A thermoelectric assembly and a method of operating a thermoelectric assembly are provided. The thermoelectric assembly includes at least one thermoelectric subassembly configured to be in thermal communication with a heat source and configured to be in thermal communication with a heat sink. The at least one thermoelectric subassembly includes at least one thermoelectric element including a hot side at a first temperature and a cold side at a second temperature lower than the first temperature. The thermoelectric assembly further includes a controller in operative communication with the at least one thermoelectric subassembly. The controller is configured to adjust the first temperature by adjusting an electrical current of the at least one thermoelectric subassembly.
Adjust a first temperature by adjusting an electrical current of at least one TE subassembly.
SYSTEM AND METHOD FOR PREVENTING OVERHEATING OR EXCESSIVE BACKPRESSURE IN THERMOELECTRIC SYSTEMS

RELATED APPLICATIONS

[0001] This application claims the benefit of priority to U.S. Provisional Appl. No. 61/746,960, filed on Dec. 28, 2012 and incorporated in its entirety by reference herein.

BACKGROUND

[0002] 1. Field
[0003] The present application relates generally to thermoelectric cooling, heating, and power generation systems, in particular, systems and methods for preventing overheating, excessive backpressure, or both.

[0004] 2. Description of the Related Art
[0005] Thermoelectric (TE) devices and systems can be operated in either heating/cooling or power generation modes. In TE heating/cooling devices and systems, electric current is passed through a TE device to pump the heat from the cold side to the hot side. In thermoelectric generators (TEGs), heat flux (e.g., thermal energy, temperature difference, temperature gradient) is converted into electricity. In some applications, the heat (e.g., thermal energy, flux, etc.) is a by-product of an energy intensive process, such as internal combustion (e.g., within an engine) or industrial manufacturing of metals. A portion of the heat flowing through the TEG is converted into electricity, while the rest (unconverted heat) exits the TEG and is removed. Heat removal is typically performed by a heat transfer medium (e.g., fluid) such as air or a liquid that carries or moves it away from the TEG. Typically, the heat transfer medium is actively circulated by fans, pumps or other devices.

[0006] TE modules have been manufactured for specific niche heating and cooling applications and power generation applications. These modules include TE materials connected together with electrodes and sandwiched between two substrates. These modules have been used as building blocks for thermoelectric devices and systems. They have often been connected to heat exchangers, sandwiched between hot and cold (or waste and main) sides.

SUMMARY

[0007] In certain embodiments, a thermoelectric assembly is provided. The thermoelectric assembly comprises at least one thermoelectric subassembly configured to be in thermal communication with a heat source and configured to be in thermal communication with a heat sink. The at least one thermoelectric subassembly comprises at least one thermoelectric element comprising a hot side at a first temperature and a cold side at a second temperature lower than the first temperature. The method comprises adjusting the first temperature by adjusting an electrical current of the at least one thermoelectric subassembly.

[0008] In certain embodiments, a method of operating a thermoelectric assembly is provided. The thermoelectric assembly comprises at least one thermoelectric subassembly in thermal communication with a heat source and in thermal communication with a heat sink. The at least one thermoelectric subassembly comprises at least one thermoelectric element comprising a hot side at a first temperature and a cold side at a second temperature lower than the first temperature. The method comprises adjusting the first temperature by adjusting an electrical current of the at least one thermoelectric subassembly.
deflectors, and a gap defined by the flow deflectors and having a selectively variable size, in accordance with certain embodiments described herein.

[0017] FIG. 7 schematically illustrates an operation map in accordance with certain embodiments described herein in which the inlet temperature is the vertical axis and the mass flow rate is the horizontal axis.

[0018] FIG. 8 schematically illustrates a sleeve (as might be installed in TEG assembly in FIG. 4A), flow deflectors, external spring, and gap, in accordance with certain embodiments described herein.

[0019] FIG. 9A schematically illustrates an example spring with a "C" shape in accordance with certain embodiments described herein.

[0020] FIG. 9B schematically illustrates an example motion of a "C"-shaped bimetal spring when exposed to external forces in accordance with certain embodiments described herein.

[0021] FIG. 10 schematically illustrates an example portion of a TEG assembly comprising a plurality of selectively movable fins in accordance with certain embodiments described herein.

[0022] FIG. 11 schematically illustrates an example TE assembly in accordance with certain embodiments described herein.

[0023] FIG. 12 schematically illustrates an example output of the TE assembly of FIG. 11.

[0024] FIG. 13 schematically illustrates an example portion of a power generator system in accordance with certain embodiments described herein.

[0025] FIG. 14 schematically illustrates various thermal resistances in the thermal path of a thermoelectric assembly in accordance with certain embodiments described herein.

[0026] FIG. 15 is a flow diagram of an example method of operating a TE assembly in accordance with certain embodiments described herein.

[0027] FIG. 16 schematically illustrates an example TEG with a valved pre-heat exchanger coil in accordance with certain embodiments described herein.

[0028] FIG. 17 schematically illustrates an example portion of a TEG with a phase-change material in accordance with certain embodiments described herein.

[0029] FIG. 18 schematically illustrates a portion of a TEG with an evacuated barrier in accordance with certain embodiments described herein.

[0030] FIG. 19 schematically illustrates an example portion of a TEG configured to allow expansion to create a thermal short in accordance with certain embodiments described herein.

[0031] FIG. 20 schematically illustrates an example portion of a TEG configured to allow expansion to create a thermal open in accordance with certain embodiments described herein.

[0032] FIG. 21 schematically illustrates an example portion of a TEG configured to allow expansion to create a thermal open in accordance with certain embodiments described herein.

DETAILED DESCRIPTION

[0033] Although certain configurations and examples are disclosed herein, the subject matter extends beyond the examples in the specifically disclosed configurations to other alternative configurations and/or uses, and to modifications and equivalents thereof. Thus, the scope of the claims appended hereto is not limited by any of the particular configurations described below. For example, in any method or process disclosed herein, the acts or operations of the method or process may be performed in any suitable sequence and are not necessarily limited to any particular disclosed sequence. Various operations may be described as multiple discrete operations in turn, in a manner that may be helpful in understanding certain configurations; however, the order of description should not be construed to imply that these operations are order dependent. Additionally, the structures, systems, and/or devices described herein may be embodied as integrated components or as separate components. For purposes of comparing various configurations, certain aspects and advantages of these configurations are described. Not necessarily all such aspects or advantages are achieved by any particular configuration. Thus, for example, various configurations may be carried out in a manner that achieves or optimizes one advantage or group of advantages as taught herein without necessarily achieving other aspects or advantages as may also be taught or suggested herein.

[0034] As used herein, the terms “shunt” and “heat exchanger” have their broadest reasonable interpretation, including but not limited to a component (e.g., a thermally conductive device or material) that allows heat to flow from one portion of the component to another portion of the component. Shunts can be in thermal communication with one or more thermoelectric materials (e.g., one or more thermoelectric elements) and in thermal communication with one or more heat exchangers of the thermoelectric assembly or system. Shunts described herein can also be electrically conductive and in electrical communication with the one or more thermoelectric materials so as to also allow electrical current to flow from one portion of the shunt to another portion of the shunt (e.g., thereby providing electrical communication between multiple thermoelectric materials or elements). Heat exchangers can be in thermal communication with the one or more shunts and one or more working fluids of the thermoelectric assembly or system. Various configurations of one or more shunts and one or more heat exchangers can be used (e.g., one or more shunts and one or more heat exchangers can be portions of the same unitary element, one or more shunts can be in electrical communication with one or more heat exchangers, one or more shunts can be electrically isolated from one or more heat exchangers, one or more shunts can be in direct thermal communication with the thermoelectric elements, one or more shunts can be in direct thermal communication with the one or more heat exchangers, an intervening material can be positioned between the one or more shunts and the one or more heat exchangers). Furthermore, as used herein, the words “cold,” “hot,” “cooler,” “hotter” and the like are relative terms, and do not signify a particular temperature or temperature range.

[0035] The term “thermal communication” is used herein in its broad and ordinary sense, describing two or more components that are configured to allow heat transfer from one component to another. For example, such thermal communication can be achieved, without loss of generality, by snug contact between surfaces at an interface; one or more heat transfer materials or devices between surfaces; a connection between solid surfaces using a thermally conductive material system, wherein such a system can include pads, thermal grease, paste, one or more working fluids, or other structures with high thermal conductivity between the surfaces (e.g., heat exchangers); other suitable structures; or combinations
of structures. Substantial thermal communication can take place between surfaces that are directly connected (e.g., contact each other) or indirectly connected via one or more interface materials.

A thermoelectric system as described herein can comprise a thermoelectric generator (TEG) which uses the temperature difference between two fluids, two solids, or a solid and a fluid to produce electrical power via thermoelectric materials. Alternatively, a thermoelectric system as described herein can be a heater, cooler, or both which serves as a solid state heat pump used to move heat from one surface to another, thereby creating a temperature difference between the two surfaces via the thermoelectric materials. Each of the surfaces can be in thermal communication with or comprise a solid, a liquid, a gas, or a combination of two or more of a solid, a liquid, and a gas, and the two surfaces can both be in thermal communication with a solid, both be in thermal communication with a liquid, both be in thermal communication with a gas, or one can be in thermal communication with a materials selected from a solid, a liquid, and a gas, and the other can be in thermal communication with a material selected from the other two of a solid, a liquid, and a gas.

