IOP Conference Series: Materials Science and Engineering

PAPER • OPEN ACCESS

# Heat transfer analysis in compact heat exchanger with fibre reinforced plate

To cite this article: M Hamood *et al* 2021 *IOP Conf. Ser.: Mater. Sci. Eng.* **1078** 012036

# Heat transfer analysis in compact heat exchanger with fibre reinforced plate

**M Hamood[1,*], A N Oumer[1], Azizuddin Abd Aziz[2], M Ishak[2], J P Siregar [1] and O Mamat[3]**

[1]Collage of Engineering, Department, Universiti Malaysia Pahang, Malaysia, 26300, Gambang, Pahang, Malaysia
[2]Faculty of Mechanical and Automotive Engineering Technology, Universiti Malaysia Pahang, Malaysia, 26600, Pekan, Pahang, Malaysia,
[3]Department of Mechanical Engineering, Universiti Teknologi PETRONAS, 32610, Seri Iskandar, Perak, Malaysia

[*]Corresponding author's email: mhhalsham@gmial.com

**Abstract.** Due to their lightweight and ease of manufacturing, fibre-reinforced composites are replacing metals in many heat exchanger applications. However, their heat transfer dissipation performance is not investigated in detail. This paper aims to study experimentally the heat transfer performance of fins made from fibre reinforced composites in compact heat exchangers. Thin fins were manufactured from reinforced fibre composites by the hot pressing technique. The fins have dimensions of 11.5 cm wide and 11.5 cm long. Five different airflow velocities with fixed water flow rates were considered in the analysis. The temperature distribution inside the tube was measured at eight different points using a K-type thermocouple.
The results showed that the water temperature at the outlet section was the highest at the lowest airflow velocity. Moreover, the air-side heat transfer coefficient increased along the tube length at all airflow velocities. The comparable heat transfer performance results make the fibre reinforced fins a good choice in the compact fin-and-tube heat exchanger.

**Keyword:** Compact Heat Exchangers; Fiber-Reinforced Composites; Heat Dissipation; Heat Transfer Coefficient.

## 1. Introduction

Heat exchangers are considered as one of the most important industrial and processing equipment used worldwide. As it is one of the applications of thermal physics (thermodynamics) and it is also considered one of the applications of heat transfer science. Heat exchangers are widely used in heating, refrigeration, air conditioning, and in power plants, chemical and petrochemical plants, in addition to oil refineries and gas processing plants. There are many classifications of heat exchangers and they vary depending on the location and the system adopted [1]. However, heat exchangers can be classified according to the type of flow arrangement. There are three arrangements for the flow of fluids in heat exchangers; the first is the parallel flow heat exchangers, the two fluids enter the heat exchanger from one side and transfer parallel to the other end of the exchanger. The second type is heat exchangers with a counter flow, the two fluids enter from the opposite sides and go in the opposite direction. Third, the heat exchangers with the crossflow, the two fluids move in a vertical position so that one of the fluids is perpendicular to the other, which this research will focus on. There are many types of heat exchangers [1], the most prominent of which is compact heat exchanger, fin and tube heat exchangers are characterized by their excellent efficacy in heat dissipation and are characterized by lightweight and space-saving, which made them used extensively in most applications engineering, for example, car coolers, heat energy conservation, air conditioners, and in aircraft and spacecraft. Heat transfer is carried out in this heat exchanger by conduction.

In the last decade, heat exchangers made of the reinforced polymer have spread, and have received great interest due to the many properties that the polymer possesses. For example, it is light in weight, easy to manufacture, and most importantly, has good corrosion resistance. On the contrary, metal heat exchangers have a lot of defects such as heavy weight and ease of corrosion, which greatly reduces its life and efficiency. In addition, polymeric heat exchangers are distinguished by their ability to insulate electricity, which makes them ideal for use in electronic devices. Finally, polymers are more resistant to chemicals than metals, which makes them more durable as a material for heat exchangers[2].

