Numerical Simulation of Fluid Flow Characteristics and Heat Transfer Performance in Graphene Foam Composite

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Abstract: Graphene foam composite is a promising candidate for advanced thermal management applications due to its excellent mechanical strength, high thermal conductivity, ultra-high porosity and huge specific surface area. In this study, a three-dimensional physical model was developed in accordance with the dodecahedral structure of graphene foam composite. A comprehensive numerical simulation was carried out to investigate the fluid flow and convective heat transfer in open-cell graphene foam composite by using ANSYS Fluent 2021 R1 commercial software. Research results show that, as porosity increases, the pressure gradient for graphene foam composite with circular and triangular cross-section struts is reduced by 65% and by 77%, respectively. At a given porosity of 0.904, when the inlet velocity increases from 1 m/s to 5 m/s, the pressure gradient is increased by 11.3 times and 13.8 times, and the convective heat transfer coefficient is increased by 54.5% and 43% for graphene foam composite with circular and triangular cross-section struts, respectively. Due to the irregularity of the skeleton distribution, the pressure drop in Y direction is the highest among the three directions, which is 8.7% and 17.4% higher than that in the Z and X directions at the inlet velocity of 5 m/s, respectively. The convective heat transfer coefficient in the Y direction is significantly lower than that along the X and Z directions. Furthermore, triangular cross-section struts induce a greater pressure drop but offer less effective heat transfer compared to circular struts. The research findings may provide critical insights into the design and optimization of graphene foam composites, and promote their potential for efficient thermal management and gas/liquid purification in engineering applications.

Keywords: graphene foam composite; pressure drop; convective heat transfer; flow characteristics

1. Introduction

With the rapid advancements in artificial intelligence and integrated circuit technologies, the power density of electronic devices and smart equipment has significantly increased. In combination with the continuous miniaturization of devices and the variability of working environments, traditional thermal management methods can no longer meet the cooling demands of the new generation of electronic devices and equipment. Porous foam materials are ideal functional materials which have been extensively applied in thermal management applications across various industries due to their high porosity, large specific surface area and excellent heat dissipation properties. Graphene foam (GF) is a three-dimensional interconnected network composed of continuous graphene sheets and numerous pores, which is commonly prepared by chemical vapor deposition (CVD) method to achieve high-quality, uniform, and scalable graphene structures with controlled thickness and minimal defects [1,2]. Attributed to excellent characteristics such as high thermal conductivity, low density, ultra-high porosity, high specific surface area, excellent mechanical properties, and low interfacial thermal resistance, GF and GF composites have...
become promising candidates for energy storage and thermal management applications, serving as heat sinks, thermal interface materials, as well as components in batteries and supercapacitors [3–7].

The heat transfer performance of GF and GF composites has been investigated by experimental measurements and numerical simulations in recent years. The experimental results of Du et al. [8] demonstrated that a novel thermal resistor prepared by using graphene/PDMS flexible foam could achieve wide-range continuously tunable and fast thermal switching function than conventional thermal switches. The experimental research on the free-standing GF skeleton showed that the thermal conductivity of the individual GF skeleton separated from the bulk GF was two orders of magnitude higher than that of bulk GF, which showed promising applications in energy-intensive industries [9]. Wei et al. [10] fabricated novel erythritol/GF composites using GFs as the porous skeleton to encapsulate erythritol. Their experimental results demonstrated that, in comparison with pure erythritol, the thermal conductivity and subcooling degree of erythritol/GF composites was increased by 26–158 times and reduced from 337.1 K to 332.4 K, respectively. Khosravani et al. [11] carried out multiscale modeling to investigate the thermal conductivity of GF/polydimethylsiloxane (PDMS) composite based on the molecular dynamics method, and they found a significant increase of about 70% in the thermal conductivity of GF/PDMS composite compared to neat PDMS due to its unique GF structure. The thermal conductivity of GF/PDMS composite experimentally fabricated by Zhao et al. [12] was even 2.95 times that of pure PDMS, mainly due to effective heat conduction caused by interconnected architecture of GF. Zhou et al. [13] established a physical model based on GF dodecahedral structure aiming to investigate the influences of experimental conditions on thermal conductivity and reveal the heat transfer mechanisms. It was concluded that the effective thermal conductivity of GF composite at temperatures above 400 K can be improved by increasing porosity, decreasing surface emissivity, and reducing surface area. Generally, the heat transfer of the GF composite takes the co-contribution of thermal conduction and thermal radiation into consideration, because the natural heat convection in the pores is usually neglected for most GF composites with a pore size smaller than 500 µm.

