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Additive Manufacturing of Surface-based Structures for Studying Fluid Flow in Heat Sinks with High-Speed Imaging

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Abstract

In microelectronics packaging, efficient thermal management is important to ensure optimal performance and longevity of semiconductor devices. This work, conducted as an undergraduate class project, combines generative design and additive manufacturing to develop heat sink concepts to enhance thermal management of microelectronics packages, using fluid flow to enable chip cooling. While this work stops shy of thermal analysis, it demonstrates the feasibility of designing and manufacturing surface-based structures within the heat sink structure itself for optimizing fluid flow, thereby enhancing heat removal without needing bulky heat sinks.

Introduction

Of the many areas that Additive Manufacturing (AM) can contribute to the domain of microelectronics packaging, one with particular interest is thermal management, due to the promise of exploiting the greater design freedom enabled by AM for performance improvements in solutions such as heat sinks, heat pipes and vapor chambers [1]. Thermal management solutions benefit from innovative distribution of surfaces to maximize available area, as well as from channels and chambers that optimize fluid flow to meet certain objectives. This work focused on heat sinks commonly used for Central Processing Unit (CPU) cooling in desktop workstations and servers. Most of the prior work in AM for heat sinks has examined the development of metal AM processes for fabricating structures made of high conductivity material such as copper and/or with innovative designs such as bio-inspired structures, cellular materials or fractal geometries [2], [3], [4], [5]. Heat sinks are essentially passive heat exchangers – this work examines using fluid flow within a heat sink to enhance heat removal from planar surfaces consistent with microelectronics package silicon die and/or heat spreaders. The key innovation in the use of this work is the exploration of fluid flow in heat sinks filled with surface-based structures, in the main Triply Periodic Minimal Surface (TPMS) structures, and the imaging of these using high speed imaging, necessitating the use of AM of heat sinks with a transparent material. TPMS structures have been explored for their potential in mechanical, thermal, fluid and acoustic applications, as well as their occurrence in biological systems [6]. While this work does not include any thermal analysis, preliminary numerical measurements on mass flow rates are reported. This work shows the potential of using AM of transparent structures coupled with high-speed imaging for understanding how design influences fluid flow, which in turn can be optimized to maximize heat removal. The next section discusses the overall approach and details methods used in this work, and is followed by the results obtained using high-speed imaging, and a discussion of these results and suggestions for future work in the conclusions.

Methods

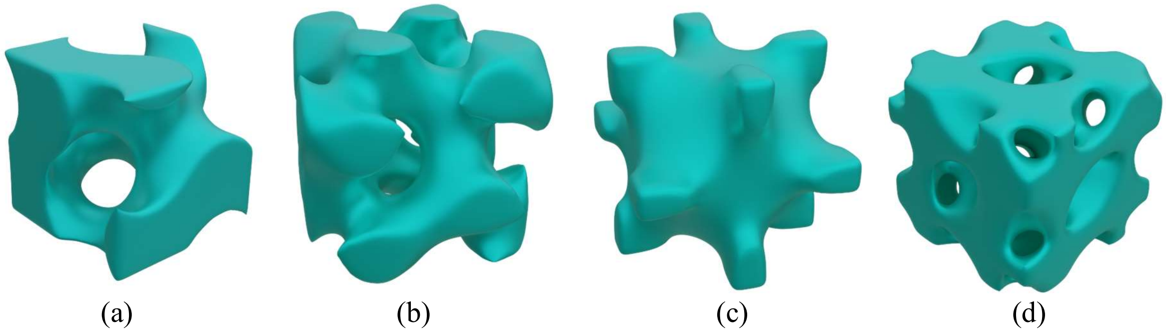
The approach in this work was to undertake the research in three parts: (i) design, (ii) manufacturing, and (iii) testing. The nTop implicit modeling software [7] was used to create designs (Figure 1a), specifics of which are discussed in the next section. The designs were manufactured on a commercial 3D Systems Projet 6000 HD stereolithography (SLA) machine, shown in Figure 1b. To ensure transparency for the purposes of imaging, the Acurra Clearvue resin was used. Finally, an off the shelf pump with a resorvoir was used to transport fluid in and out of the 3D printed heat sinks using tubing, as shown in Figure 1c. A Chronos 2.1 HD high-speed camera was used, obtaining images at a frame rate of 1906 frames per second, each frame at a 1024x1024 resolution. Not shown here, mass flow measurements were also made using a calibrated beaker and a stopwatch.

