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Convective heat transfer performance of airfoil heat sinks fabricated by selective laser melting

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ABSTRACT

This paper presents the forced convective heat transfer performances of novel airfoil heat sinks produced by Selective Laser Melting (SLM). Heat sinks with staggered arrays of NACA 0024 and NACA 4424 airfoil shaped fins were investigated experimentally and the results were compared with conventional heat sinks with circular and rounded rectangular fins. In addition, NACA 0024 heat sinks with angles of attack (α) ranging from 0° to 20° were also fabricated and the effects of the angle of attack (α) on the heat sink thermal performances were examined. Experiments were conducted in a rectangular air flow channel with tip (CL_t) and lateral (CL_h) clearance ratios of 2.0 and 1.55 and with Reynolds numbers (Re) ranging from 3400 to 24,000. Numerical studies were first performed to validate the experimental results of the circular finned heat sink and reasonably good agreement between the experimental data and numerical results were observed. Comparison of the experimental results showed that the heat transfer performances of the airfoil and rounded rectangular heat sinks exceeded those of the circular heat sink. The experimental Nusselt numbers were computed based on the heat sink base area (Nu_b) and the total heat transfer area (Nu_t). In comparison with the circular heat sink, highest enhancements in Nu_b and Nu_t of the NACA 0024 heat sink at $\alpha = 0°$ were 29% and 34.8%, respectively. In addition, the overall heat transfer performances of the NACA 0024 heat sinks were also seen to increase with increasing α. The results suggest that the streamline geometry of the airfoil heat sink has low air flow resistance, which resulted in insignificant bypass effect and thereby improving the heat sink thermal performance. In addition, the increase in α further improves the heat transfer performance of the NACA 0024 heat sinks through the formation of vortices which enhanced fluid mixing. Finally, based on the above mechanisms proposed, a semi-analytical model was developed to characterize the heat transfer performances of the NACA 0024 heat sinks for the range of α and Re tested. In comparison with the experimental data, reasonably accurate predictions were achieved with the model where the deviations in Nu_b were less than 7% for $Re \geq 6800$.

1. Introduction

Forced convective heat transfer with extended surfaces is commonly used to cool electronic devices. Air is often a preferred cooling medium as it is readily available and effective cooling can be achieved without the need of complex operating facilities. Finned arrays are commonly installed on electronic heat sources to maintain the component temperatures within the operating limits. The increase in heat transfer surface area and the induced surface-to-air interactions such as turbulent mixing, vortex shedding and thermal boundary layer disruption are the mechanisms widely suggested for the enhanced thermal performance observed. However, with the miniaturization of electronic devices and the increase in component level heat flux, the continuous development of pin fin designs with greater cooling efficiency becomes increasingly important.

Investigations on pin fin heat sinks can be broadly classified into (1) the effects of pin fin arrangement, (2) the effects of channel wall-to-fin clearance, and (3) the effects of pin fin geometry. Bilen et al. [1], for instance, investigated the heat transfer performances of in-line and staggered cylindrical fin array heat sinks with varying

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Nomenclature

A	area (m^2)
A_b	base area (m^2)
A_t	total heat transfer area (m^2)
AR	aspect ratio
B	heat sink width (m)
c	chord length (m)
C	flow channel cross section height (m)
C_s	skin friction drag coefficient
C_p	pressure drag coefficient
C_i	induced drag coefficient
CL_t	tip clearance ratio
CL_h	lateral clearance ratio
D	drag coefficient
D_c	circular fin diameter (m)
D_h	flow channel hydraulic diameter (m)
f	friction factor
h	heat transfer coefficient ($W/m^2 \cdot K$)
H	heat sink height (m)
k	turbulent kinetic energy (m^2/s^2)
k_l	thermal conductivity ($W/m \cdot K$)
Nu	Nusselt number
P	pressure (Pa)
q	heat rate (W)
q_l	heat loss (W)
Pr	Prandtl number
Re	Reynolds number
S_x	pin fin spanwise separation (mm)
S_y	pin fin streamwise separation (mm)
T	temperature (°C)
T_s	heat sink base temperature (°C)
U	velocity (m/s)
W	flow channel cross section width (m)

