Design of a Shape Memory Alloy Actuator for Self-Deployable Heat Exchangers

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Abstract. The design of thermally driven self-deployable heat exchangers is a challenging thermomechanical problem. The driving concept is the coupling of a foldable heat exchanger with Shape Memory Alloy (SMA) actuators to passively engage the deploying system. SMA materials have stress-temperature dependent mechanical behaviour, a characteristic exploited in thermally controlled actuation. This experimental work reports on the design and testing of a deployable panel driven by passive heating. The SMA actuator is a Nickel-Titanium wire (SmartFlex® Wire), supplied by SAES group® company. The maximum deploying angle of the panel is about 62 degrees and is measured if the actuator is warmed up above the austenite finish temperature through Joule effect. The tests showed that using Teflon coating or shaving foam, which reduces, thermal exchange, can increase the deploying angle up to 7 degrees. Further tests on higher performance foams and a three-wire configuration will be considered to allow the full deploying of the panel.

1. Introduction

One of the most interesting and challenging future perspectives in the heat transfer field is to build thermally driven self-deployable heat transfer devices. The idea is to exploit the already existing thermal field of the heat exchangers, to passively induce its change in shape, which is the bending of the heat receiving zone or the radiator panel. The experimental apparatus presented in this paper is part of the TOPDESS ((TwO-phase Passive thermal devices for DEployable Space Systems) project funded by the European Space Agency. The project aims at designing a deployable metallic tubular Pulsating Heat Pipe (PHP) with a Shape Memory Alloy (SMA) actuator.

The Pulsating Heat Pipe devices are passive wickless heat transfer devices made of a capillary tube arranged in a serpentine or multi-turn structure and are composed of evaporating, adiabatic and condensing sections [1]. To allow deployment, a spring shape is chosen for the adiabatic section. The folding of the device is allowed by the elasticity of the spring, while the shape memory effect is used for unfolding.

Due to the complexity of the two research fields, PHP and Shape Memory Alloy (SMA) are studied individually by means of two set-ups. The present work is mainly devoted to the design of the SMA actuator.

Shape Memory Alloys (SMAs) are already widely used in actuation in a variety of industrial sectors as they can effectively reduce the complexity of a system that uses standard technologies, such as electromechanical, hydraulic or pneumatic activation. Current literature focuses on SMA actuators for deployable structures and survey provides information on the shape of the SMAs, the strain applied on the SMAs at the temperature in stowed configuration, the heating methods, and the results on the deploying angle, more than their application. The reason is that the above information, described in detail in the following sections, is necessary for the designing of the actuator presented in this manuscript.

Katayama et al. [2] performed tests in the laboratory for the deploying of a plate. The shape memory wires are $Ni_{50.6}Ti_{49.4}$ (50.6 % Nickel, 49.4 % Titanium) with diameters of 0.6 mm and 0.7 mm and were strained up to 5%. The wires are heated by infrared quartz lamp, and this is the only paper found in the literature in which irradiation is exploited. The results show that during all the tests, the panel opened of 180 degrees with respect to the folded configuration, albeit with different times depending on the different boundary conditions. From an experimental point of view, however, they suggest the impossibility of a brazed or welded connection ends of the SMA wire for system deployment. This suggestion is considered in the design of the device presented in this manuscript.

Carpenter et al. [3] filing the patent in 1991, opens the way to a new configuration of shape memory materials based on a planar geometry (i.e. sheets). Later Carpenter et al. [4] tests the sheets for the opening of a light array photovoltaic system. The material of the sheets is known with the commercial name Nitinol®, $\mathrm{Ni_{50}Ti_{50}}$ (50 % Nickel, 50 % Titanium), and the heat is supplied through internally bonded flexible nichrome heaters. The strips are manually buckled and folded into the stowed configuration. The above-mentioned works have explored the opening of deployable systems. Vale Pereira et al. [5], on the other hand, also analyzes the closure, using two sheets, with a rectangular "dog-bone" shape. The sheets are deformed separately at room temperature in the two folded and unfolded configurations. The results show that although the mission envisaged an opening of 90 degrees, the maximum reached angle was 18 degrees. However, the authors propose the replacement of the sheets with wires to achieve the purpose.

