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DESIGN AND SIMULATION OF 3D PRINTED AIR-COOLED HEAT EXCHANGERS

R. A. Felber*, N. Rudolph*, and G. F. Nellis*

*Department of Mechanical Engineering, University of Wisconsin, Madison, WI 53706

Abstract

The use of material extrusion with conductive fillers is explored for air-cooled heat exchangers. A general overview of the manufacturing tasks, design criteria, printability constraints, and modeling techniques is given, along with experimental data from prototype testing. The first sub-scale prototype design is an air-water crossflow heat exchanger designed to transfer around 100 Watts. It was printed with unfilled conventional ABS and the air channels designed with an array of round pin fins to enhance heat transfer. The prototype was also CT-scanned for inspection of the printed pin fin shapes.

Introduction

Dry-cooling reduces or eliminates the consumption of water, which has both ecological and economic benefits. Power plants would have greater siting options if they did not need a large local water supply, thus relieving the limitation that arid regions cannot host power generation sites. Current drawbacks associated with implementing dry-cooled systems include poor efficiency due to warmer heat rejection temperatures and high capital costs associated with conventional dry-cooling systems that consist of large arrays of metal finned-tubes and plate-fins.

Advances in additive manufacturing, commonly referred to as 3D printing, have redefined the theoretical manufacturing limitations across a variety of applications. This project examines the use of 3D printing in the design of heat exchanger systems for dry cooling. Additive manufacturing techniques have a range of printing capabilities, material properties, and material costs. The technique that is most generally associated with 3D printing is material extrusion, otherwise known under the trademark Fused Deposition Modeling (FDM®). For material extrusion, raw solid polymer filament is melted and extruded through a CNC nozzle. This technique has the advantages of efficiently producing functional and durable parts with complex geometries using relatively inexpensive material. The low cost of the material and the manufacturing process allow it to be considered for large-scale systems such as those required for a dry-cooled power plant.

One characteristic of the material extrusion process is its range of material compatibility. While polymer filaments have the advantages of being relatively low cost, lightweight, durable, and corrosion-resistant, their thermal conductivity is 10 to 100 times lower than that of metals (Joen et al., 2009). This is an obvious disadvantage for their use in a heat exchanger application. However, some studies have found that replicating a conventional tubular heat exchanger with polymer decreased its cost by 2.5 times, despite its larger size, because of its decreased density and material cost (Zaheed and Jachuck, 2004). Further improvements could be made with higher conductivity and robust printability. Current work, including work associated with this project, is being done to increase the thermal conductivity of these polymers by embedding conductive fillers such as graphite, carbon black, carbon fiber, or metal particles of various shapes and sizes into the polymer filament. The use of filled polymers could increase the thermal conductivity by a factor of 10 or more (LATI, 2013).

Overview of Manufacturing Tasks

The filled polymer material used for the manufacturing in this project is not commercially available. Its thermal and mechanical properties are dependent on its filler type, volumetric content, and fabrication technique, and can be strategically designed to create unique and advantageous characteristics for the application of interest. Traditional material extrusion printing equipment is also not necessarily suitable for all filament types by default. The manufacturing efforts associated with the fabrication of the heat exchangers include compounding of the material, filament extrusion and characterization, and modification of the conventional material extrusion process for thermally conductive filament.

Compounding material and filament fabrication require unique process settings and conditions to achieve desired homogeneity and compound properties. It is especially important to ensure the material is extruded with a uniform diameter and is flexible enough to be wound into spools. Doing so with unfilled nylon material has its own difficulties, and doing so with filled nylon, embedded with conductive fillers, makes the task uniquely challenging.

Assessment of the filament also plays a role in its fabrication. For both manufacturing and design purposes, it is important that measuring and controlling material properties is also investigated in the fabrication process. Depending on the filler material, specifically the type and shape, some material properties may also be different in axial and radial directions.

Once the raw material is compounded and ready for printing, some changes are required to the material extrusion process. The incorporation of fillers increases the stiffness and viscosity and requires modification of equipment for combatting these changes. Specifically, stagnation and clogging can be prevented by redesigning the nozzle with a more gradual taper.

