Methods of Thermal Energy Storage by Using Smart Heat Pumps

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Abstract. To address energy problems in thermodynamic installations, the authors of the paper propose a working methodology in which the determining role of the exergetic aspects of the processes is especially emphasized. One of these energy problems, addressed in many papers in recent years, is of particular importance in the fight to reduce chemical and thermal pollution of the environment: the problem of storing excess energy and energy from renewable or residual sources. Approaching this issue as well from this point of view, the authors propose a series of solutions by which they seek to use the most of the exergy extracted from the available energy sources. The solutions proposed here are based on the use of an own invention, the *isothermalizer*, a particularly powerful tool, able to bring highly effective solutions to many of the problems that concern researchers determined to create a cleaner planet. Designers and users of thermodynamic systems now have the possibility of an initial choice and subsequent changes (with the change of external conditions), of their energy and exergetic efficiency, as well as the possibility of calculating the material and energy costs necessary to achieve the proposed objective. In any gas compression/expansion problem, the energy efficiency is established precisely, by choosing the isothermal speed of the process (so of the isothermal temperature), and the power density, by choosing the total surface of the thermal sponge, the flow rate and the mode of distribution of the cooling agent. As the isothermalizer is equipped with a processor that controls and modifies the isothermal speed in such a way that the exergy consumption is optimized, the energy storage processes become processes of extracting thermal energy from a tank and transferring it to another tank, a process accompanied by consumption/supply of mechanical energy.

1. Introduction

The second law of thermodynamics states that energy has both quantity and quality, and that all real processes occur in the direction of decreasing quality of energy, in the sense that thermal energy at a higher temperature is degraded when transferred to a body at a lower temperature. Finite-time thermodynamics (F.T.T) appeared for the first time in an article by Curzon and Ahlborn [1] where they observed that during a finite power cycle, the efficiency corresponding to the maximum power becomes lower than the Carnot limit [2] and were among the first to calculate how the efficiency of real processes is limited by finite rate constraints. Already in 1948, Tolman and Fine concluded that an increase in the internal entropy of a system reduces the available exergy [3]. The principle of minimum entropy generation (EMG) or the rate of entropy production was considered by Bejan of the greatest interest and regarded as an extremely useful engineering tool [4, 5]. According to the Gouy-Stodola theorem, in a system, the exergy destroyed is proportional to the total rate of entropy generation [6]. If engineering systems and their components are to function so that exergy destruction is minimized, their design must begin with minimizing entropy generation. To minimize the irreversibility of a newly designed system, the analyst, relying on heat transfer and fluid mechanics principles, by varying one or more of the physical characteristics of the system, can bring the design closer to the operation characterized by minimum entropy generation, subject to finite size and finite time constraints [5].

The concept of exergy plays a crucial role in understanding and quantifying the quality of energy in a system and its potential to perform useful work. From a scientific and engineering perspective, an analysis of exergy changes in a thermodynamic system based on the second law of thermodynamics is valuable because it offers a number of benefits compared to an energy analysis based only on the first law. These benefits include the basis for determining energy quality (or exergy content) and improving understanding of fundamental physical phenomena. The term exergy was coined in 1956 by Zoran Rant. In thermodynamics, the exergy of a system is the maximum useful mechanical work that can be produced, as the system is brought into equilibrium with its environment, by an ideal process without irreversible processes [7]. So the exergy of the system can be consumed, when useful mechanical work is produced, or it can be destroyed, in the irreversible processes of real systems. It must be emphasized that, in these irreversible processes, the total energy does not change (the first law of Thermodynamics), it only degrades, losing its ability to produce useful mechanical work. In order to obtain as much useful mechanical work as possible, the way in which irreversible processes appear and develop must be carefully analyzed to mitigate their destructive character [4, 5].

F.T.T makes a clear distinction between irreversibilities caused by processes occurring between bodies with finite temperature differences ΔT between them and the other types of irreversibilities. In the case of the first type, regardless of the lack or existence of a movement relationship between the bodies, a heat transfer process occurs in which a certain amount of thermal energy passes from the warmer body to the colder body, the total amount remaining unchanged, which produces a degradation of the total energy and the destruction of a quantity of the total exergy (that is, of the exergy content of the heat), the greater as ΔT is greater. In the case of heat engines and heat pumps, their very operation is based on the temperature differences, successively positive and negative, that appear between the working fluid and the heat sources, and their power is determined by the size of these differences. Curzon and Ahlborn were the first to calculate the value of these differences for which the maximum power of these devices is obtained.

