TRANSIENT THERMOELECTRIC COOLING

A Senior Thesis

By

Matthew Wilkins

1996-97 University Undergraduate Research Fellow

Texas A&M University

Group: ENGINEERING

Transient Thermoelectric Cooling

Matthew Wilkins
University Undergraduate Fellow, 1996 - 1997
Texas A&M University
Department of Aerospace Engineering

APPROVED

Fellows Advisor ____________________

Honors Director ____________________

ABSTRACT

A theoretical and experimental study of high current density transient thermoelectric cooling is undertaken in this paper. Both three region and five region thermodynamic heat transfer models are implemented in the theoretical study and the transient heating and cooling temperatures are evaluated at various current densities. An experimental setup was devised to resemble thermodynamic assumptions necessary for an analytical solution. Temperature profiles are generated from the heating and cooling of mercury and compared to the theoretical predictions from the three and five region thermodynamic models. The transient agreement is excellent in the three region model for lower current densities ($\approx$ 1 A/sq mm), although the steady state agreement is only marginal. The five region model qualitatively predicts the temperature profiles at higher current densities ($\approx$ 3 A/sq mm).

TABLE OF CONTENTS

LIST OF FIGURES

1. INTRODUCTION

Thermoelectric cooling is a phenomena which has been studied for over 175 years. First discovered in 1821 by Thomas Seebeck, thermoelectricity has fascinated scientists and has led to many remarkable inventions. Probably the most scrutinized area of thermoelectricity is the steady-state response [Harman and Honig, 1967]. Knowing the physical properties of the materials involved, one can calculate the steady-state temperature of the system. This is extremely useful in refrigeration systems where it is necessary to regulate temperatures.

Three primary discoveries have pioneered the work in the realm of thermoelectricity. The "Seebeck effect" was first to be discovered and occurs when a temperature gradient is applied across two dissimilar metals which are in contact with one another. A resultant potential difference can be measured which can be related to the magnitude of the temperature gradient.

The reverse process was discovered in 1834 by Jacque Peltier. Peltier noted that a temperature gradient developed when a potential difference was applied across two dissimilar metals in contact. The temperature gradient which is produced can be controlled by the amount and direction of the electrical current applied. According to Domenciali [1954], the Peltier effect can be used to create a heat source or sink depending upon the direction of the applied current. The Peltier effect is the process of interest in this study.

Lastly, the Thomson effect was discovered while trying to relate the Seebeck and Peltier effects. Thomson discovered a new form of heating that arises from passing a current through a thermal gradient. In general, this effect is small compared to the Seebeck and Peltier effects and can be ignored without significant loss in accuracy.

The ultimate goal of the project, as defined by Bhattacharyya, et al [1995], is to create an actuator using shape-memory-alloys (SMA) and thermoelectricity. SMA's have the capability to of solid-solid phase transformations between the cubic austenitic phase to the martensitic phase under the application of stress or by removing heat from the system. These metals, after being deformed, will return to their original shape by adding heat or removing stress from the system. Some measure of success has been found using semi-conductors and the thermoelectric Peltier effect to add and remove heat from SMA's to generate actuation. However, continued efforts are in progress to improve the frequency of actuation.

With the steady state response thoroughly addressed by Harman and Honig, the primary focus of this study is on the transient nature of the Peltier effect. How rapidly can one cool a system and to what temperature? Thermoelectric cooling is in large part determined by the electrical current density (amperes per unit area). Therefore, to answer the question posed, a high current density experiment has been designed. Unfortunately, one of the primary obstacles in thermoelectric cooling is the resistive heating incurred from passing large currents through metals. Therefore, a balance must be struck between the level of cooling and resistive heating. By finding the maximum temperatures changes and the maximum rate of change, we can design an actuator which will have a specified actuation performance.

2. THE PHYSICAL MODEL

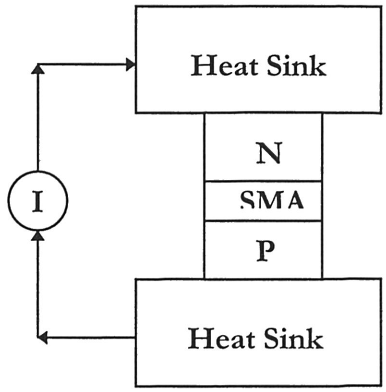

Figure 1: Original Actuator Unit Cell Design [Bhattachryya, et al, 1995]

Figure 1 is a unit cell version of the actuator design proposed in Bhattachryya, et al. A specimen of SMA wire is placed between a negatively (N) and positively (P) doped semi-conductor element (commercially available Bismuth-Telluride). As current is passed through the system from N to P, heat will be extracted from the SMA wire. Alternatively, if the current direction is reversed, heat will be added to the test specimen. Pollock (1985) provides a thorough examination of the thermoelectric process employed here.