Design

The design of the heat exchanger puts the air and water channels in cross-flow. This is typical of most gas-to-liquid heat exchangers where more of the surface area is dispersed by a large frontal area rather than long gas-side channels in order to conserve pressure drop. The specification of the heat exchanger geometry is broken into two categories: the microstructure, which refers to dimensions of an individual channel that can be repeated indefinitely, and the macrostructure, which refers to the overall size of heat exchanger formed by repeating and lengthening channels as necessary. The macrostructure depends on the microstructure geometry, the number of rows, and the number of air channels in each row. The parameters that define the heat exchanger macrostructure (Figure 1) include the following: height of the heat exchanger (defined by the number of rows), width of the heat exchanger (defined by the number of air channels in each row), and the depth of the heat exchanger.

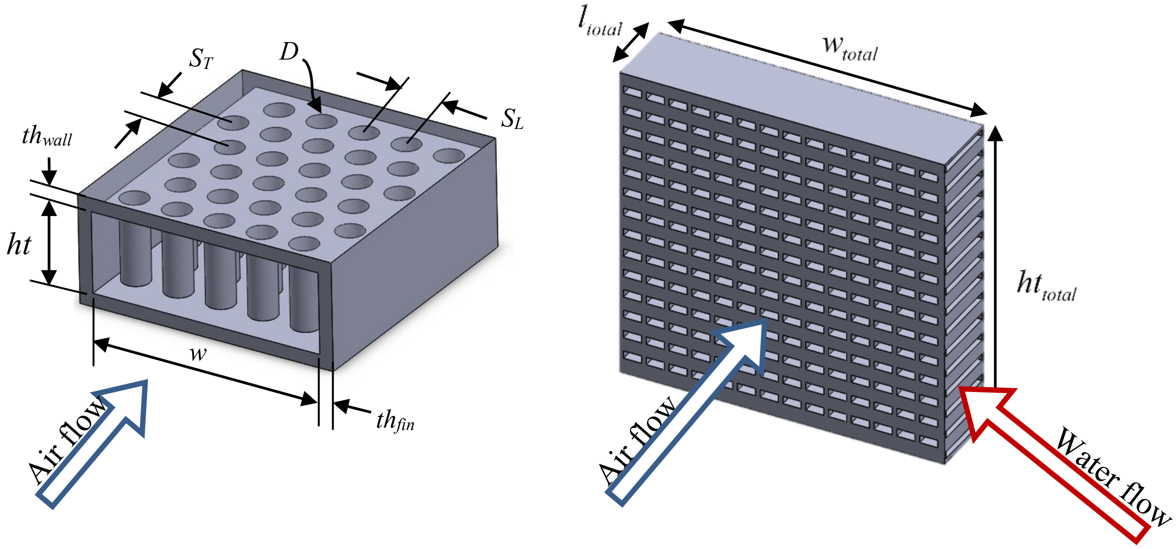

Figure 1: Geometric configuration. Left: air-side microstructure. Right: macrostructure.

Rectangular ducts were chosen for both the air and water channels. It was recognized that a larger number of shorter water channels would be more advantageous than a smaller number of taller water channels to maximize efficiency and surface area. For this reason, each water channel was sized to have a fixed 1-mm height and its width would be adjusted with the macrostructure.

The air ducts are filled with a staggered array of circular cross-sectional pin fins, as shown in Figure 1 on the left side where the top of the duct is transparent. The geometric parameters required to define this microstructure include: air-side channel height (ht) and width (w), the thickness of the walls separating the air channels (th_{fin}), the thickness of the walls separating the water and air channels (th_{wall}), the diameter of the pin fins (D), and their spacing in both the transverse (S_T) and longitudinal (S_L) directions. Straight circular pin fins were chosen for the initial design because their performance can be predicted using existing flow correlations associated with extensive research and literature for flow over tube banks. These existing correlations enabled immediate analysis of this geometry which allowed parallel progress to be made on the manufacturing side of the project.

It is understood, however, that circular pin fins may not be the optimal design, and alternative geometries are possible using material extrusion. Current work is being done to investigate different shapes of these pin fins that go beyond straight circular cylinders. For example, by streamlining the cross-section of the pin fins, the drag force can be significantly reduced, resulting in a lower pressure drop across the array. One study has been carried out specifically for flow over various cross-sectional shapes including elliptic, drop-like, and airfoil cross-sections for long fins (Sahiti et al., 2006). Another improvement being investigated is the effect of varying the cross-section of the pin fin along its length such that they have larger cross-sectional area at the base, where the rate of conduction is highest, than they do at the center of the duct, where conduction is zero. Additionally, unconventional techniques for design are being used; see the section titled “Optimization”.