The thermoelectric system can include a single thermoelectric assembly (e.g., a single TE cartridge) or a group of thermoelectric assemblies (e.g., a group of TE cartridges), depending on usage, power output, heating/cooling capacity, coefficient of performance (COP) or voltage. Although the examples described herein may be described in connection with either a power generator or a heating/cooling system, the described features can be utilized with either a power generator or a heating/cooling system. Examples of TE cartridges compatible with certain embodiments described herein are provided by U.S. Pat. Appl. Pub. No. 2013/0104953, filed Jun. 5, 2012, and U.S. Pat. Appl. Pub. No. 2013/0255739, filed Mar. 11, 2013, each of which is incorporated in its entirety by reference herein.

Certain embodiments described herein provide one or more systems and/or methods for use in thermoelectric generators (TEGs). Certain embodiments present relatively simple mechanisms to prevent TEG overheating and/or to prevent excessive backpressure (e.g., from drag produced by the fins at high working fluid, such as an exhaust gas, flow rates). Certain embodiments are compatible with a variety of different types and configurations of TEGs.

In certain embodiments, the TEG comprises one or more thermoelectric (TE) subassemblies. FIGS. 1A-1C schematically illustrate cross-sectional views of some example thermoelectric (TE) subassemblies compatible with certain embodiments described herein. Each of FIGS. 1A-1C shows a TE subassembly comprising at least one first working fluid conduit 2 (e.g., at least one region through which the fluid can flow) configured to allow a first working fluid to flow therethrough (e.g., in a direction generally perpendicular to the cross-sectional plane shown in FIGS. 1A-1C), at least one TE array 3 (e.g., a plurality of TE elements) generally surrounding and in thermal communication with the first working fluid conduit 2, and at least one second working fluid heat exchanger 4 (e.g., a plurality of external fins) generally surrounding and in thermal communication with the TE array 3, and configured to allow a second working fluid to flow therethrough (e.g., in a direction parallel to the cross-sectional plane shown in FIGS. 1A-1C). The first working fluid can be a coolant and the second working fluid can be an exhaust gas (e.g., from an engine), although other types of first and second working fluids are compatible with certain embodiments described herein.

In FIG. 1A, the at least one fluid conduit 2, the at least one TE array 3, and the at least one heat exchanger 4 each have a generally circular cross-section, while in FIG. 1B, the at least one heat exchanger 4 has a generally rectangular cross-section. In FIG. 1C, the at least one fluid conduit 2 comprises two conduits (e.g., with the first working fluid flowing in opposite directions), and the at least one TE array 3 and the at least one heat exchanger 4 are generally oblong (e.g., oval).

Various TE sub-assemblies compatible with certain embodiments described herein are described by U.S. patent application Ser. No. 13/489,237, filed on Jun. 5, 2012, titled “Cartridge-Based Thermoelectric Systems,” and incorporated in its entirety by reference herein.

In FIGS. 2A-2C, 3A, 3B, 4A, 4B, and 5, a circle (○) is used to represent a TE subassembly, such as a cartridge-shaped TE subassembly with external fins, comprising an array or assembly of stacked TE elements, button-shaped arrays, or any other array or assembly of thermoelectric devices. All of these and any other TE subassemblies of advantageous shape will be represented by an “○” as noted above.

Selectively Movable Flow Deflectors

In certain embodiments, a TE assembly 11 (e.g., a thermoelectric generator (TEG)) comprises at least one TE subassembly 12 comprising a plurality of thermoelectric elements. The at least one TE subassembly 12 is configured to be in thermal communication with at least one first working fluid 15 at a first temperature and configured to be in thermal communication with at least one second working fluid at a second temperature. The second temperature is different than the first temperature such that a temperature differential is generated across the plurality of thermoelectric elements. The TE assembly 11 further comprises at least one selectively movable flow deflector 14 configured to selectively move so as to selectively vary an amount of the at least one first working fluid 15 that is in thermal communication with the at least one TE subassembly 12. The at least one selectively movable flow deflector 14 can comprise any structure configured to be selectively movable (e.g., rotated about an axis, moved along a linear or curved path, or a combination thereof) so as to selectively deflect at least a portion of the flow of the at least one first working fluid 15. Examples of flow deflectors 14 compatible with certain embodiments described herein include, but are not limited to, vanes, baffles, surfaces, and panels.

For example, the TE assembly 11 can further comprise a fluid conduit 13 configured to have the at least one first working fluid 15 flow therethrough, and the at least one TE subassembly 12 can comprise a plurality of TE subassemblies at least partially within the fluid conduit 13 and arranged in an array. The at least one selectively movable flow deflector 14 can comprise a plurality of selectively movable flow deflectors 14.

FIGS. 2A-2C schematically illustrates an example TE assembly 11 in which an array of TE subassemblies 12 are confined in the fluid conduit 13 (e.g., a duct or region through which the fluid can flow) and comprising pairs of selectively movable (e.g., thermally active) flow deflectors 14 to selectively direct the first working fluid 15 to pass through or across the TE subassemblies 12 such that the first working
fluid 15 is selectively in thermal communication with the TE subassemblies 12. The selectively movable flow deflectors 14 corresponding to a TE subassembly 12 are selectively movable between at least two configurations. In a first configuration, a first amount of the at least one first working fluid 15 flowing through the fluid conduit 13 is in thermal communication with the TE subassembly 12. In a second configuration, a second amount of the at least one first working fluid 15 flowing through the fluid conduit 13 is in thermal communication with the TE subassembly 12, the second amount less than the first amount. In certain embodiments, the at least two configurations further comprises a third configuration in which a third amount (e.g., none) of the at least one first working fluid 15 flowing through the fluid conduit 13 is in thermal communication with the TE subassembly 12, the third amount less than the second amount.

For example, as schematically illustrated by FIG. 2A, all of the first working fluid 15 can pass through the TE subassemblies 12 under nominal design operation conditions. FIG. 2B schematically illustrates an example positional change of flow deflectors 14 at a condition where the first working fluid 15 is hotter, so that the TE subassemblies 12 should be protected from becoming too hot. In this condition, a portion 16 of the first working fluid 15 bypasses the TE subassemblies 12, thereby reducing the heat input to the TE subassemblies 12, and thereby preventing them from overheating. FIG. 2C schematically illustrates an example maximum temperature condition where the portion 16 of the first working fluid 15 bypassing the TE subassemblies 12 is essentially all of the first working fluid 16. In this condition, the selectively movable (e.g., thermally active) flow deflectors 14 have shut off the flow of the first working fluid 15 to the TE subassemblies 12.

In certain embodiments, the flow deflectors 14 may be configured to act independently of one another, so that some may be in the condition depicted in FIG. 2C and others as in FIG. 2B, or some may be as in FIG. 2B and others as in FIG. 2A. The latter case may occur when the first working fluid 15 is initially hotter than the nominal design and the mass flow rate of the first working fluid 15 is lower than the nominal design. In this condition, the first few rows of TE subassemblies 12 (e.g., the first few rows on the left side of the TE assembly 11 as shown in FIGS. 2A-2C) may be as depicted in FIG. 2B and the third row (e.g., the right-most row of the TE assembly 11 as shown in FIGS. 2A-2C) can be as depicted in FIG. 2A. In certain embodiments in which the temperature of the first working fluid 15 varies as it flows through the fluid conduit 13 (e.g., an inlet temperature at the inlet of the fluid conduit 13 and progressively lower temperatures along the fluid conduit 13 as the first working fluid 15 cools while flowing through the fluid conduit 13), the operating conditions among the TE subassemblies 12 may be different along the flow path in accordance with the operating conditions (e.g., temperatures) that the TE subassemblies 12 experience. In addition, the selective movement of the flow deflectors 14 (e.g., the setpoints or trigger values for such movement, e.g., based on values of operating conditions such as temperature of the flow deflector or the first working fluid, or heat flux of the first working fluid) can vary along the flow path in accordance with the operating conditions (e.g., temperatures, heat flux) that the flow deflectors 14 and the TE subassemblies 12 experience.

FIGS. 3A and 3B schematically illustrate an example TE assembly 21 in which an array of TE subassemblies 22 are confined in the fluid conduit 23 (e.g., a duct or region through which the fluid can flow) and the plurality of selectively movable flow deflectors 24 are located at least partially between the plurality of TE subassemblies 22 and at least one wall of the fluid conduit 23, and are selectively movable between at least two configurations. In a first configuration, a first amount of the at least one first working fluid 25 flowing through the fluid conduit 23 is in thermal communication with the plurality of TE subassemblies 22. In a second configuration, a second amount of the at least one first working fluid 25 flowing through the fluid conduit 23 is in thermal communication with the plurality of TE subassemblies 22, the second amount less than the first amount.

FIG. 3A schematically illustrates a condition wherein the TE subassemblies 22 extract the thermal power from the first working fluid 25 confined in the fluid conduit 23 which contains an extended portion 27. In the extended portion 27 are thermally active flow deflectors 24 that at nominal design prevent the first working fluid 25 from bypassing the TE subassemblies 22.

