Heat Transfer Enhancement in Tubes 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 on the convective heat transfer coefficient on the inner surface of a small-diameter tube by comparing a GRIP Metal enhanced tube with an identically sized smooth tube made of the same material.

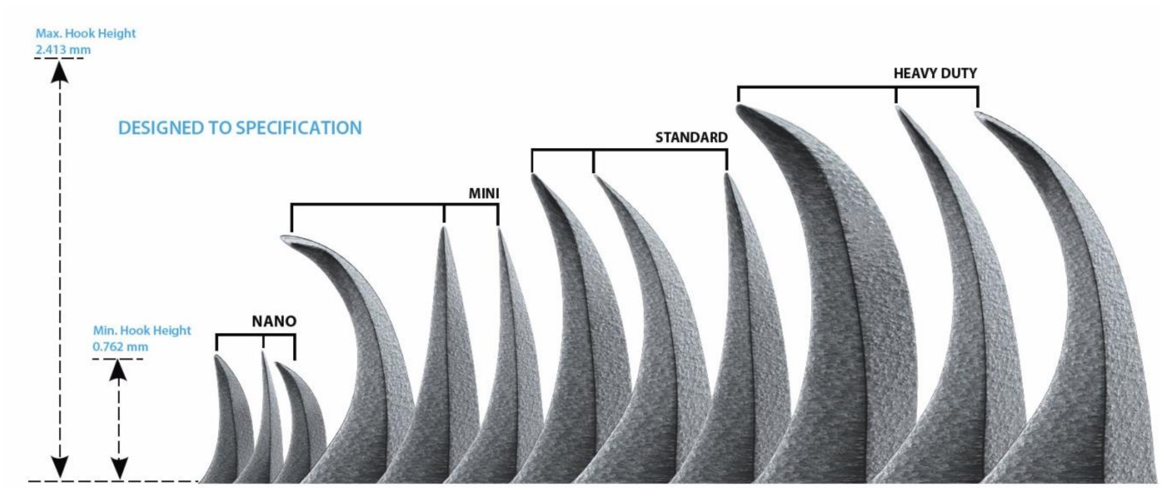
Using water as the medium flowing in the tube with the GRIP-Metal-enhanced internal surface demonstrates a significant increase (80–90%) in convective heat transfer compared with similar smooth tubes with a similar turbulent internal flow (Re ranging from 7500 to 14000). An increase in pressure drop of only between 13% to 27% was also incurred in the GRIP-Metal-enhanced tube.

GRIP Metal surface enhancement applied inside a tube represents an opportunity to nearly double heat transfer rates for fluids like water. Anticipated results for more viscous heat transfer fluids, such as oils, should be higher due to turbulence effect caused at the very surface of the tube's internal wall. Alternatively, the nearly doubling of the heat transfer coefficient means that heat exchangers can be made to be nearly half the size and weight of those manufactured with conventional smooth surfaces while incurring acceptable pressure drop penalties.

1. Introduction & Background

Enhancement of convective heat transfer inside tubes is of key importance for many industrial and commercial applications because it affords increased heat transfer or improved effectiveness. 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 to the fluid flow and require 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.



(a)

(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 quantify the effect of NUCAP's GRIP Metal surfaces on the convective heat transfer coefficient on the inner surface of a small-diameter copper tube by comparing a GRIP Metal enhanced tube with an identical-sized smooth copper tube.

2. Experimental Apparatus

2.1 Tube Samples

The internal convective heat transfer coefficient was characterized and compared between two nominally similar tubes made of identical material—a smooth tube and a tube whose inner surface was augmented with NUCAP Grip Metal features (fins). Both tubes were 1200 mm long and 10 mm in outer diameter. NPT fittings were soldered to the ends of tubes for connection to the heat transfer flow loop described below.

2.2 Flow Loop Testing and Instrumentation

The convective heat transfer coefficient was characterized for both tubes using the apparatus illustrated in Figs. 2 and 3. Here, a known heat flux is applied on the outer surface of the tubes while water flowing through the tubes removes the heat via forced convection on the internal surface. Surface temperature measurements of the tube facilitate the quantification of the average internal convective heat transfer.