The other types of irreversibilities (friction between different bodies, between different layers of moving fluids, unrestricted expansion of fluids, dissipation and deformation processes, etc.) are related to existence of motion and are determined by a wide range of phenomena (described of different laws) and physical and chemical properties of bodies. For this reason, for a simpler and more intuitive theoretical treatment, the founders of FTT, starting with Rubin, treated these irreversibilities differently and introduced for this apparatuss and circuits, the notion of endoreversible, in which only irreversibilities due to heat flows appear, method which we also adopted in the analysis of the isothermalizer.

2. The endoreversible isothermalizer

Any compressor in the state of the art (reciprocating, with solid/liquid piston, or rotary) can become an isothermalizer, if it is equipped with a system for regulating the speed of moving parts, with a thermal sponge to absorb/provide the difference in thermal energy and with an evacuation/supply system of this energy, sub-assemblies controlled in real time by a processor, programmed to achieve the constant preservation of the temperature difference ΔT between the gas and its surrounding environment (environment consisting of elements with high thermal inertia: walls, thermal sponges and the heat transfer agent, an agent that is also an equalizer of the T_{amb} temperature of these components). The device can be placed in an environment with the T_{amb} temperature but, to conserve exergy, it can be placed in a tank with liquid agent, isolated, with a T_{rez} temperature, different from the temperature of the external environment, a temperature that will have a monotonous variation, according to the accumulation of thermal energy, and the processor that coordinates the operation of the system will determine a similar variation of the temperature T_{iz}, so that the difference ΔT is preserved.

Another essential component of the isothermalizer is the gas introduction system in the enclosures. If our apparatus serves a heat engine or heat pump operating in a Carnot cycle, the inlet gas temperature T_{iz} in the first enclosure of the apparatus is set by choosing when the discharge valve of the downstream compressor/expander opens. If the working gas is at a temperature different from T_{iz} (if it is absorbed from the outside environment, or from a heat exchanger), the corresponding temperature change can be made by the isothermalizer piston itself, through commands given by the processor , to change its speed, forcing it to describe a trajectory as close as possible to the isentropic one, a trajectory that ensures minimal exergy destruction. The preferred solution is a suitable prior gas processing and temporary storage in a buffer tank.

The isothermal transformation can only be achieved if the mechanical energy introduced into the system by the moving parts and instantly taken over by the working gas in the form of thermal energy, is equal to the thermal energy that the gas gives up to its surrounding environment, to be discharged outside of enclosures (or temporarily stored). This energy is proportional both to the time interval affected by gas-medium heat transfer (equal to the duration of one cycle), as well as with the average C_{GTm} for that cycle of the global instantaneous heat transfer coefficient $C_{GT}(t)$, between the gas and its ambient medium. Therefore, for low values of the heat transfer coefficient, the speed of the moving parts (therefore, the power density of the device) must be lower, and for higher values (which implies a larger heat transfer surface, hence higher material consumption), higher power densities are obtained [8, 9].

The removal of part of the thermal energy contained in the working gas can be done only in the presence of a temperature difference ΔT. This type of irreversibility cannot be avoided. The choice of the working temperature T_{iz} of the gas (and, implicitly, the temperature difference ΔT from its ambient temperature T_{amb}) at which we want the isothermal transformation to take place is a compromise between the amount of energy consumed in addition to the ideal compression (at $\Delta T= 0$ and energy efficiency $\eta= W_{id} /W_{real}=T_{amb}/T_{amb}=1$) and the duration of a cycle (duration that dictates the power consumed). Also, the ΔT value is, at any moment, proportional to the amount of heat exchanged by the gas with its surrounding environment, the proportionality factor being a variable one: $C_{GT}(t) = \Sigma h_i(t)A_i(t)$, where $A_i(t)$ and $h_i(t)$ are, at each moment t of the transformation, the values of the contact surfaces and the heat transfer coefficients of the elements i of the device, which are in contact with the working gas. The transformation undergone by the gas is isothermal (T_{iz}=ct), if the instantaneous power $W_i(t)$ of the piston is permanently equal to the instantaneous heat $Q_i(t)$ transferred to the environment by the working gas (if ΔT and C_{GTm} are constant, and these two powers become constant), and the energy efficiency becomes, for compression:

$$\eta=W_{id} /W_{real}=T_{amb}/T_{iz} =T_{amb}/T_{amb}+\Delta T.$$

In the description [10, 11] we used the names of *isocompressor/densifier* in the case of compression and *isodetentor/rarefier* in the case of expansion for the isothermalizer.