Many studies have invented the need to develop the metal heat exchangers into exchangers made from alternative materials. Therefore, attention was focused on making compact reinforced polymer heat exchangers as a first step, due to the ability of the polymer composite material to handle liquids and gases, and its resistance to corrosion. More importantly, the polymer composite is inexpensive, light in weight, and small in size to save space. All of these advantages give the polymer material a competitive advantage over the metal heat exchangers [3]. Polymer matrix composites are among the most common advanced composites. These composites consist of a polymer thermoplastic or thermosetting reinforced by fibre (natural carbon or boron). A variety of shapes and sizes can be moulded from these materials. Along with resistance to corrosion, they provide great strength and stiffness. The reason why these are most prevalent is their low cost, high strength and simple production principles. The fibre reinforced polymer does not sufficiently dissipate heat, thus accumulating heat stress. However, its many distinctive properties such as lightweight, rust resistance and ease of manufacture, which make it a suitable choice for designing a high-efficiency heat exchanger. Eunbi Lee mentioned that some additions and improvements can be made to the reinforced polymer to increase the thermal conductivity, through-thickness using a layer-by-layer covering of inorganic crystals. Three types of inorganic crystal fillers consisting of aluminium, magnesium, and copper were used to prepare the highly thermally conductive CFRP composites through the layer-by-layer coating process. The vertical thermal conductivity of pure CFRP at a very low content of 0.01 wt percent was increased by up to 87 percent while using magnesium filler. It was also confirmed that the higher the thermal conductivity enhancement was, the better were the mechanical properties. In order to increase the thermal conductivity of composites, many different materials with high thermal conductivity have been used as fillers, such as carbon nanotubes (CNTs), boron nitride (BN), aluminium oxide, diamond, and graphene. Graphene has received more interest due to its unique structure and some of its exciting properties, such as its high thermal conductivity (Li et al., 2017).

Teweldebrhan et al. stated that the thermal conductivity measurement of suspended single-layer graphene was one of the highest thermal conductivities of currently known materials, about 5000 $Wm^{-1}K^{-1}$ [4]. A promising method of advancing the thermal conductivity of composites has been considered to be the alignment of hBN using an electric field. This allows small quantities of hexagonal boron hBN filler to be used to achieve high thermal conductivity. In addition, it was suggested that by adding electric field alumina, the thermal conductivity value of hBN / polymer composites can be increased by 15 times for 15 vol % plate-like alumina [5]. Experimental research was conducted by [6] to study the performance effect of fin types for compact finned flat-tubing of HEs. Three shape types of fins connected to three out of three flat tube bank arrays are smooth, wavy and rectangular grooved fins were used in that research. Compared to the wavy and plain fin, the rectangular fin was found to have the highest heat transfer performance where the wavy fin is greater than plain perfect. The impact of fin spacing on the fin temperature and the heat transfer coefficient of plain fin-and-tube HEs was studied by Chen and Hsu [7]. They found that the greater the distance between the fins, the higher the heat transfer coefficient. In contrast, the temperature decreased along the length of the fin. [8] performed two-dimensional numerical simulations to assess the efficiency of circular and elliptical tubes with one and two rows of tubes at the lower number of Reynolds. Their findings reveal that, under equal operating conditions, the heat exchanger with the elliptical tube provides greater overall efficiency than the heat exchanger with the circular tube. The fine thickness and tube diameter were explored by Lu et al. [9].

From his work, it is found that the heat transfer is improved by decreasing tube diameter with a set frontal inlet velocity. Thus, the purpose of this research are to investigate the heat transfer performance of compact fine-and-tube heat exchangers (CFTHE) made from reinforced polymer composites and to optimize the geometrical and process parameters for enhanced heat dissipation of fibre reinforced plate. The air of this study is to investigate the heat transfer performance of carbon fibre reinforced polymer composite fins and copper tube compact heat exchangers at various airflow velocities. The fluid medium flowing inside the tubes is water at one fixed temperature inlet value.

## 2. Methodology

### *2.1. Material*

The materials used to make a rectangular mold for the manufacturing of flat fins, a mild still was used. The drawing for the machining was done using Solidworks 2016 software. The finalized dimension of the mold is 23.5cm x 23.5cm with 2mm. After the CAD drawing, the drawing has been transferred to Mastercam software to create detailed instructions (G-code) and to automate the manufacturing process of the mold using a Computer Numerical Control (CNC) machine. After creating detailed instructions (G-code) from Mastercam software, the mold was fabricated from the mild steel plate using the CNC machine.

