AN ELECTRONIC TEMPERATURE CONTROLLER FOR THERMOELECTRICS WITH VARIABLE HEAT SINK RESISTANCE

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ABSTRACT

A temperature control circuit has been developed for a thermoelectric cooling system with a variable heat sink temperature. This design was developed for a thermoelectrically cooled helmet, but has more general application.

A PTC (Positive Temperature Coefficient) resistor is utilized to monitor heat sink temperature, supplying a feedback signal to the temperature control circuitry. This signal level is used to automatically adjust the power as the heat sink temperature varies. This temperature controller design eliminates heat sink runaway and can be "fine-tuned" for optimum cooling for whatever temperature the heat sink may be. This design would be applicable to any system where heat sink thermal runaway is required, or a fast cool-down is required using a heat sink designed for transient operation.

INTRODUCTION

Thermoelectrics are a very effective means of providing active cooling especially where versatility and temperature control is important. The typical method for controlling a thermoelectric cooling system is to install a temperature sensor in thermal contact with the cold side of the system, or better yet, the actual item to be cooled. However, there are several applications where the maximum net cooling or maximum cool-down speed is desired.

This can be accomplished by applying maximum power to the TE system. "Maximum power", as referred to herein, is the power level which provides the maximum net cooling effect. This ia a well-known value for an infinite heat sink, but the maximum power level is a function of the "softness" of the heat sink, or, how the heat sink varies with temperature for a given heat applied. For every given TE module, Buist[1] has shown that the maximum power diminishes rapidly with increasing heat sink resistance. Consequently, the maximum power will vary as factors which affect heat sink performance vary, such as air speed, for example.

The particular case studied in this paper is a temperature controller for a TE cooled safety helmet such as worn by motorcyclists or race-car drivers[2]. This case was especially complicated because the velocity of air flow over the heat sink can vary dramatically from 0 mph, when the vehicle stops, to racing speeds over 100 mph. In effect, this changes the heat sink resistance as a function of vehicle speed. Moreover, in the case of a NASCAR where the racing automobile has open side windows, the air movement over the heat sink is quite turbulent and unpredictable yielding an equally unpredictable heat sink resistance.

It was realized that a method should be employed to monitor heat sink temperature and provide feedback to the temperature control system. This signal could subsequently alter the power level to the thermoelectric cooling system for that particular condition, or temperature, of the heat sink. As a consequence, the maximum net cooling for any heat sink condition, turbulent air, rainy weather or whatever, will instantaneously and automatically be applied. The resultant from this is that no matter what the wearer may do, ride a vehicle, run, walk or even stand still, he can be assured of the maximum cooling effect under each of these conditions.

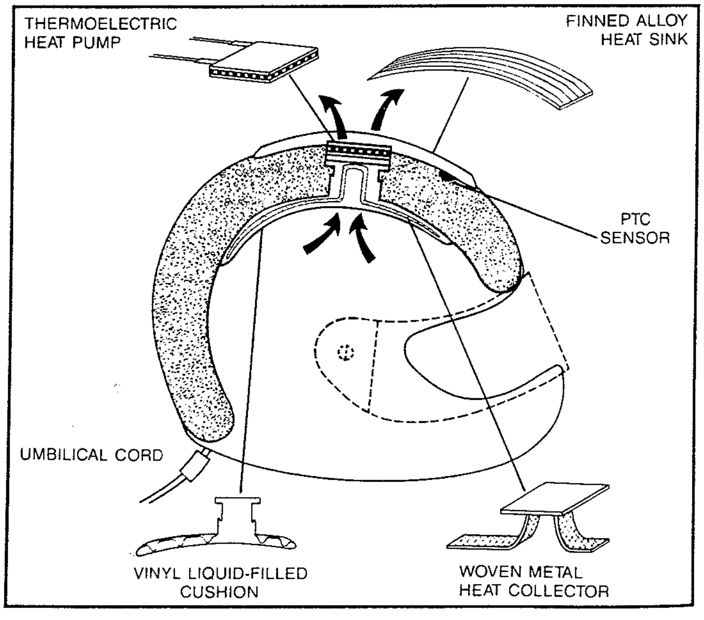

Figure 1. The helmet cooling system.

THEORY OF OPERATION

The major components of the cooling and control system are shown in Figure 1. Heat is extracted from the cooling cushion by the thermoelectric module and dissipated into the outboard heat sink. This "waste heat" is then dissipated into the air in varying degrees depending on the air flow. A PTC sensor is utilized to sense the temperature of the heat sink and feed a voltage signal back to the power control circuit. Finally, through proper design of the PTC sensor and power control amplification, the optimum power level is applied to the thermoelectric module.