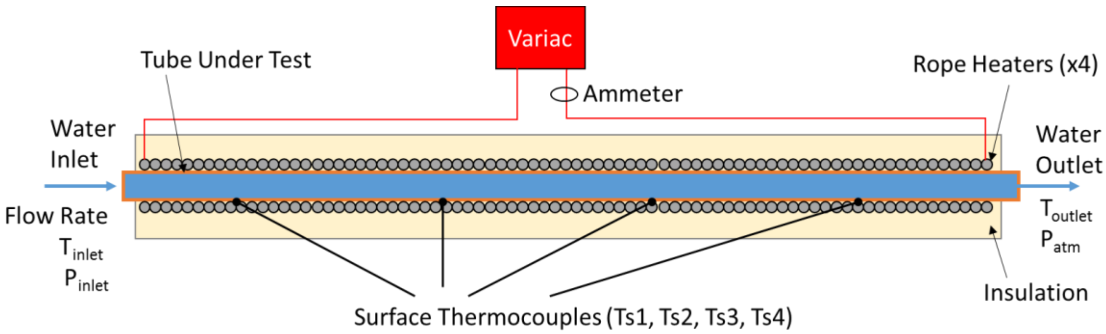


Fig. 2: Schematic of experimental setup

Each tube was instrumented with 4 T-type thermocouples (Omega SA1-T-72-SC), evenly spaced and adhered to the outer surface of the tubes such that the thermocouple junctions were in contact with the outer surface of the tube. The tubes were wrapped uniformly with four 96-inch rope heaters (McMaster-Carr, 3641K26) which applied a relatively uniform heat flux to the outer surface of the tubes. The heaters were wired in parallel to a variable AC power supply (Variac) to control the input power to the heaters. The voltage and current output of the Variac were measured using independent current and voltage meters. The entire tube assembly was insulated in approximately 25 mm of fibreglass insulation to limit heat loss to the environment. Based on the relatively high internal convection coefficients during testing and thick insulation layer, heat loss to the ambient was minimized and the heat flow into the tubes can be computed directly from the electrical power measurement given by

$$Q = IV \tag{1}$$

where Q is the input thermal power, I is the measured current, and V is the measured voltage.

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).

Water at approximately 7°C was supplied at the inlet. Its flowrate was measured using two rotameters: one for low flow ranges (up to 4 LPM) and the other for higher flowrates (up to 36 LPM scale) to ensure accuracy.

The pressure at the inlet to the tube was measured using an absolute pressure transducer (Vac to 45 PSI, Gems Sensors). The pressure drop through the tubes was computed as

$$\Delta P = P_{inlet} - P_{atm} \tag{2}$$

where P_{inlet} is the pressure measured at the inlet of the tube and P_{atm} is atmospheric pressure.

