THEORETICAL ANALYSIS OF THERMOELECTRIC COOLING PERFORMANCE ENHANCEMENT VIA THERMAL AND ELECTRICAL PULSING

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Abstract

This paper is an introduction and theoretical investigation of the fast-transient cooling characteristics of a TE module under applied high-current electrical pulses. A temperature-dependent, finite element model was developed to accurately model the fast-transient performance. Analysis of experimental data is presented to verify the accuracy and validity of the model and the conclusions derived therefrom. It has been shown that cold plate temperatures are achievable from a typical TE module beyond that obtainable by conventional, steady-state means.

The cooling enhancement is by virtue of the fact that Peltier cooling is a surface effect and extremely concentrated at the cold junction, whereas, Joule heating is a volume effect and is distributed throughout the volume of the TE pellet. As such, most of the Joule heat takes a longer time to reach the cold plate than the Peltier cooling effect. This phenomenon is theoretically demonstrated by applying a high-current pulse after the minimum steady-state cold plate temperature has been established. Calculations have shown that cold plate temperatures can be reduced by 16 K below that via steady-state means.

These transient enhancements are admittedly short-lived and have limited effectiveness. However, the results presented herein suggest that further exploitation of the fundamental differences between Peltier and Joule heat are possible. A concept is re-introduced which consists of thermally and electrically separating the cold electrode from the TE pellet. This pulse cooling concept was originally conceived over 30 years ago by Reich[1] at the Borg-Warner Research Center.

Introduction

Dr. Allen Reich[1] did a lot of pioneering work in the field of thermoelectric cooling analysis in the early 1960's. He may have been the first to recognize the potential for pulse-TE cooling by capitalizing on the fundamental differences between Peltier and Joule heat. Unfortunately, however, he preceded the age of high-speed personal computers and the accompanying analytical technologies which now provide the means for detailing the many complicated intricacies of nature. He had to rely on key, clever simplifying assumptions and solutions of difficult and complex differential equations in order to gain an analytical glimpse into the physics of thermoelectric semiconductors. Nevertheless, his work suggested the possibility of significant net cooling by thermoelectric pulsing in order to segregate the localized Peltier cooling from bulk Joule heating.

Therefore, the work presented herein is essentially computerized numerical update of a dormant, but not necessarily fruitless, idea. On the other hand, this paper is only a precursor to the real potential for pulse-TE cooling but clearly and rigorously re-establishes the existence of the potentials of enhanced TE cooling via pulsing.

Thermal Model

The key to understanding and accurately characterizing the fast-transient properties of a TE module is the development of a thermal model which incorporates as much of the real-world technical details as possible. The starting point was the finite-element, steady-state thermal model for TE pellets by Buist[2]. This model employed the speed and power of a high-speed personal computer to take advantage of simplicity but accuracy and rigor of a finite element thermal model. By making each finite element small enough, they were accurately quantified using the familiar constant parameter theory. Of course, however, the ultimate precision of this model was a consequence of accurately testing the key kinetic thermoelectric material parameters. For that model, the temperature-dependent TE material parameters were measured using the test system as described by Buist[3].

The transient model is very similar but included the added dimension of time dependence. Thermal nodes were generated for each finite element. The interactions between them were derived from the steady-state model. The details of the transient model was presented by Lau and Buist[4] together with a thorough analysis of its features and attributes. A summary of the key elements of this thermal model is given in Table 1:

Table 1

Node	Description
42	Cold Ceramic Substrate
41	Cold Copper Tabs
40	Top "Half-Slice" of TE Pellet
1-39	Imaginary "Slices" of TE Pellet from Bottom to Top
0	Bottom "Half-Slice" of TE Pellet
-1	Hot Copper Tabs
-2	Hot Ceramic Substrate
-3	Infinite Heat Sink

Physically, the configuration of system is shown in Figure 1. A typical TE module was thermally bonded to a large aluminum block which served as an infinite heat sink for the low current testing used to verify and validate the fast transient characteristics of this system. This same module was not only used for transient testing but was also tested for its TE material properties: Seebeck coefficient, electrical resistivity, thermal conductivity and figure of merit, Z. These parameters were incorporated into the transient model.

