System Description

Overview

The present invention relates to an improved operating method of the renewable source power generation method known as Ocean Thermal Energy Conversion utilizing the Magnetocaloric Effect to enhance the efficiency of the condensening system.

Detailed Description

The proposed system improves upon an existing method of renewable power generation known as Ocean Thermal Energy Conversion (OTEC) by employing the phenomenon known as the Magnetocaloric Effect (MCE). Background details of both OTEC and MCE are provided below.

OTEC is a method of power generation that uses temperature differences between ocean layers of different depths to drive a heat engine. In an OTEC system a working fluid with a low boiling point, in most cases pressurized Ammonia, is brought into thermal contact with the relatively warm waters in the upper or surface layers of a liquid body. This vaporizes the working fluid and its pressure rises. The vaporized working fluid is then used to drive a prime mover, usually a turbine driving an electrical generator. After leaving the prime mover the working fluid is brought into thermal contact with relatively low temperature water from deeper ocean layers which removes heat from the working fluid allowing it to recondense and be returned to the start of the system. This method of power generation has many advantages, being a way to continuously generate power from a widely available source with zero carbon emissions. The drawbacks of the system however prevent it from being employed on a large scale currently. These include: 1. The necessity of a high temperature differential between the warm and cold water layers, high enough differentials being almost exclusively found in tropical and subtropical waters, limiting the range of the system.

2. Related to number one, owing to the need for high temperature differentials, the cold layer water must be pumped from very deep, usually a kilometer or more, in order to reach sufficiently cold ocean layers. This presents a number of engineering challenges and confines the system mostly to large scale installations. Thus the present invention proposes the use of a condensing system that utilizes the Magnetocaloric Effect (MCE) to amplify temperature differences between the warm and cold layers and thus expand the systems range and scope. The Magnetocaloric Effect is a magneto-thermodynamic phenomenon defined as: “A reversible change in the temperature of a magnetizable substance in a magnetic field of varying intensity with the temperature rising or falling accordingly as the field intensity is increased or decreased. MCE is an intrinsic property of magnetic materials. This effect is due to the coupling of a magnetic field with the magnetic sublattice. The isothermal magnetization of a paramagnet or a soft ferromagnet reduces the entropy. In the reverse process, demagnetization restores the zero field magnetic entropy of a system. In this process, the temperature of the system is lowered. At constant pressure the entropy of a magnetic solid, $S(T\ H)$, (function of both the magnetic field strength (H) and the absolute temperature (T)) is the sum of magnetic

contribution $S_M(T\ M)$, the entropy associated with the lattice $S_L(T)$ and electronic contribution $S_E(T)$ as put in eqn [1]:

$$S(T, H) = S_{vM}(T, H) + S_{vE}(T) + S_{vL}(T)$$

The lattice and electronic contributions are essentially independent of magnetic fields, whereas the magnetic entropy is lowered due to ordering of the magnetic spins when subjected to an external magnetic field. The lowering of magnetic entropy results in an increase of the lattice entropy if the material is kept isolated from its surroundings, that is, under adiabatic conditions."[1][2]

A method for cooling using this effect follows four basic steps:

1. Magnetic field is introduced/intensity is increased to Magnetocaloric Material (MCM) held in thermal isolation, causing the temperature of the MCM to rise.
2. With the magnetic field held constant, a Heat Transfer Fluid (HTF) is brought through thermal contact with the MCM, removing the heat of magnetization.
3. The MCM is again thermally isolated and the magnetic field is removed/intensity is decreased, causing the MCM to lower in temperature.
4. A HTF is again brought through thermal contact with the now lower temperature MCM, sinking heat and lowering in temperature.

By employing a condensing system utilizing this effect the temperature differential between the Warm and Cold water layers (heat source and heat sink) may be amplified, allowing for operation across a shorter vertical pumping distance, allowing for smaller and more efficient systems to be constructed. Additionally, decreasing the minimum temperature range between Warm and Cold water layers allows the system to operate across a broader climatic range, permitting operation in temperate waters as well as tropical and subtropical waters.

Operating Methods

<u>Pre-Cooling of Incoming Cold Layer Water Stream</u>

In this arrangement the Cold Layer Water (CLW) stream from the deeper water layer is cooled prior to entering the condenser. This is accomplished by pumping the CLW through thermal contact with the Magnetocaloric Material (MCM) as it is cyclically magnetized and demagnetized. As the MCM is magnetized/demagnetized, a series of solenoid valves direct the flow of the CLW. During the magnetized stage, the discharge solenoid is open while the condenser feed solenoid is closed, allowing the CLW to remove the heat of magnetization from the MCM and discharge it outside the system. During the demagnetized stage the discharge solenoid is closed and the condenser feed solenoid is open. The CLW sinks heat to the lower temperature MCM as it passes through thermal contact. In this way the CLW temperature is lowered before it enters the condenser. A single heat exchanger arranged this way is capable of pre-cooling the CLW before entering the condenser. However, an arrangement of two or more heat exchangers, as in the illustration, allows for continuous flow of pre-cooled CLW to the condenser, as one or more heat exchanger(s) may be in the magnetized-discharge valve open-condenser feed valve closed state while the other(s) are in the demagnetized-discharge valve closed-condenser feed valve open state. A description of the illustration detailing process flow and components is provided below.