### *2.2 Fin preparation*

The fins were prepared using VORAFUSE method. It is a technique that has been developed by Dow Automotive Systems. It is the combination of epoxy resin with carbon fibre for prepreg (combination of fibres and uncured resin) applications in order to improve the handling of materials and the cycle time during the molding of composite structures. The hand lay-up process is the most commonly used manufacturing process. The fibre preforms are initially placed in a mold where an anti-adhesive coat (thin layer) is used to easily remove them. The resin material is then poured for reinforcement. The roller is used to enhance the interaction between the reinforcement and matrix materials ' successive layers. Previously, no analysis was carried out on the material form of the final shape; the parameters were therefore set at 12 cm x 12 cm and 1 mm with inline setup. With constant fin spacing, a total of 13 woven carbon fibre fins were fabricated. Similar work documented by [10].

### *2.3 Experimental setup and procedure*

The full experimental setup with the measurement instruments used in the experiment and the position of the temperature sensors in the inline fin is shown in Figure 1. Air is used as the working fluid, and in order to obtain the thermal-hydraulic performance of the fin and tube heat exchangers, the experiments were performed in an open wind tunnel. The system of the experiment consists of an inlet section, a test section, and measuring tools for air temperature and water, pressure drop, velocity of air, and controller device for water temperature. The system starts up by operating the suction fan so that air flows into the test section over the fin and tube. By using the coil heater, the water is heated between 40 to 50 ℃ in a basin, then pumped through the tube to the inlet of HE by using hot water pump (with power 22W and water flow 800L/h), and then this water returns to the basin and heated again and continues in a circular motion at the same temperature.

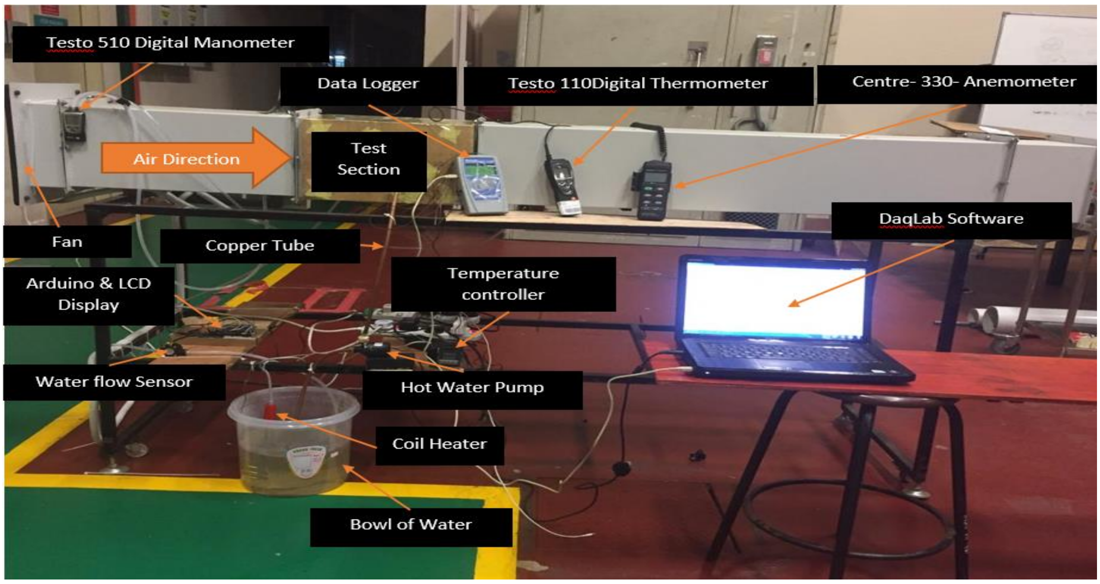


**Figure 1.** Experimental setup with measuring.

The wind tunnel is square in shape, each side is 26 cm. A straightener device has been placed at the inlet to avoid the velocity of the air flows any distortion. The test section is 1.2 meters away from the straightening device, in order to filter the air before it reaches the test section. Two holes were made for the bottom wall of the wind tunnel one before the test section and the other after it, for fixing the pitot tubes of the digital manometer. The back side of the wind tunnel has also been drilled, where a thermometer device could be installed to measure the velocity and temperature of the airflow before entering the test section. After that, air flows through the finned-and-tube HEs and then discharged to the adjacent places. The wind tunnel is also installed 50 cm high on a steel stand to reduce noise and vibration during system operation.