Fluid dynamics is also crucial for GF composites, especially in the applications relevant with gas or liquid purification and filtration [14–17]. When the fluid flows through open-cell foam materials, a forced convection flow is generated to affect the thermal performance, and the fluid flow behavior inside the porous media becomes an interesting aspect for open-cell foam materials. Zafari et al. [18] developed a 3D simulation model based on real microtomography images, and found that the pressure drop and local convection heat transfer were highly relevant with the porosity and geometric characteristics of the studied porous medium. The pressure drop of open-cell metal foams increased with the decrease in porosity and increase in pore density [19]. The heat coefficient increased with an increase in fluid velocity and porosity, but slightly decreased with the increase in pore size [20]. Moreover, micropores with different directions in the skeleton affect the fluid dynamics and thermal performance of open-cell foams. The pressure drops and heat transfer coefficients of the structure with X-direction micropores were 4.52%–6.46% lower and 1.39%–3.29% higher in comparison with those of the structure without micropores [21]. Yu et al. [22] found that the presence of skeleton micropores increased the pressure drop by 11.3%–11.7%, with the flow characteristics displaying anisotropy across the three orthogonal Cartesian axes. Notably, the Y direction exhibited the highest pressure drop, which was 31.6%–32.8% and 35.4%–36.8% higher than the Z direction in the structures without and with skeleton micropores, respectively. For irregular open-cell metal foams, the pressure drop per unit length varied quadratically with the fluid velocity, and the highest overall convective heat transfer performance was achieved at a pore density of 20 PPI and a porosity of 95% [23].

As discussed above, a variety of studies have been carried out to investigate the flow characteristics and heat transfer performance on open-cell metal foams with simplified models, rather than using GF composite with real geometries. In addition, there is a lack of systematic studies on the microstructural parameters, and their effects on fluid
flow characteristics and heat transfer performance. Correspondingly, it is in the interest of the present study to address this research gap by developing a 3D physical model based on the practical dodecahedral structures which are close to those of the real GF composite [24]. Numerical simulations were carried out to investigate the influences of cross-section shape and porosity on pressure, velocity, and temperature distributions. Furthermore, the dependence of pressure gradient and convective heat transfer coefficient on the fluid velocity and flow direction was studied.

2. Methodology

2.1. Physical Model

According to the simulation method proposed by Yang et al. [21], it is assumed that air at a temperature of 300 K flows through high-temperature skeletons at 373 K during the simulation process, in order to simulate the flow properties inside the GF composite. The topology skeletons were constructed using 3ds Max 2021 and SpaceClaim 2021 R1, based on the actual GF prepared through the CVD method. Given the complexity of the GF composite geometry and the internal tortuous, an unstructured mesh based on the polyhedral grid was generated for the volume meshing using the Meshing module embedded in ANSYS Fluent software. Additionally, the growth rate of the grids was carefully controlled, with the transition set to 1.2 in all cases. Local refinement was applied at the fluid–solid interface to ensure accurate representation. In the process of partitioning, the element size of the mesh was not greater than 1/10 of the minimum size of the model, and the maximum element length was $7.09 \times 10^{-3}$. The developed physical models are shown in Figure 1. As shown in Figure 1a, Plane1 is the cross-section located at the midpoint of the computational domain, perpendicular to the Y axis, which is selected to observe the pressure, velocity and temperature contour plots on this cross-section. In addition, 11 equally spaced cross-sections perpendicular to the flow direction (X axis) were selected as the sampling planes within the computational domain, as illustrated in Figure 1b for circular cross-section struts and Figure 1c for triangular cross-section struts. In this study, the work is carried out over structures with a porosity within 0.904–0.987 from circular cross-section struts and porosity within 0.904–0.985 for triangular cross-section struts, by varying flow velocity at 1 m/s, 2 m/s, 3 m/s, 4 m/s, and 5 m/s.

![Figure 1](image)

**Figure 1.** Schematic drawing of Plane1 and cross-section along the flow direction: (a) Plane1; (b) for circular cross-section struts; and (c) for triangular cross-section struts.

2.2. Governing Equations

The flow characteristics of an incompressible Newtonian fluid can be described by the continuity equation, momentum equation, and energy equation. The air flow at low velocity in porous foam can be considered an incompressible working medium.

The continuity equation for the fluid under steady state can be expressed by [21]:

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0$$

(1)
where \( x_i \) represents the Cartesian coordinate in the \( i \) direction; \( \rho \) is the fluid density, \( \text{kg/m}^3 \); \( u_i \) is the velocity in the \( i \) direction, \( \text{m/s} \).