(a) (b) (c)

Figure 1. Key steps in this work: (a) design of heat sinks in nTop; (b) manufacturing with 3D Systems Projet 6000 HD using clear resin to enable imaging; and (c) custom built rig for testing, using a Cronos 2.1-HD high speed camera for imaging the 3D-printed heat sinks

Design

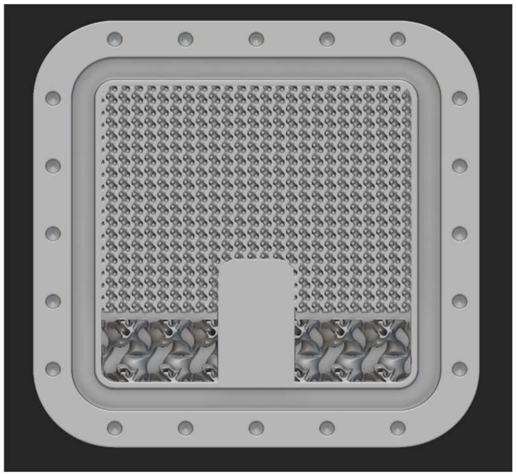
A key challenge in any design for AM strategy that involves infilling a volume with cellular materials is which topology to select from [8]. Several space-filling TPMS structures were explored, and the final selection included gyroid, split-P, Neovius, and Lidinoid [9], as shown in Figures 2a-2d.



(a) (b) (c) (d)

Figure 2. Surface based unit cell geometries used in this study: (a) gyroid; (b) Split-P; (c) Neovius; and (d) Lidinoid

Prior work showed that the gyroid structure when used in fluid flow path has lower pressure drop compared to Lidinoid and Split-P [10]. The results were obtained with the assumption of steady state flow in a linear path, as opposed to the entry and exit design in this work, shown in Figure 1c. In addition to the four surface-based unit cells shown in Figure 2, this work also explored a flow path optimized variation of the gyroid infill strategy to assess if that would improve mass flow rates. In total, six designs were fabricated, shown in Figures 3a-3f: four corresponding one each to each of