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The use of Thermoelectric Cooling for Shape Memory Wire Temperature Control

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Abstract

This paper is devoted to the study of a new field of thermoelectricity applications connected with the temperature control of shape memory alloys (SMA) actuating so-called smart structures. The possibility to speed up the cool down time for thin SMA wires using linear "sectional-flexible" thermoelectric coolers (TEC) is considered theoretically and practically. Some new technical decisions with respect to TEC configuration and heat sink construction are discussed. Results of first experiments are given.

Introduction

SMA wires contract upon heating and elongate again at low temperatures. This behavior can be exploited by using the wires as "muscles" in so-called smart structures (smart endoscopes, robot arms, aircraft and space instruments etc.). The contraction of these muscles is controlled by the Joule heating of the wire. It is thus a simple mechanism that avoids heavy weight electric engines and transmissions.

A drawback is the fact that the cooling process has to be realized by heat convection in a surrounding medium, typically air. This implies relatively small cooling rates which, moreover, can not be controlled exactly. Were it possible to overcome these drawbacks, it would greatly extend the range of SMA wires applications. TECs are very attractive in this context, in particular because of their controllability. Besides, a SMA wire and a TEC can be easily integrated, both being electrically driven .

The use of TECs for SMA wire fast cooling is a relatively new field of thermoelectricity applications. Investigations have been performed by Shahin et al. [1] and Bhattacharya et al [2]. They either used some specially designed tube-like TEC for circular cross-section wires, or they integrated the SMA wire into the TEC. Such designs have several drawbacks. In the first case, the standard TECs can not be used. As regards to integrated design, the incompatibility problem at the interface between SMA wire and semiconductor arises from the large transformation strain in the wire (typically in the order of magnitude of 5%). Besides, the requirement of a wire flexibility can not be provided.

Here, we propose the design which allow to avoid such disadvantages. The flat rectangular wire is used which gives increased surface area and provides better cooling as compared to round wire having the same cross-section area. Some special decisions with respect to the TEC configuration as well as to the heat sink construction are made to provide wire mobility combined with effective heat rejection.

This paper presents the results of preliminary experiments carried out to check the efficiency of these decisions. The technical requirements were as follows: the wire of 50mm length with a cross-section of 0.1x 0.7mm is to be cooled from 80°C to 40°C within a time from 0.1 to 1s using a TE cooling unit. Theoretical grounds for technical feasibility to solve the problem are presented. First test results are discussed.

Prospects to Reduce Cool Down Time

Cooling rate estimation. Let us consider a model of a wire in thermal contact with surroundings having the temperature T_0. The wire is maintained at an initial temperature $T(0)=T_i$ by Joule heat input. For this purpose a short electrical pulse is supplied to the wire to provide near adiabatic heating conditions.

The transient behavior of the wire after switching off the electric current is described by the differential equation:

$$c(T)G\frac{dT}{d\tau} = -\frac{F}{r_0}(T - T_0); \qquad T(0) = T_i \qquad (1)$$

where

τ is time
T is absolute temperature
c is SMA specific heat
G is a wire mass
F is a wire outer surface
r_0 is thermal resistance at the interface of a wire with surroundings related to a unit of wire surface

We assume the ratio of wire cross-section to wire length to be small enough to neglect the influence of heat conduction at the wire ends. Also the cross-section itself is so small that heat conduction through the thickness is not considered either. Thus, the wire is supposed to have uniform temperature. With this condition Eq.(1) has the following solution:

$$\tau_f = -r_0\rho_w d_e J(T_f) \qquad (2)$$

where

$$J(T_f) = \frac{1}{4}\int_{T_i}^{T_f}\frac{c(T)}{T - T_0}dT \qquad (3)$$

T_f is necessary final wire temperature
τ_f is the time to achieve the temperature $T=T_f$
$d_e = 4S/U$ is a wire equivalent diameter