The conservation of the momentum equation can be expressed by [21]:

\[
\frac{\partial}{\partial x_i} \left( \rho u_i u_j \right) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \mu \frac{\partial u_i}{\partial x_j} \right)
\]  

(2)

where \( p \) is the static pressure, \( \text{Pa} \); \( \mu \) is the fluid dynamic viscosity, \( \text{kg/(m-s)} \); \( u_i \) is the velocity in the \( j \) direction, \( \text{m/s} \); and \( x_j \) represents Cartesian coordinate in the \( j \) direction.

The conservation of energy equation can be expressed by [21]:

\[
\frac{\partial}{\partial x_i} \left( \rho u_i c_p T \right) = \frac{\partial}{\partial x_i} \left( \lambda \frac{\partial T}{\partial x_i} \right)
\]  

(3)

where \( c_p \) is the heat capacity, \( \text{J/(kg-K)} \); \( T \) is the temperature, \( \text{K} \); and \( \lambda \) is the thermal conductivity, \( \text{W/(m-K)} \).

2.3. Boundary Condition

Due to the extremely thin and relatively fragile nature of the graphene nanosheets, this study selects the nickel foam template which has not been etched away during the CVD process as the substrate to prepare graphene foam. The graphene with a thickness of 200 nm was deposited on the surface of the nickel foam to present an extremely thin layered structure. The average pore size of the GF composite with varying porosities was established at 350 \( \mu \text{m} \). Figure 2 presents the computational domains and boundary conditions of the GF composite. A cube cell of the GF composite with dimensions of 1 mm \( \times 1 \text{ mm} \times 1 \text{ mm} \) was simulated. The cube surfaces in the positive and negative directions of \( X \) in the fluid domain are set as the inlet and outlet flow conditions, respectively. The other four surfaces are set as symmetry boundary conditions. The solid surface is set as the non-slip boundary condition and named as wall. The inlet boundary condition is set as the velocity inlet, with a specified temperature of 300 K at the inlet of the fluid domain. The outlet boundary condition is set as the pressure outlet with a gauge pressure at zero.

![Figure 2. Computational domain and boundary conditions.](image)

Pressure drop per unit length, also called pressure gradient, can reflect the resistance during the flow process and is used to evaluate the flow properties of composite graphene foam, which can be calculated by the following equation [25]:

\[
\frac{\Delta P}{L} = \frac{P_{in} - P_{out}}{L}
\]  

(4)

where \( \Delta P/L \) is the pressure drop per unit length, \( \text{Pa/m} \); \( L \) is the flow length, \( \text{m} \); \( P_{in} \) is the inlet pressure, \( \text{Pa} \); \( P_{out} \) is the outlet pressure, \( \text{Pa} \).
The convective heat transfer coefficient of the fluid–solid heat exchange surface can reflect the overall heat transfer performance under forced convection, expressed by the following equation [26]:

\[
h = \frac{q}{(T_s - T_f)}
\]  

(5)

where \(h\) is the average convective heat transfer coefficient of the heat transfer surface, \(W/m^2\cdot K\); \(q\) is the heat flux density of the heat transfer surface, \(W/m^2\); \(T_s\) is the average temperature of the skeleton wall, \(K\); and \(T_f\) is the average temperature of the fluid domain, \(K\).

Dimensionless number \(Re\) is introduced to characterize the fluid flow, expressed by:

\[
Re = \frac{\rho u L}{\mu}
\]  

(6)

where \(L\) is the characteristic length, taking \(L = 1\) mm in this study.

For fluid flow in open-cell foams, a turbulent regime can be achieved at lower Reynolds numbers. For example, Della et al. [27] found that the flows became fully turbulent and highly unsteady in the case of an \(Re\) higher than 300. Based on calculations, the Reynolds number of the fluid in this study at a flow velocity of 5 m/s is 340, and it is considered that the fluid in the GF composite is under a turbulent state. Therefore, a standard \(k-\varepsilon\) model [26] is applied in this study to investigate the flow characteristics and convective heat transfer coefficient of fluid flowing through the GF composite skeleton due to its high simulation accuracy.

\(y^+\) is a dimensionless parameter used in computational fluid dynamics to evaluate the quality and resolution of the mesh near walls in turbulent flow simulations. In this study, three layers of boundary layer mesh were generated in the near-wall region of the computational domain. The partitioning process ensured that the average dimensionless thickness of the first layer of boundary grid elements was maintained at \(y^+ < 1\). The standard wall function was employed for calculation.

