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Thermo-fluidic characteristics of natural convection in honeycombs: the role of chimney enhancement

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The natural convective heat transfer performance and thermo-fluidic characteristics of honeycombs with/without chimney ex-tensions are numerically investigated. The present numerical simulations are validated by the purposely-designed experimental measurements on honeycombs with/without chimney. Good agreement between numerical simulation and experimental meas-urement is obtained. The influences of inclination angle and geometric parameters such as cell shape, streamwise and spanwise length are also numerically quantified. With the increment in inclination angle, the overall heat transfer rate decreases for the honeycombs with/without chimney. For honeycombs with the same void volume fraction but different cell shapes, there is little difference on the overall heat transfer rate. To enhance the natural convective heat transfer of honeycombs, these techniques including increasing the length of honeycomb in streamwise/ spanwise direction, increasing the thermal conductivity of hon-eycomb structure or adding a chimney extension may be helpful.

natural convection, honeycomb, adiabatic chimney, inclination angle

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1 Introduction

Low failure rate, long-term functioning reliability, high practicability and economy as well as good thermal design are the core demands for most engineering applications such as solar collector [1], heat exchanger [2], electronic devices [3] and so on. Particularly, efficient heat dissipation plays a vital role in electronic devices, e.g. LED lamps. Compared with heat sinks subjective to forced convective cooling, 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.

There are various techniques to enhance natural convective heat transfer, such as pin/plate fin arrays [4], cellular metallic foams [5], ultrasonic vibration [6], enclosures filled with nano-/micro-fluids [7,8] and geometrically designed surfaces [9,10]. Amongst them, a concept of adding an adiabatic chimney extension (originated by Haaland and Sparrow [11]) on a single heated tube was proposed by Asako et

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al. [12] to enhance natural convection. A 2.5 times higher heat transfer rate was numerically obtained. For the case of square channel, Straatman et al. [13] systemically examined the chimney effect in a single heated parallel-walled channel covered with an adiabatic extension. They found that the expanded chimney (having a longer length) offered an enhancement ranging from 30 to 250 percent.

However, although the single tube-chimney system is attractive for enhancing natural convective heat transfer, the single tube cannot be directly used as heat sink for electronics cooling. Honeycombs are naturally existing, bio-inspired structures with multiple channels with the advantage of ultra light-weight, high specific stiffness and strength as well as high specific surface area and high conductive walls, which are particularly attractive for heat dissipation. The previous investigations mainly focused on heat conduction [14–16], forced convection [17–19] and phase change [20–22] in various applications [23]. Yang et al. [24] experimentally investigated the heat transfer enhancement by adding an adiabatic square chimney on the heated hexagonal honeycomb. A strong enhancement was experimentally observed. However, little attention on the thermo-fluidic characteristics has been paid to the chimney effect of natural convection in honeycombs. The present research aims to investigate the natural convective heat transfer performance of heated aluminum (Al) honeycombs, with special focus upon the thermo-fluidic characteristics of chimney-enhanced natural convection. To validate the present numerical simulation, the heat transfer rates with/without hexagonal chimney are compared with the experimental measurements. The influence of inclination angle and geometric parameters such as cell shape, streamwise and spanwise length are also numerically quantified.

2 Numerical simulation

In the present study, a series of numerical simulations are conducted to get a physical insight into the thermo-fluidic features of natural convective heat transfer in honeycombs. Honeycombs with the same porosity but different kinds of cell shapes (in-line/staggered square, hexagon and circle, see Figure 1) are built using the commercially available software-SOLIDWORKS 2013^{TM}. The solid geometries are then imported into ANSYS ICEM CFD 14.5^{TM} to generate the mesh, favoring the preparation for the numerical models that are based on the finite volume method (FVM) embedded within a commercially available software package ANSYS-CFX 14.5^{TM}; see Figure 2.

Given the periodic structure of the honeycomb, only one-eighth of the bulk honeycomb (periodic unit cell) in the spanwise direction is consider in the present numerical model, as illustrated in Figure 2(a). To experimentally mimic the real experimental condition of natural convection in a large space and to numerically avoid specifying the unknown inflow and outflow boundaries, the one-eight honeycomb incorporated with the substrate is emerged in a big air mass (air temperature is fixed at T_∞) as the computational domain (see Figure 2(a)). This kind of boundary settings is consistent with the numerical methods reported in ref. [12]. For the case without chimney, the corresponding thermo-fluidic boundary conditions are described as follows: (1) the air inflow and outflow boundaries are separately set as opening and outlet boundaries, while the other side surfaces of the computational domain are symmetry; (2) the heating substrate of the honeycomb is set as the constant heat flux thermal boundary; (3) the end surface of the honeycomb in the spanwise direction is insulated. For the case with adiabatic chimney (see Figure 2(b)), an insulated honeycomb duplicated from the Al honeycomb is put on the top along the streamwise direction.

The incompressible steady-state natural convective laminar flow and conjugated heat transfer are described by the three-dimensional incompressible continuity, Navier-Stokes and energy equations. Boussineq assumption is made in the buoyancy item. The related thermophysical properties of aluminum and air are listed in Table 1. Three sets of the meshes with 854,682, 1,611,372 and 4,935,217 elements are used to check the mesh sensitivity, and the convergence criterion of 10^{-6} is used for each calculation.

