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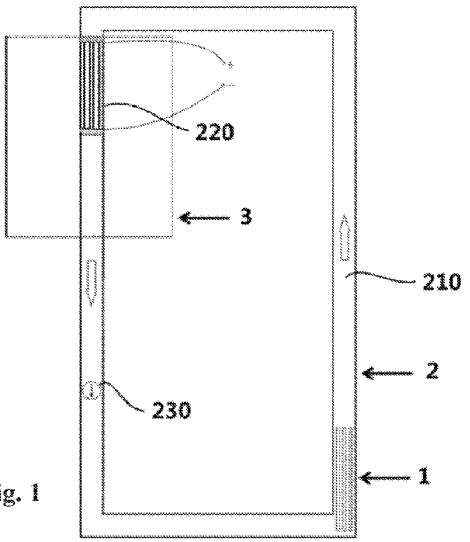


Fig. 1

(57) Abstract: Cooling system and method of the same are provided. The cooling system comprises: a coolant pathway in which, a coolant is able to flow through or by a heat source (1) and a heat reservoir (3); a thermoelectric generator (220) in thermo connection with the coolant and being operable to generate electricity; a pump powered by the thermoelectric generator (220) for driving the coolant flowing through the coolant pathway. The cooling system has improved heat transfer performance.

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THERMOELECTRIC GENERATOR BASED RESIDUAL HEAT REMOVAL SYSTEM AND METHOD OF THE SAME

FIELD OF THE INVENTION

The invention relates to the field of cooling systems. In particular, the invention provides a thermoelectric generator based residual heat removal system and method of the same.

BACKGROUND

Nuclear power plants have a number of cooling systems operable during different modes of reactor operation to remove heat produced by the reactor core. The primary operational function of the reactor is to heat a liquid coolant that is pumped through a primary coolant circuit. The primary coolant circuit has the reactor vessel in series with means for heating water to boil, that is, producing steam, with heat energy of reactor core. The steam is further used to drive turbine and electrical generator. In this way, heat energy of the core is converted into electricity while the core is cooled.

Residual heat removal system is a cooling system connected to a coolant circuit, such as the primary coolant circuit, of the nuclear power plants. When station black out accidents happen in nuclear power plants, residual heat removal systems are used to remove residual heat from the reactor core after the reactor is shut down. However, external power supply may not be available for supporting the cooling systems due to the accidents. In this condition, passive residual heat removal systems without using external power, such as natural circulation circuits, are greatly needed.

In working of natural circulation circuits, water in the circuits is heated by the reactor core and cooled by a heat reservoir such as a cooling water tank located on a higher level than the reactor core. The temperature difference of cold water and hot water results in density difference, which leads to gravity difference of water in the loop. The gravity difference drives the circulation of water. Colder, denser water in the circuits flows by way of gravity down to the reactor vessel and removes the residual heat from the reactor core. The water then becomes warmer, less dense, and is “pushed”

back up to the water tank by the cold water entering the core. The residual heat is transferred to the cooler water in the water tank.

SUMMARY OF THE INVENTION

It is one object of the invention to provide a cooling system. It is a further object of the invention to provide a cooling method. It is a still further object of the invention to provide a cooling system with improved heat transfer performance. It is a still further object of the invention to provide a cooling method with improved heat transfer performance.

The inventors have found that a major drawback of the conventional residual heat removal systems using natural circulation circuits is low heat transfer performance, which is caused by low flow rate of the circulation flow. The low flow rate is further caused by the weak driving force of water circulation circuits. The essential cause of weak driving force is the low energy conversion efficiency from heat energy to gravity energy and further to the driving force. Hence, it is of great significance to find ways to improve the energy conversion efficiency and thus to improve heat transfer performance.

The inventors found that the energy conversion efficiency can be much improved by converting heat energy into electrical energy with thermoelectric generators first and then using the electrical energy to enhance the driving force, for example, using the electrical energy to power a pump to accelerate the flow rate, thereby improving the heat transfer performance.

In accordance with one aspect of the present invention, the above and other objects can be accomplished by a cooling system comprising:

a coolant pathway in which, when operating, a coolant flows through or by a heat source and a heat reservoir;

a thermoelectric generator in thermo connection with the coolant in the coolant pathway;

a pump powered by the thermoelectric generator for driving the coolant through

the coolant pathway.

In accordance with one aspect of the present invention, it provided a residual heat removal system for a nuclear power plant, wherein the residual heat removal system comprises any of the cooling systems in the abovementioned embodiments of the present invention.

In accordance with one aspect of the present invention, the above and other objects can be accomplished by a cooling method comprising:

enabling a coolant to flow through or by a heat source and a heat reservoir, and the coolant is in thermo connection with a thermoelectric generator;

generating electricity with the thermoelectric generator when temperature difference exists around the thermoelectric generator;

pumping coolant to flow through or by a heat source and a heat reservoir, with a pump powered by the thermoelectric generator.

In accordance with one aspect of the present invention, it provided a residual heat removal method for a nuclear power plant, wherein the residual heat removal method comprises any of the cooling methods in the abovementioned embodiments of the present invention.

Compared to conventional cooling systems or methods depending on natural circulation and natural convection, the cooling systems and/or cooling methods of the present invention have at least one of the following advantages, without using external power source still:

(1) having enhanced energy conversion efficiency;

(2) having enhanced driving force;

(3) having improved heat transfer performance;

(4) having forced circulation;

(5) having forced convection heat transfer mode.

BRIEF DESCRIPTION OF THE DRAWINGS

There are shown in the drawings certain examples of the invention as presently preferred. It should be understood that the invention is not limited to the arrangements disclosed for purposes of illustration, and is capable of variations within the scope of the invention claimed. In the drawings,

Fig. 1 is a schematic of a cooling system;

Fig. 2 is a schematic of a thermoelectric generator;

Fig. 3 is a radial cross section of the thermoelectric generator according to Fig. 2;

Fig. 4 is an electrical schematic of thermoelectric modules;

Fig. 5 is a schematic of a cooling system;

Fig. 6 is a schematic of a cooling system in example 1;

Fig. 7 is a schematic of a heat transfer unit with TEGs;

Fig. 8 is a schematic of a heat transfer unit without TEGs;

Fig. 9 is temperature-time curves of cooling systems of example 1 and comparative example 1;

Fig. 10 is a voltage-time curve and current-time curve of electricity supplied to the pump in example 1; and

Fig.11 is temperature-time curves of cooling systems of example 1 with different cooling methods

DETAILED DESCRIPTION OF THE INVENTION

The present invention provides the following specific embodiments and all the possible combinations thereof. For brevity, this application does not explicitly list every specific combination of embodiments, but it should be understood in the way that all the possible combinations of every specific embodiment is specifically recorded and disclosed in the present application.

In an embodiment of the present invention, it provided a cooling system comprising:

a coolant pathway in which, when operating, a coolant flows through or by a heat source and a heat reservoir;

a thermoelectric generator in thermo connection with the coolant in the coolant pathway;

a pump powered by the thermoelectric generator for driving the coolant through the coolant pathway.

In a preferred embodiment of the present invention, it provided a cooling system, wherein the coolant in the coolant pathway is in thermo connection with the heat source and/or the heat reservoir; in particular, the coolant in the coolant pathway is heated by the heat source and/or is cooled by the heat reservoir.

In a preferred embodiment of the present invention, it provided a cooling system, wherein the coolant in the coolant pathway is able to flow from a heat source to a heat reservoir and/or flow from a heat reservoir to a heat source.

In a preferred embodiment of the present invention, it provided a cooling system, when operating, the coolant in the coolant pathway flows through a heat exchanger immersed in a heat reservoir.

In a preferred embodiment of the present invention, it provided a cooling system, wherein the coolant pathway is in thermo connection with the heat source and/or the heat reservoir; in particular, the coolant pathway is heated by the heat source and/or is cooled by the heat reservoir.

In a preferred embodiment of the present invention, it provided a cooling system, wherein the coolant pathway is a coolant circuit in which, when operating, the coolant circulates between the heat source and the heat reservoir.

In a preferred embodiment, temperature difference exists around the thermoelectric generator.

In a preferred embodiment, temperature difference exists between two sides of the thermoelectric generator.

In a preferred embodiment of the present invention, it provided a cooling system, wherein the thermoelectric generator is in thermo connection with the heat reservoir and/or the heat source.

In a preferred embodiment of the present invention, it provided a cooling system, wherein the thermoelectric generator is in thermo connection with the heated coolant in the coolant pathway and/or the cooled coolant in the coolant pathway.