Illustration Components:

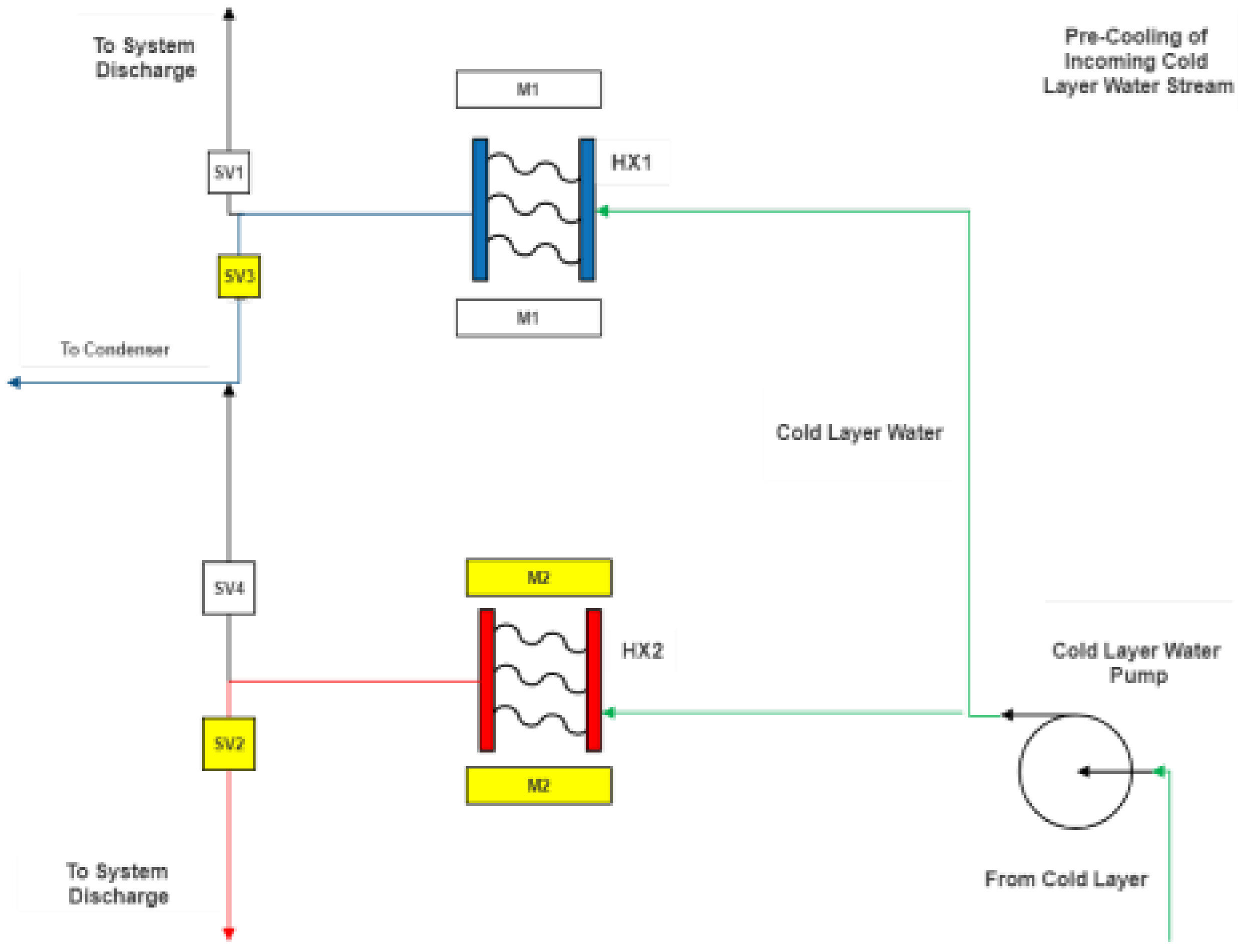
CLW Pump
CLW- Cold Layer Water flow
HX1- Magnetocaloric Material Heat Exchanger (de-magnetized, indicated by blue)
HX2- Magnetocaloric Material Heat Exchanger (magnetized,indicated by red)
SV1- Discharge Solenoid Valve (closed)
SV2- Discharge Solenoid Valve (open,indicated by yellow)
SV3- Condenser Feed Solenoid Valve (open, indicated by yellow)
SV4- Condenser Feed Solenoid Valve (closed)
M1- Magnet for HX1 (disengaged)
M2-Magnet for HX2 (engaged, indicated by yellow)

*For M1 & M2 engaged and disengaged refers to either the magnetic field being physically in or out of contact with the heat exchangers for a reciprocating/rotating magnet arrangement, or for the magnet being energized/de-energized in an electromagnet arrangement.

