Heat Transfer Enhancement in Heat Exchangers using GRIP Metal Surface Modification

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Abstract

NUCAP has developed a proprietary manufacturing process which creates high aspect ratio metal features (fins) on metal surfaces which offer increased surface area and fluid mixing. This study experimentally quantifies the effect of NUCAP's GRIP Metal surface enhancement for two heat exchanger designs: 1) on the air-side of a finned tube, water-to-air heat exchanger and 2) in a cross-flow air-to-air heat exchanger. For both heat exchangers, the GRIP Metal surface is compared with conventional flat surfaces.

For the water-to-air heat exchangers the thermal dissipation was significantly higher in the GRIP Metal enhanced heat exchanger and resulted in a 22% reduction in thermal resistance, but incurred a significantly higher air-side pressure drop.

In the air-to-air heat exchanger, the thermal performance of the polymer core was higher; however, this was primarily due to this having significantly higher flow channels and convective surface area, making a direct comparison somewhat unfair. The GRIP Metal core had a significantly lower pressure drop in this case.

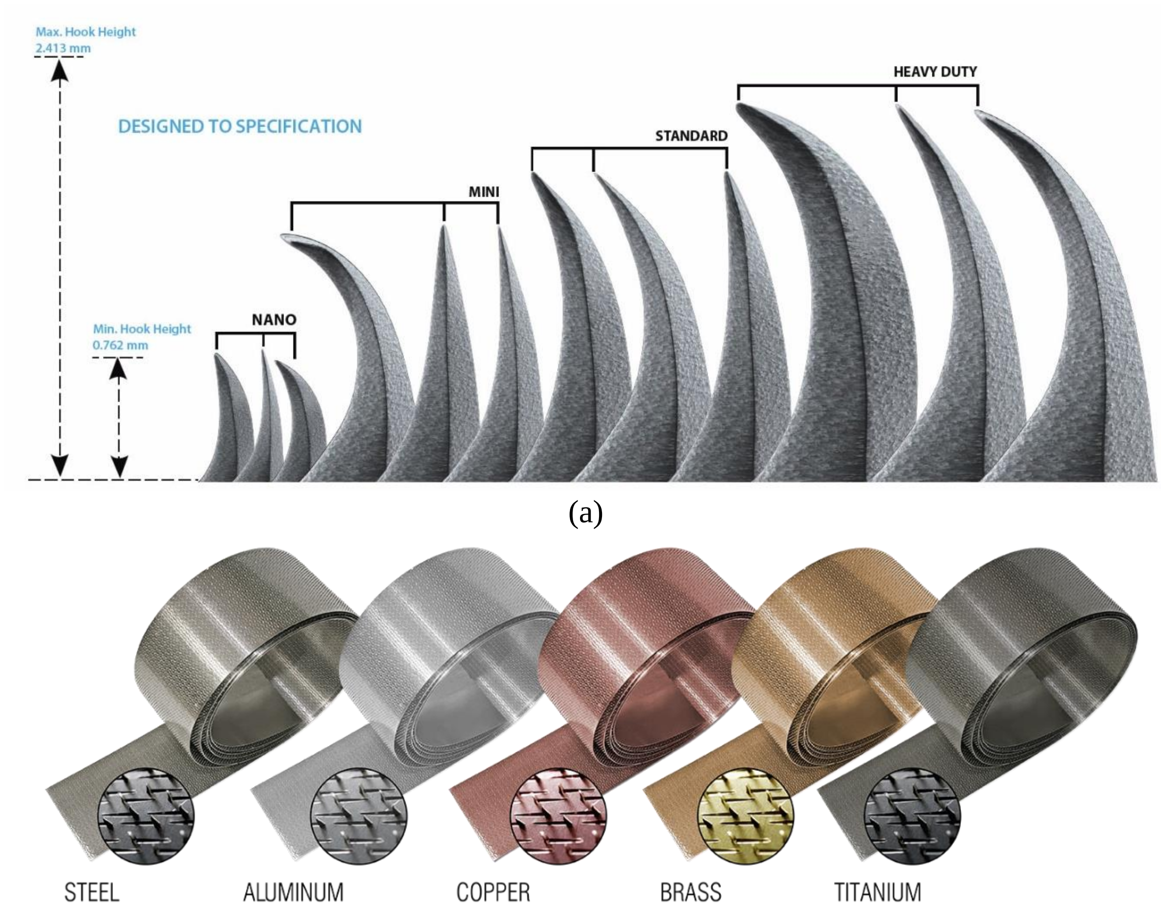
The results highlight the potential for GRIP Metal features to be used practically to significantly improve heat exchanger performance if designed and specified in an optimal fashion. Recommendations are made to further study convective heat transfer from these surfaces in a controlled and fundamental way to develop the design tools necessary to design, quantify, and optimize GRIP Metal heat transfer surfaces for any heat exchange application by developing comprehensive models to quantify heat transfer for a wide range of flow regimes, fluid types, and GRIP Metal geometries.

1. Introduction & Background

The enhancement of convective heat transfer on heat exchange surfaces is important for many industrial and commercial applications because it affords increased power delivery or improved effectiveness of the heat exchanger. It can also be used to reduce the size or weight of a heat exchanger for a given application.

Convection enhancement between the fluid and tube wall can be achieved through increasing the specific surface area (wetted surface area per nominal area) and by increasing turbulent mixing near the wall region. For practical applications it is important that the enhancement technique does not incur a significant pressure drop on the fluid flow requiring increased pumping requirements. Enhancement techniques should also be inexpensive and afford flexible manufacturing options for specific applications.

NUCAP has developed a proprietary manufacturing process which creates high aspect ratio metal features (fins) on metal surfaces, as shown in Fig. 1. NUCAP Grip Metal features offer increased specific surface area and increase fluid mixing and possible boundary layer separation which can also serve to increase convective heat transfer.



