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IN REPLY REFER TO

Attorney Docket No. 300178
16 August 2018

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Serial Number 15/628,184
Filing Date 20 June 2017
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HEAT EXCHANGER REACTIVE TO INTERNAL AND EXTERNAL TEMPERATURES

STATEMENT OF GOVERNMENT INTEREST

[0001] The invention described herein may be manufactured and used by or for the Government of the United States of America for governmental purposes without the payment of any royalties thereon or therefor.

CROSS REFERENCE TO OTHER PATENT APPLICATIONS

[0002] None.

BACKGROUND OF THE INVENTION

(1) Field of the Invention

[0003] The present invention relates to a system for harvesting thermal energy from the environment and more particularly to such a system that utilizes a heat engine to convert thermal energy to mechanical energy.

(2) Description of the Prior Art

[0004] Thermal energy harvesting systems extract thermal energy from high temperature areas of the environment in order to drive thermo-mechanical engines that perform work. These energy harvesting systems require a high temperature source, a

low temperature sink, and a heat engine to convert thermal energy to mechanical energy as heat is transferred from the high temperature source to the low temperature sink. The kinetic energy produced by the heat engine drives electro-mechanical devices that generate electricity or perform work. Heat exchanger elements are employed at the high temperature source and the low temperature sink in order to transfer energy into and out of working fluids contained in the heat exchanger elements. The thermal energy in the working fluid drives the heat engine.

[0005] Thermal energy that can be harvested is available in many locations of the environment. Solar energy can be collected in absorber plates or by focusing light energy on a heat exchanger containing a working fluid. Geothermal energy can be collected at thermal vents (on land or in the ocean) by passing a heat exchanger element over or through the thermal vent or by running a heat exchanger deep in the Earth where the ambient temperature is high. Also, ocean thermoclines can be exploited by absorbing energy from warm water at the ocean surface.

[0006] To convert thermal energy to mechanical energy, the energy absorbed from the high temperature source must be used in

a heat engine that converts a portion of the available thermal energy into mechanical work and rejects the balance of the energy to the low temperature sink. Suitable heat sinks include the Earth, a cool body of water, a radiator, and the atmosphere.

[0007] Heat engines take advantage of a temperature difference between a high temperature source and a low temperature sink to perform work in numerous ways. Modern systems include the use of thermo-constrictive materials, piezoelectrics, and shape memory alloys to convert material shape changes that are realized as the materials are cyclically heated and cooled into mechanical work. More traditional systems, such as the Stirling engine (described by James Senft in "An Introduction to Low Temperature Differential Stirling Engines", Moriya Press 1996) use expansion, contraction, condensation, and evaporation of a working fluid to drive a piston or spin a turbine in a mechanical system.

[0008] Using technology that exists in the prior art, energy harvesting systems require separate heat exchangers for the heat absorption portion of the cycle (at the high temperature source) and the heat rejection portion of the cycle (at the low temperature sink). To meet this requirement, the systems need to be configured so that the heat exchanger used for energy

absorption is placed at the high temperature source and the heat exchanger used for waste energy rejection is placed at the low temperature sink. A variety of suitable heat exchanger designs are known in the art for use in a system of this type.

[0009] The use of pipe is one such heat exchanger design known in the art. Pipe is a common element of numerous complex heat exchanger designs. In operation, heat is transferred to or from the environment, through the walls of the pipe and into or out of a working fluid inside of the pipe. Clusters of pipe are commonly placed in banks to form a radiator or are stretched over a comparatively long length where the length of the pipe provides a large surface area for enhanced heat transfer. If fluid in the pipe is hotter than the ambient temperature, heat will be transferred from the working fluid to the environment. Alternately, if the fluid in the pipe is cooler than the ambient temperature, the pipe will absorb energy from the environment.

[0010] A heat exchanger of this type does not preferentially absorb or reject heat from the environment. The resistance to a flow of heat is not direction dependent. Consequently, to extract thermal energy from the high temperature source and to reject waste energy to the low temperature sink; one heat exchanger must be precisely placed at the location of the high

temperature source and another heat exchanger must be precisely placed at the location of the low temperature sink.

[0011] A heat exchanger element that is partially in contact with the high and low temperature areas would not function effectively to either extract or reject energy from the environment. The exchanger element would reject some energy to the low temperature areas and would absorb some energy from the high temperature areas; thereby yielding a low net energy transfer. If a single conventional heat exchanger element were deployed without regard to the location of the high temperature source and the low temperature sink, following a random path through the environment, it would not be possible to determine a-priori if the working fluid would realize a net increase or decrease in thermal energy as a result of heat transfer to the environment.

[0012] The requirement for precise heat exchanger placement does not present a problem when the location and time of existence of the high temperature source and low temperature sink are fixed and known. However, if the location of the high temperature source and low temperature sink move spatially over time or are unknown at the time of deployment, a strategy must be employed to precisely place and move conventional heat

exchangers as conditions vary. There are circumstances where this strategy is not practical and others where the strategy is not possible. In those circumstances, a means to modify the structure of the heat exchanger in response to environmental conditions such that it performs differently in different conditions would be advantageous.

[0013] Bi-metallic structures are well known in the art in which the structures deform when heated or cooled. In this context, a bi-metallic structure is defined as a structure comprised of two sheets of material with different coefficients of thermal expansion bonded at their surface. When heated, the sheet with a larger coefficient of thermal expansion expands more than the sheet with a lower coefficient of thermal expansion. Because the sheets are bonded at a common face, the sheets cannot move relative to one another along the common face as the shapes of the sheets change. As a result, the sheets deform to relieve the thermally induced stress.

[0014] Bi-metallic structures are used in valves, switches, and other mechanical systems in which structural changes are needed in response to changing thermal conditions. In Riordan (United States Patent 3,225,820), a bi-metallic strip is

described that deforms under changing thermal conditions to control the thermal resistance between two parts.

SUMMARY OF THE INVENTION

[0015] It is therefore a general purpose and primary object of the present invention to provide an energy harvesting system that extracts thermal energy from high temperature areas of the environment in order to run a heat engine and rejects waste energy to low temperature areas of the environment.

[0016] It is a further object of the present invention to provide heat exchanger piping passing through the environment that absorbs heat into a working fluid moving through the piping from high temperature regions of the environment without losing heat to low temperature areas of the environment.

[0017] It is a still further object of the present invention to provide heat exchanger piping passing through the environment that rejects heat to low temperature regions of the environment from a working fluid moving through the piping without absorbing heat from high temperature areas of the environment.

[0018] It is a still further object of the present invention to place piping that absorbs energy from the environment and piping that rejects energy to the environment along paths that start and end at a heat engine.

[0019] It is a still further object of the present invention to provide a heat engine to use energy returned from piping that absorbs heat from the environment to perform mechanical work while rejecting waste heat to the fluid returned from piping that transfers heat to the environment.

[0020] To attain the objects described, the present invention combines components suitable for: absorbing heat from high temperature areas of the environment; rejecting heat to low temperature areas of the environment; and converting temperature differences in working fluids to mechanical work.

[0021] The present invention includes a heat exchanger reactive to external and internal temperatures for carrying a working fluid, including a first pipe with a first coefficient of thermal expansion and a cross-section with a first channel portion and a first stress relief portion. The first pipe is provided for containing the working fluid within the inner surface thereof.

[0022] A second pipe is provided with a second coefficient of thermal expansion and a cross section with a second channel portion with the second pipe enclosing the first pipe. The inner surface of the second pipe is in contact with the outer surface of the first pipe as an interference fit.

[0023] A third pipe with a third coefficient of thermal expansion encloses the second pipe with the third pipe having a cross-section with a third channel portion. A fourth pipe and with a fourth coefficient of thermal expansion includes a cross-section with a fourth channel portion and a fourth stress relief portion parallel to an axis of the fourth pipe with the fourth stress-relief portion having a volume and protruding away from the axis of the first pipe. The fourth pipe is positioned coaxially with and encompassing the third pipe such that the inner surface of the fourth pipe is in contact with the outer surface of the third pipe with an interference fit.

[0024] A fluid is positioned in the space defined by the inner surface of the third pipe and the outer surface of the second pipe. The first, second, third and fourth pipes have a first position responsive to internal and external temperatures in which the space defined by the second and third pipes is minimized. The second position is responsive to different

internal and external temperatures in which the space defined between the second and third pipes is maximized by expansion and contraction of the first, second, third and fourth pipes caused by differences in coefficients of thermal expansion.

BRIEF DESCRIPTION OF THE DRAWINGS

[0025] A more complete understanding of the invention and many of the attendant advantages thereto will be readily appreciated as the same becomes better understood by reference to the following detailed description when considered in conjunction with the accompanying drawings wherein:

[0026] **FIG. 1** depicts a diagram of the energy harvesting system of the present invention with heat exchanger elements distributed in an environment having time and space varying high temperature and low temperature areas;

[0027] **FIG. 2** depicts an environment with time and space varying solar heated high temperature areas and low temperature areas in the shade of trees with solar radiation indicated in the figure;

[0028] **FIG. 3** depicts the thermal distribution associated with the environment of **FIG. 2**;

[0029] **FIG. 4** depicts the same environment as **FIG. 2** with high temperature and low temperature areas, with solar radiation indicated in the figure as would be realized at a different time of day than **FIG. 2**;

[0030] **FIG. 5** depicts the thermal distribution associated with the environment of **FIG. 4**;

[0031] **FIG. 6** depicts an undersea vehicle towing a heat exchanger element through an environment with a localized high temperature source;

[0032] **FIG. 7** depicts the path that a heat exchanger element could take through the environment depicted in **FIG. 4**;

[0033] **FIG. 8** depicts the temperature variation that a working fluid in a conventional heat exchanger would experience if the heat exchanger followed the path depicted in **FIG. 7**;

[0034] **FIG. 9** depicts a cross-section of a selective heat absorption and rejection pipe of the present invention;

[0035] **FIG. 10** depicts a temperature distribution through a wall of the selective heat absorption and rejection pipe with a

gap between the inner bi-metallic pipe and the outer bi-metallic pipe;

[0036] **FIG. 11** depicts a cross-section of the selective heat absorption and rejection pipe;

[0037] **FIG. 12** depicts the temperature distribution through the selective heat absorption and rejection pipe with a minimized gap between the inner bi-metallic pipe and the outer bi-metallic pipe;

[0038] **FIG. 13** depicts the temperature variation that a working fluid would experience in the selective heat absorption and rejection pipe designed to absorb heat from the environment if the heat exchanger followed the path depicted in **FIG. 7**;

[0039] **FIG. 14** depicts the temperature variation that a working fluid would experience in the selective heat absorption and rejection pipe designed to reject heat to the environment if the heat exchanger followed the path depicted in **FIG. 7**;

[0040] **FIG. 15** depicts the segmented selective heat absorption and rejection pipe including flexibility enhancing elastomers with a cross section removed to show an internal structure;

[0041] **FIG. 16** depicts an enhanced view of the segmented selective heat absorption and rejection pipe including flexibility enhancing elastomers showing the physical relationship of the inner bi-metallic pipe and the outer bi-metallic pipe when embedded in the elastomer; and

[0042] **FIG. 17** depicts the structure of the heat absorption line manifold, heat absorption line pressure balance accumulator, heat absorption line low thermal conductivity fluid accumulator as well as a connection of the manifold to the heat absorption supply and return lines and the heat absorbing line circuit pump.