Model Verification Testing

Some initial testing at 3% of Imax was performed on the TE module as shown in Figure 1. This was performed by the same high-resolution, high-speed, integrating A/D board used in the test system[3]. However, it was set up to rapidly test and retest the voltage across the TE module upon the application of an applied current. These data are shown in Figures 2 and 3 together with the calculations produced but the transient model. Figure 2 clearly establishes the long-term accuracy of the model by the excellent closure throughout the entire cool-down process.

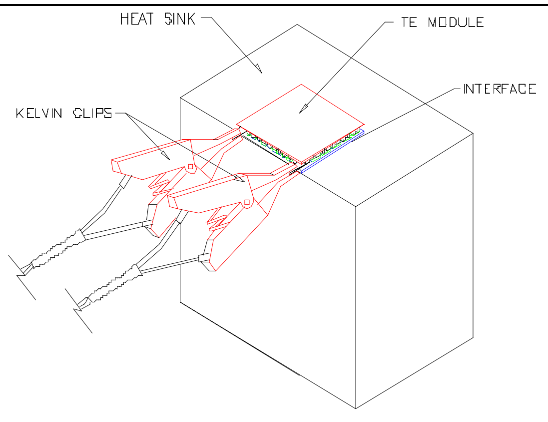

Fig. 1 Test/Model configuration

Figure 3 was generated to examine the accuracy of the fast-transient characteristics of the transient model. For this case, the module voltage was calculated for the same times as the test data. As observed, the calculations agreed with the test data to within 0.5%. This closure is very good, especially since the actual time for the test points with respect to the true power-on instant was not exactly known. It could be off by as much as 0.05 seconds. In any case, the shape of the calculated curve closely matches that of the test data thereby validating the transient model for the calculations presented.

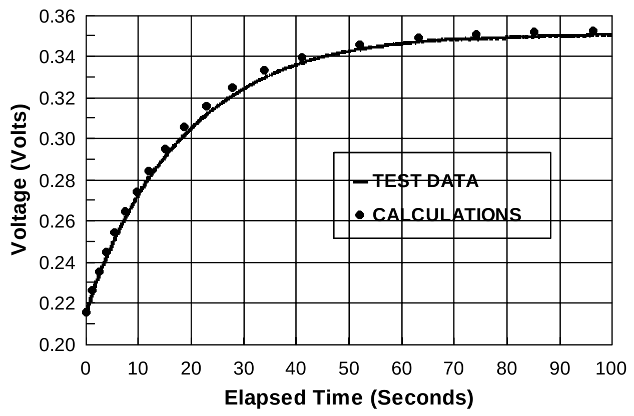

Fig. 2 Power-on to TE module until stabilization.

Calculations for Imax

The first step in establishing the feasibility for enhancement via pulsing was to calculate the performance of the TE module at Imax. Imax is defined as the current which produces maximum hot-to-cold temperature differential (delta-T), holding the hot junction to a constant 297K.

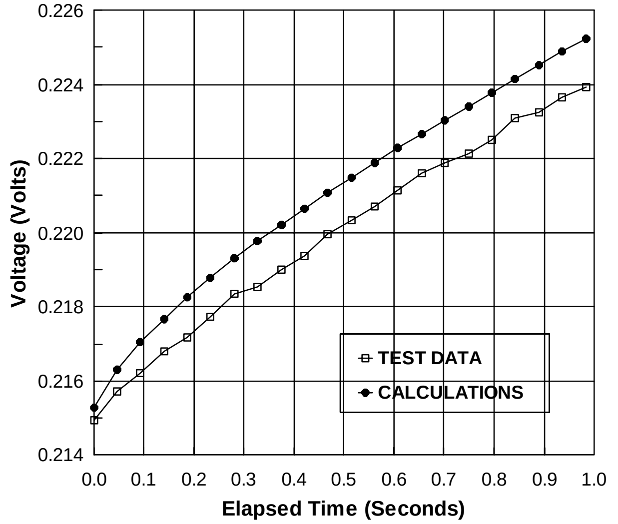

Fig. 3 Initial power-on to TE module

The calculated temperature for each node (as defined in Table 1) at selected instants of time are shown in Figures 4-6. Figure 4 depicts the temperature profiles at 10 time steps of 5 milliseconds each.