FIG. 3B schematically illustrates a condition wherein the first working fluid 25 is hotter than the nominal design condition, and as a consequence, thermally active flow deflectors 24 move into extended portion 27, thereby creating an alternate path through which a portion 26 of the first working fluid 25 can pass without being in thermal communication with the TE subassemblies 22. Another, but in this case diminished, portion of the first working fluid 25 passes through the TE subassemblies 22 and is in thermal communication with the TE subassemblies 22. As in the TE assembly 11 schematically illustrated in FIGS. 2A-2C, the selectively movable (e.g., thermally active) flow deflectors 24 may be designed to act independently of one another, so that the proportions of the portion 26 of the first working fluid 25 and the remaining portion of the first working fluid 25 are selectively changed.

FIGS. 4A and 4B schematically illustrate an example TE assembly 31 in which an array of TE subassemblies 32 are confined in the fluid conduit 33 (e.g., a duct or region through which the fluid can flow) and the TE assembly 31 further comprises at least one inner conduit 38 configured to allow at least a portion 36 of the at least one first working fluid 35 to flow therethrough and to not be in thermal communication with a corresponding portion of the plurality of TE subassemblies 32 while flowing through the fluid conduit 33, and wherein the plurality of selectively movable flow deflectors 34 are selectively movable between at least two configurations. In a first configuration, a first amount of the at least one first working fluid 35 flowing through the fluid conduit 33 is in thermal communication with the corresponding portion of the plurality of TE subassemblies 32. In a second configuration, a second amount (e.g., portion 36) of the at least one first working fluid 35 flowing through the fluid conduit 33 is in thermal communication with the corresponding portion of the plurality of TE subassemblies 32, the second amount less than the first amount.

For example, in FIGS. 4A and 4B, the TE subassemblies 32 are positioned between a wall of the fluid conduit 33 (e.g., a duct or region through which the fluid can flow) and the at least one inner conduit 38 (e.g., a sleeve or region through which the fluid can flow). Selectively movable (e.g., thermally active) flow deflectors 34 are within the at least one inner conduit 38 and are positioned as shown in FIG. 4A during operation under nominal design conditions. Under
these conditions, the first working fluid 35 is prevented from flowing through the at least one inner conduit 38 and flows through TE subassemblies 32.

[0053] FIG. 4(b) schematically illustrates a condition in which the first working fluid 35 is above the nominal design condition and could overheat the TE subassemblies 32. In this condition, the flow deflectors 34 move so as to allow a portion 36 of the first working fluid 35 to flow through the at least one inner conduit 38 and bypass the TE subassemblies 32 such that the portion 36 of the first working fluid is not in thermal communication with the TE subassemblies 32. At even higher temperatures, the flow deflectors 34 may be configured to allow a still greater portion of the first working fluid 35 to pass through the at least one inner conduit 38, further diminishing the portion of the first working fluid 35 flowing through the TE subassemblies 32 and in thermal communication with the TE subassemblies 32.

[0054] FIG. 5 schematically illustrates an example TE assembly 41 with TE subassemblies 42, a fluid conduit 43 (e.g., a duct or region through which the fluid can flow), and at least one inner conduit 48 comprising two sleeves 48a, 48b, the sleeve 48a nearest the inlet and containing selectively movable (e.g., thermally active) flow deflectors 44 and the sleeve 48b downstream of the sleeve 48a and containing selectively movable (e.g., thermally active) flow deflectors 49. Between the sleeves 48a, 48b is a gap 47 through which at least a portion of the first working fluid 45 can pass. In operation with the first working fluid 45 having a temperature above the nominal design temperature, a portion 46 of the working fluid 45 passes through the sleeve 48a and another portion of the first working fluid 45 passes through the TE subassemblies 42. Under conditions where the TE subassemblies 42 cool the first working fluid 45 sufficiently, some or all of the portion 46 of the first working fluid 45 may be directed through the gap 47 to pass through and in thermal communication with the downstream TE subassemblies 42. For this to occur, the selectively movable (e.g., thermally active) flow deflectors 49 must be at least partially closed. This can occur if the first working fluid 45 downstream of the gap 47 has been cooled sufficiently by having passed through the upstream TE subassemblies 42. For example, this may occur if the first working fluid 45 inlet temperature is sufficiently higher than the nominal design temperature and its mass flow rate is sufficiently low.

[0055] TEG assemblies with any number or configuration of TE subassemblies are compatible with certain embodiments described herein. As schematically illustrated in FIG. 5, the TEG assembly can comprise fewer TE subassemblies than do FIGS. 2-4 and 4B, or more TE subassemblies than do FIGS. 2A-2C. Furthermore, the TE subassemblies and bypass conduits (e.g., inner conduits) may be in any configuration or arrangement. For example, the TE subassemblies can be in one, two, or more rows and the bypass conduit for the working fluid may be on one or two sides (as depicted in FIGS. 3A, 3B, and 31B) in one, two, or more interior locations. Similarly, interior sleeves may have two or more sections, and wall bypasses (or sleeves) may have one, two, or more sections. Additionally, bypass conduits may be at the ends of the TE subassemblies or in the interior (e.g., as depicted in FIG. 6 described below).

[0056] In certain applications, it may be advantageous to have selectively movable flow deflectors that can respond to pressure differential between the working fluid inlet and outlet and/or between the inlet and ambient. For example, the desired performance may vary the amount of bypass working fluid as a function of a temperature, mass flow rate (or pressure differential), and possibly other variables. For example, in certain embodiments, the at least one selectively movable flow deflector is responsive to one or more of the following: (i) a temperature differential between an inlet temperature of the at least one first working fluid and an ambient temperature, (ii) an inlet temperature of the at least one first working fluid, (iii) a temperature of the at least one selectively movable flow deflector, (iv) a pressure differential between an inlet of the TE assembly (e.g., TEG) and an outlet of the TE assembly, (v) a pressure differential across the at least one selectively movable flow deflector, (vi) an absolute pressure of the at least one first working fluid, (vii) a mass flow rate of the at least one first working fluid through the TE assembly, and (viii) a flow velocity of the at least one first working fluid through the TE assembly.

[0057] FIG. 6 schematically illustrates a cross-sectional view of an example TE assembly 51, with TE subassemblies 52 in a fluid conduit 53 (e.g., a duct or region through which the fluid can flow), an interior conduit 58 (e.g., a sleeve or region through which the fluid can flow), selectively movable (e.g., thermally active) flow deflectors 54, and a gap 57 defined by the flow deflectors 54 and having a selectively variable size. The at least one first working fluid 55 flows in a direction generally perpendicular to the cross-sectional plane of FIG. 6, with a portion 56 flowing through the variable gap 57, and the remaining portion, if any, of the at least one first working fluid 55 passing through the TE subassemblies 52. The cross-sectional plane of FIG. 6 is generally perpendicular to the cross-sectional planes schematically illustrated in FIGS. 2-5.

[0058] In operation, a portion of the first working fluid 55 flows through and is in thermal communication with the TE subassemblies 52 and a portion 56 of the working fluid 55 flows through the gap 57 created by the flow deflectors 54, and is not in thermal communication with the TE subassemblies 52 when the temperature of the first working fluid 55 is sufficiently above the nominal design temperature. In certain embodiments in which there is one row of TE subassemblies 52 instead of the two rows as schematically illustrated by FIG. 6, the gap 57 can be between a wall of the fluid conduit 53 and the adjacent end of TE subassemblies 52. Certain embodiments described herein can utilize a combination of side, interior, and end bypass conduits, as well as the individual forms depicted in FIGS. 2-5.

[0059] FIG. 7 schematically illustrates an operation map 61 in which the inlet temperature 62 is the vertical axis and the mass flow rate $\dot{M}$ 63 is the horizontal axis. Nominal design inlet temperature $T_i$, 64 and mass flow rate $\dot{M}$ is defined a nominal design operating point 67. Operating curves 66 describe the design gap for flow deflectors (e.g., variable gap 57 in FIG. 6) as a function of $T_2$ and $\dot{M}$. The lowest curve 66 is designated “0” indicating that the size of the gap between mating flow deflectors is zero, such that the inner conduit is sealed to prevent any of the first working fluid 55 from bypassing the TE subassemblies 52 (e.g., the portion 56 is substantially equal to zero). The designations of the other curves 66 indicate the degree of opening, up to full open (100%). Since the curves 66 are not wholly horizontal, it can be advantageous to have a function of working fluid bypassing the TE subassemblies as a function of mass flow rate $\dot{M}$ 63, so that the TE assembly performs well over a broad
range of operating conditions. The mass flow rate $M_{63}$ correlates with the flow velocity of the working fluid in the system and in combination with temperature, correlates with pressure drop across the TE assembly. For effective operation, under most circumstances, the pressure should not exceed a predetermined design limit, e.g., 40 millibars. Thus, it is desirable to have the flow deflectors respond to pressure (or $M_{63}$) as well as inlet temperature 62.

0060] In certain embodiments, the at least one selectively movable flow deflector comprises or is mechanically coupled to at least one spring. For example, the at least one spring can be mechanically coupled to at least two selectively movable flow deflectors of the at least one selectively movable flow deflector. The at least one spring can apply at least one restoring force to the at least two selectively movable flow deflectors to control a size of at least one gap between the at least two selectively movable flow deflectors through which the at least one first working fluid can flow. In certain such embodiments, the at least one spring can be responsive to a temperature of the at least one spring such that the size of the gap is a first size when the temperature is a first temperature and the size of the at least one gap is a second size when the temperature is a second temperature, wherein, for example, the first size is larger than the second size and the first temperature is higher than the second temperature. In certain embodiments, the at least one spring can be responsive to a pressure differential across the at least one selectively movable flow deflector such that the size of the at least one gap is a first size when the pressure differential is a first pressure differential and the size of the at least one gap is a second size when the pressure differential is a second pressure differential, for example wherein the first size is larger than the second size and the first pressure differential is higher than the second pressure differential.