DETAILED DESCRIPTION OF THE INVENTION

[0043] Systems and techniques exist for capturing thermal energy from the environment to drive heat engines that perform mechanical work. The present invention is in this general category of device but utilizes a novel set and arrangement of components. These components allow the device to be used where a location of high and low temperature pockets in the environment is unknown or changing.

[0044] **FIG. 1** depicts an energy harvesting system **10** of the present invention. The energy harvesting system **10** includes two major components. The first component is an energy conversion system **20**. The energy conversion system **20** includes a heat engine **22** with an output shaft **24**, a heat rejection circuit pump **26**, a heat rejection line manifold **28**, a heat rejection line pressure balance accumulator **30**, a heat rejection line low thermal conductivity fluid accumulator **32**, a heat absorbing line circuit pump **34**, a heat absorption line manifold **36**, a heat absorption line pressure balance accumulator **38**, and a heat absorption line low thermal conductivity fluid accumulator **40**. While the heat engine **22** is depicted as an alpha-type Stirling engine, the engine could be a variety of different engines including a beta-Stirling engine, Malone engine, or phase changing engine such as a Rankine engine.

[0045] The second major component of the energy harvesting system **10** is a Selective Heat Absorption and Rejection Pipe (SHARP) heat exchanger **60**. The SHARP heat exchanger **60** includes a heat rejection supply line **62**, a heat rejection return line **64**, a heat absorption supply line **66**, and a heat absorption return line **68**. These lines are bundled together to form the SHARP heat exchanger **60**. The SHARP heat exchanger **60** is

designed to follow a path through a low temperature area of the environment and a high temperature area of the environment.

[0046] A representative environment where the location of hot and cold area change is shown in **FIG. 2**. In this environment, the sun **300** non-uniformly heats the earth **302**. Where sunlight **304** strikes the earth **302** directly, the high temperature area **250** of the environment is created. In regions of shade, the sunlight **304** is blocked and the low temperature area **200** of the environment is created.

[0047] The temperature distribution along a path extending from the left side of the environment to the right side of the environment is shown in **FIG. 3**. Interpreting the temperature distribution shown in the figure, it would be possible to place a heat absorber in the high temperature area **250** to collect thermal energy that could be used to run an engine provided that a second heat exchanger is placed in the low temperature area **200** to reject waste heat. However, as the sun **300** moves over the course of the day, the areas of the earth **302** that are heated would change (See **FIG. 4**).

[0048] In the representation of **FIG. 4**, areas that were hot (heated) are now cool and areas that were cool are now hot.

FIG. 5 shows the thermal distribution in the environment associated with **FIG. 4**. If heat exchangers had been placed based on the thermal distribution of **FIG. 2**, the heat exchangers would now be incorrectly placed to capture available thermal energy under the conditions shown in **FIG. 4**.

[0049] In **FIG. 6**, a similar hot/cold environment is depicted where a thermal vent **400** exists on the ocean floor **402** in which the thermal vent **400** creates a hot jet of fluid **404** and an associated high temperature area in the environment. An undersea vehicle **500** is shown that could benefit by absorbing heat from the hot jet of fluid **404** for use in generating on-board power. In this situation, it would be challenging for the undersea vehicle **500** to position and hold a heat exchanger element **502** in the hot jet of fluid **404**, especially if the undersea vehicle was in motion. It would be advantageous if the heat exchanger element **502** could be designed to capture energy from the hot jet of fluid **404**, even if not positioned optimally, without losing energy to low temperature areas of the environment.

[0050] In **FIG. 7**, the energy conversion system **20** and the SHARP heat exchanger **60** are shown as the system and heat exchanger would be deployed in the environment of **FIG. 4**. In

the figure, the SHARP heat exchanger **60** is placed along a path that travels through the low temperature area **200** of the environment and the high temperature area **250** of the environment. Working fluid **100** (See **FIG. 9**) is forced through the heat rejection supply line **62** and the heat absorption supply line **66** starting at point **F** and **A** respectively and subsequently passing through points **G** and **B**, and **H** and **C**. The working fluid **100** returns to the energy conversion system **20** at point **J** and **E** in heat rejection return line **64** and heat absorption return line **68**, respectively, while passing through point **I** and **D**.

[0051] It is useful to first consider the expected heat exchange process if a traditional pipe were used in a SHARP heat exchanger **60** as the heat absorption supply line **66** and the heat absorption return line **68** or the heat rejection supply line **62** and the heat rejection return line **64**. If the heat absorption supply line **66** and the heat absorption return line **68** are considered in such a heat exchanger, when the working fluid **100** leaves the energy conversion system **20**, the working fluid is at a temperature approximately equal to the average temperature of the environment.

[0052] The working fluid **100** in the traditional pipe moves through the section of the heat absorption supply line **66**

between points **A** and **B**, where the working fluid is hotter than the ambient temperature. The working fluid **100** then loses energy to the low temperature area **200** of the environment and the temperature of the working fluid decreases. As the working fluid **100** continues through the heat absorption supply line **66** from point **B** to point **C**, the working fluid absorbs energy from the high temperature area **250** of the environment.

[0053] The fluid path reverses at point **C** and the working fluid **100** returns in the heat absorption return line **68** through the high temperature area **250** of the environment, continuing to absorb energy as the working fluid travels to point **D**. Between points **D** and **E**, absorbed energy is rejected to the low temperature area **200** of the environment.

[0054] **FIG. 8** shows the temperature variation that would be realized in the working fluid **100** as the fluid travels along the path depicted in **FIG. 7** and if the heat exchanger elements **30** were standard or traditional piping.

[0055] The heat exchange behavior described above is altered by employing a Variable Thermal Resistivity Pipe **80**, termed VTRP for convenience, a cross section of which is depicted in **FIG. 9**. The VTRP **80** is comprised of an inner bi-metallic pipe **82**, an

outer bi-metallic pipe **84**, and low thermal conductivity fluid **86**.

[0056] The inner bi-metallic pipe **82** is further comprised of an internal pipe **88** with an integral stress-relieving inward-extending discontinuity **90**. In the preferred embodiment, the inward-extending discontinuity **90** is an integral part of the internal pipe **88**. Alternatively, the inward-extending discontinuity can be formed from an elastomer material. An external semi-circular pipe **92** is press fit around the exterior of the internal pipe **88** such that the external semi-circular pipe is in contact with the internal semi-circular pipe. The pressure of an interference fit and static friction prevent slip between the external semi-circular pipe **92** and the internal pipe **88**. Therefore, compression between the external semi-circular pipe **92** and the internal pipe **88** results in an effective bond between the surfaces. This bond can be improved through the use of adhesives.

[0057] The internal pipe **88** and the external semi-circular pipe **92** are made of dissimilar materials with different coefficients of thermal expansion. Typical metals used in bimetallic structures as metals with high coefficients of thermal expansion are Aluminum and Tin. A typical metal used in

bimetallic structures as a metal with low coefficient of thermal expansion is steel.

[0058] The radius of the inner bi-metallic pipe **82** will change when heated or cooled. The direction and magnitude of radial change in response to temperature variation depends on the specific materials selected, the coefficients of thermal expansion for the selected materials, the wall thickness of the internal and external semi-circular pipes, and the effectiveness of the stress relieving pipe discontinuity to allow radial expansion.

[0059] Similar to the inner bi-metallic pipe **82**, the outer bi-metallic pipe **84** is comprised of a second external pipe **94** with an integral stress-relieving outward-extending discontinuity **96**. In the preferred embodiment, the outward-extending discontinuity **96** is an integral part of the second external pipe **94**. Alternatively, the outward-extending discontinuity can be formed from an elastomer material. A second internal semi-circular pipe **98** is press fit into the interior of the second external pipe **94** such that the second internal semi-circular pipe is in contact with the second external semi-circular pipe. The second external pipe **94** and the second internal semi-circular pipe **98** are made of dissimilar

materials, each material with a different coefficient of thermal expansion.

[0060] The expansion and contraction behavior of the inner bi-metallic pipe **82** is a function of the average temperature of the bi-metallic pipe relative to a design temperature and the internal semi-circular pipe **88** and the external semi-circular pipe **92** design characteristics. The average temperature of the inner bi-metallic pipe **82** is a value between the temperature of the environment and the temperature of the working fluid **100** contained in the inner bi-metallic pipe; but the temperature of the inner bi-metallic pipe is closer to the temperature of the working fluid than to the temperature of the environment.

[0061] If the coefficient of thermal expansion of the internal pipe **88** is less than the coefficient of thermal expansion of the external semi-circular pipe **92** then the radius of the inner bi-metallic pipe **82** will decrease with an increased temperature of the working fluid **100**. Conversely, if the coefficient of thermal expansion of the internal pipe **88** is greater than the coefficient of thermal expansion of the external semi-circular pipe **92** then the radius of the inner bi-metallic pipe **82** will increase with an increased temperature of the working fluid **100**. The inward-extending discontinuity **90**

permits the inner bi-metallic pipe **82** to expand by opening the gap in the semi-circular shape rather than expanding as a result of circumferential growth.

[0062] The expansion and contraction behavior of the outer bi-metallic pipe **84** is a function of its average temperature relative to a design temperature and of the second internal semi-circular pipe **98** and second external pipe **94** design characteristics. The average temperature of the outer bi-metallic pipe **84** is a value between that of the environment and the working fluid **100** but closer to the temperature of the environment than to the temperature of the working fluid. If the coefficient of thermal expansion of the second internal semi-circular pipe **92** is less than the coefficient of thermal expansion of the second external pipe **94**, the radius of the outer bi-metallic pipe **84** will decrease with an increased temperature of the environment.

[0063] Conversely, if the coefficient of thermal expansion of the second internal semi-circular pipe **98** is greater than the coefficient of thermal expansion of the second external pipe **94**, the radius of the outer bi-metallic pipe **84** will increase with an increased temperature of the environment. The outward-extending discontinuity **96** permits the outer bi-metallic pipe **84**

to expand by opening the gap in the semi-circular shape rather than expanding as a result of circumferential growth.

[0064] The space between the inner bi-metallic pipe **82** and the outer bi-metallic pipe **84** is filled with low thermal conductivity fluid **86**. The low thermal conductivity fluid **86** resists heat flow in or out of working fluid **100** proportionally to the volume of a fluid filled gap **102** between the inner bi-metallic pipe **82** and the outer bi-metallic pipe **84**. An insulating effect is greatest when the fluid filled gap **102** between the inner bi-metallic pipe **82** and the outer bi-metallic pipe **84** is increasingly larger.

[0065] The low thermal conductivity fluid **86** is selected based on engineering constraints and operating temperatures. For optimal performance, a liquid or gas with a low thermal conductivity (relative to the pipe materials) should be selected. Common oils have thermal conductivity of approximately twenty percent of the thermal conductivity of water. The thermal conductivity of the common oils is several hundredths of that of metals. Common oils are also viscous; thus common oils offer a further benefit of resisting convective heat transfer through the fluid filled gap **102**. A known common oil is mineral oil.

