

2016

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Mao, Jia-ni; Du, Jun-yan; Wang, Shi-fei; Zhou, Jing-wei; and Wang, Yu-gang, "The Transient Supercooling Enhancement For A Pulsed Thermoelectric Cooler (TEC)" (2016). *International Refrigeration and Air Conditioning Conference*. Paper 1773.
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The transient supercooling enhancement for a pulsed thermoelectric cooler (TEC)

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ABSTRACT

Once TEC excited by a high-voltage pulse, there exists a transient thermoelectric supercooling effect, which can be enhanced by keeping on increasing the Peltier cooling effect to compensate for the negative self-heating from the Joule heating effect and Fourier heat conduction effect. After superimposing an additional voltage pulse over a steady-state reference value in a short time scale, abrupt temperature drop will be produced by several more degrees below the steady-state cold junction temperature, and even against the earlier arrival of excessively Joule heating-dominated heat accumulation at cold junctions. Most previous work mainly focused on the minimum supercooling temperature or the maximum supercooling capacity achievable for a conventional thermoelectric module based on bismuth-telluride alloys. Nevertheless, three key process control parameters, with respect to the system response time for the supercooling temperature, the holding time of the supercooling state and the recovery time back to the reference steady state, were almost overlooked. In this work, analytical solutions on the optimization of pulse shapes upon the thermal-electrical conversion mechanism were investigated, for exploring the dynamic behaviours of the main thermoelectric effects respectively on the transient response for the cold junction temperature drop and the supercooling enhancement degree during pulsed operation. Furthermore, by the combinatorial optimization of the above process control parameters and pulse shapes, the optimal characteristic parameters for TE devices pulsed with supercooling are derived. The results indicate that, the monotonically increasing quarter-wave pulse shapes (especially the quarter-sine voltage excitation), combined with the optimized pulse amplitude of 2.5 times and pulse duration of 10s, show a greater advantage to achieve high sensitivity and stability, and require less energy to reach the minimum temperature. Also, it has contributed to an increase on the effective Figure-of-merit ratio of ZT_{eff} / ZT from the previous value of 1.76 to a maximum of 2.06 (namely improved by 17%), as well as smaller temperature differences between hot and cold junctions. The discussions can be served as a theoretical basis for a pulsed TEC to improve the additional supercooling effect, and also prevent extensive heating of the material after the minimum temperature is reached, which may be attractive for compact thermal system to come up to the localized cooling level of high power packaging.

Key words: Thermoelectric cooler (TEC); Dynamic behaviour; Optimization; Supercooling effect; Pulse-excitation voltage

1. INTRODUCTION

With environmental protection and energy consumption being as the focus of global attention, to find out a way of energy conversion with high efficiency, low-cost operation, and environmental friendly has become an urgent need for the current energy subject. Especially for the continuous miniaturization and packaging density of electronic devices, the problem of heat dissipation results in increasing thermal management challenges and negative influence on its performance, reliability and working life. Although the conventional passive cooling

technologies are widely applied, such as air forced convection, liquid cooling, thermosyphon with phase change and heat pipe cooling techniques, they are reaching the limits in effectively cooling the active region with instantaneously larger magnitude of temperature drop for high power electronic packages. So, compared with vapor compression and absorption cooling systems, the use of thermoelectric cooler (TEC) is an active solid-state cooling technique of compact size, silent operation, non-refrigerants, non-mechanical drive components and precise control, of which the application potential will continue to expand. Recently, the development in the integration of TE micro-coolers into laser diode (LD) make it possible to act as the precise temperature control near the high heat flux producing regions of optoelectronic packages, where the laser wavelength and power output have large dependence on junction temperature. Obviously, there has significant potential that such a thermoelectric cooler can achieve great localized cooling capacity to come up to the cooling level of high power packaging.

