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Feasibility of Using Shape Memory Alloy (SMA) Spring to Facilitate Actuation of an Iris Coupled to a Solar Reactor

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Variation in incoming solar energy adversely affects the temperature inside the reactor and lowers its efficiency. Therefore, it is important to develop a mechanism that can maintain semi-constant temperatures inside the reactor from sunrise to sunset. In this paper, we present a promising aperture mechanism that contracting and enlarging its circular opening with the use of Nickel-Titanium Shape Memory Alloy (SMA) springs. SMA springs possess memory of their shapes at certain temperatures, and therefore, by controlling the temperature of the spring, it is possible to exert different forces. These forces may be then transferred to the variable aperture mechanism. In this study, variation of the force exerted by an SMA spring with respect to temperature was experimentally tested and viability of SMA spring use in actuating an iris mechanism aperture was examined. In order to simulate conditions under fluctuation solar radiation, a 7 kW solar simulator was used in experiments at varying power levels. It was observed that SMA springs are promising as a replacement to the actuation mechanism driven by a motor.

1. Introduction

Fluctuations of solar radiation due to the position of the sun, unavailability during night time and transient availability at various weather conditions are the main considerations while designing a solar reactor and accompanying auxiliary systems in order to achieve uniform temperature distribution and uninterrupted use of process heat in the reactor cavity. Currently, there are few techniques that are being used to cogitate accommodate the transient periods and control the reactor temperature. One of the commonly practiced methods is to adjust the mass flow rate of the feedstock which is very simple to implement. Another method is focusing and defocusing of the heliostats which requires careful control of the heliostat field. Finally, thermal storage is also being widely used to ensure continuous operation. Although these techniques are widely being practiced, there are several drawbacks associated with each of them. For example, while the temperature inside a solar reactor can be easily controlled by varying the mass flow rate of the feedstock, it disturbs the flow dynamics inside reactor (Devanuri and Ozalp, 2013). This is a major problem for cases where the flow pattern must be maintained constant, for example, in solar thermal cracking of natural gas where carbon particles clog the reactor (Shilapuram et al., 2011). To reduce carbon deposition on reactor walls and at the exit, a special swirling flow pattern needs to be maintained inside the reactor (Ozalp et al., 2011). Therefore, temperature inside the reactor should be controlled without changing the flow rate so that the flow pattern remains undisturbed. In order to achieve that, a special mechanism or a design is required. In this paper, we present a novel approach with the use of SMA springs as a promising method to actuate an iris mechanism for the maintenance of semi-constant temperature inside a solar reactor without disturbing the flow dynamics and without using any motor controlled mechanisms or apparatuses.

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2. Current state of the art

Current solar reactor designs have a fixed aperture size which does not compensate for the changes in variation in solar energy from the sunrise to sunset. On the other hand, by varying the aperture radius with incoming flux, temperature inside the reactor would be kept semi-constant in theory (Ozalp et al., 2011). Such mechanism has the potential to stabilize internal reactor operating conditions by minimizing radiation losses through the aperture and by responding to the fluctuations in solar flux by regulating the aperture area. However, it is a challenge to actuate the blades of the iris mechanism with a motor under such high temperatures even if the iris is water cooled and the motor is air cooled (Menon et al., 2013). Therefore, an alternative mechanism is needed to avoid running control system tools under high temperature. SMA springs are very promising to be considered as a viable solution. They are not being affected by the high temperature or thermal stress due to temperature changes via flux change. In fact, they make use of the temperature difference and can withstand very high temperatures. SMA springs can respond to the temperature changes due to changes in direct normal radiation and can actuate the iris mechanism blades to obtain the appropriate aperture size. It is important to select correct SMA spring and size that would yield accurate aperture size opening and closure. It is possible to create many different iris-type aperture designs, each having different components, structure, control mechanism and field of application. The designs may vary from having 4 blades or segments to having 12 blades in the case illustrated in (Echner et al., 2009), or more as illustrated in (Chang et al., 2000). The most effective aperture designs with simple aperture mechanisms will be those having a circular aperture area. The aperture mechanism developed to obtain more circular aperture and used for SMA actuation in this study is shown in Figure 1.

