An Autonomous Mechanical Maxwell's Demon

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Szilard proposes three engine models in 1929 to resolve several paradoxes arising from Maxwell's Demon[1,2]. We analyze Szilard's second demon models[1,2]. We show that the second one, apparently employs distinct molecular species and semi-permeable membranes. On this basis, we propose a fourth model of Szilard's engines. The mechanism of this model is based on Raoult's law and Van't Hoff's law in colligative properties of aqueous solutions, coupling the evaporating process of water molecules with the reverse osmosis process of water molecules, forms a spontaneous thermodynamic cycle composed.We find:(i) The cycle can proceed spontaneously in a gravitational field, without the need for an external force to do its work;(ii) The continuous flow of water molecules in the cycle, like the continuous current in a superconducting ring, can continue for a long time, but it is not a perpetual motion machine and does not violate the second law of thermodynamics;(iii) The cycle is capable of doing what Maxwell's Demon does, it is capable of producing a temperature difference in a single hot bath heated at temperature equilibrium. (iv) Its transitory functioning as an engine that converts disorganized heat energy to work is governed by the Onsager reciprocal relations. Taken together, this Szilard's fourth model is a new self-consistent, non-equilibrium thermodynamic cycle that provides a new theoretical model for understanding that quasi-perpetual motion processes and autonomous mechanical Maxwell's Demon do exist in nature.

Keywords: Maxwell’s demon, evaporation-reverse osmosis, spontaneous circulation, Onsager reciprocal relations, quasi-perpetual motion process

1. Introduction

The Maxwell's Demon has undergone many versions since its inception and is still thriving in physics today. But these models require the introduction of an outside intelligent being to do work on Maxwell's Demon. In recent years, Maxwell's Demon researchers have shifted their focus from designing Maxwell's Demon that require external manipulation to Maxwell's Demon that can operate independently and automatically. For example, physicist Leo Szilard does not like

the idea of "using supernatural, human-like intelligence to manipulate the Maxwell's Demon", and believes that it should be possible to create an automatic or even mechanical system that has the functions of a Maxwell's Demon, but fully abides by the laws of physics. While this idea is appealing, it has always existed only in theoretical scenarios[3].

We believe that Maxwell's Demon, while a feedback system, is at its core capable of creating a temperature difference in a Single Heat Bath of temperature equalization. If a mechanical system is able to create a temperature difference by operating itself in an initial environment of temperature equilibrium, then that mechanical system should be a Maxwell's Demon.

We analyze Szilard's second demon models[1,2] and propose a new model based on them, which we call "Szilard's fourth engine". The mechanism of this model is based on Raoult's law and Van't Hoff's law in colligative properties of aqueous solutions, coupling the evaporating process of water molecules with the reverse osmosis process of water molecules, forms a spontaneous thermodynamic cycle composed of quasi-permanent water molecules. This cycle fulfills the function of Maxwell's Demon.

2. Szilard's second engine

Szilard's second engine though a markedly different implementation employing a population of distinct molecular species and semi-permeable membranes, is informationally and thermodynamically equivalent to an ideal gas of the single-molecule engines[2]. The principle of the thermodynamic transformation that it realizes for measuring, controlling and erasing is shown in Fig. 1

