A STUDY OF THERMOELECTRIC DESIGN CRITERIA FOR MAXIMIZING COOL-DOWN SPEED

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Summary

The transient cool-down performance was analyzed for a modified two-stage Marlow Industries Model MI 2020 thermoelectric (TE) heat pump. A forward time differencing computer technique was imposed on a finite element thermal model of the thermoelectric heat pump to calculate the transient behavior of the device. Analysis of the computer simulations was made by comparison with steady-state optimization criteria. Some noteworthy conclusions were drawn providing guidelines for optimization of TE heat pumps for cool-down speed.

A two-stage thermoelectric design was fabricated and its transient performance was tested to validate computer simulations.

Introduction

The major emphasis in the design of thermoelectric cooling devices has been to accomplish a given cooling task while minimizing electrical power input. This minimization of input power inherently results in thermoelectric designs which have slow thermal response. Consequently, low power coolers for fast-cool applications require further considerations for improving cool-down speed through design rather than simply increasing cooler input power.

Thermal Model Description

The basic two-stage thermoelectric cooler investigated was a standard Marlow Industries Model MI 2020 heat pump. A photograph of the MI 2020 is shown in Figure 1.

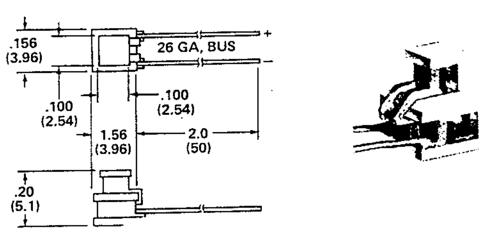


Figure 1
Two-Stage Thermoelectric Heat Pump, Model MI 2020

The function of the cooler was to cool a .118" x .118" x .008" alumina substrate mounted onto the top ceramic. Additional thermal masses on the top ceramic included metallization, solder and a glass bead type thermistor with platinum-iridium leads.

The base of the heat pump was assumed to be mounted on an infinite heat sink. A vacuum environment was assumed to surround the unit during operation. Passive thermal radiation loading from the environment, in addition to thermal conduction loading from the substrate and thermistor leads, was accounted for. No active thermal loading was present.

A finite element thermal model of the two-stage thermoelectric cooler, the substrate, and the surrounding thermal environment was generated by computer analysis. The various thermal resistances and capacitances were analyzed and simulated in the computer thermal model. The transient behavior of the actual thermal model was then approximated by a forward time differencing technique simultaneously imposed on each node of the finite element thermal model. The well known thermoelectric equations and standard heat transfer techniques were utilized to predict the transient heat fluxes and temperatures within the actual thermal model.

Design Requirements

The goal of the investigation was to design a fast-cool, two-stage thermoelectric device capable of reaching a cold side temperature, T_C, of -20°C from a base temperature, T_H, of 65°C in minimum time after electrical power application. To achieve this goal the investigation was focused on the three factors which have a major impact on the transient thermal performance, and consequently the design, of any fast-cool thermoelectric. They include:

(1) Minimization of the thermal mass of both the heat pump components and the cooled thermal load so as to minimize the amount of stored energy which must be extracted for a given cooling effect;

(2) Minimization of all thermal resistances connecting the various components throughout the heat pump, and particularly that connecting the cooled load to the heat pump itself. This will provide the most efficient heat flow paths from the cooled load to the heat sink;

(3) Maximization of the time averaged heat pumping capacity, $\overline{Q}_C$, of the thermoelectric during the cool-down period, represented by

