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A review of the capabilities of high heat flux removal by porous materials, microchannels and spray cooling techniques

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HIGHLIGHTS

- Three direct cooling techniques are presented and compared in detail.
- The thermal and flow parameters which have influence on performances are investigated.
- The spray cooling technique is characterized by the most promising thermal performances.

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ABSTRACT

Most advanced, high power technologies require a large amount of heat to be dissipated from the limited surface area or space. Solutions to such problems are vital, among others, in the field of computer microchips, where promising designs of future high power processing components can reach heat fluxes up to 500 W cm^{-2} in the background or even 1000 W cm^{-2} at the hot-spots. Such high requirements can be satisfied by so-called *Direct Cooling Techniques*, which are heat removal techniques that apply porous media, microchannel heat sinks and spray cooling. The paper presents an exhaustive comparison of the aforementioned techniques with respect to the media type, operating fluids and flow character, maximal achievable heat flux dissipation and heat transfer coefficient, pressure drop, the Reynolds number, other selected thermal and/or flow parameters. Special attention is paid to the spray cooling technique, which is the most effective direct cooling technology. For that reason, several parameters, such as: spray and fluid types, maximum achieved heat flux, heat transfer coefficient, the Sauter Mean Diameter and flow rate are studied and compared in detail.

Contents

1. Introduction

The exponential growth of the nuclear industry [1], diode lasers [2] and electronic devices [3] goes hand-in-hand with an

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increasing value of generated heat and consequently an undesirable temperature rise. The generated heat, precisely heat flux, is in turn one of the main inhibitors of technological development. A certain crucial problem of thermal management has been recently observed in the field of computer technology, where promising designs of near future high clock speed processors can reach heat flux values from 300 W cm^{-2} [4] up to 500 W cm^{-2} [5,6] in the background, or even 1000 W cm^{-2} [7] at the hot-spots. *High Heat Fluxes* (HHF) in other technologies can even exceed these values. In some fusion reactor facilities, which are being constructed within the *ITER* project, the expected heat flux is about 50 W cm^{-2} [8]. In laser diode arrays the fluxes can exceed 1000 W cm^{-2} [9,10] at temperature of 27 ± 1 °C [9].

However, the tendency of heat flux dissipation can be significantly decreased in modern multicore microchips by introducing the thread migration methods [11]. Thanks to these techniques an average heat flux can obtain values of up to 20 W cm^{-2} in the background [12] and 150 W cm^{-2} at hot-spots.

Points of inhomogeneous heat distribution (hot-spots) decrease the efficiency and reliability of processors. Moreover, in order to avoid the computer chips' failure, the microchip surface should be maintained at a temperature lower than 85 °C [4,13,14]. In fact, the present cooling techniques are not able to dissipate the assumed heat fluxes. For instance, forced air convection can remove approximately 150 W cm^{-2} [15] or slightly more with additional improvements such as the scraped surface technique [16]. Similarly, the maximal achievable heat flux of water pool boiling reaches approximately 120 W cm^{-2} [17].

Thus, a new generation of thermal management systems is essential to protect electronic devices, among others, against an increased heat flux and temperature peak, as well as to maintain a small total package volume [18]. The following three cooling techniques are very promising with respect to the requirements for compact space systems:

- heat removal technique with porous media,
- microchannel heat sinks, and
- spray cooling.

Other techniques, such as integrated heat pipe systems, are not reviewed in this paper since they belong to the so-called *Indirect Cooling Techniques*, in which the heat from high temperature regions is taken by an intermediate medium or special additional devices and transferred to low temperature regions [19,20].

The heat removal technique with porous media (in the text abbreviated to *porous media*) is based on a solid matrix material structure. The solid matrix is made of a material characterized by high thermal conductivity, which intensifies heat transfer to the coolant. The irregular structure of sintered particles [21] as well as the ordered package of spherical pebbles [22] are used.