The exhaust fan was operated with a 50 W AC current, by means of a frequency converter the fan speed was controlled to five different speeds as shown in Table 1. Since the frequency converter is not accurate to control the desired air velocity, a Digital Anemometer was used where the frequency converter is tuned Moreover, the Digital Anemometer can also measure the temperature, so the temperature of the air entering the test section is measured by it. Then the Testo 110 Digital Thermometer was used to measure the air temperature after it left the test section. The REX C-100 was also used to keep the temperature constant on the surface of the circular tube. TESTO 510 is a model of digital differential pressure manometer, and it was used to measure the pressure of air at the inlet and the outlet of the test section. Figure 2 shown the test section made of 13 reinforced polymer fins with 2 cm distance between each other and a copper tube by 5mm diameter. Eight locations were selected on the test section and connected to the K-type sensor, so that six points were distributed on the test section inside the wind tunnel (point 2, 3, 4, 5, 6, and7) and two points outside the wind tunnel, one of them in the inlet (point 1) and the other at the outlet (point 8). Then by using OM-DAQPRO-5300 data logger, the temperature was measured for the eight points for each second during two minutes, then this process was repeated for the five different velocities of the airflow, Figure 2 shows the location of the sensors in the test section.

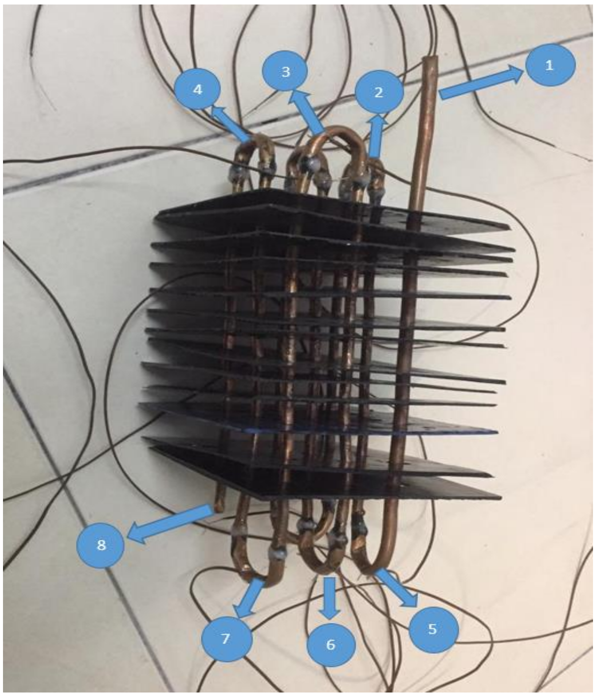


**Figure 2**. Test section and the 8 positions of K-type.

*2.4 Data reduction*

In this section, the data reduction is identified as a primary purpose for evaluating the heat transfer performance of heat exchangers by finding the heat transfer coefficient. The heat transfer rate transferred from the hot water to the tube is calculated using water properties and temperature differences.

$$Q^{\cdot} = c_p\, \dot{m}^{\cdot}\, (T_{in} - T_{out}) \quad (1)$$

Where, $C_p$, $\dot{m}^{\cdot}$ , $T_{in}$ and $T_{out}$ are the specific heat capacity of water, the water mass flow rate, hot water inlet temperature and water outlet temperature, respectively. The heat transfer coefficient was calculated using Equation (2)

$$h = \frac{Q}{A\, \Delta T} \quad (2)$$

$$\Delta T = \frac{(T_i - t_o) - (T_o - t_i)}{\ln\left[\frac{(T_i - t_o)}{(T_o - t_i)}\right]} \quad (3)$$

$$\Delta T = T_{wall} - T_{mean} \quad (5)$$

$$T_{mean} = \frac{T_{air\ inlet} + T_{air\ outlet}}{2} \quad (6)$$

Where ΔT can be calculated from the log mean temperature difference or the change between the wall temperatures and meat temperature, *h* is the heat transfer coefficient, and *A* is the surface area of the circular tube and the fin surfaces.