To find the *isothermal speed* (the equation that describes the evolution of the piston speed during an isothermal transformation), there is the way of developing a mathematical model of the isothermalizer and solving the respective differential equations, for the given initial conditions, but the method proves to be laborious and approximate, since the exact interdependencies between the parameters model are insufficiently known. The invention we propose [10, 11] avoids solving the differential equation of motion and transfers the task of finding the isothermal velocity $v_{iz}(t)$ to an automatic adjusting system. Instead of determining, with an inherent margin of error, how the instantaneous power of the mobile organ should vary, we equipped the device with artificial intelligence and introduced an *automatic adjusting device* into the system, which based on information gathered over *real time* by a series of transducers, determines, regardless of environmental variations and other disturbances that may occur, the meaning and value by which the magnitude of the force acting on those mobile components that influence the average temperature must change at that moment of the working gas (Fig.1). The procedure can be generalized, to apply it not only in the case of devices with alternative displacement, where the main regulated quantity is the speed of the piston, but to all devices with positive displacement, by introducing automatic systems for regulating the angular speed of the rotor and/or of the inlet and outlet flow rates of the cooling fluids (transferring the piston function to these fluids). In addition, the invention also describes a gas piston isothermalizer, which isothermally compresses gases in a closed enclosure with constant volume, by controlling the temperature and flow rate of the gas introduced, simultaneously with the control of the input and output flow rates of a heat transfer fluid. As in the case of rotary isothermalizers, the achievement of the isothermal transformation is done by simultaneously adjusting several parameters.

These regulation systems become the main component of all isothermalizers. The shorter the response time and the smaller the deviation of the supplied signals, the closer the transformations controlled by them are to an isotherm. The use of real-time tuning devices does not exclude a prior theoretical determination of the optimal trajectory and the use of these results in the design phase of the actuators, in order to decrease the instantaneous deviation and increase the response speed of the controller.

The acceleration of the heat transfer between the gas and its surrounding environment can be achieved by introducing a thermal sponge into the device responsible for the isothermal transformation (Fig.2). The type of sponge that the analyzed invention uses most often, due to its simplicity and effectiveness, is a deformable thermal sponge, mounted between the inner face of the piston (solid or liquid) and the cylinder cover, which deforms under the action of the moving body,

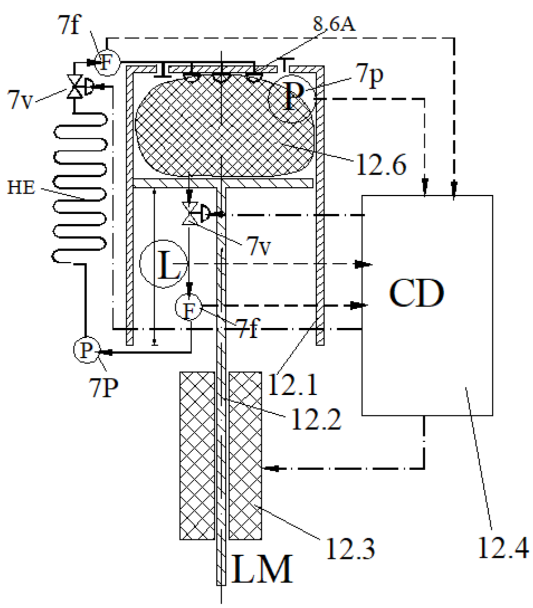

Fig.1: Isothermalizer with linear motor

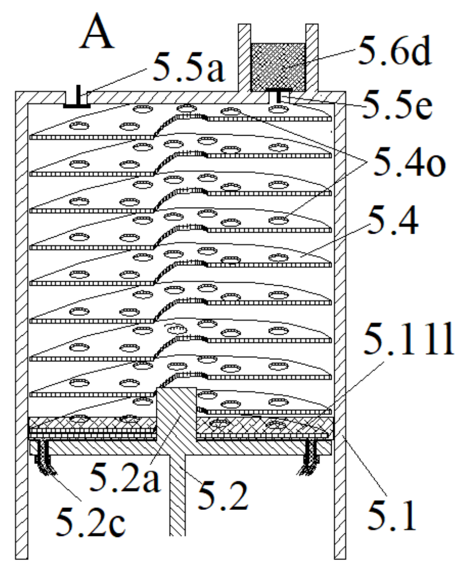

Fig.2: Thermal sponge: helical spring 5.4 with rectangular section

its component elements, having a surface, in contact with the gas, as large as possible, but constant throughout the transformation. Due to its thermal capacity much higher than that of the working gas, the total volume of the elements that make up an efficient thermal sponge can be very small, it being important that this volume is distributed efficiently over a large surface, throughout the gas volume. As a result, the power density can increase by several orders of magnitude. In isothermalisers with a high compression/expansion coefficient, the deformable thermal sponge can be supplemented with a non-deformable thermal sponge with a very large absorption surface, mounted in a small area outside the range of action of the solid piston, for example in the area located at the highest elevation of the device, an area where, due to convection, there is a tendency to accumulate gases with a temperature above the average, and the discharge of the compressed gas can be done by replacing it with liquid from the discharge pipe.

