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Experimental investigation on the thermal performance of a series loop with uniform temperature

Hao Chen, Qiang Li *

MIIT Key Laboratory of Thermal Control of Electronic Equipment, School of Energy and Power Engineering, Nanjing University of Science & Technology, Nanjing 210094, China

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ABSTRACT

This paper presents experiments and visualization on the thermal performance of phase-change heat transfer for R245fa in a novel heat sink cooled by natural convection with phase transition in the circulation loop. The influence of the filling ratio and heating power on the thermal performance of the heat sink was investigated experimentally. The experimental results indicated that the filling ratio and heating power had a significant influence on the thermal performance of the system. The system could start up successfully and operated without temperature oscillations under the given heating power range and the transient thermal response of the system under the conditions of a low filling ratio and low heating power was slower than that under other conditions. Meanwhile, the system achieved an excellent heat dissipation performance and outstanding temperature uniformity. A maximum temperature difference of 5.1 K in the evaporation substrate and 3.2 K in the condensation substrate was obtained while the heating power was 400 W and the filling ratio was 60% and the thermal resistance of 4.8×10^{-3} K/W was obtained while the heating power was 400 W and the filling ratio was 50%. Additionally, the two-phase flow of the working fluid in the passages was observed clearly and identified easily, and the evaporation of the working fluid was more intense with the increases of heating power which can be obtained by visualization results.

1. Introduction

With the improvement of electronic component technology, high integration and packing density are the development trend of electronic equipment which leads to a sharp increase in the heat flux of electronic equipment in recent years. Accordingly, the heat dissipation of electronic equipment is much more difficult and it proposes a great challenge to the reliability and service life of electronic equipment. As higher requirements are put forward for the thermal performance of electronic equipment, the scientific design of the cooling system becomes particularly important.

General cooling methods for electronic equipment mainly include natural air cooling, forced air cooling and liquid cooling. In these three traditional cooling methods, natural air cooling is an ideal cooling method on account of many advantages such as low noise, stable running, no external power and convenient. Owing to these advantages, the applications of natural air cooling in many situations, such as telecommunication equipment and base station, are extremely pervasive. Because natural air cooling has limited capacity to dissipate the heat generated by the high power electronic equipment, measures are undertaken to improve the heat dissipation capacity of heat sink cooled by natural convection. Heat sinks with fins can satisfy the heat dissipation requirements of high power electronic equipment as the surface area of heat sinks can be greatly increased. There exist many experimental and theoretical studies have been published on the performance of heat sinks with fins. Singh et al. [1] investigated the natural convection heat transfer from a finned sphere numerically in both laminar and turbulent regimes. Chang et al. [2] conducted a numerical study to examine the steady-state three-dimensional natural convective flow and heat transfer for a set of vertical fin arrays with/without dimples. By means of the finite element Galerkin method with the aid of the Arbitrary Lagrangian-Eulerian (ALE) procedure. Hsu et al. [3] Investigated the natural convection in an oscillating cylindrical enclosure to simulate heat transfer inside a buoy of a wave power generator experimentally. Joo et al. [4] Conducted the thermal optimization of vertically oriented, internally finned tubes in natural convection. Micheli et al. [5] gave an overview of micro-fins behavior taking into account, for the first time, different heat sink metrics: the fin effectiveness and the mass specific heat transfer coefficient. Senapati et al. [6] studied the entropy generation in laminar and turbulent natural convection heat transfer from vertical cylinder with annular fins and analyzed

* Corresponding author.
E-mail address: liqiang@mail.njust.edu.cn (Q. Li).

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Nomenclature

I	current (A)	*Greek symbols*	
Q	heating power (W)	cs	condensation substrate
R	resistance (K/W)	es	evaporation substrate
T	temperature (K)	max	maximum
U	voltage (V)	min	minimum

the effect of parameters like the fin to tube diameter ratio (D/d), fin spacing to tube diameter ratio (S/d) and Rayleigh number on Nusselt number. Ghalambaz et al. [7] studied a fluid–structure interaction represented by an oscillating elastic fin attached to a hot vertical wall of a square cavity. Chen et al. [8] investigated the natural convection heat transfer characteristics for vertical annular finned tube heat exchanger numerically and experimentally. All these studies have given attention to the heat sinks with fins to increase the heat transfer area and heat transfer coefficient under natural convection. However, the size of finned heat sinks should be controlled well, otherwise the weight, volume and cost increase greatly and the heat dissipation efficiency decrease significantly. More importantly, the increase of the heat transfer area could cause the uneven distribution of the heat transfer.