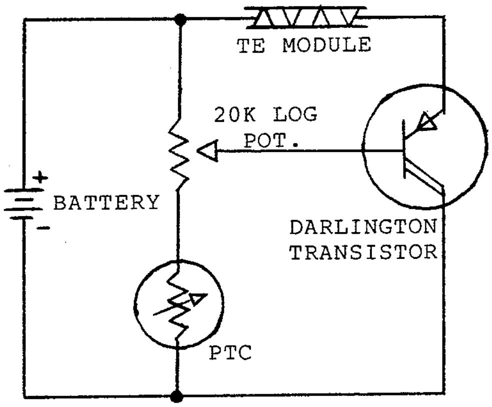

Figure 2. Simplified circuit diagram for TE cooling system controller.

ELECTRONIC CIRCUIT

The circuit diagram of the temperature control system is given in Figure 2.

The control methodology is linear. This circuit is a relatively simple control circuit and fairly inefficient from the power consumption standpoint in the mid-range of control. However, at maximum power there is very little loss of efficiency and the total power consumption in the low control range is so small that the losses are inconsequential. A linear control method was selected primarily because of the need for minimum parts and low cost and yet allowing for the simultaneous interaction of manual and automatic control.

In its basic form, the power from the battery flows through the PNP Darlington transistor which behaves like a variable resistor and consequently varies the current to the thermoelectric module. Due to the fact that this circuit is of a "Common-Collector" configuration, voltage gain is near unity. Therefore, the voltage applied at the base will approximately be the voltage at the emitter, too. There will be only a very small base current and, therefore, most "controlling" current flow is through the PTC and 20K log potentiometer. This current creates an applied voltage to the base of the Darlington dependent on the position of the potentiometer and the PTC resistance at any particular instant.

In essence, the PTC sensor is a thermally sensitive resistor which exhibits a several orders of magnitude increase in resistance over a designated temperature range. Therefore, we can anticipate that the ideal resistance versus temperature curve for the PTC sensor would be essentially flat over a region where sufficient airflow and subsequently sufficiently low temperature heat sink condition exists. We might also anticipate a rapid onset of resistance (with a corresponding voltage increase) at some high temperature to rapidly cut back power to avoid thermal run-away. In this way, the control circuit not only provides near optimum power for any given heat sink temperature, but also serves as a fail-safe, eliminating potentially catastrophic overheating in the heat sink.

EXPERIMENTAL SETUP

An important step in the design of the control system was to determine the "maximum power" condition for several combinations of ambient temperature and air speed. These data would subsequently be used to define the optimum characteristics of the PTC sensor.

The experimental configuration consisted of a sub-assembly composed of a thermoelectric module bonded to a heat sink. The cooling cushion and heat collector shown in Figure 1 were omitted in order to obtain faster stability times and a more accurate determination of optimum conditions. Consequently, temperatures achieved were considerably colder than in actual practice but the data was sufficient to determine the optimum TE voltage vs current characteristics for design of the PTC sensor.

The instrumented sub-assembly was installed in a wind tunnel. A variable fan was used to generate various air flow velocities to the heat sink. All temperatures were measured with small gauge copper constantan thermocouples located at various key thermal nodes of the system. An Omega model FMA-605-V air flow transducer was used to measure air flow. All voltage signals were taken using a PC computer in combination with an 16 bit ICS D/A board. A special computer program was written to process all data and display results in graphical form.

MANUAL POWER-CONTROL TESTS

The results of testing the unit using manually selected power levels are shown in Figures 3 and 4 for still air and 25 MPH air speeds, respectively. The optimum current to the TE cooling system versus heat sink temperature is shown in Figure 5. It was clear that, although a single PTC might be fabricated to meet any one air-flow speed, some trade-offs would be needed to achieve desired performance under all air-flow conditions.

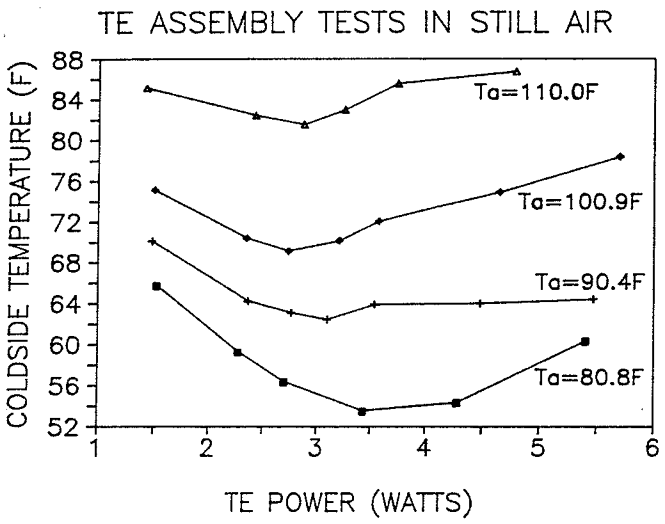

Figure 3. Delta-T tests made via manually controlled power in Still Air.