Such a deformable sponge consists of one or more solid component elements (in many configurations a liquid component is also introduced, in a fixed amount) with variable volume and/or position. The solid components of the thermal sponge have the total surface that is in direct contact with the working gas, approximately the same throughout the compression, and their degree of deformation is constantly controlled by the position of the piston, with each position of the piston corresponding to a different shape of the sponge, property ensured by the elasticity of some of its component elements, or by kinematic devices controlled by (or in correlation with) the movement of the piston. The liquid components of a thermal sponge installed in alternative devices can also play the role of a transport agent of excess thermal energy, if during the discharge and intake phases, they are replaced by cooled components, or they can take over the role of a liquid piston, if during thermodynamic transformation, the amount of liquid introduced is different from that discharged. In most rotary devices, thermal sponges made of solid elements are more difficult to make, but liquid elements of the sponge can be introduced and discharged, both from the inlet phase and during the thermodynamic transformation, in the form of a jet, of drops, of a spray, of a foam, etc., or simply by free flow. When introduced/evacuated during thermodynamic transformation, they can combine the role of a liquid piston with that of a cooling/heating agent.

To remove excess heat, the isothermalizers are equipped with a cooling/heating system, which introduces into their enclosures, during compression, a flow of heat transfer liquid, which is discharged through another pipe and transported, with the help of a pump, to a heat exchanger. If the flow rate of liquid discharged is equal to that supplied, the liquid agent is only the heat transfer liquid, but in case of inequality, the liquid agent is also the piston. Due to the existence of the thermal sponge, which makes the distance between any gas particle and the nearest heat-absorbing surface very small, it is no longer necessary to spray the introduced heat transfer agent, which greatly simplifies the construction of the device and greatly reduces energy consumption. It is sufficient for the liquid introduced to be efficiently distributed to all heat-absorbing surfaces, and to drip onto these surfaces under the action of gravitational forces. Also, this type of device lends itself very well to water foam cooling. Foam regeneration can be done by introducing gas (gas piston) at a pressure slightly higher than the instantaneous gas pressure, in strategically placed trays, which enter the composition of the thermal sponge and contain a mixture of liquid with surfactants. Cooling of the thermal sponge can also be done intermittently, by interposing, after a number of N cycles of the working gas, a number of n cycles in which, instead of gas, only cooling liquid is introduced into the enclosure.

The inlet and outlet flow rates of the liquid agent are determined by a regulator, by commands sent to the servomotors that actuate the hydraulic valves on the inlet and outlet pipes and by commands that are correlated with the commands sent by the piston actuator regulator.

3. State of the art in thermal energy storage

Capturing, storing and distributing thermal energy to distributors involves the search for the most appropriate methods and types of installations, depending on the nature of the sources and users. These searches were, in previous decades, strongly influenced by economic criteria, neglecting the criteria of chemical and thermal pollution of the environment. But, the stage in which the concentration of noxes in the water and air of the planet, the phenomenon of global warming and the effects it determines, forces humanity to a radical revision of this approach. Therefore, economic and social behavior changed their orientation, seeking to adapt to the new requirements, more environmentally friendly techniques and appliances appeared. The authors are convinced that these techniques and devices can be improved, and the field in which they are used can be greatly expanded if, in their design, greater weight is given to exergetic criteria. The isothermalizer is a solution that can be the ideal solution for a very wide range of engineering problems.

In the manipulation of thermal energy, four different situations can occur:

a) thermal energy is captured from an existing source and stored in a reservoir, until it is required by a thermal energy user. Both capture and supply can be passive (the energy is handled together with its carrier), or active (the capture and/or supply of energy is done indirectly, by means of one or more HTF heat transfer fluids and heat exchangers, and solid media can also be used for storage). During these handling operations (operations that consume a certain amount of mechanical energy), energy losses occur through thermal insulation to the outside environment and unused energy stocks, in the walls of the tank and other components of the installation, as well as in the remaining fluid. The rest of the thermal energy, although exergetically degraded, is transferred entirely to the user, albeit with a lower power density. Fig.3 shows two ways of this type of storage [14].