the four unit cell types, the fifth using the flow optimization approach in nTop, and the sixth was a baseline structure without any infill (Figure 3f). The bottom left and right corners of each design features room for the inlet and outlet flow channels that connected to the tubes leading to and from the pump and reservoir. A lid was sealed on top of each structure with 20 #4 screws and an O-ring to prevent leaks. Cross-sections of each of these six heat sinks designs are shown in Figures 4a-4b, corresponding to each of the sinks in Figures 3a-3f. Volume fractions were estimated for the internal cellular structures only – with Neovius having the highest volume fraction and thus the lowest negative space for fluid flow, and the simulation-driven gyroid having the lowest volume fraction of 0.38. Intuitively, a larger volume fraction of solid material suggests a lower mass flow rate for water going through any available negative space – this would be evaluated in this work.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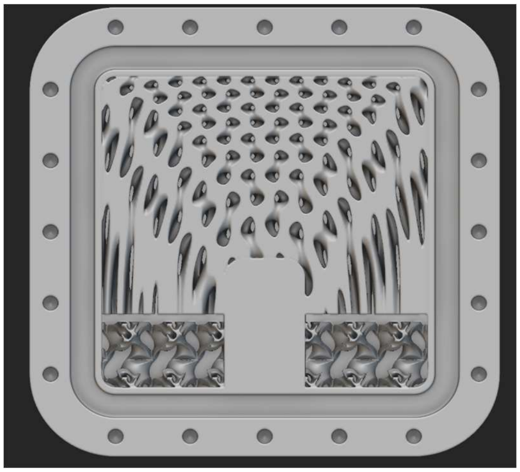
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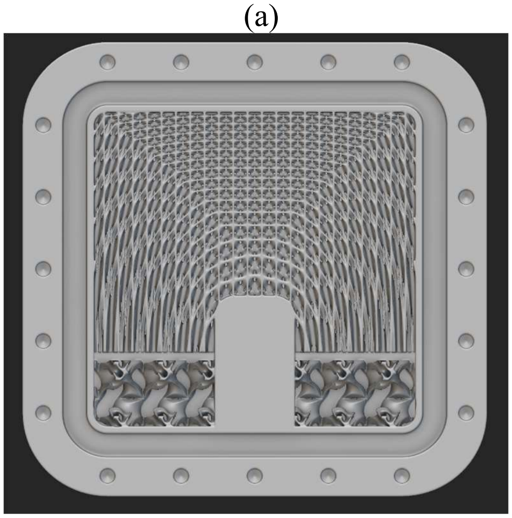
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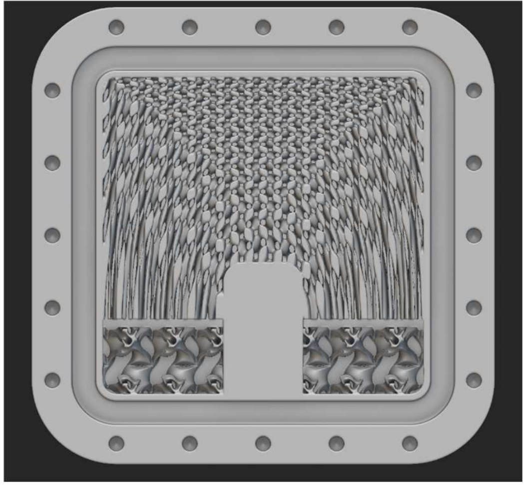
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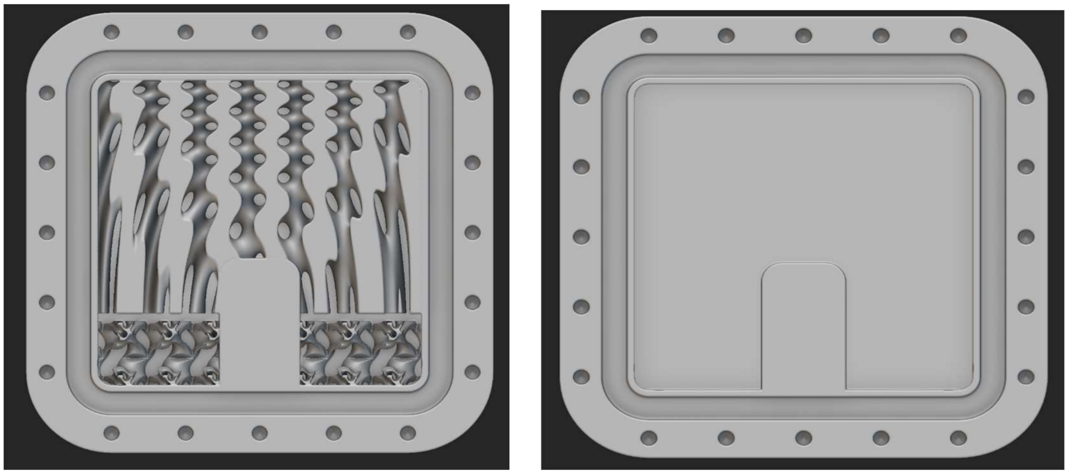
(e) (f)