$$\overline{Q}_C = \frac{1}{t_C}\int_0^{t_C} Q_C(t)\,dt \qquad (1)$$

where t = time

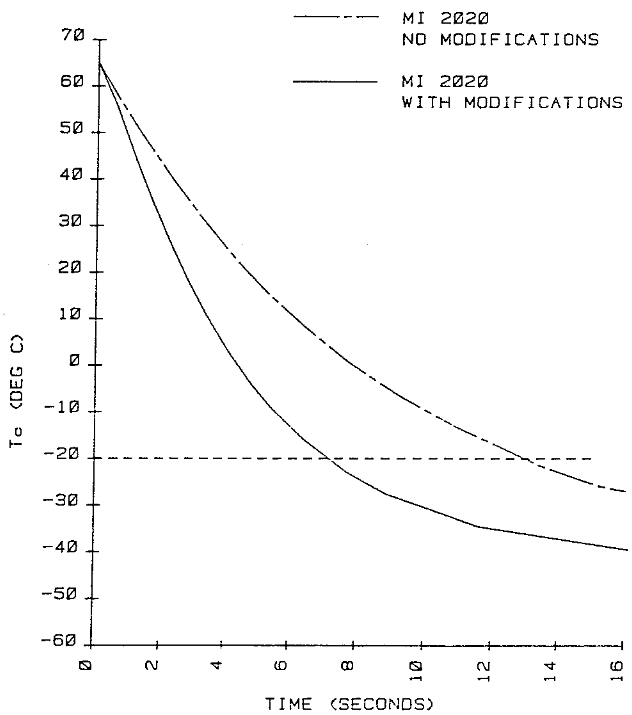
t_C = time to achieve final cold side temperature

$Q_C(t)$ = instantaneous heat pumped at cold side of TE heat pump.

Minimization of thermal mass and thermal resistances were addressed initially since these are fundamental to designing fast thermal response in any thermal system. Modifications were made subject to practical limitations. The transient performance of the modified MI 2020 is displayed in Figure 2. Its transient performance exhibited significantly faster cool-down speed compared to the conventional designs. Therefore, these modifications were incorporated into the final design.

FIGURE 2

TRANSIENT COOL DOWN OF MI2020 WITH AND WITHOUT THERMAL MASS MODIFICATIONS



Heat Pumping Capacity Maximization

Although design modifications for improving factors (1) and (2) are intuitively clear, the procedure for maximizing $\overline{Q}_c$ is considerably more complex. This is due to the fact that $Q_c(t)$ varies considerably during cool-down. The typical transient behavior of $Q_c(t)$ is illustrated in Figure 3. Note that the shaded region represents the total energy, E, extracted by the cooler from its top cold surface during the time increment t_c and is equal to the integral portion of equation (1).

The criteria for maximizing heat pumping capacity for any given steady-state condition are well known. The process can be reduced to optimally selecting Iλ and R; where I is the electrical current, λ is the TE pellet length/area and R is the ratio of thermocouples from each stage to its adjacent, next higher stage. Both of these parameters depend only on the boundary temperatures of the TE heat pump. They can be selected to produce maximum heat pumping capacity for any given base temperature and ΔT, temperature differential from base to top.