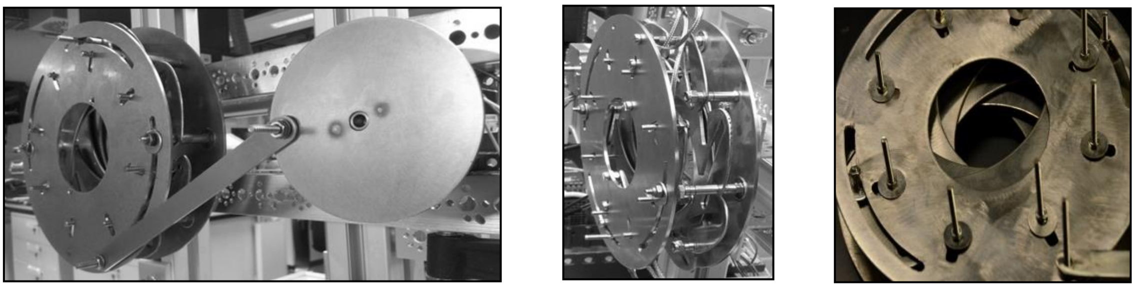


Figure 1: Variable aperture mechanism analysed in this study

This four-bar crank-rocker mechanism is employed to open/close the aperture as shown in Figure 1. Position and dimensions of the linkages are configured in such a way that the system behaves as a crank-rocker mechanism. The disk fixed to the motor (crank) is free to rotate. The top plate of the aperture (rocker) is connected to the crank via a connecting link that oscillates between two set points defined as the closing and opening angles of the aperture. In this way, no matter how many revolutions the crank plate makes, the aperture position would toggle from completely opened to completely closed position, and vice versa.

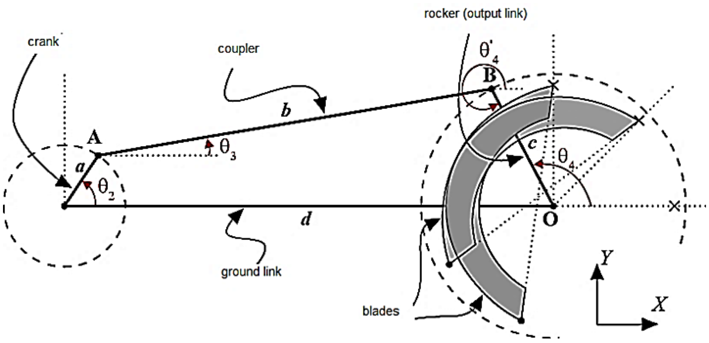


Figure 2: Four bar crank-rocker mechanism with the aperture blades

3. Calculation of variation in aperture area and identification of corresponding rotation

The first step of establishing the relationship between the SMA spring actuation and the aperture mechanism is to analyze the aperture mechanism and develop an expression that relates the aperture area and crank rotation. For this, the variable aperture shown in Figure 1 is modelled as a Grashof crank-rocker mechanism as shown in Figure 2, where the position vectors for the four links are indicated. The lengths *a, b, c* and *d* correspond to the crank (input), coupler, rocker (output) and ground link. In order to actuate the variable aperture, it is necessary to relate the aperture top plate rotation angle θ_4 to the input angle θ_2. Once the mathematical relationship between θ_4 and θ_2 is established, this information can be extended to calculate the corresponding aperture area as a function of θ_4. A brief outline of this derivation is provided below. The lengths labelled as *a, b, c* and *d* are known constants and the angle made by the ground link with the horizontal, $\theta_1 = 0$. An implicit relation between θ_2 and θ_4 can be given as follows:

$$A\tan^2\left(\frac{\theta_4}{2}\right) + B\tan\left(\frac{\theta_4}{2}\right) + C = 0 \tag{1}$$

where, $A = K_2 + K_1 + (K_3 - 1)\cos\theta_2$, $K_1 = \frac{b^2-a^2-c^2-d^2}{2ac}$, $B = 2\sin\theta_2$, $K_2 = \frac{d}{a}$, $K_3 = \frac{d}{c}$ and

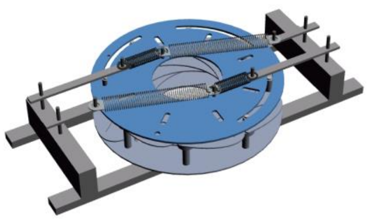
$C = K_1 - K_2 + (K_3 + 1)\cos\theta_2$. The aperture opening area is calculated by approximating it as the area A_{oct} of a regular octagon, with sides of length l_o. Length *a* can be related to length. The length r_X can be defined as the distance from the center of the octagon to one of its vertices. Each vertex of the octagon represents a position, *X* that is obtained as the point of intersection of the inner edges of any two adjacent blades of the variable aperture mechanism. The side length, lo can be related to r_X as $r_X = lo\sqrt{1 + \frac{1}{\sqrt{2}}}$. The coordinates of *X* give the magnitude of r_X which is used to get A_{oct} as follows:

$$A_{oct} = 2\sqrt{2}r_X^2 \tag{2}$$

To find the *X* coordinate; the point of intersection of adjacent blades are to be calculated. Importantly, the coordinates of *X* are obtained in terms of θ_4, and can be used to calculate r_X. From Eq(2), A_{oct} is obtained as a function of θ_4.