* The color indications listed above are used throughout the illustrations, with yellow indicating the energizing/engaging of electrical and magnetic components, red indicating Magnetocaloric Material that is magnetized, and blue indicating Magnetocaloric Material that is demagnetized.

Illustration Description:

The system illustrated contains two heat exchangers constructed of Magnetocaloric Material (MCM) (HX1 & HX2) that are alternately magnetized and demagnetized by magnets M1 & M2. The CLW Pump draws water from the Cold Layer and pumps it through thermal contact with HX1 & HX2. The illustration shows the two heat exchangers in opposite states, with HX1 being demagnetized, and therefore operating as a heat sink to cool the incoming CLW stream, and HX2 being magnetized and the incoming CLW removing the heat of magnetization. CLW passes through thermal contact with the MCM in HX1 and sinks heat to the lower temperature MCM. The solenoid arrangement after HX1 in this state has the Discharge Solenoid (SV1) closed and the Condenser Feed Solenoid (SV3) open, allowing the cooled CLW to flow to the condenser to condense the Working Fluid. The solenoid arrangement after HX2 has the Discharge Solenoid (SV2) open and the Condenser Feed Solenoid (SV4) closed, allowing the CLW to remove the heat of magnetization from the MCM in the heat exchanger and discharge it from the system. The heat exchangers alternate states, allowing for continuous flow of cooled CLW to the condenser.



Economizing Using Warm Layer Water Discharge

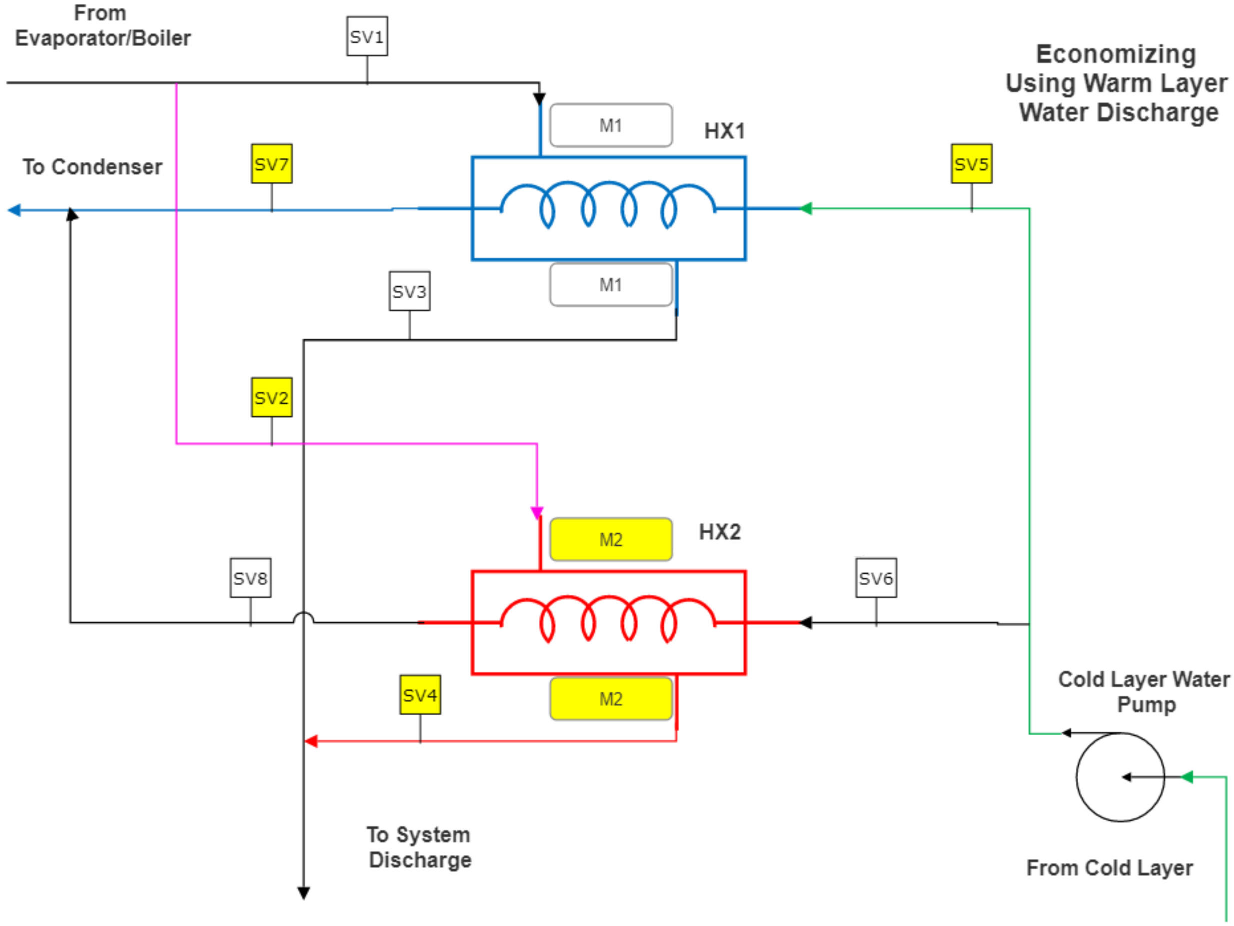
In this arrangement the Cold Layer Water is cooled prior to entering the condenser as in the previous method. In this arrangement however, the discharge of Warm Water from the Evaporator/Boiler is used to remove the heat of magnetization from the alternatively magnetizing-demagnetizing MCM heat exchangers. A detailed description is provided below.