ANSYS Fluent was used to solve the fluid flow process inside the GF composite material. A steady-state pressure solver was used for calculation. The SIMPLE algorithm was used for pressure–velocity coupling, and the PRESTO method was used to discretize the pressure equation. Thermophysical properties of materials used in the simulation are listed in Table 1.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (\rho) (kg/m(^3))</th>
<th>Specific Heat (C_p) (J/kg·K)</th>
<th>Thermal Conductivity (k) (W/m·K)</th>
<th>Dynamic Viscosity (\mu) (kg/m·s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>1.225</td>
<td>1006.43</td>
<td>0.0265</td>
<td>(1.8 \times 10^{-5})</td>
</tr>
<tr>
<td>Graphene</td>
<td>2250</td>
<td>709</td>
<td>500</td>
<td>-</td>
</tr>
<tr>
<td>Nickel</td>
<td>8900</td>
<td>460.6</td>
<td>106</td>
<td>-</td>
</tr>
</tbody>
</table>

2.4. Grid Independence Verification

In order to avoid the possible influence of the grid numbers on the simulation results, grid independence verification was carried out for the structure with circular cross-section struts with a porosity of 0.926. The mass fraction of graphene is 0.2%. The air inlet velocity is set to 5 m/s with air flowing into the foam skeleton along the X axis direction. Five different grid numbers were selected at 413,338, 616,975, 1,090,007, 1,725,933, and 2,249,465, respectively. Figure 3 shows the variation in the pressure drop per unit length with the grid numbers. It can be obviously observed that the pressure drop per unit length rapidly increases and then gradually stabilizes with the increase in grid numbers. The deviation between the pressure drops per unit length is lower than 0.5% when the grid number is more than 1,090,007, falling within the allowable error range. Taking the computational accuracy and cost into comprehensive consideration, a grid number of 1,090,007 is adopted.
in this study. Energy residuals were set to be less than $10^{-9}$, and other residuals were set to be less than $10^{-6}$ to increase the accuracy.

![Graph showing pressure drop per unit length](image)

**Figure 3.** Variation in the pressure drop per unit length with the grid number.

### 2.5. Numerical Simulation Validation

In order to validate the reliability of the developed model and numerical simulation method, the pressure drop per unit length is calculated at different inlet velocities of fluid passing through the circular cross-section GF composite with a porosity of 0.971 and 0.987. As shown in Figure 4, the simulation results were further compared with the experimental data obtained by Sun et al. [28]. It can be found from Figure 4 that the pressure drop per unit length in this study is in good agreement with the experimental data. The reason for the small deviation is that the pore structure and pore density in two studies are different. Therefore, it can be concluded that the numerical simulation method in this study is reliable for further study.

![Graph comparing simulation and experimental results](image)

**Figure 4.** Comparison between simulation and experimental results.
3. Results and Discussion

3.1. Flow Characteristics Analysis

3.1.1. Pressure Distribution

Figures 5 and 6 present the pressure distribution at the symmetry and Plane1 of the calculation domain, when the air at a flow rate of 5 m/s flows through the GF composite with a porosity of 0.904. It can be observed that the overall pressure gradually decreases along the flow direction of the air. When the air contacts the solid skeleton part, the fluid near the skeleton is blocked, resulting in an increase in the flow resistance and the largest local pressure loss. The maximum pressure is observed at the front end of the skeleton adjacent to the inlet. A negative pressure region is found at the rear end of the skeleton, with the pressure eventually returning to zero at the pressure outlet. Additionally, when the inlet and outlet sections are unobstructed by solids, the pressure distribution is uniform with high pressure at the inlet and low pressure at the outlet. When the fluid flows through the foam skeleton, there is a significant pressure drop, indicating that the pressure drop in the flow channel is primarily caused by the foam solid skeleton. It is evident that the pressure distribution in the fluid domain of the GF composite with circular cross-section struts is more uniform than that of the triangular cross-section struts. The pressure drop of the fluid is more obvious when it flows through the GF composite with triangular cross-section struts, with higher pressure loss around the convex parts of the solid skeleton.

![Figure 5](image1.png)  
**Figure 5.** Pressure distribution at symmetry of GF composite with (a) circular cross-section struts; and (b) triangular cross-section struts.

![Figure 6](image2.png)  
**Figure 6.** Pressure distribution at Plane1 of GF composite with (a) circular cross-section struts; and (b) triangular cross-section struts.

Figure 7 shows the average pressure change along the flow direction of the air at a flow rate of 5 m/s. It can be seen from the figure that the average pressure first decreases linearly along the flow direction before X reaches 0.0005 m. Then, the average pressure is almost
stabilized at the center section with X around 0.0005–0.0007 due to reduced existence of the solid skeleton at high porosity. The average pressure begins to drop again when the fluid continues to flow to a location with more solid areas. According to the previous analysis on the pressure field, the pressure drop of the fluid flowing through the foam skeleton can be attributed to the frictional resistance caused by fluid–solid contact and fluid impacting on the solid walls. Therefore, the flow performance can be optimized by modifying the skeleton structure of the GF composite.