Figure 3. Top views of heat sink designs used in this study: (a) gyroid; (b) Split-P; (c) Neovius; (d) Lidinoid; (e) field driven gyroid; and (f) a baseline with no infill

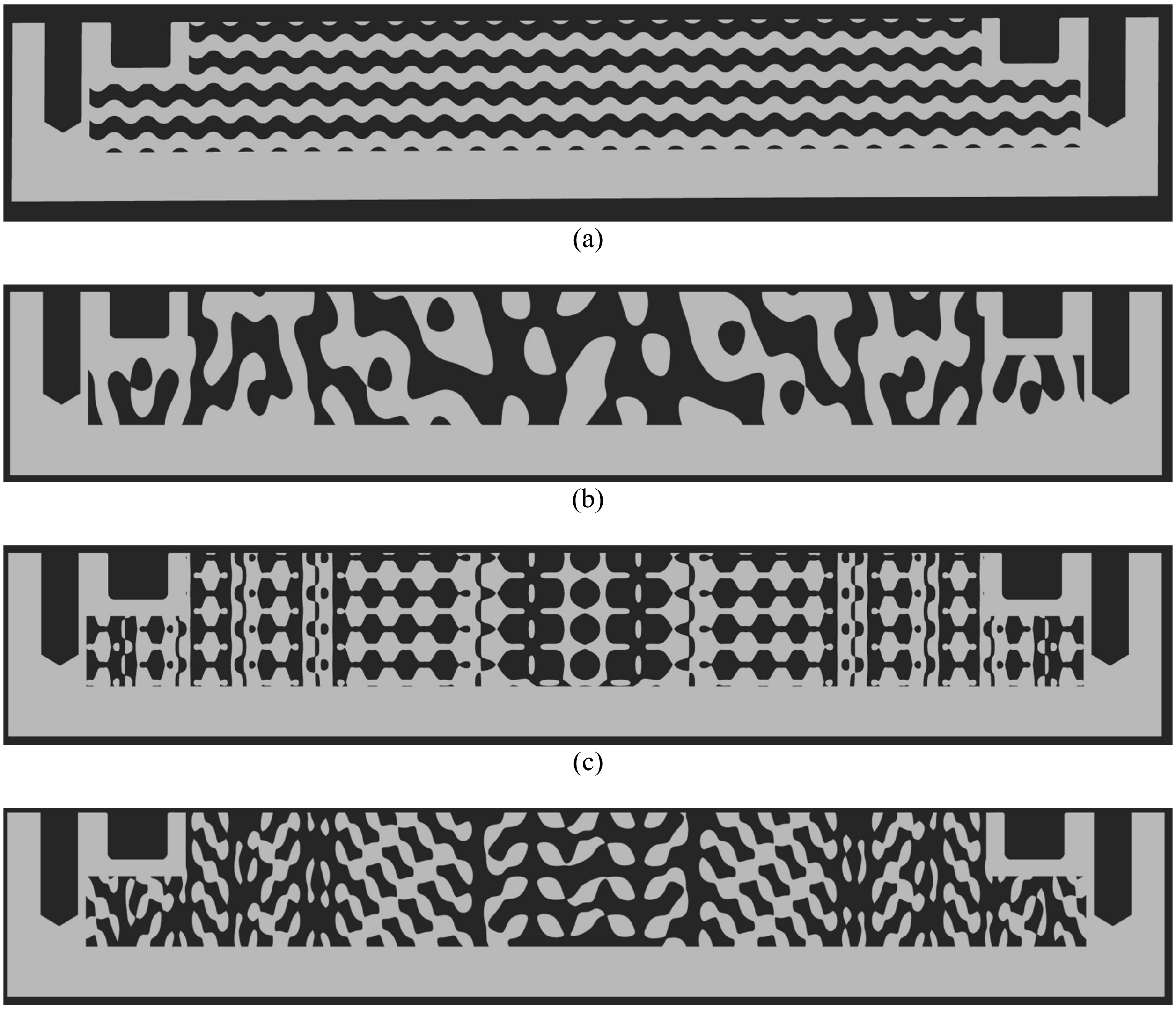