Illustration Components:

HX1 - Heat Exchanger (demagnetized)
HX2 - Heat Exchanger (magnetized)
M1 - Magnets (disengaged)
M2 - Magnets (engaged)
Cold Layer Water Pump
SV1 & SV2 - Warm Layer Water inlet solenoids to heat exchangers (SV1 closed, SV2 open)
SV3 & SV4- Warm Layer Water discharge solenoids from heat exchangers to system discharge (SV3 closed, SV 4 open)
SV5 & SV6 - Cold Layer Water inlet solenoids to heat exchangers (SV5 open, SV6 closed)
SV7 & SV8 - Cold Layer Water discharge solenoids from heat exchangers to condenser (SV7 open, SV8 closed)

Illustration Description:

Both heat exchangers are alternately magnetized and demagnetized. In the illustration HX2 is magnetized, with the Warm Layer Water inlet and discharge solenoids open. In this state the Warm Layer Water leaving the evaporator/boiler will flow through thermal contact with the magnetized MCM heat exchanger, removing the heat of magnetization before being discharged from the system. HX1 is meanwhile in the demagnetized state, with the Cold Layer Water inlet and discharge solenoids open, allowing the Cold Layer Water to flow through thermal contact with the lower temperature demagnetized MCM heat exchanger, sinking heat to it and lowering in temperature before being fed to the condenser. The heat exchangers alternate between magnetized-Warm Layer Water solenoids open and demagnetized-Cold Layer Water Solenoids open, allowing for continuous cooling of the incoming Cold Layer Water Stream.



<u>Cooling of Heat Transfer Fluid</u>

In this arrangement a Heat Transfer Fluid (HTF) circulating in a closed loop is used as the cooling fluid in the condenser in the place of CLW. Similar to the above arrangement the CLW is pumped through thermal contact with MCM heat exchanger(s). However, in this arrangement only during the magnetized stage does this occur. During the demagnetized stage the HTF is pumped through thermal contact with the MCM heat exchanger, sinking the heat picked up from the condenser to the lower temperature MCM and being cooled before returning to the condenser. A description of the illustration detailing process flow and components is provided below.

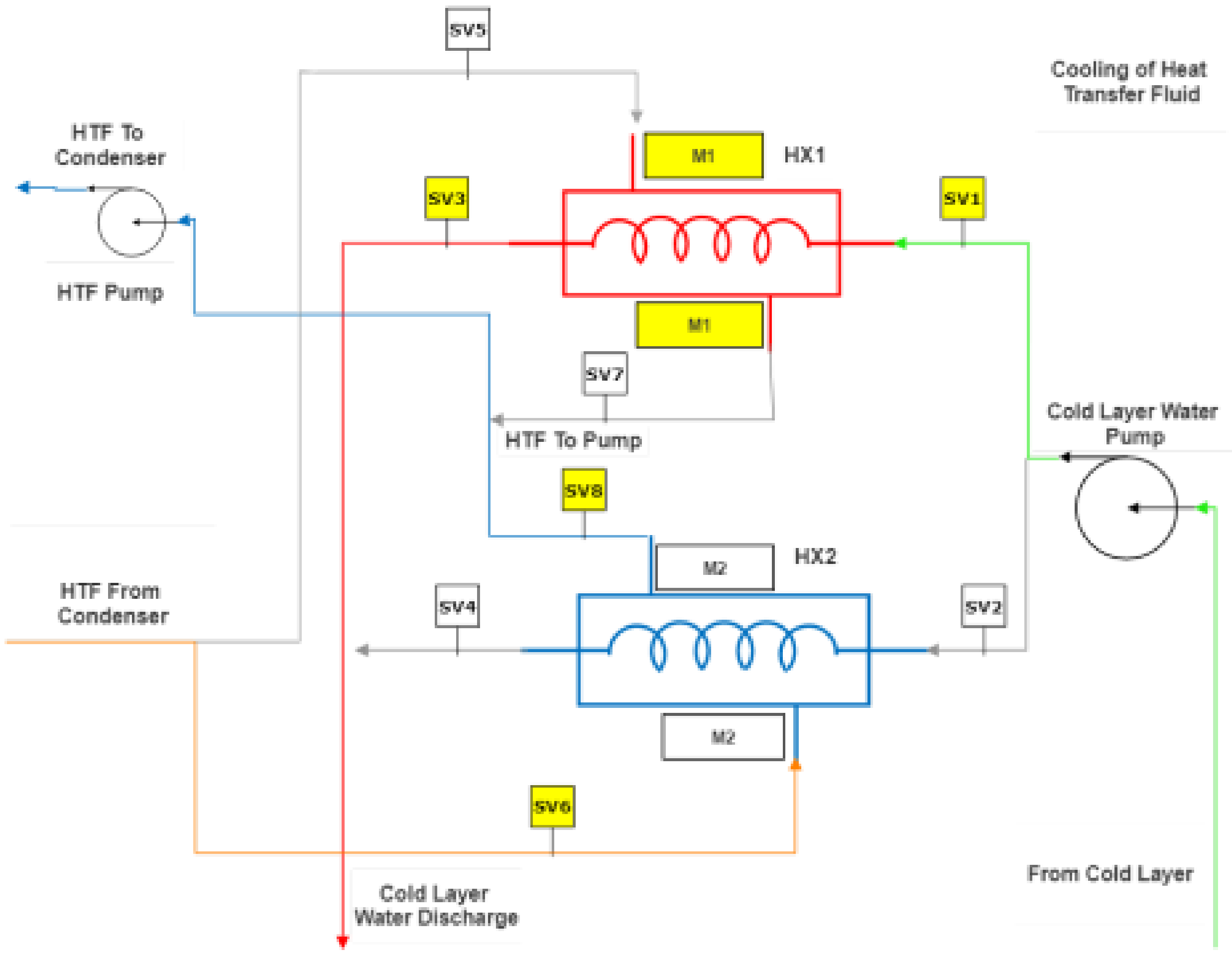
Illustration Components:

