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A Shape Memory Alloy Thermal Engine for Waste Heat Recovery

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ABSTRACT: *Concern for the well-being of our planet and mankind's ever-expanding need for power has generated considerable interest in alternative ways of generating power. Many different methods of producing power, such as fuel cells, wind turbines and solar panels, have been developed and refined in recent years. The Shape Memory Alloy heat engine, discussed in this work, is also a result of this growing interest in the quest for alternative power sources. In this paper we present a novel approach to arranging shape memory alloy (SMA) wires into a functional heat engine. Significant contributions include the design itself, a preliminary analytical thermal analysis and the realization of a research prototype; thereby, laying a foundation from which to base refinements and seek practical applications. The proposed engine consists of a set of SMA wires stretched between a fix point and a connecting rod mounted on a freewheel who act on a shaft rotating in one direction. During operation, the wires are alternatively heated with water at a temperature of 358 K, in order to obtain the contraction of the wires, and refrigerated with air at room temperature (293 K), to aloud the deformation of the wires. Potential applications may include the conversion of waste heat into shaft power.*

KEYWORDS - *Shape memory alloys, Flexinol® wires, Waste heat recovery.*

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I. INTRODUCTION

Few technologies can produce meaningful power from low temperature waste heat sources below 373 K (100 °C), but it is generally known that modern civilization produce an abundance of waste energy and even a thermodynamically inefficient technology can recover enough energy to reduce fuel consumption meaningfully. Since the 1970's energy crisis, NiTi shape memory alloy (SMA), discovered since 1932 [1, 2, 3, 4], and associated thermal engines [5, 6, 7, 8, 9], have been considered a viable heat-to-power transducer but were not adopted due to previously poor material quality, low supply, design complexity, and cost. Decades of subsequent material development, research, and commercialization have resulted in the availability of consistently high-quality, well-characterized, low-cost alloys and a renewed interest in SMA [10, 11], actually, as reported in extensive literature [12, 13, 14, 15], widely adopted in several applications like: toys, actuators, control valves, hydraulic couplings, frames etc., as a waste heat energy recovery technology.

In the available scientific literature, there are many schemes and types of operation of motor based on shape memory alloy. In general, the proposed SMA motors try to rotate the crankshaft automatically by immersing the shape memory elements automatically in both the "hot" and "cold" heat transfer fluid [16, 17]. This circumstance entails the need to confine the fluid in a container, especially for heat transfer fluids in a liquid state, introducing a certain "rigidity" into the kinematic schemes adopted [18]. In general, the various SMA motor schemes are characterized by low angular speeds, low thermal energy conversion efficiency and present a series of advantages and disadvantages.

II. ENGINE DESCRIPTION

The SMA motor scheme developed and proposed in this paper also presents a series of advantages and disadvantages which we will try to illustrate below.

The development of a new SMA heat engine scheme began with the choice of SMA alloy to adopt. The choice fell on NiTi wires marketed under the name of Flexinol® whose main characteristics are shown in Table 1. From the technical characteristics of Flexinol® it can be observed that with a maximum deformation of 4% in length, avoiding bending or twisting the wire, the number of Martensite/Austenite transformation cycles becomes practically unlimited. With this information, the operating scheme of the SMA motor has become relatively simple as long as "automatic" [17, 18] operation is given up in favor of "controlled" operation. In practice, the proposed structure involves connecting the Flexinol® wires between a fixed point and a rocker according to the illustrative image reported in Fig. 1 and in a rendering image, reported in Fig. 2, of all balancing wheels mounted on the crankshaft. Under tensile stress, the wire used has a working length of one meter and is inserted at the end of the balance arm counterbalanced by a helical spring connected to the other end of the balance. The deformation force of the wire in the Austenitic phase (low temperature) is generated through the deformation of the coil spring. By heating the wire, the transition to the Martensitic phase will allow the recovery of the deformation even in the presence of a resistant force higher than the deformation force contained, obviously, within the yield limit of the alloy. The recovery of the deformation will impose on the balance wheel a rotation of a certain angle (20° in our application) which, if transmitted to a suitable shaft, will provide the useful work of the engine. The scheme adopted is shown in Fig. 3 where the balance wheels are visible which are rotated by alternately heating the wires connected to their ends. The wires are arranged horizontally and organized in groups of four for each balance wheel. Below the various groups of wires, there is a screen equipped with vertical fins arranged between the groups of wires to create a channel, open in the upper part, which will be alternately flooded by the heating fluid (water) and exposed to the cooling fluid (air environment). The finned screen is inclined by approximately eight sexagesimal degrees to the horizontal so that the heating fluid, at the end of its action, can be evacuated into a collection tank located at the end of the channels. The heat transfer fluid is made up of water, heated to a temperature of about 85 °C, which is distributed on the stretched wires by letting it come out from two distribution tubes. The two tubes are provided with a series of holes (located in the lower wall part of the tubes) suitable for distributing the heat transfer fluid on the wires and, therefore, on the channels formed by the vertical fins. The two distributor tubes have an alternative horizontal movement to alternate the distribution of the hot fluid. In practice, while one tube distributes the fluid, the other tube returns to its initial position, obviously without distributing the fluid. In this way, it is possible to obtain sequential and continuous inclinations of the balance wheels (contraction of the wires). The two distributor tubes are connected to a toothed belt stretched between two pulleys. A brushless motor connected to one of the two pulleys allows the movement of the toothed belt and, therefore the movement of the heat transfer fluid distribution tubes. By increasing or reducing the rotation speed of the brushless, an increase/reduction in the displacement of the distributor tubes is obtained, therefore in the frequency of contraction of Flexinol® threads, or in the rotation speed of the motor shaft. This movement can be easily synchronized with the rotation of the balance wheels. The introduction of the hot fluid causes the contraction of the wires, forcing the corresponding balance wheel to oscillate through a certain angle. The oscillation of the balance wheel is transmitted to a shaft positioned centrally to the balance wheels mounted on one-way bearings CSK 6201®. The adoption of these bearings allows the transformation of the angular oscillation of the balance wheel into rotary motion of the shaft.

