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Space Power Generation with a Tether Heat-Engine

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ABSTRACT

A new concept of space power generation is presented which exploits thermal cycles of dilatation and contraction of a spinning tethered system exposed to solar radiation. The concept exploits a lightweight film made of shape memory material directly interacting with sunlight. A temperature variation cycle in the film is created by inducing periodic variation of the tether sun aspect angle. As the film length diminishes due to the increased temperature the mechanical energy of the system increases and can be used to charge an energy storage device. A preliminary assessment of the system efficiency and power density is conducted. It is seen that in spite of the relatively low efficiency -for present shape memory alloys- of the phase transformation the system can benefit from a very high ratio between collecting surface and overall mass which could make it an interesting alternative to photovoltaic systems for space power plans in the future. Current limitations appear to be in the design of an efficient power conversion and incident light modulation system.

1. INTRODUCTION

The generation of power is vital for operating and maintaining structures in space. Earth orbit satellites, interplanetary probes and planetary surface scouts need in fact to scavenge energy from the environment for their long planned operations. The generation of electric power in space is of main interest also for research focused on in-orbit energy plants that could be used as energy sources for Earth or other planets use.
When the distance from the Sun is not excessively high, power generation with photovoltaic solar array is usually the preferred option thanks to the relatively high power density with respect to other solutions. However, in spite of their good performance, the deployment of very large solar array surfaces in space is costly and technologically challenging as it generally involves multiple launches and complex unfolding and/or assembling manoeuvres. Additionally the efficiency of solar arrays is reduced with operation temperature and is degraded over time due to exposure to UV radiation and thermal cycles.
A radically different solution for space power generation may come from the unique features of shape memory material, in particular shape memory alloys (SMA). Among other properties shape memory alloys posses a very high

force density meaning they can exert relatively high forces without excessive mass penalties. Additionally SMA's can exhibit very high power density depending on the energy mechanism employed to activate them. While resistive heating is still the most commonly used driving mechanism for SMAs the use of concentrated or reflected radiant heating has been recently shown to offer the highest power density suggesting promising applications of radiant energy SMA actuators in the aerospace field [1].
In this article we explore the possibility of employing SMA as primary components of power generation systems in space.
In the proposed design a thin film of SMA is oriented towards the sun direction while spinning around its center of mass as in Fig. 5. In this way the SMA works both as a collecting surface and as an actuator converting the radiating incident power from the Sun into mechanical work against the restoring centrifugal force. A temperature variation cycle produced by an induced variation of the film sun aspect angle will permit to create the thermal gradient necessary to obtain a net amount of power for onboard use, storage or long distance transmission.
The outline of the paper is the following. First we compute the theoretical performance of a film of shape memory material used to extract mechanical energy from the solar radiation. The efficiency of the cycle and its power density will be computed based on given available technology.
Second we describe a possible implementation of an orbiting heat engine based on a spinning tethered system and compute the system mechanical efficiency. Third, we present a possible mechanism to induce a thermal gradient in the film by acting on its sun aspect angle. Conclusions are drawn highlighting the most relevant technological issues and suggesting future development.

2. CONVERTING SOLAR RADIATION INTO MECHANICAL WORK

In order to estimate the maximum thermal efficiency and power density of a solar-radiation shape-memory-actuated heat-engine we consider the idealised experimental apparatus schematised in Fig. 1.
A thin film of shape memory material placed in deep space experiences an ideal solar radiation cycle in which one side of the film is exposed to periods of full solar illumination Δt_{light} alternated to periods of full darkness Δt_{shade}. Let the tape be acted upon at both ends by a time-varying force F(t) through which a net amount of work is extracted following the deformation of the shape memory material.
Based on the work by Liu [2] the maximum amount of work the heat engine can provide is obtained by tuning Δt_{light}, Δt_{shade} and F(t) as follows. The material is initially in full shade in martensitic state and F(t) is kept equal to a constant value F_{min} which guarantees a slight stress to keep the film taut. The film is then instantaneously exposed to full solar illumination. In this way the internal stress on the tape increases until the temperature A_f is reached for which the change of phase martensite-austenite is complete and the maximum operation tension of the material is reached. During this phase F(t) is gradually increased until a value F_{max} so that no work is carried out against it before the maximum operating stress σ_{max} is reached.
The maximum force F_{max} is expressed as:

$$F_{max} = \sigma_{max} wh - \delta F$$

where δF is an arbitrarily small force.