[0066] In the state depicted in **FIG. 9**, where the inner bi-metallic pipe **82** and the outer bi-metallic pipe **84** are not in complete contact with each other, heat transfer between the working fluid **100** and the environment is impeded by the low conductivity fluid **86** in the fluid filled gap **102**.

[0067] **FIG. 10** depicts the temperature distribution through the pipe walls **82** and **84** and the fluid filled gap **102**. The convective heat transfer coefficient between the working fluid **100** and the inner bi-metallic pipe **82**, the conductive heat transfer coefficient through the inner bi-metallic pipe, the conductive heat transfer coefficient through the outer bi-metallic pipe **84**, and the convective heat transfer coefficient between the environment, and the outer bi-metallic pipe are comparatively high. However, the conductive heat transfer coefficient through the low thermal conductivity fluid **86** in the fluid filled gap **102** is low and hence the net heat transfer (noted as **Q** in **FIG. 10**) through the pipe wall from the environment and into the working fluid **100** is low.

[0068] The variable thermal conductivity feature of the current invention is realized when relative expansion and contraction of the inner bi-metallic pipe **82** and outer bi-metallic pipe **84** changes the thickness of the fluid filled gap

102 between the pipes. When the inner bi-metallic pipe **82** expands and the outer bi-metallic pipe **84** contracts in response to thermal conditions, the low thermal conductivity fluid **86** between the pipes is forced out of the fluid filled gap **102** and into a channel **104** created by the outward-extending discontinuity **96** and the inward-extending discontinuity **90**. The pipes **82** and **84** then come into contact with each other as depicted in **FIG. 11**.

[0069] In the state depicted in **FIG. 11**, where the inner bi-metallic pipe **82** and the outer bi-metallic pipe **84** are in complete contact with each other; heat transfer between the working fluid **100** and the environment is maximized by elimination of the fluid filled gap **102**. **FIG. 12** depicts the temperature distribution through the pipe walls **82** and **84** without the fluid filled gap **102**.

[0070] Referring now to **FIG. 1**, the four lines of the SHARP heat exchanger **60** (the heat rejection supply line **62**, the heat rejection return line **64**, the heat absorption supply line **66**, and the heat absorption return line **68**) are VTRPs. The heat rejection supply line **62** and heat rejection return line **64** are constructed such that the inner bi-metallic pipe **82** expands when heated because the coefficient of thermal expansion of the

internal pipe **88** is greater than the coefficient of thermal expansion of the external semi-circular pipe **92**. Similarly the outer bi-metallic pipe **84** expands when heated because the coefficient of thermal expansion of the second internal semi-circular pipe **98** is greater than the coefficient of thermal expansion of the second external pipe **94**.

[0071] The heat absorption supply line **66** and heat absorption return line **68** are constructed such that the inner bi-metallic pipe **82** contracts when heated because the coefficient of thermal expansion of the internal pipe **88** is less than the coefficient of thermal expansion of the external semi-circular pipe **92**. Similarly, the outer bi-metallic pipe **84** contracts when heated because the coefficient of thermal expansion of the second internal semi-circular pipe **98** is less than the coefficient of thermal expansion of the second external pipe **94**.

[0072] The heat transfer behavior of the heat absorption supply line **66** and the heat absorption return line **68** can be compared to a conventional pipe by considering their behavior when deployed in the environment depicted in **FIG. 7**. In this configuration, a heat absorption supply line **66** is placed along a path that begins at the energy conversion system **20** and first passes through the low temperature area **200** of the environment

and subsequently through the high temperature area **250** of the environment.

[0073] In the path, the working fluid **100** is forced through the heat absorption supply line **66** starting at point **A** and subsequently passing through points **B** and **C** in the supply line, and **D** and **E** in the heat absorption return line **68**. When the working fluid **100** leaves the energy conversion system **20**, the working fluid is at a temperature approximately equal to the average temperature of the environment. As the working fluid **100** moves through the section of heat absorption supply line **66** between points **A** and **B**, where the working fluid is hotter than the ambient temperature, the outer bi-metallic pipe **84** expands in response to a cool ambient temperature.

[0074] As the outer bi-metallic pipe **84** expands, the fluid filled gap **102** between the inner and outer bi-metallic pipes increases and fills with the low thermal conductivity fluid **86**. The net thermal resistivity of the heat absorption supply line **66** increases and heat transfer between the working fluid **100** and the environment is impeded. Although the working fluid **100** loses some energy to the low temperature area of the environment and the temperature of the working fluid drops, the rate of temperature change is low.

[0075] As the working fluid **100** continues through the heat absorption supply line **66** from point **B** to point **C**, the outer bi-metallic pipe **84** shrinks in response to the external temperatures in the high temperature area **250** of the environment. As the outer bi-metallic pipe **84** shrinks, the fluid filled gap **102** between the inner bi-metallic pipe **82** and the outer bi-metallic pipe **84** decreases and forces low thermal conductivity fluid **86** from the space between the pipes such that the pipes come into contact with each other. The net thermal resistivity of the heat absorption supply line **66** decreases and enables heat transfer between the working fluid **100** and high temperature area **250** of the environment. The fluid path reverses at point **C** and the working fluid **100** returns through the high temperature area **250** of the environment in the heat absorption return line **68**. The working fluid **100** continues to absorb energy as at the working fluid travels to point **D**.

[0076] As the temperature of the working fluid **100** increases along the path from points **B** to **D**, the inner bi-metallic pipe **82** decreases in diameter. As the diameter of the inner bi-metallic pipe **82** decreases, the required external temperature needed to cause the outer bi-metallic pipe **84** to contract and maintain contact with the inner bi-metallic pipe increases. This

external temperature requirement serves as a regulating mechanism to prevent heat loss from the working fluid **100** when external temperatures are not sufficiently high.

[0077] Between points **D** and **E**, where the working fluid **100** is hotter than the ambient temperature, the outer bi-metallic pipe **84** expands in response to the cool ambient temperature. The fluid filled gap **102** size increases and prevents heat loss from the working fluid **100**.

[0078] The net effect of the thermal resistance variation along the length of the pipe is such that the working fluid **100** returns to the energy conversion system (point **E**) hotter than when the working fluid left (point **A**).

[0079] The heat transfer characteristics of the heat rejection supply line **62** and the heat rejection return line **64** can be compared to a conventional pipe by considering the operating characteristics of the supply and return line when deployed in the environment depicted in **FIG. 7**. In this configuration, the heat rejection supply line **62** is placed along a path that begins at the energy conversion system **20** and first passes through the low temperature area **200** of the environment

and subsequently through the high temperature area **250** of the environment.

[0080] The working fluid **100** is forced through the heat rejection supply line **62** starting at point **F** and subsequently passing through points **G** and **H** in the supply line, and **I** and **J** in the heat rejection return line **64**. When the working fluid **100** leaves the energy conversion system **20**, the working fluid is at a temperature approximately equal to the average temperature of the environment.

[0081] As the working fluid **100** moves through the section of heat rejection supply line **62** between points **F** and **G**, where the working fluid is hotter than the ambient temperature, the outer bi-metallic pipe **84** shrinks in response to the cool ambient temperature. As the outer bi-metallic pipe **84** shrinks, the fluid filled gap **102** between the inner bi-metallic pipe **82** and the outer bi-metallic pipe **84** decreases and forces low thermal conductivity fluid **86** from the gap and into the channels **104**. The net thermal resistivity of the heat rejection supply line **62** decreases when the inner bi-metallic pipe **82** and the outer bi-metallic pipe **84** come in contact with one another and heat transfer is enabled between the working fluid **100** and the low temperature area **200** of the environment.

[0082] As the working fluid **100** continues through the heat rejection supply line **62** from point **G** to point **H**, the outer bi-metallic pipe **84** expands in response to the high external temperatures of the environment. As the outer bi-metallic pipe **84** expands, the fluid filled gap **102** between the inner bi-metallic pipe **82** and the outer bi-metallic pipe increases and fills with low thermal conductivity fluid **86** drawn in from the channels **104**. The net thermal resistivity of the heat rejection supply line **62** increases and impedes heat transfer between the working fluid **100** and the high temperature area **250** of the environment. The fluid path reverses at point **H** and the working fluid **100** returns through the high temperature area **250** of the environment in the heat rejection return line **64**; thereby continuing to absorb energy as the working fluid travels to point **I**. However, the energy absorption is at a reduced rate.

[0083] As the temperature of the working fluid **100** decreases along the path from points **G** to **I**, the inner bi-metallic pipe **82** decreases in diameter. As the diameter of the inner bi-metallic pipe **82** decreases, the required external temperature needed to cause the outer bi-metallic pipe **84** to contract and maintain contact is reduced. This external temperature requirement serves as a regulating mechanism to prevent heat absorption into

the working fluid **100** when external temperatures are not sufficiently low.

[0084] Between points **I** and **J**, where the working fluid **100** is hotter than the ambient temperature, the outer bi-metallic pipe **84** contracts in response to the cool ambient temperature. The size of the fluid filled gap **102** decreases until contact is made between the inner bi-metallic pipe **82** and the outer bi-metallic pipe **84**, thereby reducing the resistance to heat flow from the working fluid **100** to the environment and enabling heat loss from the working fluid.

[0085] The net effect of the thermal resistance variation along the length of the pipe is such that the working fluid **100** returns to the energy conversion system **20** (point **J**) cooler than when the working fluid left the conversion system (point **F**).

[0086] The bi-metallic pipes of the SHARP heat exchanger **60** can be constructed as continuous rigid pipes if flexibility is not a concern. Alternately, the pipes can be constructed as a flexible structure as shown in **FIG. 15** and **FIG. 16**. **FIG. 15** shows a VTRP **80** with segmented bi-metallic pipes with a cross section removed to show the internal structure. To form a flexible pipe structure, the inner bi-metallic pipe **82** and the

outer bi-metallic pipe **84** are segmented and embedded in an elastomer **112** with a high thermal conductivity.

[0087] **FIG. 16** depicts a close-up view of a cross section of the VTRP **110** with segmented construction and with the inclusion of the elastomer **112**. Although elastomers typically have low thermal conductivity as compared to metals, the insulating effect of the elastomers is minimized by keeping a surface layer **114** of elastomer to a minimum on the inside and outside of the bi-metallic pipes.

[0088] The inclusion of the inward-extending discontinuity **90** and the outward-extending discontinuity **96** in the bi-metallic pipe walls is necessary to allow the pipe to deform under changing thermal conditions. The inclusion of the inward-extending discontinuity **90** and the outward-extending discontinuity **96** also allows the pipe radius to respond to variations in internal and external pressure.

[0089] Referring now to **FIG. 17**, ambient pressure effects are further mitigated by operating the working fluid **100** at an average pressure equal to the ambient pressure. To achieve this pressure balancing, the heat absorption line pressure balance accumulator **38** (vented to the ambient pressure) is attached to

the heat absorption return line **68** at the heat rejection line manifold **36** for the working fluid **100** in the heat absorption supply line **66** and heat absorption return line **68** as shown in **FIG. 17**. The heat absorption line pressure balance accumulator **38** includes a pressure line chamber **120**, a vent chamber **122**, an elastomeric boundary **124**, and a vent port **126**.