The actuator design proposed by Bhattachryya, et al, incurred a number of problems which made comparisons between theory and experiment difficult. First, the very nature of the actuator requires movement. Movement at the interface between the SMA wire and the semi-conducting elements creates a less than desirable boundary condition which makes error difficult to track down. Second, since the SMA and semi-conductors were not bonded together on the atomic scale, the thermal and electrical transfer efficiencies were also decreased. By adding a thermally conducting paste to the contact surface, results were improved. However, despite the excellent trend comparison presented, there was a significant margin of error between the actual and calculated temperature values at any given instant in time.

Therefore, a modified experimental design was proposed by Dr. Vikram Kinra which would seek to eliminate the various possible sources of error. Figure 2 shows the new experimental setup.

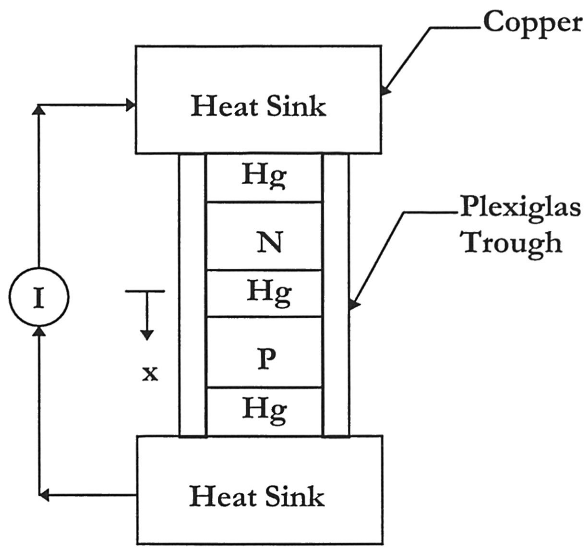

Figure 2: Schematic of Experimental Setup

To eliminate the error associated with a poor contact surface, mercury (Hg), which is in its liquid phase between -38.87 °C and 356.9 °C [Aesar, 1992], was added to the interface regions to form a "perfect" electrical, and thermal contact. Due to the fact that mercury remains liquid over a broad range of temperatures, the interfaces should be in contact at the atomic scale resulting in better transfer efficiencies.

The physical properties of mercury, however, only allow for a more efficient electrical transfer. The electrical resistivity of mercury is 95.8 x 10^{-6} microhm-cm while its thermal conductivity is 0.022 cal/(s.cm.°C) [Aesar, 1992]. As can be seen, the electrical resistance is practically zero but so is the thermal conductivity. Therefore, to two interface pools of mercury between the heat sinks and the semi-conducting elements must be made as thin as possible to reduce thermal losses.

Experimentally, the thickness of the mercury pool has a definable limit due to the fact that mercury has an extremely strong surface tension. As the mercury pool decreases in thickness (< 1 mm), surface tension causes the mercury to pull away from the semi-conductor's face and only mate with the sides of the trough which contains it. This results in a taurus shape, when viewed from the side, which allows electrical arcing across the interface. This is highly undesirable; therefore, the interface regions of mercury were maintained at approximately 2 mm in thickness.

Additionally, the SMA wire test specimen was replaced with a pool of mercury. This eliminates the mechanical contact problem by removing the movement of the SMA during phase transformation. As mentioned earlier, a better thermal and electrical contact is provided. Also, the Peltier effect of mercury, like the SMA wire, is extremely weak in comparison to that of the semi-conductor elements. Therefore, mercury should make a suitable substitute for analysis purposes.

The twin copper heat sinks which flank the N and P elements are actively cooled by water that circulates though a hole in the copper. The water is maintained at room temperature in a nearby tank. Therefore, the heat sinks can be emulated as isothermal boundary conditions when theoretically modeling the system.

3. THEORETICAL SOLUTION

The governing equations for the experimental setup described above are as follows:

$$k_i \frac{\partial^2 T_i(x,t)}{\partial x^2} + \rho_i J^2 - h\frac{P}{A}\left[T_i(x,t) - T_0\right] = C_i \frac{\partial T_i(x,t)}{\partial t}, \qquad (i = N, M, P) \tag{1}$$

$$\left(\vec{Q}_m - \vec{Q}_p\right)\cdot\hat{n} = (\alpha_p - \alpha_m)(\vec{J}\cdot\hat{n})T_p(\frac{1}{2}d_m, t) \tag{2}$$

$$\left(\vec{Q}_m - \vec{Q}_n\right)\cdot\hat{n} = (\alpha_n - \alpha_m)(\vec{J}\cdot\hat{n})T_n(-\frac{1}{2}d_m, t) \tag{3}$$

These equations were developed in Bhattacharyya, et al, (1995) for the original SMA actuator unit cell. However, they still apply to the current experiment. The subscript M denotes Mercury. $T_i(x,t)$ represents the temperature as a function of space and time. J is the magnitude of the electrical current density. P and A represent the perimeter and area, respectively, of any region with a cross-section perpendicular to the x-axis (Refer to Figure 2). Thermal conductivities are represented by k, while the convection coefficients are represented by h. The ambient temperature of the surrounding environment including the heat sinks is taken as T_0. C is the heat capacity per unit volume. Q is the heat flux across the boundary between two regions. α is the Seebeck coefficient. d_m is the thickness of the mercury test section.