3 Experimental validation

To validate the numerical simulations on the natural convective heat transfer of honeycomb, well-designed experiments schematically shown in Figure 3 are conducted. The experimental test rig is placed in a Plexiglas room that is big enough to maintain the ambient temperature stable. An Al honeycomb sample with the global size of 80 mm (length) × 74 mm (width) × 50 mm (height) is fabricated by the preci-

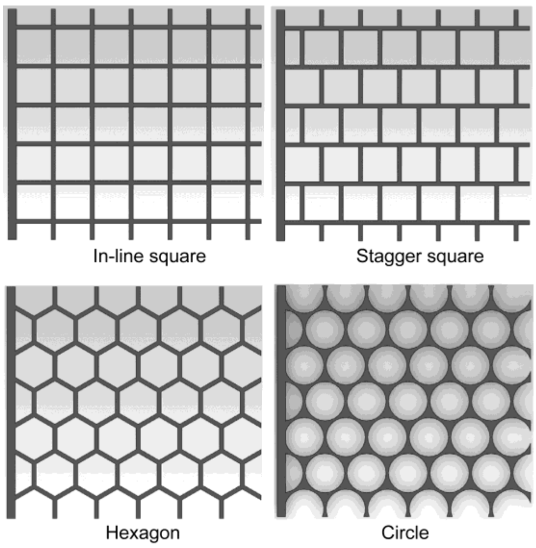

Figure 1 Four kinds of CAE-rebuilt honeycombs with various cell shapes.

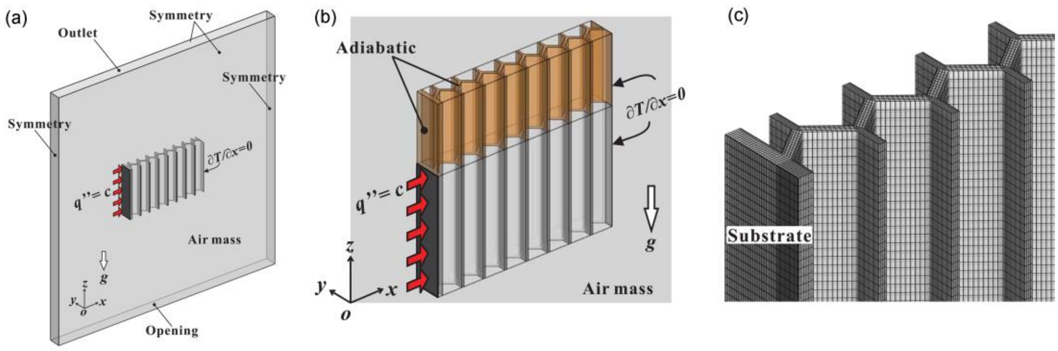

Figure 2 Numerical model for natural convective heat transfer in honeycomb: (a) schematic of computational domain without adiabatic chimney; (b) computational domain with chimney; (c) representative mesh of one selected honeycomb.

Table 1 Thermophysical properties of aluminum and air with reference temperature of 300 K [25].

	ρ (kg/m^3)	c_p (J/kgK)	k (W/mK)	β (/K)	ν_f(m^2/s)
Air	1.1614	1.007	0.0263	3.33×10^{-3}	1.577×10^{-5}
Al	2700	903	190	/	/

sion wire cutting, whose cells are hexagons with 8.9 mm and 1mm in length and thickness respectively (see Figure 3(b)). Due to the precision wire cutting fabrication process, the Al honeycomb is integrated with a 2 mm thick Al substrate, where contact thermal resistance can be safely neglected. Given the thermal boundary condition for LED devices, an electrical film heater with surface area identical to that of the honeycomb substrate is attached to the substrate, with its power input controlled by an adjustable DC power supply. Except for those faces along the flow direction (see Figure 3(a)), all the other faces of the honeycomb sample are covered with low conducting Perspex plates with a thermal conductivity of 0.2 W/(mK) for thermal insulation. To assess the chimney effect, a hexagonal honeycomb chimney fabricated by the precise laser cutting is placed above the Al honeycomb, as shown schematically in Figure 3(c). Given the installation angle of LED devices, a right-angle geometry support is designed to allow the whole test rig to continuously turn from 0° to 90°.

To quantitatively evaluate the thermal performance of the honeycomb as well as the honeycomb-chimney system, the average Nusselt (Nu_{av}) and Rayleigh ($Ra_{q''}$) numbers are introduced as: 1) Nu_{av} number,

$$Nu_{av} = \frac{h_{av} L}{k_f}, \tag{1}$$

and 2) $Ra_{q''}$ number,

$$Ra_{q''} = \frac{g\beta q'' L^4}{\alpha_f \nu_f k_f}, \tag{2}$$

where L is a characteristic length (height of honeycomb selected for the present study), k_f is the thermal conductivity of fluid phase (air), h_{av} is the average natural convective heat transfer coefficient ($h_{av} = q''/(T_w - T_\infty)$), q'' is the natural convective heat transfer rate of the honeycomb, T_w and T_∞ are the temperature of the heated substrate and environment fluid, g is gravitational acceleration; β, α_f and ν_f are the coefficient of thermal expansion, thermal diffusivity, kinematic viscosity and thermal conductivity of the fluid (air). Relevant thermophysical properties appearing in the above definition of Nu_{av} and $Ra_{q''}$ are all evaluated at the characteristic temperature (T_w+T_∞)/2. It is worth noting here that the Pr number is supposed to be constant in the present study.