[0090] The elastomeric boundary **124** deflects in response to pressure differences between the working fluid **100** in the heat absorption supply line **66** and the heat absorption return line **68** as well as responding to the pressures in the environment (ambient). Fluid from the environment is drawn in or forced out through the vent port **126** to compensate for motion of the elastomeric boundary **124**. Because the elastomeric boundary **124** cannot support a pressure difference, the pressure in the pressure line chamber **120** and vent chamber **122** are equal.

[0091] An accumulator of equivalent design and function to the heat absorption line pressure balance accumulator **38** is included for pressure balance between the low thermal conductivity fluid **86** and pressures in the environment (ambient). This heat absorption line low thermal conductivity fluid accumulator **40** is shown in the figure. The heat absorption line low thermal conductivity fluid accumulator **40**

also serves as a reservoir for the low thermal conductivity fluid **86** expelled from or drawn into channels **104** as pipe diameters change in response to operating conditions.

[0092] The heat absorption line pressure balance accumulator **38** and the heat absorption line low thermal conductivity fluid accumulator **40** are connected to the inner bi-metallic pipe **82** and the outer bi-metallic pipe **84** of the heat absorption supply line **66** as well as the heat absorption line circuit pump **34** through the heat rejection line manifold **36**.

[0093] The heat rejection line pressure balance accumulator **30**, the heat rejection line low thermal conductivity fluid accumulator **32**, and the heat rejection line manifold **28**, have equivalent designs and function to the heat absorption line pressure balance accumulator **38**, the heat absorption line low thermal conductivity fluid accumulator **40**, and the heat absorption line manifold **36**, respectively.

[0094] The energy conversion system **20** can be designed in numerous variations. In the preferred embodiment, the energy conversion system includes a heat engine **22** to convert the recoverable heat energy delivered by the heat absorption return line **68** into mechanical work. The design and operation of a

heat engine **22** to convert thermal energy to mechanical work is well known in the art.

[0095] In operation, the heat absorption line circuit pump **34** forces the working fluid **100** through the absorption line manifold **36** and into the heat absorption supply line **66**. As the working fluid **100** travels through the heat absorption supply line **66** and the heat absorption return line **68** (as part of the SHARP heat exchanger **60**) through the low temperature areas **200** of the environment and the high temperature areas **250** of the environment, the working fluid absorbs thermal energy. The working fluid **100** returns to the Stirling engine **22**, at a higher temperature than the working fluid left. Inside of the Heat engine **22**, heat from the working fluid **100** is absorbed and converted to kinetic energy in the form of rotation of the output shaft **24**. The mechanism for conversion of thermal energy to mechanical work in a Heat engine **22** is well known in the art. A by-product of the energy conversion is waste heat that must be transferred back to the environment.

[0096] The heat rejection circuit pump **26** forces working fluid **100** through the heat rejection line manifold **28** and into the heat rejection supply line **62**. As the working fluid **100** travels through the heat rejection supply line **62** and the heat

rejection return line (as part of the SHARP heat exchanger **60**) through the low temperature areas of the environment and high temperature areas of the environment, the working fluid rejects thermal energy with the working fluid returning to the Heat engine **22**, at a lower temperature than when the working fluid left. Inside of the Heat engine **22**, waste heat from the energy conversion process is transferred to the working fluid **100**.

[0097] Many modifications and variations of the present invention may become apparent in light of the above teachings. A number of alternative devices could be constructed using the same general methods discussed herein to construct devices that would be optimized for a particular purpose. For example: depending on the temperatures of the working fluid **100** the Heat engine **22** can be replaced with an engine based on Ericson or Brayton or Rankine thermodynamic cycles; the outer bi-metallic pipe **84** of the VTRP **80** can be replaced with a solid pipe to improve durability and reduce production cost at the expense of performance; and a gas can be used as the low thermal conductivity fluid **86** in the place of a liquid low thermal conductivity fluid.

[0098] In light of the above, it is therefore understood that within the scope of the appended claims, the invention may be practiced otherwise than as specifically described.

HEAT EXCHANGER REACTIVE TO INTERNAL AND EXTERNAL TEMPERATURES

ABSTRACT OF THE DISCLOSURE

The present invention includes a heat exchanger reactive to external and internal temperatures for carrying a working fluid, including two pairs of nested pipes; each pair including one pipe with a channel portion and a stress relief portion and a second pipe with just a channel portion, one of said pipes enclosing the other with an interference fit and both pipes having different coefficients of thermal expansion. The first pair of pipes positioned co-axially with and encompassing the second pair. A fluid is positioned in the space defined by the inner surface of outer pair of pipes and the outer surface of inner pair of pipes. The two pipe pairs have positions responsive to the internal and external temperatures in which the space defined by pipe pairs is either minimized or maximized by expansion and contraction of the pipe pairs caused by differences in coefficients of thermal expansion.