## 3. Result and dissection

Two random airflow velocities are selected and presented here in Figs. 3 and 4 to prove the flow and temperature distributions are at steady-state conditions at every point during the experiment. As shown in both figures, the temperature values at various thermocouple locations for the airflow velocities of 2.3 and 3.3 m/s show straight horizontal curves at all times. At the hot water inlet location (T1), there are slight temperature variations between 25-30, 50-55 and 100-105 seconds, however, these variations are insignificant. This indicates that the temperature distribution is in a stable condition at all locations. Moreover, the results indicated that as the flow advances from the inlet to the outlet section (from T1 to T8), the temperature of the working fluid decreased as expected. For both velocity cases, the temperature variation is significant between T1 & T2 and T7 & T8 while the temperature change is small for the other thermocouple locations. The temperature distribution of the working fluid measured at the fixed water flow rate of 0.22L/s are shown in Table 1. The temperature variation along the tube length was measured at eight positions at different airflow velocities which were 1.8, 2.3, 2.6, 2.8, 3.2 m/s. As can be seen from the table, a gradually decreasing trend of temperature from point T1 to T2 for all airflow velocities. The temperature drop was around 10℃ from the inlet to the outlet of the test section. This is due to the fact that the hot water loses energy to the air flowing over the surface of the tube when it advances toward the outlet section. Moreover, at one specific thermocouple location, at the outlet section (T8) for instance, the temperature variations with increased airflow velocity are not significant. However, the higher the airflow velocity, supposed to be the greater the amount of heat absorbed during the passage of the air through the test section as was reported by A. Y. Adam et al. for the case of fin-and-flat-tube compact heat exchangers made from aluminium [11]. The discrepancies might be due to low flow rate of heated water flowing through the circular tube and usage of heaters by A. Y. Adam et al. which made the wall temperatures of the tube constant at all locations.