The microchannel heat sinks are mainly intended for cooling the electronic components down [9,12,13,23–26] and can be treated as a small-scale heat exchanger, in which the fluid flows into ducts a fraction of a millimeter wide. These two techniques are similar in respect to the mechanism of heat transfer enhancement which is achieved by increasing the contact heat transfer area and by intensifying the fluid flow inside the channels.

The spray cooling technique is characterized by great performance and uniform heat distribution and, in comparison to other solutions is a reliable means of cooling electronic components sensitive to temperature [27] in the metallurgy casting process [28–30] or even in some space applications [31]. In principle, the spray cooling technique is based on fluid fragmentation caused by internal or external forces or centrifugal forces [32]. The created cloud of droplets impacts on a solid surface and absorbs the produced heat very effectively in a short period of time.

Present solutions use a liquid in a single- or two-phase cooling medium flow. In a two-phase flow, heat transfer via liquid is limited due to the boiling curve [33]. Because of the highest achievable heat transfer coefficient, the nucleate boiling regime is, from the processing point of view, most efficient [34,35]. Unfortunately, when a heat flux exceeds its *Critical Heat Flux* (CHF) value, the transfer coefficient significantly decreases and the temperature difference between the fluid and the heated surface grows rapidly, which can cause damage to the material surface. The techniques described in the paper show how to change the boiling characteristic and increase the CHF limit.

In the past, some reviews concerning the subject of the paper were considered. Ebadian and Lin [36] studied high and extremely high heat flux removal techniques, a single- and two-phase flow in a microchannel, jet impingement, sprays, wettability, and piezoelectrically driven droplets. Agostini et al. [4] reviewed single- and two-phase flows in a microchannel, single- and two-phase flows in a porous media, and jet impingement cooling. Kandlikar and Bapat [37] presented a review on microchannels, spray cooling, and jet impingement. In all of these articles it was said that only liquid cooling could satisfy the HHF capabilities. In addition, a single-phase flow was preferable to the two-phase technique, which has not been fully understood so far. In the present paper the information about the mentioned techniques is updated and compared with respect to a possible application in compact thermal management systems.

2. Porous media

A porous media is a common technique used to enhance a heat flux removal by increasing the heat transfer area between solid and fluid regions. The idea of this technique is shown in Fig. 1.

Porous media are an alternative to microchannel heat sinks, due to their manufacturing simplicity, compact size and good heat distribution of performance requirements. A characteristic structure of the porous media is composed of sintered particles made of bronze [21], stainless-steel [38], copper [39] or an irregular structure of aluminum (or other metals) foams [40,41]. Because of the good thermal contact between each particle [42], porous particles outperform non-sintered ones. As it was noticed in [43], in case of sintered metal particles heat transfer increases 15 times for water or 30 times for air in comparison to the non-sintered porous media.

Thermal parameters such as heat transfer coefficient and Colburn factor increase when the pore size decreases. The pore diameter influences the pressure drop across the porous medium as well. It is pointed out in [43] that a decrease in pore size of about 3 times from 60 μm to 20 μm approximately doubles the pressure drop. As the pressure drop is proportional to the square of the mean flow velocity [44], it is recommended to maintain flow inside

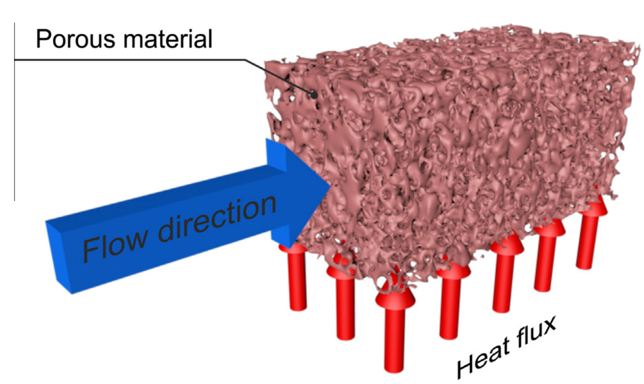

Fig. 1. Sintered particles of the porous media.