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Experimental study on transient cooling characteristics of a realistic thermoelectric module under a current pulse operation

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ABSTRACT

This paper presents an experimental investigation on cooling characteristics of a realistic thermoelectric module (TEM) that operates under single and continuous square current pulse. The experimental system is built and the related study is performed. A cooling temperature enhancement of 3.0 °C relative to steady current operation on a realistic TEM is demonstrated. Further experimental data reveal that there exists an optimum initial steady current which provides the maximum cooling temperature enhancement in the current pulse operation. In addition, the value of the supercooling and the temperature overshoot always stay close. Moreover, continuous temperature enhancement in each current pulse is achieved on a realistic TEM operated with continuous current pulses. Cooling temperature in each current pulse shows an increasing trend similar to that of a first order step response. The cooling characteristics under different cooling loads are quite similar, except for the different initial temperatures.

1. Introduction

Thermoelectric coolers (TECs) are solid-state refrigeration devices offering advantages of prompt response, precise temperature control, compact size and no moving parts. These benefits make TEC a promising solution for active cooling [1–5]. Three main effects dominate the cooling characteristics of a TEC, Peltier, Joule and Fourier effects. Peltier effect occurs at the very interfaces of a thermoelectric element and Joule effect, however, produces Joule heat uniformly throughout the whole thermoelectric element. While the operating current steps to a higher level, there will be an intense Peltier cooling produced at the thermoelectric element interface before the increased Joule heat reaches. Temporarily, an extra cold side temperature drop can be achieved. This fundamental difference between the Peltier and Joule effect leads to unique cooling characteristics when a TEC experienced an operating current switch. This phenomenon is called the thermoelectric supercooling effect (ΔT_{sc}). Furthermore, by using a current pulse, a TEC can even temporarily break the maximum cooling temperature difference which is confined by the figure of merit of a thermoelectric material under steady current operation [6–8]. This further increased temperature difference relative to the steady current operation is called the cooling temperature enhancement (ΔT_{enh}).

This thermoelectric supercooling phenomenon has been studied extensively in the recent years [9–17]. Shen et al. [9] simulate the voltage pulse operation cooling performance by taking into account the cooling load and hot side heat transfer coefficient. Lv et al. [13] proposed a three-dimensional, multiphysics and transient model and investigated the current shape impact on the thermoelectric transient cooling. Lv et al. [17] also proposed a new design concept for two-stage thermoelectric super-cooling to enhance the maximum temperature drop. Ma and Yu numerically investigated the temperature overshoot characteristics [15] and the cooling performance under continuous current pulse operation [16] on a realistic TEC with ceramic plate. However, researches mentioned above are all based on numerical results. Although Snyder et al. [6] experimentally achieved approximately 9 K temperature enhancement (ΔT_{enh}) relative to the steady current operation, their TEC only consists of a thermoelectric element couple and there is no ceramic plates.

Nevertheless, in practical applications, a thermoelectric cooler must comprise electrically insulting and thermally conducting ceramic plates which impact the supercooling effect significantly [15]. In steady current operations, ceramic plates only manifest themselves in thermal conductivity which is at least one order greater than that of a thermoelectric element [18]. Therefore, the influence of the ceramic plate is not a major consideration in steady current operation in realistic thermoelectric modules. However, in current pulse operations, the heat conduction is transient and material heat capacity plays an important role. Ceramic plate

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Nomenclature

A	area (m^2)	enh	enhancement
a, b, d	coefficient in fitting	fh	cooling fluid at hot end
T	temperature (°C)	h	hot side
ΔT	temperature difference (°C)	hs	heat sink
I	current (A)	max	maximum
$I_{s,opt}$	optimum steady current	min	minimum
Q_c	cooling load (W)	opt	optimum
Q_v	volumetric flow rate	osh	overshoot
		p	pulse
Greeks symbols		pd	pulse duration
τ	time (s)	pmax	maximum value during a pulse
		pmin	minimum value during a pulse
Subscripts		ps	steady value corresponding to pulse level
c	cold side	s	steady
cp	current period	sc	supercooling
crit	critical		

in realistic thermoelectric module possesses specific heat at least three times greater than thermoelectric element [18]. Numerical results show that pulse temperature enhancement would be significantly mitigated on realistic thermoelectric module [15]. Although Shen et al. [9] conducted a preliminary experimental study on transient cooling of thermoelectric modules and achieved some trend consistency in the experimental results, the time scales in the experimental and simulation results are evidently different. Therefore, a more elaborately designed experimental system and the corresponding comprehensive experimental study are quite necessary. Moreover, all the previous researches are related to single current pulse cooling except for one numerical study [16] concerning the continuous pulse cooling on TEC. It is quite necessary to present experimental demonstration for a realistic thermoelectric module achieving the continuous temperature enhancement in each current pulse under continuous current pulse operation.