Two approaches can be taken to achieve the analytical solution of this problem based upon the number and type of assumptions made. If one makes the assumption that the mercury interface region between the N and P semi-conductors and the copper heat sinks is thin enough to be ignored, then one would have a three-region thermodynamic model. On the other hand, if one does not ignore the effects of the mercury interfaces, then a five-region model would result. The five region model is obviously more complicated and computationally expensive. Therefore, we would like to use the three-region model if the accuracy permits.

A three-region software code was written by A. Bhattacharyya[1] in FORTRAN. This code solves the system of Eqs.(1-3) with the following assumptions:

- The interfaces are in perfect thermal contact.
- Heat transfer due to convection is negligible.
- The Seebeck coefficient does not change with temperature.
- Thomson heat is neglected.
- Peltier and Joule heating are the sole sources of heat in the system.
- The Seebeck coefficients for both N and P are equal and independent of temperature.
- The physical constants for mercury are approximated by their nominal published values.
- The effect of the interface regions on the system are negligible.

A five region code, developed by Mark Honea[2] in Mathematica, makes the same assumptions with the exception that the mercury interfaces are assumed to have an effect on the system.

The physical constants used in the aforementioned codes are shown in Table 1.

	α_s (V/K)	k (J/(mm.s-K))	ρ (Ω-mm)	C (J/(mm^3-K))
Mercury	-	8.65×10^{-3}	9.59×10^{-2}	1.88×10^{3}
P (N)	2.15×10^{-4}	1.63×10^{-3}	1.15	4.35×10^{3}

Table 1: Physical Constants for Mercury, P, and N

[1] Center for Mechanics of Composites, Texas A&M University.

[2] Graduate Research Assistant to Dr. Vikram Kinra, Texas A&M University.

4. EXPERIMENTAL AND THEORETICAL RESULTS AND THEIR COMPARISON

4.1 Theoretical Results

Looking back at Eqs. (2) and (3), one will notice that the heat transfer is directly proportional to the applied current density. This fact is illustrated in Figure 3 with the theoretical temperature profiles for various electrical current densities using the three-region model. As the current density increases, the temperature gradient dramatically increases. However, the resistive heating term in Eq. (1) is a function of the current density squared. Therefore, there should be a point at which the system is no longer cooled, but rather it will be heated. This can be seen in the case of J = 3.125 A/sq mm. The steady state temperature at J = 2.500 A/sq mm is approximately 25 °C, whereas the steady state temperature for J = 3.125 A/sq mm is only 13 °C. This trend continues as the current density is increased even higher. For safety purposes, this study did not go beyond 50 A of electrical current.

Examining Figure 4, the five-region model results, will show some interesting phenomena which did not appear in the three-region model. In this model, the interface pools of mercury were added to the system. One will notice that both the J = 2.500 and 3.125 A/sq mm cases show a marked difference from the three-region model. The J = 2.500 A/sq mm cases shows a hint of an upward turn after reaching the minimum temperature. The steady state temperature is actually higher than that predicted in the three-region model. More significant is the change in the J = 3.125 A/sq mm case. The upward turn is extreme, and the steady state temperature is approximately half way between the ambient and the minimum temperatures.

Figure 5 compares the theoretical results for two cases, J = 0.625 and 3.125 A/sq mm, using the three-region (3R) and (5R) region models. Here one will see the dramatic difference

