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Heat transfer and pressure drop in laterally perforated-finned heat sinks across different flow regimes

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ABSTRACT

Experiments were performed to investigate pressure drop and forced convection heat transfer from laterally perforated-finned heat sinks (LA-PFHSs) across a wide range of flow regimes ranging from laminar to turbulent. Perforations with square cross sections were implemented equidistantly along the lateral surfaces of the fins. Results were compared with those of the solid-finned heat sink (SFHS) that was used as the base of comparisons. Thermal-fluid characteristics were investigated under the changes in both perforation size and porosity. The pressure drag in LA-PFHSs was found as the dominant component of the total drag compared with the friction drag. Thermal performances of LA-PFHSs were categorized into three types of industrial demands that require overall colder heat sinks, more uniform temperature heat sinks, and lighter heat sinks. For this purpose, three performance parameters were defined, and each performance parameter was associated to a specific category of industrial demand. It was found that if the optimum range of porosities is obtained at a given perforation size, LA-PFHSs lower both thermal resistance and temperature non-uniformity across the heat sink base without increasing the pumping power. The excellent advantage of LA-PFHSs in weight sensitive applications was demonstrated through a new performance parameter as the mass-based thermal resistance, and 41–51% lower mass-based thermal resistance compared with that of the SFHS was achieved using LA-PFHSs with the maximum porosity, without increasing the pumping power.

1. Introduction

The low cost and simplicity of air-cooled heat sinks have made them among the most widely used thermal management solutions in low to intermediate heat flux applications. However, air-cooled heat sinks are susceptible to the drawbacks of low heat transfer coefficients, as well as relatively large temperature variations across the heat sink bases. In real applications, these limitations cannot be resolved by increasing the flow rates since the airflow is usually laminar or weakly turbulent in air-cooled heat sinks due to limited space or pumping power [1]. However, since the thermal characteristics of an air-cooled system are dictated by the thickness of the boundary layer formed over the surface, interrupting the boundary layer in order to hinder its further growth over the surface would potentially improve thermal performances. Among different boundary layer interruption techniques, perforated fins lead to lighter systems due to perforations, which would be valuable for weight sensitive applications like those in the aerospace industry.

Generally, perforations are implemented either along the length of the fin or on the lateral surface of the fin. The heat sink made with the former and latter groups of fins is called a longitudinal perforated-finned heat sink (LO-PFHS), and a lateral perforated-finned heat sink (LA-PFHS), respectively. While the heat transfer enhancement in a LO-PFHS is mainly due to increasing the heat transfer area [2–7], the boundary layer interruption resulting from the frequent terminating and restarting the boundary layer over perforations is the main mechanism to enhance the heat transfer rates in LA-PFHSs. Practically, inserting longitudinal perforations along the length of fins requires complex and expensive manufacturing processes, while inserting perforations on the lateral surfaces of either thin or thick fins can be performed through much easier and lower-cost manufacturing processes. Such advantage makes LA-PFHSs potentially more interesting for industrial applications. For this reason, investigating pressure drop and heat transfer characteristics of LA-PFHSs is the focus of the present study.

However, instead of well-documented thermal-fluid characteristics of a solid-finned heat sink (SFHS, imperforated heat sink), such knowledge in LA-PFHSs is limited mostly due to a lack of detailed and fundamental related investigations. The complex thermal-fluid physics in a LA-PFHS is mainly due to frequent boundary layer interruptions

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Nomenclature

A	Exposed area of a fin, including the surfaces inside the perforations (m^2)
d	Distance between the plane of the embedded thermocouple and the fin/channel base (m)
$D_h = \frac{2HW_{\mathrm{ch}}}{H+W_{\mathrm{ch}}}$	Channel hydraulic diameter (m)
f_{app}	Apparent friction factor
h	Heat transfer coefficient (W m^{-2} K^{-1})
H	Channel height (m)
K_c	Sudden contraction loss
K_e	Sudden expansion loss
K_s	Thermal conductivity of the heat sink (W m^{-1} K^{-1})
L	Channel length (m)
L_P	Perforation length (m)
M	Mass of fins (kg)
MBTR	Mass-based thermal resistance (kg K W^{-1})
N	Number of channels
N_P	Number of perforations
N_R	Number of perforation rows
P_p	Pumping power (W)
Q	Heat (W)
Q_{input}	Electrical input heat (W)
Re	Reynolds number based on the channel hydraulic diameter
$\mathrm{Re}_{\mathrm{le}}$	Laminar-equivalent Reynolds number
R_{HS}	Heat sink thermal resistance (K W^{-1})
S_x	Horizontal distance between adjacent perforations (m)
S_y	Vertical distance between adjacent perforations (m)
t_b	Heat sink base thickness (m)
t_f	Fin thickness (m)
T_b	Heat sink base temperature (K)
T_{film}	Film temperature (K)
T_i	Inlet air temperature (K)
T_o	Outlet air temperature (K)
$T_{s,\mathrm{avg}}$	Average fin/channel base temperature (K)
U	Approach velocity (m s^{-1})
$\dot{V}_{\mathrm{ch}}$	Volume flowrate inside the channel (m^3 s^{-1})
$\dot{V}_t$	Volume flowrate inside the duct (m^3 s^{-1})
W	Heat sink width (m)
W_{ch}	Channel width (m)
ΔP	Pressure drop (Pa)
ΔT	Temperature difference (K)