Wire diameter [mm]	0,38
Traction force (heating phase) F_t [N]	22
Deformation force (cooling phase) F_r [N]	4
Maximum deformation [%]	4
Density ρ [kg/m3]	6450
Specific heat c [kj/kgK]	0.832
Latent heat of transformation Lht [kj/kg]	2.236
Temperature of starting Austenite phase [°C]	68
Temperature of ending Austenite phase [°C]	78
Temperature of starting Martensite phase [°C]	52
Temperature of ending Martensite phase [°C]	42

Table 1. Flexinol® wire main characteristics

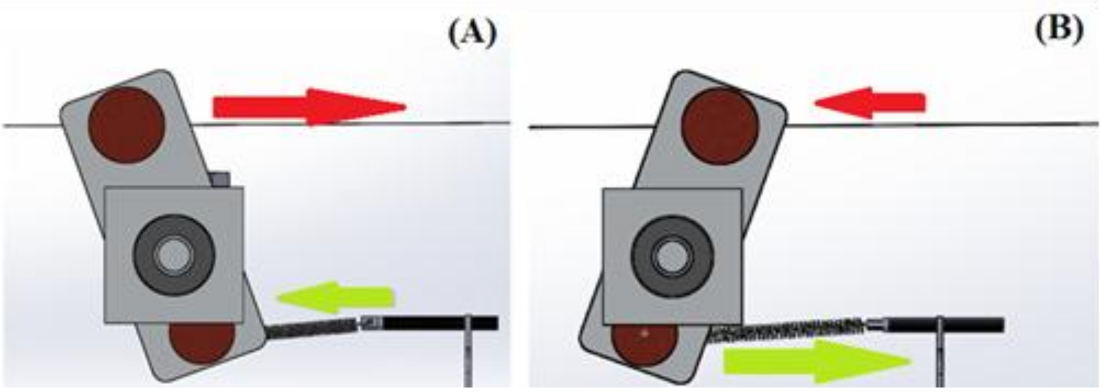

Figure 1. Images of the working principle of balancing wheel. Austenite phase (A); Martensite phase (B).

Considering the length of the single arm of the balance wheel, equal to 0.11 m, with a wire one meter long, with a maximum deformation of 4%, we obtain that the maximum rotation of the balance wheel, and therefore of the shaft that passes through it, is equal to 20° sexagesimals. For a complete revolution of the shaft, it is necessaire 18 sets of rocker arms, coil springs, and sets of Flexinol® wires. To maintain a minimum degree of rotation, overlap and greater rotation uniformity, twenty groups of cranks, springs and wires were adopted as seen in Fig. 2 (rendering image) and in Fig. 3 (real photo).