A different shape is proposed by Nagano et al. [6], they present an SMA spring that drives a shaft for the deployment of a reversible thermal panel. In addition, a bias spring allows the panel to close. The SMA spring is made of $\mathrm{Ni_{54.5}Ti_{44}}Co_{1.5}$ (54.5 % Nickel, 44 % Titanium, 1.5% Cobalt) and the actuator housing is heated by a flexible thermal strap. The authors focus their discussion about the results mainly on the radiation and absorption of the panels. They confirm, however, the thermal hysteresis of the SMA and state that to achieve the goal of 0-180 degrees opening, it is necessary to have higher deployment torque. The field of application does not only concern the opening/closing of radiant panels, but also the deployment of antennas, as founded by Lan et al. [7]. Six Nitinol® wires of diameter 0.8 mm were elongated by 4% at room temperature and were fixed on each primary beam for the actuation. By supplying heat to the wire through the Joule effect, the opening angle reached was 165 degrees. Differently from previous works, Paik et al. [8] studies the shape of the Nitinol® sheet for maximizing the applied strain, two designs that resemble the letters Y and Z by means of laser micromachining and annealing. In addition, they tested the actuator under two different heating conditions. By Joule effect, such that the actuator is used as the resistance in electrical circuit or by Ni-Cr heating coil which heats only the hinge area. The results show that the second solution is better because the transformation temperatures are reached with less time in the section affected by the movement. Further on, Paik et al. [9] exploit an innovative way to heat the actuator, by 'printing' the heater on the actuator body in the pre-annealed state and found lower response times of the actuator system.

The literature shows that, by the time being, the best performing shape of SMA is the wire, and this allows a one-dimensional approach to the problem. In the present work the actuator is a Nitinol® wire, which is commercially and readily available and has already been extensively studied. Moreover, the most common and reliable way used to supply heat to an SMA specimen is the Joule effect. The authors choose to provide heat by means of a heater to simulate passive heating and therefore a passive actuation system. For this reason, with the same constrain and environmental condition, the Nitinol® wire is heated, first, by Joule effect to define the maximum deploying angle of the device (section 4.2). Furthermore, the past works presented such that far have dealt with the technological aspect of surface movement. The present authors are also interested in modelling the SMA penomenon by means of an analytical approach as described by Bacciotti et al. [10], a thermomechanical model to simulate and predict the shape memory effect (SME). The experimental apparatus, described in this manuscript, will be used to experimentally verify the model.

2. Shape memory effect

By Considering a shape memory effect application, starting from twinned martensite and applying deformation at constant temperature, causing martensite detwinning, the SMA can recover its shape when the temperature is increased due to the transition of the martensite/austenite crystal structure. The transition temperatures are the Austenite start/finish (A_s / A_f) and the Martensite start/finish (M_s / M_f) (Figure 1). In particular, with reference to Figure 1, starting from detwinned martensite (zone 0), obtained after mechanical deformation, the SMA is subsequently heated (red line – Fig.1) above A_f and the SMA regain its original shape by transforming back into the parent austenitic phase, zone 4 in figure 1. Figure 1 shows the material phase transition, from Martensite (zone 0) to Austenite (zone 4) or vice versa, as a function of stress and temperature. The zones between number 5 and 8, concern the mechanical deformation at rest temperature, while from zone 2 to 3, different percentages of martensitic and then austenitic phase in the sample, as described in detail by Bacciotti et al. [10].

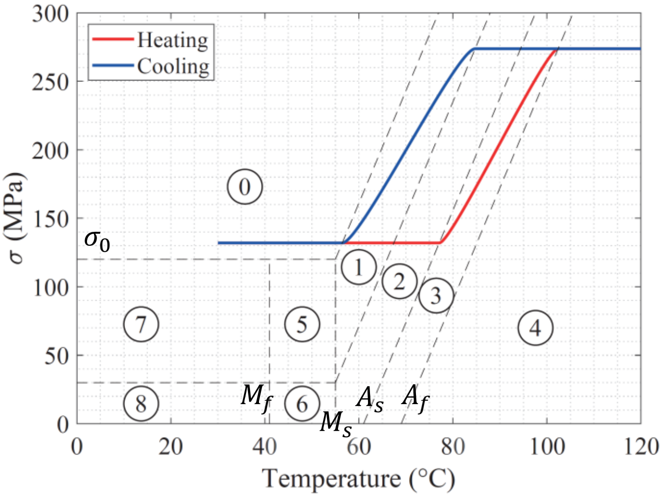

Figure 1 Uniform temperature model, heating and cooling processes: stress over temperature [10]

3. Design and task of the experimental apparatus

The prototype of the deployable panel equipped with a shape memory actuator (SMA wire, diameter 0.5 mm, length 160 mm) is shown in Figure 2. The SMA wire, after being mechanically elongated to achieve detwinned martensite, is installed in the device, passing over two pulleys and it is counter-acted by a torsional spring, which keeps the device closed. Once the wire is heated, it shortens itself due to SME and applies a force on the moving plate of the device in order to deploy it.