(b)

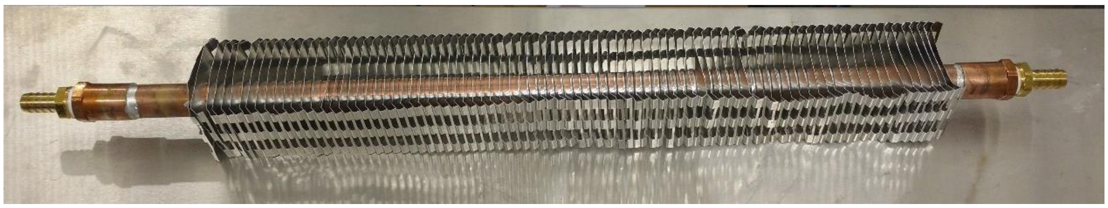
Figure 1: Side view of a) GRIP Metal features and b) GRIP Metal features on metal surfaces

The objective of the present work is to experimentally evaluate and compare the effect GRIP Metal enhanced surfaces have on the thermal performance of both a water-to-air finned tube heat exchanger and an air-to-air crossflow heat exchanger.

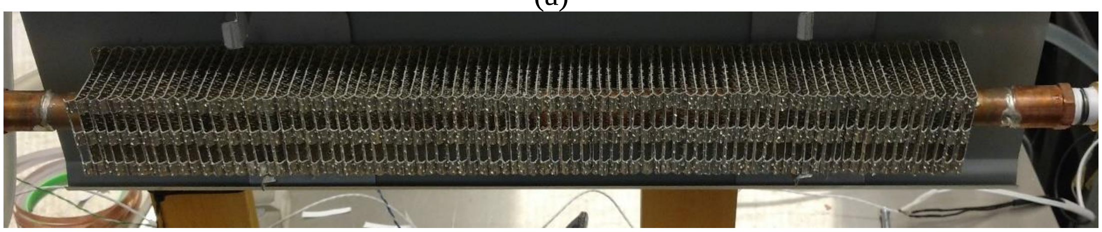
2. Experimental Apparatus

2.1 Water-to-Air Heat Exchangers

The performance of two water-to-air heat exchangers of nominally identical size were fabricated and tested to quantify the effect of GRIP Metal features on the heat transfer and pressure drop. The convectional finned tube and the corresponding GRIP Metal finned tube heat exchangers are shown in Fig. 2. Here, both heat exchangers consist of 85 fins (55 mm x 60 mm fins) press-fitted to a 7/8” OD tube. Nominal flow area of the finned region is approximately 500 x 60 mm.



(a)



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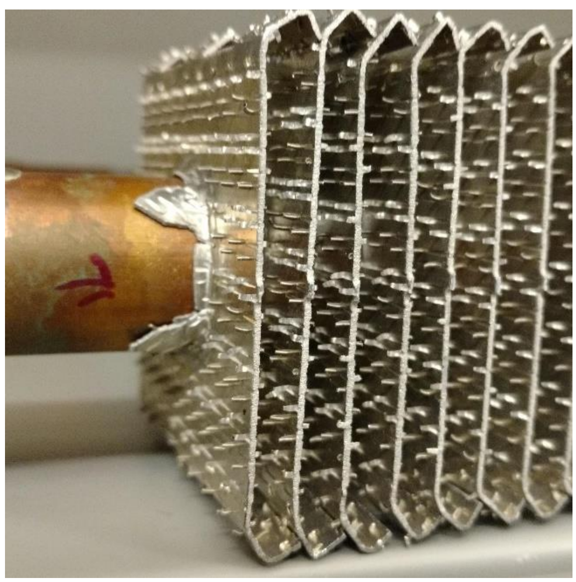


(c)

Figure 2: a) Conventional finned tube, b) GRIP Metal enhanced finned tube, and c) close-up view of GRIP Metal enhanced fins

2.2 Water-to-Air Test Apparatus

The heat transfer performance of these water-to-air heat exchangers was characterized using the apparatus shown in Figs. 3 and 4. Here, hot water with a controlled inlet temperature flows through each heat exchanger. The heat exchangers are placed in an enclosed duct and air flows over the fins to dissipate a quantity of thermal power which is quantified by measuring the flowrate of the water temperature drop. The thermal dissipation can then be used to calculate the thermal resistance of the heat exchanger.

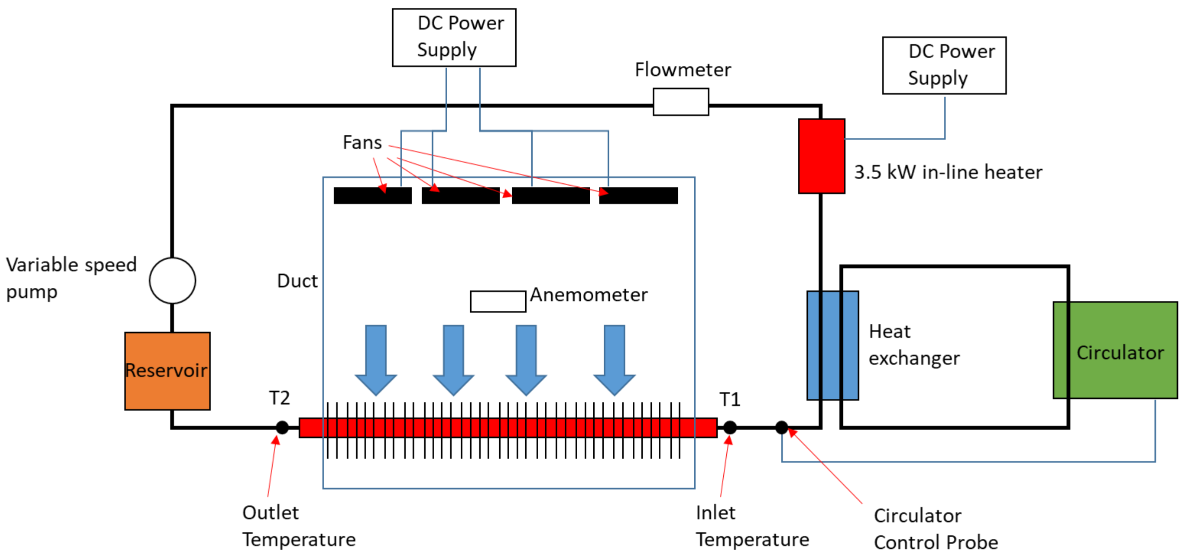


Fig. 3: Schematic of experimental setup

The water was heated using a 3.5 kW in-line water heater which was controlled using a DC power supply. Fine-tuning of the inlet temperature was achieved using a temperature-controlled circulator and secondary water-to-water heat exchanger installed just prior to the inlet.