Much work has been conducted in the past to study the cooling performance of Bi_2Te_3 -based TEC both theoretically and experimentally in nonlinear steady state. It turns out that any thermocouple as an energy converter can be expressed in terms of Peltier effect, accompanied by the irreversible effects of Joule heating effect and Fourier heat conduction effect. During the thermoelectric cooling process, Peltier cooling is an interface effect that occurs instantaneously closer to the top surface of the cold junction, while Joule heating and Fourier heat conduction are the volumetric effects that need to take more time to diffuse heat throughout the volume of the thermoelectric elements and affect the temperature at the cold side subsequently. Thus, if a sudden change of a large magnitude is superimposed above the original steady-state optimal current value during the cool-down period, a transient cold spike will appear at the cold junction [1, 2, and 3].

Based on the interesting phenomenon of transient thermoelectric cooling behavior, various pulsed operation modes of TEC have been investigated to keep on increasing the Peltier effect to compensate for the Joule heating and Fourier heat conduction effects arriving at the cold junction, and enabled the cold junction of TEC to obtain transient temperature depressions that are significantly above the maximum cooling capacity at the steady state, or made cooling efficiency increased dramatically under the smaller temperature differences between the hot and cold junctions [4, 5, 6]. Using this idea, Snyder et al. [7] established the semi-empirical relationships of the basic parameters for pulsed thermoelectric cooling effect, and studied the influence of pulse amplitude and steady-state reference temperature on characteristic time and temperature of pulsed supercooling. Thonhauser et al. [8] presented the optimization analysis on the pulsed supercooling for several pulse shapes that required less energy and resulted in an increase of efficiency, and also investigated the influence of the pulse shape upon the cooling mechanism. Chakraborty et al. [9] focused on the theoretical modeling of a pulsed TEC using the classical thermodynamic framework of the Gibbs law and depicted temperature-entropy (T-s) methodology to map for the energy flow by transient operation. Zhou et al. [10] showed the analytical solution of pulsed operation with the boundary condition of ignoring the thermal load at the cold junction of TE element, and then achieved the maximum cooling temperature significantly with optimal inhomogeneous thermoelectric materials, together with the validation by the finite-difference time-domain simulation.

However, most previous work of the transient thermoelectric effect mainly focused on the minimum temperature achievable. As well known, the transient thermoelectric supercooling performance is tightly correlated with the pulsed operation forms, geometry parameters of thermocouples, electrical (thermal) contact resistance and the heat transfer performance of heat sinks coupled with TEC, etc. But the issues of the response time to reach a desired temperature, holding time of supercooling state and the recovery time back to the steady state, as well as the boundary effect on the thermal-electric transmission due to the subsistent thermal and electrical contact resistance at the interface of junctions, were overlooked. And above all, there is an inherent disadvantage of the

analytical method by the classical steady model to predict such dynamic behavior as transient thermoelectric effect of pulsed cooling mode, which is only applicable to the traditional steady-state operation of TEC driven by direct current. In this paper, we systematically investigated the analytical solution for the supercooling with a finite cold surface thermal load and contact resistance calculated during transient voltage pulse superimposed on the steady-state condition, for exploiting the coupling relationship among Peltier, Joule heating and Fourier heat conduction effects in the short time scale, along with the influence on refrigerating characteristics, and then discussing the optimal pulse mode for TE devices. Since affected by various kinds of unstable factors such as external environment and energy dissipation between current carrying parts, etc, the system current cannot be quickly stable against a pulsed current shock, but remains a period of fluctuation near the design value. And then, to guarantee the precise control for the pulsed cooler and reduce the experimental error, a testing power supply was designed composed of high frequency pulse generator as the controlled voltage pulse signals. As a result, the transient supercooling performance under different pulsed voltage modes was controllable and tested easily.

II. NUMERICAL METHODS

The system is fully determined by the corresponding heat equation and its boundary conditions. Considering to accurately defining the heat flow along the thermocouple arm, the theoretical analysis can be approximated into a one-dimensional problem with constant material properties. Due to symmetry, it is sufficient to analyze only one side of of a thermoelectric cooler utilizing an n- and p-type material. Hence, the corresponding energy conservation equation is formulated as Eq. (1):

$$\lambda \frac{\partial^2 T(x, \tau)}{\partial x^2} + \frac{I^2}{A^2 \sigma} = \rho c_p \frac{\partial T(x, \tau)}{\partial \tau} \quad (1)$$