As pointed out by Katayama et al. [2], for system deployment the connection ends of the SMA wire cannot be brazed or welded, as metal-joining process produce a thermal variation that compromises the shape memory effect. The wire, in this device, is clamped between two blocks of Teflon in the insulated section and copper in the heated section. To avoid the slipping of the wire during the unfolding of the panel, once the two blocks are packed, the wire is crimped at the ends by a support with a screw (Figure 2a).

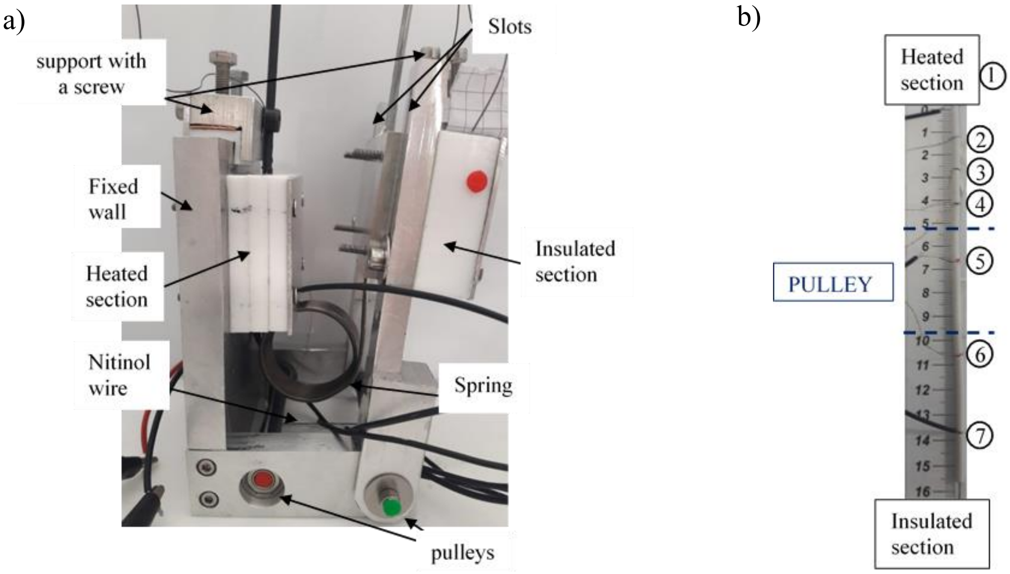

Figure 2 a) Experimental apparatus, b) Thermocouple's position

The insulated section is made of PTFE and is screwed to an aluminum block, which binds the spring, and to two vertically movable aluminum arms (Figure 2a), which compel the rotation around the spring axis and thus the panel. Furthermore, the Teflon block can be tied at different heights thanks to the slots on the two arms, and therefore, tests on different initial lengths of SMA wire are possible. However, the experimental tests are carried out at the same initial length (160 mm). The wire and spring are thermally connected by two copper plates, evaporator spreader (evaporator section), and are heated by a thermofoil heater produced by Minco® (model: HM6969). The Teflon insulates the heated section, and the heater is inserted between the last two blocks (Figure 2a). The wire is instrumented with seven T-type micro thermocouples (0.127 mm diameter, maximum error = ±0.3 °C). As shown in Figure 2b, the first thermocouple is positioned inside the copper package, while the next three are positioned at 1.5 cm from each other. The fifth thermocouple is positioned at 2.5 cm from the fourth, while the sixth and seventh at 3.5 cm from the previous.