The water inlet and outlet temperature were measured using 3.175 mm (1/8 inch) diameter, 4-wire RTDs inserted through Swagelok T-fittings at the inlet and outlet of the tubes under test. These RTDs were calibrated simultaneously to reduce the uncertainty in this temperature difference measurement to approximately ±0.01K (less than 1% of typical measured values).

The water flowrate was measured using an Omega FTB604 flowmeter with an accuracy of ± 1% of reading. The water was circulated at a constant rate of approximately 1 to 3 LPM using a diaphragm pump.

Air was directed through the fins of the heat exchangers using a custom acrylic duct, as shown in Fig. 4. Four 120 mm fans controlled using a DC power supply allowed for a wide range of airspeeds to be evaluated. A PyleMeters digital anemometer (PMA90) was used to measure inlet airspeed with an accuracy of ± 3%.

Ambient (inlet) air temperature was measured using a T-type thermocouple.

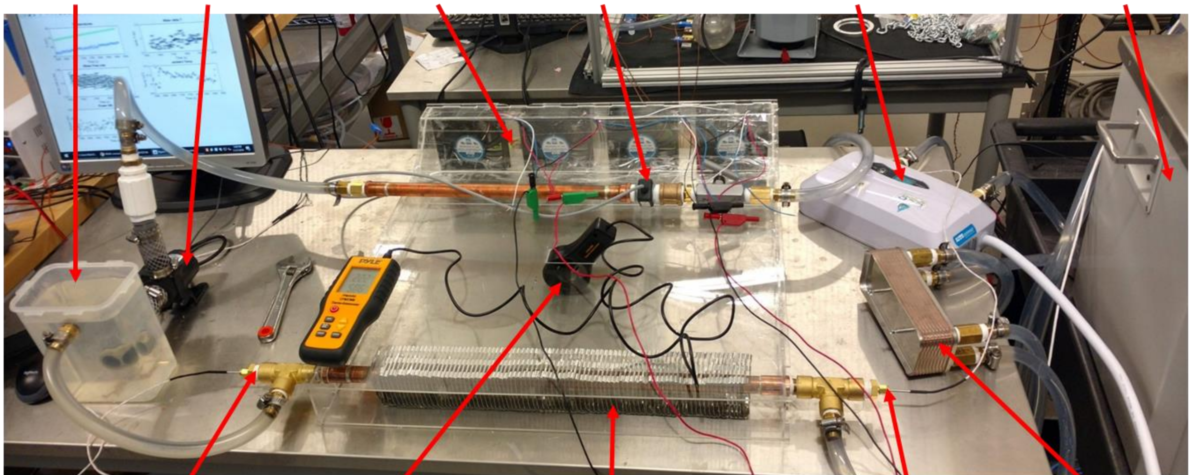


Fig. 4: Experimental setup

The thermocouple and RTD readings were monitored continuously using an Agilent 34970A data acquisition unit connected to a PC running a custom MATLAB script to log the data.

At steady state, the dissipated heat, Q, was computed using the temperature difference, the water flowrate, and the temperature difference between the inlet and outlet (Eq. 1).

$$Q = \dot{m} c_p \left(T_{inlet} - T_{outlet} \right) \tag{1}$$

where $\dot{m}$ is the mass flowrate of water, c_p is the specific heat of water, and T_{inlet} and T_{outlet} are the inlet and outlet temperatures of the water, respectively.

The thermal resistance of the heat exchanger can be quantified as

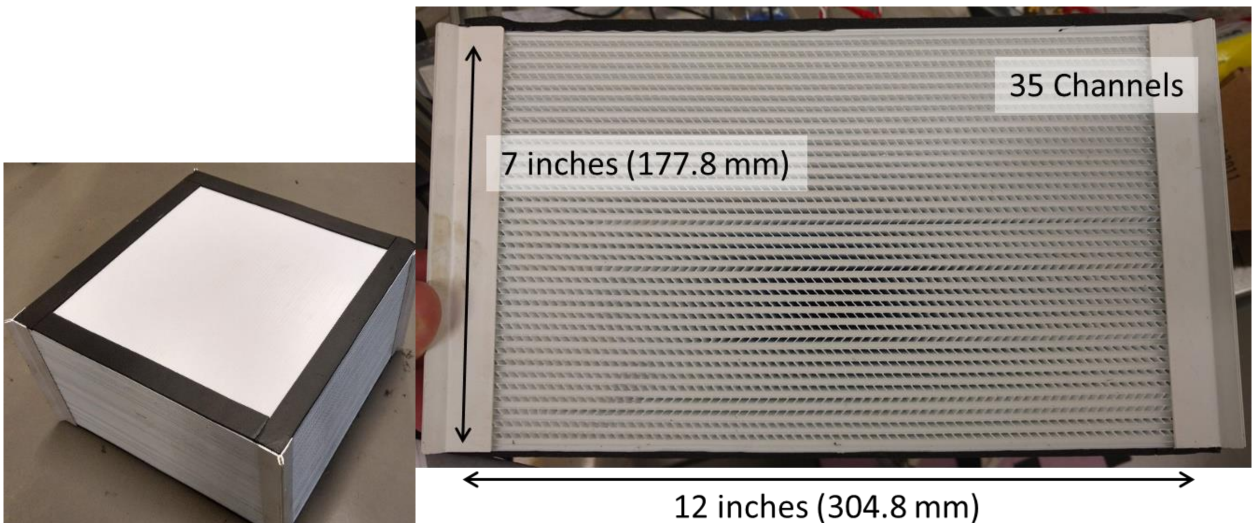
$$R = \frac{T_{inlet} - T_{amb}}{Q} \tag{2}$$

where T_{amb} is the ambient air temperature.