Here, $T(x, \tau)$ is the temperature distribution with $x \in [0, L]$, $a = \lambda / \rho c_p$ is the thermal diffusivity, λ is the thermal conductivity, S is the Seebeck coefficient, and σ is the electrical resistivity, along with the cross-sectional area A and the arm length L of the thermocouple. The two terms in the left side of Eq. (1) show the heat conduction due to a temperature gradient, and Joule heating produced by the presence of electrical current. As well, the Thomson heat term due to the thermo-electromotive force, determined by the product of Seebeck coefficient and temperature gradient, also can be considered as the internal heat source in the energy balance equation only if the Seebeck coefficient is calculated as temperature dependent and driven by high current in the system, or else, Thomson heat term makes negligible corrections for the equation. To simplify the calculation, our study only focuses on the various shaped pulse forms, and consequently neglected the temperature dependency of the material thermal properties in the analytic process, where the transient thermoelectric effects with minimum temperature achievable did not change drastically along with the temperature action effect of the material-specific constants (especially for the low ZT materials) by the previous calculations. Furthermore, assume that there is a finite thermal load of Q_a attached to the cold junction ($x=0$), and the hot side ($x=L$) is maintained at a constant hot side heat sink temperature, together with the simplified boundary conditions in Eq. (2) and Eq. (3):

$$T(x=L, \tau) = T_h \quad (2)$$

$$-\lambda \frac{\partial T(x, \tau)}{\partial x} \Big|_{x=0} = \frac{SIT(L, \tau)}{A} - Q_a \quad (3)$$

And the initial condition is:

$$T(x,0) = T_a \quad (4)$$

Under the unsteady conditions, the variable current due to the thermo-electromotive force between the junctions of TE element can be defined as Eq. (5):

$$I = (U - S\Delta T)\sigma A/L \quad (5)$$

Here, ΔT is the temperature difference between the cold side and hot side of the thermocouple, and U is the input voltage. Following the energy conservation within a control unit, the transient equation is solved by the finite difference method numerically and a scheme of forward difference in time and centered difference in space is chosen. It can be expressed as Eq. (6):

$$T_n^{(i+1)}(x,\tau) = \left(1 - \frac{2\alpha\Delta\tau}{\Delta x^2}\right) T_n^{(i)}(x,\tau) + \frac{\alpha\Delta\tau}{\Delta x^2} [T_{n+1}^{(i)}(x,\tau) + T_{n-1}^{(i)}(x,\tau)] + \frac{I^2\Delta\tau}{\rho c_p A^2 \sigma} \quad (n = 2, 3, \dots) \quad (6)$$

Coupled with the boundary condition for the cold surface temperature distribution, we can get Eq. (7):

$$T_N^{(i+1)}(x,\tau) = \left(1 - \frac{2SI\Delta\tau}{\rho c_p A\Delta x} - \frac{2\alpha\Delta\tau}{\Delta x^2}\right) T_N^{(i)}(x,\tau) + \frac{2\alpha\Delta\tau}{\Delta x^2} T_{N-1}^{(i)}(x,\tau) + \frac{2Q_a\Delta\tau}{\rho c_p \Delta x} \quad (7)$$

Where n is the space node, i is the time node, $\Delta\tau$ is the characteristic time step, Δx is the characteristic space step. In the expression Eq. (6) and Eq. (7), numerical stability will be achieved when the coefficients of both $T_n^{(i)}(x,\tau)$ and $T_N^{(i)}(x,\tau)$ terms are positive. Besides, the spatial grid needs to set small enough to improve the numerical accuracy in the difference procedure.

In general, the temperature drop ΔT can be related to the figure of merit $Z = 2\Delta T/(T_h - \Delta T)^2$, so that we can calculate an effective figure of merit ZT_{eff} taking into account the supercooling during the voltage pulse, as Eq. (8):

$$\frac{ZT_{eff}}{ZT} = \frac{\Delta T}{\Delta T_{ss}} \cdot \frac{(T_h - \Delta T_{ss})^2}{(T_h - \Delta T)^2} \quad (8)$$

Where ΔT_{ss} denotes the steady-state temperature drop between the hot junctions and cold junctions, by using $\Delta T_{ss} = T_h - T_c$, and $\Delta T = T_h - T_{min}$.