Printability Considerations

The design of the prototype to be printed and tested has a few additional considerations to be made regarding its printability, which mostly stems from printing parameters, one of which is the print orientation. The print orientation greatly influences how the part will be printed. It refers to the direction in which the part is built, which dictates how the part is sliced into cross-sections. In most cases, a certain print orientation is chosen to minimize print time and support structure. Since both of these factors affect the cost of the print with increased labor, machine use, and material required, the orientation is not a trivial parameter.

A general starting point was to set the side of the part with the largest surface area parallel to the build platform (Figure 2) because it is more efficient to print a smaller number of large cross-sections than a larger number of small cross-sections. Another consideration accounted for overhangs and hollow sections. Specifically in the material extrusion process, there exists a "critical angle" θ in which any overhang that is less than this angle (relative to the build platform) requires material below it. When it hangs over a hollow section, support structure is required. This was encountered in two regions with the desired print orientation, and care was taken in the design of those regions to exceed the critical angle (Figure 3). With this design and print orientation, no support structure was needed for the prototype and the entire heat exchanger was able to be printed as a single piece, thus eliminating any excess material or post-processing.

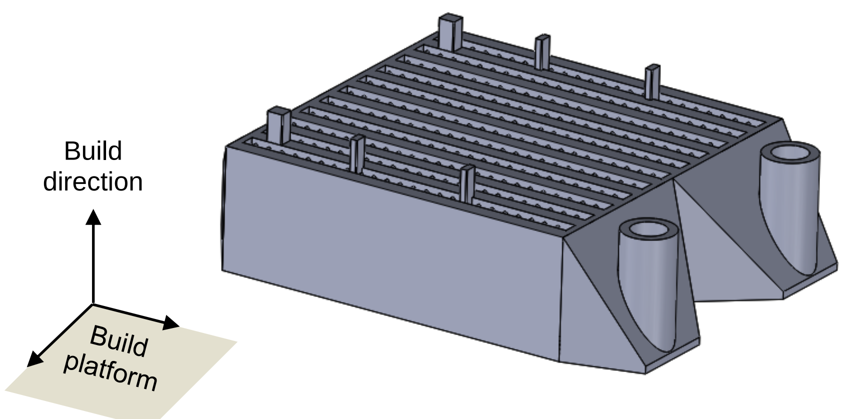

Figure 2: Representation of print orientation.

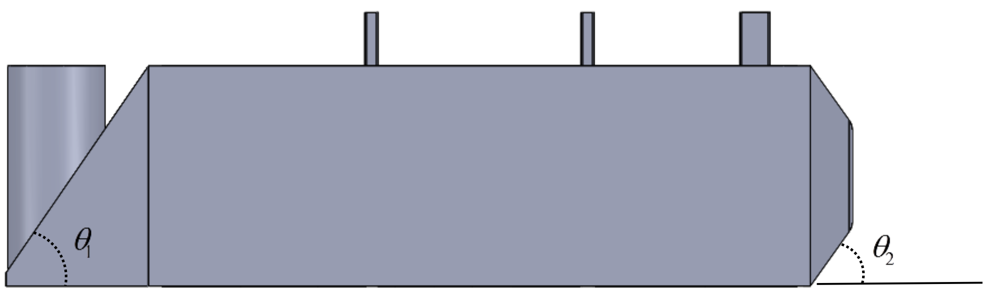

Figure 3: Critical angle illustration.

One problem that was encountered, however, was the orientation in which the fins inside the air channels were printed. The first prototype was designed with arrays of 1-mm round pin fins, but it was suspected that they would not be able to be printed perfectly round. A computed tomography (CT) scan was done on the first prototype to investigate the shape of the fins as printed. Figure 4 shows a scan in the cross-section of a fin array. It can be seen that not only are the fins not round, but they are irregularly shaped, and inconsistencies exist. The average diameter of each fin is approximately 1 millimeter, as designed, but the surface area would be greater than a round fin due to the apparently bumpy surface.