Determination of Nu_{av} using the present experimental setup is affected by the following parameters: q'', T_w, T_∞, k_f and L. With L and k_f fixed, the errors associated with the measurement of Nu_{av} may be estimated as [26]:

$$\frac{\Delta Nu_{av}}{Nu_{av}} = \sqrt{\left(\frac{\Delta q''}{q''}\right)^2 + \left(\frac{\Delta T_w}{T_w - T_\infty}\right)^2 + \left(\frac{\Delta T_\infty}{T_w - T_\infty}\right)^2}. \tag{4}$$

The substrate and the ambient temperature are separately estimated by the arithmetically averaged temperatures measured by T-type thermocouples (CO-T2, Omega™) fixed in three grooves and the big chamber. The heat flux is measured by a heat flux sensor (HFS-3, Omega™) connected to a digital voltage scanner. Based on the manual of sensor uncertainties from Omega™, the error associated with the temperature and heat flux are ±0.2°C and ±2%, respectively. Therefore, the overall uncertainty in the present measurement of Nu_{av} was estimated to be less than 4.5%.

4 Results and discussions

4.1 Validation of numerical simulations

In the present study, the overall heat transfer rate and the thermo-fluidic characteristics are investigated by 3D numerical simulation. To validate the present numerical model, the overall heat transfer rate (Nu_{av}) of honeycomb without

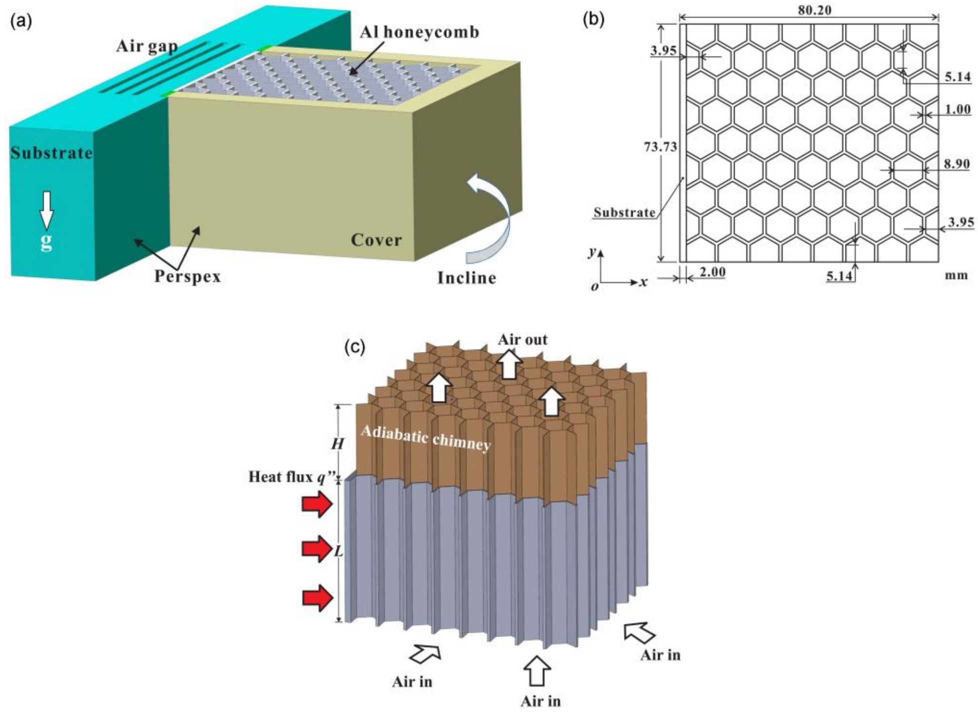

Figure 3 Experimental setup for natural convection in Al honeycomb with hexagonal cells: (a) Schematic of test rig with right-angle geometry support; (b) honeycomb size; (c) schematic of Al honeycomb heat sink with chimney.

chimney is compared with the experimental measurements [24] for a wide range of $Ra_{q''}$ number, as shown in Figure 4(a). Within the laminar flow range ($Ra_{q''} = 3.13\times10^7$– 1.56 $\times10^8$), the numerically-simulated Nu_{av} number (in the vertical direction, $\theta = 0°$) increases significantly with the $Ra_{q''}$ number, showing a good agreement with the experimental data as well as the reported correlation (maximum deviation within ±8%). For the case of hexagon chimney, comparison between the present experimental measurements and numerical simulations is conducted in Figure 4(b) as well. A satisfactory agreement is observed for various dimensionless chimney height (H/L = 0.2–1.0).