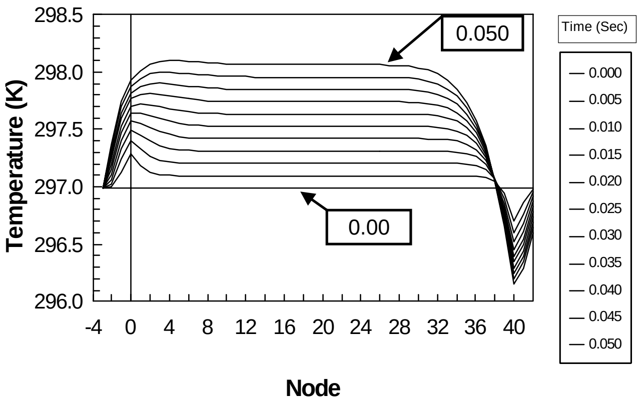

Fig. 4 Temperature profiles during first 50 mill-seconds of cool-down, Current = Imam

It is evident that the main body of the TE pellets is heated (even the hot junctions adjacent to the "infinite" heat sink) but the Peltier cooling is clearly overcoming Joule heat at the localized area near the cold junction. It is also clear that the delta-T between the main body of the TE pellet and the cold junction interface is considerably larger than that between the heat sink and the cold ceramic plate. This was intuitively obvious but the cool-down speed of the cold ceramic plate was slower than anticipated. However, it did close quite well with experiment as illustrated in Figure 2.

Figure 5 illustrates the profiles over a longer time period (one second). It is observed that the Peltier cooling had greater and greater impact on the TE pellet even though Joule heating had significantly heated the main body of the TE pellet 16K above the heat sink temperature. It was also interesting to note that the TE pellet cold junction + copper tab + ceramic nodes rapidly approached a near-isotherm.

The long-term temperature profiles, including the final steady-state temperature profile (96.28 seconds) are shown in Figure 6. Note that maximum heating in the TE pellet occurs in approximately 2.4 seconds. However, Peltier cooling eventually overcomes all but the nodes very close to the hot junction. It is also interesting to note that the TE pellet hot junction runs 2-3K warmer than the heat sink. This fact, of course, must be accounted for in order to accurately model TE module performance. Finally, the accuracy of the model is further verified by the observed 60K delta-Tmax that one would expect for a TE module operated in dry nitrogen from a 297K heat sink. The cold side temperature of 237K represents the lowest possible temperature for steady-state operation representing the baseline temperature from which pulsing enhancements were measured.