S is a wire cross-section
U is a wire cross-section perimeter
ρ_w is SMA density

To make an exact calculation of the cool down time, the temperature dependence of a SMA specific heat must be taken into account. Corresponding experimental data for M45-NiTi SMA are shown by dots in Fig. 1. It is seen that $c(T)$ dependence shows sharp peak in the region of 332.5K which corresponds to a phase change in the SMA. To use these data in our calculations their approximation was made separately in the temperature ranges from 293 to 332.5K and from 332.5 to 373K. In both cases the Lorentzian approximation of the form

$$c(T) = a_0 + \frac{a_1}{1 + \left(\dfrac{T - a_2}{a_3}\right)^2} \qquad (4)$$

occurred to be the best one. The coefficients a_k are given in Table 1. Corresponding approximation is shown at Fig.1 by solid lines. Using this approximation the averaged specific heat of the SMA in the temperature range from 40 to 80°C is calculated as 1.1J/(gK). This gives the total heat of 44 J/g to be absorbed from a wire.

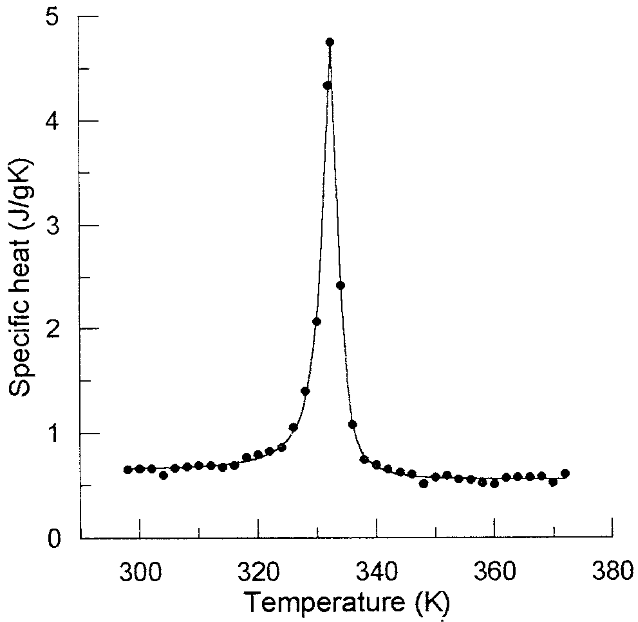

Figure 1: Specific heat temperature dependence for M45-NiTi SMA

Eq. (2) together with relations (3) and (4) allows to numerically evaluate the time τ_f which is necessary to achieve the specified final temperature of a wire T=T_f. One can see that this time is proportional to the outer thermal resistance $\tau \propto r_0$. Let us consider these quantities for different heat exchange conditions.

Table 1. Coefficients of approximation of specific heat temperature dependence for M45-NiTi SMA

Temperature (K)	a_0	a_1	a_2	a_3
From 293 to 332.5	0.6441	4.2789	332.86	2.1177
From 332.5 to 373	0.5488	4.2165	332.543	1.2991

Passive cooling in still ambient air. The outer thermal resistance for heat convection is defined as

$$r_0 = \frac{1}{h_m} = \frac{d_e}{\kappa_m Nu} \qquad (5)$$

where
h_m is the heat exchange coefficient
$\mathrm{Nu} = \dfrac{h_m d_e}{\kappa_m}$ is the Nusselt number
κ_m is the air thermal conductivity

The subscript "m" shows that the property is related to the averaged wire temperature $T_m = (T_i + T_f)/2$.

The Nusselt number for natural convection is defined as follows [3]

$$Nu = \begin{cases} 0.5 & Gr\,\mathrm{Pr} \le 10^{-3} \\ 1.18(Gr\,\mathrm{Pr})^{1/8} & 10^{-3} < Gr\,\mathrm{Pr} < 500 \end{cases} \qquad (6)$$

where
Pr is the Prandtl number
$\mathrm{Gr} = \dfrac{g d_e^3}{\nu_m^2} \beta (T_m - T_0)$ is the Grashof number
g is free fall acceleration
ν_m is air kinematic viscosity
$\beta = 1/T_m$ is the coefficient of air thermal expansion

Eq. (2) to (6) are used to define SMA wire cooling rate. Two types of SMA wire both having the same cross-section area were considered: the round wire with diameter of 0.3mm (d_e=0.3mm) and the rectangular one 0.1x0.7mm in cross-section (d_e=0.175mm). Other conditions are specified as follows: T_i=80°C, T_f=40°C, T_0=20°C, ρ_w=6.5g/cm^3.