4.2 Effect of honeycomb size (streamwise and spanwise direction)

The buoyancy-driven fluid flow in a channel is distinct from external natural convection, due mainly to the fact that the fluid development is confined by the channel wall. After a fully development, the flow boundary layers for each channel wall converge, leading to a thermal plume in the center of the channel. For honeycombs with multiple channels, the thermal plumes converge to the center of the honeycomb as illustrated in Figure 5, where the simulated flow field in the honeycomb and the corresponding temperature distribution are shown for a selected honeycomb slice. It is worth noting here that the maximum local Nu number is observed away from the heated substrate in the spanwise direction, which may be due to the fact that the thermal saturation (thermal boundary layer converged) may be formed in the channels near the heated substrate (see Figure 5(b)).

The size of honeycomb, namely the length in both streamwise and spanwise directions, may influence the thermal and flow resistance in honeycombs. To investigate the size effect, we performed numerical simulations of natural convective heat transfer in hexagonal honeycombs with various sizes. As the height of honeycomb (in the streamwise direction) increasing from 10 to 50 mm, the heat transfer rate is dramatically increased. For instance, an increment of around 100 % is observed when the honeycomb height is increased from 10 to 50 mm. Figures 6(b)–(d) display the simulated temperature distribution of the fluid inside the channels of the honeycomb with a height of 10, 20 and 30 mm. With the increase in honeycomb height, the maximum temperature of the heated fluid decreases and the convergence extent of the thermal plume is weakened.

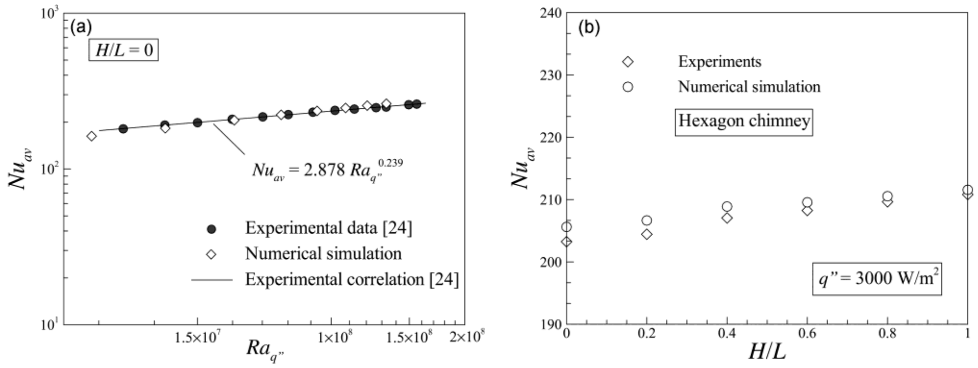

Figure 4 Nu_{av} number in vertical orientation plotted as a function of $Ra_{q''}$ number for hexagonal honeycomb: (a) comparison between simulation and experiment [24] without chimney (H/L=0); (b) comparison with hexagon chimney at a given heat input (q'' = 3000W/m^2).

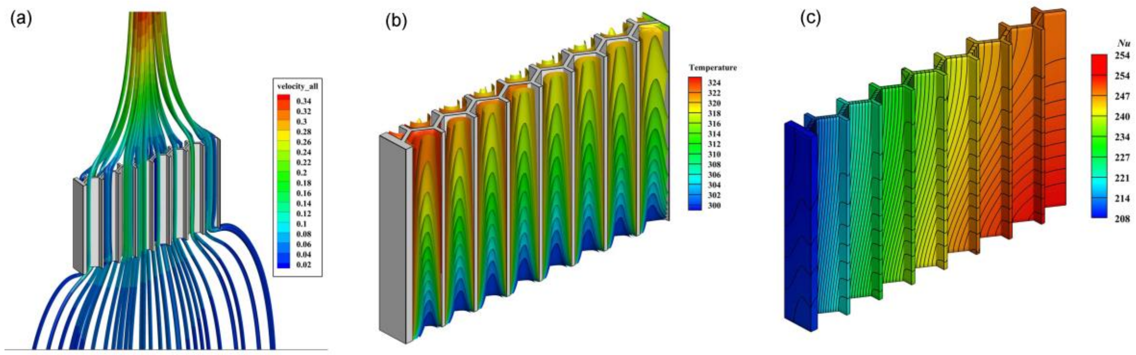

Figure 5 Thermo-fluidic characteristics of natural convective heat transfer in a hexagonal honeycomb with a height of 50 mm: (a) simulated flow lines; (b) simulated temperature distribution of fluid inside the honeycomb channel; (c) simulated local distribution of Nu number.