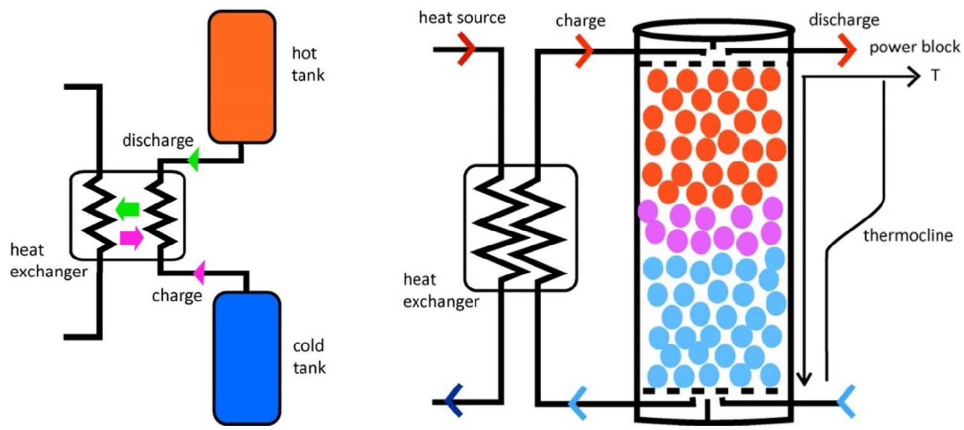

Fig.3 Sensible heat-storage system principle: a) two-tankstoragesystem
b) single-tank thermocline-based TES integrated in to a CSP plant.

b) thermal energy is captured from an existing source, stored in a reservoir and used as a heat source for a heat engine. If the energy capture is done with the destruction of a minimal amount of exergy (without insulation losses, in heat exchangers with minimal pressure losses and with a minimal entropy generation rate) the heat exergy captured from the primary source can be exploited to the maximum. Fig.4 shows such an example, applied to a CSP [14]

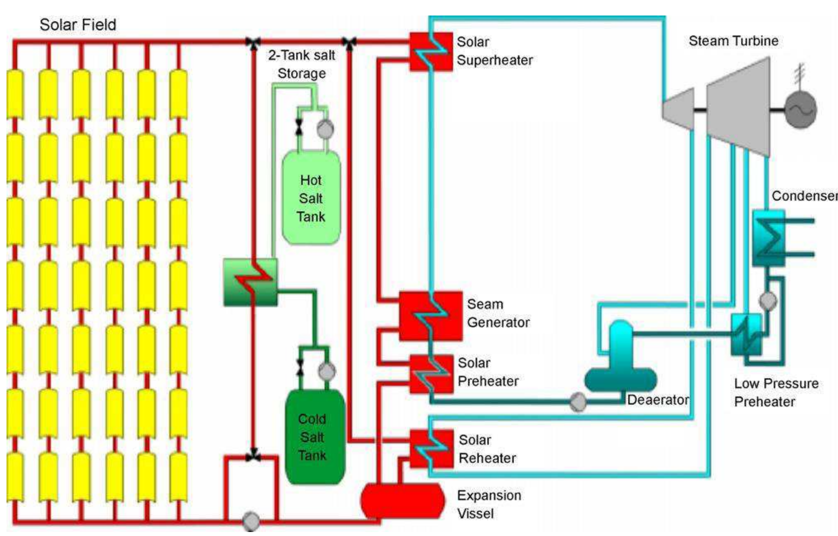

Fig. 4. Schematic of a parabolic trough power plant with two-tank molten salt storage [15].

c) thermal energy is captured from a source with low thermal potential by means of a heat pump whose mechanical work is added to the energy captured and stored in a reservoir for use by users as a source of thermal energy. If the electrical energy consumed by the pump comes from renewable sources, that installation is totally non-polluting. The installation in Fig.5 shows a residential heating installation with the help of thermal energy captured from the ground.

d) the thermal energy stored in the tank comes from a source with low thermal potential, captured with the help of a heat pump that uses excess mechanical work, and is extracted with the help of a heat engine that provides mechanical energy, usually in the form of electricity for to be used by users when such a request arises (Carnot batteries)

Carnot batteries (Fig.6) are the most promising energy storage systems. They are modular, have no geographic constraints, can use cheap, abundant, non-toxic materials and can use existing

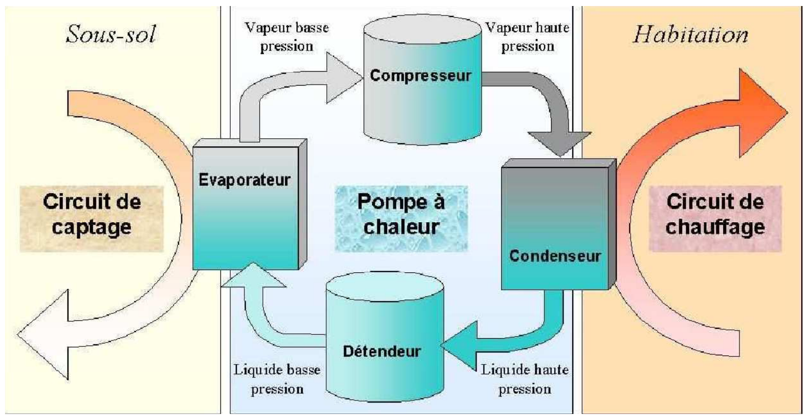

Fig.5. Operation of a geothermal heat pump with an intermediate fluid [16]