Further analysis is planned for evaluation of these irregularly-shaped fins. The implications of these inconsistent fin shapes are unknown, and in order to better predict how other fin shapes and sizes would be printed, a test piece with a variety of fin shapes has been printed and scanned for a printability study. These shapes vary from round to elliptic to airfoil, and they also vary in sizes ranging from 0.4-mm to 2.4-mm in the flow direction. Analysis of these shapes will help determine any trends in which some shapes are printed, potential design techniques to combat irregularities, and possibly a certain minimum feature size that is deemed unattainable with the current methods of printing.

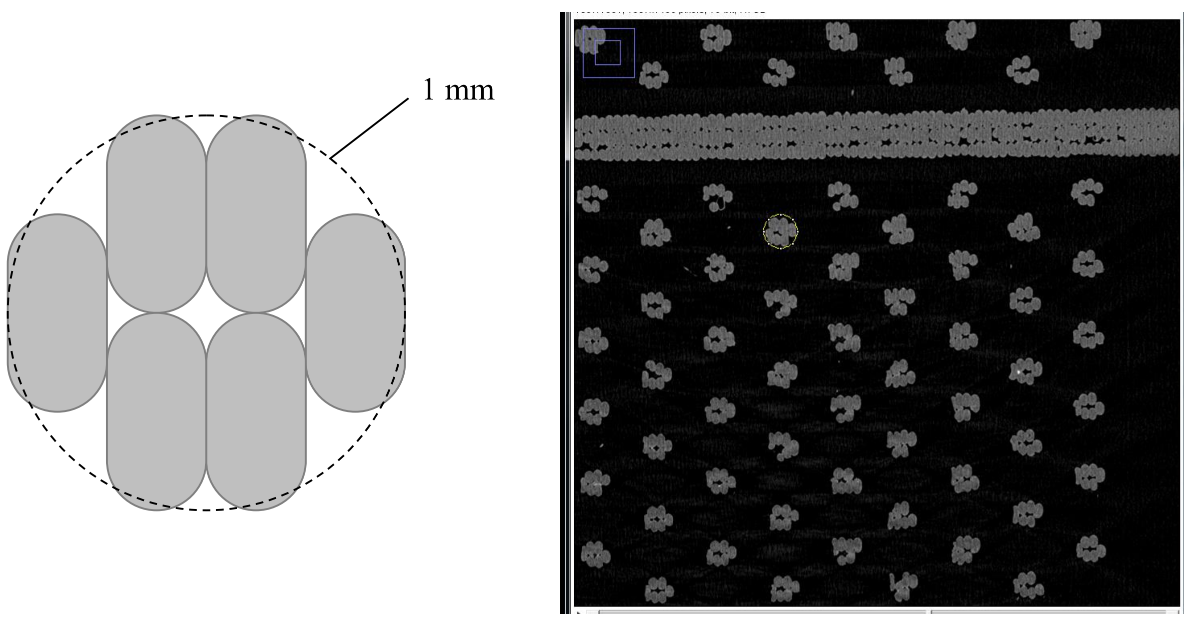

Figure 4: Cross-sectional view of pin fin array in CT scan.

Analytical Performance Simulation

An analytical model was developed using Engineering Equation Solver (EES) software (Klein, 2015). The purpose of this model is to evaluate the performance of the cross-flow heat exchanger shown in Figure 1.

Some assumptions were made to develop this model. Because the temperature and pressure changes expected for both fluids are relatively small, their thermodynamic and transport properties do not change significantly within the heat exchanger; therefore, these properties are treated as being constant and are evaluated at each fluid's average temperature. The heat capacity rate of the water will be significantly greater than that of the air and therefore the temperature drop of the water is small compared to the temperature rise of the air; therefore, the surface temperature inside the air-side channels is treated as spatially uniform. In a steam condenser the temperature will be nearly constant on the water side as long as pressure drop is small. The apparatus used to provide flow to both sides of the heat exchanger must be designed to uniformly distribute the flow; it is therefore assumed that there are no flow non-uniformities in the heat exchanger. The exterior of the heat exchanger will be well-insulated so that the rate of heat loss to the environment is negligible; the model assumes no heat transfer between the heat exchanger and its surroundings.

The heat transfer rate of the heat exchanger and the air-side pressure drop are among the parameters of most interest. The heat transfer rate is calculated with the epsilon-NTU heat exchanger analysis method using the conductance of the heat exchanger as calculated by a thermal resistance network. The network incorporates the convection on the water-side channels, the conduction through the walls, and the convection on the air-side channels. The convection on the air-side channels includes both the channel surfaces and the extended surfaces of the pin fins.