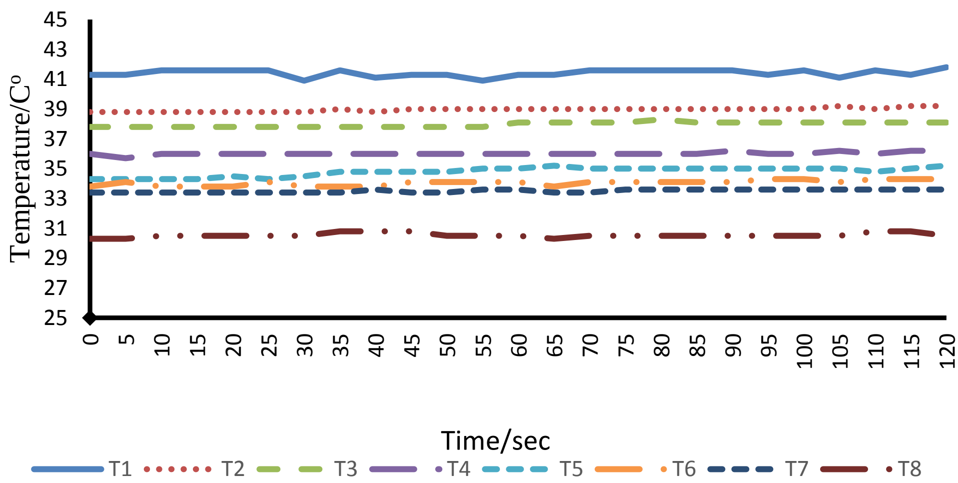


**Figure 3.** Variation of temperature with time at various thermocouple locations for the air velocity of 2.3 m/s.

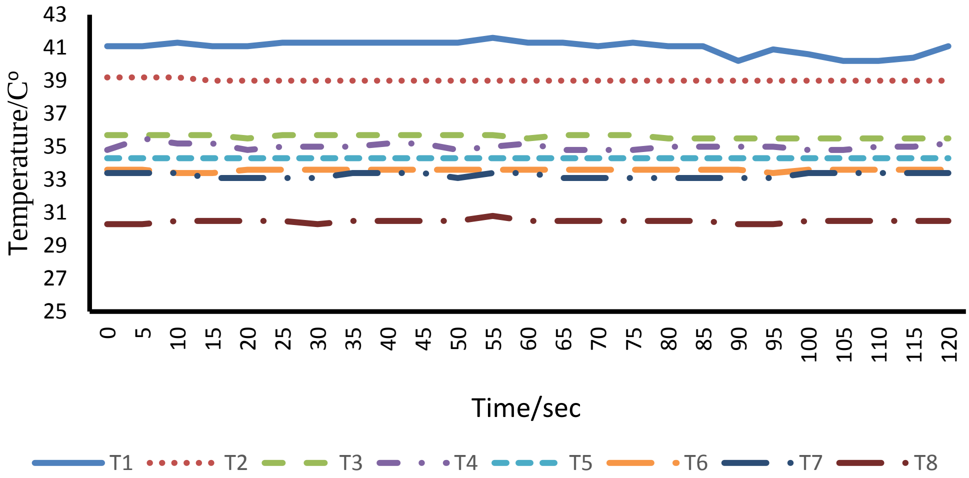


**Figure 4**. Variation of temperature with time at various thermocouple locations for the air velocity of 3.2 m/s.

**Table 1.** Temperature for each position during the five different velocity.

| Temperature position | Temperature C | | | | |
|---|---|---|---|---|---|
| | 1.8 m/s | 2.3 m/s | 2.6 m/s | 2.8 m/s | 3.2 m/s |
| T1 | 41.3 | 41.8 | 41.6 | 40 | 41.1 |
| T2 | 38.5 | 39.2 | 39.5 | 39.2 | 39 |
| T3 | 37.8 | 38.1 | 38.3 | 38.1 | 35.5 |
| T4 | 36 | 36.2 | 36.2 | 36 | 35.2 |
| T5 | 34.3 | 35.2 | 35 | 35 | 34.3 |
| T6 | 33.6 | 34.3 | 34.3 | 33.3 | 33.6 |
| T7 | 33.4 | 33.6 | 33.6 | 34.3 | 33.4 |
| T8 | 30.3 | 30.5 | 30.5 | 30.5 | 30.5 |

Figure 5 depicts the effects of airflow velocity on the local air-side heat transfer coefficient (*h*). This figure reveals that the local air-side heat transfer coefficient has increased significantly when the hot water travelled from the inlet to the outlet section of the tube at all airflow velocities. In general, the effect of airflow velocity on the heat transfer coefficient is negligible. However, However, as the water flow advances towards the outlet (*x* increases), it can be noticed a trend characterized by the increase of *h* with decreasing air flow rate. These different behaviours are associated with the time required by the air to absorb more heat from the hot water when travelling at low speed. It is difficult to generalize the overall trend as it might change when the waterside mass flux is changing instead of kept constant.

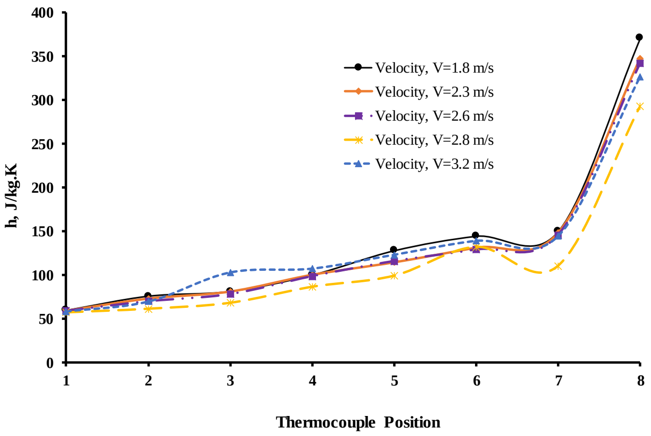


**Figure 5.** Heat Transfer Coefficient Variation of the Air-Side with Thermocouple Positions

## 4. Conclusion

From the heat transfer results, it was found that the fins made of the fibre-reinforced composite can be used in compact heat exchangers due to the heat dissipation performance is comparable with the conventional heat transfer materials. Through the experiment, which was for five different velocities of airflow, it was observed an average of 10 °C decrement in the water-side temperature. However, at the constant water-side flow rate, increasing the air-side flow rate has an insignificant effect on the average air-side heat transfer coefficient at all tube locations. Hence, fibre-reinforced fins can be used as an alternative material for heat dissipation in the compact heat exchanger.