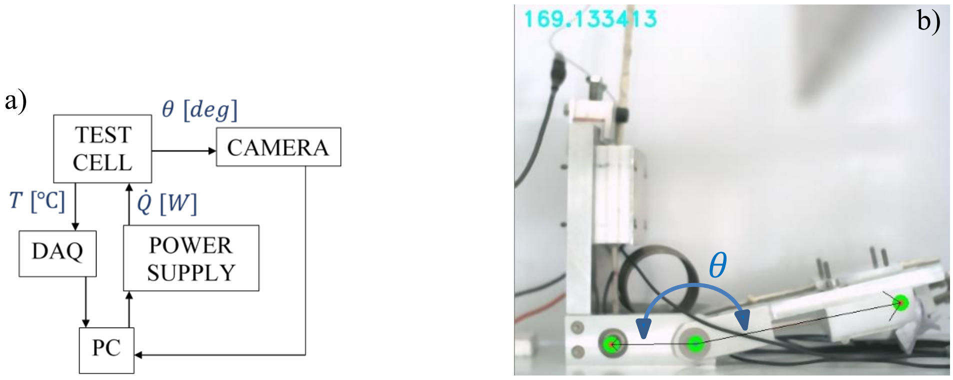

Figure 3 a) Experimental layout b) Dynamic deploying angle measurement

Figure 3a shows the layout of the experiment, the wire temperature is controlled by a programmable power supply (GW-Instek®, PSH-6006A, maximum error on the heating power = ±3 W), under two different heating conditions by Joule effect (Figure 3b), an electric current is supplied to the ends of the wire, or by a heater coupled with two copper plates, which bind the wire in the heated section.

A camera (figure 3) records the deploying of the insulated section and the angle of rotation is measured by video recognition (red and green marks in figure 2a). Then, the angle can be measured dynamically by placing vectors between the green points and the two red points (figure 3b – e = ± 0.4 degrees).

4. Experimental Results

Experimental tests are performed on the Nickel-Titanium wire (SmartFlex® Wire - $d_{wire} = 0.5\,mm$), supplied by SAES®, to verify the deploying of a panel by passive heating. First, the transformation temperatures (see section 2) are measured using a Differential Scanning Calorimeter (section 4.1). Then the wire is heated by Joule effect to determine the maximum deploying angle of the panel (section 4.2). At last, the wire is heated by means of a heater coupled copper package (section 4.3), with three different levels of wire insulation, as summarized in Tab. 1.

Table 1 Test Conditions and Results

Heating	Test	Insulation	K [W/m K]	T_1^{max} [°C]	T_2^{max} [°C]	θ [deg]	comments
active	1	NO	-	120	120	62	-
passive	2	NO	-	120	41	1	-
	3	Teflon	0.2 [11]		46	2	Coating, d_{ins} = 3 mm
	4	Aqueous Foam	0.1 [12]		53	4	Filling empty volume of the device envelope
				145	55	7	

4.1. Differential Scanning Calorimetry (DSC) Analysis

With the aim of designing a thermally controlled actuator, the transformation temperatures (see section 2) of the material, used as the actuator, are measured experimentally. The transformation temperatures are obtained by means of a Differential Scanning Calorimeter (DSC). The Nickel-Titanium sample, SmartFlex® Wire (mass 5.9 mg ± 0.1 mg, length 4.5 mm and diameter 0.5 mm) is supplied by SAES ®. Figure 5 shows the sample temperature as a function of the power ($\dot{Q}$ [mW]) required to maintain a constant heating and cooling rate (3°C/min). The zero line (red in Fig. 4) measured when the instrument being empty, while the measured (black Fig. 4) is obtained when the instrument is loaded. The actual trend (green Fig.4) is obtained by subtracting the zero from the measured data so as to eliminate systematic errors. When the sample is heated from martensitic state, the transformation to austenite starts at A_s. The endothermic reaction during the reverse transformation requires that additional heat power is supplied to the specimen to maintain the prescribed constant heating rate (β) and it is shown as a transformation "peak" during heating (65 –75 ℃ – Fig. 4). A similar peak is also recorded during the cooling process (60-35 ℃ – Figure 4), when the exothermic transformation from austenite to martensite takes place.