2.3 Air-to-Air Heat Exchanger Test Setup

A Softaire RHRV-C100P fresh air-to-air heat exchanger, shown in Fig. 5a, was used to compare the thermal performance of the standard polypropylene core (Fig. 5b) to that of a custom fabricated stainless-steel core enhanced with GRIP Metal features, shown in Fig. 5c.

(a)



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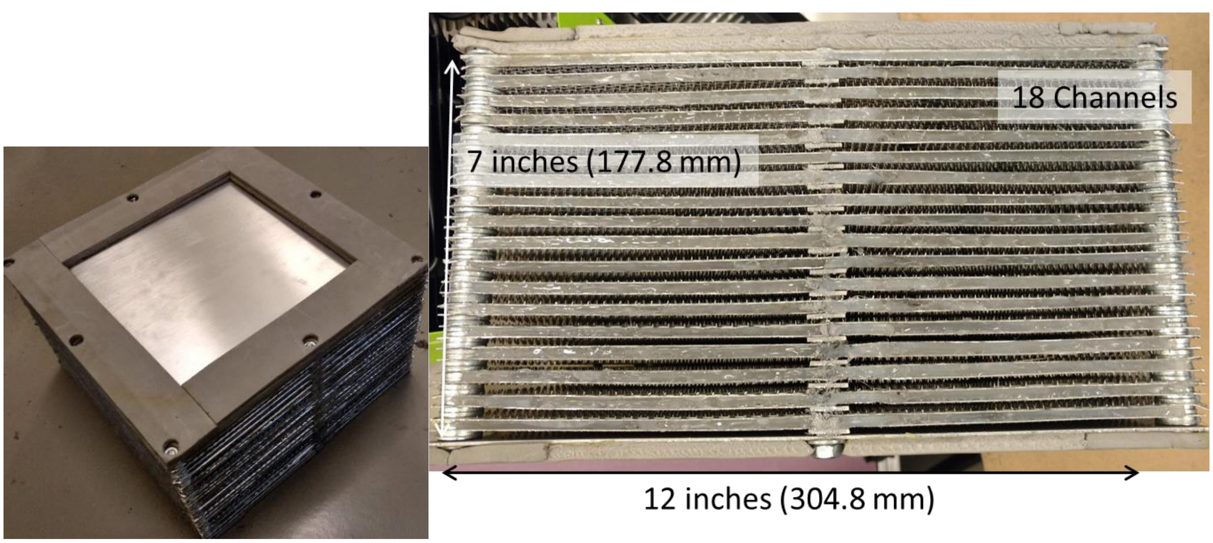
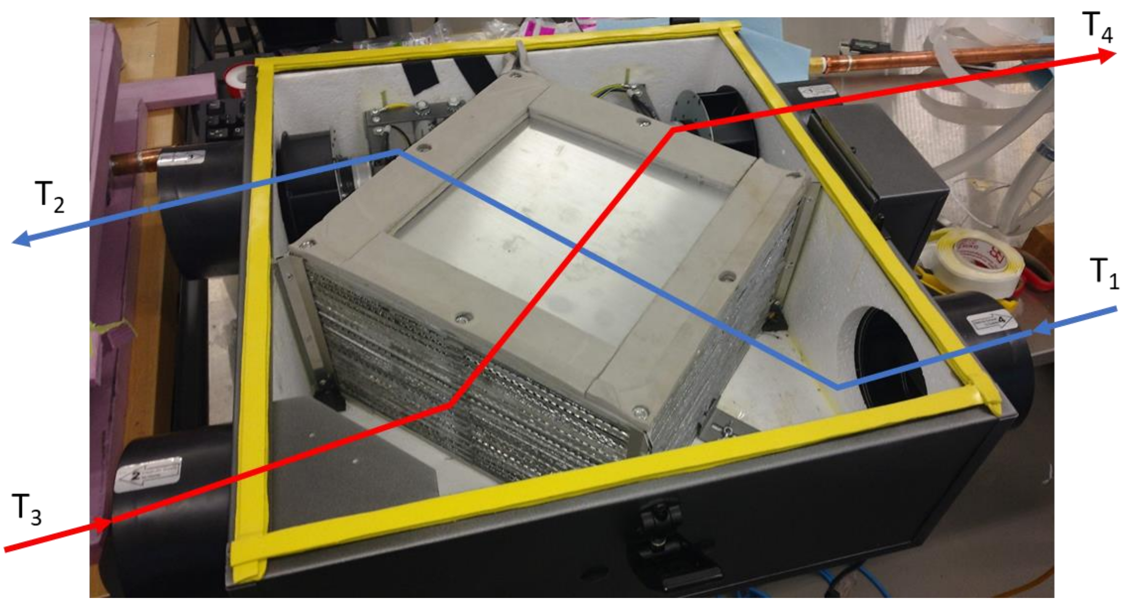


(c)

Fig. 5: a) Softaire air-to-air heat exchange unit, b) standard polymer core, c) GRIP Metal enhanced metal core

The heat exchanger operates in a crossflow configuration, as shown in Fig. 6a. Here, hot air entering a T_3 transfers heat through the core to the cold stream which enters at T_1 and exits warmer at T_2.

The inlet air at T_3 was pre-heated to approximately 51°C using a liquid-to-air radiator fed by a temperature-controlled water circulator. The radiator was incorporated into a 3D-rinted duct at the inlet of T_3, as shown in the bottom left of Fig. 6b. These ducts also incorporated mounting for thermocouples for air temperature measurement at all locations and two vane anemometers (Pyle-Meters digital anemometers, PMA90) which were used to measure the air flow rate for both streams with an accuracy of ± 3%, as shown in the bottom right of Fig. 6b. The cold side relied on ambient air which was nominally 23°C at the inlet (T_1). The airflow for each side was adjusted manually using the potentiometers in the control box of the unit.