In this way the shape memory material will begin to contract just prior to reach its maximum tension so that the work W can be extracted:

$$W = F_{\max}\Delta\ell$$

Where $\Delta\ell$ is the total length variation of the tape.

As soon as the contraction phase is terminated the force is brought back to F_{min} and the radiation on the film is instantaneously blocked. The material will then start to cool down and, consequently, will expand by $\Delta\ell$ to its original length as a result of the austenite-martensite transformation.

We will now proceed to compute the thermal efficiency of the cycle and the estimated power density of the heat-engine as a function of the different thermal and geometrical properties of the shape memory actuator.

From a theoretical point of view it is known that a heat engine thermal efficiency cannot exceed the Carnot thermal efficiency:

$$\eta_{Carnot} = 1 - \frac{T_{cold}}{T_{hot}} \qquad (1)$$

where T_{hot} and T_{cold} are the two phase transitions temperatures of the actuator.

The fact that the range of temperature of current shape memory materials is relatively small limits their Carnot efficiencies. The most favourable shape memory alloy known today in terms of efficiency is NiTi, for which $\eta_{Carnot} \approx 10\%$.

Future advances in material science and nanotechnology may contribute to increase the operating temperature of these materials and in turns their efficiency.

In the real case the efficiency of a heat-engine does not reach the Carnot efficiency due to the non-reversible nature of the transformations involved.

For the case of the solar-radiation heat-engine described above we define the solar-thermal efficiency as the ratio of total incident solar energy that is converted into mechanical work:

$$\eta = \frac{W_{cycle}}{S_0 w \ell \Delta t_{cycle}} \qquad (2)$$

Where S_0 is the Sun incident power flux [W/m^2]. From now on we will adopt the value S_0 = 1371 W/m^2 corresponding to 1AU distance from the Sun.

Likewise, we define the power density of the system as the average power extracted from the cycle divided by the mass of the shape memory alloy tape plus the power conversion unit, the latter being a subsystem dedicated to the conversion of mechanical power into electrical.

$$P = \frac{W_{cycle}}{\Delta t_{cycle}(m_{tape} + m_{PCU})} \qquad (3)$$

Where W_{cycle} is the net work extracted from the heat-engine cycle, Δt_{cycle} its duration and P_{sun} the incoming radiating power from the sun on the fully illuminated side of the SMA tape.

The work W_{cycle} depends on the geometrical and mechanical properties of the shape memory material and can be computed as:

$$\begin{aligned} W_{cycle} &= F_{\max}\Delta\ell - F_{\min}\Delta\ell \\ &= \sigma_r w h \varepsilon_r \ell \end{aligned} \qquad (4)$$

Where $\sigma_r = \sigma_{max} - \sigma_{min}$ is the recovery stress of the shape memory material and ε_r its maximum deformation.

Ultimately the solar thermal efficiency yields:

$$\eta = \frac{\sigma_r \varepsilon_r h}{S_0 \Delta t_{cycle}} \qquad (5)$$

And the specific power:

$$P = \frac{\sigma_r \varepsilon_r}{\Delta t_{cycle}\left(\rho + \frac{m_{PCU}}{w h \ell}\right)} \qquad (6)$$

In order to evaluate these two quantities the only information needed is the time Δt_{light} necessary to reach the temperature of full austenite phase transformation upon heating and under maximum tension (A_f) and the time Δt_{shade} necessary to reach the temperature of full martensite phase transformation (M_f) upon cooling and under minimum tension.

Starting from the material in full martensitic state and at temperature M_f solar radiation is activated. At this point the material will experience a radiation-based temperature increase superimposed to a phase transformation to austenite.

Following the first principle of thermodynamics the corresponding energy balance is written as:

$$q_{rad}^{in} - q_{rad}^{out} = q_{\Delta T} + q_{MA} + \frac{dW_{out}}{dt} + \frac{dE_{el}}{dt} \qquad (7)$$

Where q_{rad}^{in} is the thermal flux, integrated on the film surface, of the incoming solar radiation, q_{rad}^{out} is the one associated with outgoing radiation, $q_{\Delta T}$ is due to a temperature increase of the material, q_{MA} is associated with the phase transition martensite-austenite, W_{out} is the work done by the film against the external environment and E_{el} is the strain energy accumulated in the material following the increase in tension.