4. Selection of SMA spring and use of SMA spring to control aperture rotation

With the use of springs made of shape memory alloys, it is possible to control the opening of this aperture mechanism by changes in the amount of incoming energy. Identification of the most suitable SMA type for this application was made based on our previous experience on a number of different ideas for SMA based actuators such as SMA based devices for sun tracking Rao et al. (2013), SMA based bending and expansion devices with smart bias Rao et al. (2013), and an SMA based device for operating automatic window blinds without motors, sensors or controllers Sivakumar et al. (2010). While the current actuator is restricted to shape memory springs with actuation temperatures in the vicinity of 100 °C, commercial NiTiPt wires with actuation temperatures of 350 °C have been developed. Furthermore, recently NASA has revealed shape memory wires made of NiTiPt. These alloys can operate at temperatures of 1,000 °C or higher depending on the weight percentage of Pt. Thus it is potentially possible to use these in solar reactor aperture control as well. Because SMA alloys have the ability to return to a previously defined shape or size upon application of certain thermal procedure, they are perfect materials to control solar reactor aperture opening and closing. In this study, a nickel-titanium one-way shape memory alloy is used. Two SMA springs were used along with two regular extension springs to bias the SMA springs. The springs were connected to the aperture as shown in Figure 3.



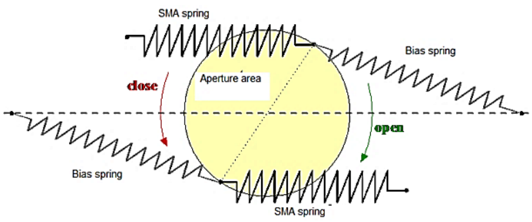


Figure 3: Experimental setup to control aperture opening and closing with SMA springs (left), SMA and bias springs for opening and closing of the aperture area (right)

When the SMA springs are heated, their structure changes to the highly elastic austenite form overcoming the stiffness of the bias springs and rotating the aperture flange. When the SMA springs cool down their structure begins to transform from austenite to martensite. Thus, their stiffness reduces and when the stiffness value is below than that of the bias springs, the aperture rotates in the clockwise direction.
One of the challenges in designing SMA actuators with bias springs is the fact that the bias springs induce a variable force on the SMA, thus limiting its stroke. In order to overcome this problem, the bias springs were positioned in such a way that the net torque due to the bias spring is almost constant. This was done by mounting the bias springs in such a way that as the spring extends and its tension increases, the angle between the spring and the radius of the rotating aperture decreases thus partially compensating for the change in the angle and providing an approximately constant opening torque irrespective of the tension in the springs. Figure 4 shows the angular relation between the SMA and the bias spring along with the geometric distances which relate the position of the springs.

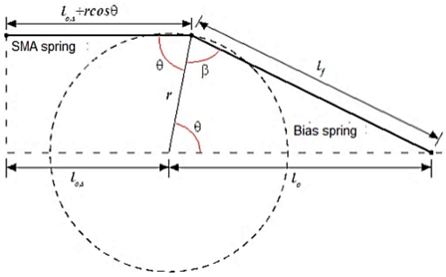


Figure 4: Arrangement of SMA spring w.r.t the bias spring on aperture

The torque versus angle relation for the bias spring is as follows:

$$\tau = r.Fsin\beta \tag{3}$$

$$\tau(\theta) = rk\left[1 - \frac{l_i}{l_f(\theta)}\right] l_o sin\theta \tag{4}$$

$$l_f(\theta) = \sqrt{l_o^2 + r^2 - 2rl_o\cos\theta} \tag{5}$$

In deriving the above equation, we have set the free length of the bias spring to be l_i and have used the sine rule and the cosine rule. The torque of the SMA spring is a function of temperature and aperture rotation angle, $\tau_s = f(T,\theta)$. In order to quantify the variation of the stiffness of the SMA spring with temperature, a series of tests of the sma springs were carried out with different dead loads and at the A_s and M_f temperature, and the change in the spring extension was noted. Based on this, a linear variation of the SMA stiffness with temperature was assumed. Our results are in accord with what is used in conventional SMA design (Warram, 1993). Based on the geometry shown in Figure 3, we can derive the torque produced by the SMA spring as a function of the temperature and rotation angle as follows:

$$\tau_s = r.F_s sin\theta \tag{5}$$

$$k(T) = k_m T + k_o \tag{6}$$

$$\tau_s = f(T,\theta) = r(k_m T + k_o)(l_{o,s} + rcos\theta - l_{i,s})sin\theta \tag{7}$$

In the above equation, k *(T)* is the temperature dependent stiffness of the SMA spring and $l_{i,s}$ is the initial (coil bound) length of the spring.

5. Experiments and results

Feasibility of using SMA springs to open and close the iris aperture mechanism was tested in two methods: first with electric heating, and next with the use of solar simulator as the heat source. The first set of experiments was done with five SMA springs for the following experiments: *(1)* timing the opening/closing of the aperture with SMAs, and *(2)* determination of SMA behaviour at low and high temperatures with respect to its force deflection curve. For the first test, two SMA springs were connected in series to a 2.5 V DC power supply. Relatively high electrical resistance of the SMA resulted in electrical heating of the SMA and therefore initiated its phase transformation. Once the aperture radii reached the lower limit (r_{close}), the power supply was switched off and the SMA was allowed to cool down. When the SMA temperature was decreasing, the bias spring stiffness took over and the aperture area started to opening. Duration of the time taken for the aperture to open and close between two fixed radii was noted for each pair of SMA springs. The average aperture opening and closing radii considered during time measurement are: r_{open} = 36.59 mm and r_{close} = 26.37 mm. For the second experiment, an SMA spring in its austenite size and shape but in the martensite form at room temperature was loaded with known mass and the corresponding deflection was noted. The SMA spring was then heated so that it returned to its memorized shape. Next, it was allowed to cool to return to martensite phase.

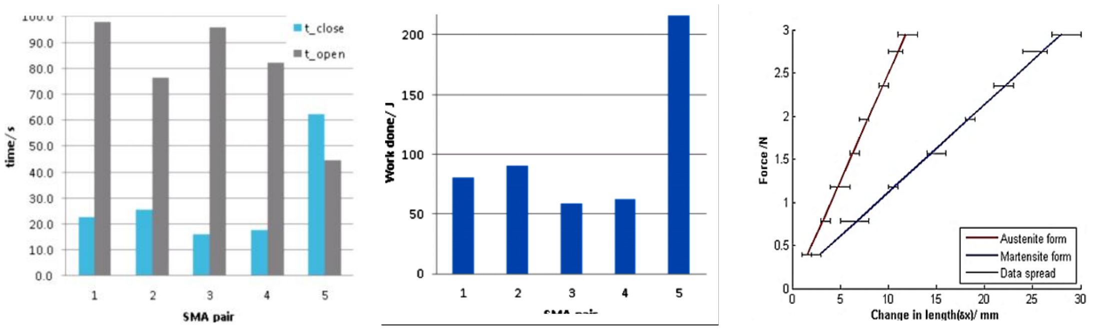


Figure 5: Experimental results for different SMA spring pairs

Figure 5 shows the results for the opening and closing of the aperture for the five pairs of SMA springs. Except for SMA pair 5, the rest of the pairs take significantly less time to close the aperture than to open it ($t_{close,\ avg}$ ≈ 20 s, $t_{open,\ avg}$ ≈ 88 s). This is due to the relatively high rate of heating caused by the continuous supply of electrical power until r_{close} was reached. It takes more time for the bias springs to open the aperture as a result of the slow rate of cooling of SMAs by natural convection. The response time for opening and closing of the aperture is significantly less than the time scales involved with daily variations in solar irradiation due to weather changes. The force-deflection of the SMA springs is plotted in Figure 5 along with the spread in deflection (δx) for each loading. The mean value for the SMA spring constant at the high temperature was k_H = 249 N/m whereas it was k_L = 102 N/m at low temperature. Since the transformation from martensite to austenite begins at A_s and reaches completion at A_f; k_H and k_L were assumed to correspond to A_f and A_s. Because A_f and A_s values are known from the manufacturer database, Eq. (6) gives that k_m = 7.38 N/m and k_o = –2,320 N/m. For static equilibrium of the aperture, $\tau(q) = \tau_S(T,\theta)$. Therefore, Eq(3) and Eq(5) were solved for the equilibrium temperature and rotation angle. If the SMA is at T_{eqm} then the system is in static equilibrium. On the other hand, for temperatures below T_{eqm}, the regular spring will bias the SMA spring and the aperture will open.