In a preferred embodiment of the present invention, it provided a cooling system, further comprising one or more agitator(s) powered by the thermoelectric generator; preferably, the agitator(s) is/are for enhancing heat exchange between the coolant in the coolant pathway and the heat reservoir.

In a preferred embodiment of the present invention, it provided a cooling system, further comprising one or more heat exchanger(s) fluidly connected to the coolant pathway, such as connected into the coolant pathway; preferably, the heat exchangers are for realizing heat exchange between the coolant in the coolant pathway and the heat reservoir. In a preferred embodiment, the heat exchanger(s) is/are pipe-type heat exchangers.

In another embodiment of the present invention, it provided a cooling system, further comprising one or more heat sink(s), such as cooling fin(s). The heat sink(s) may be in thermo connection with the thermoelectric generator and the heat reservoir. For example, the heat sink(s) may be connected to or fixed on the thermoelectric generator. Preferably, the heat sink(s) is/are for enhancing heat exchange between thermoelectric generator and the heat reservoir. The heat sinks may improve output power of the thermoelectric generator.

In a preferred embodiment of the present invention, it provided a cooling system, further comprising a check valve connected to the coolant pathway and being in parallel with the pump.

In a preferred embodiment of the present invention, it provided a cooling system, wherein the check valve is for allowing the coolant in the coolant pathway to flow only in a determined direction passing the valve, and the valve is opened only when the pump or the thermoelectric generator fails.

In a preferred embodiment of the present invention, it provided a cooling system, wherein the thermoelectric generator comprises one or more thermoelectric modules, which includes n-type and p-type semiconductors.

In a preferred embodiment of the present invention, it provided a cooling system, wherein the thermoelectric modules are electrically connected in series, in parallel or in series-parallel.

In a preferred embodiment of the present invention, it provided a cooling system, wherein the coolant is selected from the following substances including: water, aqueous solution, organic solution, gas, liquid metal or molten salts.

In a preferred embodiment of the present invention, it provided a cooling system, wherein the heat reservoir is located higher than the heat source.

In a preferred embodiment of the present invention, it provided a cooling system, wherein the coolant pathway is fluidly isolated with the heat reservoir.

In a preferred embodiment of the present invention, it provided a cooling system, wherein the cooling system does not have external power supply.

In a preferred embodiment of the present invention, it provided a cooling system, wherein the thermoelectric generator has a pipe-like structure.

In a preferred embodiment of the present invention, it provided a cooling system, wherein the thermoelectric generator is connected to the coolant pathway, with coolant passing through it.

In a preferred embodiment of the present invention, it provided a cooling system, wherein the heat reservoir is a coolant storage tank.

In a preferred embodiment of the present invention, it provided a cooling system, wherein the heat reservoir has lower temperature than the heat source.

In a preferred embodiment of the present invention, it provided a cooling system, wherein the thermoelectric generator generates electricity by being heated by the coolant in the coolant pathway from one side and/or being cooled by the coolant in the coolant storage tank from the other side.

In a preferred embodiment of the present invention, it provided a cooling system, wherein the thermoelectric generator generates electricity by being heated by the coolant in the coolant pathway from inside and/or being cooled by the coolant in the coolant storage tank from outside.

In a preferred embodiment of the present invention, it provided a cooling system, wherein the thermoelectric generator is submerged in the coolant storage tank.

In a preferred embodiment of the present invention, it provided a cooling system, wherein the coolant in the coolant storage tank is selected from the following substances including: water, gas, liquid metal or molten salts.

In an embodiment of the present invention, it provided a residual heat removal system for a nuclear power plant, wherein the residual heat removal system comprises any one of the cooling systems in the abovementioned embodiments of the present invention.

In a preferred embodiment of the present invention, it provided a cooling system, wherein the heat source is a reactor core.

In a preferred embodiment of the present invention, it provided a cooling system, wherein the heat reservoir is a water tank.

In a preferred embodiment of the present invention, it provided a cooling system, wherein the coolant pathway is a water circuit, such as the primary coolant circuit, of the nuclear power plant.

In an embodiment of the present invention, it provided a cooling method comprising:

enabling a coolant to flow through or by a heat source and a heat reservoir, and the coolant is in thermo connection with a thermoelectric generator;

generating electricity with the thermoelectric generator;

pumping the coolant to flow through or by a heat source and a heat reservoir, with a pump powered by the thermoelectric generator.

In a preferred embodiment of the present invention, it provided a cooling method, wherein pumping the coolant to flow through a heat exchanger emerged in a heat reservoir, with a pump powered by the thermoelectric generator.

In a preferred embodiment of the present invention, it provided a cooling method, wherein the coolant in the coolant pathway is able to flow from a heat source to a heat reservoir and/or from a heat reservoir to a heat source.

In a preferred embodiment of the present invention, it provided a cooling method, wherein the heat reservoir is a coolant storage tank.

In a preferred embodiment of the present invention, it provided a cooling method, further comprising agitating the coolant in the coolant storage tank by using electricity produced by the thermoelectric generator.

In a preferred embodiment of the present invention, it provided a cooling method, further comprising realizing heat exchange between the coolant in the coolant pathway and the heat reservoir with one or more heat exchanger(s).

In a preferred embodiment of the present invention, it provided a cooling method, further comprising enhancing heat exchange between the thermoelectric generator and the heat reservoir with one or more heat sink(s).

In a preferred embodiment of the present invention, it provided a cooling method, further comprising allowing the coolant to flow only in a determined direction passing the valve, and the valve is opened only when the pump or the thermoelectric generator fails.

In a preferred embodiment of the present invention, it provided a cooling method, wherein generating electricity with the thermoelectric generator when temperature difference exits around the thermoelectric generator, for example, when temperature difference exits between two sides of the thermoelectric generator.

In a preferred embodiment of the present invention, it provided a cooling method, wherein generating electricity with the thermoelectric generator by heating the thermoelectric generator with the coolant in the coolant pathway and cooling the thermoelectric generator with the heat reservoir.

In a preferred embodiment of the present invention, it provided a cooling method, wherein the method using any one of the cooling systems in the abovementioned embodiments of the present invention.

In an embodiment of the present invention, it provided a residual heat removal method for a nuclear power plant, wherein the residual heat removal method comprises any one of the cooling methods in the abovementioned embodiments of the present invention.

The following figures and Examples further describe the embodiments of the present invention in detail.

Referring to Fig. 1, a preferred cooling system 2 according to one embodiment of the present invention is shown. A coolant pathway 210 is arranged such that a coolant is able to flow through a heat source 1 and a heat reservoir 3, so that the coolant could transfer heat from heat source 1 to heat reservoir 3. For example, the coolant pathway passes through the heat source 1 and the heat reservoir 3. In another embodiment, the coolant pathway may pass nearby the heat source 1 and the heat reservoir 3.

In a preferred embodiment, the coolant pathway 210 is a coolant circuit, such as a coolant loop with coolant circulating therein. The coolant in the coolant pathway could be cooled by the heat reservoir 3 and be heated by the heat source 1 circularly.

In a preferred embodiment, the coolant pathway may comprise one or more conduit(s) or pipe(s), such as a closed loop of conduit(s) or pipe(s). The coolant pathway may be made of steel, aluminum alloy or resin. The coolant pathway may be in thermo connection with heat source 1 and/or heat reservoir 3. For example the coolant pathway may pass through heat source 1 and/or heat reservoir 3.

Still referring to Fig.1, a thermoelectric generator (hereinafter referred to as TEG for short) 220 is in thermo connection with the coolant in the coolant pathway 210. Temperature difference exists around TEG 220 so that it is operable to generate electricity. TEG 220 could be a solid state device that converts heat (temperature

differences) directly into electrical energy through a phenomenon called the Seebeck effect.

In a preferred embodiment, temperature difference may exist between two sides of TEG 220, creating a temperature gradient therein. Therefore, TEG 220 is able to generate electricity due to its thermoelectric property.

In a preferred embodiment, TEG 220 may comprise one or more thermoelectric module(s), which is/are made of thermoelectric materials such as bismuth telluride (Bi_2Te_3), lead telluride (PbTe) or silicon germanium (SiGe). TEG 220 may be plate like or pipe like. The power of TEG 220 may be determined by heat it absorbed and the conversion efficiency.

In a preferred embodiment, TEG 220 may be in thermo connection with the coolant in the coolant pathway 210 and the heat reservoir 3. Thus, it is able to generate electricity when being heated by the coolant in the coolant pathway 210 from one side while being cooled by the heat reservoir 3 from the other side.

Still referring to Fig.1, a pump 230 is connected to the coolant pathway 210, the pump is powered by the TEG 220 for forcing the coolant in the coolant pathway to flow through the coolant pathway 210.