![Figure 7](image)

**Figure 7.** Average pressure along the flow direction.

3.1.2. Influence of Porosity on Pressure Drop

Figure 8 presents the variation in pressure drop per unit length with the porosity when the air flows through the GF composite at the inlet rate of 5 m/s. As can be seen in Figure 8, the pressure gradient decreases with an increase in the porosity for both types of struts. Specific to circular cross-section struts, the pressure gradient decreases from 65,330 Pa/m to 21,426 Pa/m when the porosity increases from 0.904 to 0.987. For the triangular cross-section struts, the pressure gradient decreases from 121,290 to 28,308 Pa/m, corresponding to the porosity increase from 0.904 to 0.985. It can be attributed to the combination influences of increase in fluid channels, and decrease in wall friction, flow resistance, and inertial effects. In addition, at a given porosity, the pressure gradient across the triangular cross-section struts is consistently higher than that across the circular cross-section struts, which is more evident at lower porosities.

![Figure 8](image)

**Figure 8.** The pressure drop per unit length versus the porosity.
3.1.3. Influence of Velocity and Cross-Section Shape of Struts on Pressure Drop

Figure 9 shows the relationship between the pressure gradient and the inlet velocity for circular and triangular cross-section struts with different porosities. It can be observed from Figure 9 that the pressure gradient highly depends on the fluid inlet velocity, and the pressure gradient increases with increasing the inlet velocity. At the same flow rate, the pressure gradient for fluid passing through GF composite with lower porosity is higher than that with higher porosity. Furthermore, as the velocity increases, the increase magnitude of pressure gradient of fluid flowing through GF composite with lower porosity is also higher than that with higher porosity. Specifically, when the inlet velocity increases from 1 m/s to 5 m/s, for GF composite with circular cross-section struts, the pressure gradient increases from 5765 Pa/m to 65,330 Pa/m at 0.904 porosity, and from 2263 Pa/m to 21,426 Pa/m at 0.987 porosity, increasing by 11.3 and 9.5 times, respectively. For GF composite with triangular cross-section struts, the pressure gradient increases from 8771 Pa/m to 121,291 Pa/m at 0.904 porosity, and from 2812 Pa/m to 28,308 Pa/m at 0.985 porosity, increasing by 13.8 and 10 times, respectively.

![Figure 9](image)

**Figure 9.** The pressure gradient versus the inlet velocity of the GF composite with different porosities for (a) circular cross-section struts; and (b) triangular cross-section struts.

Figure 10 shows the pressure gradient variations when the fluid flows through circular and triangular cross-section struts at a given porosity of 0.904 at different inlet velocities. From Figure 10, it can be observed that the pressure gradient of fluid flowing through circular and triangular cross-section struts are relatively close at low velocities. However, the difference between circular and triangular cross-section struts is enlarged as the velocity increases. The increase in the magnitude of the pressure gradient of the triangular cross-section struts is higher than that of circular cross-section struts, which indicates that the pressure gradient variation of the fluid flowing through the triangular cross-section struts is more sensitive to changes in velocity.

![Figure 10](image)

**Figure 10.** The pressure gradient versus the inlet velocity of the GF composite at a porosity of 0.904.
3.1.4. Influence of Flow Direction on Pressure Drop

Due to the non-uniform distribution of the GF composite skeletons in the X, Y, and Z directions, the obstruction of the solid skeletons varies when the fluid enters the fluid domain from different directions. Therefore, a comparison of the pressure drop is carried out for the fluid entering from the X, Y, and Z directions of the computational domain at the given porosity of 0.904, with the results shown in Figure 11. It can be observed that the pressure drop shows a similar trend when the fluid flows into the computational domain from three different directions. As shown in Figure 11a, there is no significant difference in the pressure drop among the three directions when the fluid flows through circular cross-section struts at low velocities. As the velocity increases, the pressure drop remains consistent when the fluid flows from the Y and Z directions. The pressure drop in the X direction is lower than that in another two directions, and the difference slightly increases with the increasing velocity. As shown in Figure 11b, for triangular cross-section struts, there is also no significant difference in pressure drop among the three directions at low velocities. However, differences in pressure drop can be obviously observed as the velocity gradually increases. The pressure drop in the Y direction is the highest among the three directions, which is 8.7% and 17.4% higher than that in Z and X directions at the inlet velocity of 5 m/s, respectively. The results demonstrate that the GF composite exhibits anisotropic characteristics in the three flow directions for the specified structure.