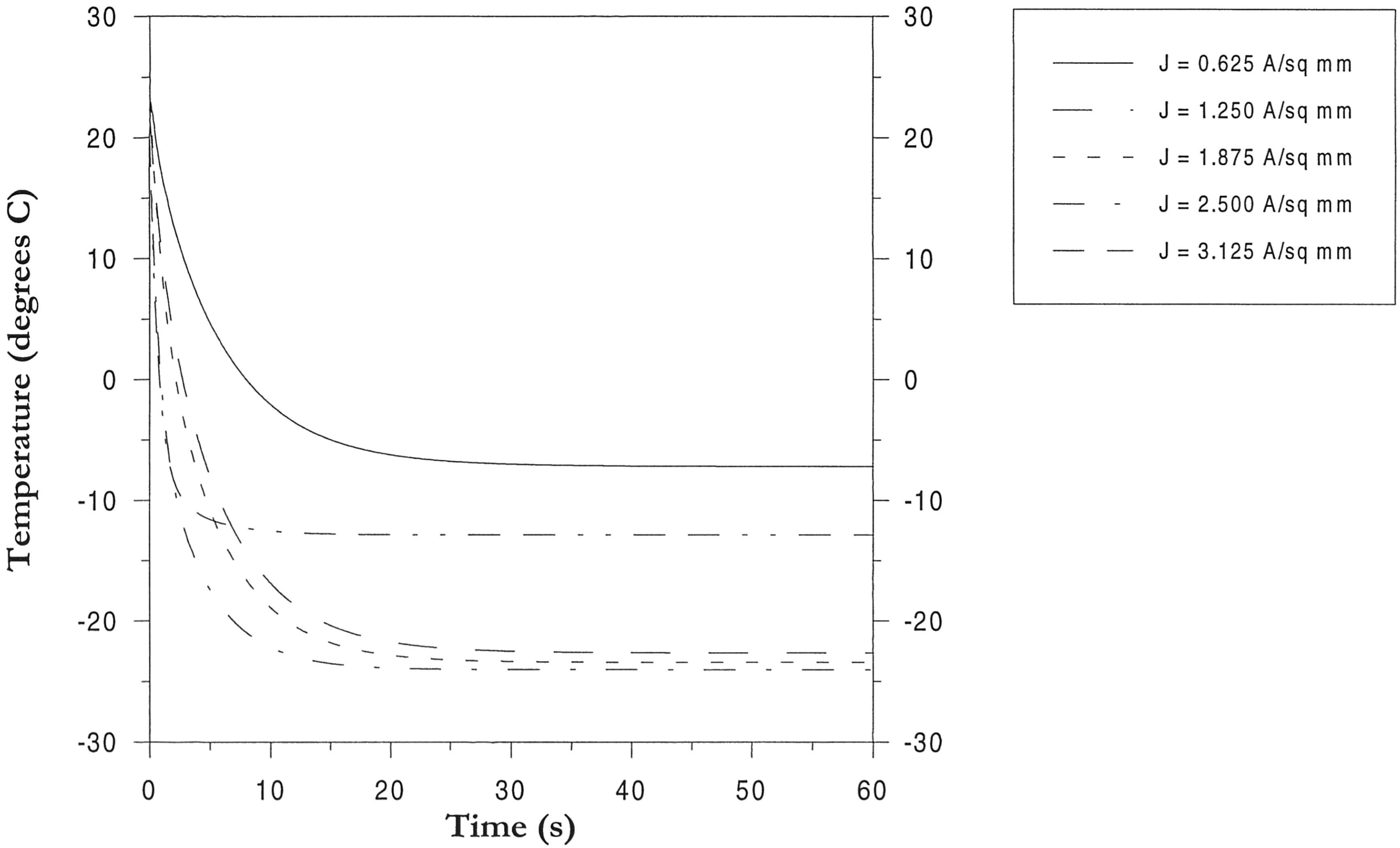

Figure 3: Theoretical Temperature Profiles for Various Current Densities Using the Three-Region Model