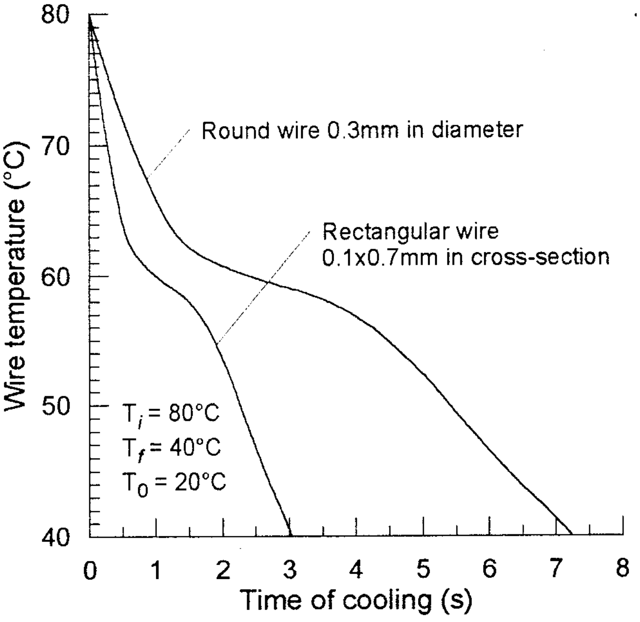

Figure 2: Dynamics of SMA wire cooling at open air .

Calculation results are shown in Table 2 and at Figure 2. It is seen that the flat wire has the advantage of considerably shorter cool down time as compared to the round one (3.0 and 7.2 s correspondingly), this being due to smaller equivalent diameter. For this reason, this wire configuration is further considered in our study.

Table 2. Heat exchange characteristics of SMA wires

Wire configuration	d_e (mm)	Nu	h (W/(m^{2}K))	r_0 (Km^2/W)	τ_f (s)
round d=0.3mm	0.3	0.83	80.5	0.0124	7.2
flat 0.1x0.7mm	0.175	0.68	112.7	0.0089	3.0

Active wire cooling in a narrow slot. For SMA wire active cooling, it is convenient to insert it in a rectangular groove fabricated in the TEC cold substrate, which is maintained continuously at $T=T_0$. In this case the tolerance δ for the groove thickness must be foreseen to provide wire mobility. This tolerance value will define the thermal resistance at the SMA wire outer surface. To estimate its value we will consider the worst case when the wire is co-axially located in the groove with clearance of $\delta/2$. In this case, the outer thermal resistance is as follows:

$$r_0 = \frac{\delta}{2\kappa_m} \tag{7}$$

Let us compare the cooling rates in active and passive modes of cooling. It is seen from (2) that for the same wire configuration the ratio of cool down times is as follows:

$$\frac{\tau_{fa}}{\tau_{fp}} = \frac{r_{0a}}{r_{0p}}, \tag{8}$$

where subscripts "a" and "p" relate to the active and passive mode of cooling. With consideration of (5) and (7) this gives

$$\tau_{fa} = \delta\frac{Nu}{2d_e}\tau_{fp} \tag{9}$$

So the inequality $\delta<2d_e$ / Nu is the necessary condition for the reduction of cooling time. For rectangular wire 0.1x0.7 mm one has δ_{max} value of 0.51mm, which can be easily obtained. Using Eq.(9) together with data from Table 2 one can find that to achieve a cooling time in the range from 0.1 to 1s the groove tolerance values from 0.017 to 0.17mm have to be provided. In practice, the actual cool down time will be smaller because of the most probable wire shift away from axial position.

