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Experimental Characterization of the Convective Heat Transfer from Shape Memory Alloy (SMA) Wire to Various Ambient Environments

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ABSTRACT

While Shape Memory Alloys (SMA) have many actuation benefits (high energy density, compact, low cost, etc.), they are commonly restricted by limited frequencies governed by convective heat transfer. To increase frequency performance and at the same time reduce excess power consumption, it is critical to properly characterize and understand the heat transfer from SMA wires. Unfortunately, this requires an accurate surface temperature measurement under a fixed input power, which is difficult to obtain using traditional methods because of the nature of SMA (thin wires, large strains, heat activation, etc), particularly when submerged in a liquid cooling medium. This paper introduces a non-invasive technique to calculate the convective coefficient, *h*, for SMA by employing the material's temperature-induced strain to estimate the surface temperature. This method is used to indirectly measure the convective coefficient for a range of ambient media including air (free and forced convection), oil, water and thermally conductive grease across a range of commonly utilized SMA wire diameters (6- 20 mil). Empirical correlations to the collected data are formulated to provide a mathematical relationship to calculate the *h*-value in material models or continuous optimization algorithms. These fits are intended to provide better estimates of convection, which may be used for computational optimization of SMA actuators ensuring that power draw is minimized and dynamic performance needs are met.

Keywords: Shape Memory Alloy, Cooling, Convection Coefficient, H-Value, Environment

1. INTRODUCTION

Since their discovery, NiTi Shape Memory Alloys (SMA's) have been used in a diverse range of applications that take advantage of the material's high energy density, large actuating strain, and extremely low weight and size [1-10]. When subjected to a temperature change, SMA undergoes a martensitic/austentic transformation with considerable recoverable strain that produces usable work. Typically, SMA is employed as an actuator by electro-resistively heating the material, and then cooling and deforming the material under a lower stress to close the work cycle. This mode of SMA operation can be found in many existing applications including robotic actuators [4-6], latches and ratchets [7], biomedical tools [8], and vibration cancellation systems [9,10].

Unfortunately, the broad application of SMA to actuation is limited by cyclic performance and power consumption [2]. The cyclic performance can be improved by increasing the convective properties of the cooling medium, but this comes with a penalty of increased power draw during heating. Decreasing the actuator wire diameter can also produce faster responses, though this decreases the force output. Understanding these trade-offs is crucial since over-specifying cooling for an actuator may employ wires of insufficient diameter (producing inadequate force) or use a medium with unnecessarily high convective properties leading to excess power consumption. Under-specifying the cooling for an actuator can result in dynamic performance losses since the wire is inadequately cooled during each return cycle.

Thus, to optimize SMA during dynamic cycling, it is important to be able to predict the heat transfer and use this for the best selection of diameter and ambient environment fluids. Unfortunately, this is complicated for commonly used SMA wires since measuring the surface temperature (T_s) to calculate the convective coefficient h is challenging. With traditional materials, experiments to measure the convective heat transfer from long cylinders [11,12] have been accomplished by mounting thermocouples to large diameter cylinders (e.g. 28 mm [13]) to monitor the cylinder surface temperature for a fixed ambient temperature (T_a) and applied power P. Knowing the cylinder surface area A, Newton's law of cooling with negligible radiation [14] (due to relatively low surface temperatures),

$$\frac{dQ}{dt} = P = hA(T_s - T_{amb}), \tag{1}$$

is applied to solve for h. This method is typically not possible with SMA because it is difficult to mount thermocouples to the smaller diameter wires and to keep them connected over the large strains (4-8%) of the SMA during temperature induced transformation. Thermocouples are also invasive since heat is transferred to the thermocouple and the grease used to ensure proper thermal connection. This inaccurately reduces the measured surface temperature, particularly for the smaller diameter commercial SMA wires which are on the order of the smallest thermocouples [15]. Applications using regular metallic wires overcome this size issue because it is possible to correlate temperature to changes in electrical resistivity of the material; but, in SMA the resistivity is non-monotonic with temperature and changes with cyclic history [16]. Direct surface temperature measurement using IR cameras is difficult due to problems focusing on a thin wire, and thermal images cannot be captured in environments other than air (e.g. thermal grease, oil, and water) [17]. To estimate the convective coefficient, there are non-dimensionalized empirical relationships in the literature [11,12] that may be scaled down to the smaller SMA wire with diameters between 6 to 20 mils (0.15 to 0.51 mm). But even at larger diameters (28 mm), these broad models provide accuracies only up to 20% [14] which is not sufficient when accurate predictions of speed and power draw are needed.

