensation chamber (20) to prevent vapour flow/bubbles penetrating into the liquid return line (13) and into the liquid accumulator reservoir (6) of the stabilization-compensation chamber (10).

6. Loop heat pipe apparatus (1) for heat transfer and thermal control, according to any of the preceding claims, wherein the remote compensation chamber (20) is connected with the two-phase reservoir (5) of the stabilization-compensation chamber (10) by the two-phase line (12) and with the liquid accumulator reservoir (6) of the stabilization-compensation chamber (10) by the direct liquid return line (13).

7. Loop heat pipe apparatus (1) for heat transfer and thermal control, according to any of claims 1 to 5, wherein the remote compensation chamber (20) is connected with the two-phase reservoir (5) of the stabilization-compensation chamber (10) by the two-phase line (12) and with the liquid accumulator reservoir (6) of the stabilization-compensation chamber (10) by the liquid return line (13) and the liquid transport line (24).

8. Loop heat pipe apparatus (1) for heat transfer and thermal control, according to any of claims 1 to 5, wherein the remote compensation chamber (20) is connected with the two-phase reservoir (5) of the stabilization-compensation chamber (10) by the two-phase line (12) and with the liquid accumulator reservoir (6) of the stabilization-compensation chamber (10) by one liquid line (13) which has two functions: to transport liquid to the bayonet (7) entrance of the evaporator (2) from the condenser (27) via the liquid transport line (24), and to return liquid from the remote compensation chamber (20).

9. Loop heat pipe apparatus (1) for heat transfer and thermal control, according to any of the preceding claims, further comprising several evaporators (2).

10. Loop heat pipe apparatus (1) for heat transfer and thermal control, according to any of the preceding claims, further comprising several condensers (27).

11. Loop heat pipe apparatus (1) for heat transfer and thermal control, according to claim 9 or 10, comprising a capillary blocker in the liquid transport line (24) in the liquid inlet of every evaporator (2).

12. Loop heat pipe apparatus (1) for heat transfer and thermal control, according to claim 10, comprising a capillary blocker in the liquid outlet of every condenser (27).

13. Loop heat pipe apparatus (1) for heat transfer and thermal control, according to any of the preceding claims, further comprising external auxiliary means for subcooling of liquid inside of liquid accumulator reservoirs (6) of stabilization-compensation cham-

bers (10).

14. Loop heat pipe apparatus (1) for heat transfer and thermal control, according to claim 13, wherein the external auxiliary means for subcooling of liquid inside of liquid accumulator reservoirs (6) of stabilization-compensation chambers (10) are cold bias links or thermal electric coolers.