Greek symbols

β	A percentage of change in the mass-based thermal resistance of the SFHS
ε	The fraction of cross section of the duct that air passes through
$\eta_{\mathrm{LA-PFHS}}$	Effectiveness of a LA-PFHS
θ	Normalized temperature non-uniformity
μ	Dynamic viscosity (Pa s)
ρ	Air density (kg m^{-3})
ϕ	Porosity

Subscripts

LA-PFHS	Lateral perforated-finned heat sink.
max	Maximum
min	Minimum
SFHS	Equivalent property of the solid-finned heat sink at the pumping power of a LA-PFHS

over perforations, as well as the flow interactions over perforations, which result a complexity in the key parameters (like the entrance length) that are required to characterize the flow and heat transfer inside the channels. As the first related comprehensive studies, Shaeri et al. [8,9] computationally investigated fluid flow over the perforations, pressure and friction drags, temperature distribution across the fins, and heat dissipation from LA-PFHSs at different perforation sizes and porosities in turbulent and laminar flows. In conclusion, they correlated Nusselts numbers as functions of porosity and Reynolds numbers, but those correlations were not physics-based and developed only through a curve-fitting process. These studies were motivations for further related research. Ismail et al. [10] extended the study by Shaeri et al. [8] by changing the cross sections of the perforations from square to circle, hexagon, and triangle. Willockx [11] used the inverse heat conduction problem technique to solid and laterally perforated fins, but the temperature measurement and the accuracy of the solution were affected by a systematic error due to the camera lens reflection. However, Willockx [11] confirmed the results in [8] about the thinning of the boundary layer due to a negative pressure gradient in the perforation. Dhanawade et al. [12,13] and *Al*-Doori [14] experimentally reported enhancement of heat transfer coefficients from LA-PFHSs by relying on the exposed area of the LA-PFHSs, which includes the surfaces inside the perforations as well. Also, although there are several studies about laterally perforated fins in other air-cooled systems rather than heat sinks [15–18], because of the frequent flow interactions over perforations with each other along relatively long fins in LA-PFHSs, thermal-fluid physics in a LA-PFHS is different from that in perforated fins investigated in [15–18].

In addition, the lack of fundamental research about thermal-fluid characteristics of LA-PFHSs has resulted in limited understanding of the industrial benefits of these cooling devices, as such still SFHSs are the dominant heat sinks used in real applications. To the best knowledge of the authors, regardless of the lack of sufficient knowledge behind thermal-fluid physics in LA-PFHSs, the main reason for uncertainty in leveraging LA-PFHSs as primary thermal management solutions in industrial applications is the lack of accuracy in describing thermal performances of LA-PFHSs. For example, reporting heat transfer coefficients of LA-PFHSs based on their exposed area would be confusing due to a monotonic change in the exposed area by increasing the porosity. The results from our recent research in [19] showed that increasing the porosity beyond a threshold value deteriorates thermal performances. In addition, the authors demonstrated the capability of LA-PFHSs to improve the laminar thermal performances without any penalty in the pumping power, through an experimental study by considering a wider range of perforation sizes and porosities [19]. Besides, for the first time, local thermal resistances inside the channels of LA-PFHSs were presented in [19]. The present study is a further extension of our recent research in [19] to turbulent flows with the main focus on presenting valid techniques to describe thermal performances of LA-PFHSs to use in industrial applications. For this reason, based on a design goal, cooling performances of LA-PFHSs are categorized into three industrial demands that require (i) colder heat sinks to dissipate a fixed amount of heat, (ii) more uniform temperature on the heat sink bases, and (iii) lighter heat sinks. Square cross sectional perforations with three different sizes are implemented on the lateral faces of the fins, and an individual perforation size is investigated in five different porosities. The results are compared with those of the SFHS that is used as the base of comparisons. The present study is the first experimental attempt to address the industrial benefits of LA-PFHSs across all flow regimes by considering a wide range of perforation sizes and porosities.