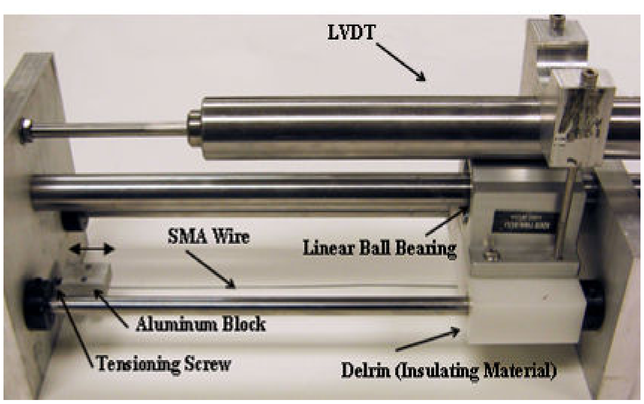
This paper introduces a new experimental method to calculate the convective properties of SMA. This method uses measurements of the SMA's midpoint in strain recovery as a function of temperature to predict the wires' surface temperature when transforming under resistive heating while exposed to a convective medium. Using this method, the convective properties are calculated for a variety of SMA wires ranging in diameter from 6 to 20 mils in a range of convective media including still air, mineral oil, thermally conductive grease, and water. The effects of forced convection in air are also studied for several different flow rates. The experimental results of all these conditions are presented and fitted with empirical correlations to produce continuous functions for the convective heat transfer coefficient. These functions are based on physical variables such as wire diameter, fluid properties, temperature, and flow rate, and optimized based on existing correlations found in literature [14]. The continuous fits to the measured data are intended to be used for better estimates of convection, which engineers can use for computational optimization of SMA actuators ensuring that dynamic performance needs are met and power draw is minimized.

2. SMA Midpoint Transformation Temperature Measurements

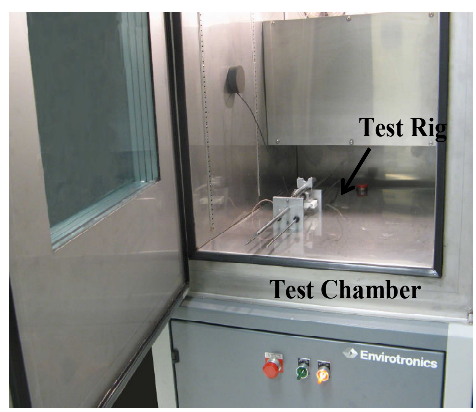
In this new method of convective heat transfer measurement, Newton's law of cooling (Equation 1) is still used but the surface temperature is not directly measured. Instead, surface temperature is mapped to strain recovery under temperature controlled tests under near-zero load. To simplify the correlation, only the midpoint in strain recovery and the associated transformation temperature is documented for the mapping and is assumed to be constant under near-zero loads.

To obtain the midpoint transformation temperatures for the SMA wires, each sample was heated in an Envirotronics FLX-300 environmental chamber while recording strain. For each test, a 7 inch sample of 70 ^{o}C Flexinol (Dynalloy) SMA was installed in the test setup (Figure 1) with one end of the SMA connected to a very low friction sliding stage that moves when the SMA is heated, while the other end was attached to an aluminum block fixed by a tensioning screw. The austenite free-length reference was set by heating the wire and adjusting the wire-tension through the tensioning screw until all slack was taken out. A residual tension remained in the wire to offset the very small friction in the linear ball bearing. The wire was allowed to cool and strained to a 4.5% elongation from its austenite free length by adjusting the tensioning screw (Figure 1a). The ambient temperature inside the chamber was slowly increased (several minutes per degree near transition) to ensure proper mixing. The SMA contracted when the ambient temperature reached the transformation temperature, and full motion recovery occurred within 1 degree C for all wires. This displacement was measured with a LVDT sensor monitored by an oscilloscope. The midpoint transformation temperature was recorded when the slider position was half way between the 4.5% prestrain and the austenite zero strain.