TEC Operation Mode

At the first look the variant of pulse driven non-stationary TEC for cooling-heating a wire seems most attractive. A performance estimation of such a device was undrtaken first of all. The problem of the time dependent temperature distribution in a TEC was formulated and solved with consideration of the specific heat of joined masses. It turned out that the use of a pulse driven TE heat pump fails to solve the specified thermal problem. The reason lies in the relatively large additional specific heat of the ceramic substrate at the TEC cold side, which is many times more than for a SMA wire. Thus a large waste heat must be driven back and forth with a pulsed TEC which results in an unacceptably high cooling power. So the combination of a continuously working TEC and a pulse driven SMA wire was accepted, the system operation being as follows. The TEC maintains its cold side substrate at a constant temperature T_0. The SMA wire is energy fed periodically during extremely short pulses τ_j in near adiabatic condition. When the feeding is cut, heat is rejected quickly from the wire into the cold ceramic during the pause time τ_p. This cycle is repeating periodically. To preserve waste power losses, the temperature of cold ceramic is measured with feed back to the TEC current control. Thus, if the wire is switched off for a long time the cooler will be switched off automatically.

TEC Optimization

For short responce time, the TEC must be optimized with respect to a minimal pause between the energy pulses. The peculiarity of the problem is a severe restriction on overall system dimensions. It is not acceptable to have the total dimension of a TEC and heat sink more than 10mm in diameter. This leads to a TEC optimization problem under constrained heat exchange conditions.

Let us consider a unit of wire length. To maintain the cold ceramic at a specified temperature T_c, the TEC cooling capacity Q_c must be equal to the averaged power of the heat pulse into the wire $Q_c = E_j / (\tau_j + \tau_p)$, where E_j is the pulse energy per unit wire length. So the minimum pause duration τ_p corresponds to the maximum TEC cooling power. To find the optimal TEC parameters, the following model considering hot side thermal resistance R_t must be used:

$$Q_c = \varphi(\alpha T_c j - \frac{1}{2} j^2\rho - \kappa(T_h - T_c)) \tag{10}$$

$$Q_1 = \varphi(\alpha T_h j + \frac{1}{2} j^2\rho - \kappa(T_h - T_c)) \tag{11}$$

$$T_h = T_0 + Q_1 R_t \tag{12}$$

where

$$j = il; \qquad \varphi = F/l \tag{13}$$

i	is electrical current density
l	is TE leg length
F	is the total cold junctions area
Q_1	is the heat dissipated at the TEC hot side
α, ρ, κ	are Seebeck coefficient, resistivity and thermal conductivity of TE material
T_h	is absolute temperature of TEC hot junctions

As a first approach, we assume that R_t is independent of T_h. Then for specified j and φ the system (10) to (12) define uniquely the unknown Q_c, Q_1 and T_h values. The problem is to find such j and φ which provide the maximum Q_c value under restrictions (11) and (12).

Lagrange's method to solve the problem gives the following optimality conditions:

$$j_0 = \frac{\alpha(T_h - T_c)}{\rho(M-1)}$$

$$\varphi_0 = \frac{1}{\kappa R_t} \frac{COP}{1 + \frac{\alpha j_0}{\kappa} COP} \qquad (14)$$

$$COP = \frac{T_h - T_c}{T_c} \frac{M - T_h/T_c}{M+1}$$

$$M = \sqrt{1 + z(T_h + T_c)/2}\,; \qquad z = \frac{\alpha^2}{\rho\kappa}$$

which include the unknown T_h value. To find this value, the following iteration process was used. As a first step the initial value $T_h = T_h^{(1)}$ is to be set and the optimal j_0 and φ_0 values have to be found with this $T_h^{(1)}$ value using Eq.(14). Then the first $Q_h^{(1)}$value and a new $T_h{=}T_h^{(2)}$ value will be obtained from Eq. (11) and (12). This iteration process has to be repeated until the next $T_h^{(n)}$ value will deviate from previous one by not more than a specified small error. After j_0 and φ_0 are determined the optimal i and F values can be evaluated easily from Eq. (13) for any specified l value.