In this paper, we present an experimental investigation of a realistic thermoelectric module under current pulse operation. The influence of the initial steady current on the TEC cooling characteristics in a current pulse operation is examined in detail. The experimental data of supercooling effect and the temperature overshoot are compared and analyzed. Furthermore, continuous current pulse experiments are conducted. The impact of the cooling load and the current pulse period on the transient thermoelectric cooling under continuous current pulse operation is investigated.

2. Experimental instruments and system

Fig. 1(a) displays an overview photograph of the experimental system and Fig. 1(b) shows the corresponding flowsheet. A water circulating system is built and used to provide water flow with specific temperature to remove the heat dissipated from the hot side of a thermoelectric module. A Julabo F32-EH refrigerating and heating circulator is adapted as the water bath. It is able to provide fluid with a temperature range of −35 to 150 °C and temperature stability of ±0.03 °C to regulate the water temperature in heat sink. Five Pt100 temperature sensors with 0–50 °C measuring range and 0.15% accuracy are installed to monitor the water temperature at the illustrated locations (Fig. 1(b)). The Volumetric flow rate in the heat sink Q_v is measured by a turbine flowmeter with 1–10 L min^{-1} measuring range and 0.5% accuracy. The employed thermoelectric cooler (UT15,200,F2,4040,TA,W6, Laird) has 200 thermoelectric couples and a 40×40 mm^2 cold side area.

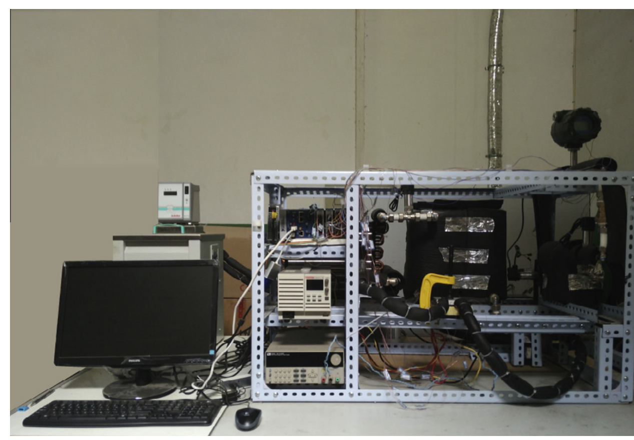

Fig. 1(a). The overview photograph of the experimental system.

According to our measurement, the thermoelectric element cross-sectional area is 1.40×1.40 mm^2. The relevant property parameters of thermoelectric element, metal strip and ceramic plate can be found in Ref. [18]. The thickness of the ceramic plate, aluminum electrical strip and thermoelectric element is 0.97, 0.47 and 0.45 mm, respectively. The distance between two thermoelectric elements is 0.50 mm. The power source Keithley 2260B and IT6942B supply direct current to the thermoelectric module and the thermal load heater with 57 mA and 13.5 mA accuracy, respectively. A HY510 thermal grease with thermal conductivity greater than 1.93 W·m^{-1}·K^{-1} is used between the solid interfaces to decrease the thermal contact. As shown in Fig. 1(b), a G-type clamp is employed to apply the holding pressure on all components. The holding pressure is maintained to be maximum throughout all the experimental tests. Several Omega T-type thermocouples (TT-T-36-SLE) are employed to the hot and cold side ceramic surfaces of the thermoelectric module to measure the temperature. These thermocouples possess a metal core diameter of 0.06 mm and prompt response. This is crucial in the temperature measure in a transient thermoelectric cooling experiment.

An NI cDAQ-9132 controller is adapted and the corresponding Labview program is developed to perform data acquisition and instrument control. All the signals from the thermocouples, Pt100 temperature sensors, flowmeter, power source Keithley 2260B and IT6942B are acquired and processed by NI cDAQ-9132 controller. There is a signal outputting module (NI 9263) employed