Renewable and Sustainable Energy Reviews 82 (2018) 901–914

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Overview of micro-channel design for high heat flux application

Nor Haziq Naqiuddin[a], Lip Huat Saw[a,*], Ming Chian Yew[a], Farazila Yusof[b], Tan Ching Ng[a], Ming Kun Yew[a]

[a] Lee Kong Chian Faculty of Engineering and Science, UTAR, Kajang 43000, Malaysia
[b] Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, 50603, Malaysia

ARTICLE INFO

Keywords:
Micro-channel
Heat sink
Nano-fluids
Solar cell
Fuel cell

ABSTRACT

Recent advancement in the micro-scale and nano-scale electronics systems, the demand of an innovative solution for the thermal management to dissipate the high amount of heat flux generated have become more rigorous to ensure good reliability of the devices. Micro-channel heat sink has been introduced to dissipate the heat flux with capacity of 10 MW m^{-2}, which providing an ideal solution in the thermal management technology. Researches have been done experimentally or numerically to investigate effect of different geometric designs of micro-channel heat sinks to promote better heat transfer between micro-channel walls and cooling fluid. Other than micro-channel geometric design, type of cooling fluids and two-phase flow boiling are important issues in the micro-channel based thermal management system. In addition, applications of nano-fluids in the micro-channel heat sink are also highlighted which helps in improving the thermal conductivity of the coolant and leads to better heat dissipation rate. In addition, applications of micro-channel in the engineering sector such as solar cell, fuel cell and medical devices are reviewed. For the literature, implementation of micro-channel in the electronic devices as a thermal management solution is highly recommended due to its ability to protect and prolong the lifespan of electronic devices.

1. Introduction

Thermal management plays a significant role in many engineering applications especially in the design of electronic devices. Advancement of electronic technology has led to stringent thermal management requirement to match the electronic devices power density. Hence, heat transfer at the micro-scale level has gained astounding demands and opportunities for thermal management system research and development. Moreover, advancement in the modern microelectronics industry and followed by the trend of increasing packaging density, acceptable heat removal target was 10 MW m^{-2} and surface temperature must be less than 373.15 K for nanometer size of the chip in the regular microelectronic devices [1]. Furthermore, demand for cost-effective cooling solution has been increasing due to market demand for cheaper electronic devices [2]. In 2012, International Technology Roadmap for Semiconductor (ITRS) indicated that in 2020, integrated circuit (ICs) power density will increase up to 1 MW m^{-2}. This further indicates that traditional cooling solution cannot cope with high heat flux generated by the IC chips [3]. Furthermore, ITRS also highlighted that optimum junction temperature for semiconductor is about 358.15 K [4]. Number of transistors per unit area continued to increase in the past five decades and this trend is expected to progress affirmed by the Moore's Law. Later production of electronic chips is likely to develop about 5 MW m^{-2} of background heat fluxes and there will be more than 10 MW m^{-2} at hot spots. This has become a real challenge to remove heat generated from the ICs [5,6]. Therefore, heat generation problem needs to be solved urgently to ensure smooth operating of the device and growth of the electronics industry. In order to maximize the device performance and cycle life, the device must be configured with an optimum cooling solution. Besides, characteristic length of the cooling devices needs to be reduced to improve compactness of the system. Hence, micro-channel heat sink is the most favourable cooling solution for high-power density devices [7]. Micro-channel heat sinks have found its applications in real life applications such as military and defence, bio-engineering, medical, nuclear industry, solar cell, fuel cell and electronic industry. There are many factors influence the micro-channel heat transfer performance such as channel geometry design, rarefaction, surface roughness, fluid viscosity, electrostatic effect, channel wall axial heat conduction, shape factor, etc. These factors must be taken into account in the micro-channel heat sinks design [8].

1980s, Tuckerman and Pease compared the performance of the micro-channel heat sink with conventional or macro-channel heat sink. In the single-phase fluid flow, heat transfer rate is significantly enhanced by using micro-channel heat sink. High heat transfer

* Corresponding author.
E-mail addresses: sawlh@utar.edu.my, bernardsaw81@yahoo.com (L.H. Saw).

http://dx.doi.org/10.1016/j.rser.2017.09.110
Received 21 February 2017; Received in revised form 3 June 2017; Accepted 26 September 2017
Available online 06 October 2017

Nomenclature

ρ	Density of the fluid, kg m^{-3}
u	Velocity of the fluid, ms^{-1}
L	Characteristic linear dimension, m
μ	Dynamic viscosity of the fluid, kg m^{-1} s^{-1}
d	Channel height, m
r_i	Radius of convex curved (or inner) surface, m

performance exhibited from the micro-channel heat sinks is contributed by expanding the overall heat transfer area to volume ratio [1,4]. Therefore, micro-channel heat sink has an advantage in the thermal management due to smaller geometry size and low coolant flow requirements [9]. Heat transfer of the micro-channel takes place either toward or away from the separating wall in a transient manner. Two crucial occurrences associated with the heat transfer in the micro-channel are cooling fluid flow and channel walls heat transfer [10]. For a single-phase liquid cooling, up to 7.9 MW m^{-2} of heat flux and 0.09 kW^{-1} of thermal resistances can be dissipated easily through the micro-channel heat sink [2,11].