![Figure 11](image)

**Figure 11.** The pressure gradient versus inlet velocity in the three directions of the GF composite with: (a) circular cross-section struts; (b) triangular cross-section struts.

3.2. Velocity Field Analysis

Figures 12 and 13 show the velocity field distribution at the Symmetry and Plane1 section of the calculation domain when air flows through the GF composite at different flow rates. It can be noted that, the velocity distribution of the fluid at the inlet is relatively uniform, and the velocity of the fluid flowing around the skeleton is significantly reduced due to the influence of solid skeleton resistance. The flow velocity at the larger pores in the porous channel is higher than that at the initial inlet, which increases faster after passing through the pores, forming a flow acceleration area at the pores. The maximum velocity is observed in the pore channels between the skeletons, while the minimum velocity occurs at the ligament connections of the skeleton facing away from the inlet. The velocity around the skeleton approaches zero due to the existence of viscous resistance. According to the velocity profiles, obtuse angular structures parallel to the flow direction significantly obstruct the flow when the fluid flows through the GF skeleton. The velocity drops rapidly in closed areas. However, the flow velocity on both sides of the skeleton may exceed the inlet velocity due to the fluid diversion around the solid skeleton. The diverted fluid converges after bypassing the skeleton to accelerate the velocity, and turbulence in the porous area further disrupts the boundary layer near the skeleton, thereby enhancing the fluid flow and heat transfer.
Figure 12. Velocity distribution at symmetry of GF composite with (a) circular cross-section struts; and (b) triangular cross-section struts at velocity of 5 m/s and porosity of 0.904.

Figure 13. Velocity profiles at Plane1 of the GF composite with the cross-section struts of (a) circular at porosity of 0.904, \( v = 1 \) m/s; (b) triangular at porosity of 0.904, \( v = 1 \) m/s; (c) circular at porosity of 0.904, \( v = 3 \) m/s; (d) triangular at porosity of 0.904, \( v = 3 \) m/s; (e) circular at porosity of 0.904, \( v = 5 \) m/s; (f) triangular at porosity of 0.904, \( v = 5 \) m/s; (g) circular at porosity of 0.987, \( v = 5 \) m/s; and (h) triangular at porosity of 0.985, \( v = 5 \) m/s.
To better understand the impact of different inlet velocities on the internal flow field of fluid, Figure 13a–f show the velocity profiles within the GF composite with circular and triangular cross-section struts at inlet velocities of 1 m/s, 3 m/s, and 5 m/s, respectively. Evidently, increasing the inlet velocity significantly affects the internal velocity distribution. As the velocity increases, the fluid flow within the GF composite is more easily influenced by the solid skeleton. Overall, the increase in inlet velocity leads to higher fluid velocity throughout the computational domain, resulting in a larger velocity gradient along the flow direction, which is especially noticeable at the outlet. However, there are still regions of stagnation fluid near the solid skeleton where the local velocity is zero. It can also be observed that, during the flow process, a portion of the outlet velocity exceeds the inlet velocity, which primarily occurs in the pore regions at the outlet without obstruction by the skeleton. On one hand, the fluid accelerates as it bypasses the solid skeleton during the earlier flow. On the other hand, convective heat transfer is accompanied by the fluid flowing along the skeleton surface at a higher temperature, which will increase the fluid temperature and convert some thermal energy into kinetic energy.

Figure 13c,f show the velocity distributions of fluid flows through the GF composite with circular cross-section struts and triangular cross-section struts at the porosity of 0.904 and inlet velocity of 5 m/s. It is evident that the velocity distributions in the front end of both types are quite similar. However, as the fluid passes through the middle section of the skeleton, the GF composite with the circular cross-section struts has a more significant impact on the velocity distribution than that with triangular cross-section struts, resulting in a more turbulent internal flow. The maximum velocity within the GF composite with triangular cross-section struts is higher than that in the GF composite with circular cross-section struts. This is due to the higher resistance encountered by the fluid when flowing through the triangular cross-section struts, which requires a higher velocity to overcome the resistance and navigate around the skeleton.

As an important parameter of porous foam materials, the porosity directly impacts the internal flow resistance. Figure 13e–h show the velocity distribution of fluid at an inlet temperature of 5 m/s when it flows through the circular cross-section struts with a porosity of 0.904 and 0.987, and triangular cross-section struts with a porosity of 0.904 and 0.985, respectively. It is evident that lower porosity has a larger strut diameter and smaller internal pores, which leads to higher fluid velocities in the case of flowing through the skeleton. Thus, lower porosity enhances the flow disturbance and velocity uniformity within the flow field. The higher resistance of the GF composite with lower porosity also leads to more obvious flow lag zones.