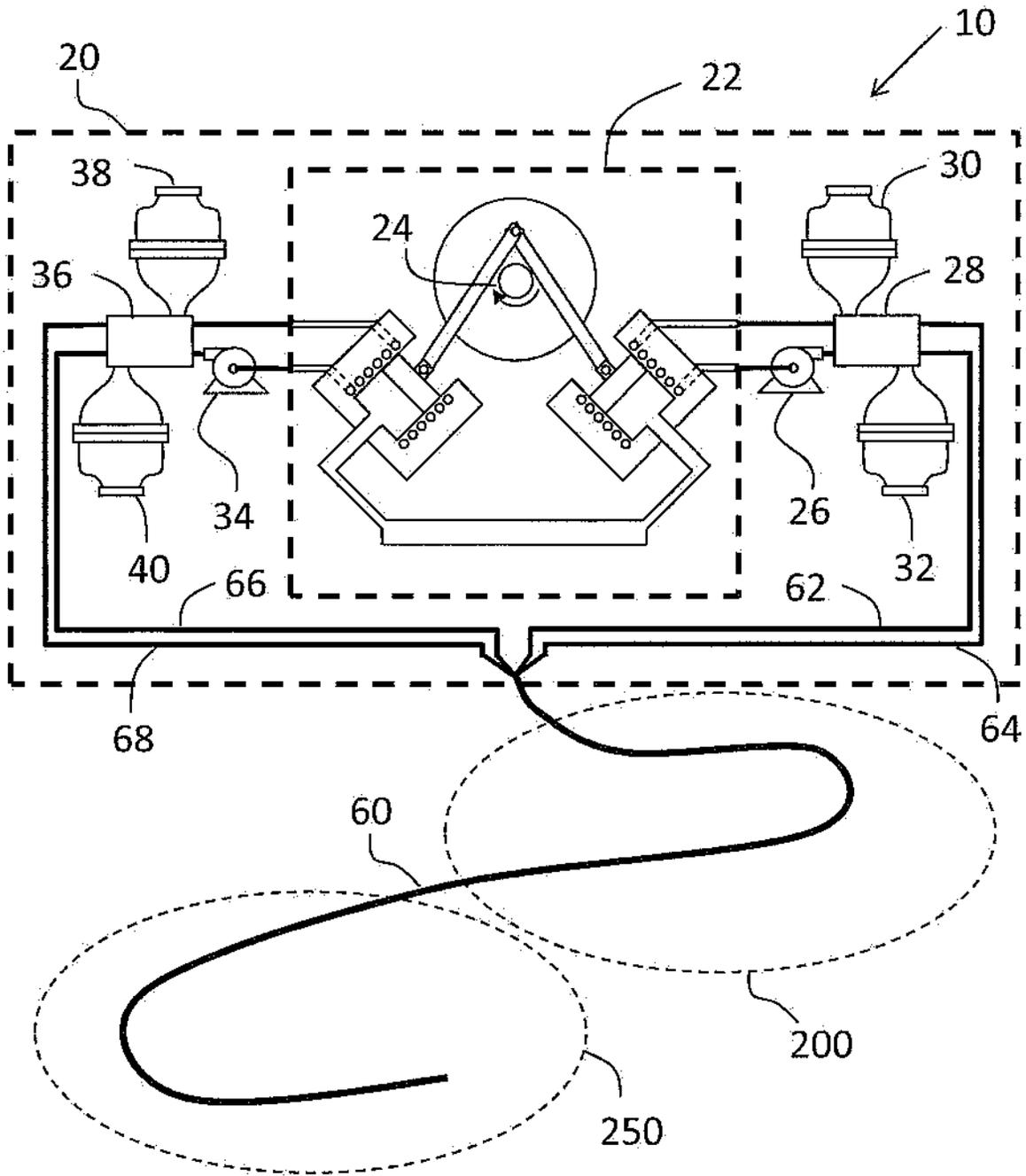


FIG. 1

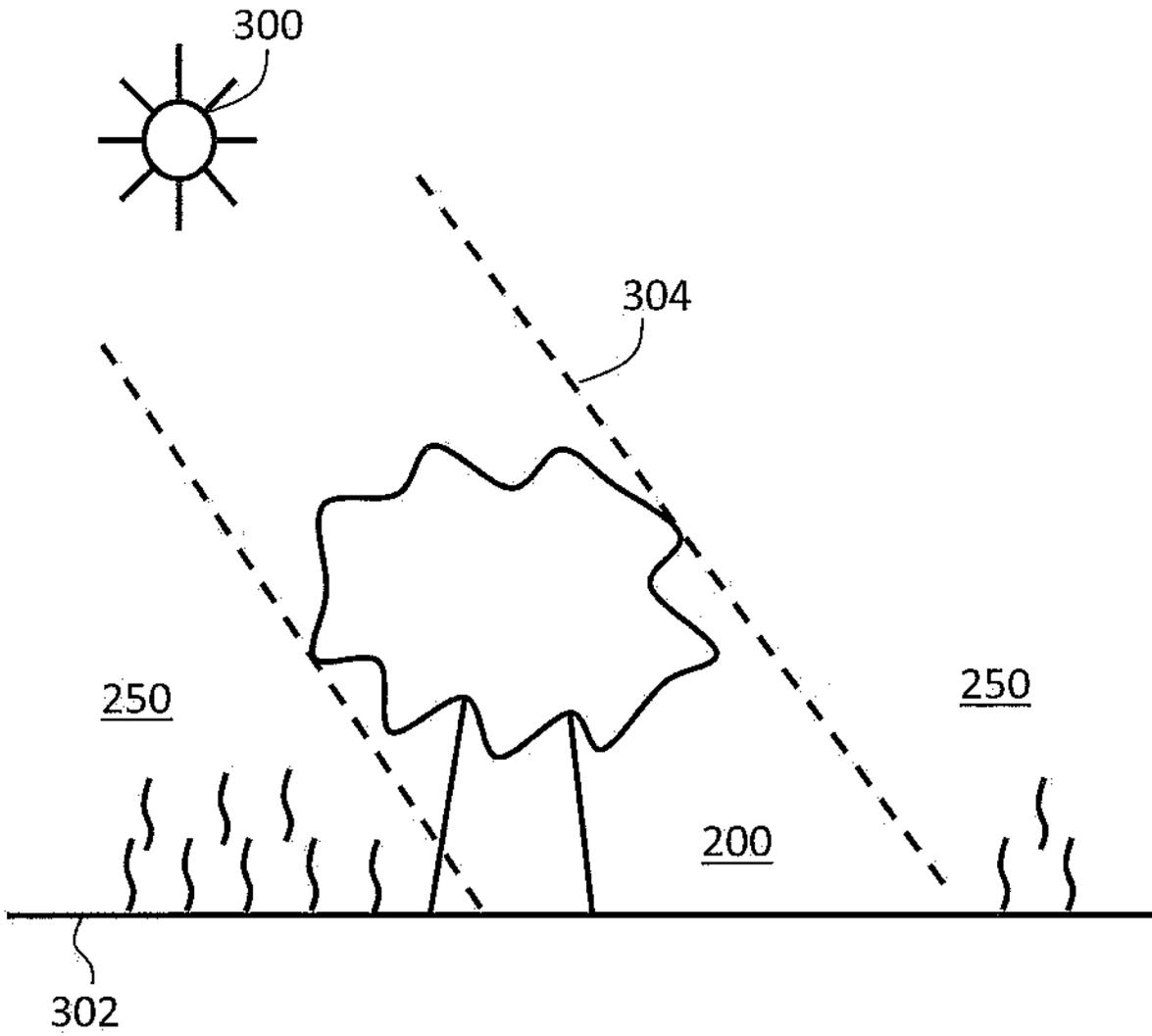


FIG. 2

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FIG. 3

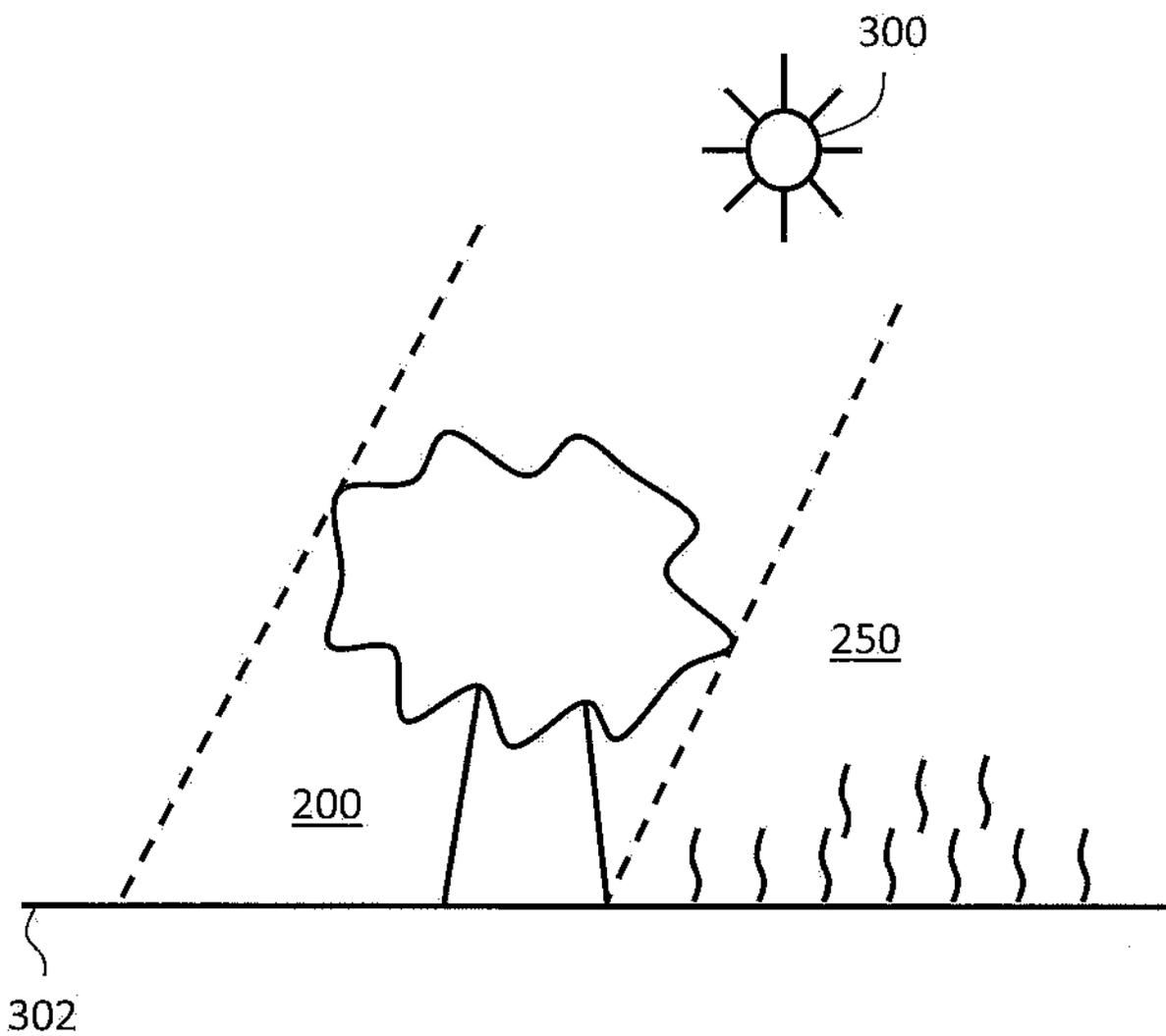


FIG. 4