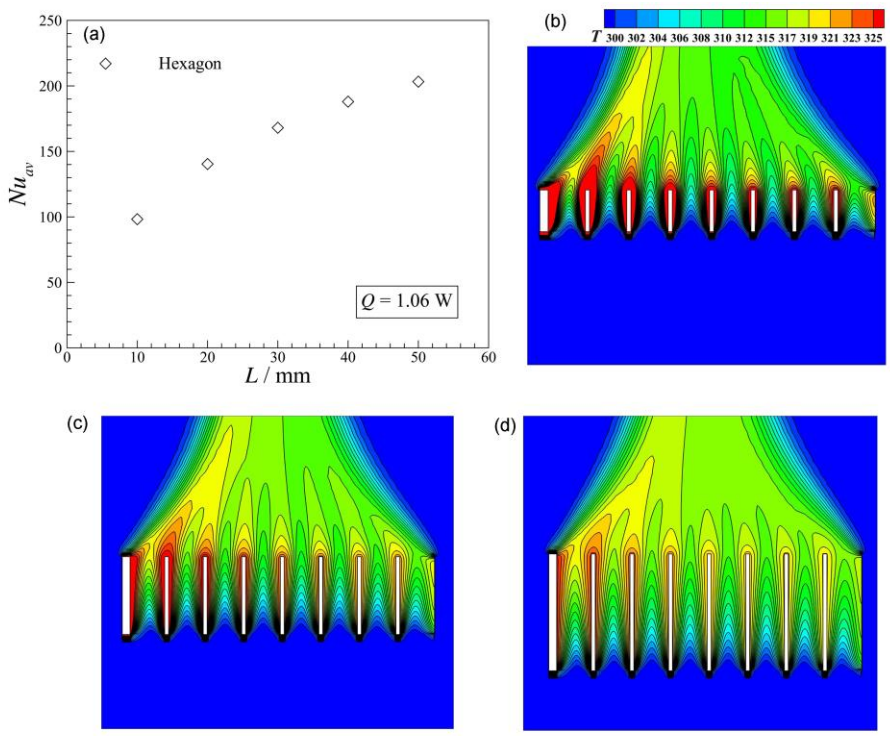

Figure 6 Effect of honeycomb height (streamwise direction) on the heat transfer rate at a given heat flux of q'' = 3000 W/m^2: (a) overall heat transfer rate; (b)–(d) simulated temperature field of honeycomb with a height of 10, 20 and 30 mm.

As the length of honeycomb (in the spanwise direction) increasing, namely from 1 cell to 8 cells, similar increasing trend is observed (see Figure 7(a)). For example, the overall heat transfer rate (Nu_{av}) of the honeycomb with 7 cells is 4 times higher than that with 1 cell. However, the further increment of cell number does not lead to higher heat transfer rate, i.e. little increase in heat transfer rate is obtained when the cell number is higher than 7. This indicates that the flow resistance may increase higher than the contribution of the heat transfer resulted from the increased surface area in the spanwise direction. Besides, for the sake of bigger size in the spanwise direction, the thermal plume seems much bigger. (see Figure 7(b)–(d)).

4.3 Effect of chimney enhancement

Distinct from forced air convection, the driving force for natural convection is sensitive to the resistance of flow. Typical enhancement techniques for heat transfer by enlarging surface area or increasing flow disturbance are not applicable in the case of natural convection, as the flow resistance dramatically increases as well. Therefore, to enhance natural convective heat transfer in heated Al honeycombs, the concept of adding an adiabatic extension to the honeycomb is assessed.

Figure 8(a) compares the heat transfer performance of heated hexagonal honeycomb with hexagon and square chimney extensions. By adding a square or hexagon chimney, the Nu_{av} number is increased and the enhancement increases with the chimney height for the range of chimney height to honeycomb ratio H/L = 0–1.0 [24].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. If no chimney is added, the heated fluid 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 the density difference between the outlet and inlet to suck the fluid (see Figures 8(c)–(d)). Meanwhile, the mass flow rate also increases that is helpful for further heat transfer enhancement (see Figure 8(b)).

For a given chimney height (Figure 8(a)) and heating power (q''= 3000W/m^2), the enhancement by the square chimney is much stronger than that by hexagon chimney. This may be explained from the point of single tube-chimney system. For a single circular tube-chimney system, it has been reported [12] that the heat transfer enhancement by chimney is increased with the ratio of chimney to tube diameter. For the presently investigated multi-tubes (honeycomb), these tubes share the square chimney, leading to a bigger chimney to tube diameter ratio than unity (hexagon

