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Experimental investigation of chimney-enhanced natural convection in hexagonal honeycombs

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Abstract The natural convective heat transfer performance of an aluminum hexagonal honeycomb acting as a novel heat sink for LED cooling is experimentally investigated. The concept of adding an adiabatic square chimney extension for heat transfer enhancement is proposed, and the effects of chimney shape, height, and diameter are quantified. The average Nu_{av} of a heated honeycomb with straight chimney is significantly higher than that without chimney, and the enhancement increases with increasing chimney height. At a given chimney height, honeycombs with divergent chimneys perform better than those with convergent ones. For a fixed divergent angle, the Nu_{av} number increases monotonically with increasing chimney height. In contrast, with the convergent angle fixed, there exists an optimal chimney height to achieve maximum heat transfer.

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Keywords natural convection, honeycomb, adiabatic chimney, experiment

The functioning of electronic devices, especially white light-emitting diode (LED) lights, depends largely on the operating temperature. Under high operating temperatures they may fail prematurely due to thermal runaway, epoxy degradation, and thermal stressing, and thus efficient heat dissipation is essential for long-term reliability. Natural convection across compact heat sinks such as pin/plate fin arrays has been widely employed for electronics cooling, due mainly to their high reliability and noise-free characteristics. However, relative to forced convection, the low heat transfer (HT) efficiency of natural convection limits significantly its application in power electronics carrying higher thermal load.

A variety of techniques have been proposed to enhance HT in natural convection such as pin/plate fin arrays,[1] cellular metallic foams,[2] ultrasonic vibration,[3] enclosures filled with nanofluids[4] and wavy surfaces.[5] From the perspective of heat transfer enhancement, these techniques may be classified into two categories. One is to increase the total HT area; the other is to directly increase the HT coefficient. For the former, by employing a heat sink having a larger specific surface area, the overall heat flow can be significantly increased. For the latter, there are many ways to enhance the HT coefficient, such as rough surface to reduce boundary layer thickness,[6] turbulator to intensify flow mixing,[7] and increased flow velocity.[8] However, it needs

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to be noted that unlike forced convection, the driving force for natural convective flow is the buoyancy force caused by density difference of fluid and this buoyancy lift is sensitive to flow friction. Therefore, increasing the specific surface area may increase the flow resistance which in turn will reduce the mass flow rate, thus limiting the enhancement in convective heat transfer.

Haaland and Sparrow[9] investigated the chimney effect in a channel with heat source. Asako et al.[10] successfully applied the concept of chimney effect[9] to enhance natural convection in a single heated tube. They added an adiabatic circular extension (chimney) to the heated tube having constant wall temperature and obtained optimal chimney diameter and height for maximum HT. The numerical calculations showed that the heat transfer rate for a single heated tube with a chimney of optimal diameter was about 2.5 times higher than that without chimney. Subsequently, Straatman et al.[11] systemically examined the chimney effect in a single heated parallel-walled channel covered with an adiabatic extension (straight chimney). They found that by adding a straight chimney with height from 1.5 to 4 times the channel height, the HT was increased from 10% to 30%. In particular, an expanded chimney (having a longer length) offered an enhancement from 30% to 250%. However, although the single tube-chimney system is attractive for enhancing natural convective heat transfer, the single tube can not be directly used as heat sink. Combining multiple single pipes with a substrate enables the use of chimney effect for cooling the electronic devices. To this end, Shahin and Floryan[12] numerically evaluated the increase of HT in a system of 2D infinite channels with adiabatic chimneys, and demonstrated that periodic channels with adiabatic chimneys offered better thermal performance (higher HT rate) than bare channels.

Metallic honeycombs are bio-inspired structures that combine multiple 2D channels. In addition to structural advantages such as ultra light-weight, periodic topology, high specific stiffness and strength, they also possess high specific surface area and high conductive walls that are attractive for heat sink constructions. A number of investigations have been carried out to characterize the HT performance of metallic honeycombs, covering heat conduction,[13,14] forced convection,[15,16] and phase change[17] in different applications.[18] However, no study on natural convection in honeycombs exists in the open literature. The present research aims at experimental investigaion on the natural convective HT performance of heated aluminium (Al) honeycombs, with special emphasis placed upon the enhancement of HT by adding an adiabatic square extension (chimney). The effects of chimney shape (straight, convergent, and divergent), height, and diameter are experimentally quantified.