It is worth to note that the joint optimization of a TEC current and a TEC surface reduces the optimal problem to the case of COP maximum as it is seen from Eq. (14).

Heat Sink Optimization

Some preliminary remarks. To specify the heat sink thermal model, some special preliminary decisions regarding the TEC configuration as well as heat sink construction have to be made. As SMA wires are used to actuate flexible structures, the cooling unit needs to exhibit a certain flexibility as well. To meet this requirement, it is reasonable to make it as an assembly of small linear segments connected in a series sircuit. Another problem is to make the heat sink a small-size, light-weight and very effective device. Our calculations show that the problem can be solved with a spring like heat sink which envelopes the linear TEC body. Thin wires have the advantage of a high heat convection coefficient being able to achieve the value of 100 W/(m^{2}K) and more. This is much higher than for any other type of heat exchanger surface under free convection conditions.

Heat sink thermal resistance. Let us consider the thermal resistance of a spring section related to a unit of SMA wire length. The total spring surface is as follows:

$$F_s = \pi^2 d D n \qquad (15)$$

where d is wire diameter
D is spring diameter
n is number of spring rings per SMA wire length unit

We will define the thermal resistance per spring unit length in a form

$$R_t = \frac{1}{hF} = (\pi^2 D n \kappa_a\, Nu)^{-1} \qquad (16)$$

where κ_a is air thermal conductivity. The Nu value can be obtained from Eq. (6).

Calculation Results

Calculations are made to evaluate the parameters of a cooler which provide a minimal pause between heat pulses into the SMA wire. All calculations relate to 1cm long SMA wire with cross-section of 0.1x0.7mm. The initial data are given in Table 3. The calculation results are shown at the Table 4.

Table 3. Initial data for TEC parameters evaluation.

Parameter	Symbol	Value
Temperatures (°C):		
Ambient air	T_a	20
Cold ceramic	T_c	25
SMA wire initial	T_i	80
SMA wire final	T_f	40
SMA density (g/cm^3)	ρ_w	6.5
Heating pulse parameters:		
Pulse energy (J/cm)	E_i	0.2
Pulse duration (s)	τ_i	0.01
TE materials characteristics:		
Seebeck coefficient (μV/K)	α	187
Resistivity (10^{-3}Ohm cm)	ρ	0.779
Thermal conductivity (10^{-3}W/(cm K))	κ	15.1
TE leg dimensions (mm):		
Cross-section	S	0.6x0.6
Length	l	1.5
Heat sink dimensions (mm):		
Wire diameter	d	0.15
Spring diameter	D	6
Number of spring rounds (1/cm)	n	10

Table 4. Parameters of optimized cooling unit (related to 1 cm of SMA wire length)

Parameter	Symbol	Value
Heat sink thermal characteristics:		
Heat exchange coefficient (W/(m^{2}K))	h	100.5
Thermal resistance (Kcm/W)	R_T	96.9
Optimal TEC characteristics:		
Number of TE legs	N	16
Cooling power (W)	Q_c	0.209
Electrical current (A)	I	0.65
Voltage (V)	V	0.47
Power consumption (W)	P	0.302
Hot side temperature (°C)	T_h	69.5
Minimal pause between heat pulses into SMA wire (s)	τ_p	0.95

It is seen that with the TEC having 16 TE legs a pause of less than 1s can be achieved, the TEC power consumption being of 0.3W per 1cm of SMA wire. It was found also that considerable deviations from the optimal TE leg number have poor effect on the necessary pause value.