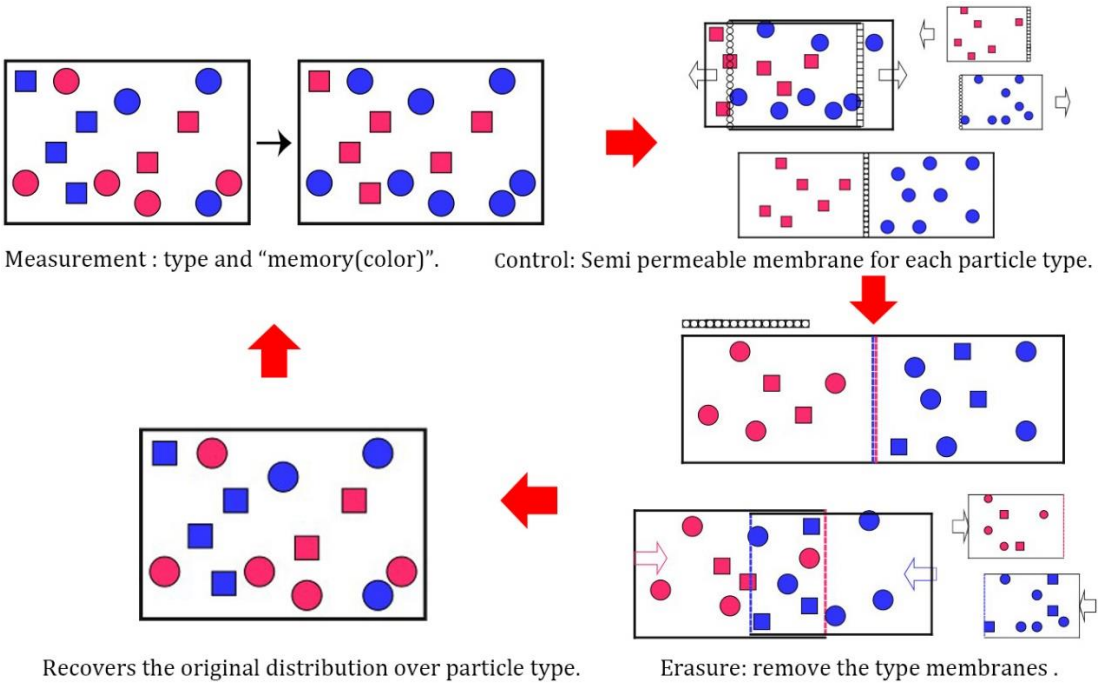

Fig. 1. Szilard's second engine employing a population of distinct molecular species and semi-permeable membranes to achieve thermodynamic transformations of measurement, control, and erasure[2]. Reprinted from *Variations on a Demonic Theme: Szilard's Other Engines,* by Kyle J. Ray, James P. Crutchfield. arXiv:2003.09990.

Sziard's second engine requires the introduction of a metaphysical, human-like intelligence to operate Maxwell's demons in order to keep the cycle running autonomously. He thought that it should be possible to construct autonomous, maybe even mechanical, systems that act like a demon yet fully obey the laws of physics—a fully inclusive conceptual approach[3].

3. Raoul's law and Van't Hoff's law

3.1 Raoul's law

The principle of Raoul's law is shown in Fig. 2.

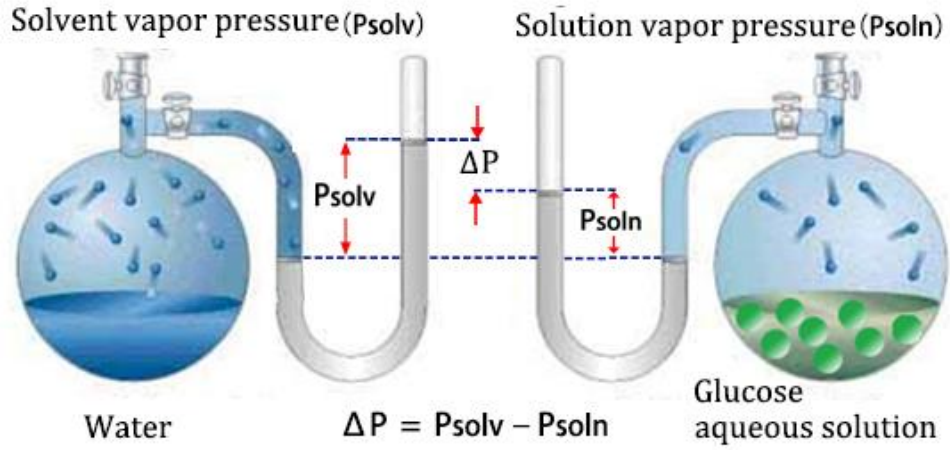

Fig. 2. Drop of solution vapor pressure: Raoul's law.

As shown in Fig. 1, the saturated vapor pressure of the glucose solution of water is less than the saturated vapor pressure of pure water. According to Raoult's law [4–6] in colligative properties of aqueous solutions, in a non-electrolyte and non-volatile dilute solution, the relative decrease of the solvent vapor pressure is proportional to the concentration of the solute. Its mathematical expression is:

$$\Delta P = P \cdot X \tag{1}$$

ΔP is the drop of the vapor pressure of the solution, P is the saturated vapor pressure of the pure solvent, and X is the mole fraction of the solute.