III. METHOD VERIFICATION

To further validate the rationality of numerical results, the arrangement of system assembly and testing points, such as the hot junction temperature T_h , the cold junction temperature T_c , and the polyurethane foam insulation layer temperature T_{jc} , are respectively shown in FIG.1 and FIG.2, which were used to monitor the dynamic temperature variation under 5 non-steady working conditions as shown in FIG.3. Besides, the transient response of cold junction temperature to the abrupt change of step voltage was carried out by a commercial TEC1-12706 cooler of single stage in FIG. 4. Unless otherwise specified, ambient temperature T_a is set as 21°C. Else, the

maximum temperature difference at steady state is $\Delta T_{ss} = 68^\circ\text{C}$, and the recommended optimal voltage

$U_{ss} = 6V$ ($I_{ss} = 2A$) with maximum cooling efficiency during the cool-down steady state.

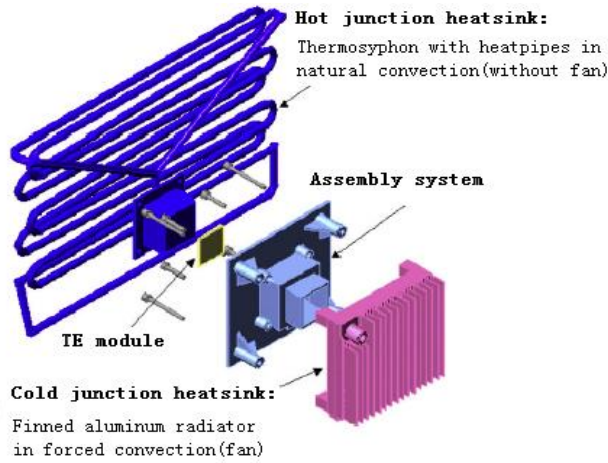


FIG 1. The system assembly of a thermoelectric cooler FIG.2 The arrangement of 3 testing points for dynamic temperature monitoring

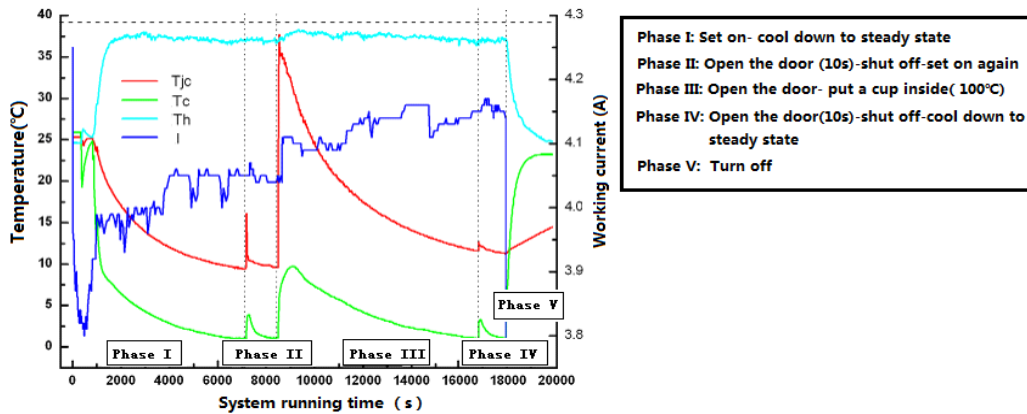


FIG.3. The experimental measurements for the dynamic temperature distribution

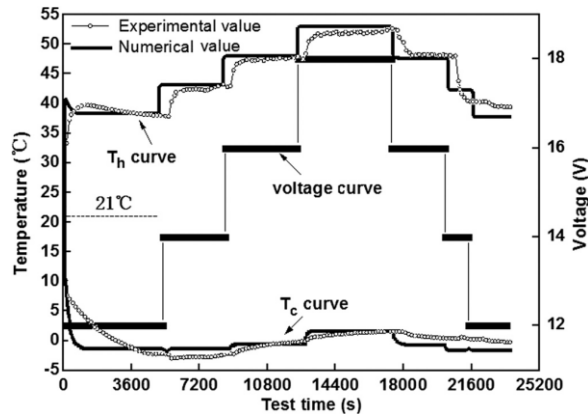


FIG.4. The comparison analysis of numerical results and experimental results on the response of cold junction temperature T_c to the step voltage

