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Performances of thermoelectric cooler integrated with microchannel heat sinks

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Abstract

In this study, experimental and theoretical studies on thermoelectric cooler (TEC) performance for cooling a refrigerated object (water in a tank) were performed. Microchannel heat sinks fabricated with etched silicon wafers were employed on the TEC hot side to dissipate heat. The measurements show that the temperature of the refrigerated object decreased with time. A theoretical model based on a lumped system was established to predict the transient behavior of the variation in temperature for the refrigerated object with time. The theoretical predicted temperature variation was in good agreement with the measured data. The relationship among the heat sink thermal resistances, TEC electric current input and minimum refrigerated objected temperature was examined based on the theoretical model. The calculated minimum temperatures were showed for the several cases of heat sink thermal resistance on the TEC hot side and electric current input. The minimum temperature can be obtained by increasing the electrical current input and decreasing the heat sink thermal resistance.

Keywords: Research; Refrigerating system; Thermoelectricity; Microchannel; Cooling; Water; Modelling; Transient behaviour; Temperature

Performance d'un refroidisseur thermoélectrique muni de puits thermiques à microcanaux

Mots clés : Recherche ; Système frigorifique ; Thermoélecticité ; Microcanal ; Refroidissement ; Eau ; Modélisation ; Régime transitoire ; Température

1. Introduction

Refrigeration is required for many applications from our daily life such as refrigerators and air conditioning to high technologies such as electronic cooling and biochemical industry. The physical size for each application is one of the factors in refrigeration system design. For example, a refrigeration system must have a size compatible to that of a chip due to the limited space in practical electronic device cooling applications. In domestic applications, the size and weight of refrigeration systems should be small and light for easy handling. Therefore, developing a miniature sized refrigeration system is an important issue in the future applications not only for the high technology but also for improving our living quality.

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Nomenclature

A_b	microchannel heat sink base plate area, m^2
A_{eff}	effective fin heat transfer area, m^2
c	specific heat of water, 4178 J/kg K
D_h	microchannel hydraulic diameter, m
G	thermoelectric element geometric factor, 1.186×10^{-3} m
H	depth of microchannel, m
h_{ave}	average convective heat transfer coefficient in microchannel, W/m^2 K
I	electric current, A
K	thermoelectric element thermal conductivity, 1.5 W/m K
k_s	thermal conductivity of microchannel heat sink material, W/m K
L_s	microchannel heat sink base plate thickness, m
$\dot{m}$	mass flow rate, kg/s
N	number of thermoelectric element pairs, 127
n	number of heat sink microchannels
Q	coolant volume flow rate, m^3/s
Q_c	heat transfer rate at the TEC cold side, W
Q_h	heat transfer rate at the TEC hot side, W
R_{th}	heat sink thermal resistance, K/W
T_c	TEC cold side temperature, K
T_h	TEC hot side temperature, K
T_{heq}	equivalent TEC hot side temperature, K
T_{hmax}	maximum TEC hot side, K
T_t	tank water temperature, K
T_{fin}	coolant temperature at the beat sink inlet, 298 K
T_{fout}	coolant temperature at the heat sink exit, K
V	volume of tank, 1.18×10^{-3} m^3
W_f	bottom width of the microchannel wall, m
W_t	top width of the microchannel, m
W_b	bottom width of the microchannel, m
Greek symbols	
α	Seebeck coefficient, 2×10^{-4} V/K
ρ	electrical resistivity of the TEC material, 10^{-5} Ω m
ρ_f	water density, 996 kg/m^3

Miniature refrigeration systems have received much attention since the pioneer work by Little [1,2]. The review paper by Pelan et al. [3] summarized several current and future miniature refrigeration cooling technologies for high power microelectronics. A miniature vapor compression refrigerator could be a future solution for electronic heat management and other applications. In such a refrigeration system, the maximum power dissipation rate and lowest temperature that could be attained are 350 W and 12 °C [3], respectively. The miniature vapor compression refrigerator principle is the same as that for a conventional sized refrigerator except that the size is reduced to the centi- or milli-meter order. Currently a miniature vapor compression refrigerator is under development using microelectromechanical system (MEMS) technologies [4–6]. The main difficulty is the micro-scale compressor design and fabrication [7]. Another possible candidate that might also fit the requirement is a mini-scale capillary pump loop (CPL) [8]. Operating such a system is similar to the mini-scale vapor compression refrigerator except that the working fluid is driven by capillary pressure.

Both the miniature scale vapor compression refrigerator and CPL are not commercially available. The only commercially available miniature size refrigerator today is a thermoelectric cooler (TEC). The basic TEC operating principle can be found in thermodynamic textbooks [9]. It is composed of a number of pairs of n- and p-type semiconductor materials. The thermoelectric materials are connected electrically in series and thermally in parallel and integrated with two ceramic plates forming the cold and hot sides of the module. Heat is removed from the cold side when electric current passes through the module. According to the data provided by suppliers [10,11], the TEC is less efficient than the vapor-compression system, but it represents the most direct way of utilizing electricity to pump heat. Moreover, it possesses advantages such as high reliability, flexibility in packaging and integration, low weight, silence and environmentally friendly technology. These characteristics make the TEC a candidate for electronic cooling applications.

The TEC can be operated only in a certain temperature difference range between the cold and hot sides depending on the input electric current and thermoelectric material properties. To maintain the temperature difference within the operating range, all TEC operations require a heat sink on the hot side to dissipate heat away from the TEC. Therefore, heat sink design is one of the most important factors affecting TEC performance. To obtain the best performance, a TEC must be designed with heat sink thermal resistance as small as possible. The conventional heat sink unit utilized at the TEC hot side is composed of fins and a fan. The fins are employed to increase heat transfer area. The fan conducts heat transfer through convection. Although the thermal resistance of such a unit can be as low as 0.1 K/W [10], it is usually larger in size. The conventional heat sink can only be employed in situations where space is not restricted. Besides the conventional heat sink unit, phase change materials and heat pipes can also be employed as a heat sink for the TEC hot side [12].

The microchannel heat sink is proposed in this study to reduce both the thermal resistance and heat sink size.