The procedure was repeated several times for a range of SMA wires (6 to 20 mils). The measured midpoint transformation temperatures (Table 1) varied across the various wire diameters tested. Variations were also observed between spools of same diameter wires, but were constant and repeatable for segments of wire taken from the same spool. For example, 10 mil SMA segments had a midpoint transformation temperature of 59 ^{o}C consistently for one spool, but when a different spool was tested this temperature went up to 62 ^{o}C. From the results, it is assumed that most of the variation in the midpoint transformation temperature was related to variations in processing and not the geometric properties such as wire diameter.



(a) Experimental Test Apparatus



(b) Apparatus in Environmental Chamber

Figure 1. Test Apparatus for midpoint transformation temperature measurements. Convective heat transfer tested in low-friction apparatus that measures strain. Temperature applied and monitored by an environmental chamber.

Table 1. **Midpoint transformation temperatures measured at a midpoint strain of 2.25% for the wire diameters tested.**

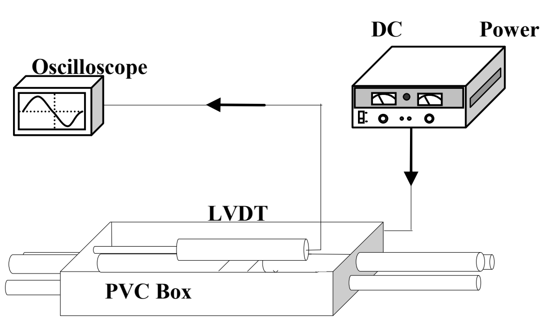
Wire Diameter (mils)	Midpoint Transition Temperature T_s (^oC)
6	61
8	59
10	59
12	57
15	61
20	63

3. Convective Coefficient Measurements and Correlations

The midpoint transformation temperature correlation table was used to calculate the convective coefficient *h* for the variety of wire diameters (Table 1) under different environmental conditions. The SMA samples were tested under varying steady-state resistive heating in air (at various flow rates), still oil, thermally conductive grease, and still water. This combination of media and wire diameter selections were intended to span a wide range of cooling conditions. Empirical models based upon traditional methods [14] were formulated with free parameters *C* and *m* optimized using a generalized reduced gradient (GRG) to provide a best fit to the data. These correlations provide a mathematical relationship to calculate the convective coefficient in material models or continuous optimization algorithms.

3-1. Experimental Setup and Procedure

Each test was conducted with the same experimental apparatus used in the midpoint transformation tests; however, the wire was electro-resistively heated via a DC power supply (Figure 2) instead of environmentally heating the SMA. Input power to the wire was computed from the applied voltage and current, measured by voltage and current probes connected to an oscilloscope. The apparatus was placed with the SMA in a horizontal configuration inside a leak-proof PVC box filled with the various environmental fluids at known temperatures (monitored by a thermocouple). For the free convection in air tests, the PVC box was covered to ensure that stray air currents did not affect the measurement. Forced convection in air was conducted outside the box, with an electrical fan whose proximity and speed were varied to produce a desired test flow rate that was measured by a hot wire anemometer. Tests were conducted at flow rates of 150, 250, 450, and 625 ft/min. In all experiments, the input



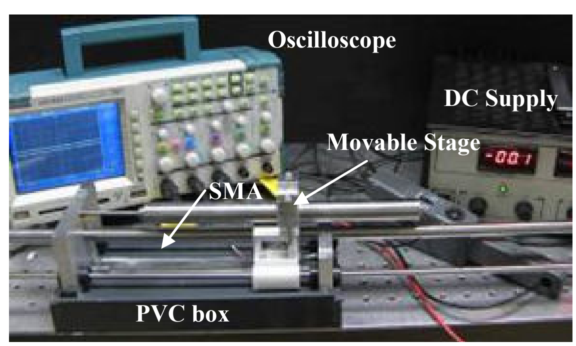


Figure 2. Experimental test apparatus for h-value testing in various media. Leak-proof PVC box is filled with various fluids tested. Strain is monitored while applying electrical power, which is recorded at the midpoint transformation strain.

power was slowly increased and recorded when the half-way displacement between "twinned" martensite and austenite (at the midpoint transformation temperature) occurred. The recorded power along with the associated ambient temperature and midpoint transformation temperature (Table 1) were used in Newton's law of cooling, Equation 1, to predict the convective coefficient, h. For each wire diameter listed in Table 1, the test was repeated in air (free and forced), mineral oil, thermal grease, and distilled water.