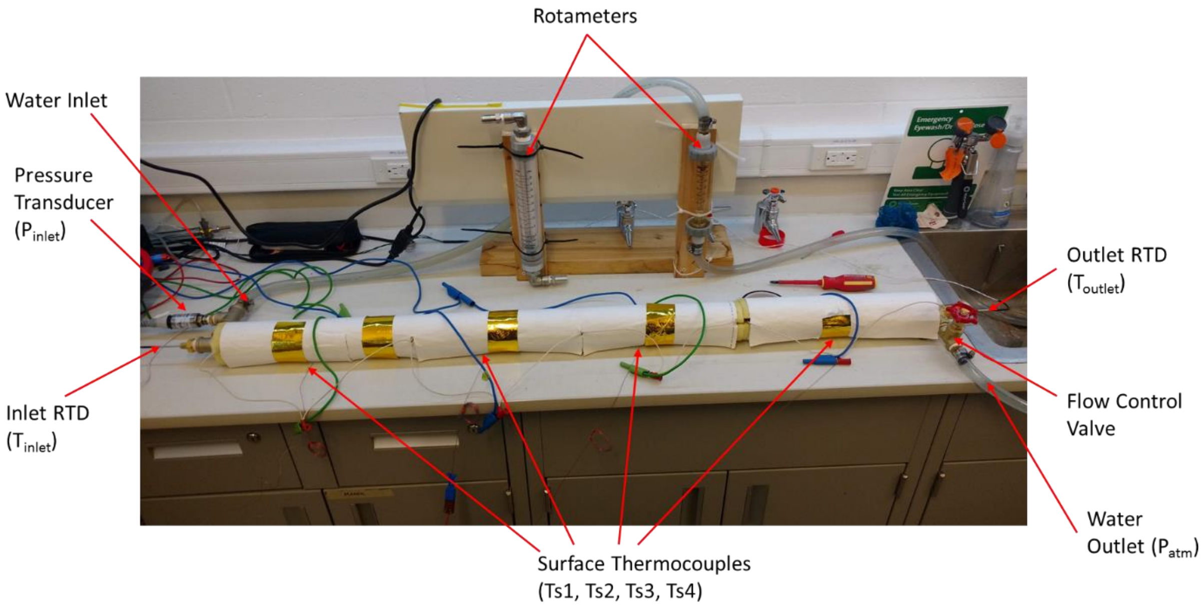


Fig. 3: Experimental setup

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

2.3 Data Reduction

At steady state, the heat flux into the tube was computed using the input electrical power (Eq. 1). The average internal convective heat transfer coefficient was calculated using the log-mean temperature difference (LMTD) as

$$h_{avg} = \frac{Q}{A\frac{\left(T_{outlet} - T_{inlet}\right)}{\ln\left(\frac{T_s - T_{inlet}}{T_s - T_{outlet}}\right)}} \tag{3}$$

where Q is the applied input power, A is the nominal convective surface area on the inner surface of the tubes, T_s is the average surface temperature of the tubes, and T_{water} is the average water temperature between T_{inlet} and T_{outlet}.

Results are plotted as a function of the flow Reynolds Number (Re) which is defined as

$$\mathrm{Re} = \frac{DV_{avg}}{\nu} \tag{4}$$

where D is the nominal inner diameter of the tubes, V_{avg} is the average flow velocity, and v is the kinematic viscosity of the fluid.