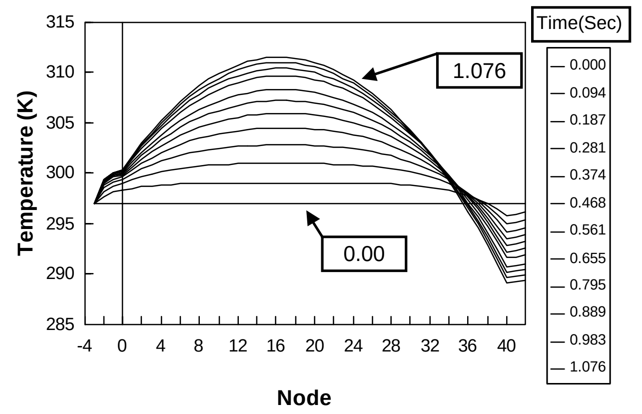

Fig. 5 Temperature profiles during first second
Current = Imax

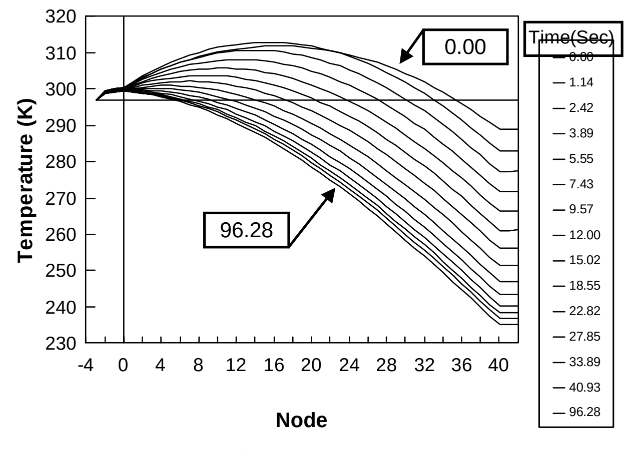

Fig. 6 Temperature profiles until stabilization,
Current = Imax

High-Current Pulse Cooling

Starting from the maximum steady-state cooling condition (the curve labeled 96.28), the current was stepped upward from Imax=3 amps in accordance with that shown in Figure 7. Obviously, if one waited until stabilization, the cold junction would be warmer than the "baseline" temperature. However, for the first few 10ths of a second, the cold junction becomes cooler.

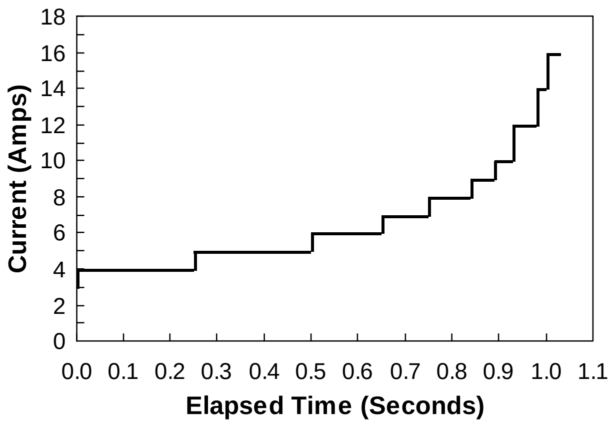

Fig. 7 Current applied to TE module after DTmax

This fact is illustrated by the profile data shown in Figure 8 and the lower curve shown in Figure 9. Once the delta-T enhancement began to maximize (and fall off if left in that condition), the current was stepped up to 5 amps. This process was continued by sequentially increasing current whenever each enhancement appeared to maximize.

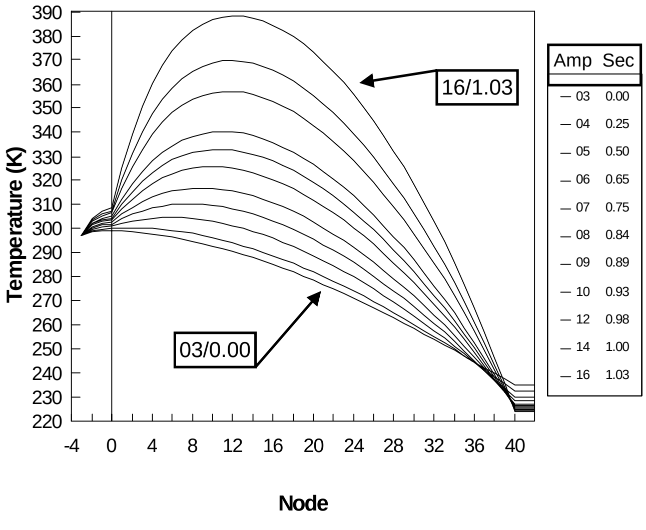

Fig. 8 Temperature profiles during current pulse.

Clearly, from Figure 8, the main body of the TE pellet heats up but the cold side gets colder with each current step. This process was repeated, but this time, neglecting the mass of the tab and ceramic. This case yielded a 16K enhancement over delta-Tmax. See Figure 9.