3-2. Convection in Air

There exists a tradeoff between simplicity and performance for cooling in air. For free convection (cooling in still air), no additional complications are introduced to the system, though the convection heat transfer is low. To improve convection, flowing air may be introduced through a fan, producing forced convection. While this often requires additional power draw and system complications, the resulting heat transfer improvements may be sufficient for a given application's speed and power requirements. This section studies both free and forced convection for SMA wires of varying diameter to provide a better understanding of the heat transfer effects under these regimes.

3-2-1. Free Convection

In the experimental results for cooling in still air (Figure 3) a significant dependency on wire diameter is evident. Overall, the convective heat transfer coefficient decreases as the wire diameter is increased – for 6-mil wire, the h-value is 153 $W/m^2 K$, while the h-value for 20-mil wire is reduced by 44% to 68 $W/m^2 K$. At the limits, the h-value for the collected data should theoretically approach infinity at very small wire diameters and zero at very large diameters. This is because a very large

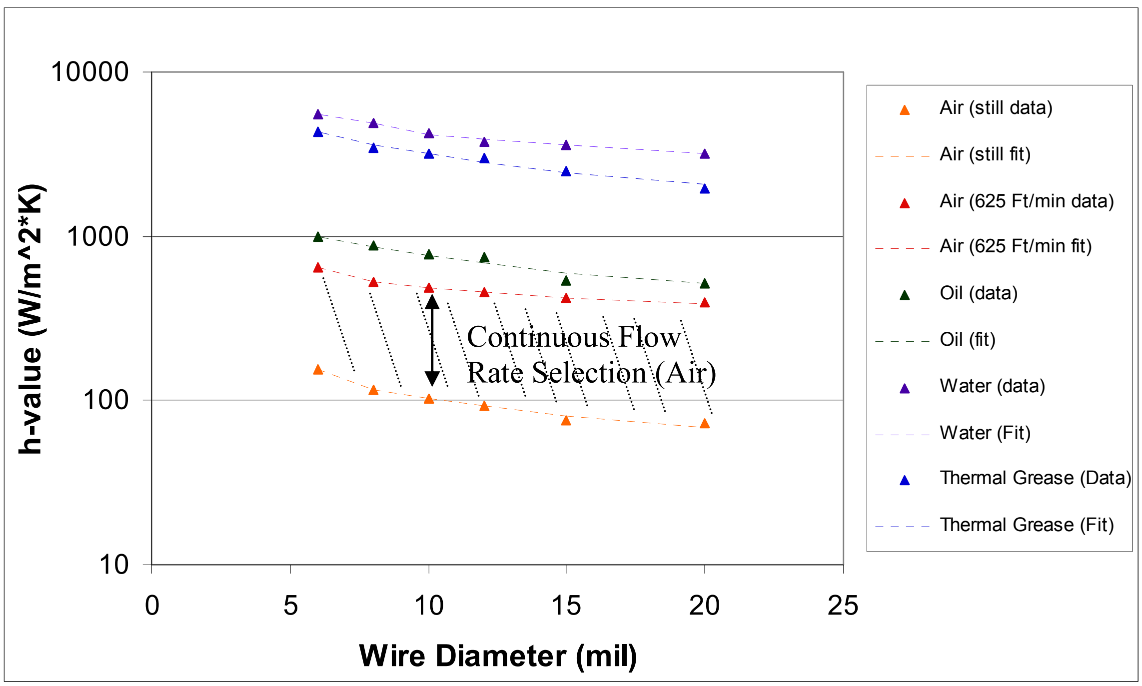


Figure 3. Convective heat transfer coefficients in different media. The measured h-value decreases somewhat with wire diameter and varies greatly with cooling medium. The empirical fits plotted with the data closely match the form of the functional dependence. A very large design range is represented in this space (ranging nearly two orders of magnitude). Forced convective air flow range represents continuous space.

diameter cylinder would restrict convective flow and the primary mechanism of heat transfer would be through conduction across the fluid. Conversely, an extremely small cylinder would produce very little resistance to fluid flow, and convective heat transfer would dominate.