The second set of experiments was done with solar simulator. In order to quantify the variation of force exerted by an SMA spring with respect to temperature, an experiment shown in Figure 6 was setup.

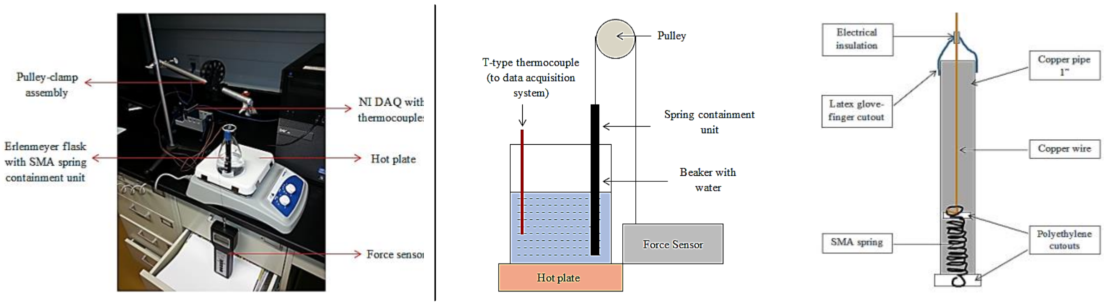


Figure 6: Experimental setup and schematic illustration of the parts

A tension SMA spring was used for this experiment. Fig. 6 shows a schematic of the experiment setup and a cross section of the spring containment unit placed in the Erlenmeyer flask. Prior to the experiment, the spring was stretched beyond its elastic limit at room temperature using a 400 g weight. The temperature was increased by heating the hot plate and the force exerted by the spring was measured by a force sensor. The hot plate provides a specified constant heat flux to the beaker. Real-time variations of temperature and spring force were recorded and the results are plotted below.

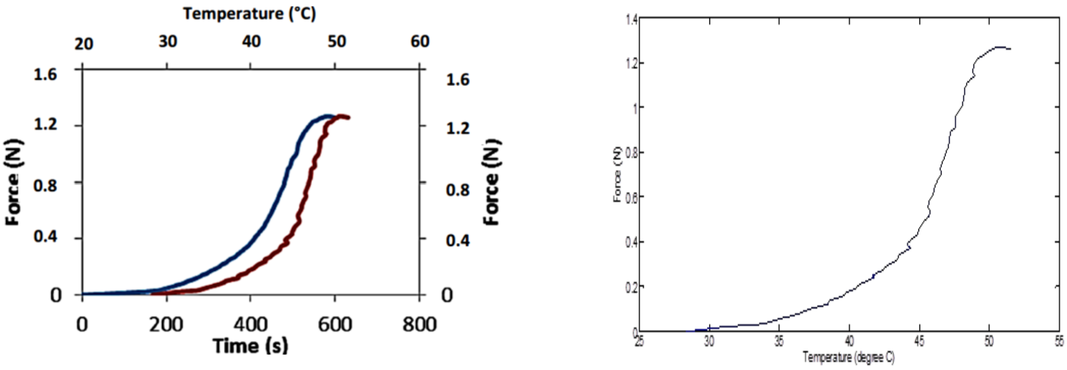


Figure 7: Variation of force exerted by spring with time and variation of force exerted by spring with temperature of the spring

After completing this step, the same experiment was repeated with the solar simulator. The setup was shifted to the front of the simulator.

6. Conclusions

The goal of this paper was to evaluate the possibility of using SMA springs to actuate a variable aperture mechanism that helps maintain the efficiency of a solar reactor. Theoretical and experimental proof-of-concept of an SMA controlled variable aperture mechanism was presented. It was observed that, when the SMA springs were heated, their structure changed to the highly elastic austenite form overcoming the stiffness of the bias springs and rotating the aperture flange. The time response of the actuation was observed to be relatively small when compared to the time involved in variations in solar radiation. All experiments presented above showed that by employing a heating mechanism for an SMA spring, it is possible to replace the linkages with these springs and remove the usage of the motor altogether. Using SMA springs instead of the motor can not only save energy but also simplify the control setup.

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