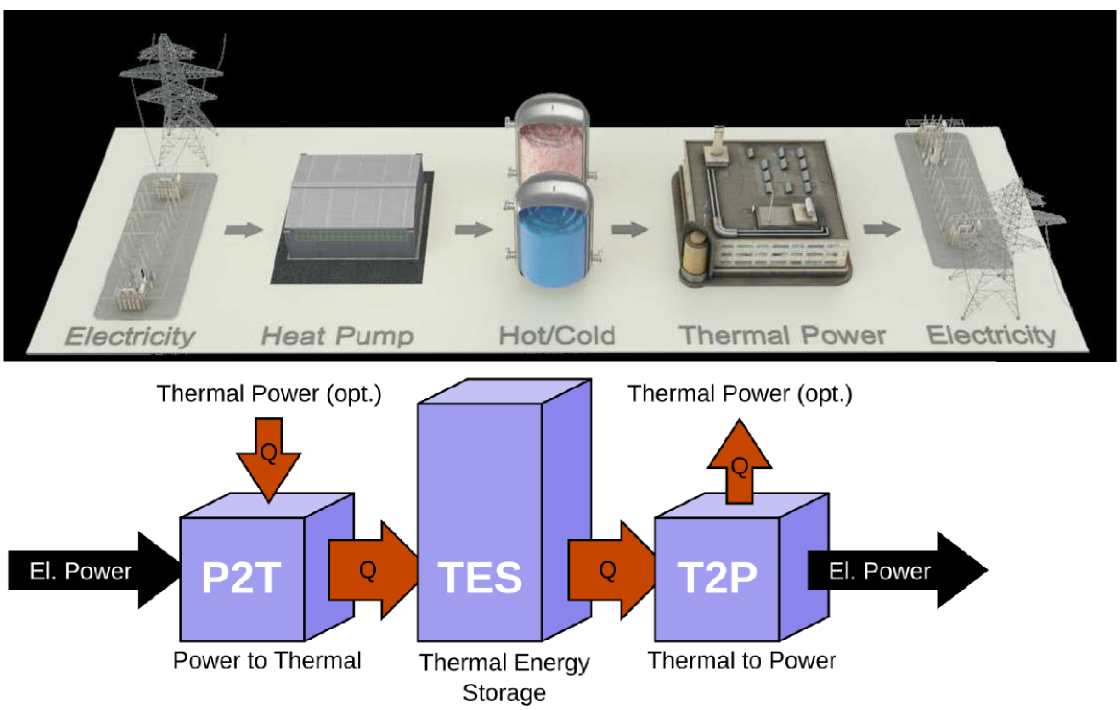

Fig. 6. Schematic diagram of the Carnot battery [20]

technologies. If several HTFs are used successively, for adjacent temperature ranges, and as a storage medium one or two solid mediums, resistant to high temperatures, possibly in combination with encapsulated materials that undergo a phase change (PCM) in the range respectively, if the thermal insulation of the tank is efficient, the stored thermal energy can grow a lot. Consequently, the power density of the system is comparable to that of chemical batteries, including Li-Ion ones. The disadvantage of the prior art Carnot batteries is their low round-trip efficiency (40-70%, the low values being for high temperatures) due in particular to the high exergy losses in in heat transfer processes from heat pumps and heat engines. Among the systems of this type, which have been experimented, we list [17-20]:

a) Isentropic Ltd: Brayton cycle power circuit, based on Argon, with two adiabatic piston compressors, segmented packed beds of rocks, between 500°C and -150°C.

b) Malta Inc.: Brayton cycle power circuit, with 4 air-based turbomachines, with recuperator, with storage in molten salts at 565°C and glycol/water mixture at −60°C

c) Highview Power: Power circuit: air-based Brayton cycle, Storage: liquified air at −196°C, packed beds of rocks for hot storage

d) Siemens Gamesa: Power: Steam turbine, air as the HTF, Storage in volcanic rock at 700°C

e) Saipem: two tanks filled with temperature-resistant storage materials (basalt pebbles). For refractory materials heated to 1000°C, a power density of 600 kWh/m3 (hot solid volume) can be achieved, compared to 200 kWh/t for a full Li-ion battery.