Laboratory Testing of the Cooling Unit

Experimental sample configuration. The cooling unit for a SMA wire with a length of 50mm and a cross-section of 0.1x0.7mm was manufactured and tested. The goal was to achieve wire cooling from 80°C to 40°C within a time less than 1s. To secure wire flexibility, the unit was made as an assembly of 5 small sections (Figure 3). Each section of 1cm length (Figure 4) itself is an assembly of two linear TE modules soldered together along their cold ceramics. To insert the SMA wire, a groove of 0.12x0.8 mm in cross section was made along the cold ceramics interface. The assembly is embedded into a copper spring with a diameter of 6mm working as an effective heat sink.

It was found above theoretically that the section with 16 TE legs is optimal. Unfortunately, this variant is not industrial because of its poor mechanical strength. So a section with 32 TE legs was reproduced in practice, each of two modules in a section having two rows of 8 TE legs. Our estimations show that it results in a pause increase of 0.1s only.

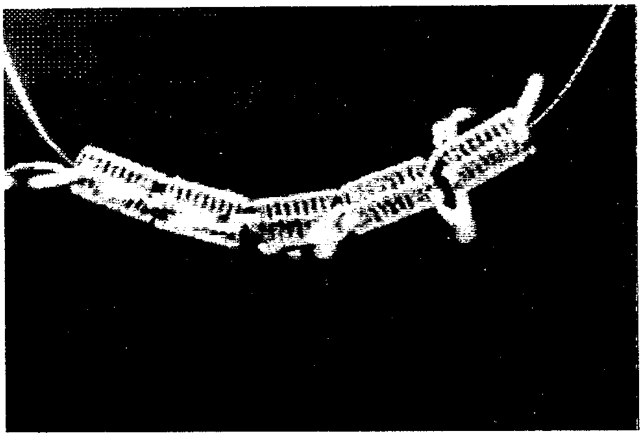

Figure 3: Thermoelectric unit for cooling SMA wire

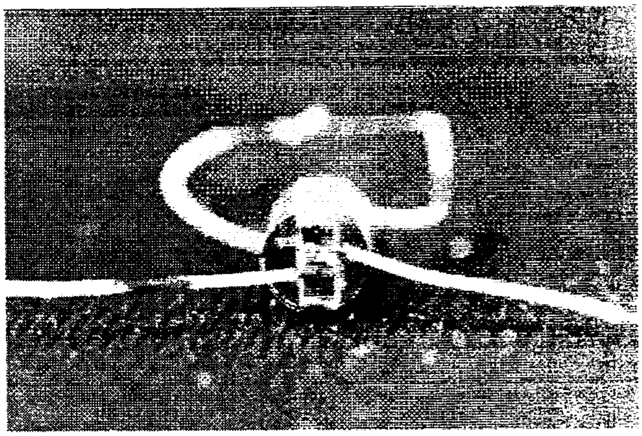

Figure 4: The section of thermoelectric cooling unit

Test results. To define the TEC section cooling capacity it was tested with a heat load at the cold side. To simulate the SMA wire, the heater in a form of a narrow steel strip was inserted into the cold ceramic groove. The TEC was supplied with a current in the range from 0.05 to 0.6A. The heat load from the heater which is necessary to maintain the TEC cold ceramic at the constant temperatures 25 and 28°C was measured for each TEC current. The tests showed that the TEC section maximum cooling capacity at the temperature of 25°C is about 42mW (Figure 5) which is considerably less than theoretically predicted value. The optimal current is of 0,3A this being only a half

of calculated quantity. Also the hot side temperature corresponding to the theoretical current optimum occurred to be much higher than it was predicted. This indicates definitely that the actual heat sink thermal resistance was somewhat higher than the calculated one. Another possible source of the above mentioned discrepancies may be the additional heat gains to the TEC cold side from the enveloping heat sink. So, for farther progress in this direction, the heat sink configuration must be improved to increase TEC efficiency.