To produce a continuous correlation to the data presented in Figure 3, Morgan's correlation for an isothermal horizontal cylinder [11] was used as a basis for its commonality and relative simple form. In this empirical model, the non-dimensional Nusselt number (ratio of convection to conduction in the fluid) is approximated from

$$\overline{Nu}_d = \frac{\bar{h}D}{k} = CRa_D{}^m , \tag{2}$$

where $\bar{h}$ is the average convective coefficient for the wire, D is the wire diameter in meters, and k is the thermal conductivity of air (in unites of W/m.K). The Rayleigh number, $Ra_{d,}$ for a cylindrical shape is defined as

$$Ra_d = \frac{g\beta(T_s - T_a)D^3}{\upsilon\alpha} . \tag{3}$$

In Equation 3, g is the acceleration due to gravity, β is the thermal expansion coefficient of the fluid (K^{-1}), T_s is the wire's surface temperature, T_a is the fluid's ambient temperature (K), D is the wire diameter, v is the fluid's kinematic viscosity (m^2/s), and α is the thermal diffusivity (m^2/s). All fluid properties are evaluated at a film temperature estimated as the average of the surface temperature (estimated to 60 ^oC) and the ambient temperature (23 ^oC), and the values are listed in Table 2. Substituting the Rayleigh number, Equation 3, into the Nusselt number correlation, Equation 2, and solving for the convection coefficient allows,

$$\bar{h} = kC\left(\frac{g\beta(T_s - T_a)}{\upsilon\alpha}\right)^m D^{3m-1} . \tag{4}$$

This equation for the average convective coefficient yields additional mathematical insight towards the physical limits on diameter. If $3m$ is less than 1, which is true for all proposed fits (Table 3), h approaches zero for large D and infinity for small D. This is in accordance with the limitations of convection due to fluid flow discussed earlier. To optimize the empirical fit, values for C and m were adjusted using a generalized reduced gradient algorithm (GRG) that minimized the average fit error to the collected data to only 2.4% (Figure 3). These parameter values are listed in Table 2 for the two Rayleigh number regimes that the experimental conditions fell within.

Table 2. Fluid properties for tested media. Properties for air and water were taken from [18], while oil was taken from [14]. Thermal grease properties were not known other than the thermal conductivity, listed by the manufacturer [15]. All properties evaluated at film temperature of 42 ^oC.

Fluid	**Kinematic Viscosity v (m^2/s)**	**Thermal Conductivity k (W/m.K)**	**Prandtl Number Pr**	**Thermal Diffusivity α (m^2/s)**	**Thermal Expansion Coefficient β (1/K)**
Air	1.71E-05	2.72E-2	0.712	2.40E-05	3.18E-03
Oil	1.6E-04	1.43E-1	1.97E3	8.23E-08	7E-04
Thermal Grease	unknown	2.3	unknown	unknown	unknown
Water	6.29E-07	6.34E-01	4.00	1.57E-07	3.9E-04

Table 3. Fit parameters for collected cooling data. Parameters for fits based on those suggested by Morgan [11] for free cooling and Hilpert [19] for forced. Values based on experimental data are given for C and m, along with an additional free variable R for thermal grease.

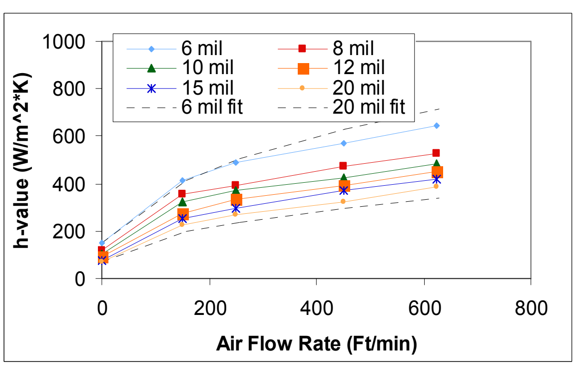
Medium	Ra_d	C	m	R
Still Air	10^{-10}-10^{-2}	0.875	0.038	
	10^{-2}-10^{2}	1.477	0.142	
Moving Air	10^{-2}-10^{2}	1.235	0.377	
Mineral Oil	10^{-2}-10^{2}	1.600	0.137	
Thermal Grease		2.998	0.130	10.3
Water	10^{-2}-10^{2}	1.021	0.169	
	10^{2}-10^{4}	0.868	0.208	