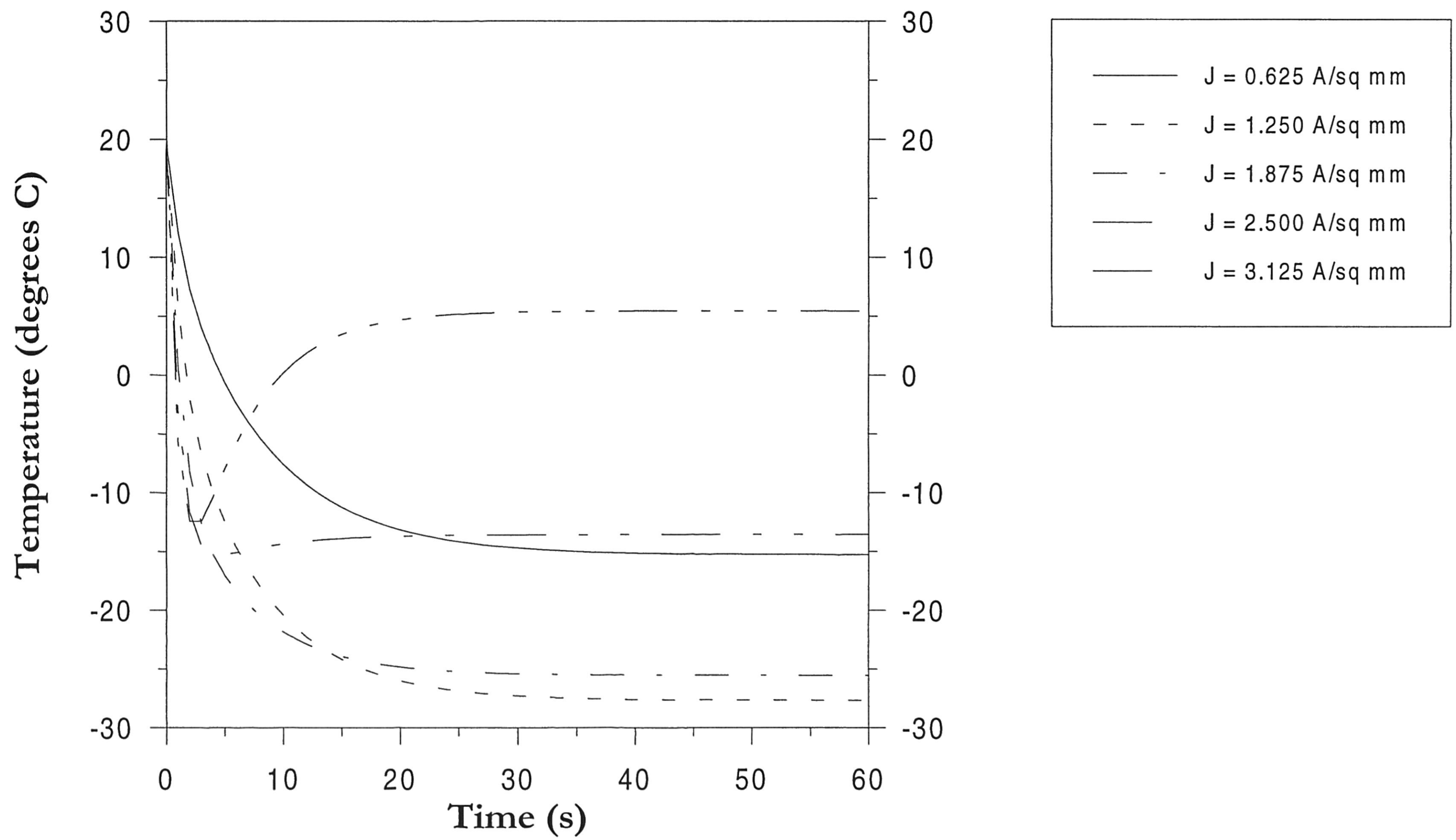

Figure 4: Theoretical Temperature Profiles at Various Current Densities Using the Five-Region Model