As shown in FIG.3, the curves indicate that the cold junction temperature takes slower cooling rate but faster recovery time from the transient cooling state to the next new steady state. When the system power was shut down, it is obvious that the heat flow dramatically transferred backward from hot side to cold side. During the short period of time, the Peltier cooling effect disappeared instantaneously. And then, the internal heat accumulation generated by the electrical power consumption, played a dominant role in the process of thermal balance, resulting in a tendency to stable at the ambient temperature. As shown in FIG.4, the junction temperature data in the second half tests under the step voltage of decreasing monotonic trend, shows relatively

shorter time to reach next new steady state, but corresponded with higher cold junction temperature than the data in the first half one. It indicates that the excessively Joule heating-dominated heat accumulation within the TE element is decreased by more significant level than the Peltier cooling with the reduction of step voltage. In general, the experimental measurements fit well to the prediction trend as the numerical results on the whole, except for slightly deviation at the initial stage. This may be due to the simplified interfacial effect without seriously concerned with the adversely parasitic temperature between junctions, and the heat flow simplified to an one-dimensional heat transfer problem, consequently produced with the overestimation for Peltier cooling effect and also the time delay for the internal heat diffusion to the junction surface. Instead, the deviation tendency gradually decreases by the abrupt change of increasing monotonic trend, probable due to the Peltier cooling effect increasingly dominated to compensate for the irreversible heat dissipation. According to the analysis above, the numerical solution is available for the following simulation on the transient behavior of the supercooling phenomenon, especially with the monotonically increasing pulse shapes, which show a greater advantage to achieve high sensitivity and stability, and require less energy to reach the minimum temperature.

IV. RESULTS AND DISCUSSION

A. The effect of pulse amplitude

Taking the basic square voltage pulse as an example, the results for the pulse amplitudes on the transient supercooling effect are showed in FIG.5 and FIG.6. Obviously, the cold junction temperature is influenced greatly by the electric power input, which is proportional to the square of the area underneath the voltage pulse. Clearly, pulse of higher electric power input resulted in a lower temperature.

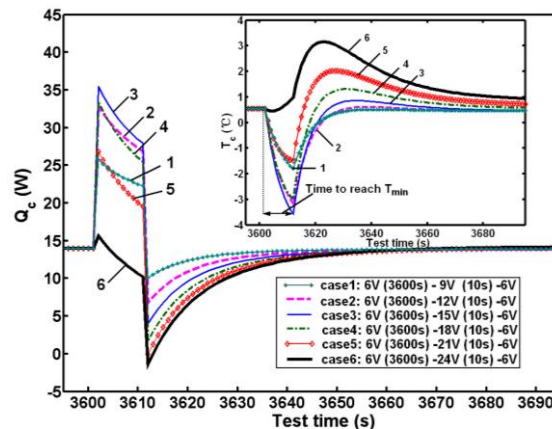


FIG.5. The effect of pulse amplitudes on the corresponding cooling power and cold junction temperature with the superimposed square pulse voltage of magnitude $1.5U_{ss}$ \square $4U_{ss}$.