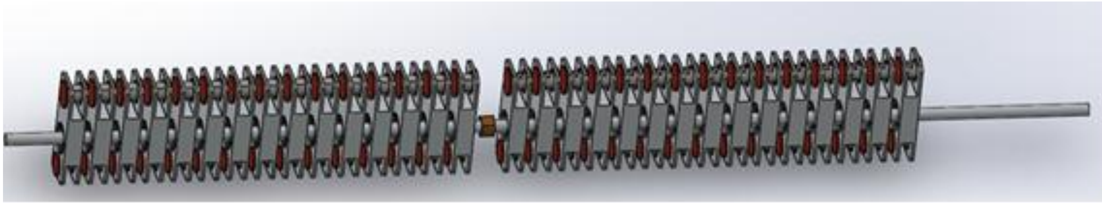

Figure 2. a rendering images of the balancing wheels and related shaft

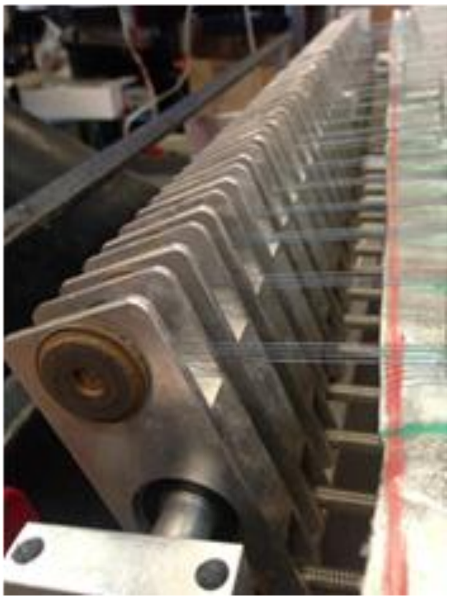

Figure 3. Image of the balance wheels realized.

For the preliminary tests on the working machine, the heating fluid (water) was obtained heating water by means of an electric heater with a nominal power of 1.5 kW. Water was heated in a vessel positioned over the distribution tubes; in this way the heating fluid can be distributed by means of gravity.

Figure 4. An overall view of the realized machine.

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Figure 5. An image of the proposed SMA engine at work.

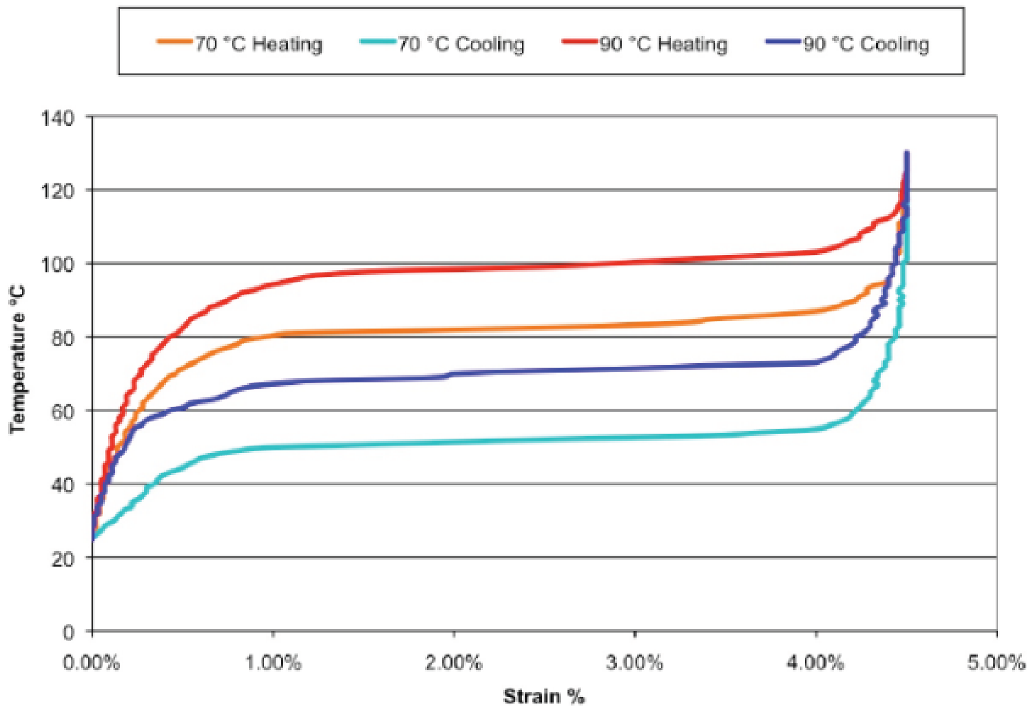

Figure 6. Flexinol® Strain-Temperature diagram for different temperatures.

III. RESULTS AND DISCUSSION

The realized machine, visible in Figg. 4 and 5, was used for preliminary operational tests. First of all, we started feeding the machine with water heated to 358 K (85 °C) to check if all the Flexinol® threads work correctly, all the rocker arms rotate to the desired angle if the movements of the distribution pipes are smooth enough to guarantee a sequential and synchronized contraction of the threads, etc. Basically, we tested if everything worked reasonably.