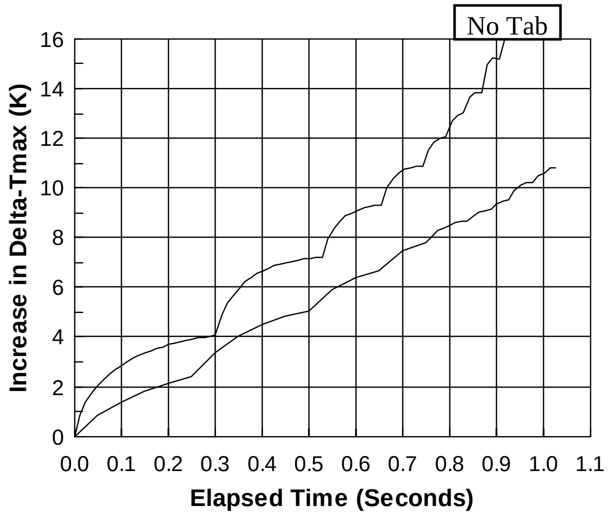

Fig. 9 Delta-T enhancement via pulsing

Conclusions

A finite element thermal model for accurately calculating the fast transient performance of a TE module has been developed. It was used to examine some possibilities for cooling enhancement via pulsing as suggested over 35 years ago. It was concluded that, indeed, enhancement is achievable but it is of such short duration it would have very limited application. Nevertheless, if a low-temperature infra-red "snapshot" is ever needed, this technique could be used to boost the cooling possibly more than 15K. Actually, no attempt was made to optimize the high current pulse waveform. Therefore, it may be possible to achieve even higher delta-T enhancements that the calculated 16K case produced quite arbitrarily. Finally, the model used for these calculations can be applied to the pulse cooling concept originally conceived by Reich[1]. A possible configuration is shown in Figure 10.

Initially, the removable cold tab is thermally and electrically in contact with the N and P TE pellets. This not only completes the electrical circuit but also makes thermal contact with the TE pellet cold junctions. Now, a larger-than-Imax current is applied and the tab is momentarily cooled as described above. However, instead of ever-increasing the current, the cooled tab is removed and isolated (see lower sketch of Figure 10). While it "thermally coasts", the excess heat build-up in the TE pellets is conducted into the heat sink and dissipated. As soon as the TE pellet is thermally stabilized, the process can be repeated and the electrode receives another cooling "pulse". This is just a concept at this time but the means for studying this possibility has now been established.

References

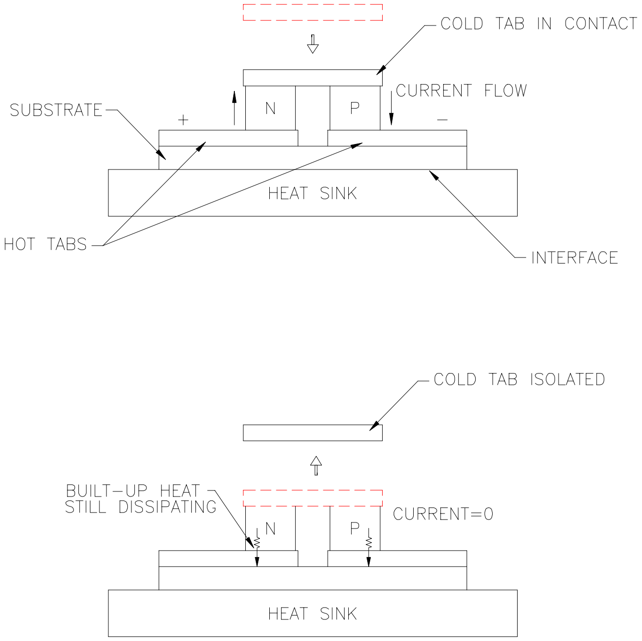

Fig. 10 Pulse TE cooler configuration

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