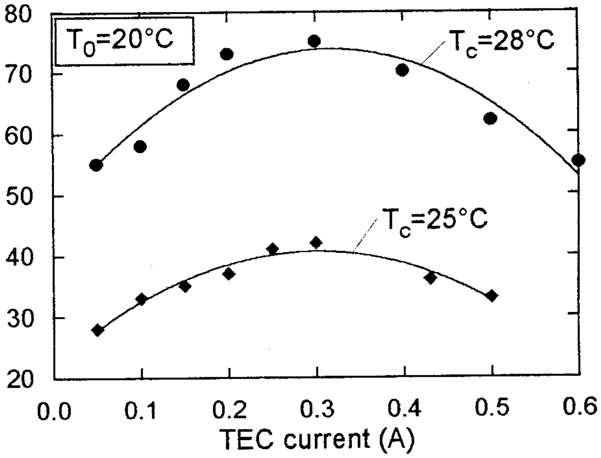

Figure 5: Dependence of the TEC section cooling capacity on feeding current for two values of cold side temperatures.

Measurement of SMA Actuator Performance

Subsequently, the cooling unit was tested together with a SMA wire that was periodically heated by an electric current through the wire. The resulting wire contraction was measured in two modes of operation: passive cooling in ambient air and active cooling with the TEC.

Passive cooling in ambient air. The experiment starts with an elongated wire under a tensile load of 10N at room temperature (21°C). In 5s an electric current is applied to the wire and its Joule heating causes the temperature to rise quickly up to about 75°C (upper curve in Fig. 6). Subsequently, the current has been shut off, and the temperature drops to 55°C in about 5s. During this period, the wire reaches its original length again, which is indicated by the lower curve in the figure. One clearly sees that the period of activation is limited by the slow cooling behavior.

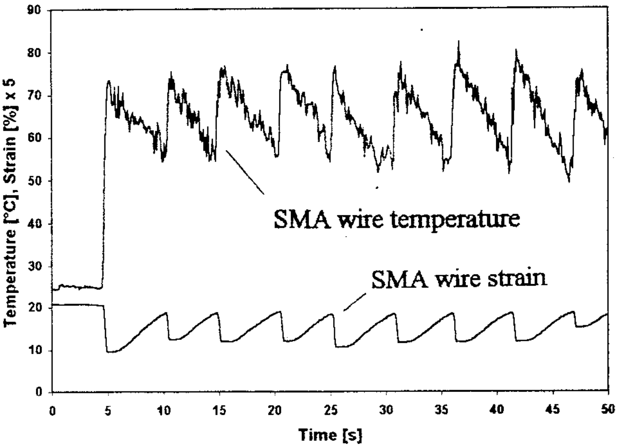

Figure 6: SMA wire behavior, when periodically heated by an electric current in ambient air.

Active cooling with TEC driven in stationary operation mode. Figure 7 shows the wire behavior for the case of active cooling with the optimum current of I=0.3A. The lower curve again is the wire contraction, while the middle and upper curves are TEC cold and hot side temperatures, respectively, measured by two thermocouples mounted on the device. The TEC is activated at τ=7s, and the temperature rise at the hot and temperature drop at the cold side can be seen up to about τ=16s. At this instant, the wire is heated for the first time. Apart from the resulting wire contraction, it leads to a steep temperature increase at the TEC's cold side while the hot side remains at its temperature. When the current through the wire is switched off, the cold side temperature slightly decreases. The hot side, however, starts to heat up as the energy removed from the wire has now arrived. Continuing activation leads to increasing temperature levels between 40°C and 45°C for the cold side stationary state and about 55°C at the hot side.

Figure 8 (passive cooling) and Figure 9 (TEC cooling) zoom in the contractive behavior of the wire. We observe the heating phase to be equal in both cases, but the cool down time decreases from 4.8s in the passive case to typically 2.4s in the case of TEC cooling. This is a first success, showing the potential of TEC cooling of SMA wires. Two points, however, remain to be solved:

a) the cool down time still needs to be decreased and
b) for real control applications, the cooling unit needs to be driven in instationary operation mode.