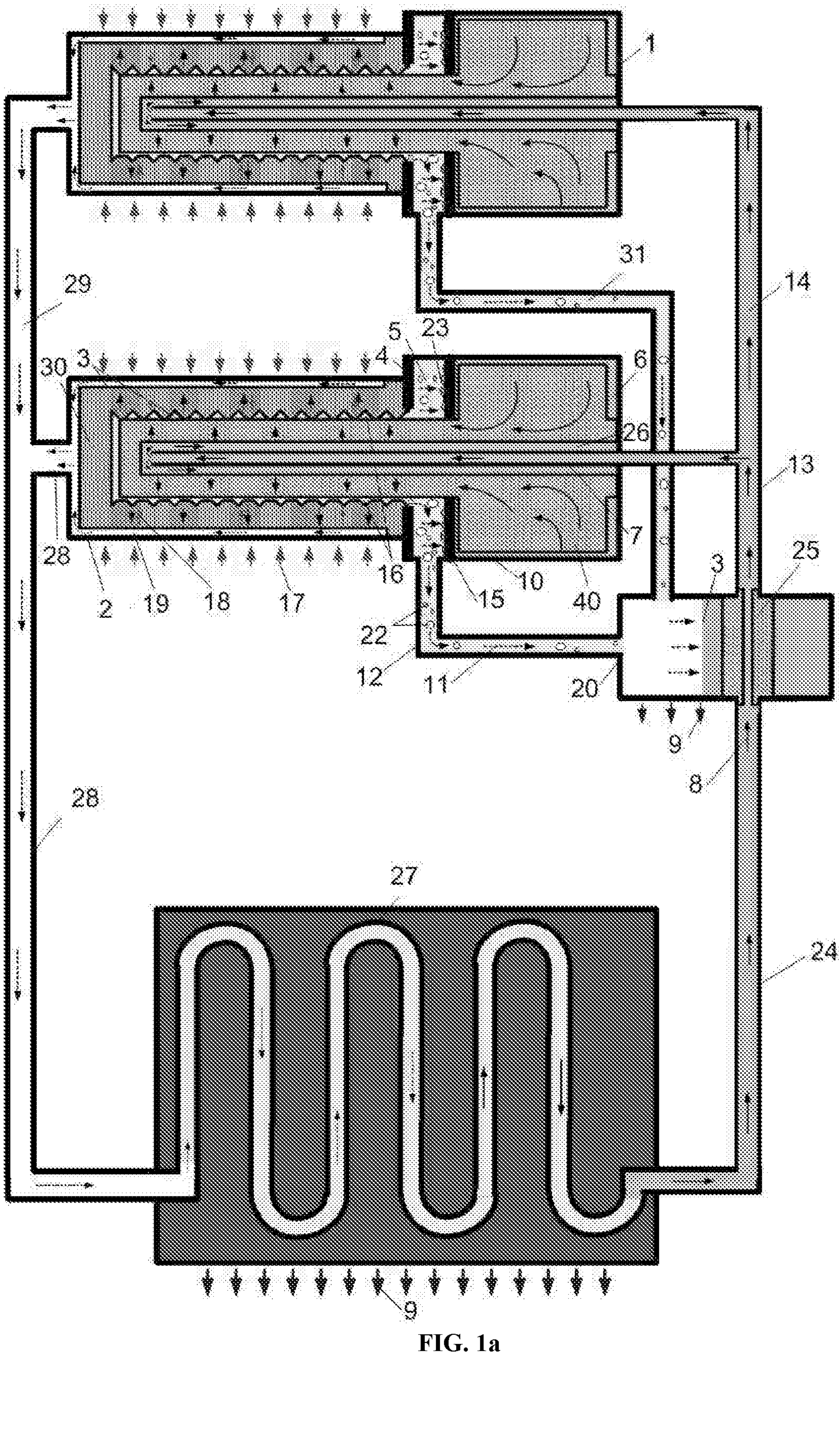
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FIG. 1a

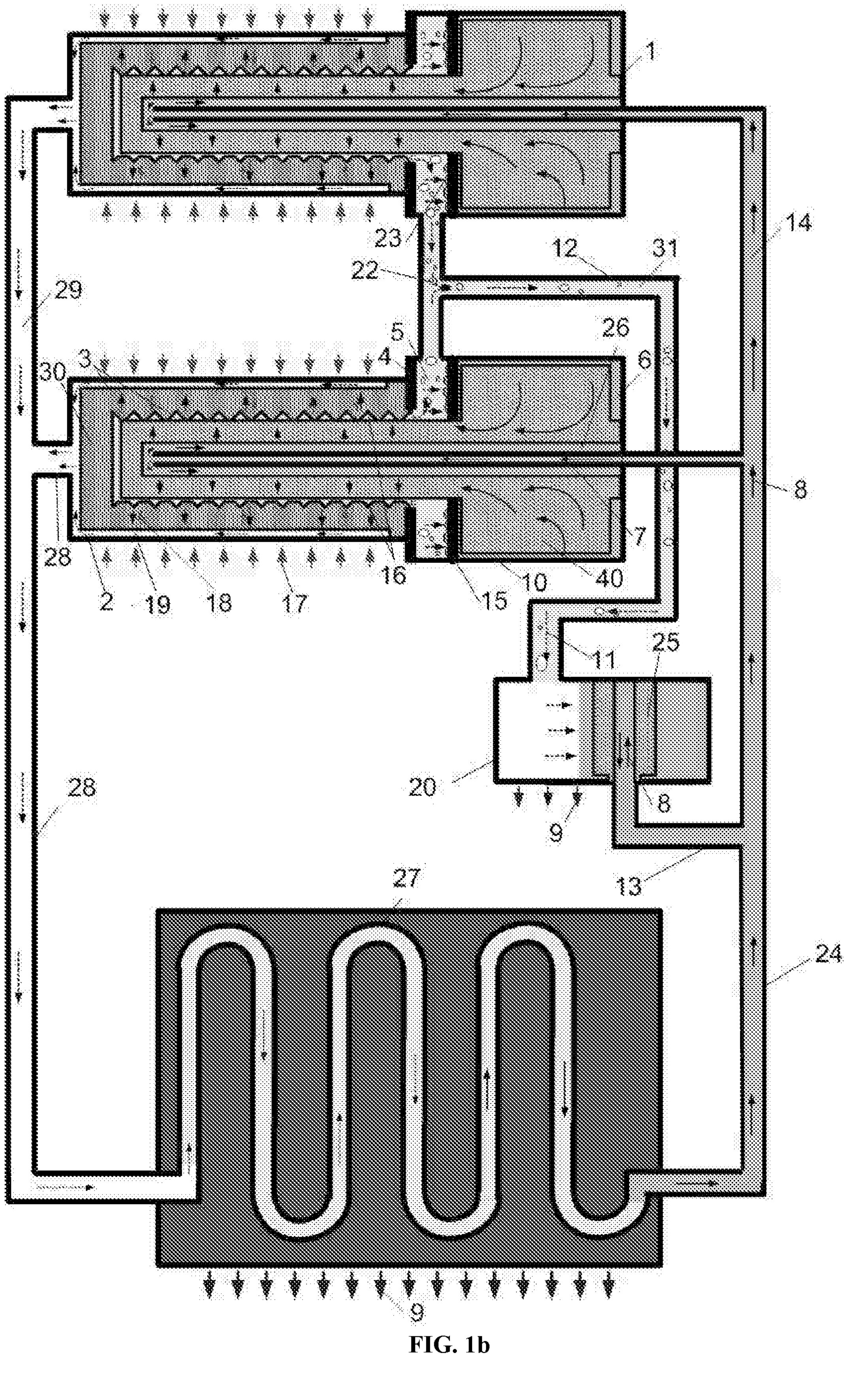
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FIG. 1b