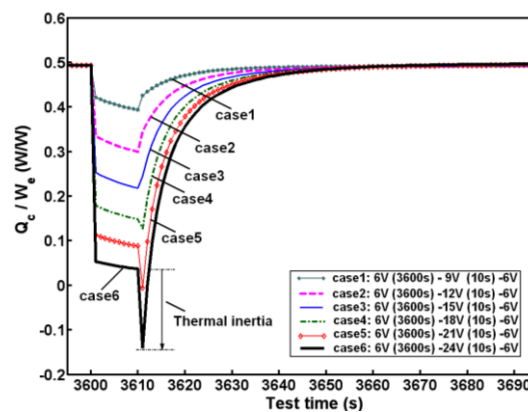


FIG.6. The proportion of cooling power to the corresponding total electrical conversion with the superimposed

square pulse voltage of magnitude $1.5U_{ss} \square 4U_{ss}$

As previously mentioned, if a sudden voltage change of a large magnitude, the interface effect of Peltier cooling located closer to the top surface of the device, appears firstly with a time constant of about 1-3s, and then, a transient cold spike will appear at the cold junction subsequently. On the other hand, Joule heating and Fourier heat conduction effects are volume or bulk effect that arrive later to reach the surface with a time constant of about 10-15s, which cause the cold side supercooling temperature to rise again. The reason for the difference in the two time constants can be considered as the thermal inertia of thermoelectric materials, generated by its thermal resistance, thermal capacity and thermal conduction paths and so on. Thus, once the pulse amplitudes under an active control within the reasonable voltage range, the transient thermoelectric supercooling can be enhanced by the Peltier effect increasingly dominated to compensate for the irreversible heat dissipation of the Joule heating and Fourier heat conduction effects. In addition, the pulse amplitude of magnitude $2.5U_{max}$, as the case 2 in FIG.5, can achieve the minimum supercooling temperature T_{min} with the maximum duration and the fastest recovery to the steady state, associated with the presence of the maximum cooling power Q_c which is proportional to the significant levels of supercooling focused electric energy conversion. These results are in good agreement with those presented in [11]. Yet, there still exists the exception that the cold junction temperature may rise up abruptly and surpass the original value of the cool-down steady state if the pulse amplitude of too great magnitude starts as the case 5 in FIG.5, which can be attributed to the excessive heat accumulation dissipated within the TE elements, thus affecting the minimum temperature that can be reached during the pulsed operation.

B. The effect of pulse shape

In principle, the transient supercooling can be enhanced by shaped pulses, and one can reduce the cold junction temperature to any desired level by periodically increasing the voltage during a pulse. In order to study the influence on the transient temperature drop at the cold junction, we give comparison of several basic forms of pulse shapes to match with a fixed steady-state reference voltage. As the curves shown in FIG.8 and FIG.9, the operation modes by different pulse shapes superimposed on the cool-down steady state are illustrated to indicate the effect of pulse shapes with the corresponding characteristic time such as the time to reach the minimum cold junction temperature, the duration of the supercooling state and the recovery time to the next new steady state. Obviously, the curves show different degrees of absolute minimum cold junction temperature T_{min} by the different time scales. What is worth mentioning, at the initial stage of the voltage pulse, the pulse shapes (as the case3, case4 and case6 presented in FIG.7) firstly show the competition of remarkable supercooling effect along with the abruptly increased cooling capacity. Gradually, contrast to the aforementioned monotone decreasing pulse shapes, the advantage of the monotonically increasing pulse shapes (as the case1, case2 and case5 presented in FIG.7) will become dominated in the Peltier cooling capacity, and finally show a longer time span, a lower cold junction temperature T_{min} except for a slower time scale to reach T_{min} , which can be attributed to the monotonically increasing pulse voltage leading with the time delay in the arrival of excessive heat accumulation by the Joule heating and Fourier heat conduction effects. In inclusion, the results indicate that, the monotonically increasing quarter-wave pulse shapes (especially the quarter-sine voltage excitation), which are more appropriate to achieve the minimum supercooling temperature of the maximum time duration and the fastest recovery time to the steady state, as well as the presence of the maximum cooling power for the system.