## Acknowledgements

The authors would like to thank Universiti Malaysia Pahang and the Ministry of Higher Education Malaysia for the financial support given under FRGS/1/2019/TK03/UMP/02/18 and RDU190319, respectively.

## References

[1] Kuppan Thulukkanam, "Classification of Heat Exchangers," 2013, pp. 1–77.

[2] M. A. Arie, A. H. Shooshtari, R. Tiwari, S. V. Dessiatoun, M. M. Ohadi, and J. M. Pearce, "Experimental characterization of heat transfer in an additively manufactured polymer heat exchanger," *Appl. Therm. Eng.*, vol. 113, no. November, pp. 575–584, 2017, doi: 10.1016/j.applthermaleng.2016.11.030.

[3] L. Zaheed and R. J. J. Jachuck, "Review of polymer compact heat exchangers, with special emphasis on a polymer film unit," *Appl. Therm. Eng.*, vol. 24, no. 16, pp. 2323–2358, 2004, doi: 10.1016/j.applthermaleng.2004.03.018.

[4] D. Teweldebrhan *et al.*, "Superior thermal conductivity of single layer graphene," *Nano Lett.*, vol. 8, p. 902, 2008.

[5] X. Zheng, S. Kim, and C. W. Park, "Enhancement of thermal conductivity of carbon fibre-reinforced polymer composite with copper and boron nitride particles," *Compos. Part A Appl. Sci. Manuf.*, vol. 121, no. August 2018, pp. 449–456, 2019, doi: 10.1016/j.compositesa.2019.03.030.

[6] H. U. Choi and R. Fatkhur, "Experimental Investigation on Effect of Fin Shape on the Thermal-Hydraulic Performance of Compact Fin-and-Tube Heat Exchangers Experimental Investigation on Effect of Fin Shape on the Thermal-Hydraulic Performance of Compact Fin-and-Tube Heat Exchangers," 2018, doi: 10.1088/1757-899X/318/1/012070.

[7] H. T. Chen and W. L. Hsu, "Estimation of heat transfer coefficient on the fin of annular-finned tube heat exchangers in natural convection for various fin spacings," *Int. J. Heat Mass Transf.*,

vol. 50, no. 9–10, pp. 1750–1761, 2007, doi: 10.1016/j.ijheatmasstransfer.2006.10.021.

[8] L. A. O. Rocha, F. E. M. Saboya, and J. V. C. Vargas, "A comparative study of elliptical and circular sections in one- and two-row tubes and plate fin heat exchangers," *Int. J. Heat Fluid Flow*, vol. 18, no. 2, pp. 247–252, 1997, doi: 10.1016/S0142-727X(96)00063-X.

[9] C. W. Lu, J. M. Huang, W. C. Nien, and C. C. Wang, "A numerical investigation of the geometric effects on the performance of plate finned-tube heat exchanger," *Energy Convers. Manag.*, vol. 52, no. 3, pp. 1638–1643, 2011, doi: 10.1016/j.enconman.2010.10.026.

[10] P. Moorthy, A. N. Oumer, and M. Ishak, "Experimental Investigation on Effect of Fin Shape on the Thermal-Hydraulic Performance of Compact Fin-and-Tube Heat Exchangers," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 318, no. 1, 2018, doi: 10.1088/1757-899X/318/1/012070.

[11] A. Y. Adam, A. N. Oumer, A. Alias, M. Ishak, and M. M. Noor, "Investigation of thermal-hydraulic performance in flat tube heat exchangers at various tube inclination angles," *Int. J. Automot. Mech. Eng.*, vol. 14, no. 3, pp. 4542–4560, 2017, doi: 10.15282/ijame.14.3.2017.12.0359.