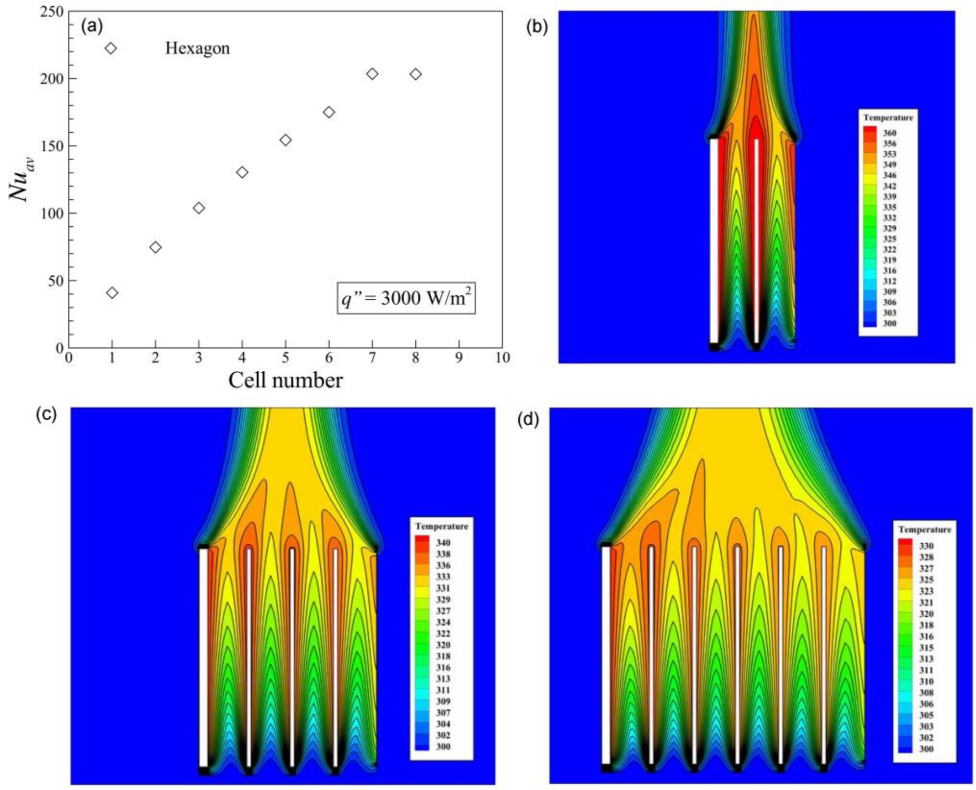

Figure 7 Effect of cell numbers of honeycomb (spanwise direction) on the heat transfer rate at a given heat flux of q'' = 3000W/m^2: (a) overall heat transfer rate; (b)-(d) simulated temperature field of honeycomb with 2, 4 and 6 cells.

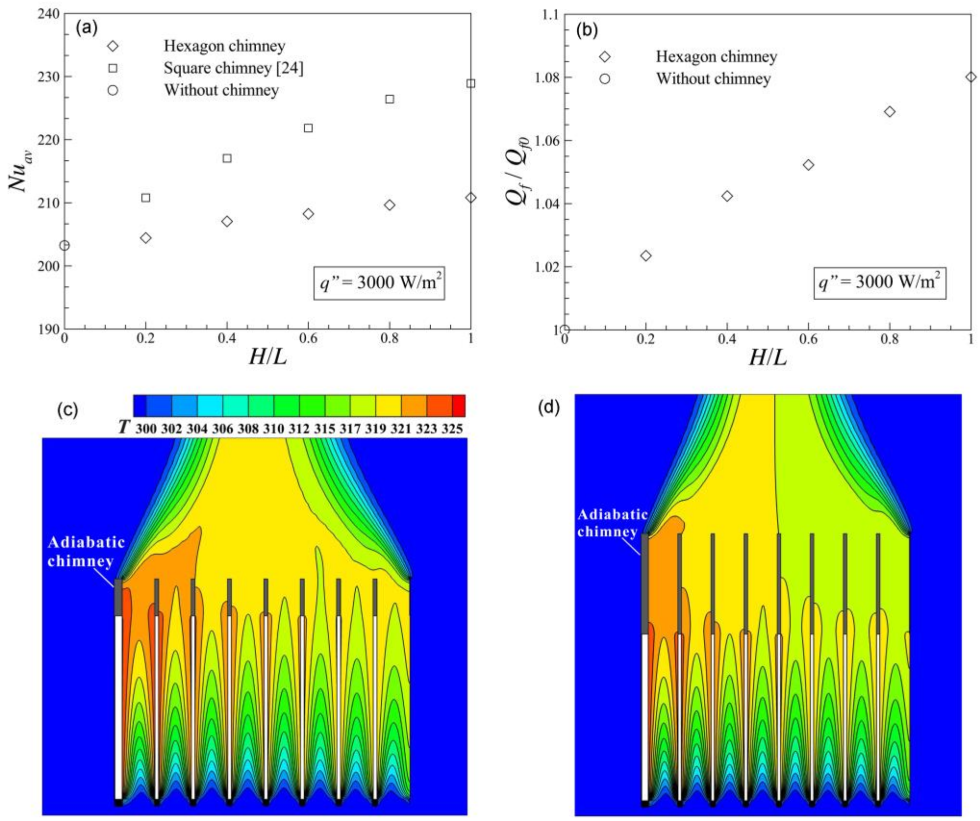

Figure 8 Heat transfer enhancement by chimney extensions: (a) comparison of heat transfer rate by hexagonal and square chimneys based on the measurements; (b) simulated total mass flow rate of honeycomb with hexagonal chimney; (c)-(d) temperature field of honeycomb with hexagonal chimney with H/L = 0.2 and 0.6.

chimney). Therefore, the square chimney performs much better enhancement in natural convective heat transfer.

4.4 Effect of inclination angle

Given the installation situation of electronic devices, such as LED lamp, the heated substrate may not always parallel to the acceleration of gravity. To address its influence, we defined the inclination angle as the one between the heated substrate and the positive z-axis (the direction of gravity) and performed numerical simulations on the 3D steady state natural convective heat transfer of hexagonal honeycomb with/without hexagon chimney at a given heat input q''= 3000 W/m^2. As illustrated in Figure 9, as the honeycomb is gradually inclined, the Nu_{av} number gradually decreases for both cases (with/without hexagon chimney). Relative to the vertical orientation (θ = 0^o), the Nu_{av} number is decreased by about 20% at a clockwise inclination angle of θ = 60^o.