In a preferred embodiment, pump 230 is a device that moves fluids (liquids or gases), or sometimes slurries, by mechanical action. For example the pump 230 may be an electric pump. The pump 230 may also be a positive displacement pump, an impulse pumps or a dynamic pump.

During normal operating conditions, a coolant is able to flow through the coolant pathway 210. In one embodiment, the coolant may be heated by the heat source 1 and cooled by the heat reservoir 3. The TEG 220, which is in thermo connection with the coolant in the coolant pathway 210 and the heat reservoir 3, is heated by the coolant in the coolant pathway from one side and cooled by the heat reservoir 3 from the other side, thereby generating electricity. Meanwhile, the pump connected into the coolant pathway is powered by the TEG 220, forcing the coolant to keep flowing in the coolant pathway.

Therefore, without using external power supply, the cooling system of the present invention is able to convert heat energy into electrical energy first and then using the electrical energy to enhance the driving force, which further accelerates coolant flow rate in the coolant pathway, the heat transfer performance of the cooling system is thereby improved.

Heat reservoir 3 is a thermodynamic system with a heat capacity that is large enough that when it is in thermal contact with another system of interest or its environment, its temperature remains effectively constant. It is an effectively infinite pool of thermal energy at a given, constant temperature. The temperature of the reservoir almost does not change when heat is added or extracted because of the substantially infinite heat capacity. Heat reservoirs may be lakes, oceans, rivers, air, or coolant tanks (containing coolant).

As to the coolant in the coolant pathway or the coolant in the coolant tank, the preferred coolant is water although other fluids can be used. Gases such as air, carbon dioxide, helium and dry steam may be used as coolants in nuclear reactors. Liquids such as water, single-phase pressurized water, two phase boiling water or fog, heavy water, terphenyl, hydrogenated terphenyl, molten bismuth and molten salts such as fluorides may also be used as coolants.

Referring to Fig 2, a preferred TEG 220 according to one embodiment of the present invention is shown. The TEG 220 has a pipe-like structure through which liquid or gas can flow. The pipe-like TEG 220 may be in fluid connection with the coolant pathway 210 so that the coolant is able to flow through the TEG 220 (as indicated by the arrows). In a preferred embodiment, heat reservoir 3 is a water tank containing cooling water and TEG 220 is submerged in the heat reservoir 3. During normal operation, TEG 220 is heated by the coolant flowing therein from inside and cooled by the cooling water in the water tank from outside, thereby, TEG 220 generating electricity for powering the pump 230. TEG 220 may comprise one or more thermoelectric modules 221.

Referring to Fig. 3, a radial cross section of the TEG 220 according to Fig. 2 is

shown. The TEG 220 comprises one or more thermoelectric modules 221. The thermoelectric modules 221 comprise a plurality of p-type semiconductors 221a and n-type semiconductors 221b, which are alternately arranged in circumferential direction of the TEG 220. These semiconductors (221a, 221b) are electrically connected in ends by electrical conductor 221c to create a continuous current of electricity. Additionally, electrical insulators 221d could be used to prevent short circuits between the semiconductors (221a, 221b) and to isolate the thermoelectric modules 221 from external environment. Preferably, TEG 220 may be coated by layers of heat conductor 222 from outside, which work as protective overcoats. The p-type and n-type semiconductors (221a, 221b) could be made of thermal electrical materials such as Bi_2Te_3. In practices, TEG 220 may be constructed in other convenient forms.

As shown in Fig.2, TEG 220 may comprise one or more thermoelectric modules 221. **Referring to Fig. 4,** an electrical schematic of thermoelectric modules 221 of TEG 220 is shown. Thermoelectric modules 221 are electrically connected in series-parallel. In particular, two thermoelectric modules 221 linked in series are linked in parallel with another two thermoelectric modules 221 also linked in series, and finally these four thermoelectric modules 221 are linked in series with another four modules having the same electrical connection. In practices, thermoelectric modules 221 may be electrically linked in other convenient forms.

Referring to Fig 5, a preferred cooling system 2 according to one embodiment of the present invention is shown. The heat reservoir 3 is located higher than the heat source 1. A check valve 240 is connected to the coolant pathway, being in parallel with the pump 230. The check valve 240 allows coolant to flow through it in only one direction, practically in this case, downwards (as indicated by arrows).

In normal condition, when TEG 220 and pump 230 are well-functioning, the cooling system 2 works in the forced circulation mode, in which the coolant is pumped to flow through the coolant pathway, and the check valve 240 is closed due to pressure difference between inlet and outlet of the pump. However, in failure condition of TEG or pump, the cooling system 2 works in natural circulation mode. Temperature

difference between the heated and cooled coolant, such as water in one embodiment, in the coolant pathway 210 can lead to density difference, which results in gravity difference between the heated water and cooled water. As is well known, heated water has smaller density than cooled water, and consequently is lighter than cooled water. Since heat reservoir 3 is located higher than heat source 1, the heated water is more likely to flow up to the heat reservoir 3 and the cooled water is more likely to flow down the heat source 1. Therefore, the check valve 240 is opened by the gravity difference of heated and cooled water, allowing the water in the coolant pathway to flow only in the determined direction (as indicated by arrows).

Still referring to Fig 5, according to one embodiment of the present invention, the cooling system may further comprise one or more heat exchanger(s) 250. In an embodiment, the heat exchanger(s) 250 may be fluidly connected to the coolant pathway. Preferably, the heat exchanger(s) 250 is/are for realizing heat transfer between the coolant in coolant pathway 210 and heat reservoir 3.

In a preferred embodiment, the heat exchanger(s) 250 may be pipe-type heat exchanger(s). The heat exchanger(s) 250 may be made of heat conduction material, such as stainless steel. In another embodiment, the heat exchanger(s) 250 may be made of thermoelectric material and be able to work as TEG(s) or the heat exchanger(s) 250 may be configured with TEG(s), such as pipe-like TEG(s). In a preferred embodiment, the TEG 220 is heated by the coolant in the heat exchangers and cooled by the reservoir.

Still referring to Fig 5, according to one embodiment of the present invention, the heat reservoir 3 is a coolant storage tank containing coolant. TEG 220 is submerged in the coolant storage tank. One or more agitator(s) 260, which are powered by TEG 220, are installed in the coolant storage tank. The agitators 260 are operable to agitate the coolant in the coolant storage tank, create forced convection heat transfer between coolant in the coolant storage tank and coolant pathway 210, or between coolant in the coolant storage tank and TEG 220. By improving the heat transfer between TEG 220 and heat reservoir 3, the output power of TEG 220 could

also be improved.

The abovementioned cooling system may be used as a residual heat removal system for a nuclear power plant. In a preferred embodiment, the residual heat removal system comprises any of the cooling systems in the abovementioned embodiments. The coolant pathway 210 is connected to a coolant circuit, such as the primary coolant circuit, of the nuclear power plant. The heat source 1 is the reactor core of the nuclear power plant. The heat reservoir 3 is a water tank containing cooling water.

In a preferred embodiment, it provided a residual heat removal system for a nuclear power plant. The coolant pathway is a closed loop of coolant pipes. One section of the coolant pipes is connected to the pressure vessel of reactor core of the nuclear power plant for bringing heat away. Another section of the coolant pipes is fluidly connected to heat exchangers and the heat exchangers are submerged in a water tank, wherein the heated coolant could be cooled by cooling water. A thermoelectric generator is linked with the coolant pipes and is also submerged in the water tank. The thermoelectric generator is arranged such that it is heated by the coolant in the coolant circuit from the inside and cooled by the water in the water tank from the outside. As temperature difference exits between two sides of the thermoelectric generator, it is able to generate electricity. An electrical pump is connected to the coolant pipes. The pump is powered by the thermoelectric generator and is able to pump the coolant to circulate between the reactor core and the heat exchangers in the water tank, keeping removing heat. Therefore, the residual heat removal system is able to continuously remove heat from the reactor core without using external power source.

Preferably, a check valve is connected in the coolant loop and connected in parallel with the pump. The check valve allows coolant to flow only in one direction, and open only when the TEG or the pump fails. One or more heat exchangers may be fixed in the coolant loop and one or more agitators may be installed in the water tank.

To accomplish one or more objects of the present invention, a cooling method could also be used. The cooling method comprises:

enabling a coolant to flow through or by a heat source and a heat reservoir, and the coolant is in thermo connection with a thermoelectric generator;

generating electricity with the thermoelectric generator;

pumping the coolant to flow through or by the heat source and the heat reservoir, with a pump powered by the thermoelectric generator.