The mechanism of solution vapor pressure drop can be explained by the model in Fig. 3 and Fig. 4:

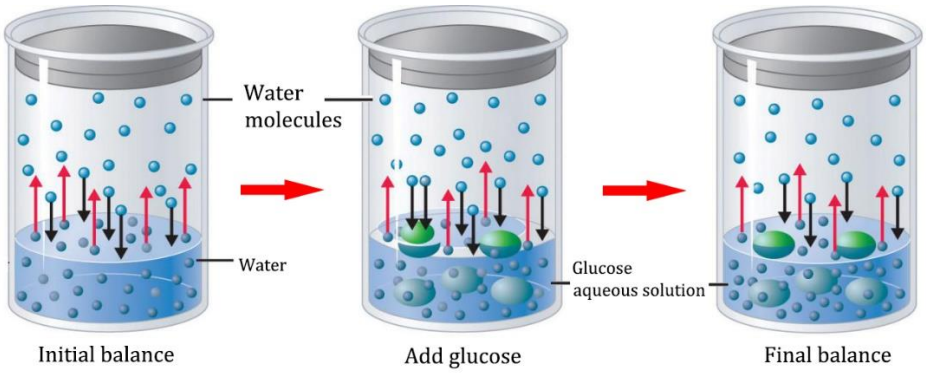

Fig. 3. Model of the mechanism of solution vapor pressure drop.

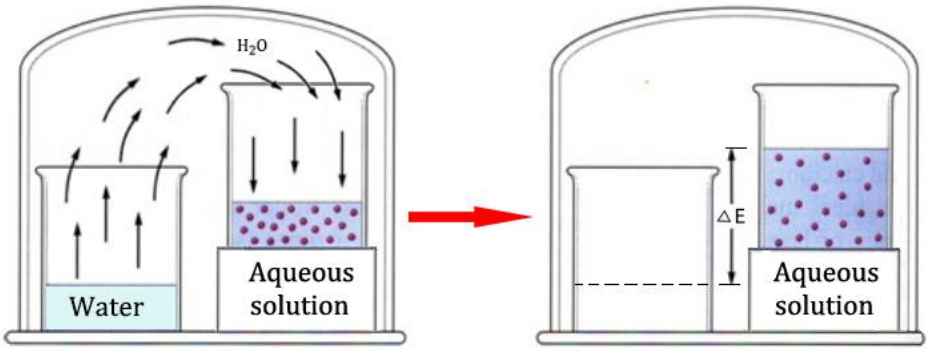

Fig. 4. Experiment of migration of water molecules to higher places.

The experiment seems to go against common sense physics, but it is not. This is because the energy between the water molecules is unbalanced, and there is an energy rise and fall, resulting in the higher energy water molecules always escaping into the upper space, and eventually diffusing and migrating into the upper solution surface under the influence of the vapor pressure difference, thus increasing the total potential energy of the system. The increased potential energy is converted by heat energy drawn from the environment, i.e., $\Delta E = Q$ absorption.

3.2 Van't Hoff's law

The principle of Van't Hoff's law is shown in Fig. 5.

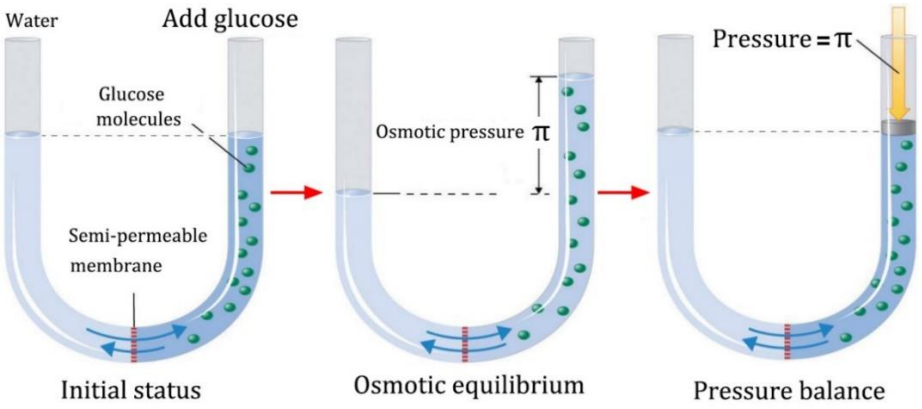

Fig. 5. Water molecules osmosis process and reverse osmosis process.