For the present analysis we make the assumption that the last two terms have a small influence on the equilibrium temperature of the film. This assumption is acceptable if we consider the low thermal efficiency of the transformation which means the power extracted from the material deformation is much smaller than the integrated thermal fluxes present in Eq. (7). Inertia forces associated with the material deformation have also been neglected. A more refined analysis including the neglected terms will be performed in the future.

After developing Eq. (7) we obtain

$$w\ell a S_0 - 2\ell w \sigma e T^4(t) = w h \ell \rho \left(c\frac{\partial T}{\partial t} + \frac{\partial H_{MA}}{\partial t} \right) \qquad (8)$$

where

σ= Boltzmann constant=5.67×10^{-8} [W m^2 K-4]
e= tape average emissivity in the working temperature range (0<e<1).
a= tape absorptivity with respect to solar spectrum (0<a<1).
ρ= material density [kg/m^3]
ΔH_{MA}(>0)=specific enthalpy of martensite-austenite phase change [J/kg]
c=material specific heat [J/(kg K)]

The martensite-austenite transformation is analogous to the endothermal phase transition of ice to water but it is non-isothermal and occurs in the temperature interval $A_s \le T \le A_f$ starting from the beginning of the austenite transformation (for $T=A_s$) and continuing until the end completion ($T=A_f$) This fact makes it difficult to solve Eq. (8) also because the dependency of the phase transformation enthalpy flux with the material temperature, which would be needed to solve Eq. (8), has not been determined yet. Nevertheless since the purpose of our analysis is to give an estimate of the time needed to complete the transformation we can simplify the analysis by assuming an isothermal phase change followed by a heating process. It is easy to demonstrate the there exist a temperature $A_s \le T^* \le A_f$ that when chosen as reference temperature for a constant-temperature phase transition process provides the same phase-transition time associated with the real non-isothermal process. For the purpose of the analysis it is reasonable to assume T^* as the average between M_f and A_f. In this way the time needed for completing the transformation can be derived from Eq. (8) as:

$$\Delta t_{MA} = \frac{\rho h \Delta H_{MA}}{aS_0 - 2\sigma e\left[(A_f + A_s)/2\right]^4} \quad (9)$$

Following the phase transformation the system thermal behaviour is described by the heat-balance differential equation derived from Eq. (8):

$$\frac{\partial T}{\partial t} + \frac{1}{\rho ch}\left(2\sigma e T^4 - aS_0\right) = 0 \quad (10)$$

Equation (10) is a first-order non-linear differential equation which needs to be solved numerically to provide the time interval Δt_A needed to reach the maximum austenite temperature A_f. Finally the total sunlight exposure time becomes:

$$\Delta t_{light} = \Delta t_{MA} + \Delta t_A \quad (11)$$

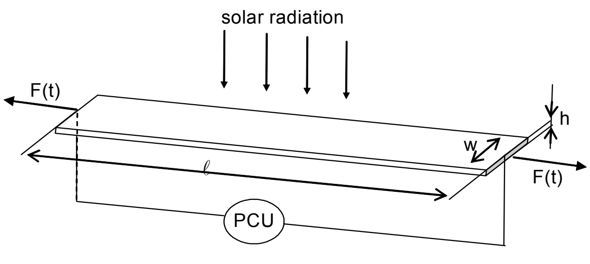

Fig. 1: Schematic of heat-engine based on irradiated shape memory tape

The time Δt_{shade} needed to complete the cooling process can be computed in a similar manner. First the time austenite-martensite phase change time is computed as:

$$\Delta t_{AM} = -\frac{\rho h \Delta H_{AM}}{2\sigma e\left[(M_f + M_s)/2\right]^4} \quad (12)$$

Where ΔH_{AM}(<0) is the specific enthalpy of the austenite-martensite phase change [J/kg] and (M_s,M_f) are the temparature of beginning and end of the martensitic phase transition.
The differential equation governing the cooling process yields:

$$\frac{\partial T}{\partial t} + \frac{2\sigma e T^4}{\rho ch} = 0 \quad (13)$$

Which provides the time span Δt_M needed to reach the minimum martensite temperature M_f. Finally the overall cooling period is computed as:

$$\Delta t_{shade} = \Delta t_{AM} + \Delta t_M \quad (14)$$

The analysis conducted so far gives important guidelines on how to choose the material and geometrical properties of the shape memory film in order improve the performance of the system. These can be summarised in the following points.

