International Journal of Heat and Mass Transfer 86 (2015) 531–541

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Heat transfer performance of the pin–fin heat sink filled with packed brass beads under a vertical oncoming flow

Tzer-Ming Jeng *, Sheng-Chung Tzeng, Qiong-Yao Huang

Department of Mechanical Engineering, Chienkuo Technology University, 500 Changhua, Taiwan, ROC

ARTICLE INFO

Article history:
Received 2 December 2014
Received in revised form 12 March 2015
Accepted 13 March 2015
Available online 30 March 2015

Keywords:
Oncoming air flow
Packed brass beads
Pin–fin heat sink
Heat transfer

ABSTRACT

This study experimentally investigated the fluid flow and heat transfer characteristics of the pin–fin heat sink fully filled with packed brass beads under a vertical oncoming air flow. The dimensions of the pin–fin heat sink were fixed. A constant heat flux was applied on the bottom of the heat sink. The pin–fin heat sinks of various pin–fin side lengths and pin–fin interval spaces filled with brass beads of various diameters would result in different porous properties, leading the corresponding changes in the behaviors of the fluid flow and heat transfer. The results indicated that, for the same Reynolds number (*Re*) of oncoming flow, the pin–fin heat sinks with packed brass beads (Group 3) have significant heat transfer gains (17.0–78.4% and 95.8–311.2% at $Re = 10{,}000$, respectively) by comparing with the corresponding pure pin–fin heat sinks (Group 1) and pure packed-brass-beads heat sinks (Group 2). The Nusselt-number empirical formula of the Group 3 heat sink was provided in some superposition form of the Group 1 heat sink and Group 2 heat sink. The heat-transfer superposition effect fell remarkably when the porosity of the Group 3 heat sink was notably lower than those of the corresponding Group 1 heat sink and Group 2 heat sink. Besides, based on the same dimensionless pumping power, the Group 3 heat sink generally has higher heat transfer performance than the corresponding Group 1 heat sink and Group 2 heat sink, except a few exceptions at smaller dimensionless pumping power.

1. Introduction

With rapid development of industry, power machines and electronic products are developing towards compactness and high functionality, and the heat dissipated per unit volume increases continuously. Thus, how to dissipate heat effectively is the important topic for related industries. The impingement cooling is the most extensively used and efficient cooling technique at present, the cooling fluid impacts the heating surface directly and fully, thus increasing the heat transfer of heat sink greatly. The combination of impingement cooling technique and finned heat sink is the main assembly design extensively applied to electronic equipment heat sinking at present [1–5]. The traditional finned heat sink is no longer able to meet the cooling requirement of electronic modules with rapidly growing functions. Therefore, the development and application of novel heat sinks become the important direction in the research on improving and enhancing the cooling function of this type of assembly.

The porous medium heat sink has a very large heat transfer area, and the internal porous structure can disturb the fluid, so as to increase the additional thermal dispersion conductivity of fluid. The overall convection heat transfer effect will increase greatly, and the effect on heat transfer enhancement is significant. Hence, it is very suitable as high efficiency heat exchange component [6–10]. The metal porous material made heat sink has excellent heat-transfer capacity. Many studies have discussed its heat transfer characteristics with impinging flow [11–14]. Fu and Huang [11] analyzed the thermal behaviors of packed spheres in different shapes with impinging jet. Their findings indicate that the key factor influencing the heat transfer is how much air flow can penetrate through the packed spheres to approach the bottom heating surface. Therefore, the critical parameters are the distance between jet nozzle and packed spheres, the shape of packed spheres and the fluid type in designing such cooling system. Kim et al. [12] measured the heat transfer of aluminum foams under the air jet flow of single-hole nozzle or 3×3 nozzle array. Their experimental results showed that the heat transfer of the aluminum-foam heat sink was higher than traditional pin–fin heat sink by 2–29%. Besides, the multi-hole nozzle had higher forced convection heat transfer capacity than single-hole nozzle at high

* Corresponding author at: Department of Mechanical Engineering, Chienkuo Technology University, No. 1, Chieh Shou N Rd., Changhua 500, Taiwan, ROC. Tel.: +886 4 7111111x3130; fax: +886 4 7357193.