The mechanism of osmotic pressure (π) generation is similar to that of vapor pressure drop. In a dilute solution, the osmotic pressure of the solution has little

to do with the type of solute, but is mainly related to the molar tration of the solute. The osmotic pressure, π may be related to the mole fraction of water, XA as

$$\pi = -(RT/Vm)\ln XA, \quad (2)$$

where R is the gas constant, T is absolute temperature and Vm is the molar volume of water. For dilute solutions, eq. (3) simplifies to well-known van't Hoff's expression that directly relates osmotic pressure with the solute concentration:

$$\pi = CRT \quad (3)$$

π is the osmotic pressure and **C** is the Molar concentration, **R** is the gas constant, and **T** is the absolute temperature[7–13].

If a pressure higher than the osmotic pressure (π) is applied to the solution surface, water molecules can be penetrated from the solution into the pure water through the semi-permeable membrane, which is called reverse osmosis (RO).

If the two nozzles at the upper end of the U-shaped pipe in Fig. 5. are connected, the evaporating process of water molecules and the reverse osmosis process are coupling together, what may happen?

4. "Evaporating-reverse osmosis" cycle

As shown in Fig. 6:

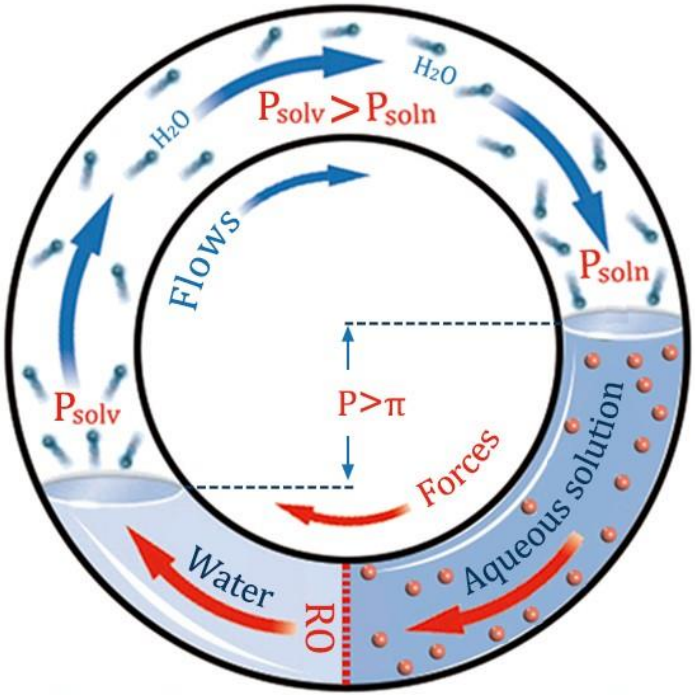

Fig. 6. "Evaporating-reverse osmosis" cycle of water molecules.

On both sides of the semi-permeable membrane (molecular sieve) at the bottom of the ring-shaped closed container are water and an aqueous solution (the solute is hardly volatile). It can be known from the drop effect of solution vapor pressure that water molecules are continuously evaporated and transferred in the aqueous solution. It can be known from the reverse osmosis effect that water molecules will

continue to penetrate into the water through the semi-permeable membrane (molecular sieve). This forms a cycle: the "evaporating-reverse osmosis" cycle.

There are many non-equilibrium mechanisms in the cycle: (i) Water molecule energy fluctuation mechanism. The energy of water molecules is not balanced. There will always be higher energy water molecules escaping from the water surface to become water vapor molecules; (ii) Mechanism of solution vapor pressure drop. The saturated vapor pressure (Psolv) of the pure water surface is greater than the saturated vapor pressure (Psoln) of the solution surface, that is Psolv> Psoln, which causes the water vapor molecules to continuously migrate from the water surface to the solution surface and raise the solution surface; (iii) Liquid pressure gradient mechanism in the gravity field. Under the action of the gravity field, there is a pressure gradient in the liquid. When the solution surface rises, the pressure gradient is increased, which destroys the original osmotic balance, that is P> π, so that some water molecules in the solution reverse osmosis into the pure water on the left. In this way, the three mechanisms are coupled together to form a cycle.