One difficulty that is encountered is estimating the heat transfer coefficient and pressure drop within the air-side channels specifically. Though the flow over the pin fins can be approximated using known external flow correlations for a bank of tubes (Žukauskas, 1972) it is not an exact representation of the actual flow conditions because of the small size of pin fins and the presence of the surrounding walls. To achieve a better estimate of the heat transfer coefficient and pressure drop for this geometry, computational fluid dynamics (CFD) will be used. The results from the CFD simulations will then be embedded within the analytical model in EES.

Experimental Performance

A prototype heat exchanger was printed using unfilled ABS material (Figure 5) to demonstrate the printability of the heat exchanger and to validate the model. The prototype was designed with eleven air channels and six two-pass water channels. An array of 1-mm pin fins were printed inside the air channels and all walls were designed with 0.8-mm thickness. The thermal conductivity of the material was approximately 0.2 W/m-K. The prototype was tested over the velocity range shown in the table and the heat transfer results were compared with the analytical model. The experimental heat transfer rate is calculated using energy balances on both the air and water side.

Table 1: Experimental operating conditions

Pressure (both sides)	**Inlet Temperature** *Air*	**Inlet Temperature** *Water*	**Inlet Velocity** *Air*	**Flow Rate** *Water*	**Material Conductivity**
Atmospheric	22°C	60°C	0.35 – 1.35 m/s	0.35 LPM	0.2 W/m-K

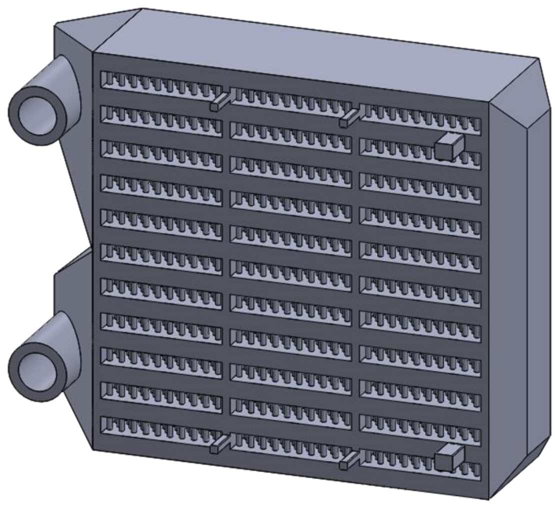

Figure 5: Prototype heat exchanger printed using material extrusion with ABS.

The experimental data and the model prediction of that data from the model correlates well for the range of air velocities tested. This demonstrates an agreement between the model and experimental results for a low-conductivity case. The pressure drop was also measured and compared to that predicted from the model, which shows that the calculated and experimental pressure drops deviate by a factor of about 20% at the higher velocities. This deviation is likely caused by variations between the model and the print itself, as previously described in the "Printability Considerations" section, specifically referring to the size and shape of the pin fins.