0061] In certain embodiments, the curves 66 of FIG. 7 can be matched approximately by adding spring restraints to the flow deflectors and/or configuring them to be advantageously flexible to respond to a combination of temperature and pressure differential. For example, the length, thickness, width and Young's modulus of the flow deflector material may be configured so that the flow deflector flexes to act like a proportional flapper valve when exposed to a sufficiently high pressure differential. Advantageously, such flow deflectors can be positioned generally as depicted in FIGS. 3A, 3B, 4A, 4B, and 5 such that high-pressure differentials will tend to force the flow deflectors to open a conduit or region through which the fluid can flow.

0062] Other methods can be used in certain embodiments to give the desired position change in adjacent flow deflector gaps as a function of pressure differential. As an example, FIG. 8 schematically illustrates a sleeve (as might be installed in TE assembly 31 in FIG. 4A) 78, flow deflectors 74, external spring 79 and gap 77. Under a combination of inlet working fluid 67 temperature sufficiently above the nominal design and high-pressure differential, the gap 77 can be controlled to allow a predetermined amount (e.g., a design amount) of working fluid 67 to pass through the gap 77. In certain such embodiments, the force-deformation and durability of the spring 79 dimensions and material(s) can be chosen to be suitable for the intended application.

0063] In certain embodiments, the spring 79 may also be configured to have suitable force-deformation and temperature responsive characteristics. For example, the spring 79 may be in a “C” shape, as schematically illustrated in FIG. 9A. The spring device 81 comprises a generally “C”-shaped bimetal portion 89 and attachment features 82 (e.g., tabs or protrusions) configured to mate or couple to the flow deflectors. When cold, the bimetal spring portion 89 forms a small gap 87 that becomes larger when hot, as depicted on the right-side portion of FIG. 8A. This motion can allow flow deflectors (not shown) to open or, alternately, with simple design alterations, force open flow deflectors.

0064] FIG. 9B schematically illustrates an example motion of the “C”-shaped bimetal spring 81 when exposed to an external forces F' 83 and F 84. At low (or zero) force F 83, the bimetal spring 83 is depicted as a generally “C” shape. Under higher forces F' 84 in the general direction shown, the spring 89 deflects as shown in the right-hand portion of FIG. 9B so as to increase the size of the gap 87. Alternately, forces F' in the generally opposite direction (e.g., pinching the attachment features 82 toward one another), can change the shape of the bimetal spring 89 in the opposite direction, so as to decrease the size of the gap 87.

0065] Using design techniques, such as CAD modeling, selectively movable (e.g., thermally active and/or pressure-responsive) flow deflectors can be designed to deflect so as to generally approximate the desired response to pressure differential (or mass flow rate $M_{63}$) and inlet temperature 62, as depicted in FIG. 7. Alternately, some or all of the temperature response and pressure differential response may be in any suitable combination of flow deflectors and external actuators, such as thermally active springs of any suitable design. More generally, external thermally and/or pressure differential components may be used to move flow deflectors entirely or move flow deflectors in combination with force and/or temperature active flow deflectors.

0066] In certain embodiments described herein, bimetal thermal actuation is used. In certain other embodiments, other activation mechanisms can be used, including but not limited to fluid expansion (e.g., Bourdon tubes), solid phase change materials, liquid/solid and gas/liquid phase change materials, shape-memory materials, and any other advantageous thermally responsive material. Similarly, pressure-sensitive deflection systems including springs of all shapes, diaphragms, compressible fluid actuators, are compatible with certain embodiments described herein.

0067] Also, in certain embodiments, external signals and electric power may be applied to provide the desired force-temperature-movement characteristics for the system. As an example, a resistive heater, in good thermal contact with bimetal flow deflectors, can add heat to at least a portion of the flow deflector to adjust deflection of the flow deflector. Such a device can be controlled by an external electronic controller and receive inputs from the controller, temperature and/or pressure sensors, speed sensors, and any other advantageous external input to adjust flow deflector position.

Selectively Movable Fins

0068] The description above addresses certain embodiments comprising selectively movable flow deflectors or baffles that are controlled to adjust or modify the flow of the at least one first working fluid. In certain embodiments, the TE assembly (e.g., TEG) can comprise at least one TE subassembly comprising a plurality of TE elements and a plurality of selectively movable fins. The at least one TE subassembly can be configured to be in thermal communication with at
least one first working fluid at a first temperature and configured to be in thermal communication with at least one second working fluid at a second temperature, wherein the second temperature is different than the first temperature such that a temperature differential is generated across the plurality of TE elements. The plurality of selectively movable fins can be in thermal communication with the plurality of TE elements and configured to be in thermal communication with the at least one first working fluid. The plurality of selectively movable fins can be configured to be selectively movable to modify or adjust a flow of the at least one first working fluid.

Fig. 10 schematically illustrates an example portion of a TE assembly comprising a plurality of selectively movable fins in accordance with certain embodiments described herein. The fins can comprise a bimetallic disc or leaf, or can comprise at least one of the group consisting of: a bimetallic material, a solid phase change material, a liquid/solid phase change material, a gas/liquid phase change material, and a shape-memory alloy. Example fins compatible with certain embodiments described herein can comprise one or more of the following: (i) pyrolytic graphite/Cu clad with stainless steel, (ii) high thermal conductivity multi-metal composite that is thermally active in the desired temperature range (e.g., Kanthal or other), (iii) phase change material systems that deflect at a target temperature range (e.g., shape memory alloy) with or without a second material for thermal conductivity increase or to assist movement, and (iv) external thermally active material to block, divert, or apportion working fluid flow.

When in a nominal operating condition (e.g., the at least one first working fluid at a nominal temperature), the fins can be in a first configuration, an example of which is shown in the upper portion of Fig. 10. When in a cool operating condition (e.g., the at least one first working fluid is at a temperature less than the nominal temperature), the fins can be in a second configuration, an example of which is shown by the dashed lines in the lower portion of Fig. 10 (and denoted by label 92a). When in a hot operating condition (e.g., the at least one first working fluid is at a temperature greater than the nominal temperature), the fins can be in a third configuration, an example of which is shown by the solid lines in the lower portion of Fig. 10 (and denoted by label 92b).

For example, the fins on the hot side of the TE subassembly can change their shape to allow more or less flow through them. They can be designed to also bend in such a way as to reduce heat transfer surface area without affecting pressure drop of the at least one first working fluid. As schematically shown in Fig. 10, two example fins can press against each other to cut off a fraction (e.g., 50%) of their normal fin area and not affect flow. In certain embodiments, the fins are configured to move or bend as to get out of the way of the flow of the at least one first working fluid so that they reduce the pressure drop of the at least one first working fluid.

Electrical Over-Temperature Control

Certain TE assemblies (e.g., certain TE heat engines) have the unusual property that the apparent thermal conductivity of the TE assembly is a function of the current (and current flow direction) through the TE assembly. In certain embodiments, the inherent nature of thermoelectric materials is used to adjust the thermal conductivity of the thermoelectric elements to protect the thermoelectric elements from thermal damage. The temperature at which at least one portion of the TE assembly (e.g., at least one TE subassembly, at least one TE element) is exposed during operation can be adjusted (e.g., controlled, maintained) to be below a threshold damage temperature at which the at least one portion of the TE assembly experiences temperature-generated damage. For example, the controller can be configured to maintain the temperature to be below a threshold damage temperature at which the at least one thermoelectric subassembly or the at least one thermoelectric element experiences temperature-generated damage. Examples of such temperature-generated damage include, but are not limited to, overheating the soldered joints of TE elements to electrical shunts. Such overheating can lead to solder reflow that may result in increasing electrical and thermal contact resistances of the joint, increased brittleness of the joint, or leakage of molten solder to undesired areas. Another example of temperature-generated damage can occur at an interface between the TE assembly and a cold side heat exchanger. If such an interface is filled with a thermal interface material, such as thermal grease, the thermal interface material may dry out upon overheating, leading to a drastic increase of the thermal resistance. In both of these examples of temperature-generated damage, the increases of thermal contact resistance may result in a runaway thermal event, where the increase of contact resistance results in even higher temperatures at the elements and joints, further exacerbating the problem and potentially destroying the device. In certain embodiments, the current can be adjusted or modified to help dissipate more or less heat depending on the desired performance or conditions. For example, a control method (e.g., performed by a controller comprising at least one processor, at least one computer, or at least one microcontroller) can be used to protect a thermoelectric system from over-temperature conditions (e.g., to keep the thermoelectric system within a desired or predetermined temperature range).

In certain embodiments, a TE assembly (e.g., a TEG, a TE heat engine) comprises at least one TE subassembly configured to be in thermal communication with a heat source and configured to be in thermal communication with a heat sink. The at least one TE subassembly comprises at least one TE element comprising a hot side at a first temperature and a cold side at a second temperature lower than the first temperature. The TE assembly further comprises a controller in operative communication with the at least one TE subassembly. The controller is configured to control the first temperature by adjusting an electrical current of the at least one TE subassembly.