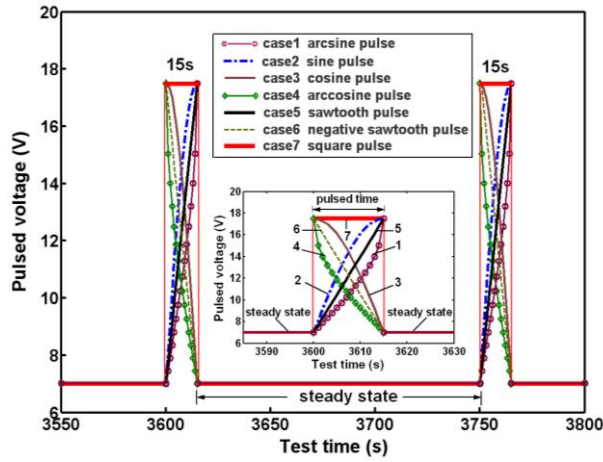


FIG.7. Different shapes for the voltage pulse with superimposed pulse voltage of magnitude $2.5U_{ss}$

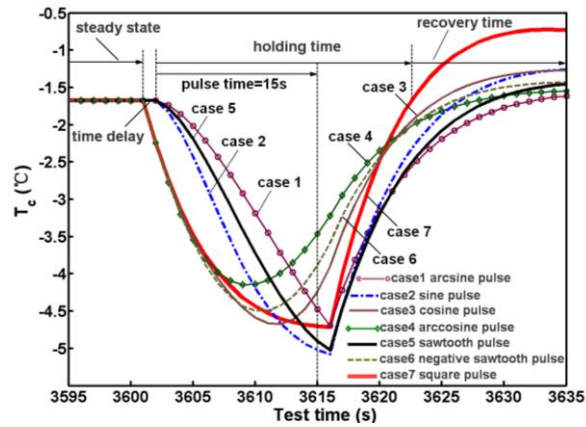


FIG.8. The effect of pulse shapes on the cold junction temperature with superimposed pulse voltage of magnitude $2.5U_{ss}$.

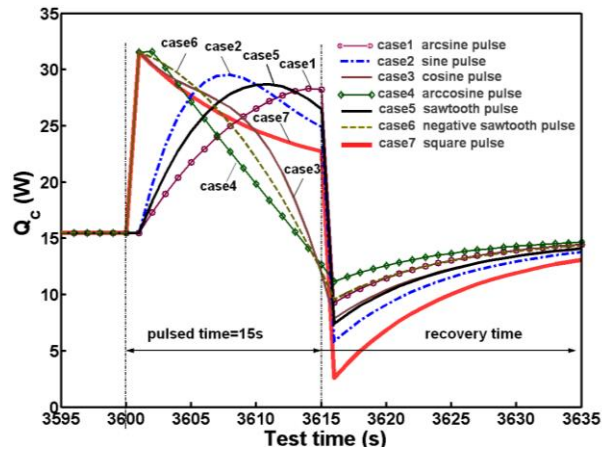


FIG.9. The effect of pulse shapes on the cooling power with superimposed pulse voltage of magnitude $2.5U_{ss}$.

C. The effect of periodic pulse signals on the system stability

Since the supercooling temperature is greatly affected by the amplitude of the voltage pulse superimposed on the steady state, it should be noted that the periodic pulse signals has direct influence on the degrees that the minimum supercooling temperature T_{min} can be reached (as shown in FIG.10) and the enhancement levels of supercooling capacity and the temperature difference between two sides (as shown in FIG.11 and FIG.12), which also further affects the cooling efficiency during the pulsed operation. These differences can be explained in the

following way: the higher the steady-state reference voltage, the lower the cold junction temperature remains during the cool-down steady state. And accordingly, after the pulse starts, the system immediately make full use of more temporary Peltier cooling effect available by less electrical conversion to achieve the desired level of minimum supercooling temperature T_{min} before the pulse stops.