CLW(Cold Layer Water) Pump
HTF(Heat Transfer Fluid) Pump
CLW- Cold Layer Water flow
HX1- Heat Exchanger One (magnetized)
HX2- Heat Exchanger 2 (demagnetized)
SV1 & SV2- CLW inlet solenoids to heat exchangers (SV1 open, SV2 closed)
SV3 & SV4- CLW discharge solenoids from heat exchangers (SV3 open, SV4 closed)
SV5 & SV6- HTF inlet solenoids to heat exchangers (SV5 closed, SV6 open)
SV7 & SV8- HTF discharge solenoids from heat exchangers (SV7 closed, SV8 open)
M1- Magnet for HX1 (engaged)
M2- Magnet for HX2 (disengaged)

Illustration Description:

Two heat exchangers constructed of MCM (HX1 & HX2) are alternately magnetized and demagnetized by magnets (M1 & M2). Two pumps, the CLW Pump and the HTF Pump, pump their respective fluids through thermal contact with the two heat exchangers. The direction of fluid flow is controlled by solenoid valves (SV1-SV8). In the illustration, M1 is engaged and HX1 is magnetized. SV1 and SV3 are open, allowing the CLW to be pumped through thermal contact with HX1, removing the heat of magnetization and discharging it outside the system. SV5 and SV7 are closed, preventing HTF fluid flow through HX1. M2, meanwhile, is disengaged and HX2 is demagnetized. SV2 and SV4 are closed, preventing CLW flow through HX2. SV6 and SV8 are open, allowing the HTF to be pumped through thermal contact with the colder demagnetized MCM in HX2 and sink heat removed from the working fluid in the condenser before returning to the HTF pump to be pumped back to the condenser. The system alternates states, magnetizing one heat exchanger and pumping CLW through while demagnetizing the other heat exchanger and pumping HTF through. This enables the system to provide continuous cooling to the condenser.