Greek Symbols

α	angle of attack
ε	turbulent energy dissipation rate (m^2/s^2)
Γ	circulation (m^2/s)
ν	kinematic viscosity (m^2/s)
ν_t	turbulent kinematic viscosity (m^2/s)

Subscripts

ave	average
b	base
fc	forced convection
in	inlet
nc	natural convection
out	outlet
rad	radiation
s	solid
sim	simulated
sys	system
t	total

Constants

A	constant in Eqs. (40) and (42)
B	constant in Eqs. (40) and (42)
C_r	constant in Eqs. (23) and (40)
C_1	constant in k-ε model
C_2	constant in k-ε model
C_μ	constant in k-ε model
m	constant in Eq. (19)
n	constant in Eq. (19)
σ_k	constant in k-ε model
σ_e	constant in k-ε model

fin separation in the streamwise direction. It was determined that the staggered arrangement resulted in higher heat transfer enhancement than the in-line arrangement and the maximum heat transfer was recorded with the fin separation-to-diameter ratio of 2.94. Subsequently, Jeng and Tzeng [2] studied the performances of square fin arrays with varying streamwise and spanwise fin separations using the transient single-blow technique. The fin Nusselt number of staggered square fins was determined to be approximately 20% higher than the in-line circular fins and the best performing staggered square fins have inter-fin pitches of 1.5 in both streamwise and spanwise directions. Similar studies were also performed by Akyol and Bilen [3] and Bilen et al. [4] with hollow rectangular and tube fins and the relationships between fin arrangement and heat transfer performance were correspondingly established. In the above studies, staggered arrangements have demonstrated higher heat transfer performances as compared to in-line arrays as a result of the increased turbulence mixing but due to the additional obstruction to the fluid flow imposed by the staggered arrangement, higher pumping power across the heat sinks is also required.

In many practical applications, heat sinks are often mounted on electronic heat sources where they are not fully shrouded. As the fluid tends to seek the path of least resistance, the existence of tip and lateral clearances may result in significant amount of air flow bypassing the fins, reducing the air velocity through the fins and affecting the heat sink performance. Over the years, the effects of clearance ratio on the hydraulic and thermal performances of the heat sinks have also been critically examined. For instance, Sparrow et al. [5] analyzed the laminar heat transfer characteristics of longitudinal fin arrays and determined that in the presence of larger tip clearance and smaller fin spacing, heat transfer by forced convection was negligible along the fins but increased evidently near the fin tip. Dogruoz et al. [6] experimentally investigated the hydraulic resistance and heat transfer characteristics of in-line square fin array with tip clearance-to-fin height ratios (CL_t) ranging from 0 to 3 and concluded that the effects of fin geometry on the hydraulic resistance of the heat sinks diminished with increasing CL_t. In addition, experiments conducted at the approach velocity of 4 m/s also revealed that the heat sink thermal resistance has relatively low sensitivity to the change in CL_t. In the studies performed by Elshafei [7], the CL_t of 0.22 exhibited higher Nusselt number as compared to the fully-shrouded configuration and it was suggested that the clearance gap served as turbulence promoter to increase the heat transfer rate. In addition to experimental investigations, numerous models which included the effects of bypass were also proposed to predict the heat sinks performances. For instance, Jonsson and Moshfegh [8] investigated the performance of heat sinks with different tip and lateral clearances and developed empirical bypass correlations to predict the heat sinks' Nusselt number and dimensionless pressure drop. On the other hand, Dogruoz et al. [6] developed a semi-analytical two-branch by-pass model by assuming that the air flow through the heat sink does not change along the streamwise direction and subsequently included the effects of air leakage from the heat sink [9]. In the above models,