However, heat transfer performance of the micro-channel in the single-phase convective is subjected to cost, pressure drop across the micro-channel and development of large temperature gradient on the flow path as well as amount of heat dissipated was limited by the choice of coolant used [1,10]. Moreover, non-uniformities in temperature distribution will cause hotspots and reduce the efficiency and reliability of the electronic devices [12]. Experimental and numerical simulation have been conducted to investigate the effect of various shape factors and optimize the cooling performance in the micro-channel heat sinks. Various type of micro-channel heat sinks are available in the market such as wavy fin micro-channel, pin-fin micro-channel, oblique fin micro-channel, double-layered micro-channel, etc. These micro-channel designs have proven to be an effective solution in dissipating the heat flux which will be discussed further in the next section.

Thermal conductivity of the cooling fluid can be improved by adding metallic fine suspended particles into the base fluid. Heat transfer performance using nanofluids is more effective than pure coolants. This is due to nanofluids have higher thermal conductivity to transfer the heat out of the devices [9]. However, there are negative effects associated with nanofluids such as drastic pressure drop, fouling, clogging, sedimentation and erosion that will harm the cooling system. However, recent development of the nanotechnology made it possible to produce a smooth plate channel that can overcome this problem [7]. Thermal and hydrodynamic boundary was interrupted periodically by a smooth plate channel which promotes better mixing at different temperatures of fluid parcel [13]. In addition, flow boiling with micro-channel heat sinks has shown a great potential for high heat flux application. However, growth of the bubble will cause flow reversal, oscillation of fluid flow, oscillating of system pressure and slip phenomenon at the micro-channel wall will cause the flow field not fully developed [1,9]. Therefore, it is important to investigate the factors affect the heat transfer mechanism in the micro-channel heat sink [11].

In this study, a critical review on the application of micro-channel heat sinks as a thermal management for high heat flux electronic devices will be presented. This encompassed different geometric design and performance of micro-channel under different flow condition which includes laminar, turbulent and flow boiling. Besides, applications of micro-channel in the renewable energy field such as solar energy, fuel cell, heat exchanger, etc will be discussed as well. The paper is organized as follows, section two describes different geometric design of the micro-channel such as straight channel, wavy channel, pin-fin, fan-shaped ribs, dimples, oblique fin and common cooling fluids used. Section three describes the numerical simulation results of the micro-channel heat sink. Section four describes the two-phase flow boiling in the micro-channel heat sink and section five describes the introduction of nanofluids in the micro-channel heat sink. Section six describes various applications of micro-channel in the fuel cell, solar cell, heat exchanger, etc. Finally, section seven summarizes the different findings in the literature review and concludes the paper.

2. Geometric design and coolant

Geometrical design of the micro-channel is crucial to understand the mechanism of the heat transfer enhancement. Researchers have discovered that mechanisms of heat transfer can be improved through thinning of the thermal boundary layer, fluid mixing and increase fluid flow velocity gradient on the heated surface [14]. Rise of pumping power, small channel width-to-depth ratio and the large channel fin width-to-depth ratio were observed for the heat transfer enhancement in the micro-channel heat sink [15]. Micro-channel with ribs, grooves, cavities and complex structure have become one of the potential solutions for the heat transfer enhancement [14,16].

Other than geometric design optimization, cooling fluids is another important factor affect the micro-channel heat transfer enhancement. There are many researches focus on the direct contact of cooling fluid with the heat sink which involved heat transfer between fluids through a separating wall in the transient manner. Thus, higher heat transfer coefficient can be achieved by improving the cooling fluids properties, which in turn enhanced the micro-channel heat sinks heat transfer performance. Most electronic applications are air cooled and the present data showed that air cooling contributed about 33% of the overall energy bill of the system. If the cooling system is replaced by liquid cooling, a significant reduction of the energy consumption can be achieved. Liquid cooling with micro-channel heat sinks has been proved to be an effective and more favourable approach for high heat dissipation due to several advantages such as high cooling capacity, anti-seep, high integration, compactness, quiet operation, multiple pattern and ease of fabrication.

Water can be used as a cooling fluid due to its excellent thermal properties. Besides, non-toxic nature of the water has an advantage for cooling applications [17]. Sharma et al. have extensively studied the cooling of non-uniform multicore microprocessor power map by employing a static and energy preserving method to develop the micro-channel heat sinks. Fine and coarse channels are rationally distributed over the hotspots and background respectively. While flow throttling zone is incorporated to distribute the flow in the different region of the chip. Simulation results showed that an improvement up to 57% in chip temperature by using uniform embedded micro-channel and uniform flow distribution. Besides, about 30% improvement in chip temperature was achieved by using non-uniform embedded micro-channel and non-uniform flow distribution design [18]. Jaikumar et al. investigated the enhancement of boiling performance based on hypothesis that micro-channel heat sinks have superior rewetting pathways and porous coating will provide additional nucleation sites [17]. Separate liquid-vapour pathways were developed by the cohesive mechanism and promote suspension of critical heat flux by constantly feeding the nucleation sites with liquid. Thus, it has fulfilled the electronic application by satisfying the cooling requirement for maximum allowable temperature of about 358.15 K.

Mohammadian et al. investigated the effect of internal and external cooling of Li-ion battery by passing electrolyte and water through micro-channel integrated with the battery. It is showed that internal cooling improved the temperature uniformity and also reduced the bulk temperature inside the battery. Internal cooling is more effective in reducing the deviation of the internal temperature 5 times higher than that of the external cooling [21]. Ethylene glycol is used to improve the freezing and boiling point of the water [19,20]. However, thermal conductivity of ethylene glycol and water are very low and result in poor convective heat transfer. However, by incorporating graphene nanoplatelets into the ethylene glycol and water to form a nanofluid