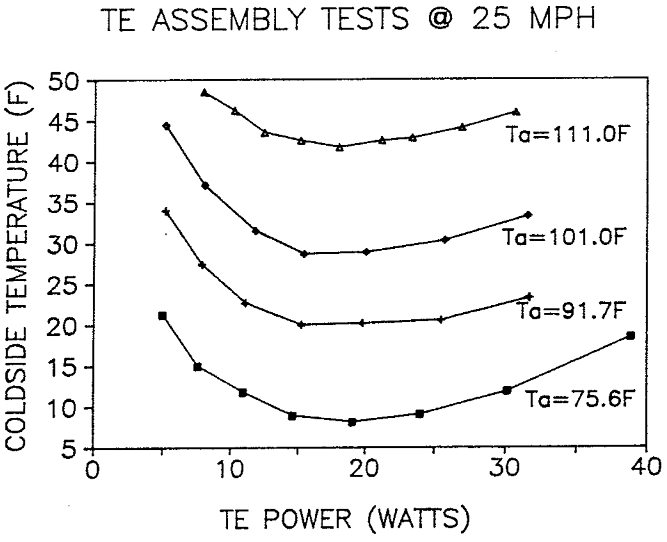

Figure 4. Delta-T tests made via manually controlled power at 25 MPH Air speed.

At first glance of Figure 5, it would appear that a single PTC could not be designed to provide the characteristics needed for more than one air flow condition. That is, the PTC must somehow be sensitive to the air flow speed in addition to heat sink temperature in order to provide two different power levels for a given heat sink temperature <u>at the TE module location</u>.

However, that was indeed accomplished. The PTC was attached to the heat sink but far forward on the heat sink. This location is, of course, still heated by the TE power, but Buist[2] has shown that this spot runs considerably cooler that the TE module location due to preferential cooling of the oncoming ambient air flow. In other words, the heat sink runs more isothermal with no air flow making the PTC warmer for a given TE module power level. All of this results in the desired effect of overall less power applied in still air and increasingly more power applied with increasing air speed.

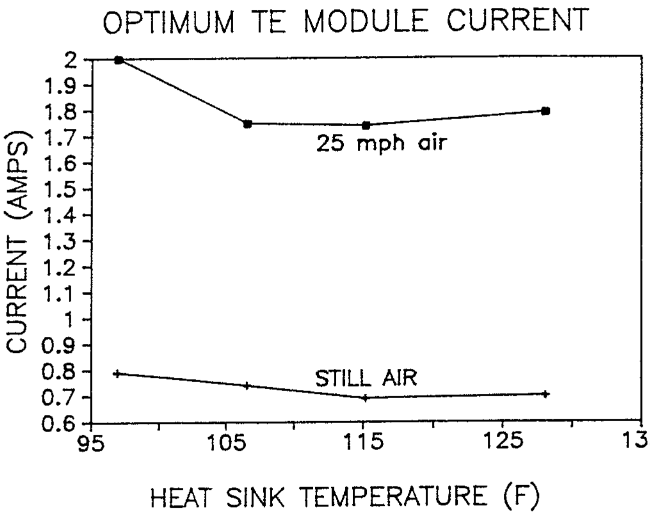

Figure 5. Optimum TE module current versus heat sink temperature.

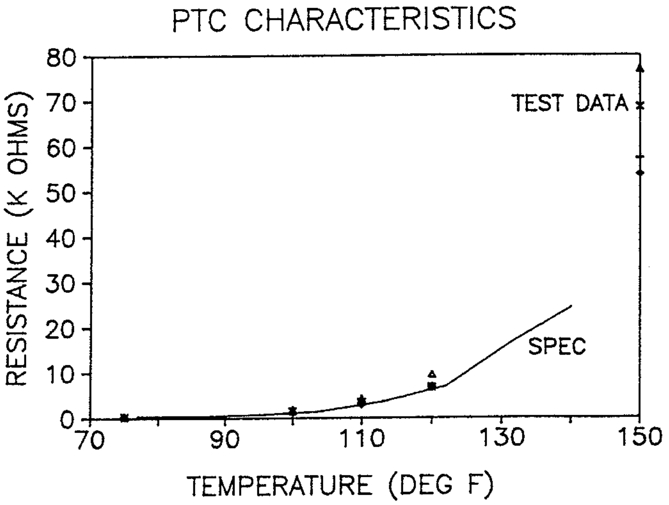

Figure 6. PTC resistance versus temperature.