5 / 17



FIG. 5

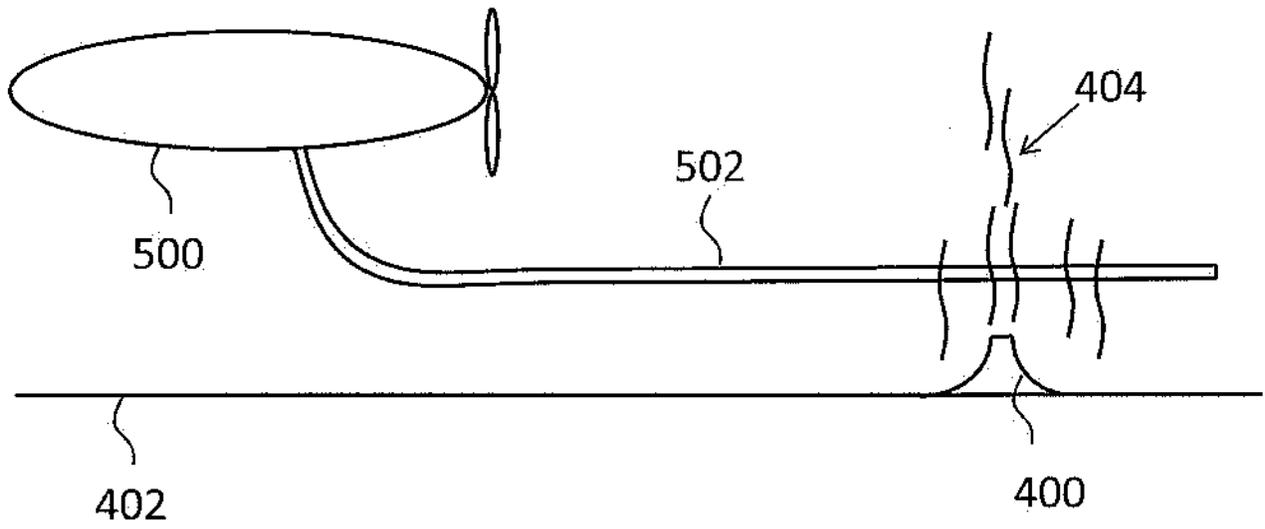


FIG. 6

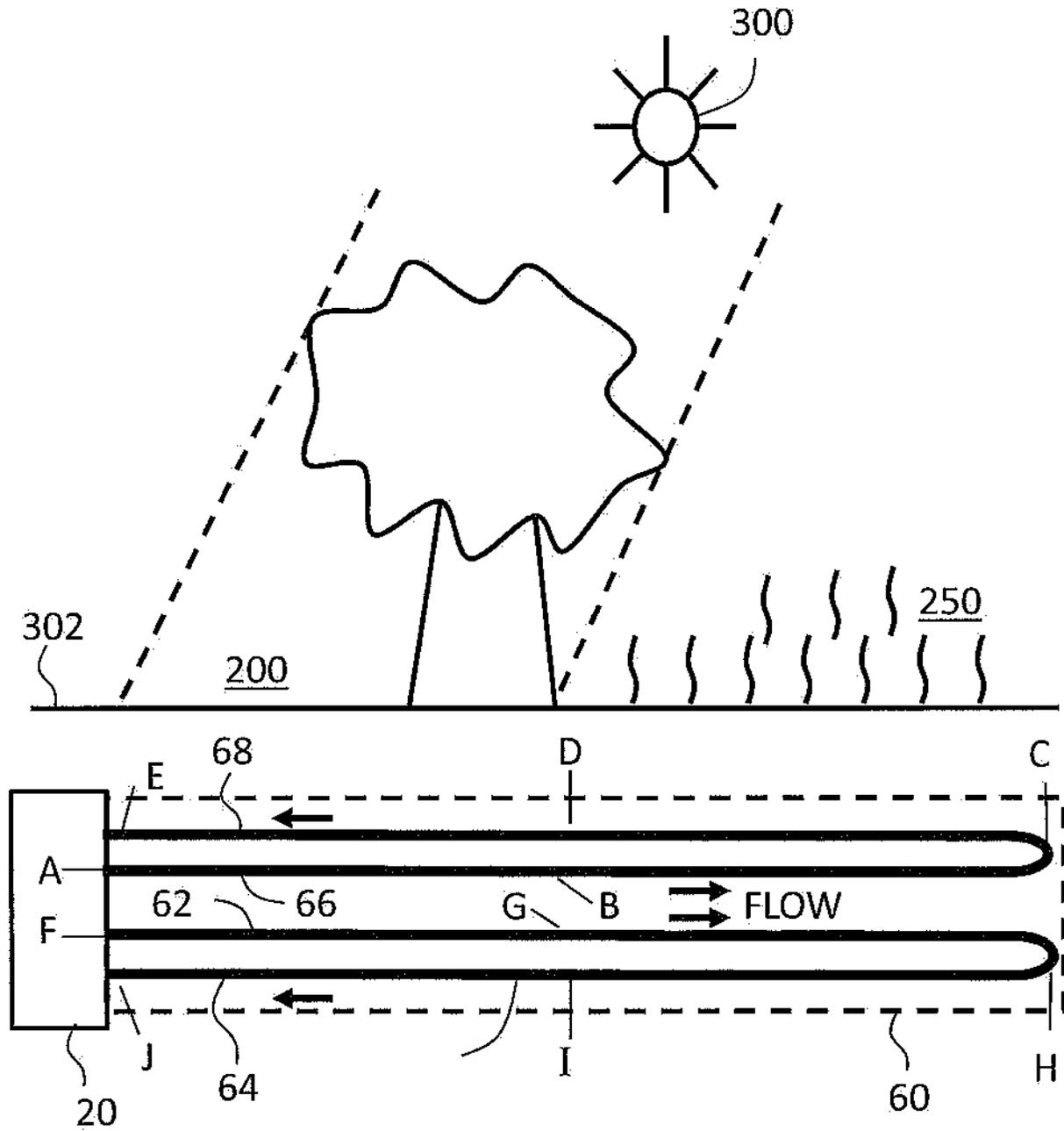


FIG. 7

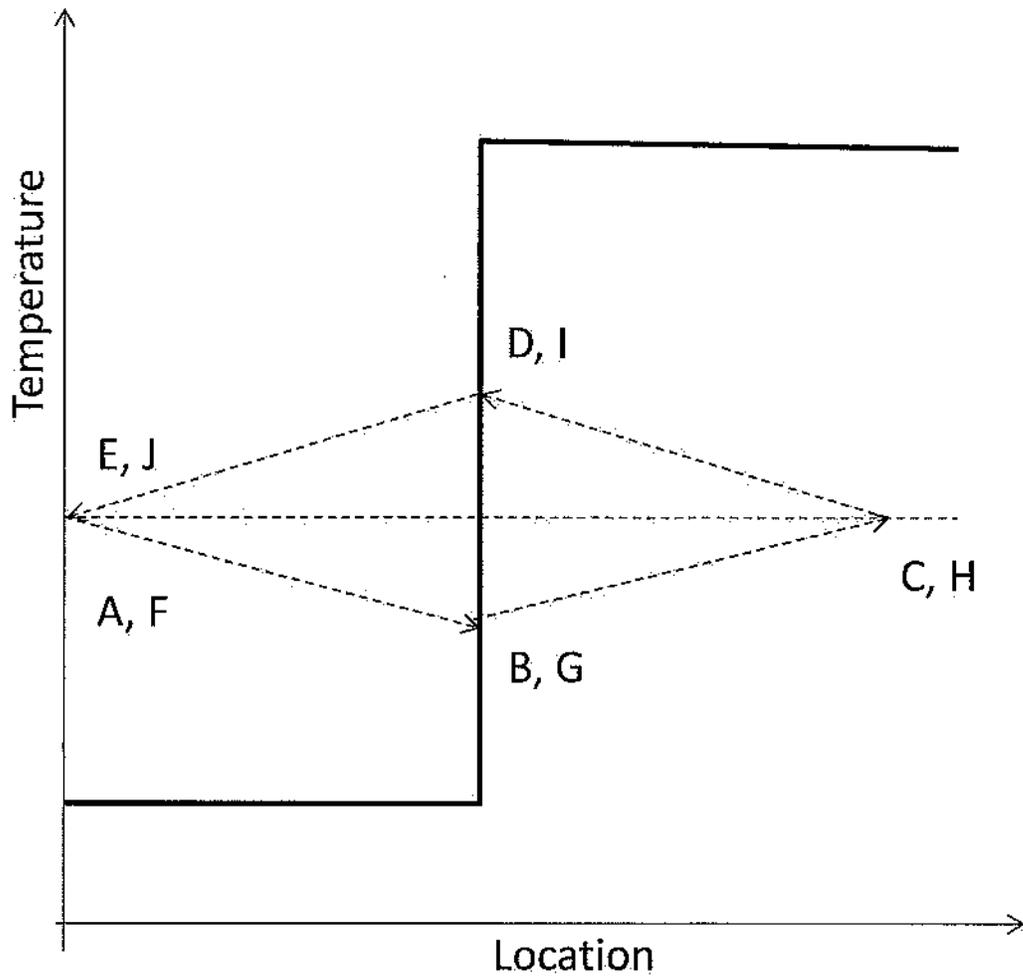


FIG. 8

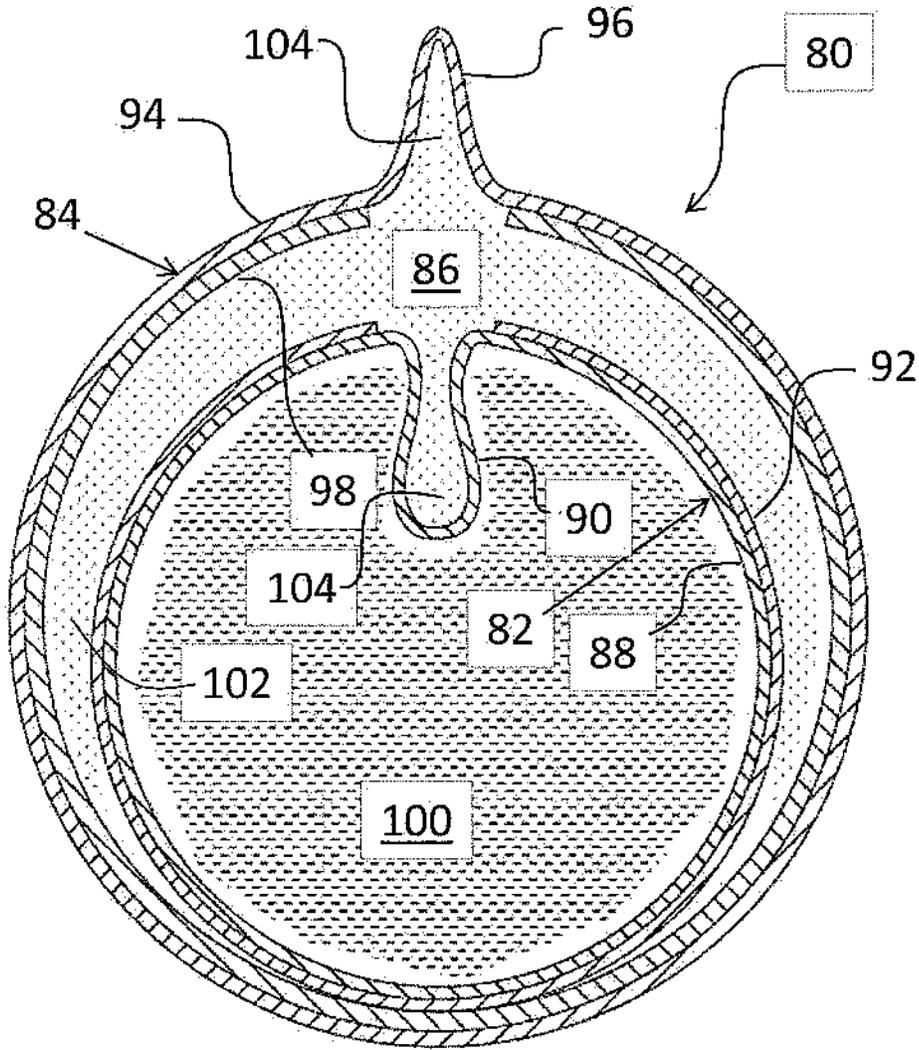