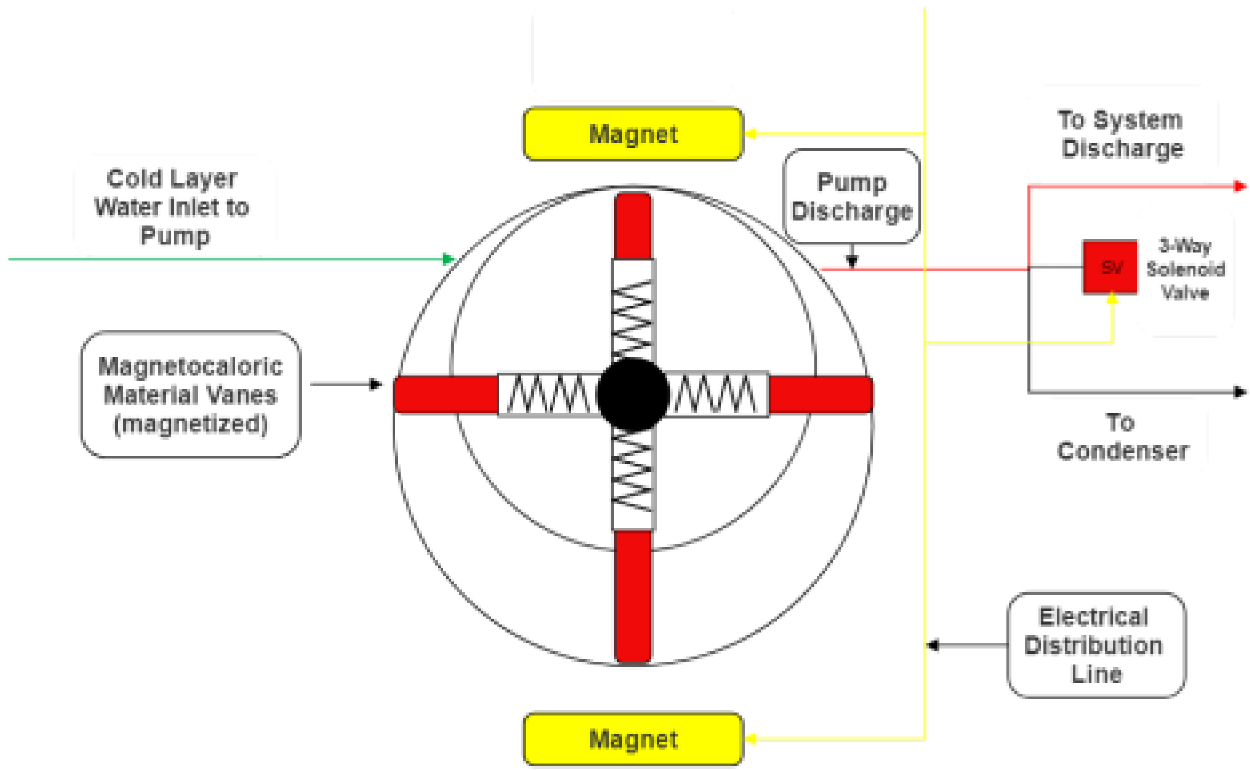
*The above described arrangement may also be employed to directly condense the working fluid in the heat exchanger, with the working fluid taking the place of the heat transfer fluid in the illustration and description.



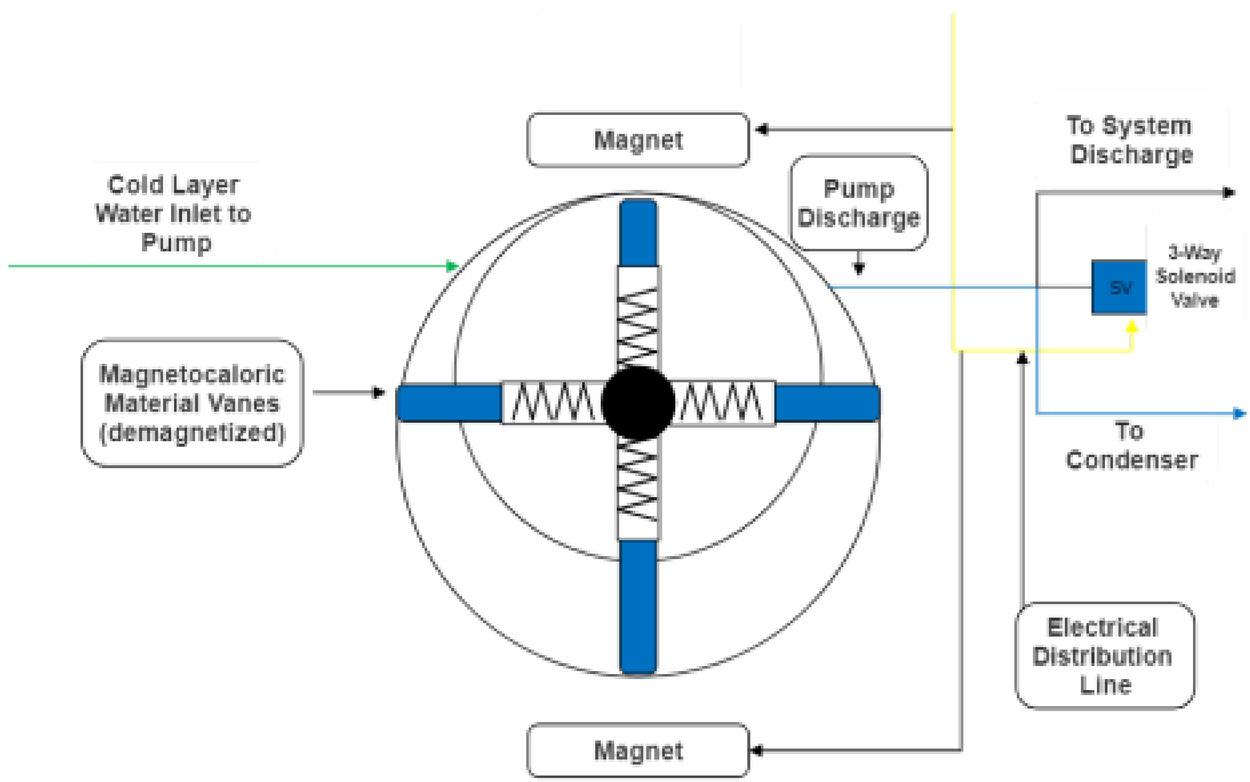
<u>Magnetocaloric Material Pump</u>

In this arrangement the components of the Cold Layer Water pump physically contacting the fluid are composed of or imbued with magnetocaloric materials with a magnetic field cyclically engaging and disengaging. In the illustration a vane type pump is shown with vanes constructed of magnetocaloric material. With the magnets engaged a three-way solenoid directs flow to the system discharge, allowing the Cold Layer Water to remove the heat of magnetization from the vanes and discharge it from the system. With the magnets disengaged the Cold Layer Water sinks heat vanes and lowers in temperature and the three-way solenoid directs flow to the condenser. In the illustration the magnets are electromagnets fed by the power distribution line from the prime mover generator to the parasitic loads.