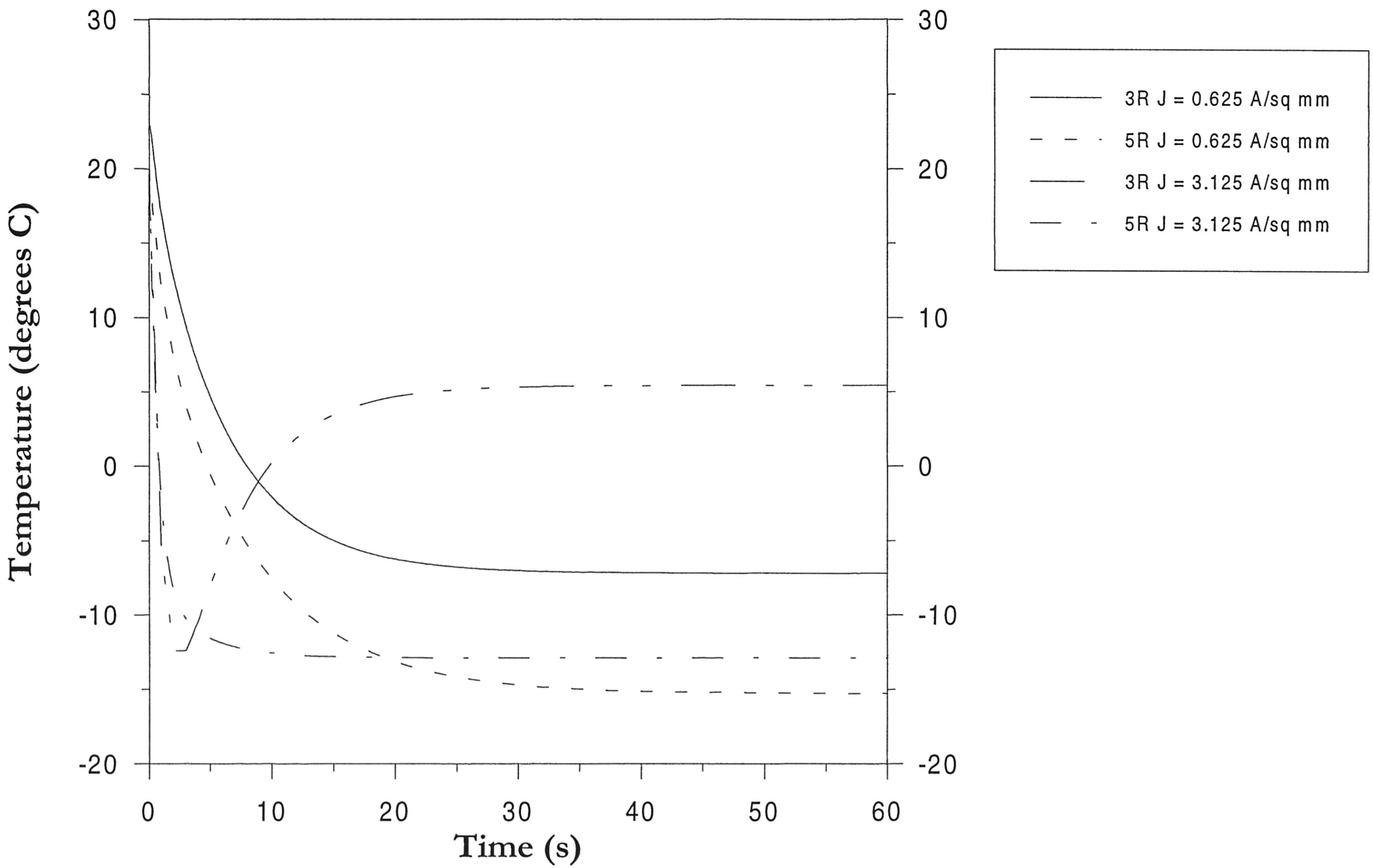

Figure 5: Comparison of Three-Region and Five-Region Theoretical Results

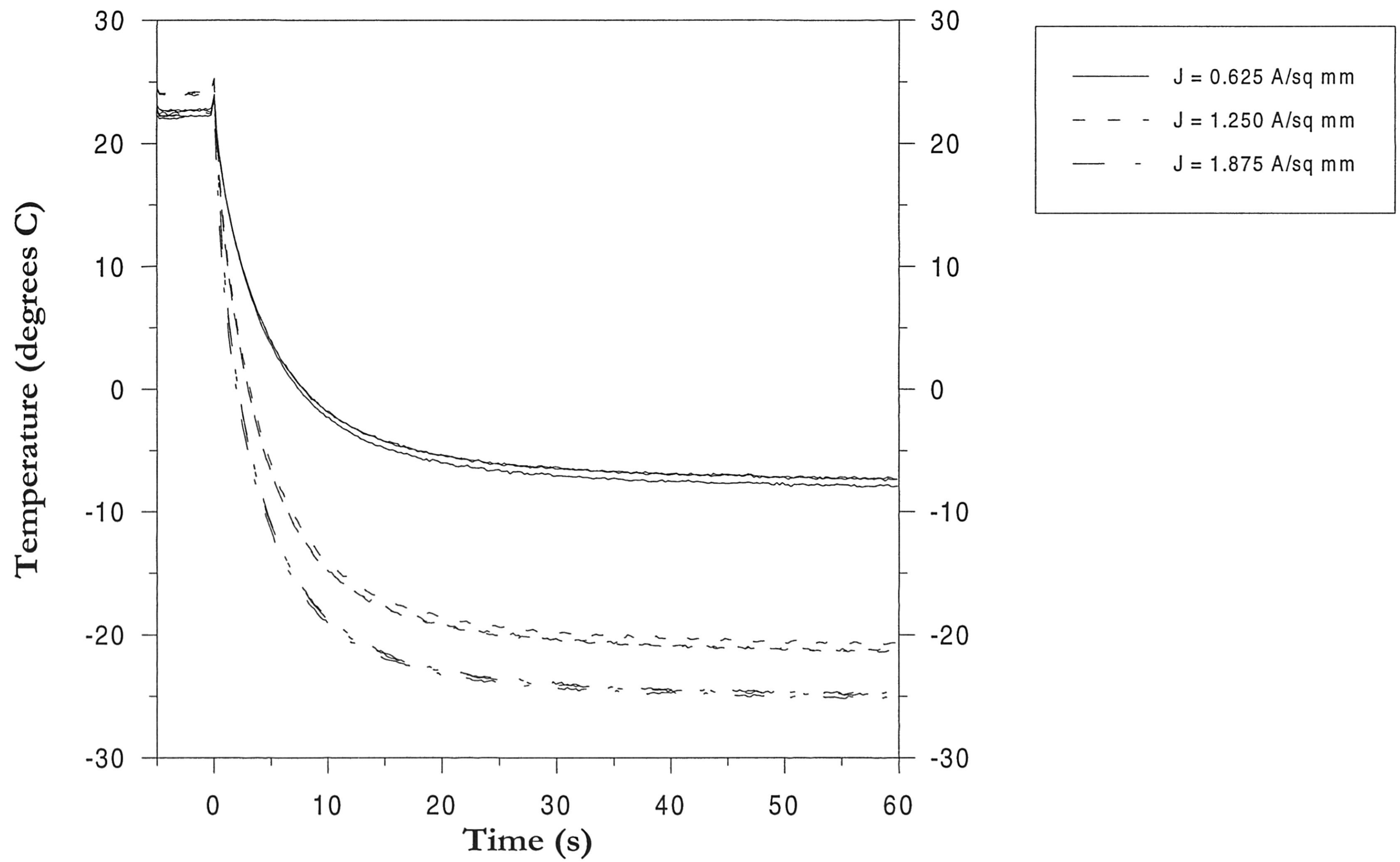

Figure 6: Experimental Data at