***<u>Shape memory material properties</u>*:**

The following properties are intrinsic of the shape memory material employed.

1) Elongation (ε_r): It should be as high as possible as it acts on both thermal efficiency and specific power in a linear fashion (Eq.s 5-6).
2) Recovery stress (σ_r): it has a similar effect as (ε_r) (Eq.s 5-6). Additionally it can affect the kinetics of the phase transformation by influencing A_f and M_f. In fact as an increase in σ_{max} increases the austenite conversion temperature

A_f[1] the thermal process becomes slower, which affects both η and P in a negative way. Nevertheless it can be seen that an increase of maximum stress is always beneficial as long as it does not exceeds the mechanical limit at which the material ceases to work correctly.

3) Specific heat (c): It should be as low as possible in order to speed up the kinetics of the thermal process.
4) Material density (ρ): it should be as low as possible as ρ is present at the denominator of Eq. (6). Moreover a low density speeds up the kinetics of the thermal process (Eq.s (5-9)).
5) Transition temperatures (A_f,M_f):
6) Transformation enthalpies (ΔH_{MA}, ΔH_{AM})

Among the different shape memory materials available today NiTi shape memory alloys offers the most favourable properties for this application (ρ=6450 kg/m^3, c=320 Jkg^{-1}K^{-1}, ΔH=25000 J/kg, ε_r=0.08, M_f=315.15 K, A_f= 351.15K, σ_r=565 MPa) and will be used as reference material throughout this article.

***Geometrical properties*:**

1) Thickness (h): Decreasing the film thickness h benefits the specific power through a decrease mass and an improvement of the thermal process. Numerical results show that the overall effect on the efficiency is also beneficial.
2) Width (w): In the hypothesis that the mass of the power conversion unit is independent of the tape width, an increase in w provides a higher specific power (Eq.6). In other words by increasing the illuminated section of the tape and going towards very large power plants the tape mass becomes more and more dominant with respect to the mass of the other system components.
3) Length (ℓ): Has the same effect as w.

***Surface properties*:**

The following properties characterise the surface of the tape and can be modified by coating techniques.

1) absorptivity (a): Should be as high as possible to speed up the martensite-austenite phase transition and austenite heating process.
2) emissivity (e): During the M→A transition it should be as low as possible to avoid heat to be wasted through radiation instead of contributing to the phase transformation. Vice versa it should be high during the A→M transformation to speed up the cooling process. Overall, numerical simulations show that there is an optimal value of emissivity for which the minimum thermal cycle duration is achieved.

[1] Experiments performed with Differential Scanning Calorimeter (DSC) have shown that the phase transition temperatures are, with good approximation, linearly dependent on the stress according to: $T_{tr}(\sigma_1) = CT_{tr}(\sigma_0)\Delta\sigma$ where C^{-1} is the slope of the stress-temperature line and is roughly the same for all the transition regions.

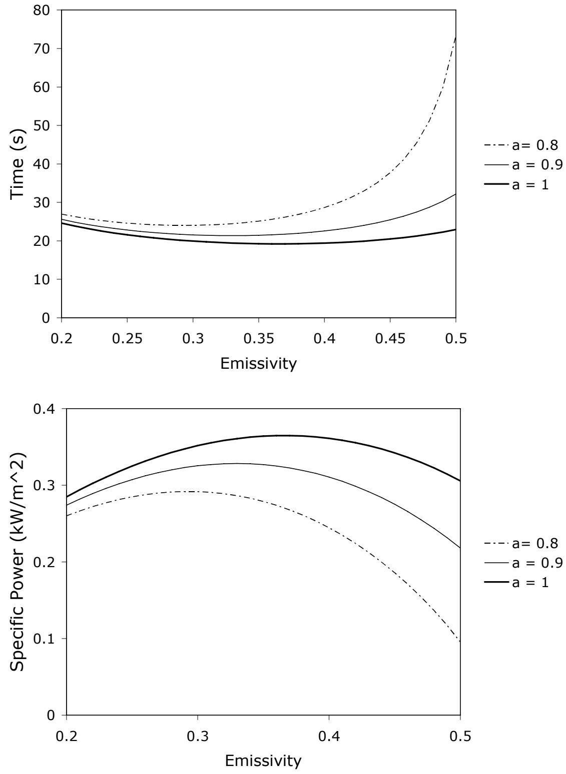

Fig. 2(a,b):Total thermal cycle duration and specific power for different absorptivity and emissivity values assuming a NiTi shape memory film of 25 μm thickness