Fig. 11 schematically illustrates an example TE assembly (e.g., a TEG, a TE heat engine) in accordance with certain embodiments described herein. The TE assembly comprises at least one TE subassembly comprising at least one hot side electrode, at least one cold side electrode, one or more P-type TE elements, and one or more N-type TE elements. The at least one hot side electrode can comprise at least one hot side shunt in thermal communication with a hot side heat source and the at least one cold side electrode can comprise at least one cold side shunt in thermal communication with a cold side heat sink. The TE assembly further comprises a controller in operative communication with the at least one TE subassembly. In operation, the presence of a temperature differential between the hot side heat source and the cold side heat sink causes thermal power to flow...
from the hot side heat source 105 through the at least one hot side electrode 101, through the one or more P-type TE elements 103 and one or more N-type TE elements 104, through the at least one cold side electrode 102, and to the cold side heat sink 106. Heat passage through the one or more P-type TE elements 103 and one or more N-type TE elements 104 produces a voltage differential between points 108 and 109. If current flows (not shown) between points 108 and 109, a portion of the thermal power going into the at least one hot side electrode 101 is converted to electric (current-voltage, or I-V) power and can exit through the at least one cold side electrode at points 108 and 109.

[0075] Three basic equations are useful to describe steady state operation of the TE assembly 100:

\[ Q_{\text{in}} = P + Q_{\text{e}} \]  

where

\[ Q_{\text{in}} \] = hot side thermal power in
\[ Q_{\text{e}} \] = cold side thermal power out
\[ P \] = electrical power out

\[ Q_{\text{in}} = \alpha(T_H - T_C) + \frac{V^2}{2R} + R \Delta T \]  

(2)

where

\[ \alpha \] = Seebeck coefficient
\[ T_H \] = hot side temperature
\[ T_C \] = cold side temperature
\[ R \] = internal electrical resistance of the engine
\[ \Delta T \] = temperature differential across the TE elements

\[ V = \alpha(T_H - T_C) - IR \]  

(3)

For explanatory purposes, TE material properties can be assumed to be independent of temperature, all parasitic losses (e.g., interfacial thermal and electrical resistances) are negligible and can be ignored, and operation can be assumed to be steady state. Under these conditions, Equations (2) and (3) result. However, in certain embodiments, the TE material properties may or may not be independent of temperature, parasitic losses may or may not be negligible, and operation may or may not be steady state. In certain such embodiments, the operative equations may include additional terms not expressed in Equations (2) and (3).

[0086] An example output of one embodiment of the TE assembly 100 is depicted in FIG. 12. The vertical axis to the left is voltage 201, the horizontal axis is current 202, V_out 203 is the voltage at I=0 and I_out 204 is the voltage at V=0. Voltage versus current line 206 comes from Equation (3), electric power produced (i.e., IV=P) is depicted in curve 208, and has a maximum 213 at current 205 (1/2 I_max). Thermal power Q_th into the TE assembly 100 is on the right side vertical axis 209. Q_th as a function of current I is denoted by line 207, and Equation (2) includes other parameters as well. In FIG. 12, Q_th at I=0 is denoted by point 210, Q_th at maximum power 213 is denoted by point 212, and Q_th at I=I_max is denoted by point 211. At the maximum power 213, voltage=1/2 V_out 203 and current=1/2 I_max 204.

[0089] Certain embodiments described herein advantageously utilize the change in Q_th as a function of current I. Considering Q_th as a function of current, Q_th(I), it is evident from Equation (2) that Q_th(I) changes with I.

[0090] Equation (2) can be used to evaluate Q_th(I) at convenient values of I (e.g., I=0, I=1/2 I_max, and I=I_max) to better understand various configurations in accordance with certain embodiments described herein. Let:

\[ I_M = \frac{\Delta T}{R} \]

\[ I = \frac{\Delta T e}{R} \]

then for the case with no parasitic losses:

\[ Q_{\text{in}}(0) = k \Delta T (ZT_{\text{in}}(1 - \frac{\Delta T}{2T_H} + 1)) \]

(6)

\[ Q_{\text{in}}(I) = k \Delta T (ZT_{\text{in}}(1 - \frac{\Delta T}{2I M} + 1)) \]

(7)

As an example, if:

\[ T_H = 550^\circ K \]
\[ T_C = 400^\circ K \]
\[ ZT = 1.2 \]
The ratio of $Q_{H}(1)$ (e.g., the TE assembly is internally shorted) to $Q_{H}(0)$ (e.g., open circuit) is:

$$\frac{Q_{H}(1)}{Q_{H}(0)} = 2.04$$  \hspace{1cm} (12)

If external power is supplied, so that current $I_{202}$ can be greater than $I_{204}$, $Q_{H}$ can be greater than at $I_{M}$. A maximum value for $Q_{H}$ occurs when:

$$I = \frac{aT_{H}}{R}$$

so that:

$$Q_{H(\text{max})} = kT_{H}(\frac{ZT_{H}}{2} + 1) \text{ and}$$

$$\frac{Q_{H(\text{max})}}{Q_{H}(0)} = \frac{T_{H}}{2T}(\frac{ZT_{H}}{2} + 1)$$  \hspace{1cm} (13)

With parameters (9)-(11) and sufficient external power applied,

$$\frac{Q_{H(\text{max})}}{Q_{H}(0)} = 5.87$$  \hspace{1cm} (15)

Similarly, if electric power is applied so that a current flows (e.g., current $I_{202}$ is less than zero) to the left of the voltage axis $201$ intercept with the current axis $202$ in FIG. 12, $Q_{H}$ can be smaller than $Q_{H}(0)$ 210.

The changes in $Q_{H}$ as a function of electric current allow external control of current to determine the heat flux into the hot side, and hence the thermal impedance of the TE assembly 100 (e.g., TEG, TE heat engine). Current can be controlled using the controller 107, which, in certain embodiments, comprises at least one switch, relay, or other structure which can be selectively used to short the current produced by the TE assembly 100. For example, the controller 107 can be configured to selectively switch such that the voltage across the at least one TE element 103, 104 is substantially equal to zero. In certain embodiments, the controller 107 is configured to selectively adjust the heat flux $Q_{H}$ into the hot side, and hence the temperature of the hot side. For example, the controller 107 can comprise at least one temperature-sensitive switch, relay, or other structure (e.g., solid-state switches, solid state relays) configured to selectively adjust the current in response to the hot side temperature or in response to a signal indicative of the hot side temperature. Such solid-state switches may need to be robust in operating at elevated temperatures, as the operating environment of the TE assembly 100 can be above the comfort zone of regular semiconductor devices. For example, such solid-state relays may use silicon carbide, SiC, instead of silicon, since SiC devices can be designed to operate at higher temperatures than those made of silicon.

In certain embodiments, the controller 107 can be configured to adjust the hot side temperature to be less than or equal to a predetermined value. This predetermined value can be below a threshold damage temperature at which the at least one TE subassembly 110 experiences temperature-generated damage. For example, the predetermined value can be below a threshold damage temperature at which the at least one TE element 103, 104 experiences temperature-generated damage. In certain embodiments, the controller 107 is further configured to calculate the electrical current expected to maintain the hot side temperature to be less than or equal to the predetermined value.

FIG. 13 schematically illustrates an example portion of a power generator system 300 comprises a TE assembly 301 (e.g., TEG, TE heat engine) with external fins 302 that are in thermal contact with working fluid 303 on the hot side, and a conduct 305 through which a liquid coolant 306 flows on the cold side, and TE assembly 301 is operatively connected (e.g., electrically) to a controller 306 (e.g., at least one processor, at least one computer, at least one microcontroller). In certain such embodiments, the system can be protected by having the controller 306 vary electric current flow (not depicted) through TE assembly 301 as described herein.

The thermal heat transfer through a TE assembly can be depicted by a network 400 of thermal resistances. Simplified, for explanatory purposes, FIG. 14 provides a schematic diagram that depicts various thermal resistances in the thermal path of the TE assembly 301. Hot working fluid 401 is at temperature $T_{H}$ 409, and coolant 403 is at temperature $T_{C}$ 410. Examples of thermal resistances which govern heat flow are the fin-to-hot working fluid thermal resistance $R_{TF}$ 402, thermal resistance within fin $R_{TF}$ 403, thermal resistance within hot side electrode $R_{TG}$ 404, thermal resistance within the TE subassembly $R_{TE}$ 405, thermal resistance within the cold side electrode $R_{CE}$ 406, and thermal resistance between the cold side duct and coolant $R_{C}$ 407. If all thermal resistances are assumed constant except for $R_{TF}$ 405, the effect on TE hot side temperature $T_{H}$ 411 of varying $R_{TF}$ 405 can be explained without significantly altering the result in many usage cases.