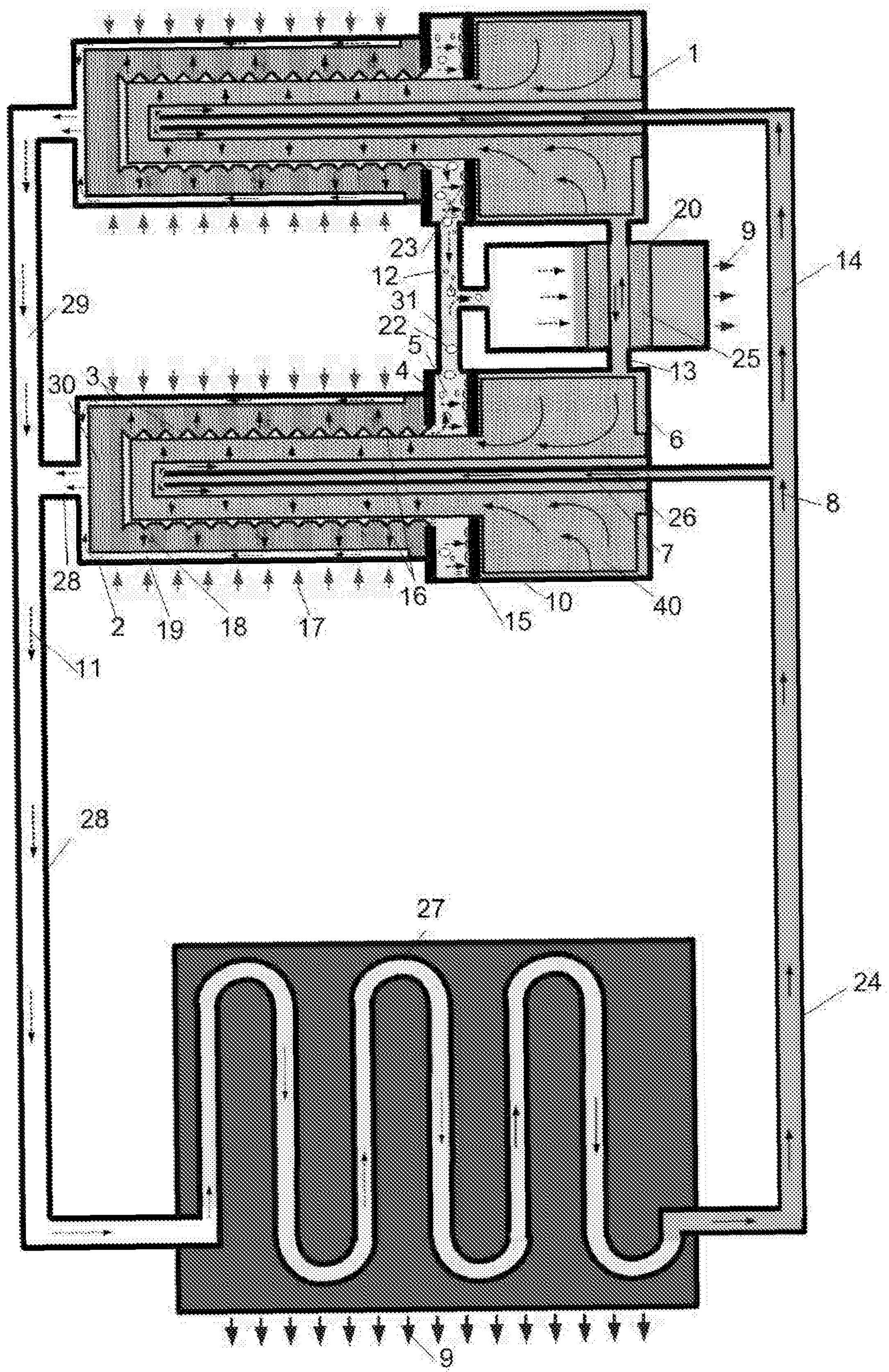
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FIG. 1c