Three Current Densities Showing Repeatability

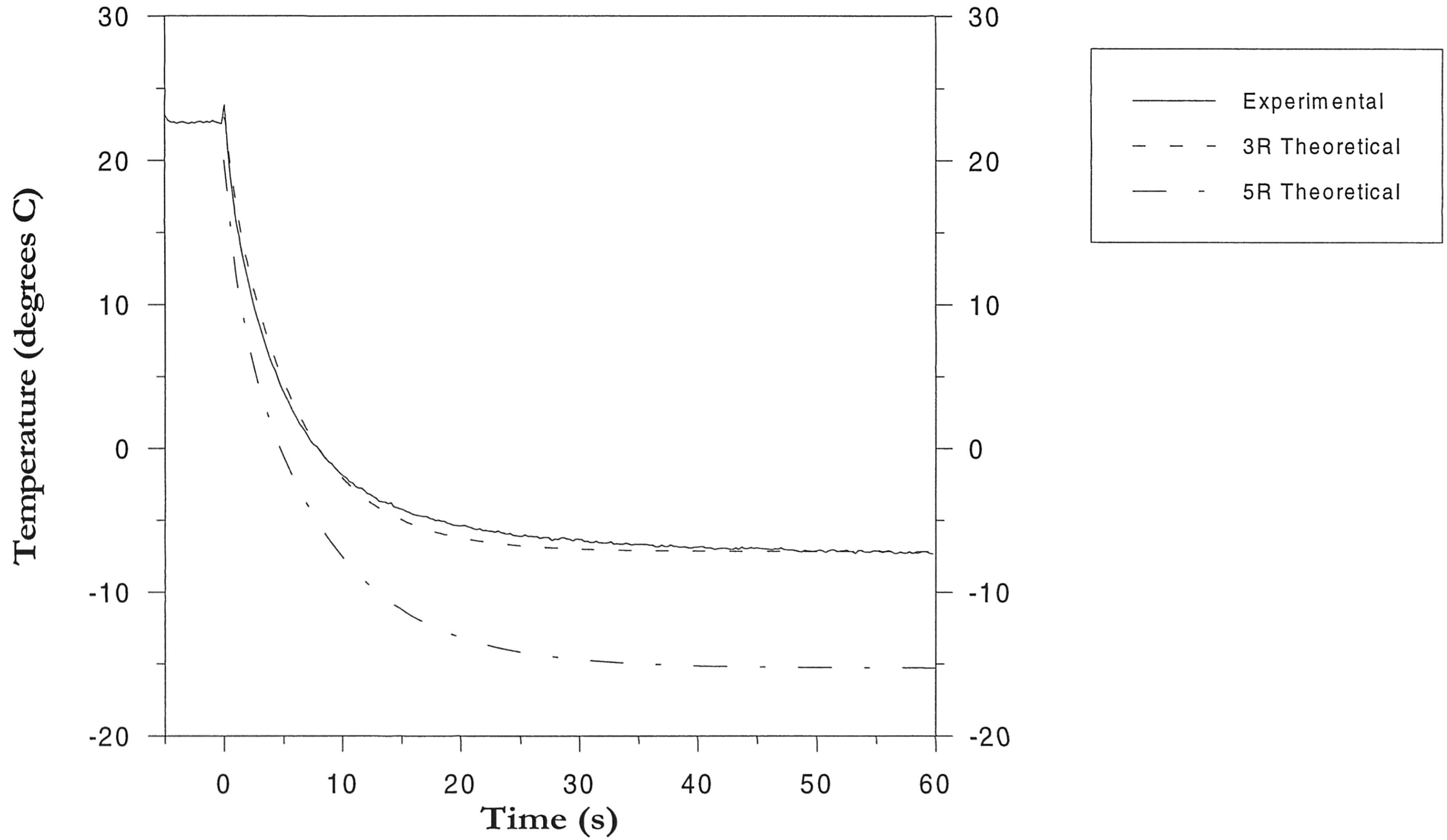

Figure 7: Comparison of Theoretical and Experimental Temperature Profiles for J = 0.625 A/sq mm.