Generally, the hot working fluid to fin thermal resistance $R_{TF}$ 402, the hot side fin thermal resistance $R_{TF}$ 403, and the TE element thermal resistance (which varies) $R_{TF}$ 411 are relatively large. For explanation, smaller thermal resistances are grouped together and their relative grouped magnitude is estimated or ignored, in comparison to that of the principal thermal resistances. Thus, relative thermal resistances, with $R_{TF}$ 402 as a reference, can be:

$$\frac{R_{F}}{R_{TF}} \approx 0.2, \frac{R_{TF}}{R_{TF}} \approx 0.0, \frac{R_{C}}{R_{TF}} \approx 0.4, \frac{R_{TF}}{R_{TF}} = 1.0 \text{ K/watt}$$  \hspace{1cm} (16)

If, for example, when

$$I = \frac{1}{2}I_{M} = \frac{aT}{2R}$$

assuming

$$T_{TF}=700° K, T_{TF}=352.7° K, T_{H}=550° K \text{ and}$$

$$T_{TF}=150° K, \text{ then}$$

$$Q_{TF}(\varepsilon=0.5)=125 \text{ Watts}$$  \hspace{1cm} (19)
Algebraic manipulations of steady state heat flow equations with temperature independent parameter, or one dimensional simulations, yields approximate results in Table 1, for $\varepsilon=0.5$.

<table>
<thead>
<tr>
<th>$V_{IM}$</th>
<th>0.0</th>
<th>0.5</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{IM}$ (°K)</td>
<td>700</td>
<td>700</td>
<td>700</td>
</tr>
<tr>
<td>$T_{IMR}$ (°K)</td>
<td>578.2</td>
<td>550</td>
<td>532.2</td>
</tr>
<tr>
<td>$T_{EC}$ (°K)</td>
<td>393.3</td>
<td>400</td>
<td>408.6</td>
</tr>
<tr>
<td>$T_{CPR} = T_{CR}$ (°K)</td>
<td>184.9</td>
<td>150</td>
<td>123.6</td>
</tr>
<tr>
<td>$T_{C}$ (°K)</td>
<td>352.7</td>
<td>352.7</td>
<td>352.7</td>
</tr>
<tr>
<td>$Q_{b}$ (Watts)</td>
<td>101.5</td>
<td>125</td>
<td>130.8</td>
</tr>
</tbody>
</table>

[0098] Also shown in Table 1 are the results for $I_{IM}=0$ and $I_{IM}=1.0$. Using the same design properties with $T_{IM}=700°$ K and $T_{IM}=352.7°$ K, $T_{CPR}$, decreases with increasing current $I_{IM}$, even though $T_{IM}$ and $T_{C}$, are fixed. Thus, even if $T_{IM}$ increased to a moderate amount (e.g., $20°$ K), $T_{IMR}$ could be maintained at or below the operating temperature of 550 for $I_{IM}=0.5$ by increasing $I_{IM}$ to 1.0.

[0099] FIG. 15 is a flow diagram of an example method 450 of operating a TE assembly in accordance with certain embodiments described herein. In certain embodiments, the TE assembly comprises a TE subassembly in thermal communication with a heat source and in thermal communication with a heat sink. The at least one TE subassembly comprises at least one TE element comprising a hot side at a first temperature and a cold side at a second temperature lower than the first temperature. For example, FIGS. 11 and 13 schematically illustrate TE assemblies compatible with the method 450.

[0100] In an operational block 452, the method 450 comprises adjusting the first temperature by adjusting an electrical current of the at least one TE subassembly. In certain embodiments, the method 450 further comprises calculating the electrical current expected to maintain the first temperature to be less than or equal to the predetermined value.

[0101] In certain embodiments, adjusting (e.g., controlling) the first temperature comprises maintaining the first temperature to be less than or equal to a predetermined value. The predetermined value can be below a threshold damage temperature at which the at least one TE subassembly experiences temperature-generated damage (e.g., at which the at least one TE element experiences temperature-generated damage).

**Mechanical Over-Temperature Control**

[0102] In the description below, various configurations that utilize mechanical means for thermoelectric assembly (e.g., TEG) overheating protection are described. These various means can be used individually or in combinations of two or more with one another, and/or with the electrical over-temperature control and/or the selectively movable flow deflectors or fans described above.

**Valved Pre-Heat Exchanger Coil**

[0103] In certain embodiments, a thermoelectric assembly 500 (e.g., TEG) comprises at least one conduit 502 configured to have at least one working fluid 504 (e.g., exhaust gas from an engine) flowing therethrough. The TE assembly 500 further comprises at least one thermoelectric subassembly 505 configured to receive at the least one working fluid 504 from the at least one conduit 502. The TE assembly 500 further comprises a coolant system 506 in thermal communication with the at least one conduit 502, wherein the coolant system 506 is configured to selectively cool the at least one working fluid 504 flowing through the at least one conduit 502. The coolant system 506 comprises at least one valve 508 configured to adjust coolant flow through at least a portion the coolant system 506 in response to at least one temperature of the at least one working fluid 504.

[0104] In certain embodiments, the TE assembly 500 further comprises at least one temperature sensor 510 configured to generate at least one signal indicative of at least one temperature of the at least one working fluid 504, and the at least one valve 508 is configured to adjust the coolant flow in response to the at least one signal from the at least one temperature sensor 510. In certain other embodiments, the at least one valve 508 comprises a passive device (e.g., a thermostat) and the TE assembly 500 does not comprise the temperature sensor 510.

[0105] FIG. 15 schematically illustrates an example TE assembly 500 (e.g., TEG) in accordance with certain embodiments described herein. In certain embodiments, the coolant system 506 comprises a coolant coil 512 wrapped around the at least one conduit 502 just prior to the one or more TE subassemblies 505 of the TE assembly 500. A coolant fluid flows through the coolant coil 512 when the valve 508 is opened in the coolant coil 512. The valve 508 can be triggered by a temperature of the at least one working fluid 504. In certain such embodiments, the system would not increase engine backpressure and would not extract heat when the valve 508 is closed.

[0106] In certain embodiments, the coolant coil 512 can be evacuated or can be empty when not in use, as opposed to containing coolant fluid. In certain such embodiments, the coolant fluid can be allowed to boil out of the coolant coil 512 and to condense downstream of the coolant coil 512 once the valve 508 is closed. The outlet section of the coolant coil 512 can also be mounted with the lowest head in order to take advantage of gravity to help drain the coolant coil 512 when not in use.

**Phase-Change Material**

[0107] In certain embodiments, a TE assembly 600 (e.g., TEG) comprises a plurality of TE elements 602 and at least one heat exchanger 604 configured to be in thermal communication with at least one working fluid. The TE assembly 600 further comprises at least one interface structure 606 in thermal communication with the at least one heat exchanger 604 and the plurality of TE elements 602. The at least one interface structure 606 comprises at least one material configured to undergo phase changes which result in corresponding changes of thermal conductance of the at least one interface structure 606.

[0108] FIG. 16 schematically illustrates an example portion of a TE assembly 600 in accordance with certain embodiments described herein. The at least one interface structure 602 comprises an interface layer or contact layer comprising a phase change material that changes phase, thereby causing a change in contact or thermal resistance. This phase change material could be in a containing shell in thermal communication with the at least one heat exchanger 604 and at least one shunt 608 in electrical communication with the plurality of TE elements 602. When the temperature gets too hot (e.g.,
above a nominal operation temperature), the phase-change material can change from solid to liquid and/or gas, thereby reducing the thermal conductivity of the interface. The phase-change material can reversibly change phase back to an interface having a higher thermal conductivity when the temperature decreases (e.g., approaches the nominal operation temperature). For example, when the temperature is at a cold temperature (e.g., lower than the nominal operation temperature), the phase-change material can be a solid, providing the best thermal conductivity between the plurality of TE elements 602 and the heat exchanger 604. When the temperature is at a hot temperature (e.g., at the nominal operation temperature), the phase change material can be a liquid, providing good thermal conductivity between the plurality of TE elements 602 and the heat exchanger 604. When the temperature is at a very high temperature (e.g., above the nominal operation temperature), the phase change material can be a gas, providing poor thermal conductivity between the plurality of TE element 602 and the heat exchanger 604.

Example phase-change materials in accordance with certain embodiments described herein include, but are not limited to, cesium (e.g., 300 C-600 C), potassium (e.g., 400 C-1000 C), and sodium (e.g., 500 C-1100 C). These liquid metals can be contained in structures comprise Alloy 600, Haynes 230 (e.g., for higher-end temperatures), and austenitic stainless steel (e.g., for lower-end temperatures). In certain embodiments, the phase-change material can be nonmetallic or metallic with a low thermal conductivity. The phase change of the phase change material can be reversible and can have a high heat capacity (e.g., as high as possible). A higher temperature material similar to barium titanate, which displays positive temperature coefficient, could be used. Phase shifters can be used to adjust the temperature when phase changes take place in such phase change materials. Other materials which are known in the art of heat pipes and thermal planes can also be used in accordance with certain embodiments described herein.

Evacuated Barrier

In certain embodiments, a TE assembly 700 (e.g., TEG) comprises a plurality of TE elements 702 and at least one heat exchanger 704 configured to be in thermal communication with at least one working fluid 706 (e.g., an exhaust gas from an engine). The TE assembly 700 further comprises at least one interface structure 708 (e.g., an interface layer) in thermal communication with the at least one heat exchanger 704 and the plurality of TE elements 702. The at least one interface structure 708 is configured to have a first portion at a first temperature and a second portion at a second temperature less than the first temperature. The at least one interface structure 708 comprises a chamber 710 containing a material 712 that is responsive to the first temperature and the second temperature by having a first mass density in the first portion and a second mass density in the second portion, the second mass density greater than the first mass density.