FIGURE 3

INSTANTANEOUS HEAT PUMPING CAPACITY VS. TIME DURING TRANSIENT COOL-DOWN PERIOD

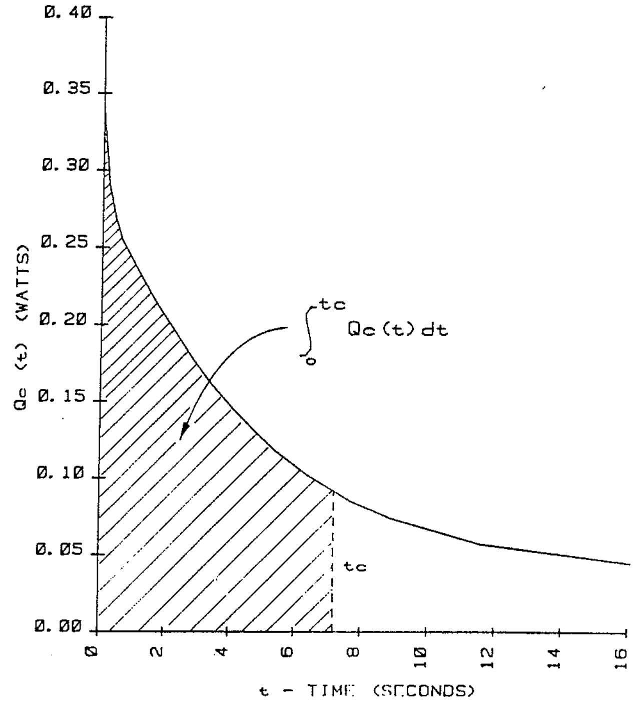
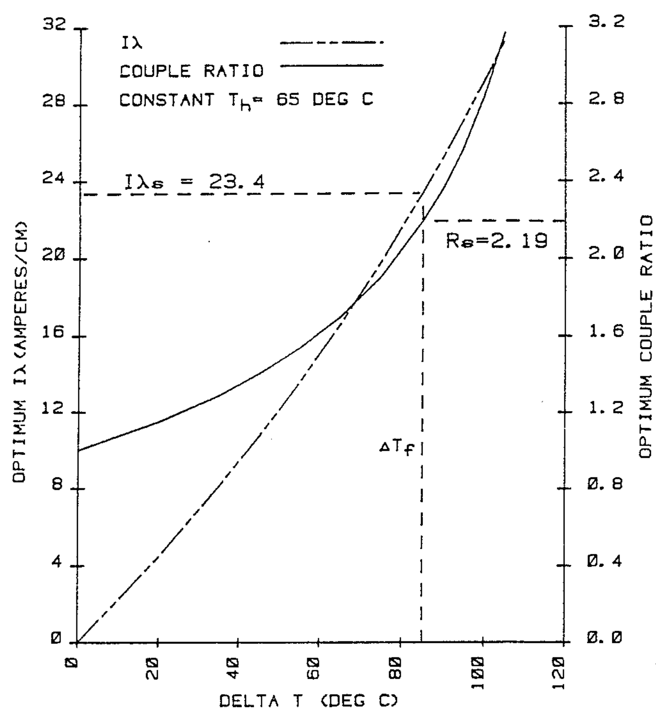


FIGURE 4

OPTIMUM STEADY STATE Iλ & COUPLE RATIO VS. ΔT FOR A TWO STAGE THERMOELECTRIC HEAT PUMP



The problem in maximizing the dynamic heat pumping capacity in transient design is that ΔT starts at zero and increases to a final ΔT, ΔT_f. The optimum values for $I\lambda$ and R throughout this excursion are shown in Figure 4 for steady-state conditions. The values at ΔT_f, $I\lambda_s$ = 23.4 amps/cm and R_s = 2.19, represent the quantities one would select to optimize steady-state performance for the final ΔT. However, a significant variance exists throughout the cool-down period and it is not obvious which $I\lambda$ and R will maximize $\overline{Q}_c$.

$I\lambda$ Optimization

Calculations of $\overline{Q}_c$ were made for various values of $I\lambda$ and holding couple ratio to R_s. The results are illustrated in Figure 5. It is interesting to note that, although the optimum steady-state $I\lambda$ varied from zero to $I\lambda_s$, the value that produced the maximum $\overline{Q}_c$, $I\lambda_T$, was approximately 55% higher than $I\lambda_s$. The symmetry of this curve suggests that the penalty for being above or below $I\lambda_T$ is equal, thus favoring the left side of the peak from power input considerations.

Couple Ratio Optimization

Calculations of $\overline{Q}_c$ were made holding $I\lambda$ to $I\lambda_T$ and varying R around R_s. The results are illustrated in Figure 6. The value that maximized $\overline{Q}_c$, R_T, was very close but slightly ($\approx$5%) below R_s. Unlike $I\lambda_T$, the value R_T fell within the steady-state range of values illustrated in Figure 4.

Couple ratio is directly associated with the magnitude of a cooler's ultimate steady-state ΔT. Thus, as R is decreased significantly below R_s, a point will be reached where it is no longer possible to achieve ΔT_f. This essentially is why the curve drops rapidly to the left. The fall-off to the right is less severe and is due primarily to the proportionally smaller top stage and thus lesser $Q_c(t)$.

Experimental

A special cooler, Model SP 1154, was designed maintaining $I\lambda$ and R as close as possible to $I\lambda_T$ and R_T, respectively. Compared to the original MI 2020, one thermoelectric couple was added to the top stage giving the cooler an R of 7/3 = 2.33 thereby approaching closely the value for R_T.

Test results are shown with the computer simulation in Figure 7. This data illustrates not only the progress achieved in overall cool-down speed from Figure 2 but also serves to validate the computer simulations.