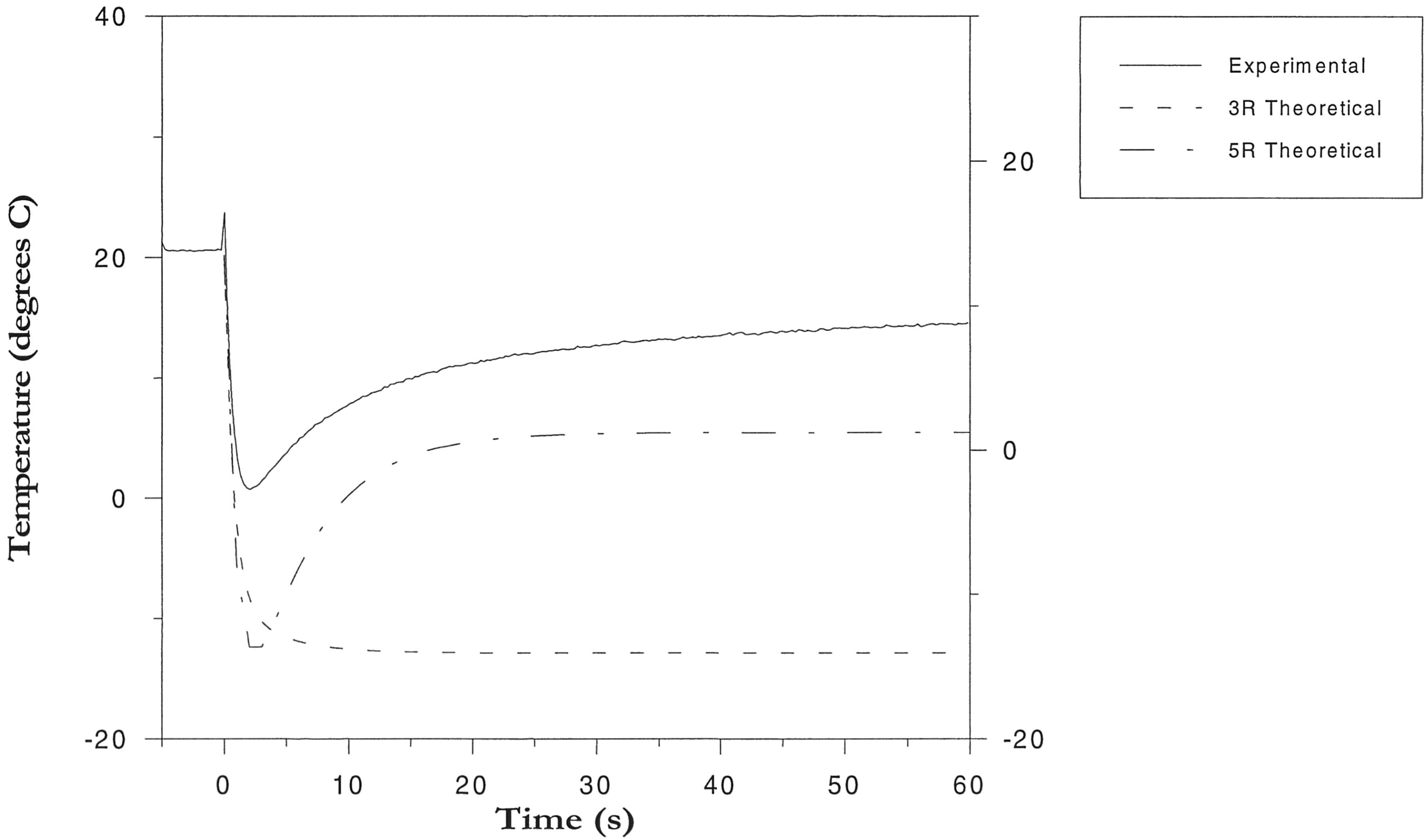

Figure 8: Comparison of Theoretical and Experimental Temperature Profiles for J = 3.125 A/sq mm

in the J = 3.125 A/sq mm case. Also note how the inclusion of the interface region resulted in a temperature difference of approximately 10 degrees in the case of J = 0.625 A/sq mm. Obviously, the three and five region models produce dramatically different temperature profiles. However, which model is correct?

4.2 Experimental Results

Figure 6 illustrates some typical data runs at three current densities. This data has been smoothed using a four point averaging scheme due to the fact that the A-to-D board in the computer has a sample rate of over 1000 Hz. Therefore, the data presented is a filtered average in an effort to remove noise and produce visible trends.

The data collected in this study is highly repeatable. For each current density, the experiment was run at least three times. This can be seen for the three sample current densities. The temperature profiles lie almost exactly on top of one another. Slight variations in the position of the thermocouple (device used to measure temperatures using the Seebeck effect) can cause the discrepancies seen between individual runs.

4.3 Comparison of Results

Comparing the theoretical and experimental results answers the question posed concerning which model, the three region or the five region, is correct. Figure 7 shows an experimental temperature profile for J = 0.625 A/sq mm compared to the predicted values. Here, one can see that the three-region model has an excellent comparison with the experiment. However, the five region model has over predicted the steady state cooling of the system.

Now, examine Figure 8 which compares the results for J = 3.125 A/sq mm. The three-region model is clearly insufficient to predict the temperature profile for high current densities. The five-region model, although it does not explicitly agree with the experiment, shows a remarkable qualitative comparison.

4.4 Conclusions

Based on the information in this study, the current models are insufficient to individually predict the transient nature of this experiment. The three-region model is highly accurate at lower current densities. On the other hand, the five-region model is more accurate at higher current densities, but still does not accurately predict the temperature profile. Therefore, further study is required to improve the theoretical models. However, this study can be used to qualitatively compare results.

ACKNOWLEDGEMENT

I would like to thank Dr. Vikram Kinra for allowing me to participate in this ongoing project. Without his assistance, none of this would be possible. Additionally, I would like to thank Mark Honea and Terry Clancy, graduate assistant researchers, for their insight and advice.

REFERENCES

1. "Aesar," John Matthey Co., 1992.

2. Bhattacharyya, A., D. C. Lagoudas, Y. Wang and V. K. Kinra, 1995, "On the Role of Thermoelectric Heat Transfer in the Design of SMA Actuators: Theoretical Modeling and Experiment," *Smart Materials and Structures*, Vol. 4, 1995, pp. 252-263.

3. Domenciali, C. A., 1954, "Irreversible Thermodynamics of Thermoelectricity," *Reviews of Modern Physics*, Vol. 26, No. 2, pp. 237 - 275.

4. Harman, T. C., and J. M. Honig, 1967, "Thermoelectric and Thermomagnetic Effects and Applications," Mc-Graw Hill Book Co., New York.

5. Pollock, D. D., 1985, "General Principals and Theoretical Considerations of Thermoelectric Phenomena," *CRC Handbook on Thermoelectricity*, pp. 7-17.