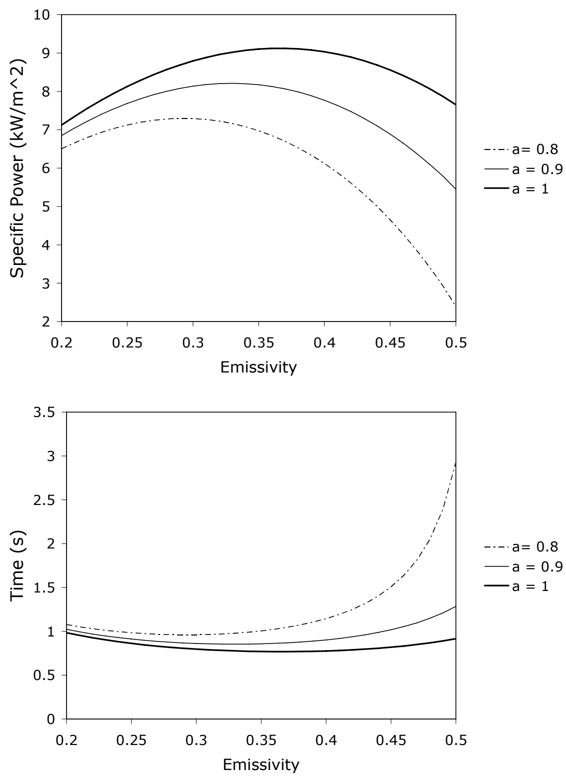

Fig. 3(a,b):Total thermal cycle duration and specific power for different absorptivity and emissivity values assuming a NiTi shape memory film of 1 μm thickness

Figures 2-4 show the performance in terms of cycle duration and power density for NiTi films[2] of 25μm and 1μm thickness and employing a coating material to tailor the surface thermal properties.

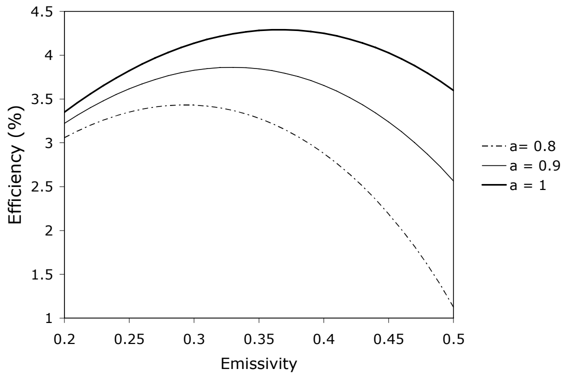

Fig.4: Thermal efficiency of a NiTi shape memory film for different absorptivity and emissivity values (the value is virtually independent of the film thickness).

3. POSSIBLE IMPLEMENTATION OF AN ORBITING SOLAR HEAT-ENGINE

The real implementation of a solar-mechanical energy conversion plant in space faces two main challenges. The first is concerned with the creation of a reaction force acting on the shape memory film which can be varied in time between a maximum and a minimum value in order to extract energy out of the system following the mechanism described in the previous chapter. The second is the creation of a light-shade cycle which can be tuned to the thermal response of the shape memory film. The two issues are discussed in the following.

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[2] Computation was performed considering specifications of on-way High-Temperature Flexinol Muscle Wires produced by Dynalloy Inc www.robotstore.com/download/MWPBv4.00_FlexSpecs.pdf

Energy extraction from a spinning configuration

Consider a shape memory film deployed radially to form a gyrostat spinning with a given angular momentum L as shown in Fig. 4. The film is connected with the central hub via a relatively short tether whose length is variable. Let r ∈ [r_{min} r_{max}] be the controlled tether length, ℓ ∈ [ℓ_{min} ℓ_{max}] the length of the film (ℓ_{min} corresponding to full austenite and ℓ_{max} to full martensite state), d=kℓ the distance of the film gyration radius from the tether/film interface where 0<k<1 is a parameter which depends on the variation of the film cross section along its length. The mass-optimal film tapering is obtained by imposing constant stress in the film section. This will result in an exponential variation of the cross section with the distance x from the hub centre [3]:

$$A_x = A_\ell \exp\left[\frac{v^2\rho}{\ell^2\sigma}\left(\frac{\ell^2}{2}-\frac{x^2}{2}\right)\right] \qquad (15)$$