3-2-2. Forced Convection

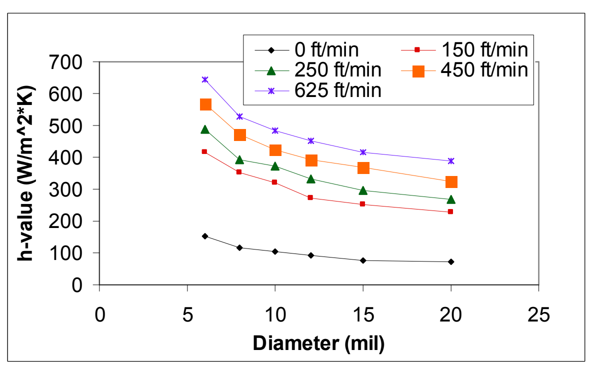
When subjected to forced convection, the h values for the SMA increased with flow rate but demonstrated a similar dependence on diameter as observed under free convection. For example, the results (Figure 4a and b) show that the convective coefficient decreases by 40% under a fixed flow rate of 625 ft/min when the wire diameter is increased from 6 to 20 mils. This change in h between different diameters also existed for other constant flow rates (see family of curves in Figure 4b), decreasing on average by 47% with average deviations of 3%. The family of curves in Figure 4a shows the increasing trend with increasing flow rates, and heat transfer is improved under forced convection by an average factor of 4.9 (with 8% average deviation) for all wire diameters under a flow rate of 625 ft/min.

An equation of the form proposed by Hilpert [19] for horizontal cylinders under forced convection was used as a basis for constructing a continuous correlation for its relative simplicity. In this correlation, the Nusselt number is related to the Reynolds number Re_d and Prandtl number Pr as,

$$\overline{Nu_d} = \frac{\bar{h}D}{k} = C\,\mathrm{Re}_d^{\,m}\,\mathrm{Pr}^{1/3} \tag{5}$$



(a) Flow Rates



(b) Diameter

Figure 4. Effect of air flow rate on the convective coefficient for varying diameter. Experimental data and three empirical fits are shown for air at 22 °C. h-values decrease with increasing wire diameter, and increase with a decaying amount for increasing air flow rates, spanning a wide range of h-values.

where C and m are correlation constants (Table 3) and k is the thermal conductivity. The Reynolds number is defined as

$$\mathrm{Re}_d = \frac{uD}{\upsilon}, \tag{6}$$

where u is the flow rate, D is the wire diameter in meters, and v is the kinematic viscosity. For the data correlation, all fluid properties were evaluated at an estimated film temperature of 41 ^{o}C and are listed in

Table 2. As for the free cooling correlation, the mathematical limits on wire diameter of Equation 5 match physical intuition. For values of m less than 1, the predicted h value approaches infinity at very small diameters and zero at very large diameters.

Using the GRG algorithm, values of C and m (Table 3) were optimized in Equation 5 to minimize the average fit error to 6.4% for the range of data, capturing the effects of both diameter and flow rate. Figure 4a displays these fits for the upper and lower bounding cases for wire diameter, and shows the adjusted fit over many wire diameters under and air flow rate of 625 ft/sec. For most data points, the predicted error was small but the model did deviate by as much as 13% for the maximum airflow speed of 600 ft/min for the 20 mil wire. This deviation may be due to a combination of the model's limitations in correlation and experimental error such as possible non-uniform airflow speeds.

3-3. Free Convection in Mineral Oil

While increasing the air flow rate dramatically improves the convective heat transfer performance (Figure 4a), higher frequency applications may warrant a change in medium since producing very high air flow rates may become impractical due to fan size and power consumption. Mineral oil is an attractive alternative to air cooling due to its higher convective abilities and very high electrical resistance (greater than 10^{10} ohms/m [20]). Due to these favorable thermal and electrical properties recent experiments have been conducted in building submerged computers to improve cooling performance [21].