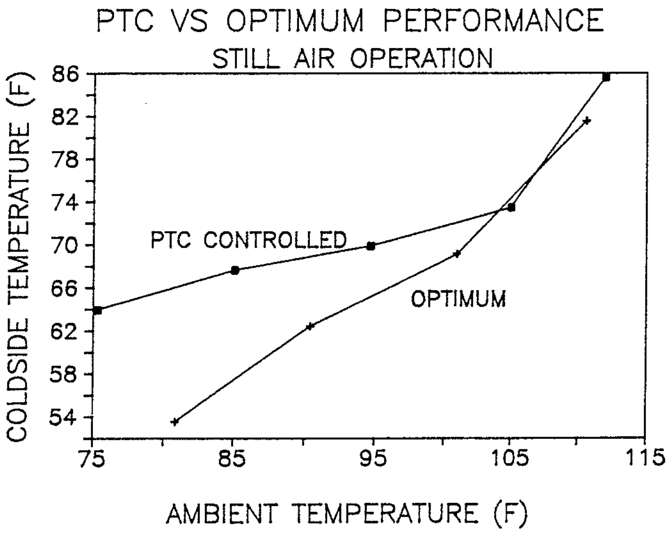

Figure 7. Cooling performance versus ambient temperature for manual and PTC-automated control in still air.

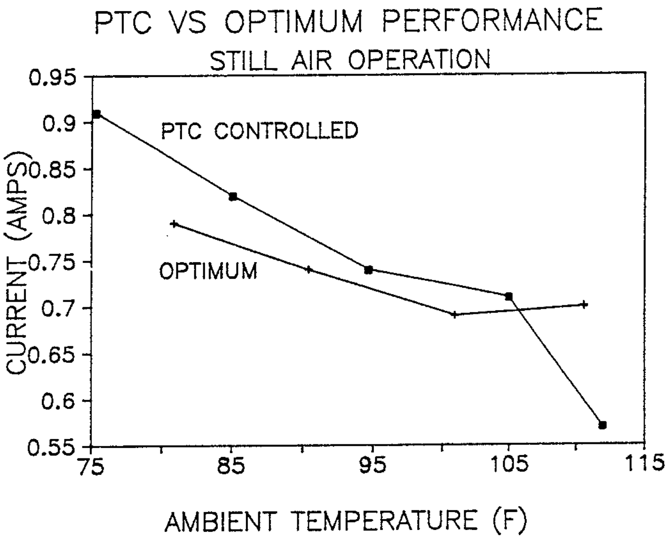

Figure 8. TE module current versus ambient temperature for manual and PTC-automated control in still air.

All of these factors were taken in to consideration and the best resistance vs temperature curve was derived from this data for the PTC sensor. These data plus an acceptable tolerance range are illustrated in Figure 6. These specifications were provided to Sensor Laboratories of California who fabricated a custom PTC with the resulting characteristics also shown in Figure 6 for comparison.

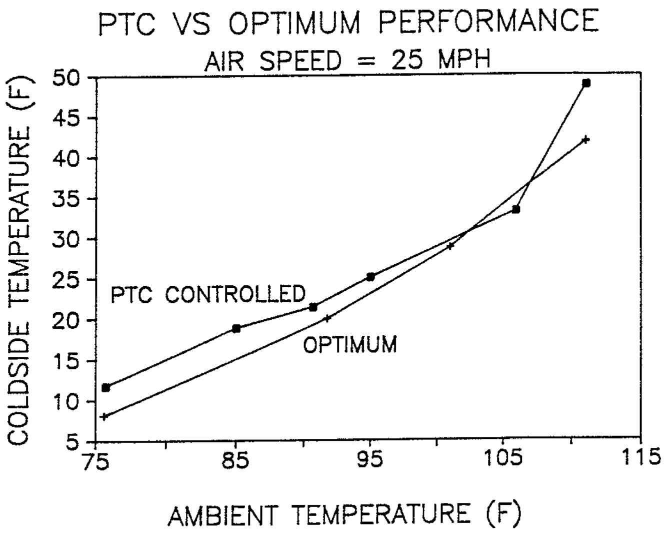

Figure 9. Cooling performance versus ambient temperature for manual and PTC-automated control in 25 MPH air.