where:
v= end mass tangential velocity [m/s]
σ= nominal material stress [N/m^2]
ρ= film density [kg/m^3]
$A_\ell = m_B \dfrac{v^2}{\sigma\ell}$ = end mass film cross section [m^2],
where m_B is the value of the end mass.
The surface area of the tapered film can be calculated as:

$$S_{film} = \int_0^{\ell_0} \frac{A_x}{h} dx = m_B v^* \sqrt{\pi}\,\frac{erf(v^*)\exp(v^{*2})}{h\rho} \qquad (16)$$

where:

$$v^* = v\sqrt{\frac{\rho}{2\sigma}}$$

and h is the film thickness.

The tether/end-mass ratio can also be computed [3] and yields:

$$\frac{m_{film}}{m_B} = \sqrt{\pi}v^* \exp(v^{*2}) erf(v^*) \qquad (17)$$

Which shows that the end mass can be made negligible compared to the film by increasing the system tangential velocity v or decreasing the maximum stress σ.
The gyration radius d of the tapered section can also be derived from Ref [3] so that the inertia parameter k yields:

$$k = \frac{d}{\ell} = \sqrt{\frac{\frac{\sqrt{\pi}}{2v^*}\exp(v^{*2})erf(v^*)}{1+\sqrt{\pi}v^*\exp(v^{*2})erf(v^*)}} \qquad (18)$$

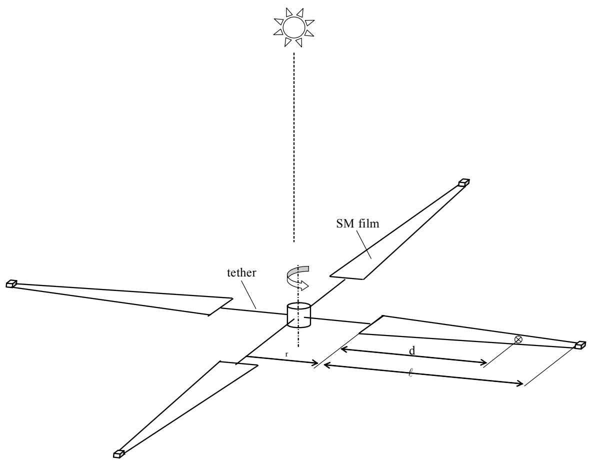

Fig. 5: Schematic of a possible spinning heat-engine based on irradiated shape memory tape

At this point the thermodynamic energy extraction cycle can be described as follows:

1) *First phase*: The film is at its maximum length ℓ=ℓ_{max} in full martensitic state. The tether is reeled in from its maximum length r_{max} to its minimum length r_{min} at the expense of electrical power (or using stored mechanical power from other parts of the gyrostat).

2) *Second phase*: The film is exposed to sunlight and start shrinking therefore increasing its tension until it reaches a critical length $\ell_{min}<\ell^*<\ell_{max}$ for which the tension at the tether/film interface is equal to the maximum operational tension τ_{max} for the shape memory film.
3) *Third phase*: The film continues to shrink from ℓ^* to ℓ_{min} as it increases its temperature. But while doing that the tether is reeled out from r_{min} to $r^*<r_{max}$ to keep the tension at the stationary value τ_{max}. In this process a positive work is extracted.
4) *Fourth phase*: while the film is still at its minimum length $\ell=\ell_{max}$ the tether is reeled out further with decreasing tension until $r=r_{max}$. In this way additional work is extracted.
5) *Fifth phase*: the film enters the shade phase and expands from ℓ_{min} to ℓ_{max} hence closing the cycle.

We now compute the efficiency of the energy extraction from the cycle as a function of the different design parameters.

Conservation of angular momentum provides the tension at the tether/film interface as:

$$\tau = \frac{L^2}{m_{tot}(k\ell + r)^3} \qquad (19)$$

where $m_{tot}=m_{film}+m_B$ is the total mass of the system.