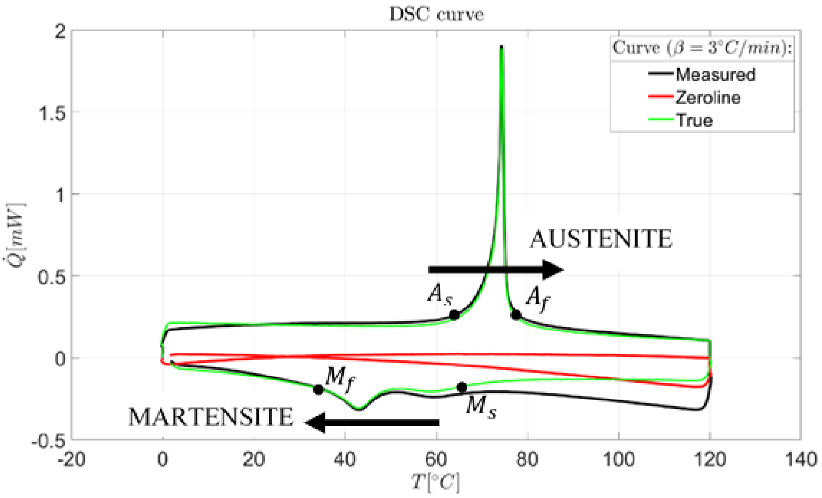

Figure 4 - DSC Transformation Temperature

4.2. Maximum deploying angle – Joule effect

The maximum deploying angle of the panel (θ) is measured under Joule heating and Figure 3b shows the system during the tests. Figure 5 shows the temperature trend as a function of the deploying angle during the test under Joule heating. The maximum deploying angle is $\theta^{Joule} = 62$ deg. The panel unfolding is instantaneous during the test for a temperature leap from 106 °C to 162 °C.

The transformation temperature does not appear to agree with the range found by the DSC analysis, that is 65 –75 ℃ (Section 4.1), but this may be due to friction in the kinematic mechanism of the panel, which delays its opening. A tensile test with Joule heating will be performed to verify the transformation temperature of the wire and the actual shrinking. In addition, the anomalous temperature trend above 106 °C suggests a change in the SMA electrical resistance in the transition from martensite to austenite.

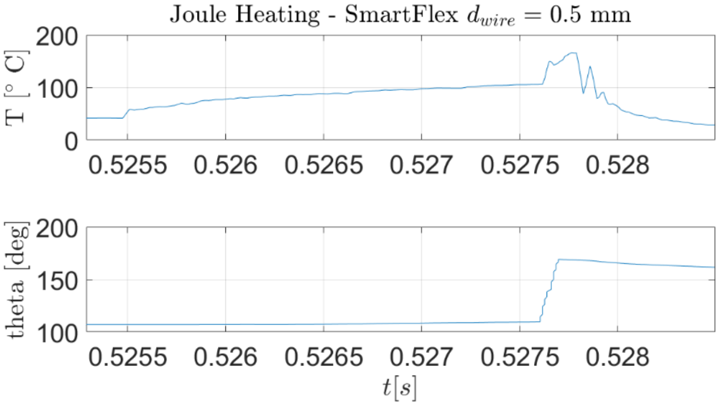

Figure 5 a) Temperature and b) Deploying angle temporal trend for the SMA wire

4.3. Deploying angle – Heater

The tests, under passive heating, are carried out under three wire insulation conditions, as summarized in Tab. 1. In addition, Figure 6, Figure 7 and Figure 8 shows the temporal trend of the wire temperature and deploying angle. The maximum temperature reached in position 1 is $T_1^{max} = 120$ ℃. Figure 6 shows the results of the tests carried out on the wire without insulation, as it is evident from the plot, the limit due to the passive heating is represented by the non-uniformity of the temperature along the wire which implies a non-complete deformation in the austenitic phase and therefore in the partial unfolding of the panel, in this case of only 1 degree (Tab.1). Comparing the results with Figure 7, Teflon insulation with a diameter of $d_{ins} = 3\ mm$ improves the deploying by only 1 degree compared to the uninsulated case and the maximum temperature in position 2 by 5 ℃. Significant advantages are obtained by filling all the empty volumes of the device envelope with aqueous foams. Indeed, as can be seen in Figure 8, the panel unfolds 4 degrees and in position 2 a temperature of 53 ℃ is reached (Tab.1). In this last test, the temperature in position 1 is increased up to 145 ℃, reaching a deploying angle of 7 degrees and a temperature in position 2 of 55 ℃. Further tests will be carried out with more performing foams and a three-wire configuration will be considered to allow the full deploying of the panel.

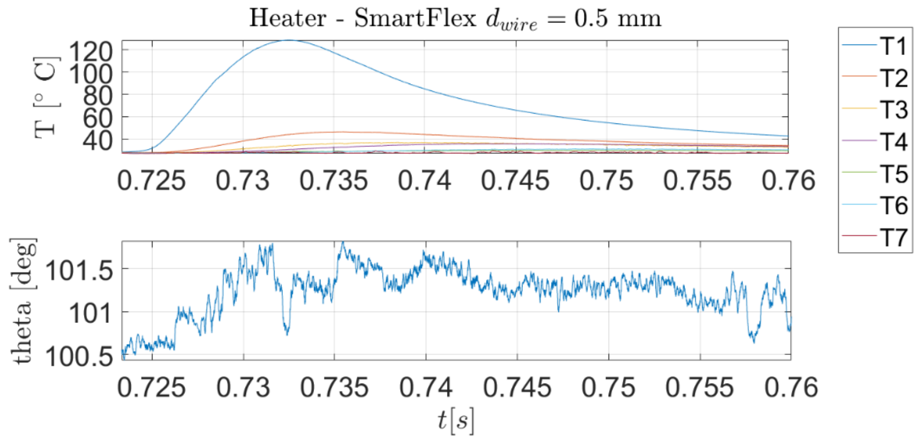

Figure 6 a) Temperature and b) Deploying angle temporal trend for the non-insulated SMA wire