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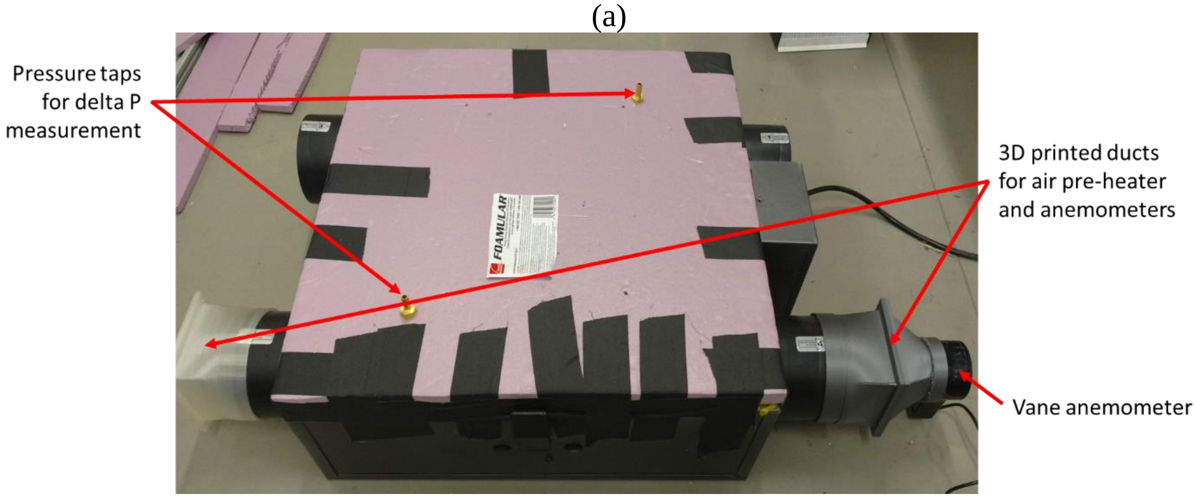


(b)

Fig. 6: a) Air flow paths through the crossflow heat exchanger, b) instrumentation and pre-heating ducts

The pressure drop through the heat exchanger was characterized by measuring the differential pressure within the triangular plenums formed at the exit of the heat exchanger core using a Fluke 922 Micromanometer. The location of these pressure taps is shown in Fig. 6b.

The thermocouple readings were monitored continuously using an Agilent 34970A data acquisition unit connected to a PC running a custom MATLAB script to log the data. Pressure drop and flowrates were recorded manually.

The effectiveness, ε, of a heat exchanger is defined as the ratio of actual heat transfer to maximum possible heat transfer given by

$$\varepsilon = \frac{\dot{m}_{cold} C_p \left(T_2 - T_1\right)}{\dot{m}_{cold} C_p \left(T_3 - T_1\right)} \tag{3}$$

where $\dot{m}$ is the mass flow rate, C_p is the specific heat of the air, and T_1 is the cold-side inlet temperature, T_2 is the cold-side outlet temperature, and T_3 is the hot-side inlet temperature (refer to Fig 6a).

3. Results & Discussion

3.1 Water-to-Air Heat Exchangers

The thermal dissipation of the water-to-air heat exchanger as a function of air flow rate is shown in Fig. 7. Here, as expected, the thermal dissipation depends on the air velocity through the fins and is seen to rise steadily as air speed is increased. Both the standard finned tube and the GRIP-Metal-enhanced finned tube exhibit this behaviour. However, at a given airspeed the GRIP Metal heat exchanger offers significantly higher thermal dissipation, generally dissipating approximately 30% more power than the standard finned heat sink.

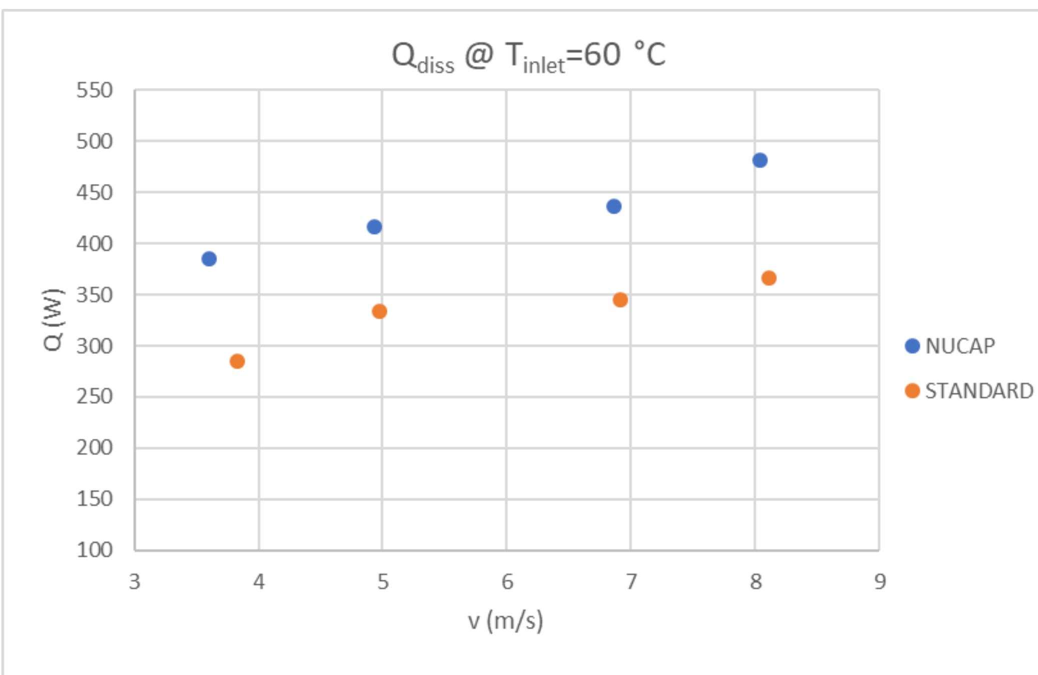
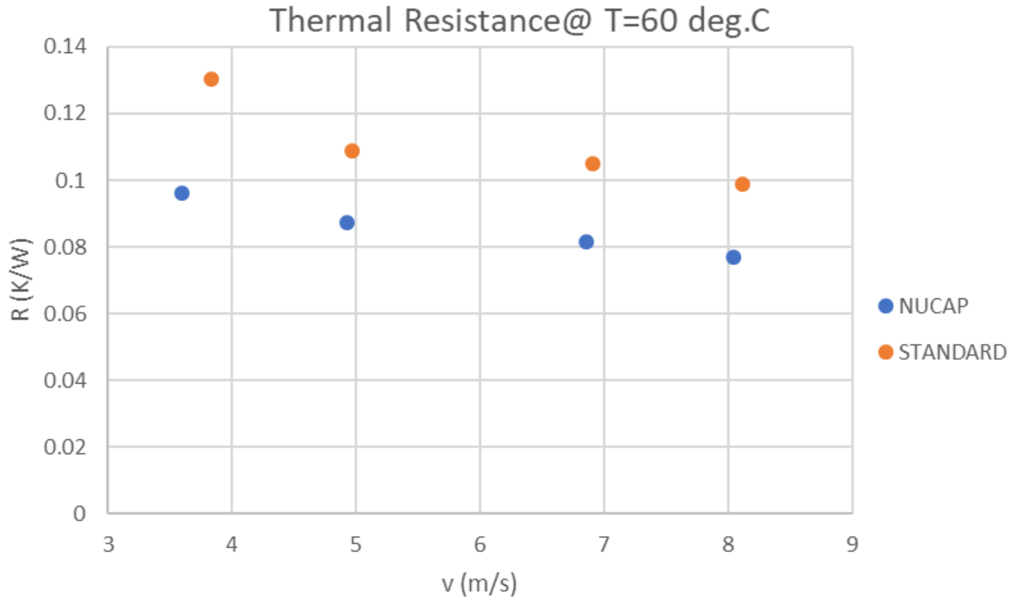