To experimentally investigate the thermal performance of chimney-enhanced natural convection HT in hexagonal honeycombs, a purposely-designed test rig consisting of Al honeycomb sample, adiabatic chimney extensions, power supply system and data acquisition system is built. The Al honeycomb integrated with a 2 mm thick Al substrate is fabricated by precision wire cutting. The test sample, with size of 0.08 m (length) $\times$ 0.074 m (width) $\times$ 0.05 m (height), contains hexagonal holes of 5.14 mm and 1 mm in length and thickness, respectively. To model typical thermal boundary condition for LED devices, an electrical film heater with surface area identical to that of honeycomb substrate is attached to the substrate, with its power input controlled by an adjustable DC power supply. Except for those faces along the z-axis direction (parallel to the substrate), all the other faces of the honeycomb sample are covered with low conducting Perspex plates with thermal conductivity of 0.2 W$\cdot$(m$\cdot$K)$^{-1}$ for thermal insulation. To assess the chimney effect, a square extension fabricated with Perspex plates is placed above the honeycomb, as shown schematically in Fig. 1. The height, size (length and width), and type (straight, convergent, or divergent) of the chimney are varied to investigate their effects on natural convective HT in the honeycomb-chimney system (HCS). The measurements are all performed in a big chamber capable of maintaining a stable thermal and fluid surrounding.

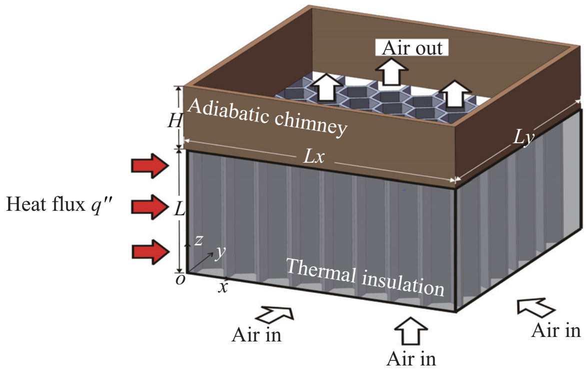

Fig. 1. Schematic of Al honeycomb heat sink with straight chimney and constant heat flux thermal boundary.

For quantitative evaluation of the thermal performance of the HCS, the average Nusselt ($Nu_{\rm av}$) and Rayleigh ($Ra_{q''}$) numbers are introduced as $Nu_{\rm av} = h_{\rm av}L/k_{\rm f}$, $Ra_{q''} = g\beta q''L^4/(\alpha_{\rm f}\nu_{\rm f}k_{\rm f})$, where L is a characteristic length (height of honeycomb selected for the present study), g is gravitational acceleration, q'' is the HT rate of natural convection in the HCS (i.e., net heat input by electrical heater), whilst β, $\alpha_{\rm f}$, $\nu_{\rm f}$, and $k_{\rm f}$ are the coefficient of thermal expansion, thermal diffusivity, kinematic viscosity, and thermal conductivity of the fluid (air), respectively. The average natural convective HT coefficient $h_{\rm av}$ in the definition of $Nu_{\rm av}$, is obtained by $h_{\rm av} = q''/(T_{\rm w} - T_\infty)$ where $T_{\rm w}$ and T_∞ are the temperature of the heated substrate and environment fluid. Relevant thermophysical properties appearing in the above definition of $Nu_{\rm av}$ and $Ra_{q''}$ are all evaluated at the characteristic temperature $(T_{\rm w} + T_\infty)/2$. It is worth noting here that the Pr number is not varied as the measurements are performed in air only.

The test data are all obtained under steady-state condition: fluctuations in both the average substrate temperature and the temperature difference between the substrate and ambient are restricted to within ±0.2 K during a period of 100 min. Determination of $Nu_{\rm av}$ using the present experimental setup is affected by the following parameters: q'', $T_{\rm w}$ T_∞, $k_{\rm f}$, and L. With L and $k_{\rm f}$ fixed, the errors associated with the measurement of $Nu_{\rm av}$ may be estimated as[19] $\Delta Nu_{\rm av}/Nu_{\rm av} = \sqrt{(\Delta q''/q'')^2 + [\Delta T_{\rm w}/(T_{\rm w} - T_\infty)]^2 + [\Delta T_\infty/(T_{\rm w} - T_\infty)]^2}$.

The error associated with the temperatures $T_{\rm w}$ and T_∞ measured by respectively averaging the readings of nine identical thermocouples embedded in the substrate and distributed in the big chamber (four thermocouples) was estimated to be 0.2°C. The minimum substrate temperature difference $(T_{\rm w} - T_\infty)$ was measured to be about 13.1°C at $q'' = 1\,208.9$ W/m^2. The error of q'' measured by the heat flux gauge was estimated to be within 2%. Overall, the uncertainty in the present measurement of $Nu_{\rm av}$ was less than 2.94%.