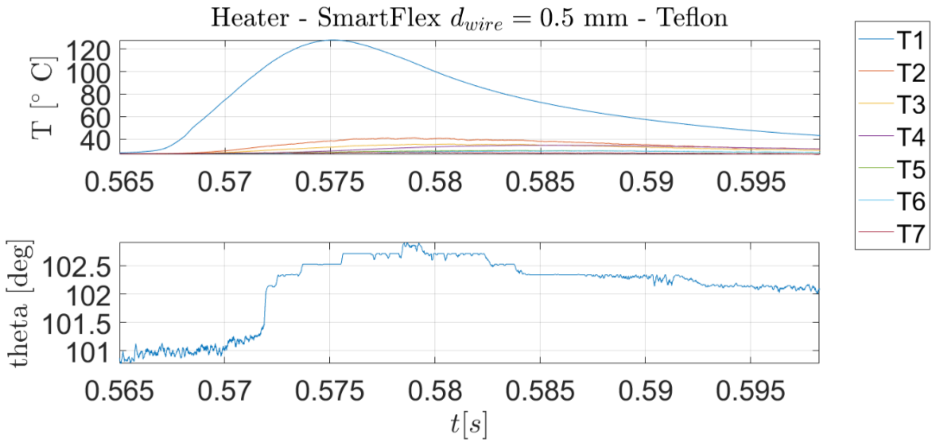

Figure 7 a) Temperature and b) Deploying angle temporal trend for the Teflon-insulated SMA wire

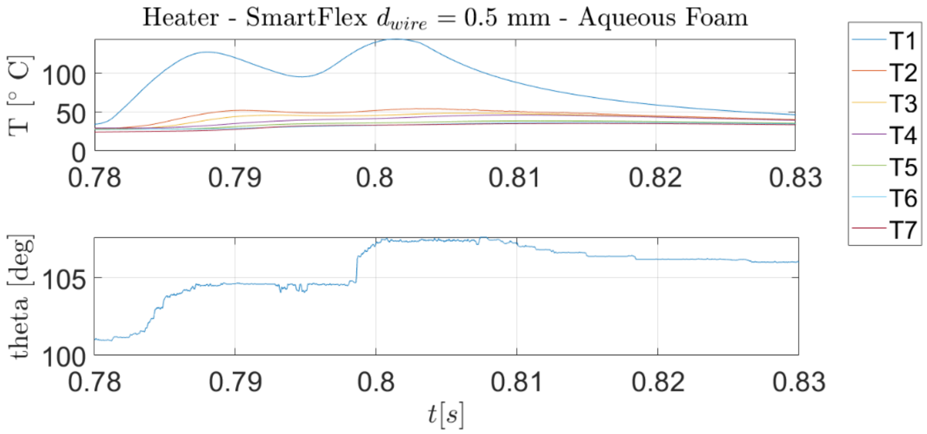

Figure 8 a) Temperature and b) Deploying angle temporal trend for the Acqueous Foam-insulated SMA wire

5. Conclusion

The design and testing of a deployable panel actuated by passive heating is experimentally carried out. The SMA actuator is a Nickel-Titanium wire (SmartFlex® Wire), supplied by SAES group® company. Two test cases were considered, differing in the heating strategy. Firstly, Joule effect was used to uniformly warm up the SMA wire, up to the temperature of 120 °C. In this case the device unfold considerably, allowing the panel to deploy up to 62 degrees. On the other hand, if the wire is heated warming up a heater at the wire end up to 120 °C, the temperature along the wire is not constant and the portion of the wire which experience phase transformation is small. For this reason, the achieved panel deployment is in the range 1-7 degrees, depending on the wire insulation. In particular, if the wire is not insulated, only 1 degree are obtained, while filling the empty volume of the device envelope with shaving foam, a larger portion of the SMA wire experience phase change and the deployment angle reaches 7 degrees.

Nomenclature

T	Temperature	℃
θ	Deploying angle	deg
K	Thermal Conductivity	W/m K
d	diameter	mm

Subscripts

max	maximum
ins	insulation

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