In a preferred embodiment of the present invention, it provided a cooling method, wherein the coolant in the coolant pathway is able to flow from a heat source to a heat reservoir and/or from a heat reservoir to a heat source.

The heat reservoir may be a coolant storage tank and the cooling method may further comprise agitating the coolant in the coolant storage tank with one or more agitator(s) which are powered by the thermoelectric generator.

The cooling method may further comprise realizing heat exchange between the coolant in the coolant pathway and the heat reservoir with one or more heat exchanger(s).

The cooling method may further comprise allowing the coolant to flow only in a determined direction by using a check valve, and the check valve opens only when the pump or the thermoelectric generator fails.

The cooling method may further comprise generating electricity with the thermoelectric generator by heating the thermoelectric generator with the coolant in the coolant pathway and cooling the thermoelectric generator with the heat reservoir.

The abovementioned cooling method may be used as a residual heat removal method in a nuclear power plant. In this case, the heat source 1 a may be a nuclear reactor; the heat reservoir 3 may be a water tank; the coolant pathway 210 may be a coolant circuit connected to a coolant circuit, such as the primary coolant loop, of the nuclear power plant. In a preferred embodiment, under emergency conditions, the coolant could be piped to the coolant pathway to get greater long term capacity for residual heat removal when auxiliary power supplies are limited.

In the following, an example of the cooling system of the present invention and a comparative example are described.

EXAMPLE 1

As shown in Fig 6, a cooling system 2 is provided for transferring heat from a heat source 1 to a heat reservoir 3. The cooling system 2 comprises a coolant pathway 210 in which, when operating, a coolant flows through the heat source 1 and the heat reservoir 3. The cooling system 2 also comprises a thermoelectric generator 220 in thermo connection with the coolant in the coolant pathway 210 and a pump 230 powered by the thermoelectric generator 220 for driving the coolant flowing through the coolant pathway 210.

Specifically in this example, the heat source 1 is a hot water tank containing 13.8 litres hot water with an initial temperature of 87℃. The heat reservoir 3 is a cold water tank containing 26 litres cold water with an initial temperature of 17℃. The coolant pathway is a closed loop of water pipes passing though the hot water tank and the cold water tank. The size of the water pipes (inner diameter × wall thickness) is Φ7×2mm and the loop pressure is 0.101325MPa.

Fig 7 is a schematic of heat transfer unit 260 with TEG, wherein A and B are plan view and side view of the unit respectively. Referring to Fig 6 and Fig. 7, the cooling system comprises a plurality of heat transfer units 260 with TEGs 220. Each unit 260 comprises a heat exchanger 250, two TEGs 220 and two heat sinks 252. In particular, the heat exchanger 250 includes two pipes 251 fluidly connected to the water pipe 210 and the heat exchanger 250 is emerged in the cold water tank 3. The heat transfer area of each heat exchanger 250 is 55×55mm. Being fixed on the heat exchanger 250, the TEG 220 is heated by the water in the pipes 251 and being cooled by the water in the cold water tank 3. The heat sink 252 is fixed on the TEG 220 for enhancing the heat transfer performance. In particular, four heat transfer units 260 with TEGs 220 are fluidly connected into the coolant pathway 210 and are immerged in the cold water tank 3.

Fig. 8 is a schematic of heat transfer unit 270 without TEG, wherein A and B are plan view and side view of the unit respectively. Referring to Fig.6 and Fig.8,

furthermore, the cooling system comprises a plurality of heat transfer units 270 without TEGs. Each unit 270 comprises a heat exchanger 250 with two heat sinks 252 fixed on it. The heat exchanger 250 and the heat sink 252 are the same as those of heat transfer units 260 with TEGs. In particular, heat transfer units 270 without TEGs are fluidly connected into the water pipe 210 and immerged in the hot water tank 1. Still referring to Fig.6, position of the cold water tank is higher than the hot water tank. The height difference between heat transfer units 260 with TEGs in cold water tank and the heat transfer units 270 without TEGs in hot water tank is 0.5 meter.

Still referring to Fig.6, a valve V1 is connected in series with the pump 230. Another valve V2 is connected in parallel with the valve V1 and the pump 230. When valve V1 is open and valve V2 is closed, the pump is able to force the water to flow. When valve V2 is open and valve V1 is closed, the pump 230 will be bypassed.

Thermal insulation layers are attached outside of hot water tank and cold water tank. With insulation layers, heat dissipation into the environment is decreased.

Parameters of the cooling system of example 1 are summarized in Table. 1.

Table. 1 Parameters of the TEG based residual heat removal system

Parameters	Values
TEG type	TEG1-241-1.4-1.2
TEG number	8
Heat transfer areas of heat exchangers	55mm×55mm
Heat transfer units number in hot water tank	6
Heat transfer units number in cold water tank	4
Height difference between heat transfer units in two tanks	0.5m
Size of pipes (inner diameter×wall thickness)	Φ7×2mm
Volume of water in hot water tank	13.8 litres
Volume of water in cold water tank	26 litres
Initial temperature of hot water tank	87℃
Initial temperature of cold water tank	17℃

Loop pressure	0.101325MPa

In example 1, valve V1 is open and valve V2 is closed. Water in the loop is heated in the hot water tank, and cooled in the cold water tank. For heat transfer units 260 with TEGs in the cold water tank, temperature difference between hot water in the heat exchanger and cold water in the tank leads to voltage difference. In this way, part of thermal energy of hot water is converted into electricity. The electricity is supplied to the pump, which drives circulation flow in the loop.

COMPARATIVE EXAMPLE 1

In comparative example 1, TEGs not are employed in the natural circulation loop. Valve V2 is open and valve V1 is closed. As the pump 230 is bypassed, the circulation flow is driven by gravity difference only and thereby a natural circulation loop is built. Other parameters of comparative example 1 are the same as those of example 1, for comparing the cooling capacity of the cooling systems of example 1 and comparative example 1.

Referring to Fig.6, water in the hot water tank is heated to 87℃ with the heater 410. Then, the heater 410 is turned off and the hot water is cooled by cooling systems of example 1 and comparative example 1 respectively. Variations of hot water temperature with time are recorded by thermometer 420 and are used as an indicator of cooling capacity of different methods or cooling systems.

Fig. 9 is temperature-time curves of cooling systems of example 1 and comparative example 1. Temperature ($T_{hot\ water}$) variation of hot water cooled by different methods can be seen. For the case in which hot water is cooled by the TEGs powered flow (example 1), hot water temperature decreases much more quickly than that cooled by the natural circulation flow (comparative example 1). For temperature decrease from 87℃ to 70℃, cooling of natural circulation flow (comparative example 1) costs 3033s, while cooling of TEGs driven flow (example 1) only costs 1211s. In other words, cooling capacity of the loop with the TEGs powered pump (example 1) is

2.5 times as great as the natural circulation loop (comparative example 1).

Fig. 10 is the voltage-time curve and current-time curve of electricity supplied to the pump in example 1. In the case hot water is cooled by the TEGs powered flow, voltage and current supplied to the pump are measured, as shown. The initial power supplied to the pump is around 3.07W. Naturally it decreases with decrease of hot water temperature.

The experiment of cooling methods conversion is also conducted. In this experiment, firstly, valve V1 is open and valve V2 is closed, the hot water is cooled by forced flow driven by the pump of example 1. After around 400s, the pump is turned off and the valve V2 is opened. As temperature difference and density between riser pipe and downcomer has been established, hot water in the tank is cooled by natural circulation flow in example 1. This experiment validates that in the failure case of TEGs or the pump, circulation flow in the system can converts to natural circulation flow from forced flow, which removes heat from the heat source in this case. Fig.11 shows temperature ($T_{hot\ water}$) variation of hot water cooled by TEGs powered flow which further converts into natural circulation flow. Before the pump is stopped, hot water is cooled by the TEGs powered flow and its temperature drops fast. After that, hot water is cooled by natural circulation flow and its temperature drops slower.

With the experiment work, feasibility of the TEG based residual heat removal system is validated. With the TEGs powered pump, cooling capacity of the system is increased by as much as 1.5 times comparing with the natural circulation system. With temperature difference around (e.g. between two sides of) TEGs, enough electricity can be produced to power the pump. In case of failure of TEGs or the pump, circulation flow in the system can convert from forced flow to natural circulation flow.

In conclusion, compared to the cooling systems or methods based on natural circulation loops, the cooling system or methods of the present invention have improved heat transfer performance.