A thermal plume forms in the buoyancy-driven fluid flow after a full development. When the channel is inclined, the fluid still tries to flow vertically for the driven force is gravity; see Figures 9(b)–(e). At the entrance of the channel, the fluid adjacent to the heated wall (i.e., substrate) flows along the wall surface due to wall confinement. At the exit of the channel, the thermal plume twisted against the inclination direction. Thermal saturation (convergence of thermal and fluid boundary layer) will occur faster than that without inclination, leading to a lower mass flow rate and velocity. The buoyancy-driven channel flow will eventually change into internal natural convection as the inclination reaches 90^o where the suction phenomenon (chimney effect) in a channel vanishes.

4.5 Effect of thermal conductivity of honeycomb

Among the various factors on the natural convective heat transfer in honeycombs, the thermal conductivity of the honeycomb structure plays a vital role in the overall heat transfer performance. To address this issue, numerical simulations on the natural convection of the hexagonal honeycomb made by typical metals are conducted, as demonstrated in Figure 10. At a given heat input, e.g. q'' = 3000 W/m^2, the heat transfer rate is strongly affected by the thermal conductivity of honeycomb structure, showing an increasing trend. It is worth noting here, however, that the heat transfer rate does not increase a lot (only less than 6%) when the structural metal changes from Aluminum to Copper (the thermal conductivity is increased by more than 60%). It indicates that the copper honeycomb is not necessary for the aim of further heat transfer enhancement, in the

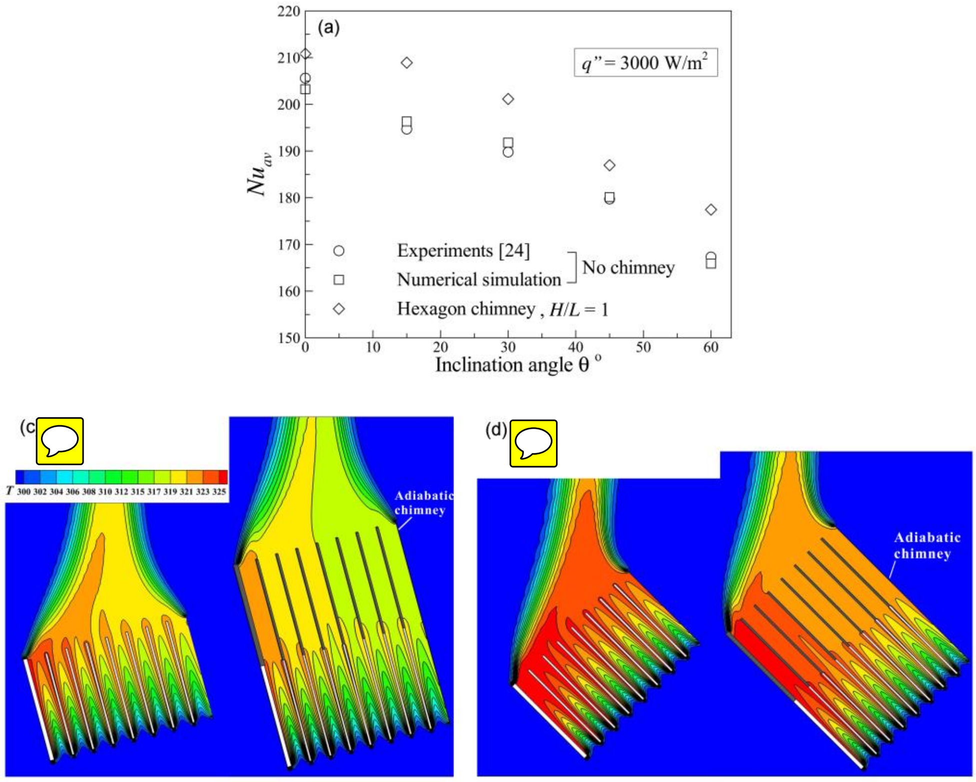

Figure 9 Effect of inclination angle on overall heat transfer rate for heated honeycomb with (H/L=1) and without chimney at a given heat flux of q'' = 3000W/m^2: (a) Comparison of heat transfer rate; (b) 15° with/without chimney; (c) 45° with/without chimney.

Table 2 Thermophysical properties of typical metals with a reference temperature of 300 K [25].

	Carbon steel	Iron	nickel	Zinc	Aluminum	Copper
ρ (kg/m^3)	7840	7870	8903	7140	2710	8930
c_p (J/kg K)	465	455	444	388	902	386
k (W/m K)	49.8	81.1	90.7	121	237	398

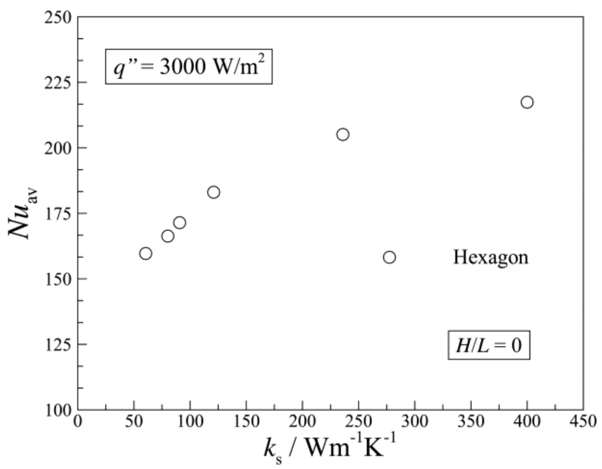

Figure 10 Effect of thermal conductivity of honeycomb structure on the thermal performance of hexagonal honeycomb in vertical orientation (inclination angle θ = 0°) at a given heat flux of q'' = 3000 W/m^2.

perspective of cost effectiveness.