The "evaporating-reverse osmosis" cycle cannot run forever. This is because a small part of the hardly volatile solute molecules may evaporate. During the reverse osmosis process, defects in the semi-permeable membrane (molecular sieve) may also allow very few solute molecules to pass through and be transferred to water. These processes make the concentration of the aqueous solution gradually decrease, and the entropy value of the circulatory system gradually increases, eventually leading to the termination of the "evaporating-reverse osmosis" cycle process. So the "evaporating-reverse osmosis" cycle does not violate the second law of thermodynamics.

In the Earth's gravitational field, these mechanisms will not disappear for a certain period of time, and the cycle can run spontaneously for a "long enough period". But in a weightlessness environment, the cycle no longer exists.

5. A **new variant of Szilard's second engine**

By Onsager reciprocal relations[14,15]:

$$Lij=Lji \tag{4}$$

We know that forces can produce flows, and flows can produce forces. A "force" (e.g., differential vapor pressure, voltage) can produce (or influence) a "flow" (e.g., steam flow, electric current), and this "flow" can also produce another "Force" (e.g., temperature difference).

An example of Onsager reciprocal relations is the Peltier effect [16] in electric currents:

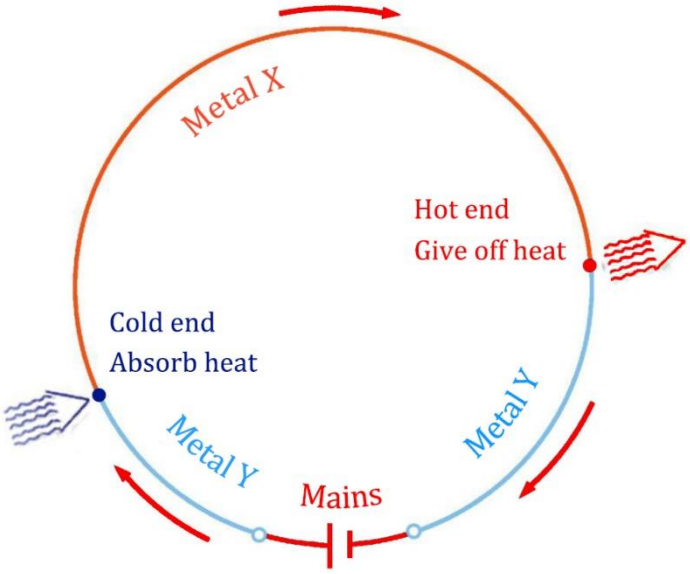

Fig. 7 . Peltier effect

That is, when there is a current through the circuit composed of different conductors (metal X and metal Y), in addition to generating irreversible Joule heat, with the direction of the current at the joints of the different conductors will appear with the different conductors of heat absorption, exothermic phenomenon.