FIG. 17 schematically illustrates a portion of a TE assembly 700 (e.g., TEG) in accordance with certain embodiments described herein. As the material 712 (e.g., gas) in the interface structure 708 heats up in a hotter portion of the interface structure 708 (e.g., a higher temperature region of the interface layer), it is “pumped” to a cooler portion of the interface structure 708 (e.g., a lower temperature region of the interface structure 708), thereby evacuating the hotter portion and increasing thermal conductance in the cooler portion, where condensation may occur or at least a higher density gas. For example, a thermal plane can be used as the interface structure 708 to move heat from the hotter portion to the cooler portion (e.g., from the higher temperature region of the interface structure 708 to the lower temperature region of the interface structure 708), thereby distributing the heat where it can best be used.

For example, the interface structure 708 (e.g., interface layer) can be filled with a phase change material 712 that changes from solid to liquid to gas. If the heat continues to rise, the gas pressure builds and the gas moves from the hotter area to a colder area of the interface structure 708. With the hot gas leaving the hottest area, leaving behind an interface region with a poorer and poorer thermal conductivity and improving or increasing the thermal conductivity of the colder part of the interface structure 708 downstream.

Materials 712 for the interface structure 708 in accordance with certain embodiments described herein include, but are not limited to, cesium (e.g., 300 C-600 C), potassium (e.g., 400 C-1000 C), and sodium (e.g., 500 C-1100 C). These liquid metals can be contained in structures comprise Alloy 600, Haynes 230 (e.g., for higher-end temperatures), and austenitic stainless steel (e.g., for lower-end temperatures). In certain embodiments, the material 712 can be nonmetallic or metallic with a low thermal conductivity. The material 712 can undergo a reversible phase change at a predetermined temperature and can have a high heat capacity (e.g., as high as possible). A higher temperature material similar to barium titanate, which displays positive temperature coefficient, could be used. Phase shifters can be used to adjust the temperature when phase changes take place in such materials. Other materials which are known in the art of heat pipes and thermal planes can also be used in accordance with certain embodiments described herein.

In certain embodiments, the material 712 can comprise pyrolytic graphite, having a high cross-plane thermal conductivity and a low through-plane thermal conductivity. Using such a material in the interface structure 708 could distribute the heat throughout the TE assembly 700 before overheating the hottest section or portion of the TE assembly 700.

Expansion to Create Thermal Short

In certain embodiments, a TE assembly 800 (e.g., TEG) comprises at least one TE element 802, at least one hot side shunt 804 in thermal communication with a first side of the at least one TE element 802, and at least one cold side shunt 806 in thermal communication with a second side of the at least one TE element 802. The TE assembly 800 further comprises at least one first thermal path for heat flow from the at least one hot side shunt 804, through the at least one TE element 802, to the at least one cold side shunt 806. The TE assembly 800 further comprises at least one structure 808 in thermal communication with the at least one hot side shunt 804. The at least one structure 808 comprises a portion configured to respond to a temperature of the at least one hot side shunt 804, wherein the portion has at least two configurations comprising a first configuration and a second configuration. In the first configuration (when the temperature is greater than a predetermined temperature), the portion forms at least one second thermal path for heat flow (e.g., conductive heat flow) from the at least one hot side shunt 804 to the at least one cold side shunt 806 without passing through the at least one TE element 802. The at least one second thermal path has a
thermal resistance that is sufficiently low such that a substantial amount of heat flows through the at least one second thermal path. In the second configuration (when the temperature is less than or equal to the predetermined temperature), the portion does not form the at least one second thermal path or the at least one second thermal path has a thermal resistance sufficiently high such that an insubstantial amount of heat flows through the at least one second thermal path.

[0116] FIG. 18 schematically illustrates an example portion of a TE assembly 800 (e.g., TEG) in accordance with certain embodiments described herein. The at least one structure 808 can comprise a portion 810 of the hot side shunt 804 that does not have continuous contact with the cold side shunt 806 during normal operation. However, when an over-temperature condition occurs, the portion 810 of the hot side shunt 804 bridges a gap (e.g., by thermal expansion, denoted in FIG. 18 by arrows 812) to make contact with the cold side shunt 806. This contact can create a thermal short (e.g., a thermal path having a thermal resistance sufficiently low such that a substantial amount of heat flows through the thermal path). In certain such embodiments, more heat is dissipated from the hot side of the TE element 802 to the cold side of the TE element 802, thereby reducing the temperature of the hot side of the TE element 802. In certain embodiments, this contact also creates an electrical short (e.g., an electrical path having an electrical resistance sufficiently low such that a substantial amount of electrical current flows through the electrical path) between the hot side shunt 804 and the cold side shunt 806. In certain other embodiments, this contact does not create an electrical short between the hot side shunt 804 and the cold side shunt 806.

[0117] Example materials for the structure 808 that creates the thermal short have a higher coefficient of thermal expansion (CTE) than does the TE elements 802. For example, the material can comprise Cu when the TE elements 802 comprise SKU or can comprise Al when the TE elements 802 comprise Bi2Te3. To avoid the electrical short in addition to the thermal short, the material can comprise a ceramic or dielectric material (e.g., a dielectric material at an end of a metallic member or a coating of the metallic member with a dielectric material). In certain embodiments, a compliant interface, such as a screen or mesh, can be used to accept the thermal short member as it expands from the hot side shunt 804 to the cold side shunt 806.

Expansion to Create Thermal Open

[0118] In certain embodiments, a TE assembly 900 (e.g., a TEG) comprises at least one TE element 902, at least one hot side heat exchanger 904 configured to be in thermal communication with at least one working fluid, at least one hot side shunt 906 in thermal communication with a first side of the at least one TE element 902, and at least one cold side shunt 907 in thermal communication with a second side of the at least one TE element 902. The TE assembly 900 further comprises at least one structure 908 configured to respond to a temperature of the at least one hot side shunt 906, wherein the TE assembly 900 is configured to change between at least two configurations. In a first configuration (when the temperature is less than a predetermined temperature), the TE assembly 900 has at least one first thermal path for heat flow from the at least one hot side heat exchanger 904, through the at least one hot side shunt 906, through the at least one TE element 902, to the at least one cold side shunt 907. The at least one first thermal path has a thermal resistance sufficiently low such that a substantial amount of heat flows through the at least one first thermal path. In a second configuration (when the temperature is greater than or equal to the predetermined temperature), the TE assembly 900 does not have the at least one first thermal path or the at least one first thermal path has a thermal resistance sufficiently high such that an insubstantial amount of heat flows through the at least one first thermal path.

[0119] In certain such embodiments, the thermal open is created between the hot side heat exchanger 904 and the hot side shunt 906. For example, the at least one hot side heat exchanger 904 can be in thermal communication with the at least one hot side shunt 906 when the TE assembly 900 is in the first configuration, and the at least one hot side heat exchanger 904 can not be in thermal communication with the at least one hot side shunt 906 when the TE assembly 900 is in the at least one second configuration. FIG. 19 schematically illustrates an example portion of a TE assembly 900 (e.g., TEG) in accordance with certain embodiments described herein. The hot side heat exchanger 904 comprises a plurality of fins 910, which can serve as the at least one structure 908. Under normal or low-temperature operating conditions, the fins 910 are in conductive thermal communication with the at least one hot side shunt 906 as shown by the upper diagram of FIG. 19. If the fins 910 get too hot (e.g., under over-temperature operating conditions), the fins 910 expand away from the hot side shunt 906 such that the fins 910 are no longer in conductive thermal communication with the at least one hot side shunt 906 as shown by the lower diagram of FIG. 19, thereby reducing the temperature of the hot side shunt 906. For example, the fins 910 can be sweat fit to the hot side shunt 906. If the temperature of the exhaust gas gets too hot (e.g., a predetermined amount above a nominal operating temperature), the fins 910 can expand such that the fins 910 are no longer be in conductive thermal communication with the hot side shunt 906. An example structure compatible with certain embodiments described herein is described by U.S. patent application Ser. No. 13/489,237, filed on Jun. 5, 2012, titled “Cartridge-Based Thermoelectric Systems,” and incorporated in its entirety by reference herein. The hot side heat exchanger fins 910 can comprise a stainless steel material with a higher CTE than the hot side shunt 906 which can comprise Cu. The fins 910 can expand away from the hot side shunt 906 as the temperature increases.

[0120] In certain other embodiments, the thermal open is created between at least one shunt and at least one TE element. FIG. 20 schematically illustrates an example portion of a TE assembly 1000 (e.g., TEG) in accordance with certain embodiments described herein. If the hot side of the at least one TE element 1002 gets too hot, the at least one hot side shunt 1004 can thermally expand away from the at least one cold side shunt 1006, thereby creating a thermal open between the at least one TE element 1002 and the at least one cold side shunt 1006. For example, the at least one hot side heat exchanger 1008 can be rigidly attached to the at least one hot side shunt 1004 and can expand away from at least one the cold side heat exchanger 1010 which is rigidly attached to the at least one cold side shunt 1010. The at least one TE element 1002 can be rigidly attached to the at least one hot side shunt 1004 which expands away from the at least one cold side shunt 1006. While such a configuration may not fully protect the at least one TE element 1002 from overheating, it does
disconnect the heat flow into the cold side, which may be desirable to prevent the cooling system from exceeding its capacity.