4. Smart heat engines and heat pumps

Most of the storage systems described, introduced on the market at a time when the effects of pollution were not felt so strongly, were oriented towards an energetic treatment of the problems. We easily notice the use of electricity for the direct heating of stored materials as well as thermal transfer processes between bodies with very large initial temperature differences, processes that destroy a good part of the available exergy.

In systems perfectly insulated from the outside, whose exergy (relative to the temperature of the external environment) is clearly defined, the processes in the system, that lead to exergy destruction, do not lead to total thermal energy decrease. If real processes of energy transformation from one form to another are also involved, exergy destruction has an effect on the amount of mechanical work that can be extracted from the system, and system performance, reflected by the P2P round-trip efficiency indicator, decreases. In the energy production systems of the last decades, measures have been taken to counteract this effect, through the emergence of recovery systems and cogeneration systems, but the state of the art, in relation to cogeneration engineering, is very incomplete and disparate and takes into account especially particular configurations [21].

In the energy storage systems we propose, we have considered several rules:

- to be avoided: heat and pressure losses between system elements, as well as between them and the outside, direct contact between gases with different temperatures and/or pressures, electrical heating of system components
- all heat transfer processes between two media should be done with minimal entropy generation
- all heat transfer processes between the system and the external environment should be isothermal, with minimum ΔT
- the speed with which the pressure jumps are made in the devices intended for this purpose, to be a compromise between the thermal energy given to the environment and the mechanical energy lost in the friction processes
- the mechanical devices should be located, whenever possible, inside the system, so that the exergy transformed into thermal energy can be accumulated and finally, extracted for the consumers of this type of energy (cogeneration)
- the use of versatile devices, capable of easily changing the main parameters of the working regime (power, temperature, initial/final volume)

- the introduction of some processors into the system, capable of finding and maintaining, through commands sent to the mobile organs, the most favorable working regime

The simplest P2P (power-to-power) system, in which these rules can be implemented, is the system composed of two very well thermally insulated tanks, one hot and one cold, in each tank being placed an isothermalizer, which together with two reversible compressors mounted between isothermalizers, form a direct or inverted Carnot circuit, depending on the direction in which the working gas flows. Being thermally isolated from the environment, the mechanical energy taken from the outside, less the destroyed exergy, is taken over by the heat pump, transformed into thermal energy and stored simultaneously in the two tanks, to constitute the energy source to feed the thermal engine, which it returns this energy to the outside, when it is required. The exergy destroyed and stored as thermal energy in the hot tank can be a source in cogeneration. The power of the system depends on the power of each isothermalizer, so on the heat transfer surface of the two thermal sponges. The fluid used for heat transfer in isothermalizers can even be the storage liquid in the tank. If its characteristics are not suitable for efficient storage, or if the storage temperature exceeds the evaporation temperature, one or more tanks and the corresponding heat exchanger are inserted (accepting the additional exergy losses).

Thermal sponges made of solid materials can be inserted into these tanks to increase the density and storage temperature. The endoreversible system is a Carnot system that develops maximum power with a Chambadal-Novikov efficiency $\eta=1-(T_L/T_H)^{1/2}$, where T_L is the temperature of the cold tank, and T_H that of the hot tank. This power is controlled by the system processor, by controlling the temperature differences between the gas and the thermal sponge inside each isothermalizer. If T_L/T_H has a small value, the ratio between the maximum and minimum pressure in the system can reach high values and the Carnot circuit is more difficult to achieve. In this case, adiabatic compressors can be replaced with heat exchangers (Stirling or Ericsson circuits), but their use causes additional exergy losses. Also, for some temperature ranges, instead of Carnot-type circuits, Rankine-type or ORC-type circuits can be made with neutral refrigerants, but these are not as versatile, and the exergy losses are higher.