In the present study, the overall thermal performance (evaluated by $Nu_{\rm av}$) of a honeycomb heat sink (without chimney, i.e., $H/L = 0$) is investigated by experimentation. The experimentally measured $Nu_{\rm av}$ number of natural convective HT in the system is strongly dependent on the $Ra_{q''}$ number, as shown in Fig. 2. Within the present laminar flow range ($Ra_{q''} \in [3.13 \times 10^7, 1.56 \times 10^8]$), the $Nu_{\rm av}$ number increases significantly as the $Ra_{q''}$ number is increased. The test data of the $Nu_{\rm av}$ number may be correlated to the $Ra_{q''}$ number using the least square method with a coefficient of association $R^2 = 0.999$, as $Nu_{\rm av} = 2.878 Ra_{q''}^{0.239}$. Further, the smooth plate is also included for comparison.[20] The $Nu_{\rm av}$ number for the heated Al honeycomb is 4-fold greater than that for the smooth plate over the present $Ra_{q''}$ number range.

To avoid extra flow resistance by typical enhancement techniques for natural convective HT via enlarging surface area or increasing flow disturbance, the concept of adding an adiabatic extension to the honeycomb is assessed. Figure 3 displays the experimentally measured HT performance of heated Al honeycomb with varying chimney heights. By adding a straight chimney of the same size as the honeycomb, the $Nu_{\rm av}$ number is markedly increased and the enhancement increases as the chimney height (H/L) is increased within the experimental range (0–4.5 times the honeycomb height). The enhancement is caused by the increased mass flow rate due to the chimney suction effect. As the fluid (air) is heated in the vertical channel, it flows upwardly due to fluid density difference along the vertical direction from the tube inlet to outlet. Without adding chimney, the thermal fluid flow exiting the honeycomb will converge to the ambient fluid. Upon adding an adiabatic chimney, the fluid with higher temperature and velocity (compared with those of the ambient fluid) continues to flow upwardly, maintaining further the density difference between the outlet and inlet to suck the fluid. Meanwhile, the fluid velocity in the chimney is also increased that is helpful for further HT enhancement.

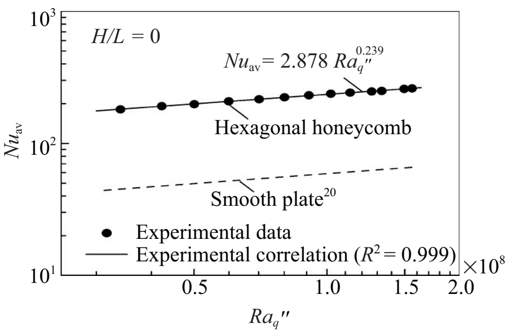

Fig. 2. $Nu_{\rm av}$ plotted as a function of $Ra_{q''}$ for heated honeycomb without chimney.

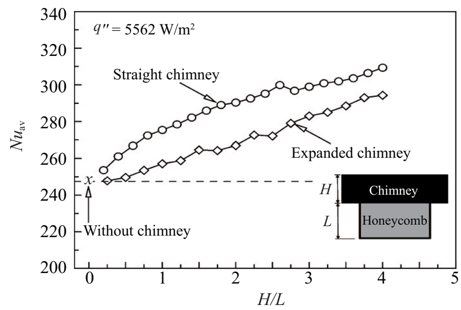

Fig. 3. $Nu_{\rm av}$ plotted as a function of H/L for fixed heat flux.

In addition to the influence of H/L upon the $Nu_{\rm av}$ number, the influence of chimney size (length and width) is also analyzed via measurement. To this end, an expanded chimney having twice the length and width of the honeycomb is added to the honeycomb. Figure 3 shows that the $Nu_{\rm av}$ number with expanded chimney is significantly larger than that without chimney but considerably smaller than that with straight chimney. For a single circular tube-chimney system, it has been reported[10] that the HT enhancement by chimney is sensitive to the chimney to tube diameter ratio $R_{\rm CT}$. As this ratio is increased, the enhancement initially increases and then decreases. For the presently investigated multitubes (honeycomb), the average $R_{\rm CT}$ falls within the decreasing range of enhancement. Therefore, relative to a straight chimney, to enlarge the chimney size will not further enhance the HT performance, which is quantitatively consistent with Ref. 10.