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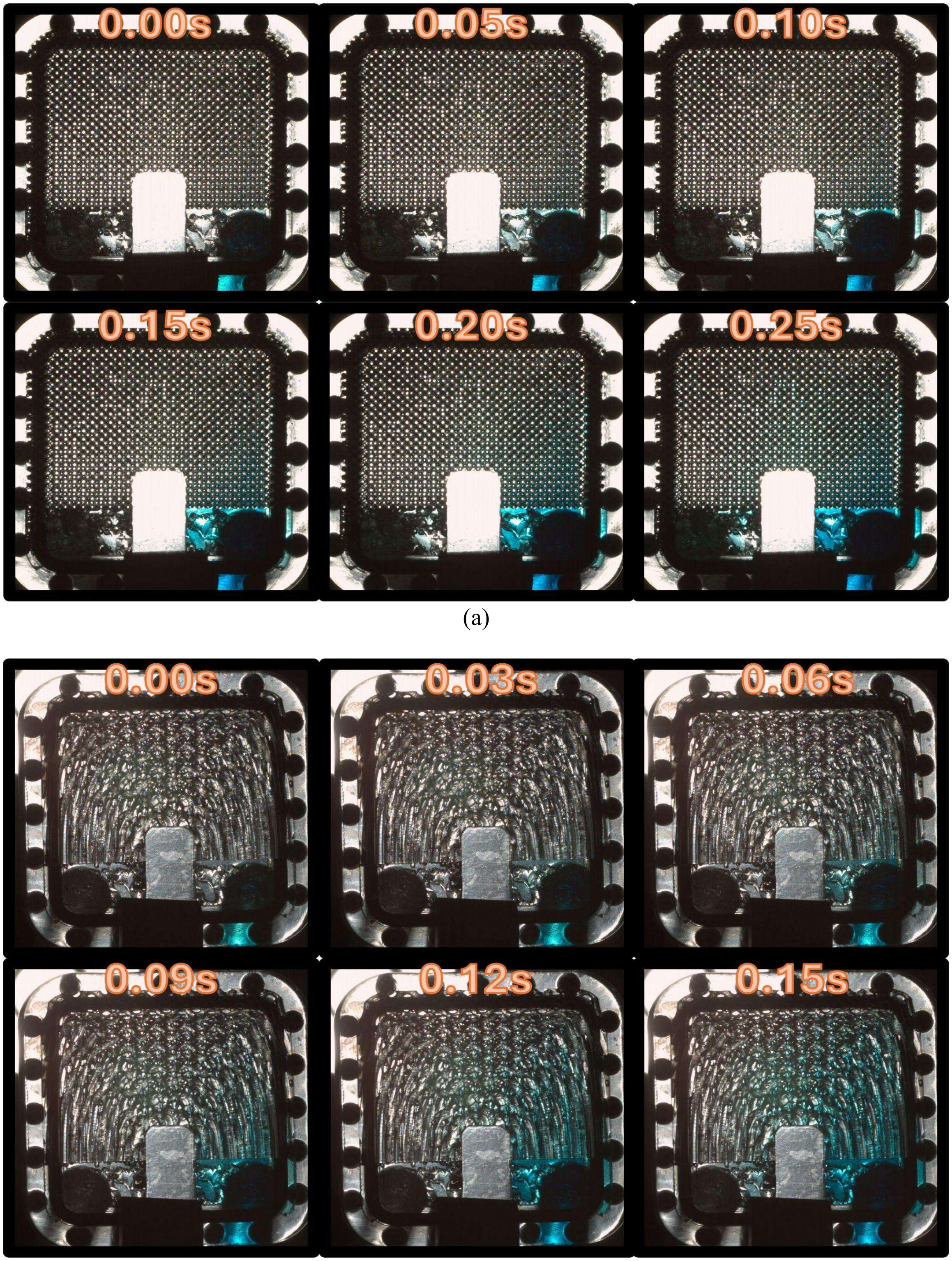
Figure 4. Section views of heat sink designs used in this study: (a) gyroid; (b) Split-P; (c) Neovius; (d) Lidinoid; (e) field driven gyroid; and (f) a baseline with no infill