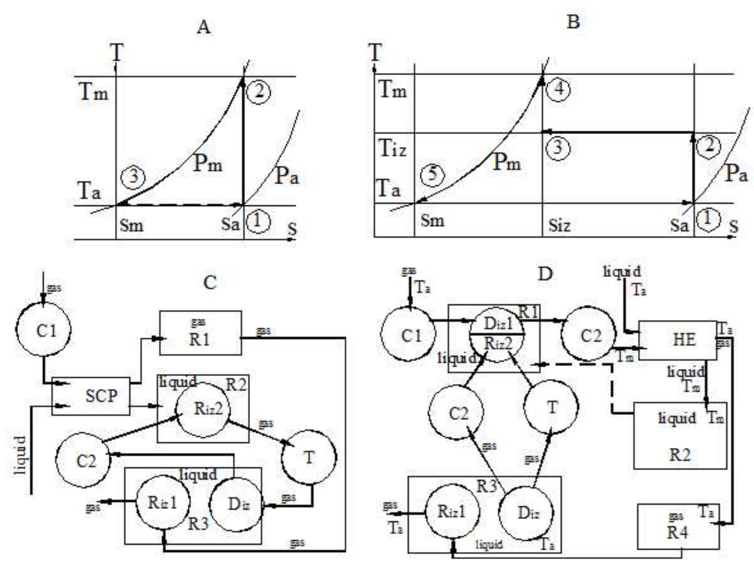

Fig. 7. Smart Thermal Energy System: A, B: T-s diagrams
C: with one storage stage D: with two storage stages

In previous works [11, 23] some examples of such systems are described. In Fig.7C, a Smart Temperature energy Storage (STES) system is described, similar to the TES systems of the state of the art, in which the gas is compressed adiabatically by the compressor C1, from the pressure Pa and temperature Ta, to the pressure Pm and temperature Tm (curve 1-2 on the T-s diagram, Fig.7A), then it is cooled to the temperature Ta (curve 2-3 on the T-s diagram, Fig.7A) and stored in the reservoir R1. Unlike the systems in the state of the art, in which the thermal energy of the gas is transferred, by direct transfer, to a thermal sponge composed of solid materials (rocks, concrete blocks, walls of a cavern, etc.), with significant exergy losses, in STES , this energy is gradually released, at a ΔT controlled by the processor, to a storage liquid in a heat exchanger, and the resulting liquid, with a temperature close to Tm, is stored in the reservoir R2. The energy supplied to the network when a load peak occurs on the consumption network is provided both by the isothermal expansion of the gas in R1 and by starting the heat engine operating after a Carnot cycle, with variable hot source temperature, formed by the rarefier Riz2, the turbine T (or an adiabatic piston expander), the Diz densifier and the C2 adiabatic compressor. If the rarefier Riz1 and the densifier Diz are located in the same tank R3, the expansion of the gas in the rarefier is done by absorbing the thermal energy given off by the densifier Diz. The storage system described in Fig.8 is a Carnot battery, mainly composed of two isothermalizers Diz and Riz, mounted in the tanks Rd and Rr, respectively, two reversible piston compressors, Cp and Tp, devices that form a heat pump in during the storage process and a thermal engine during the discharge process. The devices are mounted in the tank Rd (hot) and Rr (cold), respectively, in which there is a thermal agent used in a temperature range, but which, for a different temperature range, can be replaced by another agent, stored in tanks R1 and R2, respectively. The working agent, which evens out the temperature of the thermal sponges of the isothermalizers, is circulated with the help of pumps P1 and P2 and through the storage tanks with solid materials suitable for the respective temperature range. If suitable materials are used, including PCM, storage temperatures below 100K and above 1200K can be achieved. The energy efficiency of the endoreversible system is $\eta=(T_H-T_C+\Delta T_H-\Delta T_C)/(T_H-T_C-\Delta T_H+\Delta T_C)$. Some examples of such systems are described in previous works [11, 23].

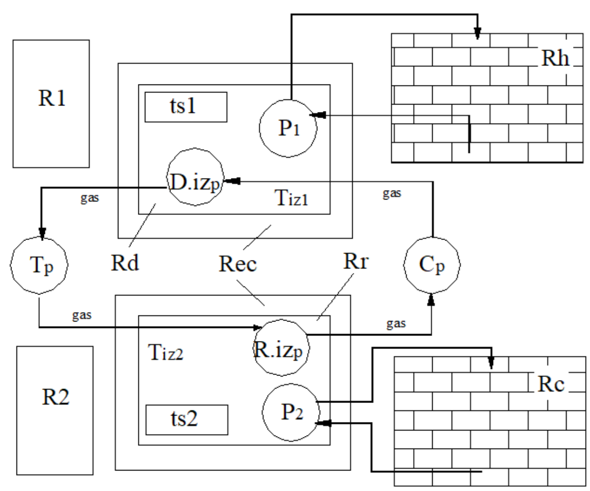

Fig.8. Smart Thermal Energy System as Carnot battery

5. Conclusions

The storage of energy in thermal reservoirs cumulates a number of advantages, compared to the systems of the state of the art, due to which, this system can find a wide use in the energy, chemical, metallurgical, construction materials, etc. industries. Associated with innovative air treatment systems, it can serve social and residential air conditioning and domestic hot water installations, and if suitable materials and safe implementation solutions are found, they can contribute to the decarbonization of all types of means of transport.

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