To gain a more detailed understanding of the velocity changes, Figure 14 illustrates the variation in average velocity along the flow direction of the air at an inlet velocity of 5 m/s. Evidently, the average velocity of the fluid shows an overall increasing trend as it passes through the GF composite skeleton. However, there are two instances of velocity decline observed at X = 0.0004 and X = 0.0007, after which the velocity briefly decreases before rising again. It indicates that there is significant velocity fluctuation within the GF composite, primarily influenced by the solid skeleton. Moreover, the velocity variations in the triangular cross-section skeleton, as well as the average outlet velocity, are higher than those in the circular cross-section skeleton.

![Figure 14. Average velocity along the air flow direction.](image-url)
3.3. Temperature Distribution

Figures 15 and 16 show the temperature profiles at symmetry and Plane1 when the air flows through the circular and triangular cross-section struts with a porosity of 0.904 at 5 m/s. At the inlet, the temperature distribution is relatively uniform due to the lack of heat source. When the low-temperature air at 300 K impacts a high-temperature foam skeleton at 373 K, the convective heat transfer causes the high-temperature foam skeleton to continuously transfer heat to the low-temperature air. The fluid region closer to the foam skeleton has a higher temperature and a greater temperature gradient. The fluid temperature in the pores formed between the foam skeleton is lower because it is farther from the high-temperature surface and therefore not effectively heated. Additionally, the fluid temperature distribution at the rear end of the solid skeleton is more uniform compared to the front end of the skeleton, which can be attributed to the fluid bypassing and the increased fluid turbulence. The flow velocity is lower in the flow stagnation zone formed at the rear end of the skeleton, resulting in more gradual heat transfer and a more uniform temperature distribution. There is no obvious difference in the temperature distribution for circular and triangular cross-section struts.

Figure 15. Temperature distribution at symmetry: (a) circular cross-section struts; and (b) triangular cross-section struts at a velocity of 5 m/s and a porosity of 0.904.

Figure 16. Temperature distribution at Plane1: (a) circular cross-section struts; and (b) triangular cross-section struts at a velocity of 5 m/s and a porosity of 0.904.

Figure 17 shows the changes in average temperature along the flow direction as fluid flows through GF composite with two different cross-sectional shapes with a porosity of 0.904 at velocity of 5 m/s. It can be seen that the overall temperature of the low-temperature fluid increases after passing through the high-temperature foam skeleton. This is mainly due to convective heat transfer between the fluid and the foam skeleton surface, transferring heat from the high-temperature skeleton to the low-temperature fluid. The decrease in average temperature in the middle and the significant drop at the end are due to the higher number of voids in the pore region near the center of the skeleton. These voids prevent
the heat transferred by the skeleton from effectively raising the overall temperature of the fluid passing through. Similarly, the rear part of the computational domain is mostly occupied by pores, which prevents the fluid from being effectively heated and leads to a temperature drop. By comparing the temperature changes along the flow direction for the fluid passing through the two different cross-sectional struts, it is found that the temperature change trends are consistent. The minor differences are due to the different contact areas resulting from the varying shapes of the struts. In combination with the temperature distribution, it can be concluded that the pores and the interlaced structure within the GF composite increase the contact area between the solid and the fluid, thereby enhancing the heat transfer effect. The high-temperature skeletons can effectively heat the low-temperature fluid passing through it.

**Figure 17.** Average temperature variations along the X direction.

Figure 18 shows the influence of inlet velocity on the average temperature at the outlet of GF composite with a porosity of 0.904. It can be observed that the average temperature at the outlet gradually decreases as the flow velocity increases. This indicates that, as the flow velocity increases, the mass flow rate of the fluid increases and more low-temperature fluid participates in heat exchange, resulting in a reduction in the overall temperature rise of the fluid flowing through the skeleton. The fluid that absorbs heat can flow away faster, which facilitates the absorption of heat by the unheated fluid at the solid wall surface, thereby enhancing heat transfer efficiency.