FIGURE 5

TIME AVERAGED HEAT PUMPING CAPACITY VS. NORMALIZED $I\lambda$ FOR R = 2.19

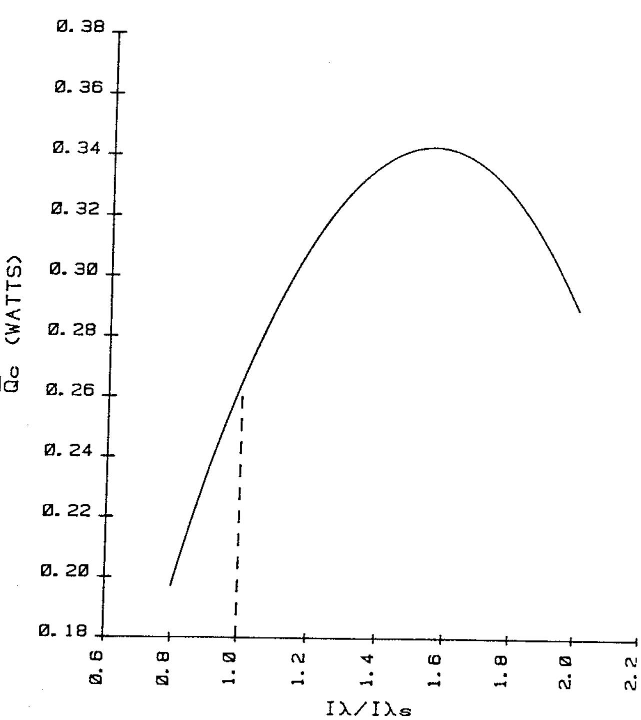
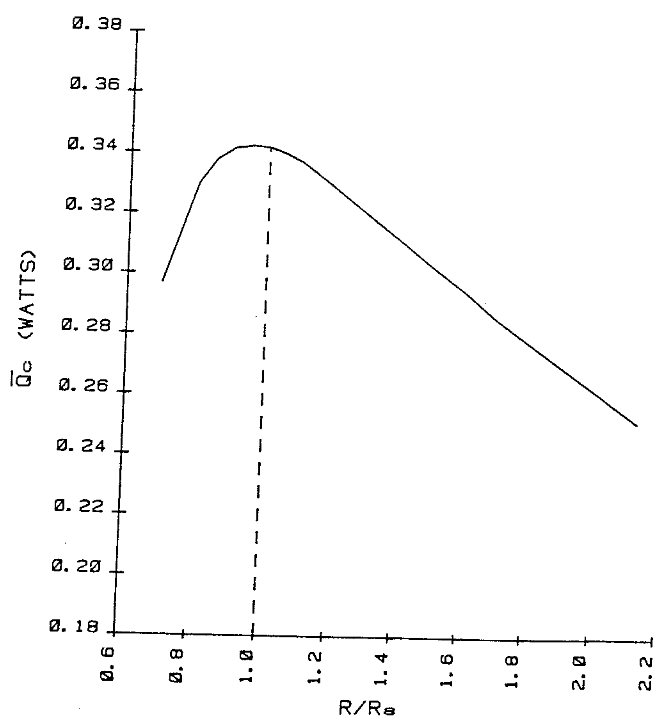


FIGURE 6

TIME AVERAGED HEAT PUMPING CAPACITY VS. NORMALIZED COUPLE RATIO FOR $I\lambda$ = 36.2 AMPS/CM



Conclusions

Analysis of a small, low-power two-stage thermoelectric heat pump was made in order to modify it to improve cool-down speed. The following procedure was derived for re-defining the thermoelectric design parameters derived from steady-state optimization:

1. Determine the optimum efficiency, steady-state design parameters for the final ΔT: $I\lambda_s$ and R_s.
2. Adjust R_s downward by 5%.
3. Adjust $I\lambda_s$ upward by 55%.

The above procedure applied to the specific case studied improved $\overline{Q}_c$ and thus cool-down speed by 29%.

Further study is underway to test the above procedure for general applicability as a guideline for cool-down speed design optimization.

FIGURE 7

ACTUAL EXPERIMENTAL TRANSIENT PERFORMANCE OF SP 1154 VS. COMPUTER SIMULATED TRANSIENT PERFORMANCE