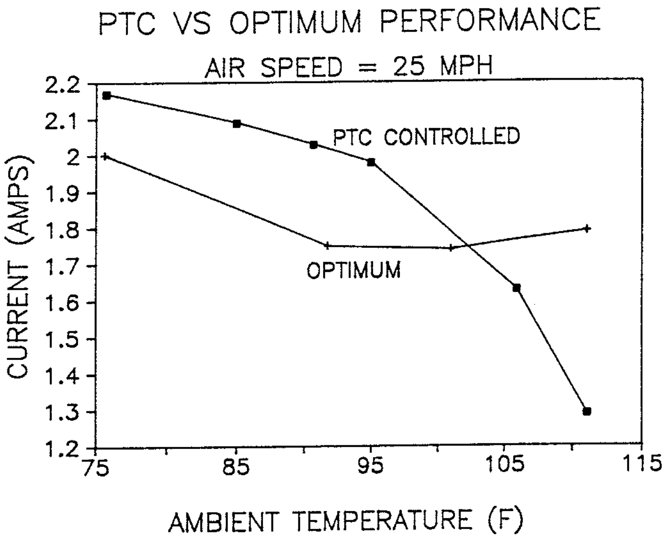

Figure 10. TE module current versus ambient temperature for manual and PTC-automated control in 25 MPH air.

AUTOMATIC POWER-CONTROL TESTS

A controller was fabricated utilizing the circuit diagram shown in Figure 2 and the actual PTC sensor characteristics of Figure 6. The PTC was installed into the system as shown in Figure 1 and tests made at various combinations of ambient temperature and air speed. These results, together with the manually determined maximum power conditions, are shown in Figures 7 and 8 for still air and Figures 9 and 10 for 25 MPH air speed.

Notice that the optimum power level is achieved for an ambient of about 100°F for both air flow conditions. The fall-off in the PTC-controlled cold side temperature above and below this ambient is a result of the crossing of the PTC vs manually controlled current levels shown in Figures 8 and 10.

DISCUSSION

The control unit described herein was designed to perform several functions. First and foremost was the elimination of catastrophic heating due to thermal run-away of the heat sink. Consequently, one characteristic of the PTC was that it must have a rapidly increasing resistance at high temperatures to rapidly cut back power to the system and eliminate a high temperature build-up in the heat sink. Clearly, this fail-safe objective was achieved.

Ultimately, the power to the TE modules was controlled by the temperature of the PTC. The experimentally determined optimum power level was very complicated because it was not only dependent on the hot side of the TE module but also on the air flow rate. Nevertheless, a spot on the heat sink was discovered to have temperature dependence on both of these factors in a desired sense. The resultant was that the automatic PTC controlled cooling performance of the TE system was actually better than one might first expect from initial examination of manual test results. In fact, it provided cooling performance within a few degrees F of optimum for all flow rates in the 95-105°F ambient range - where maximum cooling would be desired most.

Certainly, an exotic multiple sensing system could be designed to provide more nearly optimum power under all conditions, but it would also be more expensive, less reliable and certainly less commercially significant.

CONCLUSIONS

The special application considered in this paper was to provide a means of automatically controlling the power of a thermoelectric cooling system to yield maximum net cooling for a heat sink whose performance can vary. Although further "fine tuning" of the PTC Sensor is possible, the practicality of producing a low cost but effective system has been established. It should be pointed out, however, that the key to this design is the temperature dependent nature of a PTC. Its characteristics must be chosen or designed for a given system. That is, a unique PTC will exist for each unique thermoelectric system. Of course this method is not limited to linear control regimes as PTC's could be used in other types of temperature control circuits such as switching proportional designs, for example.

Another expansion of this control methodology is applicable in the area of fast cool-down applications particularly where transient type or phase-change material heat sinking methods are employed. Here, the PTC could be used to provide maximum net cooling yielding maximum cooling speed at every instant during cool-down even as the heat sink warms.

REFERENCES

[1] R.J. Buist & P.L. Townsend: "Thermoelectric Cooler Performance Corrections for Soft Heat Sinks", Proceedings of the "6th International Thermoelectric Energy Conversion Conference", March, 1986.

[2] "The Thermoelectrically Cooled Helmet"; R.J. Buist & G.D. Streitwieser. Proceedings of the 7th International Conference on Thermoelectric Energy Conversion", March 1988.