Although the invention has been explained with reference to the foregoing embodiments, it should be understood that other changes and modifications may be

made to the foregoing embodiments without departing from the scope or spirit of the invention. Alternative configurations may be used, such as a greater or smaller number of heat exchanges, without departing from the scope of the invention. A plurality of cooling apparatus could be used depending on design requirements and overall cost considerations. The placement and the number of heat source(s), coolant pathway(s), thermoelectric generator(s), thermoelectric module(s), heat reservoir(s), pump(s), heat exchanger(s), agitator(s), check valve(s) and so forth could also be optimized to meet specific applications.

CLAIMS

What we claimed is:

1. A cooling system comprising:

a coolant pathway in which, when operating, a coolant flows through or by a heat source and a heat reservoir;

a thermoelectric generator in thermo connection with the coolant in the coolant pathway;

a pump powered by the thermoelectric generator for driving the coolant through the coolant pathway.

2. The cooling system as claimed in claim 1, wherein the coolant in the coolant pathway is in thermo connection with the heat source and/or the heat reservoir; in particular, the coolant in the coolant pathway is heated by the heat source and/or is cooled by the heat reservoir.

3. The cooling system as claimed in claim 1, wherein the coolant in the coolant pathway is able to flow from a heat source to a heat reservoir and/or flow from a heat reservoir to a heat source.

4. The cooling system as claimed in claim 1, when operating, the coolant in the coolant pathway flows through a heat exchanger immersed in a heat reservoir.

5. The cooling system as claimed in claim 1, wherein the coolant pathway is a coolant circuit in which, when operating, the coolant circulates between the heat source and the heat reservoir.

6. The cooling system as claimed in claim 1, wherein temperature difference exists around the thermoelectric generator.

7. The cooling system as claimed in claim 1, wherein temperature difference exists between two sides of the thermoelectric generator.

8. The cooling system as claimed in claim 1, wherein the thermoelectric generator is in thermo connection with the heat reservoir and/or the heat source.

9. The cooling system as claimed in claim 1, wherein the thermoelectric

generator is in thermo connection with the heated coolant in the coolant pathway and/or the cooled coolant in the coolant pathway.

10. The cooling system as claimed in claim 1, further comprising one or more agitator(s) powered by the thermoelectric generator; preferably, the agitator(s) is/are for enhancing heat exchange between the coolant in the coolant pathway and the heat reservoir.

11. The cooling system as claimed in claim 1, further comprising one or more heat exchanger(s) fluidly connected to the coolant pathway, preferably, the heat exchangers are for realizing heat exchange between the coolant in the coolant pathway and the heat reservoir.

12. The cooling system as claimed in claim 1, further comprising a check valve connected to the coolant pathway and being in parallel with the pump.

13. The cooling system as claimed in claim 12, wherein the check valve is for allowing the coolant to flow only in a determined direction through the coolant pathway when the pump or the thermoelectric generator fails.

14. The cooling system as claimed in claim 1, wherein the thermoelectric generator comprises one or more thermoelectric module(s), which include(s) n-type and p-type semiconductors.

15. The cooling system as claimed in claim 14, wherein the thermoelectric modules are electrically connected in series, in parallel or in series-parallel.

16. The cooling system as claimed in claim 1, wherein the coolant in the coolant pathway is selected from the following substances including: water, gas, liquid metal or molten salts.

17. The cooling system as claimed in claim 1, wherein the heat reservoir is located higher than the heat source.

18. The cooling system as claimed in claim 1, wherein the coolant pathway is fluidly isolated with the heat reservoir.

19. The cooling system as claimed in claim 1, wherein the cooling system does not have external power supply.

20. The cooling systems as claimed in any one of claims 1~19, wherein the thermoelectric generator has a pipe-like structure.

21. The cooling systems as claimed in any one of claims 1~19, wherein the thermoelectric generator is connected into the coolant pathway, with coolant flowing through it.

22. The cooling systems as claimed in any one of claims 1~19, wherein the heat reservoir has lower temperature than the heat source.

23. The cooling systems as claimed in any one of claims 1~19, wherein the heat reservoir is a coolant storage tank.

24. The cooling system as claimed in claim 23, wherein the thermoelectric generator generates electricity by being heated by the coolant in the coolant pathway from one side and/or being cooled by the coolant in the coolant storage tank from the other side.

25. The cooling system as claimed in claim 23, wherein the thermoelectric generator is submerged in the coolant storage tank.

26. The cooling system as claimed in claim 23, wherein the thermoelectric generator generates electricity by being heated by the coolant in the coolant pathway from inside and/or being cooled by the coolant in the coolant storage tank from outside.

27. The cooling system as claimed in claim 23, wherein the coolant in the coolant storage tank is selected from the following substances including: water, aqueous solution, organic solution, gas, liquid metal or molten salts.

28. A residual heat removal system for a nuclear power plant, wherein the residual heat removal system comprises the cooling system as claimed in any one of claims 1-27.

29. The residual heat removal system as claimed in claim 28, wherein the heat source is a reactor core.

30. The residual heat removal system as claimed in claim 28, wherein the heat reservoir is a water tank.

31. The residual heat removal system as claimed in claim 28, wherein the coolant pathway is connected to a coolant circuit, such as the primary coolant circuit, of the nuclear power plant.

32. A cooling method comprising:

enabling a coolant to flow through or by a heat source and a heat reservoir, and the coolant is in thermo connection with a thermoelectric generator;

generating electricity with the thermoelectric generator;

pumping coolant to flow through or by the heat source and the heat reservoir, with a pump powered by the thermoelectric generator.

33. The cooling method as claimed in claim 32, wherein pumping the coolant to flow through a heat exchanger emerged in a heat reservoir, with a pump powered by the thermoelectric generator.

34. The cooling method as claimed in claim 32, wherein the heat reservoir is a coolant storage tank.

35. The cooling method as claimed in claim 33, further comprising agitating the coolant in the coolant storage tank by using electricity produced by the thermoelectric generator.

36. The cooling method as claimed in claim 32, further comprising realizing heat exchange between the coolant in the coolant pathway and the heat reservoir with one or more heat exchanger(s).

37. The cooling method as claimed in claim 32, further comprising allowing the coolant to flow only in a determined direction by using a check valve, and the check valve opens only when the pump or the thermoelectric generator fails.

38. The cooling method as claimed in claim 32, wherein generating electricity with the thermoelectric generator when temperature difference exits around the thermoelectric generator, for example, when temperature difference exits between two sides of the thermoelectric generator.

39. The cooling method as claimed in claim 32, wherein generating electricity with the thermoelectric generator by heating the thermoelectric generator with the

coolant in the coolant pathway and cooling the thermoelectric generator with the heat reservoir.

40. The cooling method as claimed in any one of claims 32~39, wherein the method using the cooling system as claimed in any one of claims 1-28.

41. A residual heat removal method for a nuclear power plant, comprising the cooling method as claimed in any one of claims 32-40.