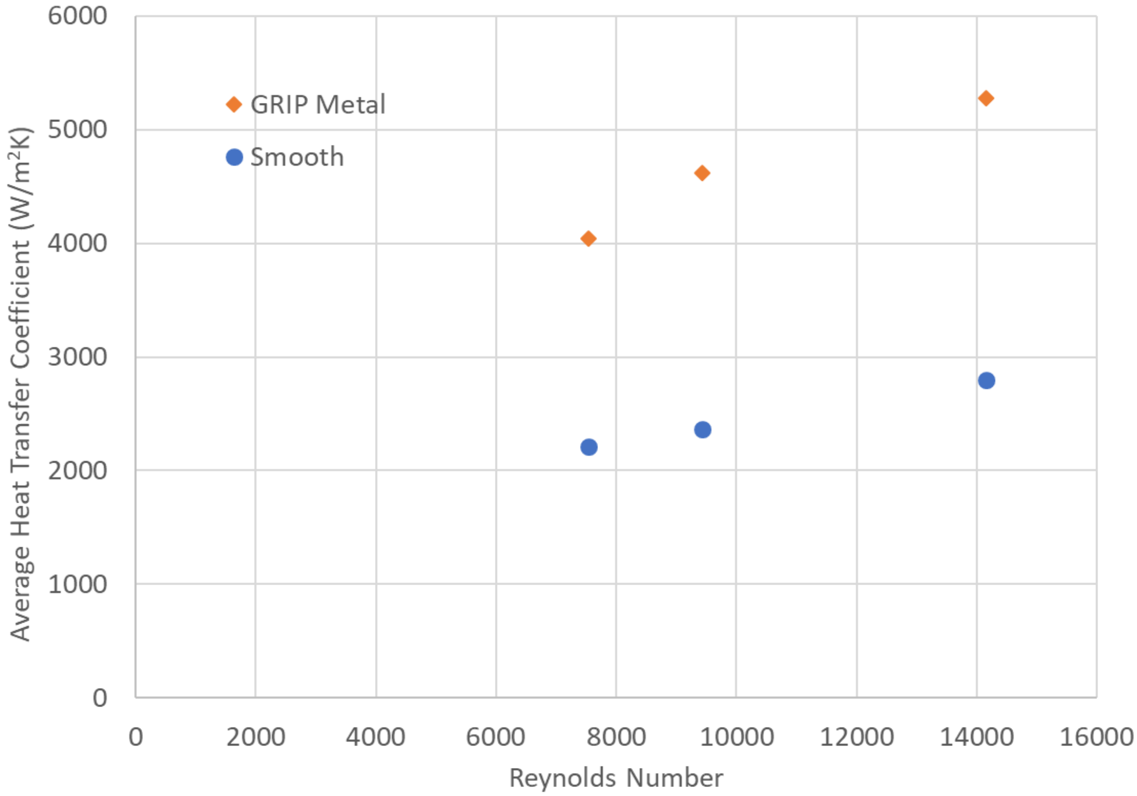


Fig. 4: Variation of average heat transfer coefficient, h_{avg}, with Reynolds number