Fig. 7: Thermal dissipation of water-to-air heat exchanger at water inlet temperature of 60°C



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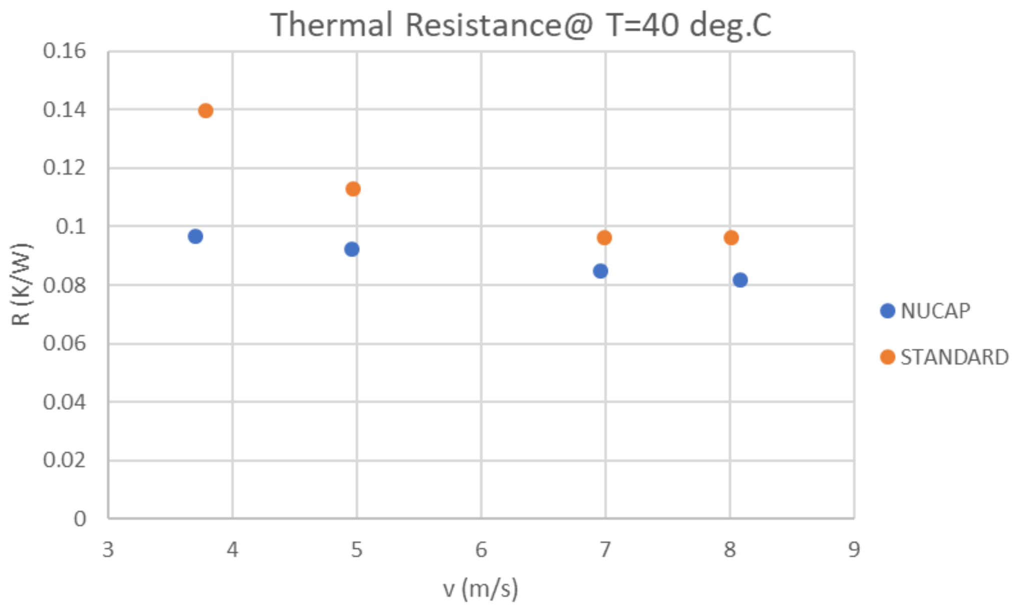


(b)

Fig. 8: Thermal resistance of water-to-air heat exchanger for a) GRIP Metal finned tube, b) standard finned tube

A similar scenario is revealed when these results are viewed in terms of the thermal resistance of the heat exchanger, defined by Eq. 2. The thermal resistance of both the standard finned tube and the GRIP-Metal-enhanced finned tube are show in Fig. 8. At an inlet water temperature of 60°C (Fig. 8a), the thermal resistance of both heat exchangers decrease with air velocity due the increase in convective heat transfer associated with increased air speed. However, the thermal resistance of the GRIP Metal enhanced finned tube is on average 22% lower than the standard finned tube.

This can be attributed in part to the increased specific surface area offered by the fins as well as some degree of improved mixing and energy exchange between the air and the fins.

As would be expected, a similar trend is observed for the case of a lower inlet water temperature (Fig. 8b). Here, dissipated powers are lower; however, thermal resistance values are nominally the same.

The pressure drop of both heat exchangers was also characterized as a function of air velocity, as shown in Fig. 9. Here, the pressure drop across both heat exchangers increases, with flow rate with the GRIP Metal heat exchanger seeing a significantly higher pressure drop for these flow conditions.