**Figure 18.** Dependence of average outlet temperature on the inlet velocity.
3.4. Convective Heat Transfer Performance

3.4.1. Influence of Velocity and Porosity on the Convective Heat Transfer Coefficient

In our previous study [13], the heat transfer performance of GF composite has been investigated under the co-contribution of thermal radiation and thermal conduction by neglecting the natural heat convection in the pores. When the air flow through the GF composite at a fixed velocity, the resulting forced convection certainly affects the heat transfer performance, which can be expressed by the convection heat transfer coefficient. Figure 19 shows the variation in the convection heat transfer coefficient with the inlet velocity at different porosities. As shown in Figure 19, the convective heat transfer coefficient exhibits a linear increasing trend as the inlet velocity increases. The same phenomenon can also been found in other similar studies [18,21]. Moreover, for the specified GF composite, the convective heat transfer coefficient at high-porosity is higher than that at low-porosity at a given inlet velocity. Specifically, as the inlet velocity increases from 1 m/s to 5 m/s, the convective heat transfer coefficient of the GF composite with the circular cross-section struts increases from 642.8 W/m²·K to 992.8 W/m²·K at a porosity of 0.904, and from 865.2 W/m²·K to 1377.6 W/m²·K at a porosity of 0.987, respectively. For a GF composite with triangular cross-section struts, the value increases from 624.9 W/m²·K to 893.9 W/m²·K at a porosity of 0.904, and from 723.1 W/m²·K to 1121.1 W/m²·K at a porosity of 0.985, respectively. The velocity gradient of the fluid increases with the increase in inlet velocity, which further leads to an increase in fluid disturbance and enhancement of convective heat transfer between the fluid and the skeletons.

![Figure 19](image)

**Figure 19.** Influence of inlet velocity and porosity on the convective heat transfer coefficient for (a) circular cross-section struts; and (b) triangular cross-section struts.

By comparing Figure 19a,b at a given porosity of 0.904, it is evident that the convection heat transfer coefficient of the circular cross-section struts is higher than that of triangular cross-section struts, especially at high inlet velocity. This is primarily because the circular cross-section struts present less obstruction to the flow compared to the triangular cross-section struts, which allows the fluid to flow more smoothly and sufficiently through the GF composite. Moreover, the larger area of the triangular section is also a factor that reduces the coefficient of convection. As a result, the fluid after absorbing heat from the skeleton can flow away more quickly, facilitating the unheated fluid to continue to engage in convective heat exchange with the solid skeleton.

3.4.2. Influence of Flow Direction on the Convective Heat Transfer Coefficient

Figure 20 compares the convective heat transfer coefficients for fluid entering from different directions with varying flow velocities. It can be observed that, regardless of the cross-sectional shape of GF composite, when the flow direction is changed and the foam skeleton remains constant, the convective heat transfer coefficient for fluid flowing through
the foam skeleton along the Y direction is the smallest. This coefficient is significantly lower than those for fluid flowing through the foam skeleton along the X and Z directions. This indicates that the fluid entering the foam skeleton along the Y direction encounters the greatest resistance, which adversely affects its heat transfer performance.

Figure 20. The convective heat transfer coefficient versus the inlet velocity of the GF composite in three directions for (a) circular cross-section struts; and (b) triangular cross-section struts.

4. Conclusions

This study investigates the flow characteristics and convective heat transfer performance in the graphene foam composites using the numerical simulation method. The distributions of the pressure, velocity, and temperature of air flowing through the foam skeleton under forced convection conditions have been analyzed to investigate the effects of porosity, inlet velocity, and cross-sectional shape on the flow resistance and convective heat transfer of the graphene foam composites. The main conclusions can be drawn as follows.

The fluid flow and convective heat transfer can be enhanced by improving the foam porosity. With an inlet velocity of 5 m/s, when the porosity of the GF composite with circular cross-section struts increases from 0.904 to 0.987, the pressure gradient decreases from 65,330 Pa/m to 21,426 Pa/m, and the convective heat transfer coefficient increases from 992.8 W/m²·K to 1377.6 W/m²·K.

Both the pressure drop per unit length and the convective heat transfer coefficient increase as the inlet flow rate increases. At a given porosity of 0.904, the pressure drop per unit length for circular and triangular cross-section struts increases from 5764.9 Pa/m to 65,330 Pa/m, and from 8770 Pa/m to 121,290 Pa/m, respectively. Their convective heat transfer coefficient increases from 642.8 W/m²·K to 992.8 W/m²·K, and from 624.9 W/m²·K to 894 W/m²·K, respectively.

Under the same operating conditions and porosity, the GF composite with triangular cross-section struts has a more obvious accelerating effect on the fluid, causing a more significant pressure drop compared with circular cross-section struts. However, the heat transfer effect of the GF composite with triangular cross-section struts is worse than that of the circular cross-section struts.

Due to the irregular structure of the GF composite, the pressure drop and convective heat transfer coefficient are different when the fluid flows into the foam skeleton from different directions. The Y direction presents the highest pressure drop and the lowest convective heat transfer coefficient in comparison with another two directions.

In the present study, the unique compressibility of graphene foam has not been taken into account for simplification. In our future research work, the effects of compressibility on the thermal performance and fluid flow characteristics of graphene foam composite will be investigated.
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