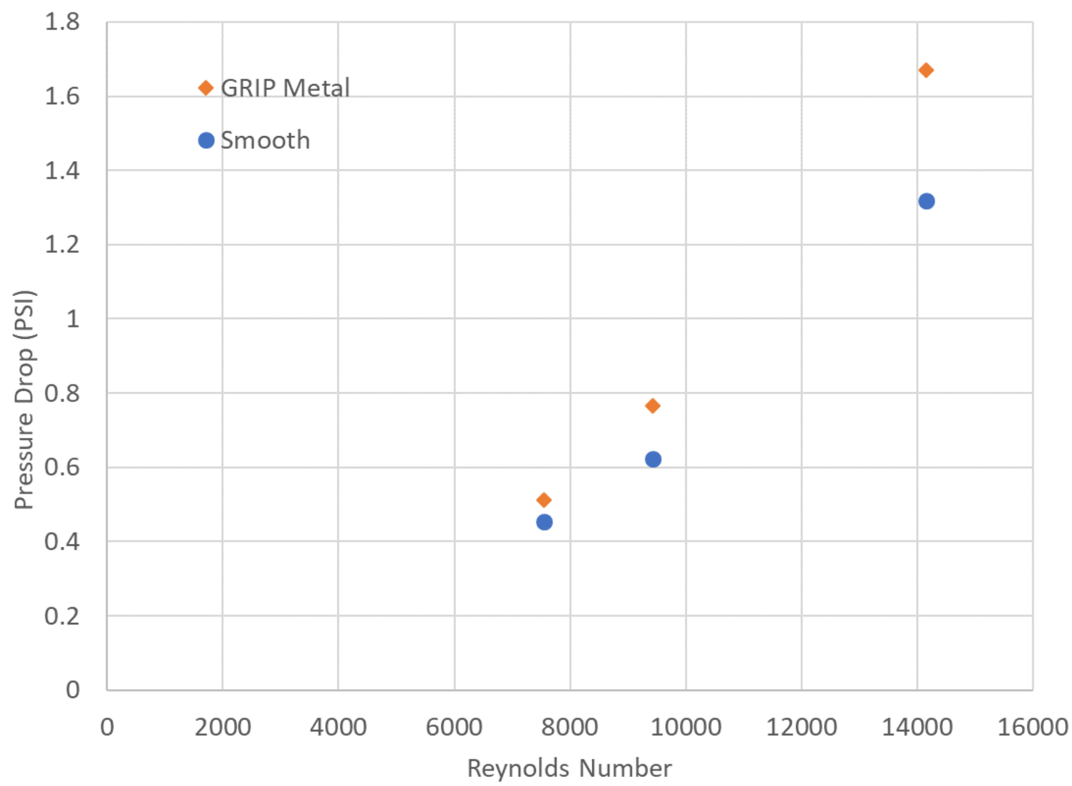


Fig. 5: Variation of pressure drop with Re

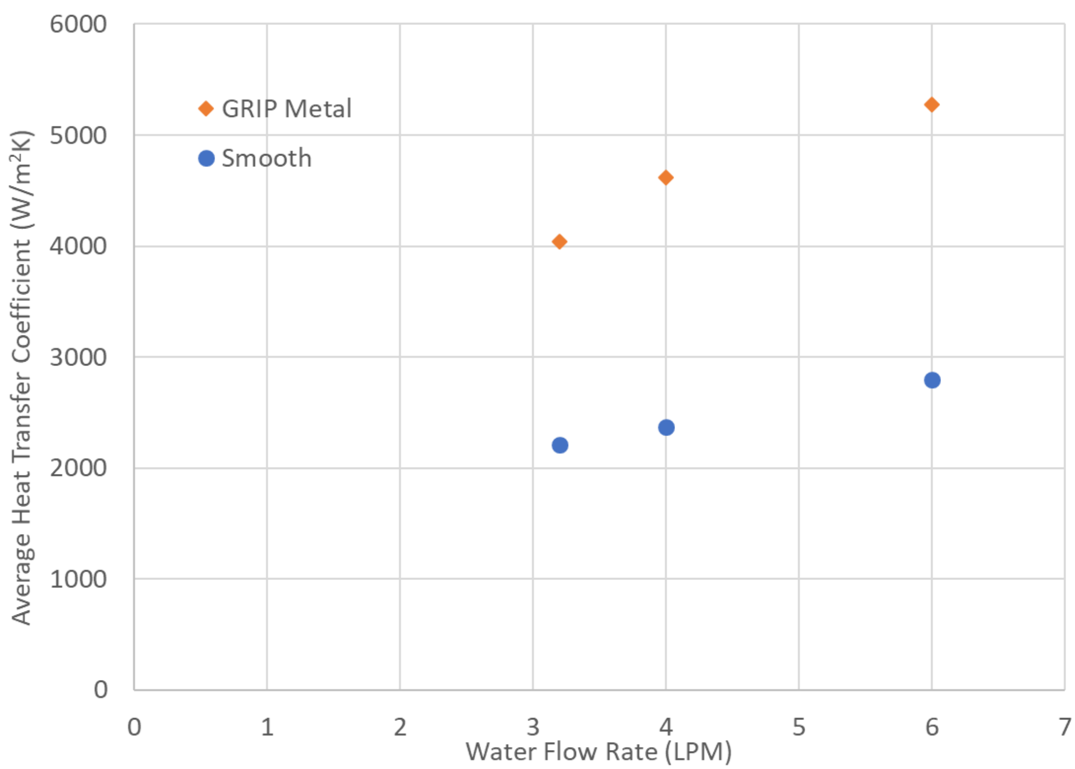


Fig. 6: Variation of average heat transfer coefficient, h_{avg}, with water flowrate