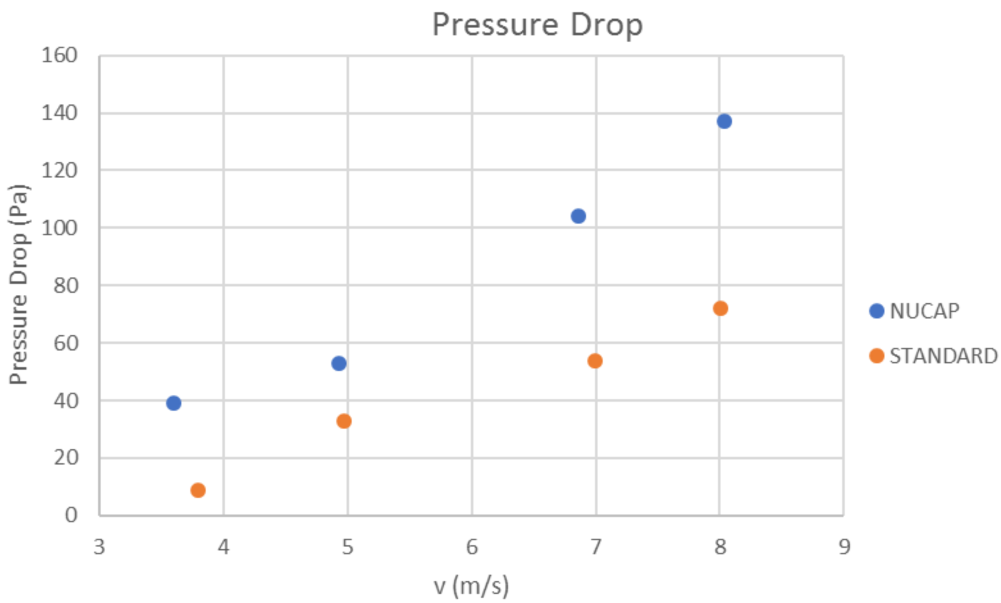


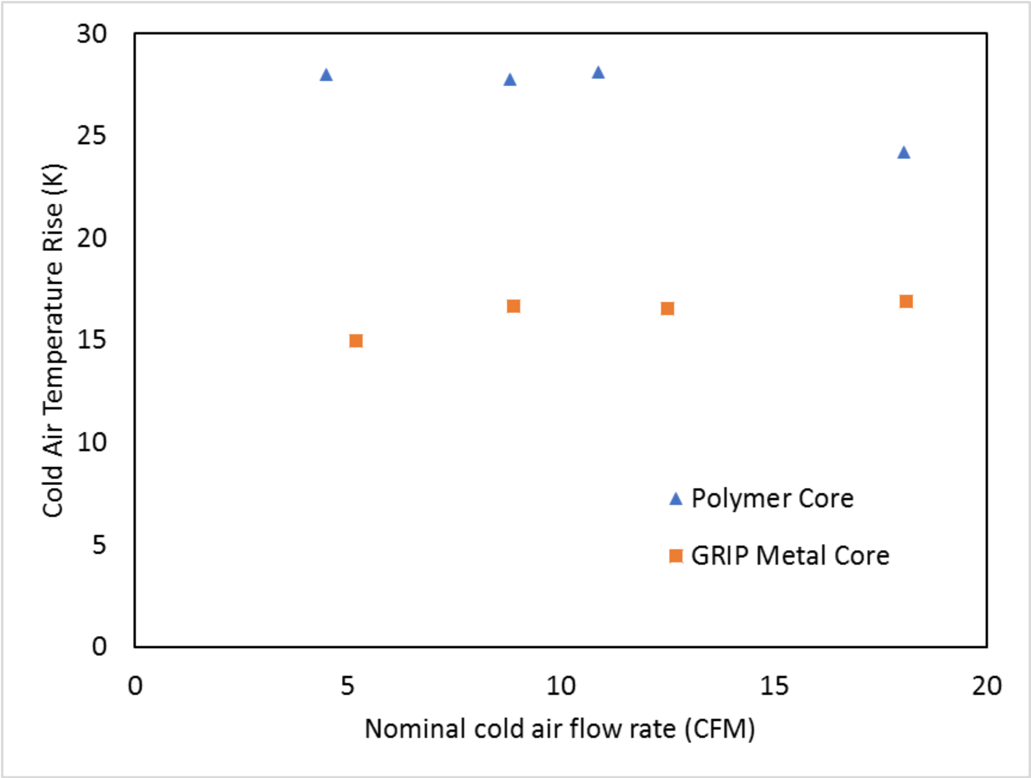
Fig. 9: Variation of pressure drop with air velocity

3.2 Air-to-Air Heat Exchangers

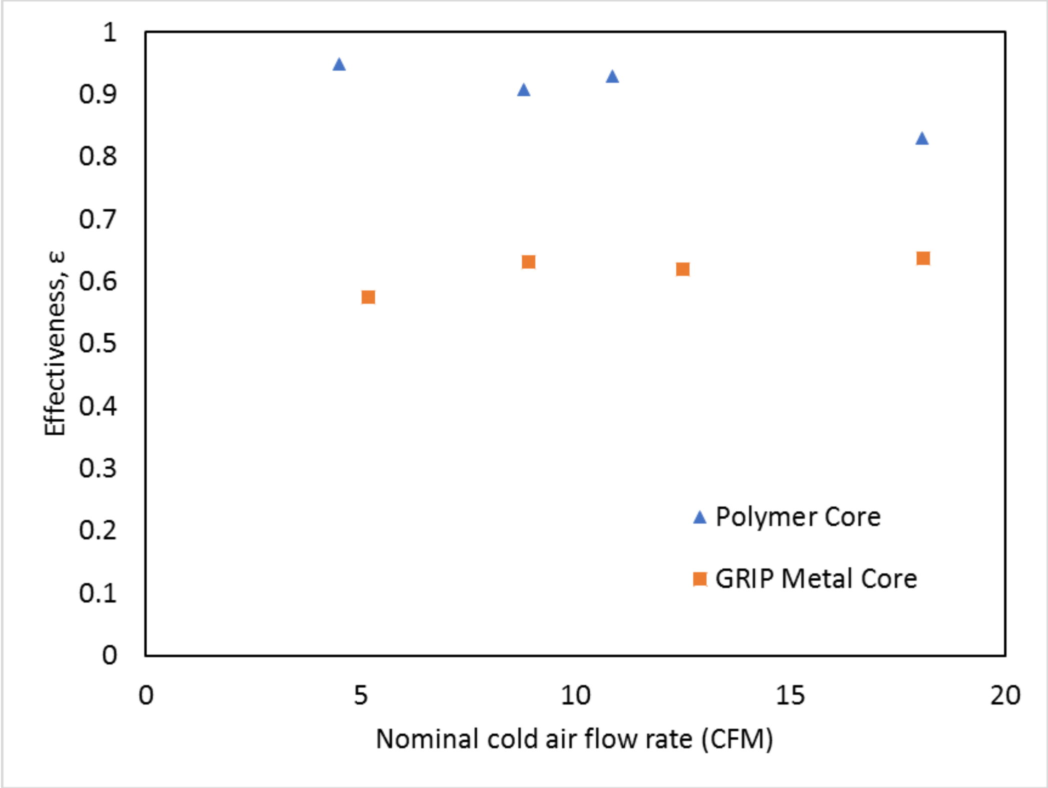
The air-to-air heat exchangers were characterized by assessing the degree to which the hot air stream heated the cooler air for a fixed hot inlet air temperature of 51°C. The temperature rise of the cold stream air as a function of airflow is shown in Fig. 10a. Generally, the GRIP Metal core managed to heat the cold air by approximately 16 K over the range of air flows while the standard polymer heated the cold-side air by approximately 24–28 K. When viewed in terms of effectiveness (Eq. 3) a similar trend is observed, as illustrated in Fig. 10b. Here, the effectiveness of the GRIP Metal core is on average 62% while the polymer core achieves between 83–94% effectiveness.