To characterize mineral oil for its potential use in submersing SMA wires, experimental cooling data was collected for technical grade, light viscosity mineral oil obtained from McMaster-Carr, Inc. Figure 3 shows a similar trend to other mediums with respect to wire diameter as an increase in diameter generally reduces the heat transfer coefficient. The h value reduction from 6 to 20 mils is 49%, which is close to the 44% reduction reported for free convection in air. In addition, when compared to free convection in air, the h value for all diameters in mineral oil was consistently higher (e.g. the convection coefficient increased by a factor of 6.5 for 6 mil., and 8.9 times for 20 mil.). For the data correlation, the exact properties of the particular mineral oil used were not known so values were estimated for general light-viscosity oil [14], and the numbers are provided in Table 2. A data-fit based using these parameters was conducted, employing the GRG optimization method to determine values for C and m in the Hilpert correlation, Equation 2. Using the values provided in Table 3 for mineral oil, the average fit error was minimized to only 3.8% (Figure 3). Overall, mineral oil provides a higher increment in performance than 625 ft/min air flow, and as an added benefit requires no additional power draw. This, however, comes with a price of packaging complexity as the mineral oil must be sealed around the SMA wires. Additionally, the viscous nature of mineral oil can be problematic and cumbersome for parts that need frequent servicing.

3-4. Effective Convection in Thermal Grease

To further improve the heat transfer from the SMA wire (beyond the performance of mineral oil) thermally conductive grease can be employed. Thermally conductive grease is typically used in the electronics industry, to improve the thermal contact between a chip and a heat sink. For applications involving SMA, it can be used in a similar fashion where the heated wire is immersed in the grease, which acts as a direct conduit to transfer heat to an ambient environment.

The experimental data shown in Figure 3 represents the convective coefficient for various diameters of SMA immersed in OmegaTherm OT-201 thermally conductive silicon paste. The paste was selected due to its very high thermal conductivity, and also its electrically insulating properties. Unlike the rest of the fluids tested in this paper, the thermal grease is highly viscous and does not flow to produce free convection. Instead, the primary mode of heat transfer is conduction. For simplicity and to allow for comparison to the other media tested, this form of heat transfer is approximated as an effective convective coefficient h.

The data in Figure 3 shows that the effective convection is still heavily dependent on wire diameter. For example, the h-value decreases by 55% between 6 and 20 mils which is on the same order as the decreases reported for air and mineral oil (44% and 49% respectively). The amplitude of the effective h values calculated for thermal grease is also significantly higher than other mediums tested. For example the effective convection at 6 mil wire diameters 4.3 times higher than the same wire in mineral oil, and 28 times than free cooling in air.

A continuous fit to the collected data was again based on Morgan's free-convection equation (Equation 2), with the fluid properties lumped into an additional free-variable R (units of $s^2/m^4.K$) since they were unknown. By substituting Equation 3 into Equation 2 and grouping terms the average convective coefficient is expressed as,

$$\bar{h} = Ck\left[gR(T_s - T_\infty)\right]^m D^{3m-1} \tag{7}$$

where the lumped fluid properties variable,

$$R = \left(\frac{\beta}{\upsilon\alpha}\right). \tag{8}$$

In the lumped correlation, Equation 7, the thermal conductivity k, was listed by the manufacturer to be 2.3 W/m.K. Using the GRG optimization method, but allowing R to vary in addition to C and m, the average fit error was minimized to 3.1%. The values of the optimized free variables are listed in Table 3, and the resulting fit is plotted with the data in Figure 3.

When compared to mineral oil, thermal grease provides significantly higher cooling allowing for higher frequency responses for a given diameter, which is important for many applications. However, thermal grease does have some disadvantages over mineral oil. For example, it is significantly more viscous and is consequently even more difficult to work with. Thermal grease is also expensive when compared to mineral oil and may become impractical when large quantities are needed.

3-5. Free Convection in Water

As long as the transition temperature for the SMA is below water's boiling point, water immersion is an effective yet simple, cooling method. For the 70 °C Flexinol wires, the water also provides a protective measure against overheating, since running excess current through the wires would cause the water to locally boil, dissipating the extra heat without damaging the wire. If the transition temperature of the wire is higher than the boiling temperature of pure water, ethylene glycol could be added to raise the fluid's boiling temperature (though this sacrifices some of the water's convective properties). Because the transition temperatures of the tested 70 ^{o}C Flexinol SMA wires were below the boiling point of pure water, the medium was tested with no additives. Additionally, to ensure that the medium's electrical resistance was very high (and that the input power measurements were accurate), technical grade distilled water from McMaster-Carr was used for the experiments.