Figure 4(a) displays the influence of chimney shape (convergent and divergent) on overall HT performance at a given $H/L = 2$. Compared with honeycombs without extensions, a significant enhancement in natural convective HT is observed for both types of chimney, but the enhancement decreases with increasing chimney degree γ (defined as the angle between the chimney side wall and the z-axis). For convergent chimney, the $Nu_{\rm av}$ number sharply decreases as the chimney angle is increased, which may be attributed to the sharply reduced mass flow rate caused by a significantly reduced flow export. For divergent chimney, the $Nu_{\rm av}$ number slightly decreases with increasing chimney angle. The bigger the flow export is, the weaker the chimney effect is. Besides, the bigger export will induce flow separation bubble in trapezoid to further dissipate the energy. It is also noted that although the enhancement by both types of chimney is reduced as the chimney angle is increased; the $Nu_{\rm av}$ number in the divergent case is higher than that in the convergent case due to higher mass flow rate in the former.

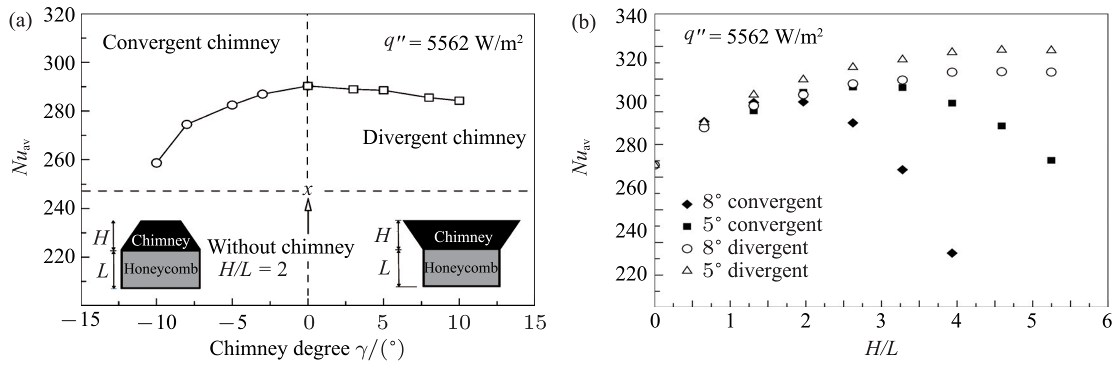

Fig. 4. HT enhancement by convergent and divergent chimneys: (a) influence of chimney degree, and (b) influence of H/L.

For both convergent and divergent chimneys, to investigate the chimney height effect, four groups of testing with the chimney degree γ fixed at 5° or 8° are conducted. The experimental results presented in Fig. 4(b) exhibit two distinct trends. Firstly, for convergent chimneys, there exists a peak of the $Nu_{\rm av}$ number as H/L is increased, which may be caused by the coupling effect between reduced mass flow rate and increased flow velocity due to smaller flow exit with increasing chimney height. The case of $\gamma = 8°$ reaches the peak first because at the same H/L, the chimney with $\gamma = 8°$ has a flow exit smaller than that with $\gamma = 5°$. Secondly, for divergent chimneys, the $Nu_{\rm av}$ number increases monotonically with increasing H/L, eventually reaching a constant value. At a given divergent chimney angle, increasing the chimney height increases the flow exit, reducing therefore the enhancement in heat transfer by chimney effect.

For a given honeycomb heat sink with fixed H/L, adding a divergent chimney with a smaller divergent angle is preferred, e.g. the enhancement by adding a 5° chimney is higher than that by adding an 8° chimney, see Fig. 4(b). When H/L is relatively small (short chimneys, with $H/L = 0$–1.5), the four kinds of chimneys exhibit similar HT behavior. However, for convergent chimneys within this range, the enhancement by adding an 8° chimney is slightly larger than that by adding a 5° chimney. This may be explained in terms of the coupling mechanisms: (1) the flow near the heated honeycomb is enhanced by the higher velocity resulting from the smaller flow exit (larger convergent angle); (2) meanwhile the mass flow rate is slightly reduced as the flow exit of a relatively short chimney (larger convergent angle) is slightly reduced. For relatively long chimneys, the techniques to induce a higher mass flow rate such as adding a divergent chimney with small divergent angle may be helpful for HT enhancement.

The natural convective HT performance of heated Al honeycombs is investigated experimentally. The $Nu_{\rm av}$ number is correlated with the $Ra_{q''}$ number using the measurement data. Conclusions drawn from the present study are summarized as follows. (1) By adding an adiabatic straight chimney, the $Nu_{\rm av}$ number of natural convection in heated honeycombs is significantly increased, and the enhancement increases with increasing H/L within the present experimental range (0–4.5 times the height of honeycomb). (2) At a given H/L, adding a divergent chimney is preferred relative to a convergent one. (3) For convergent chimney with fixed convergent angle, there exists an optimal H/L to achieve maximum HT.

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