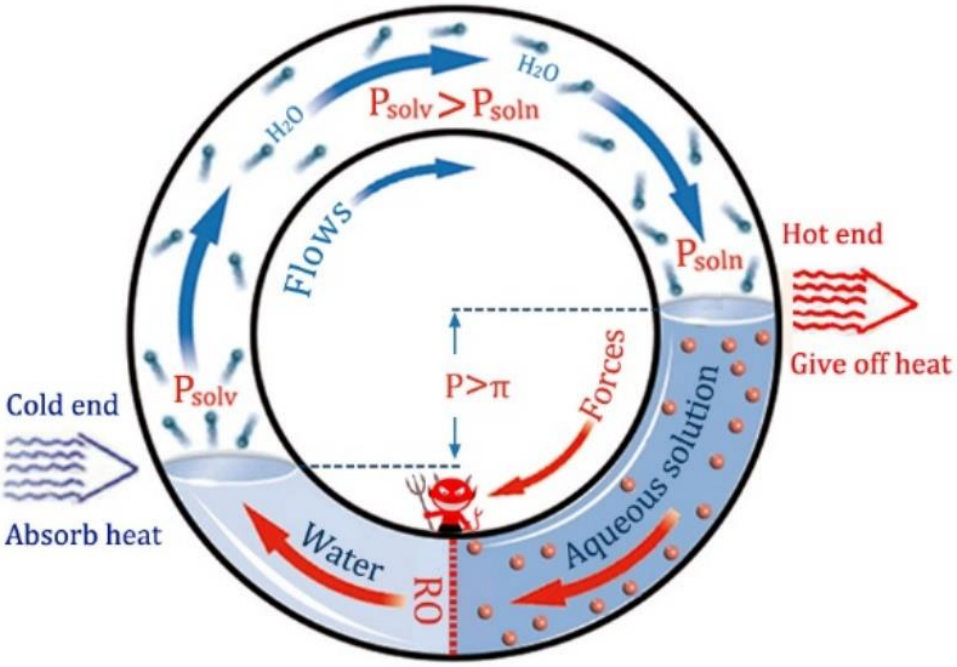

Fig. 8. Szilard's fourth engine

Let's compare the cyclic process to Peltier effect[16], as shown in Fig. 8. during the "evaporation - reverse osmosis" cycle, the molecular flow formed by the evaporation and diffusion of solvent (water) molecules will absorb heat from the solvent surface, causing the temperature of the solvent (water) surface to

decrease. This makes the surface of the solvent (water) a "cold end". When the molecular flow of solvent (water) diffuses to the surface of solution and condenses, it will give out heat to make the temperature of the surface of solution rise and become a "hot end". This creates a temperature difference in the cycle.

The cycle creates a temperature difference in a temperature-balanced ambient heat source with Maxwell's Demon characteristics. Thus, it is an automatic mechanical Maxwell's Demon.

It is a new variant of the Szilard's second mode and also differs from the other two models. It is an autonomous mechanical Maxwell's demon.We call it " Szilard's fourth engine ". It's actually a Maxwell's Demon ring.

Szilard's fourth engine does not violate the second law of thermodynamics. At first glance, it can create a temperature difference in a single heat bath with an equilibrium temperature, which seems to violate the second law of thermodynamics. However, it needs to generate more entropy to offset the entropy reduction caused by the temperature difference. This is because the solute molecules that are difficult to volatilize in the cycle also have a very small part to volatilize out, at the same time, in the reverse osmosis process, the defect of semi-permeable membrane (molecular sieve) may make a very small number of solute molecules pass through and transfer to the pure solvent, so that the concentration difference gradually decreases and the total entropy value of the circulating system gradually increases, eventually leading to "evaporation - reverse osmosis" cycle stops.

6. Extracting work from a single heat bath

Using the thermodynamic properties of the Szilard's fourth engine, we can design a special type of heat engine : "single heat bath" heat engine.

The principle is shown in Fig. 9, the vapor pressure above the pure solvent is greater than the vapor pressure above the solution, there is a gradient in the concentration of steam molecules, so that the pure solvent (water) molecules form a steam diffusion flow, pushing the turbine above the work, and condensation in the upper solution surface. This raises the solution surface, and under the action of osmotic pressure, the pure solvent (water) molecules in the solution will pass through the semi-permeable membrane (molecular sieve) and reverse osmosis to the bottom. By adjusting the control valve, a steady stream of pure solvent (water) is formed, which impulses the turbine below to do its work.