The cooling performance for distilled water was tested to be the highest among all mediums studied (Figure 3). When compared to the next highest tested medium, thermal grease, convective coefficients were approximately 1.3 times higher for 6 mil. and 1.6 times higher for 20 mil. wires when immersed in water. When compared to free cooling in air performance is dramatically increased 36.5 and 44.5 times for 6 and 20 mil wire diameters. The strong dependency on wire diameter is also present in the water cooling data, with a 43% reduction in the convective coefficient from 6 to 20 mils. The data for free cooling was used to create a fit based on Morgan's correlation (Equation 2), and all fluid properties were readily found in literature and are listed in Table 2. Values for *C* and *m* were slightly adjusted by the GRG algorithm (values listed in Table 3) to provide a continuous expression for the distilled water cooling with an average error of only 1.2%. While this high cooling performance is excellent for high-frequency applications, water cooling does increase system complexity since it must be sealed around the SMA.. Additionally, if the high cooling performance of water is not needed it can actually reduce overall efficiency producing significant losses during the heating cycle of the SMA.

4. CONCLUSIONS

This paper presents a new methodology for characterizing the convective heat transfer coefficient (commonly referred to as the *h*-value) for SMA wires of different diameter, immersed in various cooling environments. Measurements of the wires' midpoint transformation temperatures were collected and mapped to the output motion generated while heating. This calibration allowed a separate set of tests to determine the *h*-value where the motion was monitored while prescribing an input power through resistive heating. Knowing the midpoint transformation temperatures for each wire diameter, the *h*-value was computed for environmental conditions in still and moving air, oil, thermal grease, and water. SMA diameters from 6 to 20 mils (thousandths of an inch) were tested in each medium. This general methodology provides a robust solution for thin SMA wires in cooling media and overcomes issues experienced by current techniques (i.e. employing thermocouples or an IR camera).

The environmental and geometric variations tested in this study (Figure 3) represent a wide design space (spanning two orders of magnitude from ~100 W/m^{2}K to ~5000 W/m^{2}K) in which the optimal combination of cooling medium and wire diameter can be selected based on cooling needs and power restrictions. As intuitively expected, increasing the wire diameter decreased the cooling performance for all cases (average decrease in *h* was 48% between 6 and 20 mil), while increasing the air flow rate increases heat transfer. Distilled water provides the highest *h*-value of all the tested media: between 3210 and 5590 W/m^{2}K for the diameter range tested, which was as much as 1.6 times higher than that of conductive grease, and as much as 44.5 times higher than free convection in air. While providing very high heat transfer, water is more difficult to manage in an application than grease requiring better sealing than grease and special care for parts to resist corrosion, although conductive grease is significantly more expensive and is difficult to spread evenly throughout a device. Oil provided an intermediate level of *h*-value, between 512 and 997 W/m^{2}K, which is up to 7.1 times more than still air, or up to 6.3 times less than water. Oil is inexpensive and does not promote corrosion, but does require careful sealing similar to water. Still air provides a lower *h*-value, between 69 and 153 W/m^2K, but is much easier and cheaper to use in an application requiring no additional parts or installation. Forced air, on the other hand, provided *h*-values between 389 and 644 W/m^2K at a flow rate of 625 ft/min, which is up to 5.6 times more than still air at the cost of requiring fans or some other means of blowing the air. An extra advantage gained by using forced convection is the ability to adjust the *h*-value over a large range (by a factor of 1.7 in these tests), such that the balance between cyclic performance and power consumption can be adjusted to a changing application. While not included in this study due to the additional complexities involved, forced convection of other fluids (water, in particular due to its low viscosity) can also be used to increase and tailor in-situ the *h*-value, by potentially another order of magnitude as it did for air (Figure 3).

Using the general form of proposed correlations in literature for the heat transfer from a cylinder in still air and a cross-flow, empirical correlations were generated for each of the ambient media tested. Because the all-encompassing fits found in literature typically provided only general estimates of the collected data, the fit parameters were adjusted for each test condition using a GRG optimization algorithm. The resulting continuous equations closely followed the collected data in relating the heat transfer rate from the SMA wire to the wire diameter, flow rate, and fluid properties (as close as 1.2% average error for water). The empirical correlations for all of the tested data can also be used to extrapolate the wire diameter effect beyond the tested conditions if necessary. Because these correlations are continuous functions, they may readily be used in optimization algorithms to ensure that the cooling requirements are properly chosen guaranteeing frequency performance while minimizing power consumption. The new quantitative data presented in this work can also be directly applied to existing SMA models, allowing for a greater range of predictability, which can aid in producing more effective actuator designs and control algorithms.

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