*This method may alternately use reciprocating/rotating permanent or electromagnets.
*This method can alternately be used in a duel Cold Layer Water/Heat Transfer Fluid pump.



Magnet(s) Engaged and Magnetocaloric Material Magnetized



Magnet(s) Disengaged and Magnetocaloric Material Demagnetized

Magnetization Methods

Rotating/Reciprocating Magnet Arrangement

In this method magnetization of the MCM physically moves a magnetic field in and out of contact with the MCM. This is achieved by either rotating, reciprocating, or a combination of both, permanent or electro-magnet(s) at a frequency corresponding to the fluid cycles of the system. To do this, an electric motor drawing power from the prime mover generator may be used. Alternately direct mechanical power transmission from the prime mover may be provided, or the motion may be driven by a fluid motor powered by CLW or WLW (Warm Layer Water) discharge, working fluid discharge from the prime mover, etc.

Electromagnet Arrangement

In this arrangement magnetization of the MCM is achieved by cyclically energizing and de-energizing electromagnet(s) at a frequency corresponding to the system fluid cycles. The power for energizing the electromagnet(s) may be drawn directly from the prime mover generator. Alternatively, as a means of economizing the system, the electromagnet(s) may be placed in line with the electrical distribution to the ancillary parasitic loads. The latter is shown in the illustration. A description of the illustration detailing process flow and components is provided below.

Illustration Components:

Generator (Driven by Prime Mover)

Working Fluid Pump

Warm Layer Water Pump

Cold Layer Water Pump

SM1- Electrical Switching Mechanism (circuit open)

SM2- Electrical Switching Mechanism (circuit closed)

R1 & R2- AC-DC Rectifiers

EM1- Electromagnet for HX1 (de-energized)

EM2- Electromagnet for HX2 (energized)

I1 & I2- DC-AC Inverters

HX1- MCM Heat Exchanger (de-magnetized)

HX2- MCM Heat Exchanger (magnetized)

SV1- Discharge solenoid valve from HX2 (open)

SV2- Solenoid valve from HX2 to condenser feed (closed)

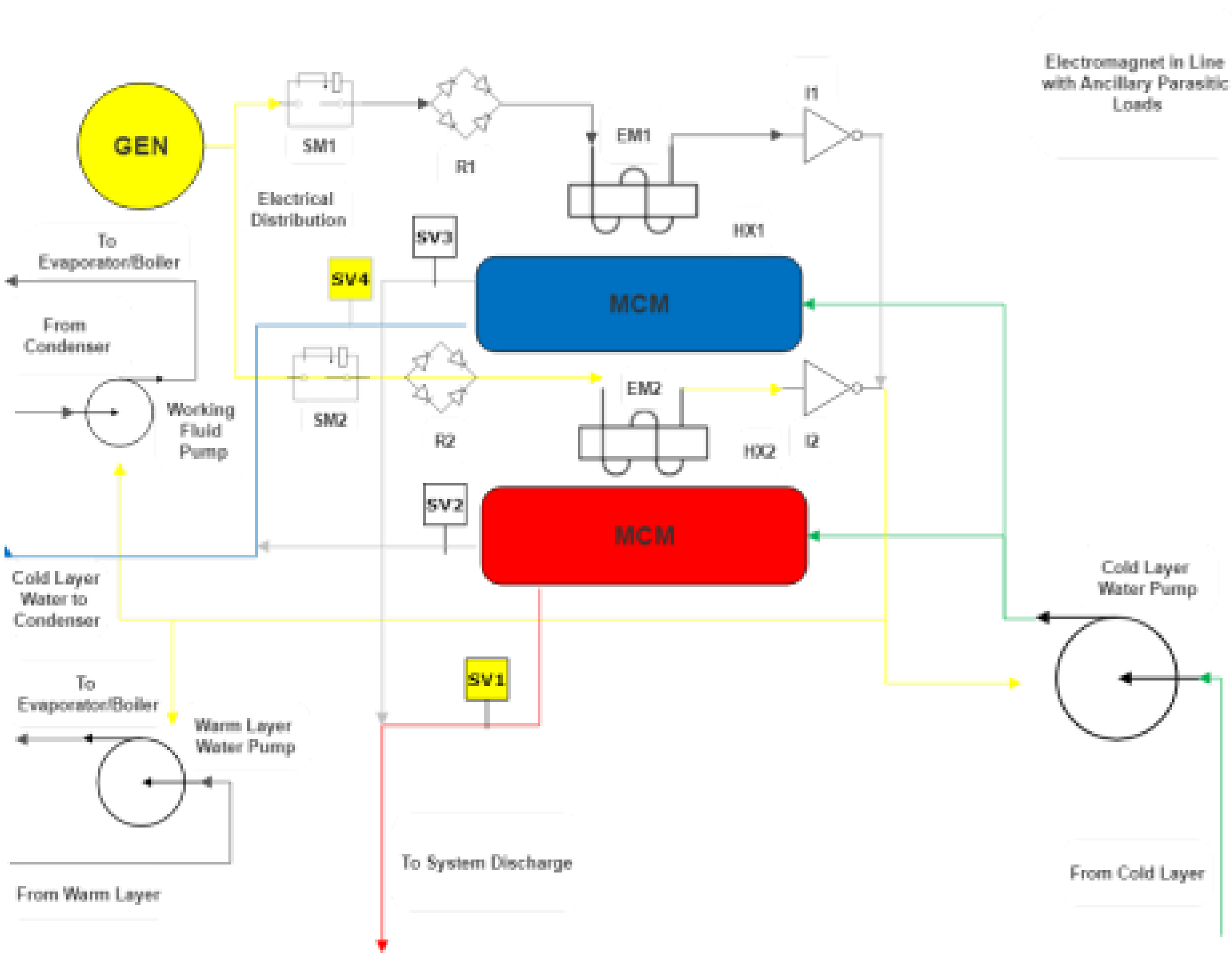
SV3- Discharge solenoid from HX1 (closed)