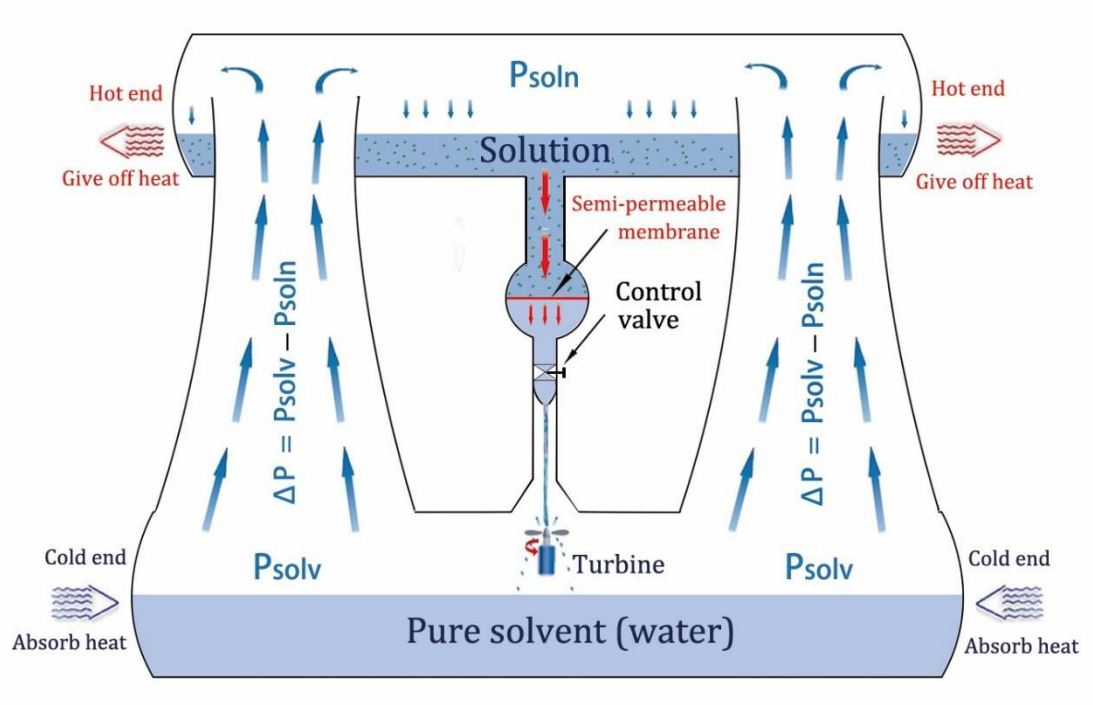

Fig. 9. heat engine for extracting work from a single heat bath

From the Onsager reciprocal relations[14,15], it can be seen that the difference in vapor concentration not only forms a vapor flow, but also absorbs the pure solvent below and the heat energy in the environment to form a heat flow. Therefore, the kinetic energy output is ultimately converted from the internal energy of the environment below.

It will be a new type of ocean thermal energy conversion device (OTEC), and it can absorb heat and convert it into work in an environment of uniform temperature (seawater). It differs from the vapor/droplet coupling and the mist flow (OTEC) cycle[17].

Someone once brought up the heat engine for extracting work from a single heat bath[18]. But this is different. This heat engine for extracting work from a single heat bath is not a perpetual motion machine and does not violate the second law of thermodynamics.

Looking to the future, as graphene membrane fabrication technology evolves, the "single heat bath" heat engine will run automatically for much longer.Is the energy gained from using it greater than the energy needed to keep it running?

We expect someone to give a rigorous thermodynamic proof of this.

7. Conclusion

The key to the persistence of the "evaporating-reverse osmosis" cycle is the semi-permeable membrane technology.Researchers at the Massachusetts Institute of Technology have used graphene to develop a graphene sieve that can precisely control the pore size of porous graphene so that water molecules can

pass through [19]. Scientists have been able to synthesize "highly oriented" and "defect-free" molecular sieves [20–23]. These new molecular sieve technologies will make the "evaporating-reverse osmosis" cycle process more durable, become a quasi-perpetual motion process.

The root cause of the "evaporation-reverse osmosis" cycle is the result of the coupling of the energy imbalance mechanism of water molecules and the pressure gradient mechanism in the gravity field. The continuous flow of water molecules in the "evaporation-reverse osmosis" cycle, it is a new spontaneous quasi-permanent flow found after the continuous current in the superconducting ring (or the normal metal ring) [24,25] and the permanent direction heat flow in the optical mechanical resonator lattice [26].

The "evaporation-reverse osmosis" cycle is arguably the automatic mechanical Maxwell's Demon equivalent predicted by Leo Szilard, because it has the Maxwell's Demon function of creating a temperature difference in an ambient heat source with a balanced temperature, and can continue to circulate automatically. It provides a theoretical model for studying the non-equilibrium quasi-permanent motion process and autonomous mechanical Maxwell's Demon .

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