[0121] Alternatively, the at least one TE element 1002 can be rigidly attached to the at least one cold side shunt 1006 such that thermal expansion moves the at least one hot side shunt 1004 away from the at least one TE element 1002. For example, the at least one hot side shunt 1004 can be in conductive thermal communication with the at least one TE element 1002 when the TE assembly 1000 is in the first configuration, and the at least one hot side shunt 1004 can not be in conductive thermal communication with the at least one TE element 1002 when the TE assembly 1000 is in the at least one second configuration.

[0122] In certain embodiments, the CTE of the materials does not impact the operation as much as in other embodiments due to the high thermal expansion difference due to large temperature differences between the hot and cold side heat exchangers. If the temperature differences between the hot and cold side are smaller, the hot side heat exchanger can have a higher CTE than does the cold side heat exchanger. In certain such embodiments, the hot side heat exchanger can comprise stainless steel or Cu, and the cold side heat exchanger can comprise Cu or Al.

[0123] Numerous embodiments have been described above. Although the invention has been described with reference to these specific embodiments, the descriptions are intended to be illustrative of the invention and are not intended to be limiting. For example, one or more aspects described in conjunction with certain embodiments can be used in conjunction with other embodiments. Various modifications and applications may occur to those skilled in the art without departing from the true spirit and scope of the invention as defined in the appended claims.

What is claimed is:

1. A thermoelectric assembly comprising:
   at least one thermoelectric subassembly configured to be in thermal communication with a heat source and configured to be in thermal communication with a heat sink, the at least one thermoelectric subassembly comprising at least one thermoelectric element configured to be at a first temperature and a cold side at a second temperature lower than the first temperature; and
   a controller in operative communication with the at least one thermoelectric subassembly, wherein the controller is configured to adjust the first temperature by adjusting an electrical current of the at least one thermoelectric subassembly.

2. The thermoelectric assembly of claim 1, wherein the controller is configured to adjust the first temperature to be less than or equal to a predetermined value.

3. The thermoelectric assembly of claim 2, wherein the predetermined value is below a threshold damage temperature at which the at least one thermoelectric subassembly experiences temperature-generated damage.

4. The thermoelectric assembly of claim 2, wherein the predetermined value is below a threshold damage temperature at which the at least one thermoelectric element experiences temperature-generated damage.

5. The thermoelectric assembly of claim 2, wherein the controller is further configured to calculate the electrical current expected to maintain the first temperature to be less than or equal to the predetermined value.

6. The thermoelectric assembly of claim 1, wherein the controller is configured to maintain the first temperature to be below a threshold damage temperature at which the at least one thermoelectric subassembly or the at least one thermoelectric element experiences temperature-generated damage.

7. The thermoelectric assembly of claim 1, wherein the controller comprises at least one temperature-sensitive switch or relay.

8. The thermoelectric assembly of claim 1, wherein the controller is further configured to be selectively switched such that the voltage across the at least one thermoelectric element is substantially equal to zero.

9. The thermoelectric assembly of claim 1, wherein the heat source or the heat sink comprises at least one working fluid, the thermoelectric assembly further comprising at least one selectively movable fluid deflector configured to selectively move so as to selectively vary an amount of the at least one working fluid in thermal communication with the at least one thermoelectric subassembly.

10. The thermoelectric assembly of claim 1, wherein the heat source or the heat sink comprises at least one working fluid, the thermoelectric assembly further comprising a plurality of selectively movable fins in thermal communication with the plurality of thermoelectric elements and configured to be in thermal communication with the at least one working fluid, the plurality of selectively movable fins configured to be selectively movable to modify a flow of the at least one working fluid.

11. The thermoelectric assembly of claim 1, further comprising:
   at least one conduit configured to have at least one working fluid flowing therethrough, the at least one working fluid received by the at least one thermoelectric subassembly from the at least one conduit; and
   a coolant system in thermal communication with the at least one conduit, the coolant system configured to selectively cool the at least one working fluid flowing through the at least one conduit, the coolant system comprising at least one valve configured to adjust coolant flow through at least a portion of the coolant system in response to at least one temperature of the at least one working fluid.

12. The thermoelectric assembly of claim 1, wherein the at least one thermoelectric element comprises a plurality of thermoelectric elements, the heat source or the heat sink comprises at least one working fluid, the thermoelectric assembly further comprising:
   at least one heat exchanger configured to be in thermal communication with the at least one working fluid; and
   at least one interface structure in thermal communication with the at least one heat exchanger and the plurality of thermoelectric elements, wherein the at least one interface structure comprises at least one material configured to undergo phase changes which result in corresponding changes of thermal conductance of the at least one interface structure.

13. The thermoelectric assembly of claim 1, wherein the at least one thermoelectric element comprises a plurality of thermoelectric elements, the thermoelectric assembly further comprising:
   at least one heat exchanger configured to be in thermal communication with the at least one working fluid; and
   at least one interface structure in thermal communication with the at least one heat exchanger and the plurality of thermoelectric elements, the thermoelectric assembly further comprising:
thermoelectric elements, wherein the at least one interface structure is configured to have a first portion at the first temperature and a second portion at the second temperature less than the first temperature, wherein the at least one interface structure comprises a chamber containing a material that is responsive to the first temperature and the second temperature by have a first mass density in the first portion and a second mass density in the second portion, the second mass density greater than the first mass density.

14. The thermoelectric assembly of claim 1, further comprising:

- at least one hot side shunt in thermal communication with the hot side of the at least one thermoelectric element;
- at least one cold side shunt in thermal communication with the cold side of the at least one thermoelectric element, wherein the thermoelectric assembly comprises at least one first thermal path for heat flow from the at least one hot side shunt, through the at least one thermoelectric element, to the at least one cold side shunt; and
- at least one structure in thermal communication with the at least one hot side shunt, the at least one structure comprising a portion configured to respond to the first temperature, wherein the portion has at least two configurations comprising:
  - a first configuration when the first temperature is greater than a predetermined temperature in which the portion forms at least one second thermal path for heat flow from the at least one hot side shunt to the at least one cold side shunt without passing through the at least one thermoelectric element, wherein the at least one second thermal path has a thermal resistance that is sufficiently low such that a substantial amount of heat flows through the at least one second thermal path; and
  - at least one second configuration when the first temperature is less than or equal to the predetermined temperature in which the portion does not form the at least one second thermal path or the at least one second thermal path has a thermal resistance sufficiently high such that an insubstantial amount of heat flows through the at least one second thermal path.

15. The thermoelectric assembly of claim 1, further comprising:

- at least one hot side heat exchanger configured to be in thermal communication with at least one working fluid of the heat source;
- at least one hot side shunt in thermal communication with the hot side of the at least one thermoelectric element;
- at least one cold side shunt in thermal communication with the cold side of the at least one thermoelectric element; and
- at least one structure configured to respond to the first temperature, wherein the thermoelectric assembly is configured to change between at least two configurations comprising:
  - a first configuration when the first temperature is less than a predetermined temperature, the first configuration having at least one first thermal path for heat flow from the at least one hot side heat exchanger, through the at least one hot side shunt, through the at least one thermoelectric element, to the at least one cold side shunt, wherein the at least one first thermal path has a thermal resistance sufficiently low such that a substantial amount of heat flows through the at least one first thermal path; and
  - at least one second configuration when the first temperature is greater than or equal to the predetermined temperature, wherein the at least one second configuration does not have the at least one first thermal path or the at least one first thermal path has a thermal resistance sufficiently high such that an insubstantial amount of heat flows through the at least one first thermal path.

16. A method of operating a thermoelectric assembly comprising at least one thermoelectric subassembly in thermal communication with a heat source and in thermal communication with a heat sink, the at least one thermoelectric subassembly comprising at least one thermoelectric element comprising a hot side at a first temperature and a cold side at a second temperature lower than the first temperature, the method comprising adjusting the first temperature by adjusting an electrical current of the at least one thermoelectric subassembly.

17. The method of claim 16, wherein controlling the first temperature comprises maintaining the first temperature to be less than or equal to a predetermined value.

18. The method of claim 17, further comprising calculating the electrical current expected to maintain the first temperature to be less than or equal to the predetermined value.

19. The method of claim 17, wherein the predetermined value is below a threshold damage temperature at which the at least one thermoelectric subassembly experiences temperature-generated damage.

20. The method of claim 17, wherein the predetermined value is below a threshold damage temperature at which the at least one thermoelectric element experiences temperature-generated damage.

21. The method of claim 16, wherein the thermoelectric assembly comprises at least one conduit configured to have at least one working fluid flowing therethrough, the at least one thermoelectric subassembly configured to receive the at least one working fluid from the at least one conduit, the method comprising selectively cooling the at least one working fluid flowing through the at least one conduit.

22. The method of claim 16, wherein the at least one thermoelectric element comprises a plurality of thermoelectric elements, the thermoelectric assembly comprising at least one heat exchanger configured to be in thermal communication with the at least one working fluid, the method comprising changing a phase of at least one material in thermal communication with at least one heat exchanger and the plurality of thermoelectric elements, wherein the phase change results in a corresponding change of thermal conductance of the at least one material.

23. A non-transitory computer storage having stored thereon a computer program that instructs a computer system to operate a thermoelectric assembly comprising at least one thermoelectric subassembly in thermal communication with a heat source and in thermal communication with a heat sink, the at least one thermoelectric subassembly comprising at least one thermoelectric element comprising a hot side at a first temperature and a cold side at a second temperature lower than the first temperature, by at least adjusting the first temperature by adjusting an electrical current of the at least one thermoelectric subassembly.