SV4- Solenoid valve from HX1 to condenser feed (open)

L1- Electrical Power Distribution (indicated by yellow line)

Illustration Description:

In this arrangement the electrical distribution lines to the ancillary parasitic loads (Working Fluid Pump, Warm Layer Water Pump, Cold Layer Water Pump) are used to magnetize a ferrous core and produce an electromagnet that magnetizes the MCM Heat Exchangers. In the illustration, electrical power from the generator feeds to two electrical switching mechanisms (SM1 & SM2). SM1 is open and the circuit is de-energized while SM2 is closed and the circuit is energized. With SM2 closed and the circuit energized, current flows through the switching mechanism to the AC-DC rectifier R2, changing the incoming current from AC to rectified DC. From R2 the rectified DC current flows to the electromagnet EM2. At EM2 the current carrying conductor is looped around a highly permeable ferrous core, producing a magnetic field that magnetizes the MCM in HX2. From here the current flows to Inverter I2 where it is changed back to AC before being distributed to the ancillary parasitic loads. This method of magnetization is shown in the illustration being used in the Pre-Cooling of Incoming Cold Water Layer Stream method, with the current energizing EM2 and magnetizing the MCM in HX2 while the discharge valve SV1 is open and the condenser feed valve SV2 is closed, allowing the CLW to remove the heat of magnetization and discharge it from the system. Electrical switching mechanism SM1 is open and the circuit is de-energized, and thus the MCM in HX1 is in the demagnetized state, the discharge valve SV3 is closed and the condenser feed solenoid SV4 is open, allowing the low temperature MCM to remove heat from the incoming CLW in HX1 before it is fed to the condenser. SM1 and SM2 alternate open and closed states to allow for cyclic magnetizing and demagnetizing of the MCM while maintaining constant current flow to the ancillary parasitic loads.



Magnetocaloric Materials

While the Magnetocaloric Effect is an intrinsic property of all magnetic materials, the materials best suited to magnetic cooling applications are those exhibiting a large temperature change relative to the exposed magnetic field strength. At present, the most promising materials for magnetic cooling applications include Gadolinium, Dysprosium, Dysprosium-Erbium-Aluminum alloy, Gadolinium-Silicon-Germainium alloy, FeRh, La0.8Ca0.2Mn03, Gd5Si2Ge2,Tb5Si2Ge2, and MnAs. These materials represent a portion of the materials currently known to exhibit large temperature changes relative to the applied magnetic field and thus hold potential for use in magnetic cooling applications. Ongoing materials research continues to identify new materials and alloys with potential in this area. Combinations and doping of these materials yield property variations that permit the tuning of the materials to meet cooling demands across a wide temperature span.

System Applications

The ability to produce usable energy from thermal differences in ocean layers across a broad climatic spectrum presents a multitude of potential applications. The most obvious would be the generation of electricity to be fed directly to nearby grids from either land based or offshore floating or fixed installations. Additionally, this method may be used as the primary power source
in land based or offshore installations using the energy generated to power Hydrogen production by desalinating seawater and separating Hydrogen and Oxygen atoms through electrolysis. The system may also be used by vessels to generate Hydrogen for propulsion, power batteries for electric propulsion systems, or power auxiliary loads. Smaller scale applications may include the powering of offshore data collection and signaling equipment.

References

1. “Magnetocaloric effect.” *Merriam-Webster.com Dictionary*
2. Y. Mozharivskyj, *Reference Module in Chemistry, Molecular Sciences and Chemical Engineering*, 2016