FIG. 9

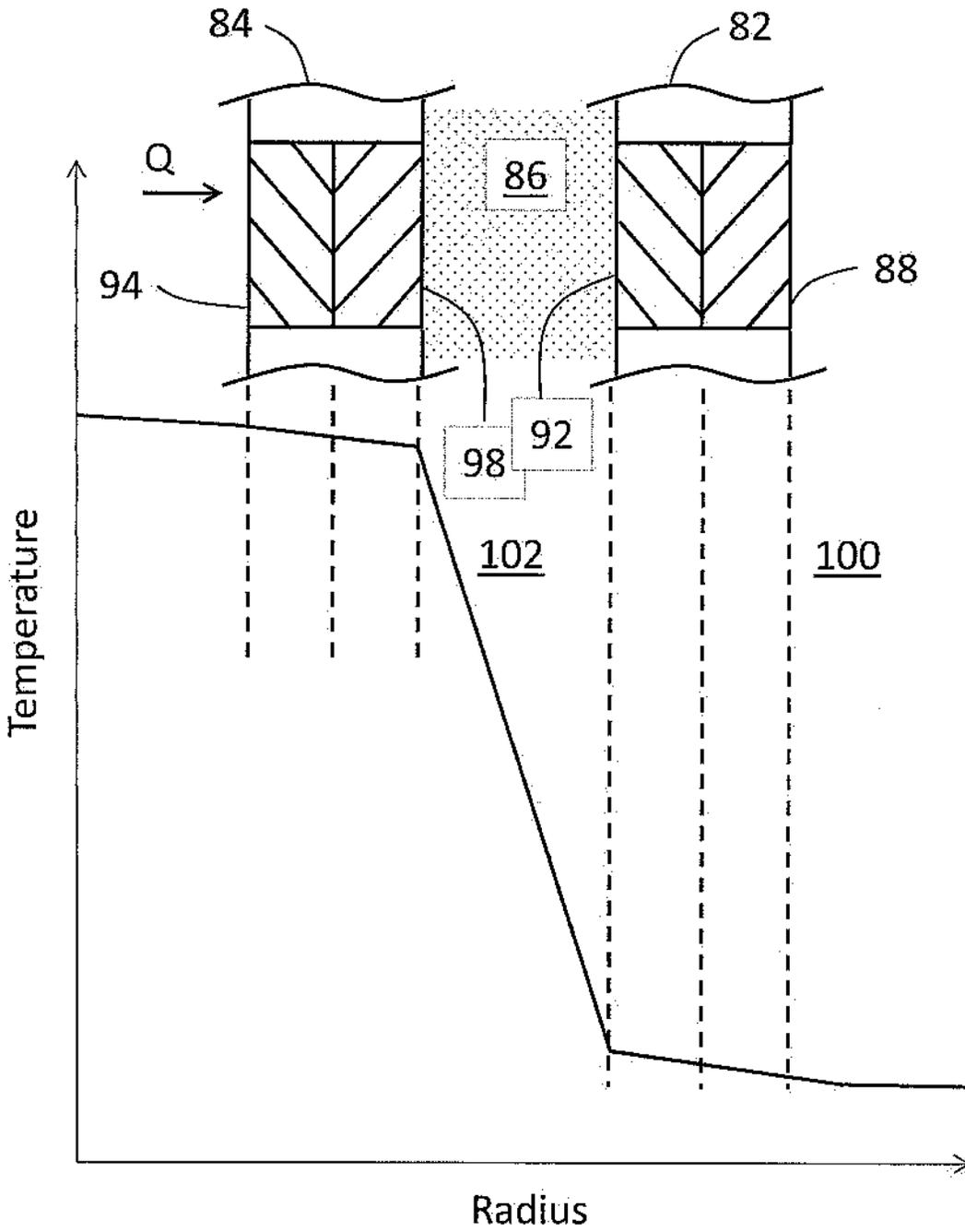


FIG. 10

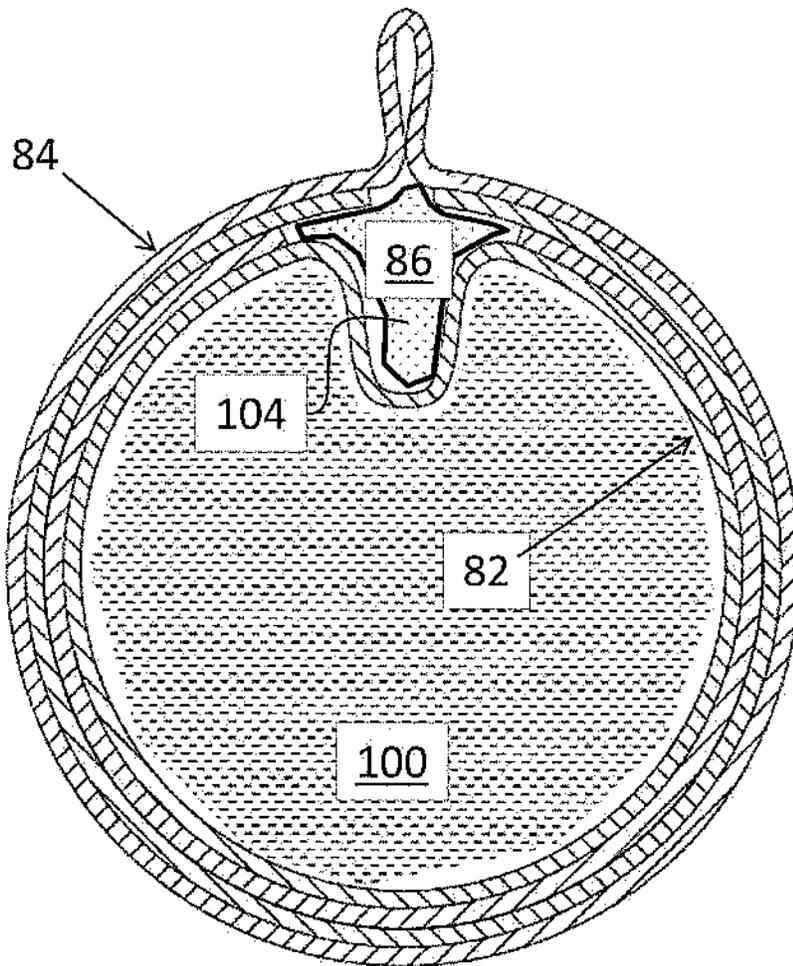


FIG. 11

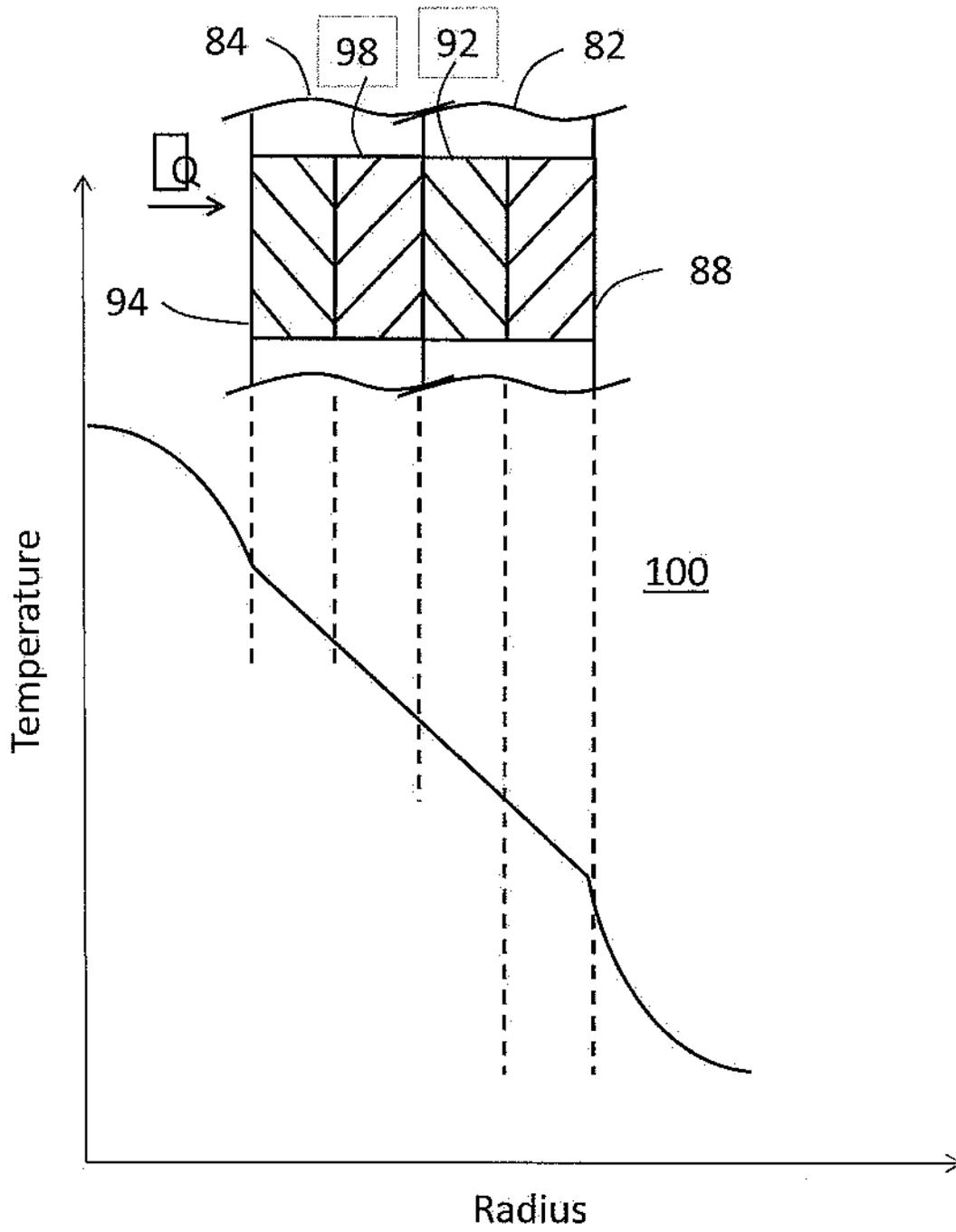


FIG. 12

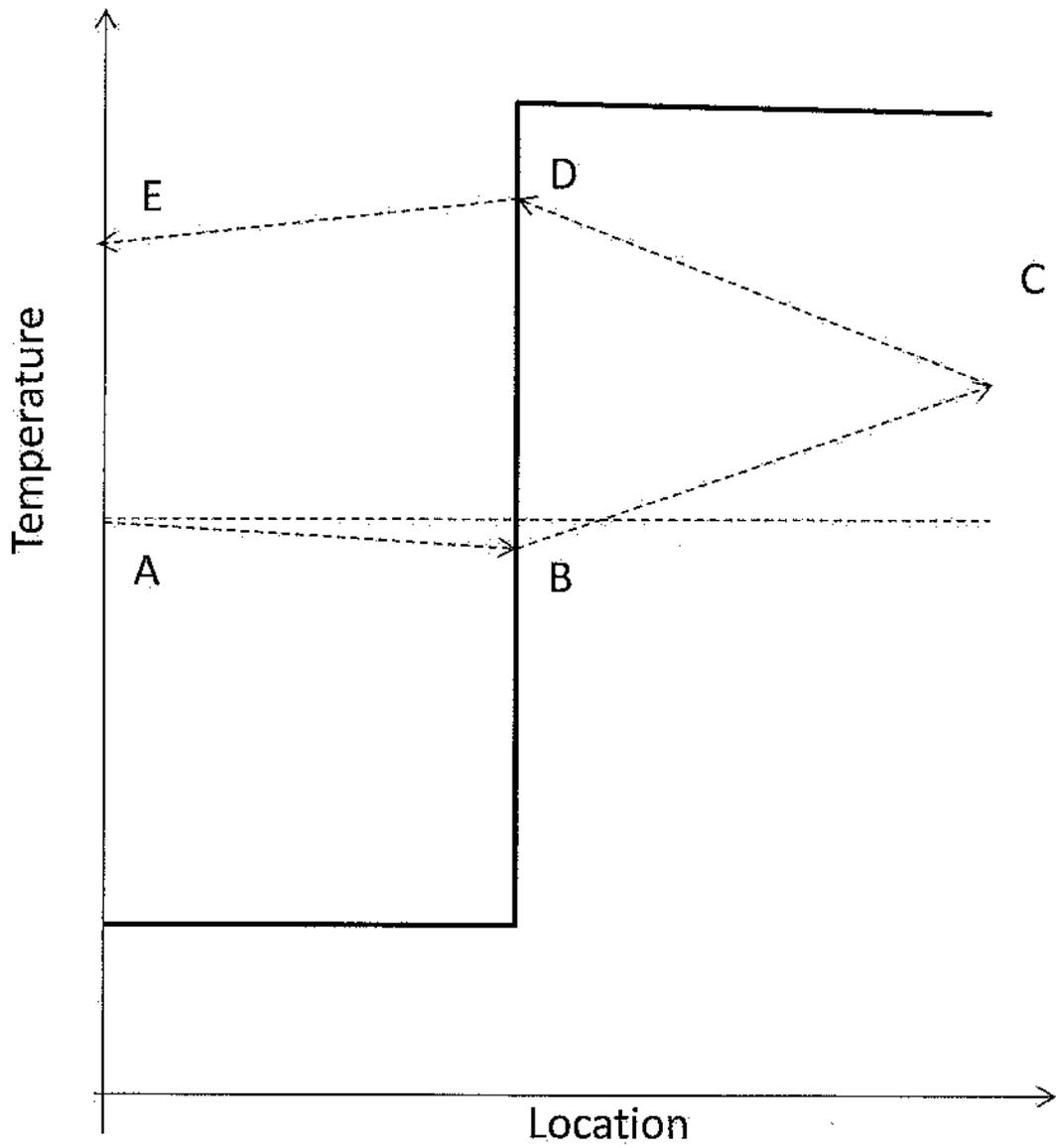