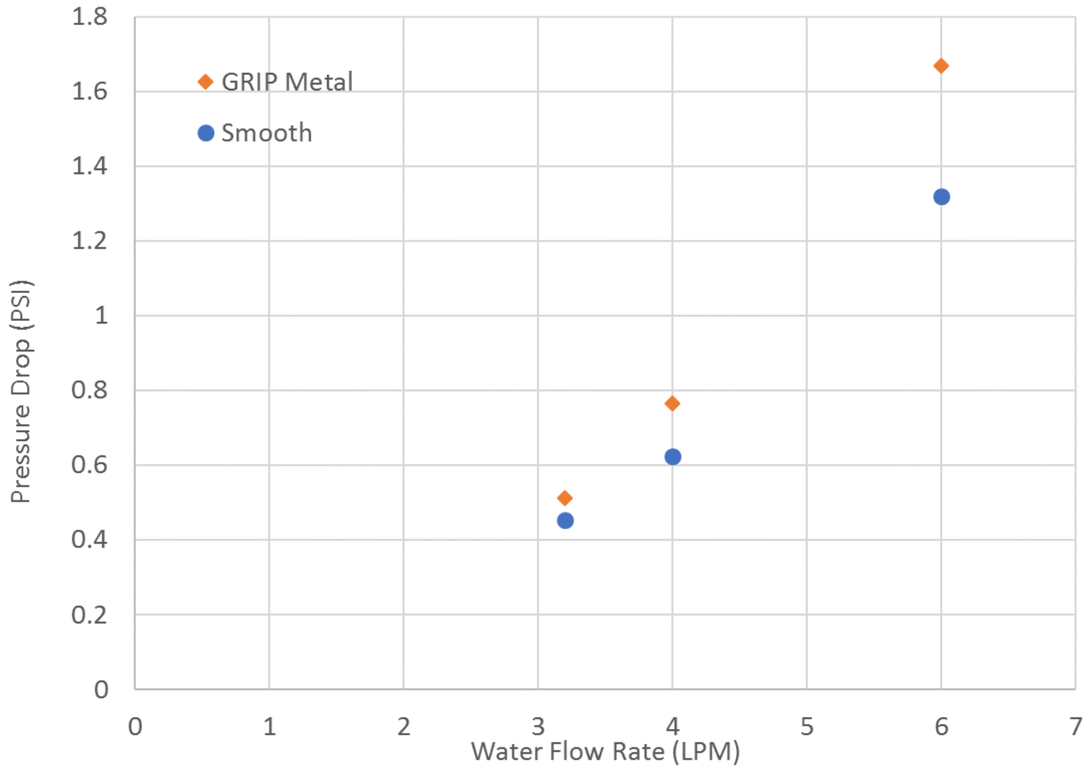


Fig. 7: Variation of pressure drop with water flowrate

3. Results & Discussion

Tests were performed for both the GRIP Metal and smooth tubes by setting a constant input electrical power of approximately 700 W to the heaters. The water inlet and outlet temperatures, along with the surface temperature of the tube, were monitored until steady state was achieved.

The average convective heat transfer coefficient inside the tube was computed by Eq. 3 and is plotted as a function of Reynolds number in Fig. 4, and the corresponding pressure drop for these tubes is plotted in Fig. 5. The average convective heat transfer coefficient and the corresponding pressure drop are plotted against water flowrate in Figs. 6 and 7.

At the lowest flow rate ($Re \approx 7500$ which corresponds to a flow rate of 3.2 LPM), the average internal convective heat transfer coefficient h_{avg} for the smooth tube is approximately 2200 W/m^2K compared with the GRIP Metal tube values of roughly 4000 W/m^2K, representing an improvement of approximately 83%. This was achieved for a relatively low pressure drop penalty of only about 13% or 0.058 PSI.

For both tubes, the average internal convective heat transfer coefficient h_{avg} increases as the flowrate is increased. At the highest Reynolds number ($Re \approx 14{,}000$ or 6 LPM), h_{avg} in the smooth tube rose to 2800 W/m^2K while the GRIP Metal tube achieved 5270 W/m^2K (88% increase) while incurring a 27% increase in pressure drop.

4. Summary, Conclusions, & Outlook

Experimental tests were performed to compare the internal convective heat transfer coefficient of smooth tubes to that of tubes augmented with GRIP Metal features (fins). The tubes with GRIP-Metal-enhanced internal surfaces demonstrated a significant increase (80–90%) in convective heat transfer compared with smooth tubes with similar turbulent internal flow while incurring an increase in pressure drop of 27%.

Since convective heat transfer is directly proportional to the surface area and the convective heat transfer coefficient, GRIP Metal surface enhancement represents an opportunity to nearly double heat transfer rates for tubes with an enhanced internal surface. Alternatively, the improvement to heat transfer can be traded off against heat exchanger size. From a practical standpoint, the nearly doubling of the heat transfer coefficient means that heat exchangers can be made nearly half the size and weight of those manufactured with conventional smooth surfaces while incurring acceptable pressure drop penalties.

Future work will examine the design factors affecting GRIP Metal convection enhancement in order to develop and validate concrete heat transfer models of GRIP Metal features. These modes 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 tube diameters s
3. Different heat transfer fluids (such as oils) which are expected to benefit from even higher values of heat exchange improvement than the increases observed when using water
4. Double-sided surface enhancement—internal and external features (fins).