E-mail addresses: tmjeng@cc.ctu.edu.tw, tm.jeng@msa.hinet.net (T.-M. Jeng).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.03.049
0017-9310/

Nomenclature

A	heated area (m^2)
A_{HT}	total heat-transfer area (m^2)
C_f	friction factor, Eq. (2)
d	average bead diameter (m)
F	inertial coefficient
g_L	longitudinal space between pin fins (m)
g_T	transverse space between pin fins (m)
H	height of test channel or height of heat sink (m)
h_{loss}	effective heat transfer coefficient for heat loss ($W/m^2/K$)
I	input current (A)
K	permeability (m^2)
k	thermal conductivity (W/m/K)
L	length of heat sink (m)
n	total numbers of brass beads
n_L	numbers of pin fins along the longitudinal direction
n_T	numbers of pin fins along the transverse direction
Nu	Nusselt number, Eq. (3)
Q_{in}	input heat (W)
Q_{loss}	loss heat (W)
Re	Reynolds number, Eq. (1)
s	side length of pin fin (m)
T	temperature (°C)
U_e	average fluid velocity at the channel exit (m/s)
V	input voltage (V)
V_j	average fluid velocity at the flow entry (m/s)
W	width of heat sink or width of test channel (m)
w_j	width of flow entry (m)
ΔP	pressure difference through heat sink (pa)

Greek symbols

ε	average porosity
μ	viscosity (kg/m/s)
ρ	density (kg/m^3)

Subscripts

d	transverse heat dispersion
e	effective
f	fluid
j	flow entry
s	solid
w	heated wall
nw	near-wall region
∞	core region or ambient
1	pure pin–fin heat sinks
2	pure packed-brass-beads heat sinks
3	pin–fin heat sinks fully filled with brass beads

Superscripts

$\bar{}$	mean value
$*$	effective

Reynolds number. Jeng et al. [13] experimentally discussed the thermal-fluidic characteristics of brass-beads packed bed with confined impinging air jet. The nozzle exit was rectangular. They indicated that the local Nusselt number of the heating surface right under the nozzle increased with decreasing the relative nozzle width. At the same pumping power, the configuration generating maximum average Nusselt number was the combination of maximum brass-bead diameter and minimum relative nozzle width. Hwang and Yang [14] numerically investigated the metallic porous block subjected to a confined turbulent slot jet. They found the impinging cooling performance can be effectively improved by employing the metallic porous block over their studied ranges.

The porous medium material has excellent flow-disturbing capacity and large heat-transfer area in a compact volume, but the bottom heat may be unlikely to be transferred to the top of porous medium structure due to worse effective thermal conductivity. If the porous medium material is combined with heat conducting columns with high thermal conductivity, the heat-transfer area is reduced partially, but the effective thermal conductivity of porous medium heat sink is increased. The overall heat-transfer capability may be enhanced, so as to meet the cooling requirement of future electronic modules at higher power. Therefore, the novel heat sinks combined with porous medium and metallic solid heat conducting columns have very high values in industrial application and academic discussion. Gill and Minkowycz [15] studied the conjugate mixed convection heat transfer along a vertical plate fin embedded in a saturated high-porosity porous medium. They numerically investigated the effects of solid boundary and inertia forces on local heat transfer for various thermal boundary conditions and pointed that those effects were important. Rizk and Kleinstreuer [16] numerically investigated the laminar heat transfer inside the porous medium channel with discontinuous heating blocks. They indicated that the porous medium could increase the heat transfer by 50%. Bhattacharya and Mahajan [17] embedded aluminum foams in the gaps of longitudinal plate-fin heat sink, and experimentally measured the heat transfer gain. The plate fin was made of aluminum alloy, transferring the heat up to the aluminum foams rapidly, which is equivalent to enlarging the heating area in contact with the aluminum foams. This configuration was proven to enhance heat transfer efficiently. DeGroot et al. [18] numerically studied the forced convection heat transfer in finned aluminum foam heat sinks. Their results indicate that adding aluminum fins into the aluminum-foam block significantly enhanced the heat transfer with only a moderate pressure drop penalty. Their work explained the heat transfer enhancement as an increase in equivalent conductivity of the finned/foam heat sink. DeGroot et al. [19] numerically explored the effect of thermal contact resistance on the performance of finned aluminum foam heat sinks. They changed contact resistances at the porous-solid interfaces up to the limit of an effectively infinite resistance and indicated that the impact of thermal contact resistance on the heat transfer performance in comparison to that for an ideal bond was small. They also showed that how the convective heat transfer enhancement could be achieved by the finned aluminum foam heat sink under poor contact conditions. Jeng and Tzeng [20] embedded a metal block into the sintered porous medium heat sink, and used that high-thermal-conductivity metal block to extend the heating surface into the porous medium, so as to enhance the overall effective thermal conductivity. Their results proved that the metal block can enhanced the heat transfer. Jeng et al. [21] embedded copper cylinders in diameter of 0.02 m and 0.03 m respectively in the aluminum-foam blocks with porosity of 0.9. Their experimental results proved that the average Nusselt number of aluminum-foam heat sink with a copper cylinder was 1.6 times of that of pure aluminum foams. Jeng and Tzeng [22] sintered 0.5–0.85 mm-diameter copper beads smoothly with the radial plate fins of the copper heat sink by thin layers at high temperature to form a LED cooling device with sintered-metal-bead-layer fins. A motor fan was