In the event that the thermal control of electronic equipment cannot meet the requirements of heat dissipation, the temperature distribution inside the electronic equipment may be uneven which leads to the generation of thermal stress in electronic equipment. The thermal stress would cause the deformation, fatigue damage and fracture in electronic equipment. Meanwhile, the stability and reliability of electronic equipment will be seriously affected. However, the traditional heat sinks with fins cannot meet the demand for temperature equalization between the components which are included in the electronic equipment. In response, vapor chamber is regarded as a promising technology to solve the requirement for temperature uniformity of electronic equipment as the vapor chamber has some excellent properties, for example, high thermal conductivity and excellent temperature uniformity. Vapor chamber is a cooling device with internal fluid channels in which phase change of the working fluid occurs. The evaporation and condensation of the working fluid inside the channels enhance the heat transfer and improve the temperature uniformity of the electronic equipment. The vapor chamber has aroused much research interests as it has excellent performance in thermal management of electronic equipment. Naphon et al. [9] performed an experiment on the thermal cooling of vapor chamber for cooling computer processing unit of the personal computer. Two different configurations of the vapor chambers with de-ionized water as working fluid are tested under the real operating conditions of PCs. Ju et al. [10] reported the design and experimental characterization of advanced evaporator wicks and thin planar vapor chambers incorporating these wicks. Tang et al. [11] designed and tested a mufti-artery vapor chamber in which the wick structure consists of sintered copper powder layers on the top and bottom plates. Pantankar et al. [12] proposed a method for thermal performance characterization of ultrathin vapor chambers cooled by natural convection. Performance metrics are developed to characterize heat spreader performance in terms of the effective thermal resistance and the condenser-side temperature uniformity. Mizuta [13] developed a type of flat laminate vapor chamber called FGHP (Fine Grid Heat Pipe) and investigated its thermal performance. The capillary and heat transfer performance of liquid spreading layers consisting of mono-layers of Cu particles was modelled and experimentally characterized and a range of optimal particle diameters maximizing their performance was identified. However, the small size of vapor chamber is unable to meet the demand of heat dissipation of the large-sized and vertically arranged electronic equipment while the vapor chamber need to be much larger than the heat source and the heat transfer performance of vertically vapor chamber is lower than the horizontally.

For the vertically arranged electronic equipment, the loop heat pipes have been successfully used based on the valid design. Loop heat pipes are passive two-phase heat transfer devices which use capillary forces generated by the porous wicks to circulate the working fluid and transfer heat for long distance [14]. There are many studies have been performed on the loop heat pipes as they have many advantages, such as high heat transfer capability, great thermal control ability and high free degree of installation [15]. The evaporator is a main part of a loop heat pipe because it acts as a capillary pump and an evaporative heat exchanger [16]. Previous investigations have been conducted to enhance the evaporator performance, for example, use various evaporator structure [17–19] and porous materials [20–22].

In this paper, a novel heat sink cooled by natural convection with phase transition in the series loop was designed and the heat sink was applied on averaging temperature and cooling the electronic equipment. The combination of vapor chamber, fins and capillary pump can meet the demand of heat dissipation and temperature uniformity of the high power electronic equipment and save the required space of cooling system. Besides, the system can maintain an excellent thermal control ability for the large-sized and vertically arranged electronic equipment. Compared with the vapor chamber, the system has the advantages of long distance heat transfer, simple structure and economical. Meanwhile, the system possesses a better temperature uniformity for large-sized electronic equipment compared with the loop heat pipe. The experiments were conducted to investigate the influence of the filling ratio and heating power on the performance of the system. Besides, the flow patterns of the working fluid at different heating power were visualized by using a high speed camera. With the research, a thermal design method of the device which couples phase change and natural convection was basically established.

2. Experimental apparatus and method

2.1. Structure of the cooling system

Fig. 1 shows the structure of the cooling system which includes evaporation substrate, condensation substrate, capillary pump, reservoir and aluminum fins. The two substrates are constructed of perspex plates and aluminum plates which contain fluid passages. The size of the aluminum plate is 735 mm × 395 mm × 6mm. The aluminum fins coupled with the plates act to increase the heat dissipation area, are 12.5 mm in pitch. The working fluid absorbs heat from the capillary pump and evaporation substrate, evaporates in evaporation substrate and condenses in condensation substrate. The heat can be transferred from the evaporation region to the condensation region through the circulation flow of the working fluid, and then released to the ambient through the