The primary reason for this discrepancy is due to the significant difference in heat exchange area between the two cores. Referring to Fig. 5, the polymer core has 35 channels while the GRIP Metal core only has 18 channels for same flow area. This significant reduction in nominal surface area severely limits the heat exchange capability of the GRIP Metal core.

This difference is further highlighted in the pressure drop measurements where, due to much more open area for air flow, the pressure drop of the GRIP Metal core is significantly lower, as illustrated in Fig. 11.



(a)



(b)

Fig. 10: a) Temperature rise of cold air stream, b) corresponding effectiveness

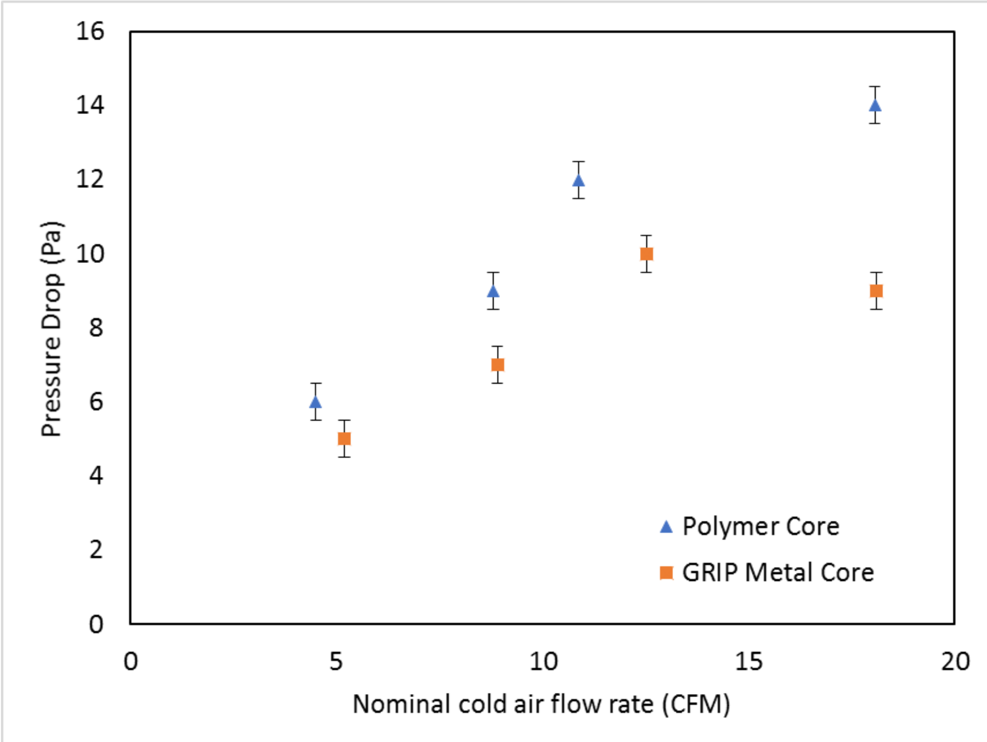


Fig. 11: Pressure drop variation with flow rate

4. Summary & Outlook

Two experimental studies were conducted to characterize the thermal performance of heat exchangers with GRIP Metal surface features to enhance convective heat transfer and, therefore, heat exchanger performance.

In the first, two water-to-air heat exchangers of nominally identical size were fabricated and tested to quantify the effect of GRIP Metal features on the heat transfer and pressure drop. Overall thermal dissipation was increased in the GRIP-Metal-enhanced heat exchanger and resulted in a 22% reduction in thermal resistance. However, this enhancement as resulted in a significantly higher air-side pressure drop.

In the second setup, air-to-air heat exchange was evaluated for a standard polymer core crossflow heat exchanger and a similar GRIP Metal core. Here, the thermal performance of the polymer core was higher; however, this was primarily due to this having significantly higher flow channels and convective surface area, making a direct comparison somewhat unfair. This is underscored by the pressure drop measurements which showed the GRIP Metal core to have a significantly lower pressure drop.

Based on these experiments, and particularly for the water-to-air case, the increased specific surface area and fluid mixing offered by the GRIP Metal features can serve to effectively increase convective heat transfer. These experiments highlight the potential for GRIP Metal features to be used practically to significantly improve heat exchanger performance if designed and specified in an optimal fashion.

Fundamental convective heat transfer studies are underway to develop the design tools necessary to design, quantify, and optimize GRIP Metal heat transfer surfaces for any heat exchange application by developing comprehensive models to quantify heat transfer for a wide range of flow regimes, fluid types, and GRIP Metal geometries.

These models will serve as design tools to develop and optimize GRIP Metal features (fins) for

1. a wider range of convective flows (wider range of Reynolds number)
2. different diameters of the tubes or channels
3. different heat transfer fluids (wider range of Prandtl number fluids, including oils) which are expected to benefit from even higher values of heat exchange improvement than the increase observed when using water or air.
4. double-sided surface enhancement—internal and external features (fins).