The choice of the system angular momentum is constrained by the need to have $\ell_{min}<\ell^*<\ell_{max}$. In other words after defining the elongation parameters ε and ε^* such as:

$$\ell_{max} = (1+\varepsilon)\ell_{min} \qquad (20.1)$$

$$\ell^* = (1+\varepsilon^*)\ell_{min} \qquad (20.2)$$

we must have $0<\varepsilon^*<\varepsilon$

The relation between ℓ^* and L can be derived from Eq. (19) after imposing $\tau=\tau_{max}$ and $r=r_{min}$. After doing that and taking into account Eq. (20.2) we obtain the angular momentum as a function of the elongation parameter ε^* as follows:

$$L = (m_{tot}\tau_{max})^{1/2} \times \left[r_{min} + k\ell_{min}(1+\varepsilon^*)\right]^{3/2} \qquad (21)$$

The (negative) work of phase one can now be computed as:

$$W_1 = \int_{r\,max}^{r\,min} \tau(\ell = \ell_{max})dr = -\frac{1}{2}\tau_{max}(r_{max} - r_{min}) \times \frac{(d^* + r_{min})^3 (d_{max} + r_{max} + r_{min})^3}{(d_{max} + r_{min})^2 (d_{max} + r_{max})^2} \qquad (22)$$

where

$$d^* = k\ell^* = k(1+\varepsilon^*)\ell_{min} \qquad (23.1)$$

$$d_{max} = k\ell_{max} = k(1+\varepsilon)\ell_{min} \qquad (23.2)$$

The (positive) work extracted in phase three can be computed as:

$$W_3 = \tau_{max}(r^* - r_{min}) \qquad (24)$$

Where r^* is obtained by plugging $\ell=\ell_{min}$, $\tau=\tau_{max}$ into eq. (19) and solving for r. After taking into account Eq. (21) we have:

$$r^* = k\varepsilon^*\ell_{min} + r_{min} \qquad (25)$$

Hence:

$$W_3 = \tau_{max} k\varepsilon^*\ell_{min} \qquad (26)$$

The (positive) work extracted in phase four is:

$$W_4 = \int_{r^*}^{r\max} \tau(\ell = \ell_{\min}) dr =$$

$$\frac{1}{2}\tau_{\max}(r_{\max} - r_{\min} - k\varepsilon^*\ell_{\min}) \times (2k\ell_{\min} + k\varepsilon^*\ell_{\min} + r_{\max} + r_{\min}) \times \frac{d^* + r_{\min}}{(k\ell_{\min} + r_{\max})^2} \quad (27)$$

Finally the overall energy extracted from the cycle is:

$$W_{tot} = W_1 + W_3 + W_4 \quad (28)$$

At this point we define the efficiency of the overall mechanical cycle as:

$$\eta_{mech} = \frac{W_{tot}}{\tau_{\max}\varepsilon\ell_{\min}} \frac{\rho\ell_{\min} A_{x=0}}{m_{tot}} \quad (29)$$

which corresponds to the ratio between the extracted energy of the cycle and the maximum work that can be done by a strip of shape memory alloy of constant cross section $A_{x=0}$ and for the same mass as the total mass of the system.

The cross section $A_{x=0}$ of the film at the tether/film interface can be computed from Eq. (15):

$$A_{x=0} = \frac{m_B v^2}{\sigma\ell_{\min}} \exp\left(\frac{1}{2}\frac{\rho v^2}{\sigma}\right) \quad (30)$$

By defining the efficiency as in Eq. (29) one can scale the results found for the ideal cycle described in the previous paragraph to its mechanical implementation. In this way the efficiency and power density yields:

$$\eta_{orbit} = \eta_{mech} \frac{\sigma_r \varepsilon_r h}{S_0 \Delta t_{cycle}} \quad (31)$$

$$P_{orbit} = \eta_{mech} \frac{\sigma_r \varepsilon_r}{\Delta t_{cycle}\left(\rho + \frac{m_{PCU}}{wh\ell}\right)} \quad (32)$$

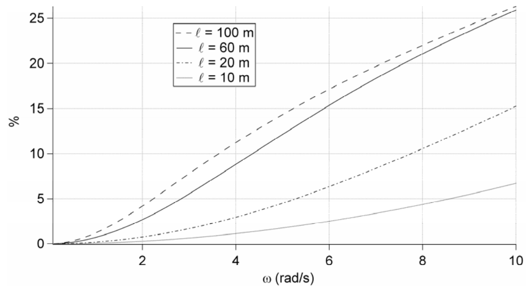

Fig. 6: Mechanical efficiency of a spinning heat-engine for different total length and rotation rates assuming r_{min}=0 and r_{max}=5 m.