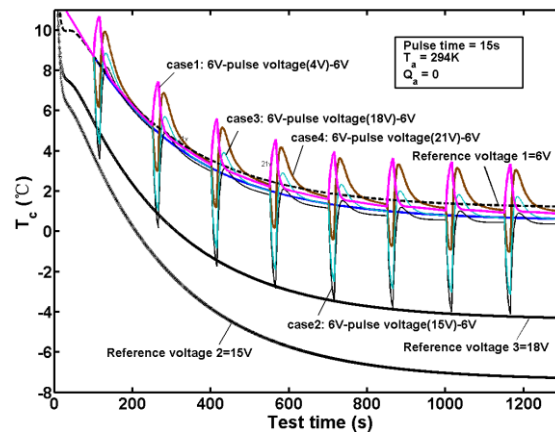


FIG.10 The effect of periodic pulse signals on the cold junction temperature

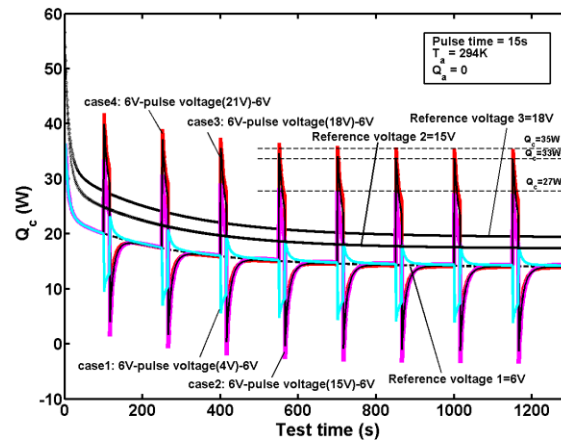


FIG.11 The effect of periodic pulse signals on cooling power

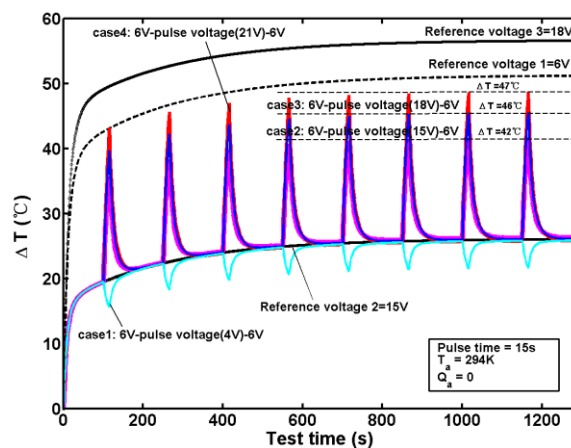


FIG.12 The effect of periodic pulse signals on temperature difference between two sides

And obviously, compared with the pulse-driven mode, it needs more time to reach the steady state together with more electrical power consumption when the system is just driven by a constant reference voltage. At the same time, when keeping on working by a high reference voltage, it indeed generates a lower constant cold junction

temperature, but there is a tendency for the hot-side heat sink to work invalid, because it has a great risk to exceed the capability limitation of heat dissipation. As a result, the periodic pulse-driven mode reflects a advantage to improve the additional supercooling effect within a short-time scale, and also prevents extensive heating of the material after the minimum temperature is reached. Furthermore, when attached to the target high heat flux producing regions, the low-cost pulse operation approach has a significant potential to act as a precise temperature control technology, and is also attractive for compact thermal system to come up to the localized cooling level of high power packaging.

V. CONCLUSIONS

In the present work, an analytical solution by the condition of transient voltage pulse superimposed on the reference steady state has been described, combined with the response of the effects of the Peltier cooling, Joule heating and Fourier heat conduction to the cold junction temperature drop and the system cooling capacity during the pulsed operation. Furthermore, by comparing the different dynamic behaviors, the advantages of certain pulse forms over others for TE devices are introduced. According to the results, with the monotonically increasing quarter-wave pulse shapes (especially the quarter-sine voltage excitation), combined with the optimized pulse amplitude of 2.5 times and pulse duration of 10s, show a greater advantage to achieve high sensitivity and stability, and require less energy to reach the minimum temperature. Also, it has contributed to an increase on the effective Figure-of-merit ratio of ZT_{eff} / ZT from the previous value of 1.76 to a maximum of 2.06 (namely improved by 17%), as well as smaller temperature differences between hot and cold junctions. By the theoretical basis, it is beneficial to guide the process control and system optimization of the transient thermoelectric cooling for a specified application.

ACKNOWLEDGMENTS

The research presented in this paper was supported by Natural Science Foundation of China (Grant No. 51406190), Natural Science Foundation of Zhejiang Province (Grant No. LQ14E060002), and "The priority among priorities" Talent cultivation project of Zhejiang Province (Grant No.150017).

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