So, as mentioned before, water was heated in an apposite vessel, employing an electric heater, and when the temperature of 358 K was reached, hot water was sent in the distribution tubes and the machine started to move. Feeding hot water at the temperature of 358 K (hot phase for recovery of the deformation and useful phase) sequentially, from the first balance wheel up to the twentieth. The contraction of Flexinol® wire connected at the single balancing wheel is done in about 0.6 seconds (time of contraction of the wire when heated) so we can obtain an oscillation of the single balancing wheel as high as 20 sexagesimal degrees every 0,6 seconds. In this way the eighteen balance wheels (of twenty) oscillate each of 20 for an overall rotation shaft equal to 360 sexagesimal degrees. The complete rotation of the shaft will be obtained in about 11 seconds, with an angular speed equal to:

$\omega = 0.57$ [radiant/second] (1)

According with the data of Tab. 1 [19], and keeping in account the length of the balancing wheel, the number of Flexinol® wires for each balancing wheel the maximum torque obtainable is:

$Cu = n \cdot (F_t \cdot b - F_r \cdot b)$ (2)

Where:
F_t is the traction force (hot phase);
F_r is the deformation force (cold phase);
b is the length of the pivoting road;
n is the number of Flexinol® wires for each balancing wheel.

According with the data of Tab. 1 the theoretical value of torque is:

$Cu = 7.6$ [Nm] (3)

The generated power is:

$P = \omega \cdot Cu = 4.3$ [W] (4)

The theoretical power generated by the proposed thermal engine will be even lower because the mechanical performance of the engine (i.e. bearing friction, shaft deformation, etc.) was not considered. In any case, the calculated theoretical power output, as calculated by the equation 4, of the engine is low (as expected). Still, it can be increased, for example, by increasing the number of Flexinol® wires for each balancing wheel. The low power generated by the proposed engine, and by the other SMA engines proposed in the literature [17, 18], is caused by the relatively low-temperature differences at which the phase transitions append (see the diagram reported in Fig. 6). In any case also a low power generate can be useful for recovery energy from waste heat. Talking about the thermal efficiency of the proposed engine, we have to considerate first the thermal energy necessary for heat the wires, from the environmental temperature to the transition temperature, and the heat absorbed during the transition Martensite/Austenite. The other heat involved in the Martensite/Austenite transition is essentially heat lost through the distribution tubes, through the finned plate, through the containment vessel etc., and will not be taken into account at this level of analysis of the operating principle of the machine.

The thermal energy necessary to heat a single Flexinol® wire with a working length of one meter is calculated as the thermal energy necessary to increase the wire temperature from T_{min} to T_{max}, plus the heat adsorbed during the phase transition, according with the equation (5) i.e.:

$Q_{in} = n \cdot \rho \cdot V \cdot c \cdot (T_{max} - T_{min}) + \rho \cdot V \cdot Lht$ (5)

Where:
n is the number of wires for each balancing wheel (4);
ρ is the density of Flexinol® wires (6450 kg/m3);
V is the volume of wire (0.113·10-6 m3);
c is the specific heat of Flexinol®;
T_{max} is the temperature of heating fluid (358 K);
T_{min} is the temperature of cooling fluid (environmental temperature 293 K);
Lht is the latent heat of transformation (2.326 kj/kg).

Whit this data the required heat for each balancing wheel is:

$Qin = 160.3$ [j] (6)

With the contraction time of 0.6 seconds, we obtain:

$Q_{in} = 267.15$ [W] (7)

And an overall efficiency of:

$\eta = P/Q_{in} = 4.3/267.1 = 0.016\cdot$ (8)

If we calculate the Carnot efficiency between the environmental temperature (T_{min}=283 K) and the temperature of the supplied hot water (T_{max}=358 K) according to the equation (9) a Carnot efficiency of ≈18% means that a not ideal cycle can reach an efficiency, has aspect, lower than Carnot efficiency (evolving between the same temperatures).

$\eta = 1- T_{min}/T_{max} \approx 0.18$ (9)

If we put in account also the mechanical efficiency, the loss of energy due to the heat exchange between the machine and the external environmental, and so on, the heat conversion efficiency of the proposed SMA heat engine will around a value of 10%.

IV. CONCLUSION

A new configuration of heat engine based on the use of Shape Memory Alloy (SMA), in particular an SMA commercially available with the name of Flexinol®, was presented, In the paper we discussed about the working principle and main constructive aspects. Some thermodynamic aspects have been also discussed. The preliminary results obtained have shown that the engine works reasonably well if supplied with hot water at a temperature of 358 K and cooled with air at room temperature (293 K) with a measured rotation speed of 0.6 radiant/second. With this angular speed an output power of 4,3 W has been estimated. During the experiments the proposed engine was placed in rotation until the available hot water runs out. The supplied hot water was appositely produced using an electric heater with a nominal power of 1.5 kW. The thermodynamic efficiency was also estimated at about 16%, but, taking into account and considering all the energy loss of the engine, qualitatively estimated, a value of efficiency of the order of magnitude of 10% seems much more reasonable.

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