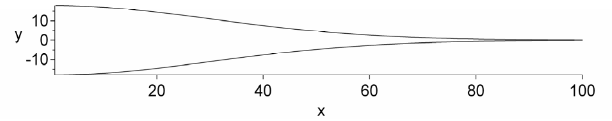

Fig. 7: Tapered film profile with ℓ=100m , m_B=0.1kg, ω=10rad/s, r_{max}=5, r_{min}=0.

Likewise the power provided by the system can be expressed as:

$$\dot{W} = \eta\eta_{mech} S_{film} S_0 \quad (33)$$

Fig.5 plots the mechanical efficiency (29) for different values of the key parameters.

The role of the different parameters on the mechanical efficiency can be summarised as follows:

Film length (ℓ_{min}): The system efficiency decreases considerably as the film length increases. This is because by having more mass distributed away from the centre of rotation the tension variation in the film is smaller.

Tether stroke (r_{min},r_{max}): the greater the stroke the better the efficiency as it increases the tension variation.

Maximum tangential velocity (v): the greater v the greater the efficiency.

Operational stress (σ): the higher σ the higher the efficiency.

Creating a temperature cycle

The results given by Eq.s (31) and (32) are still optimistic as so far it has been assumed possible for the film to pass instantaneously from a fully illuminated to a full shade condition. The engineering implementation of this requirement may pose a significant challenge.

Natural eclipses experienced on orbit can unfortunately not be exploited as the transition time to have good thermal efficiency should be of the order of a second or a few seconds (depending on film thickness). The only possibility is then either to create the eclipses artificially by acting mechanically on the system. Fig. 8 shows one possible implementation of such mechanism in which the sun lit surface of the shape memory material is folded to reduce the sun aspect angle to (ideally) zero.

Clearly depending on the mechanism characteristics a more refined thermal analysis should be conducted to assess the impact on the thermal cycle duration. Such analysis will be the subject of future research.

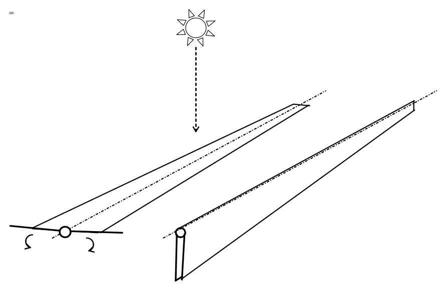

Fig. 8: Possible sun aspect angle variation mechanism

4. DISCUSSION, ISSUES AND RECOMMENDATIONS

The main issues following this preliminary analysis are mostly related to the implementation of a system able to achieve an efficient transfer of solar power to mechanical energy. If a spinning systems is used it is necessary to concentrate the most of the film surface close to the centre of rotation so that conservation of angular momentum can be better exploited to produce a larger variation in material stress and, in turns, a higher energy extraction efficiency. For the same reason it is required to increase the spin rate as much as reasonable. In addition, the required fast switching light-shade cycle may complicate the system design considerably.

For the ideal case the overall specific power, only considering the mass of the collecting film could reach very high levels (up to 2000 W/kg). On the other hand this value is likely to be considerably reduced when the mass of the overall energy conversion unit is included. Also additional loss of efficiency is expected when adding the following effects:

1- Loss of efficiency in the different mechanisms.
2- Influence of other form of radiations (e.g. IR radiation of the Earth).
3- Inertia forces on the film (so far neglected).
4- Efficiency of the light-shade transition mechanism.

5. CONCLUSIONS

The work has proven, for the first time to the authors' knowledge, that a thermodynamical cycle converting solar irradiation into electrical power can be realized in space without the use of a working fluid by exploiting the properties of shape memory materials, which are used as collecting elements and actuator simultaneously. Theoretical calculations have shown that an irradiated film of shape memory alloy can achieve very high power density with currently available materials. Key to the system performance is the use of thin shape memory films with very high surface to mass ratio.

Based on preliminary calculations and referring to state of the art shape memory materials (in particular NiTi shape memory alloys) power densities of a few hundreds of kW/kg may be achieved.

Nevertheless there remain engineering difficulties for which the concept is still not ready to be implemented in practice, at least for the time being. The first is concerned with the design of a dynamic apparatus which allows the film to rapidly switch from high to low tension so that mechanical work can be efficiently extracted. The second regards the design of a system which allows the film to pass instantaneously from a fully illuminated condition to a full shade condition.

Improvements in the system design and advances in material science and nanotechnology could make this concept an attractive alternative to photovoltaic cells in the future.

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