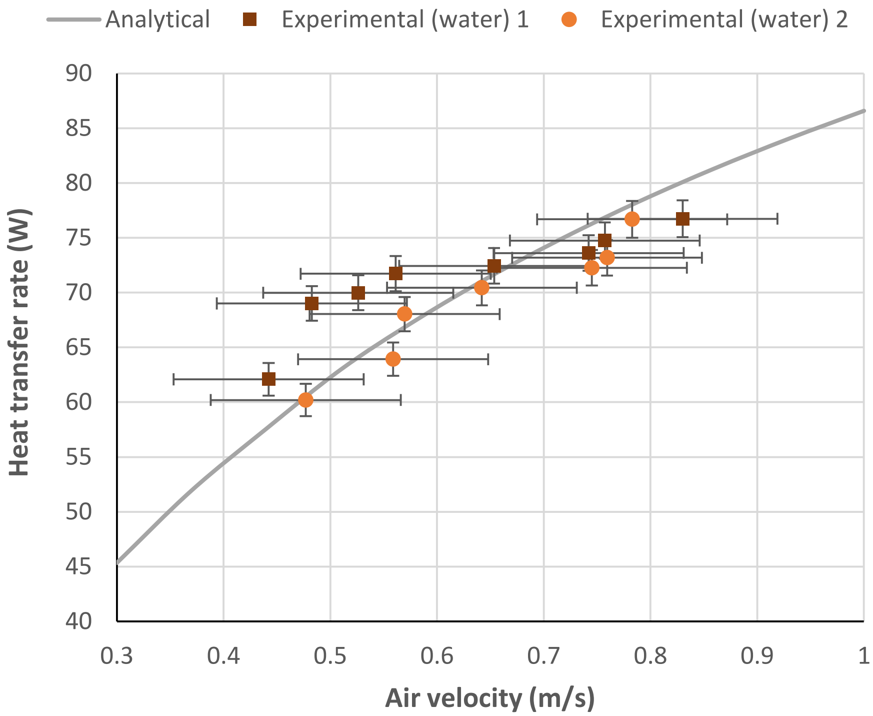

Figure 6: Experimental thermal data.

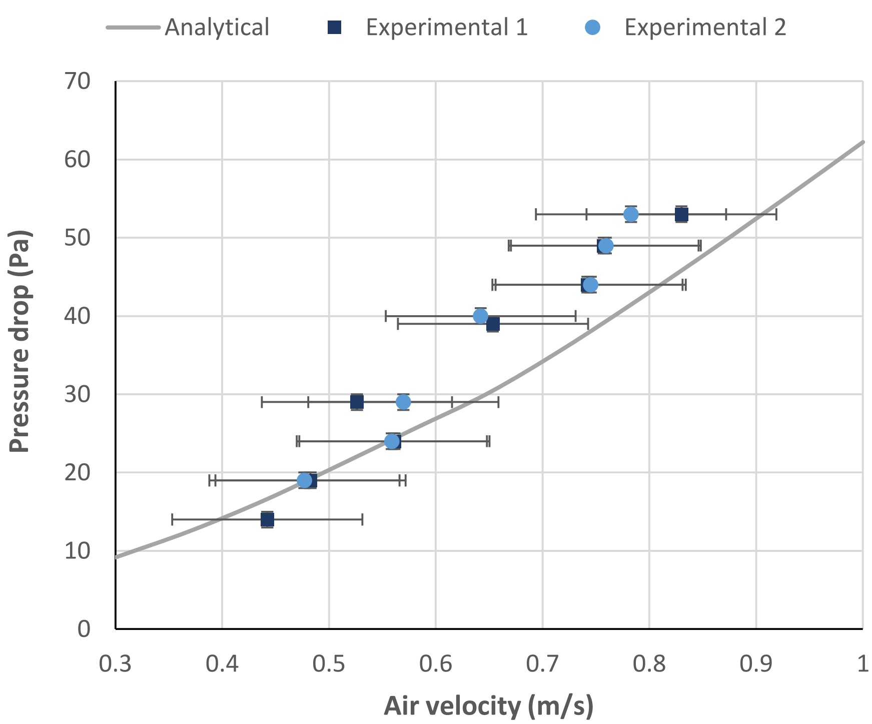

Figure 7: Experimental air-side pressure data.

Optimization

The first heat exchanger design used an array of pin fins within air channels to establish a starting point for design, analysis, and manufacturing. The project also incorporates a method of topology optimization. Traditional topology optimization is typically used for structural applications, but it can also be used for thermal-fluid type of work. Its most basic principle involves dividing a certain design space into unit cells, similar to a fine mesh. Then, with a code in which the simulation is performed, each unit cell is deemed to be either solid or empty. This analysis is initiated with an initial geometry and boundary conditions similar to CFD. The application with the air-cooled heat exchanger is to model the air channel as the design space and maximize the heat transfer rate while minimizing pressure drop. The goal would be for the topology optimization to produce potentially non-intuitive fin geometries, which might not be practical to manufacture using conventional methods, but could be manufactured using material extrusion. Such geometries are expected to be presented in future work.

Conclusions

- The parallel efforts between manufacturing, design, analysis, and optimization groups is crucially collaborative since motivations by one group can be limited by constraints from another; this ongoing work is a continually iterative process.
- Limitations on the performance of 3D printed heat exchangers go beyond the thermal conductivity of the material with which they are printed. The effort to enhance the printability of small features and thin walls should be conducted alongside that of improving the thermal conductivity.
- The model for analysis of the heat exchanger has been partially validated by experimental results. Upcoming designs and tests will be done to further observe and improve the accuracy of predicted performance.

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