FIG. 13

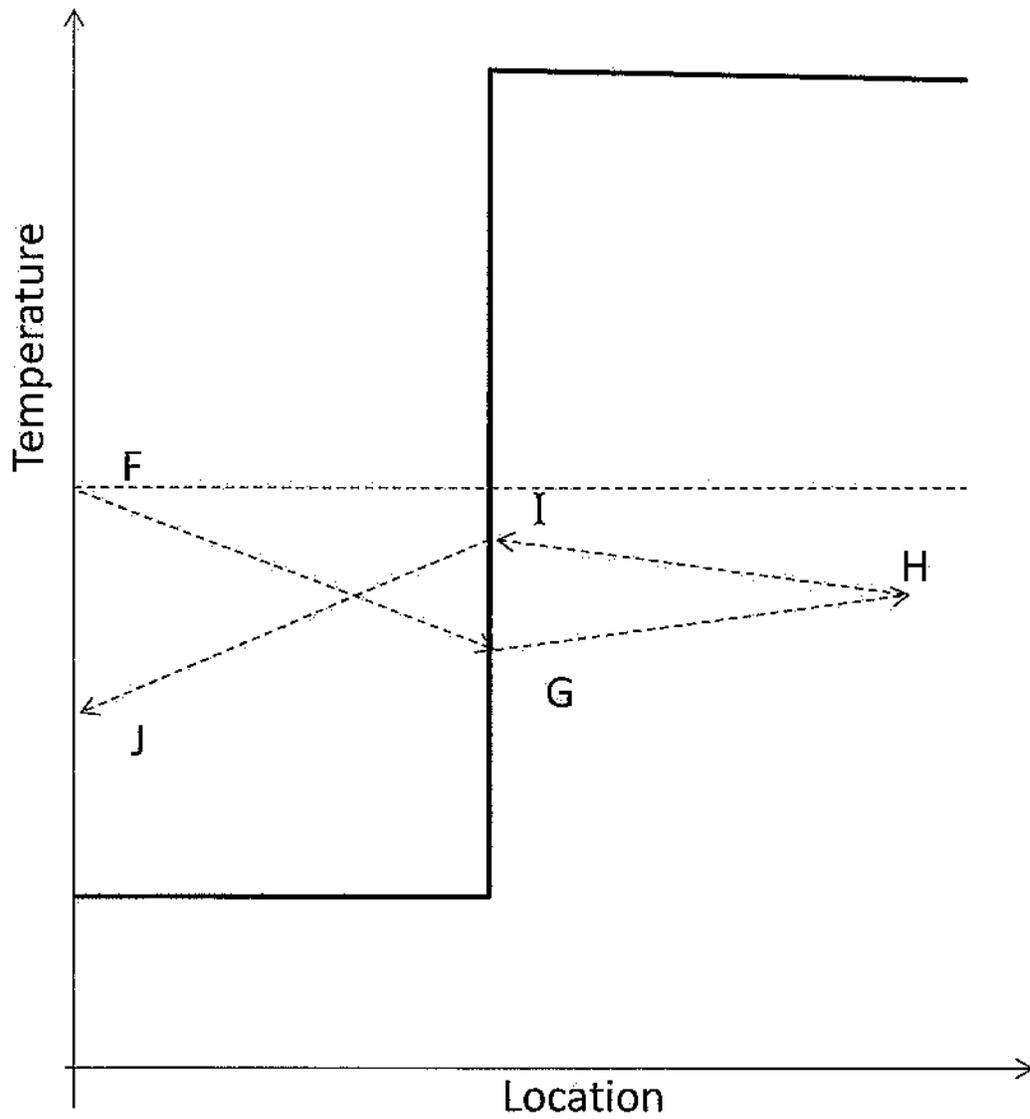


FIG. 14

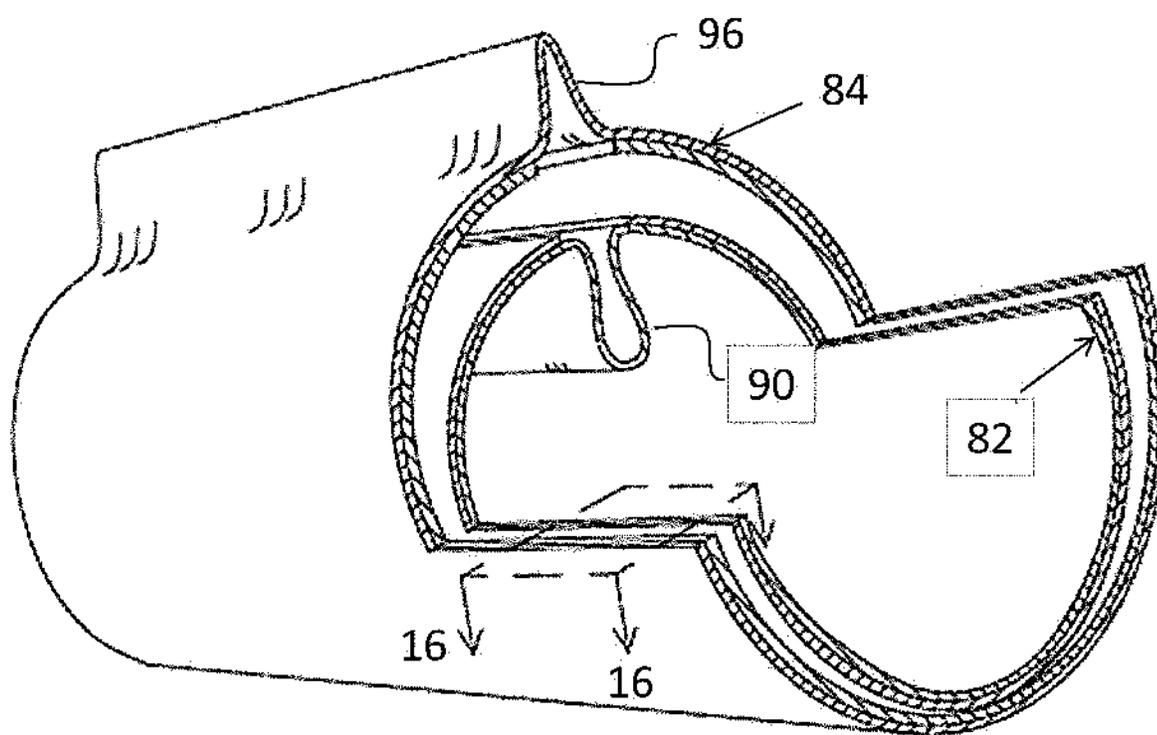


FIG. 15

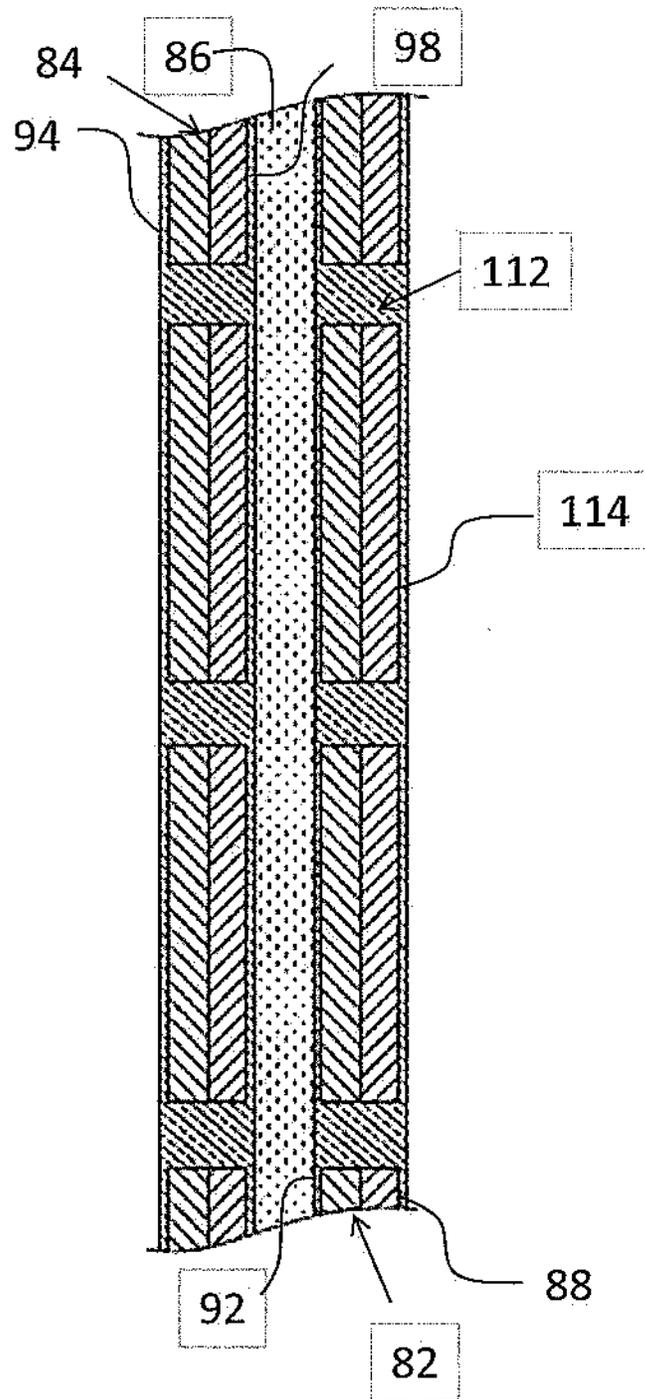


FIG. 16

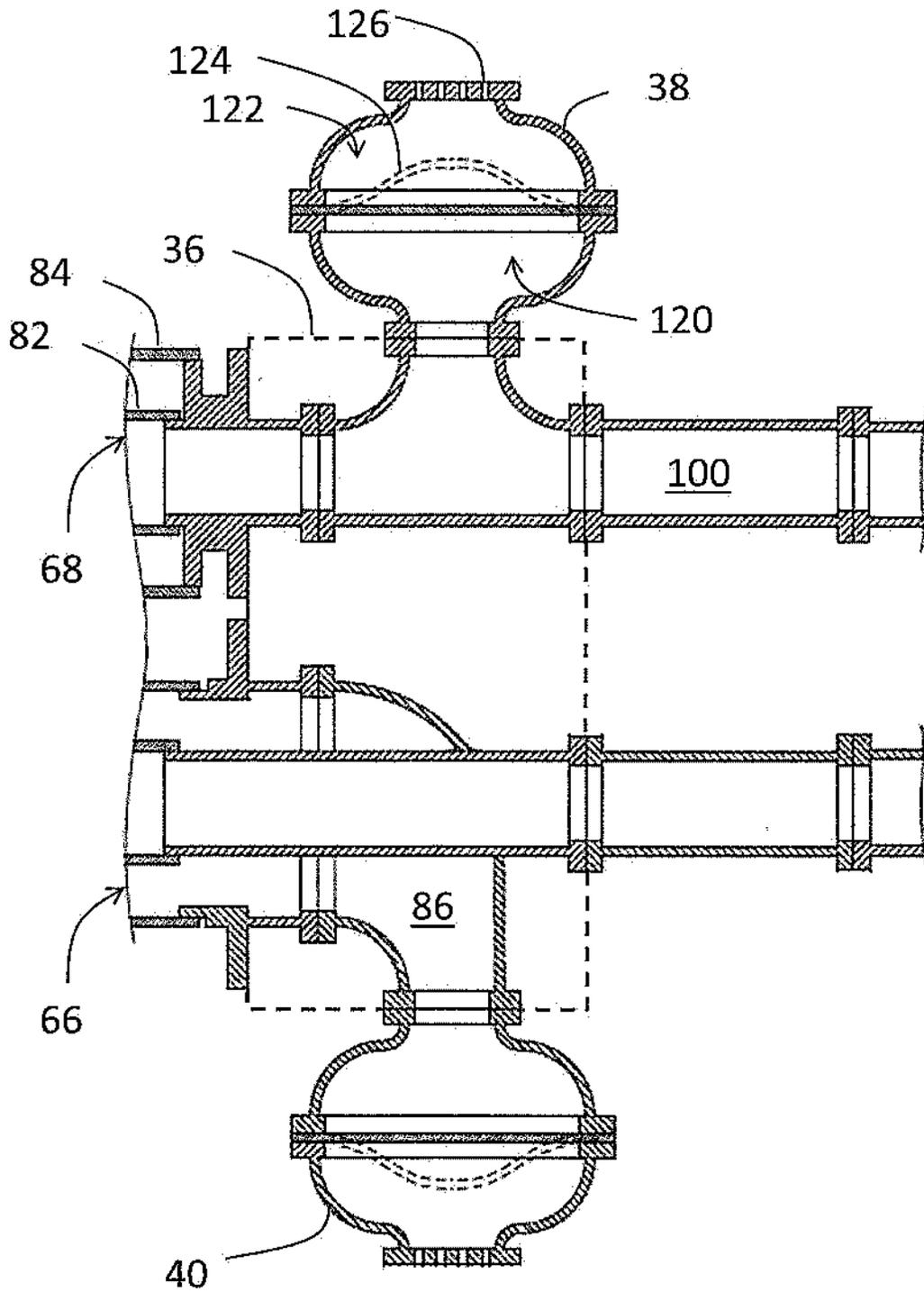


FIG. 17