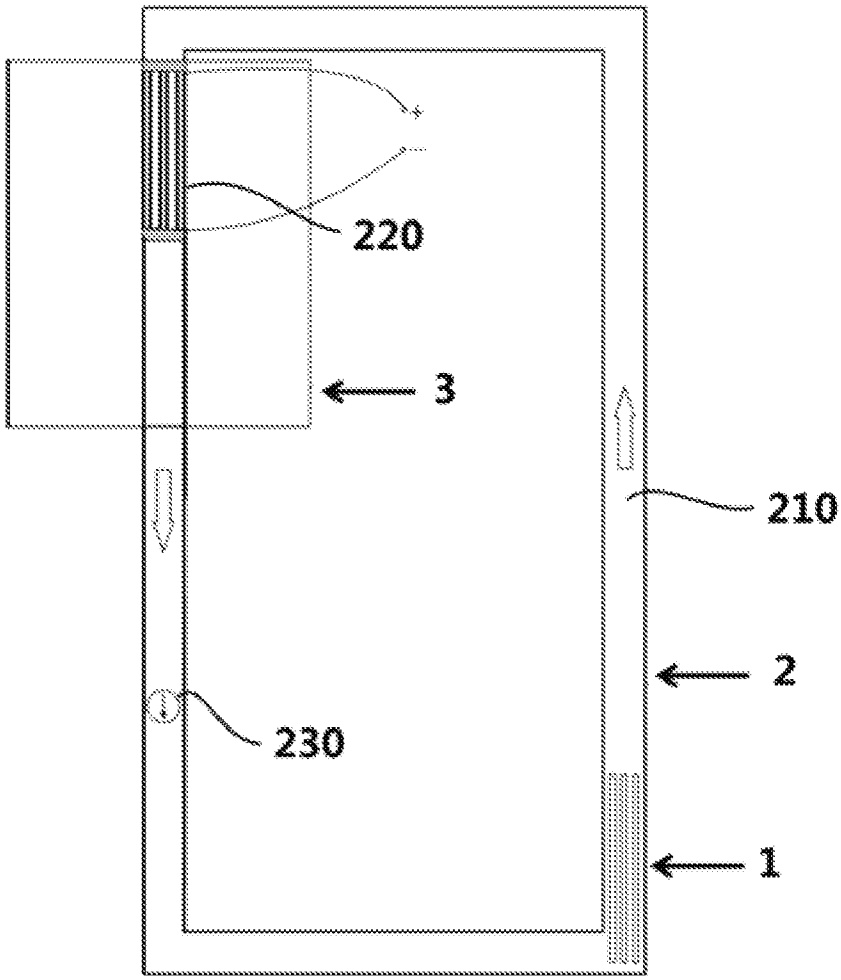


Fig. 1

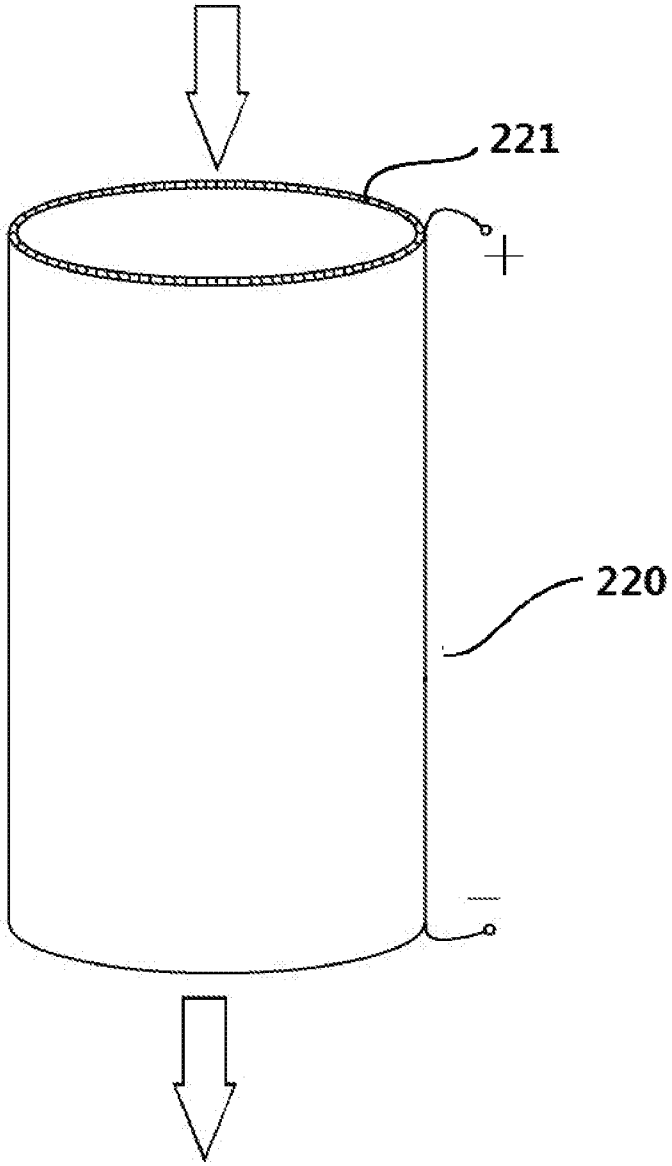


Fig. 2

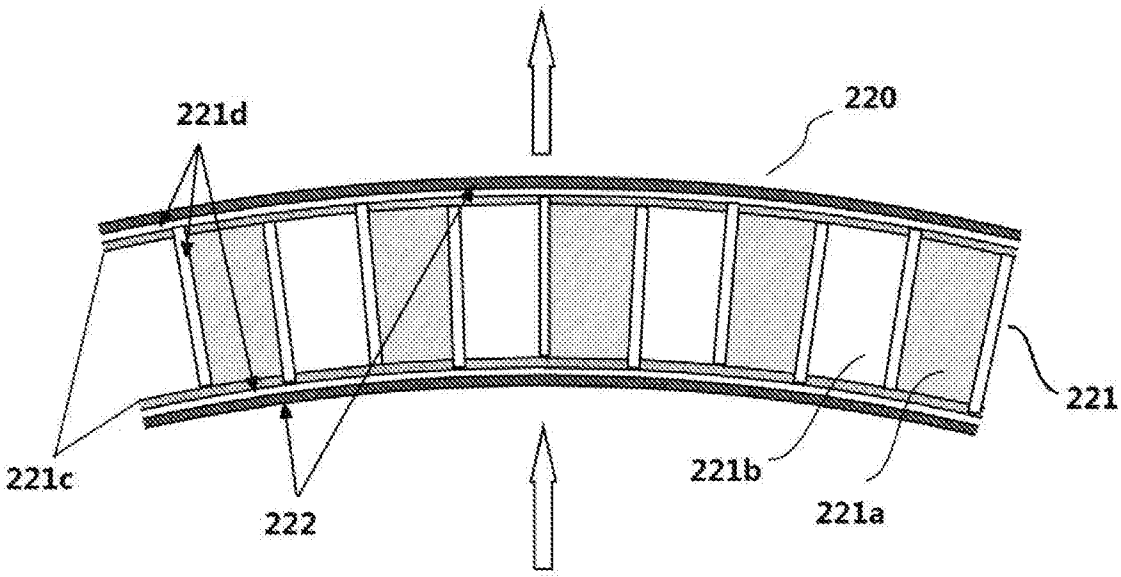


Fig. 3

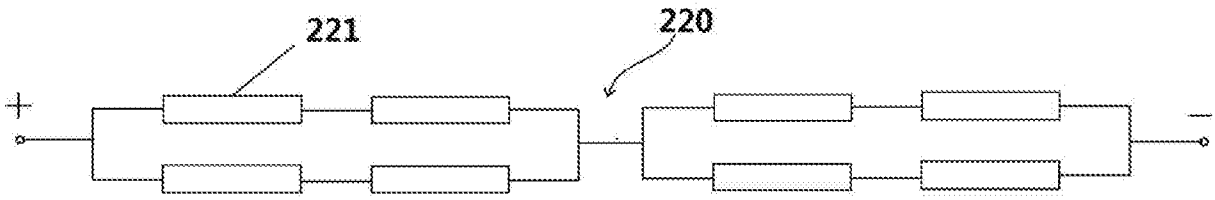


Fig. 4

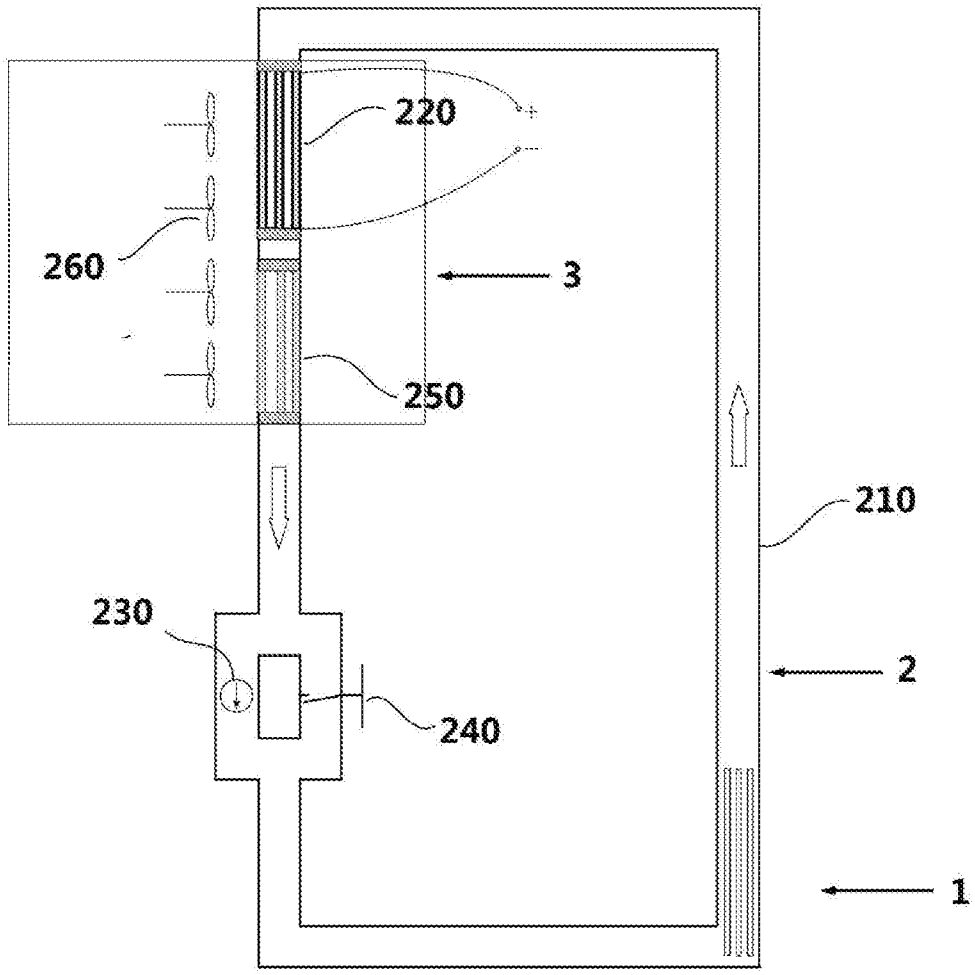


Fig. 5

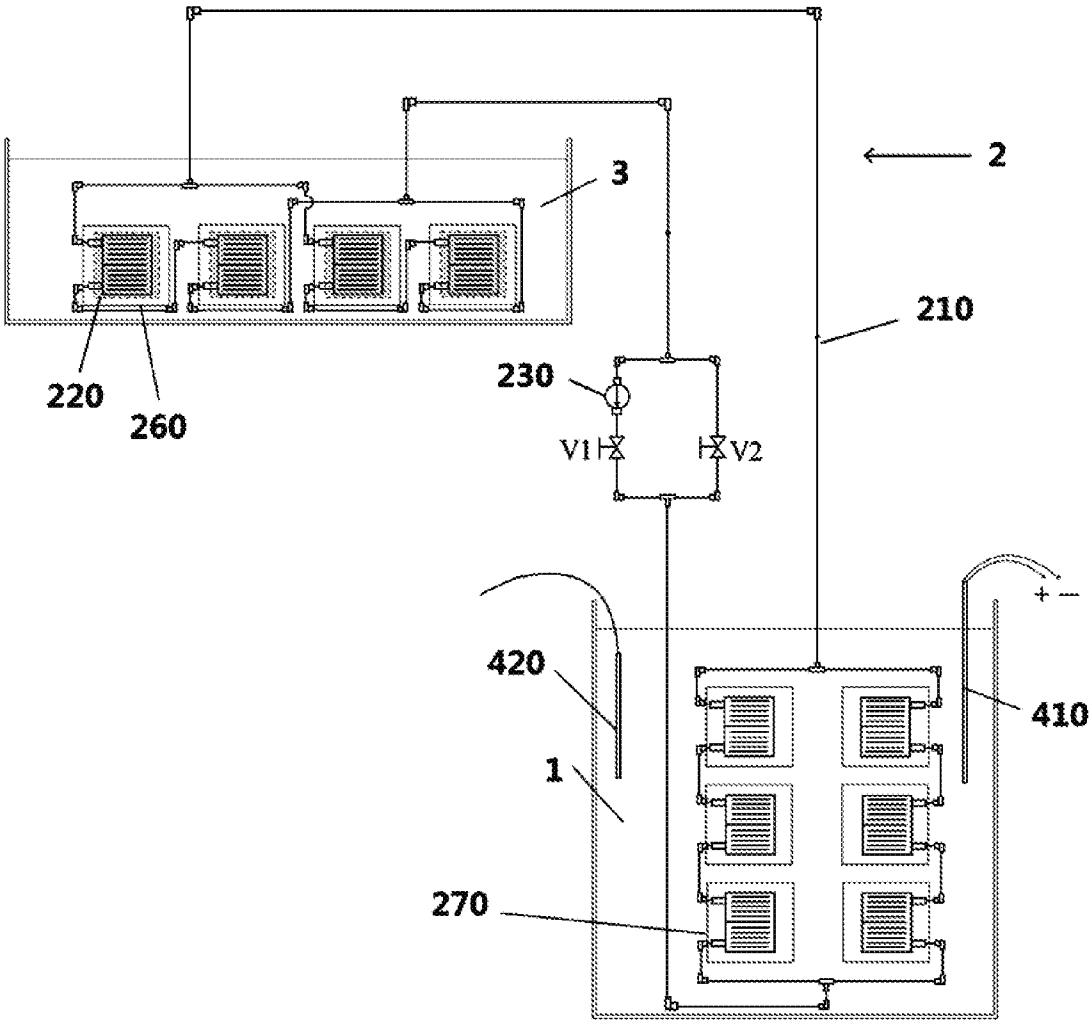


Fig. 6

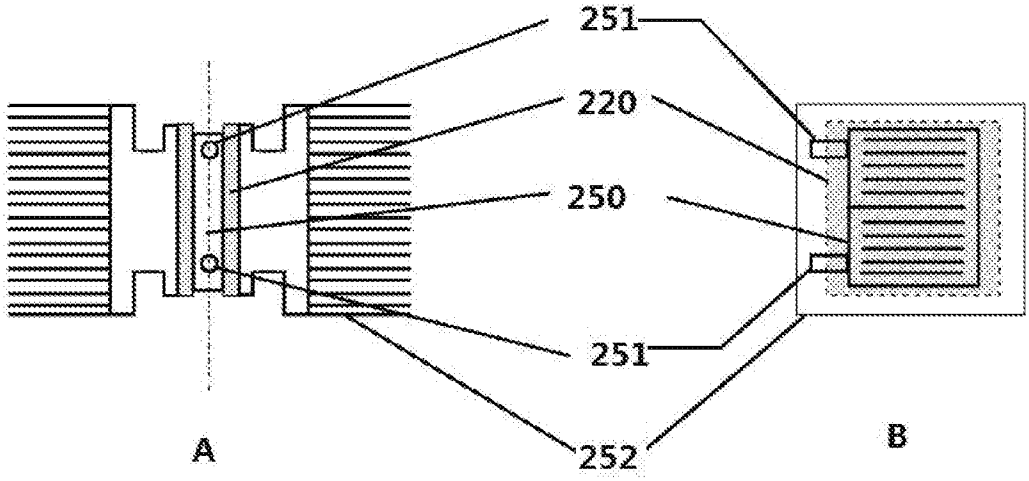


Fig. 7

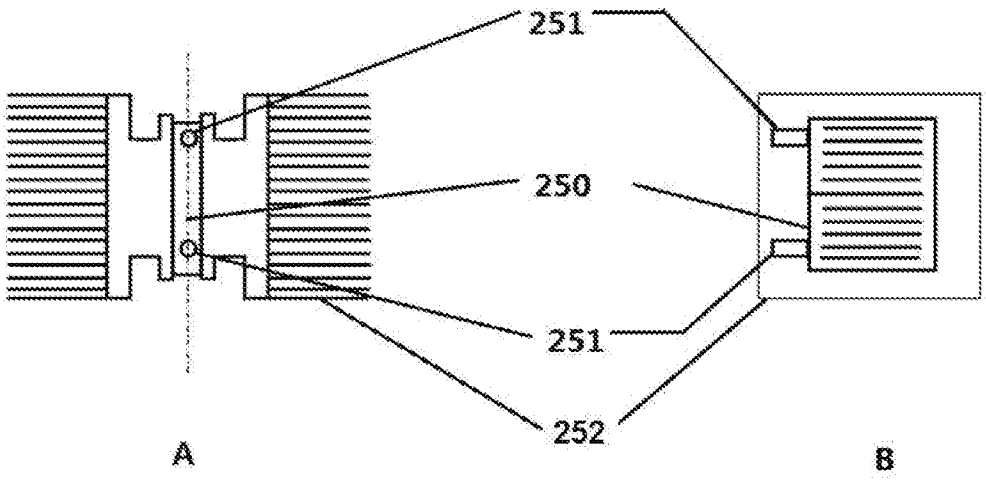


Fig. 8

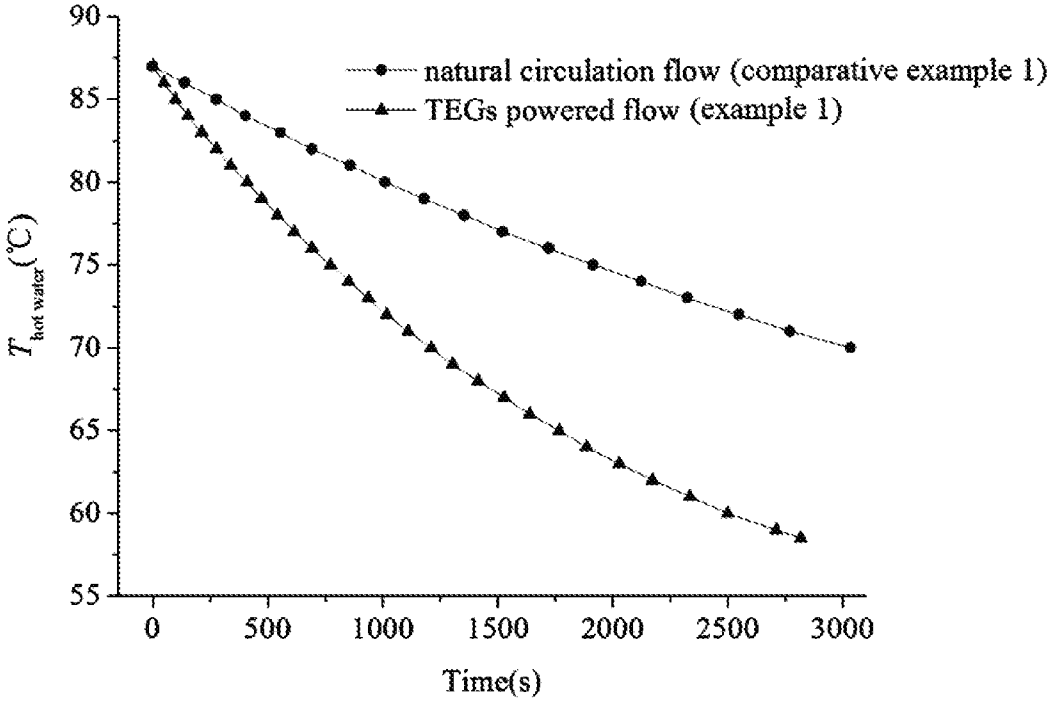

natural circulation flow (comparative example 1)
TEGs powered flow (example 1)
$T_{hot\ water}$(℃)
Time(s)

Fig. 9

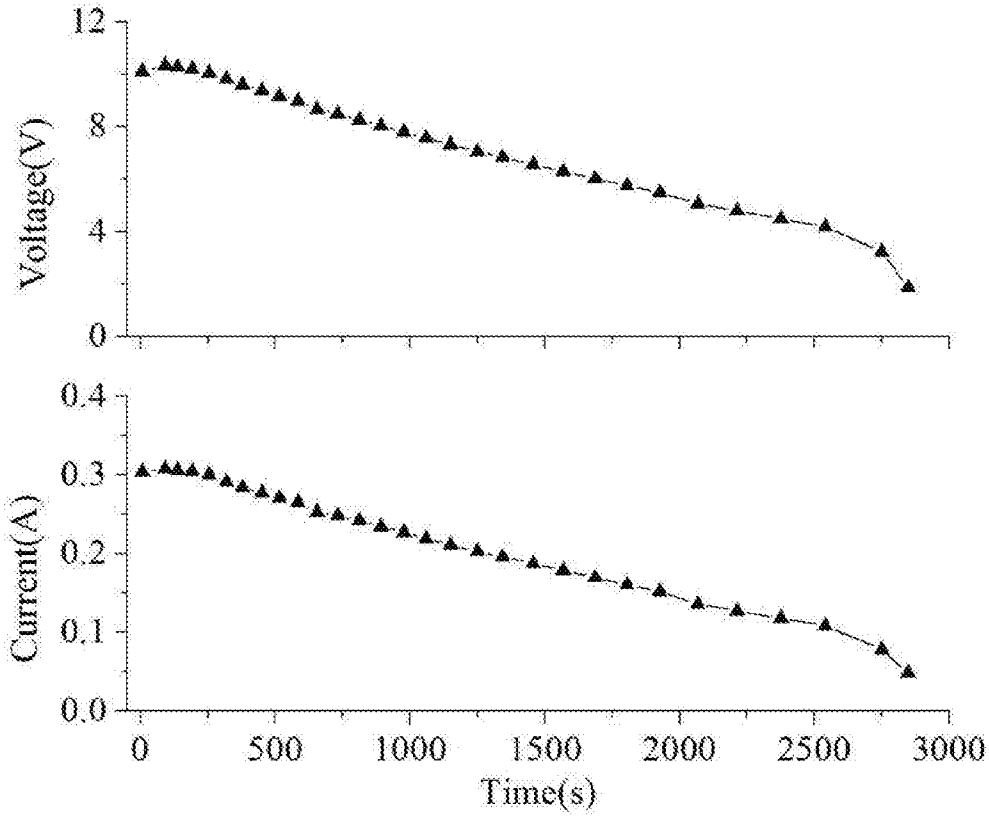

Voltage(V)
Current(A)
Time(s)

Fig. 10

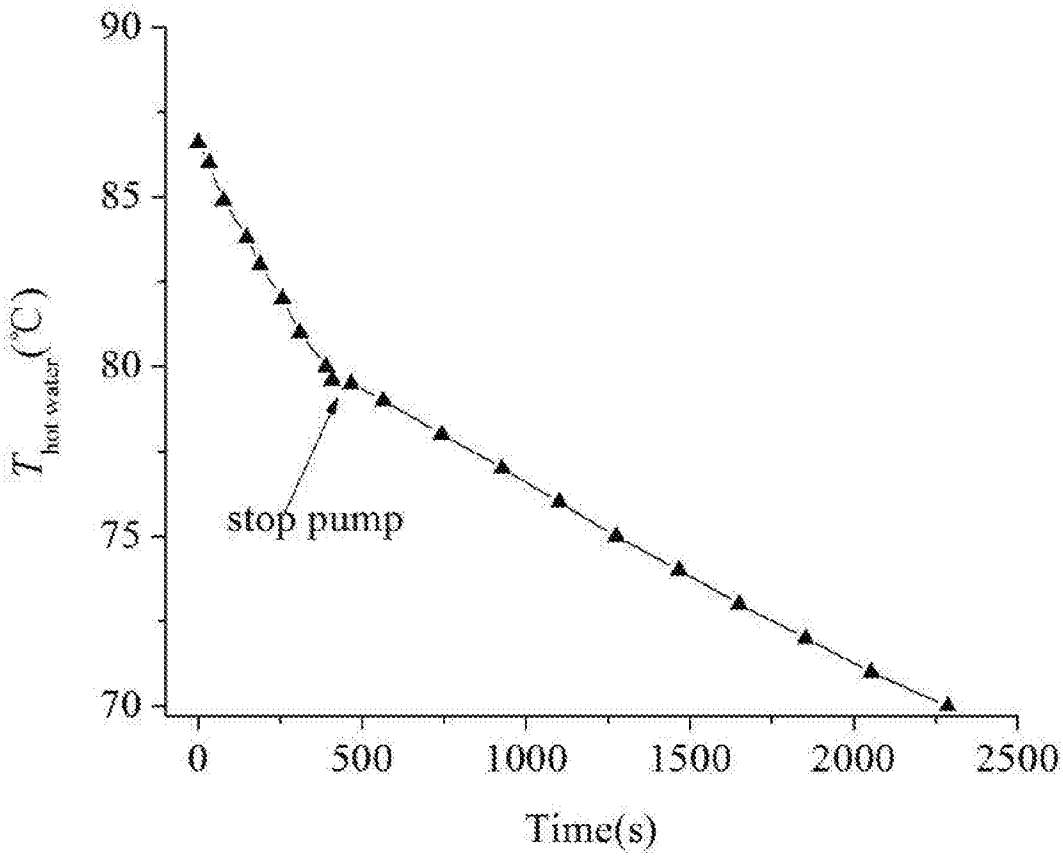

90
85
80
75
70
$T_{hot\ water}$(°C)
stop pump
0
500
1000
1500
2000
2500
Time(s)

Fig. 11

INTERNATIONAL SEARCH REPORT

International application No.
PCT/CN2016/075962

A. CLASSIFICATION OF SUBJECT MATTER

H01L 35/28(2006.01)i

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

H02N11/00;; H02N99/00;; H01L35/28;; H01L 35/30;; H01L 35/32;; G21H1/10

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

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

WPI, EPODOC, CNABS: cool+; thermo electric generat+; pump; fan; agitator; nucle; tank; water

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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☑ Further documents are listed in the continuation of Box C. ☑ See patent family annex.

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
19 November 2016	**14 December 2016**

Name and mailing address of the ISA/CN	Authorized officer
STATE INTELLECTUAL PROPERTY OFFICE OF THE P.R.CHINA **6, Xitucheng Rd., Jimen Bridge, Haidian District, Beijing 100088** **China**	**WU,Quanwei**
Facsimile No. **(86-10)62019451**	Telephone No. **(86-10)82245722**

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A	CN 102969938 A (NORTH CHINA ELECTRIC POWER UNIVERSITY) 13 March 2013 (2013-03-13) the whole document	1-41

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Information on patent family members

International application No.
PCT/CN2016/075962

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