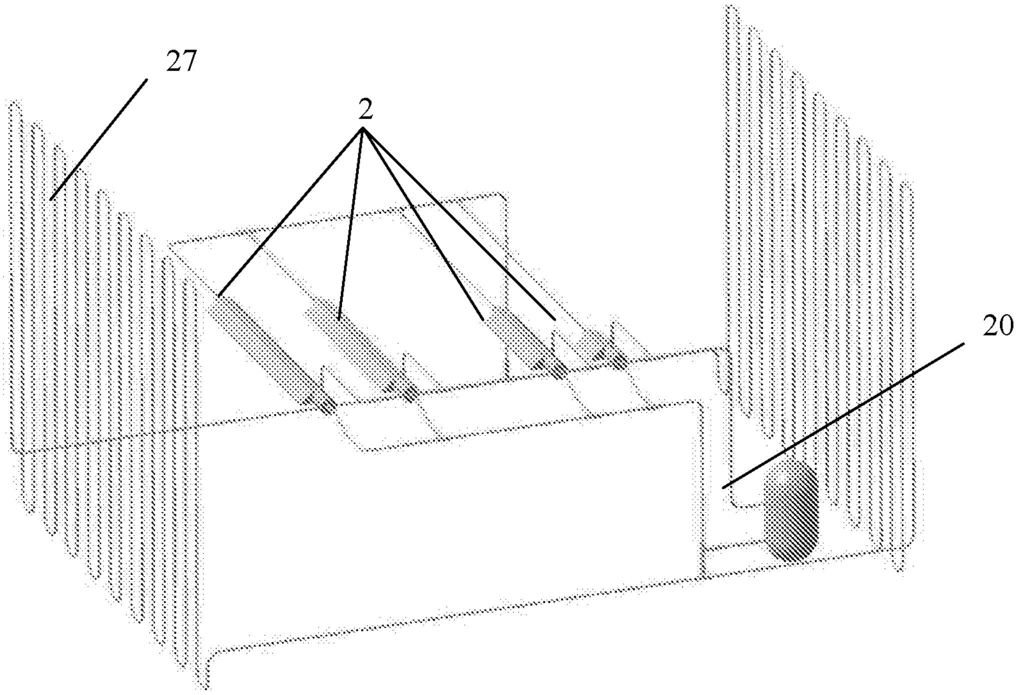

FIG. 2

INTERNATIONAL SEARCH REPORT

International application No
PCT/ES2012/070918

A. CLASSIFICATION OF SUBJECT MATTER
INV. F28D15/04
ADD.

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)
F28D

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)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 7 549 461 B2 (KROLICZEK EDWARD J [US] ET AL) 23 June 2009 (2009-06-23) cited in the application figure 1 column 5, line 67 - column 6, line 3 -----	1-14
A	US 6 227 288 B1 (GLUCK DONALD F [US] ET AL) 8 May 2001 (2001-05-08) figures -----	1-14
A	WO 98/06992 A1 (CENTRE NAT ETD SPATIALES [FR]; MACIASZEK THIERRY [FR]; MAUDUYT JACQUES) 19 February 1998 (1998-02-19) figures -----	1-14

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
10 September 2013	24/09/2013

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Fernandez Ambres, A

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/ES2012/070918

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			EP	0855013	A1	29-07-1998
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