4.6 Effect of cell shape

The above-mentioned thermo-fluidic characteristics are numerically obtained based on the honeycomb with hexagonal cells. To investigate the influence of cell shape upon the overall heat transfer rate, four kinds of honeycomb with the cell shape of hexagon, circle, staggered and in-line squares are considered. With the same void volume fraction, the numerically simulated heat transfer rates are compared in Figure 11(a), where little difference is observed (less than 1%). For a given void volume fraction, different cell shapes may result in structurally different surface-to-volume area ratio (varied around 8%) and thermally different effective thermal conductivity along the spanwise direction (varied around 10%). However, the present numerical results indicate that for the natural convection, the convective heat transfer resistance is the dominated.

Figures 11(b) and (c) illustrates the local temperature distribution of the four kinds of honeycomb, particularly showing the fluid temperature inside the channel. For the inlet slice, the constant temperature lines of each honeycomb are mimicking its cell shape; while with the thermal plume developing (along the streamwise direction), the constant temperature lines are all showing a circular shape, indicating a thickened thermal boundary layer.

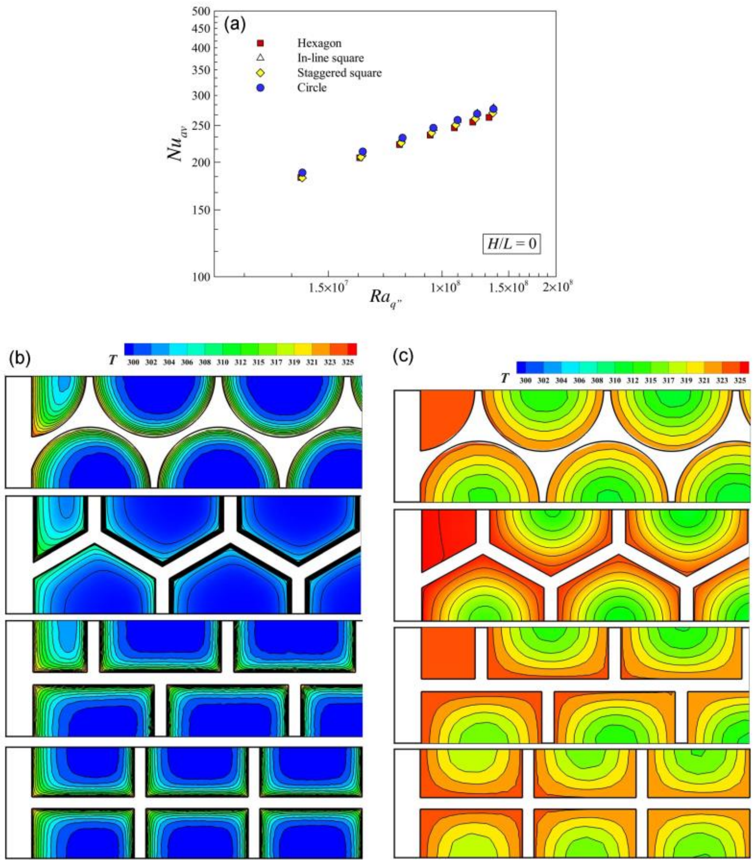

Figure 11 Effect of cell shape of honeycomb structure on the thermal performance of heated honeycomb in vertical orientation: (a) overall heat transfer rate; (b) simulated temperature field on the inlet slice; (c) simulated temperature field on the middle slice.

5 Conclusions

The natural convective heat transfer performance and thermo-fluidic characteristics of honeycombs are numerically investigated. To validate the numerical model, purposely-designed experiments are conducted. Good agreement between numerical simulation and experimental measurements is obtained. The influence of inclination angle and geometric parameters such as cell shape, streamwise and spanwise length are also numerically quantified. We may draw the following conclusions from the present investigations.

By increasing the length of honeycomb in both streamwise and spanwise direction, the heat transfer performance is markedly enhanced; while the enhancement is not increased as the cell number is bigger than 7 (length in the spanwise direction).

Both the square and hexagon chimney can enhance natural convection in honeycomb, but the square chimney performs much better enhancement than the hexagon chimney.

With the increment in inclination angle, the overall heat transfer rate decreases for the honeycombs with/without chimney.

The heat transfer rate increases with the thermal conductivity of the honeycomb structure and the Al honeycomb performs better in terms of heat transfer and cost effectiveness.

For honeycombs with the same void volume fraction but different cell shapes, there is little difference on the overall heat transfer rate of natural convection.

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