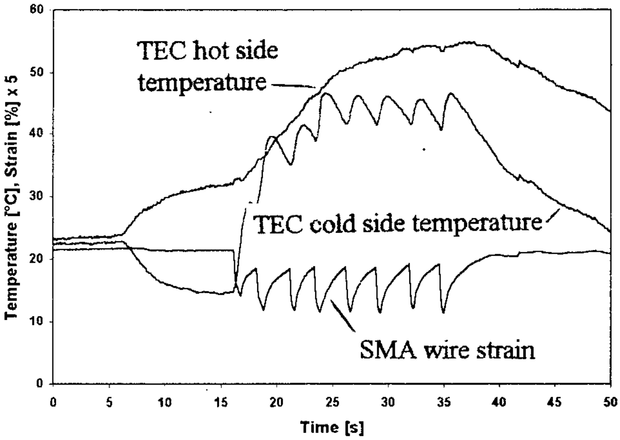

Figure 7: SMA wire active cooling.

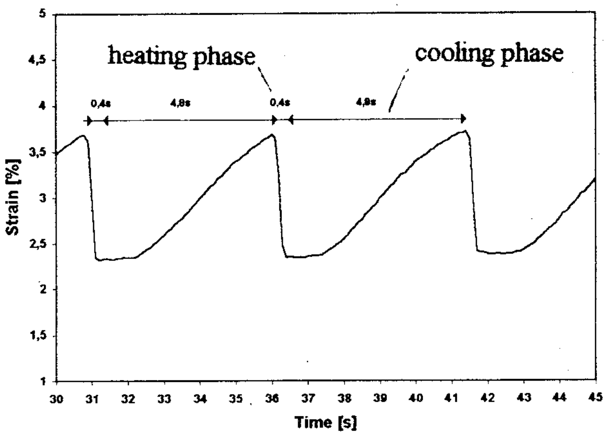

Figure 8: SMA wire behavior when cooled in ambient air.

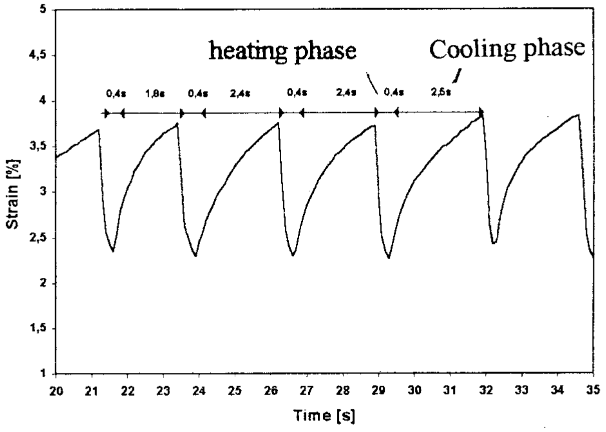

Figure 9: SMA wire behavior when cooled by the TEC.

Both points have the same cure - it is necessary to increase the heat sink performance, as already mentioned in the previous section. This can be seen from Figure 7, where the hot side temperature increases too much during the operation. This induces a heat flux to the cold side, which is counteracting the heat removal from the wire. The heat flux results in a cold side temperature of about 45°C instead of 25°C, which was assumed for the calculations. This fact explains the failure in reaching 1s cool down time.

Summary

Thermoelectric coolers can be used to speed up the cooling of shape memory wires in so-called smart structures. This is predicted theoretically and confirmed practically.

The response time for the TEC is much higher than for the wire. Thus, the use of a TEC as a transient heat pump fails to speed up SMA wire cooling. So the combination of a continuously working TEC and a pulse driven SMA wire is the best decision.

A "sandwich type" TEC layout with two linear modules soldered together, leaving a narrow slot for the SMA wire, proved to be the best solution which provides wire mobility combined with effective heat rejection.

To provide SMA wire flexibility, the cooling unit can be designed as a sectional device.

The cool down time in a range from 0.1s to 1s can be achieved potentially. However, the restrictions on the TEC and heat sink dimensions occure to be the most severe problem in attaining cooling rates below 1s.

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