Results

Results are reported here from two techniques. The first is the mass flow rate measurement, results of which are shown in Table 1. Mass flow rate was found to be not merely a function of negative space volume alone – but is likely dependent on the design itself – i.e. the nature in which the solid volume is distributed and its relation to the fluid flow path. Additionally, manufacturing deviations from intended design may also introduce some errors in this calculation. The baseline results were not reliable and are left out of this table as a result. Figures 5a-5f show high-speed image captures at different times, as determined in a post-processing image analysis software. These findings show encouraging results with regard to the use of the technique itself to assess fluid flow in these structures. The Split-P (Figure 5b) and simulation-driven gyroid (Figure 5e) designs, which showed among the highest mass flow rates also show a clearly developing path from right (inlet) to left (outlet) with good coverage across the heat sink base. The Neovius structures showed limited consistent flow across the base, as did the gyroid and Lidinoid structures.

Table 1. Mass flow results

Design	Solid Volume Fraction	Mass Flow Rate (kg s^{-1})
Gyroid	0.68	0.03429
Split-P	0.44	0.03616
Neovius	0.94	0.02280
Lidinoid	0.53	0.01673
Simulation-driven gyroid	0.38	0.03361



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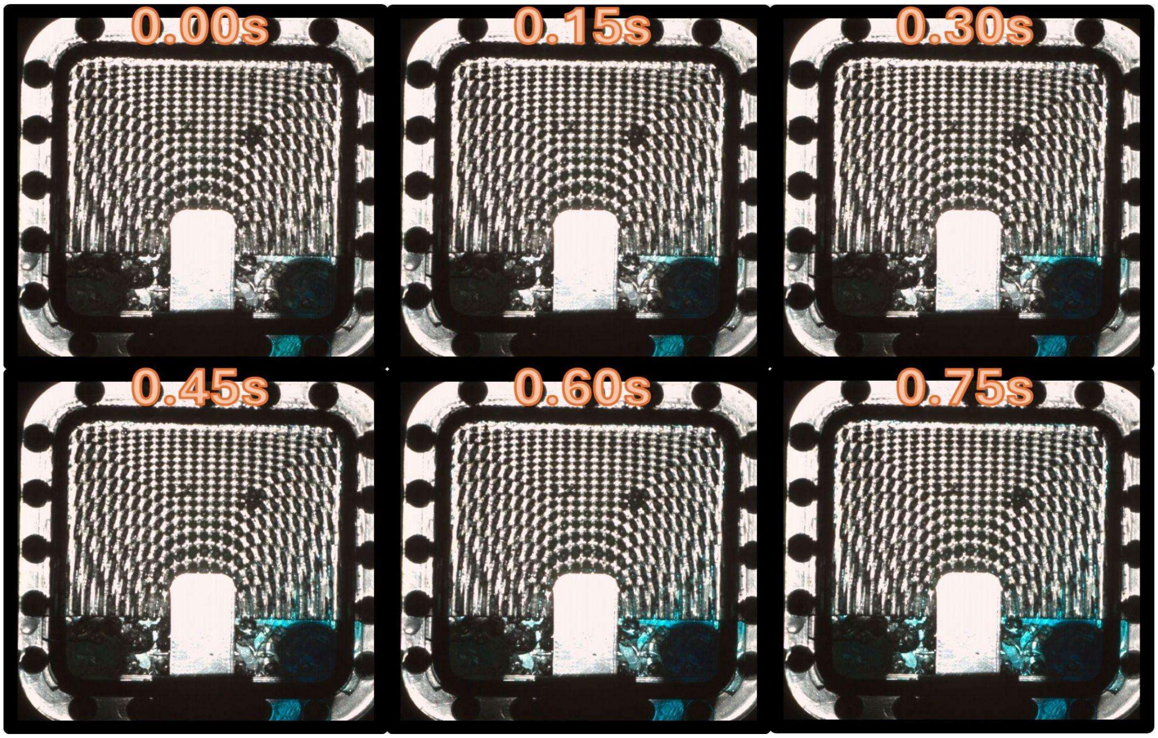

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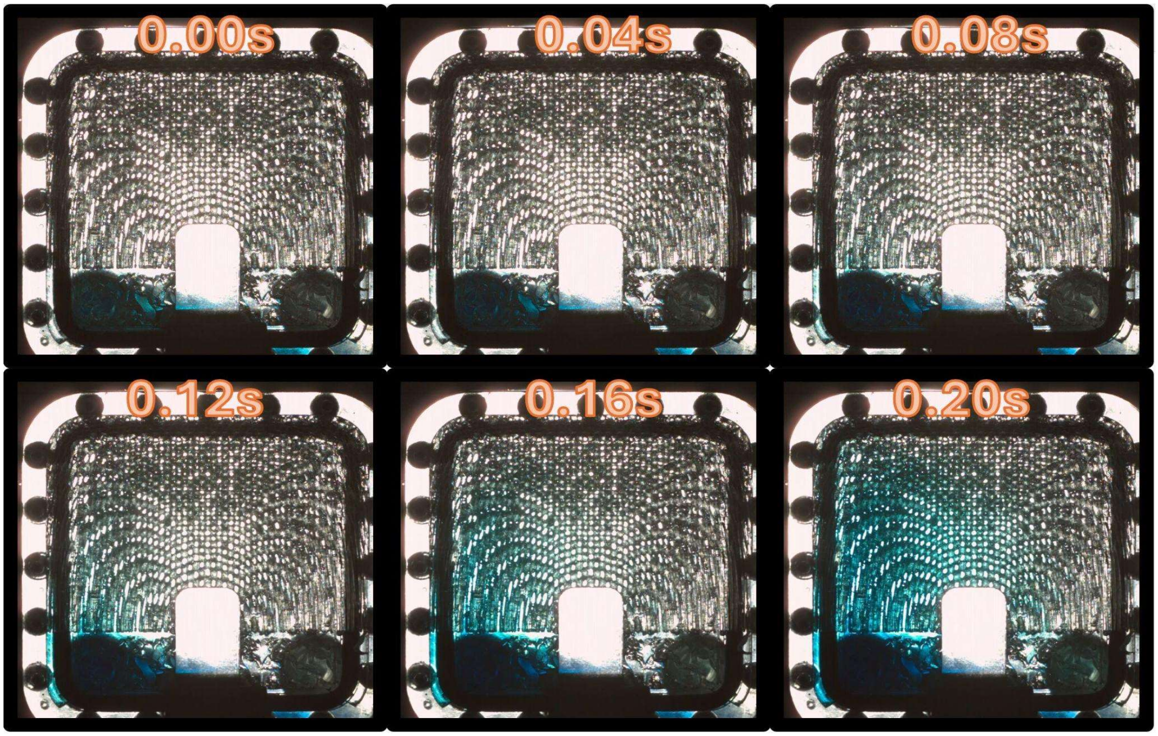

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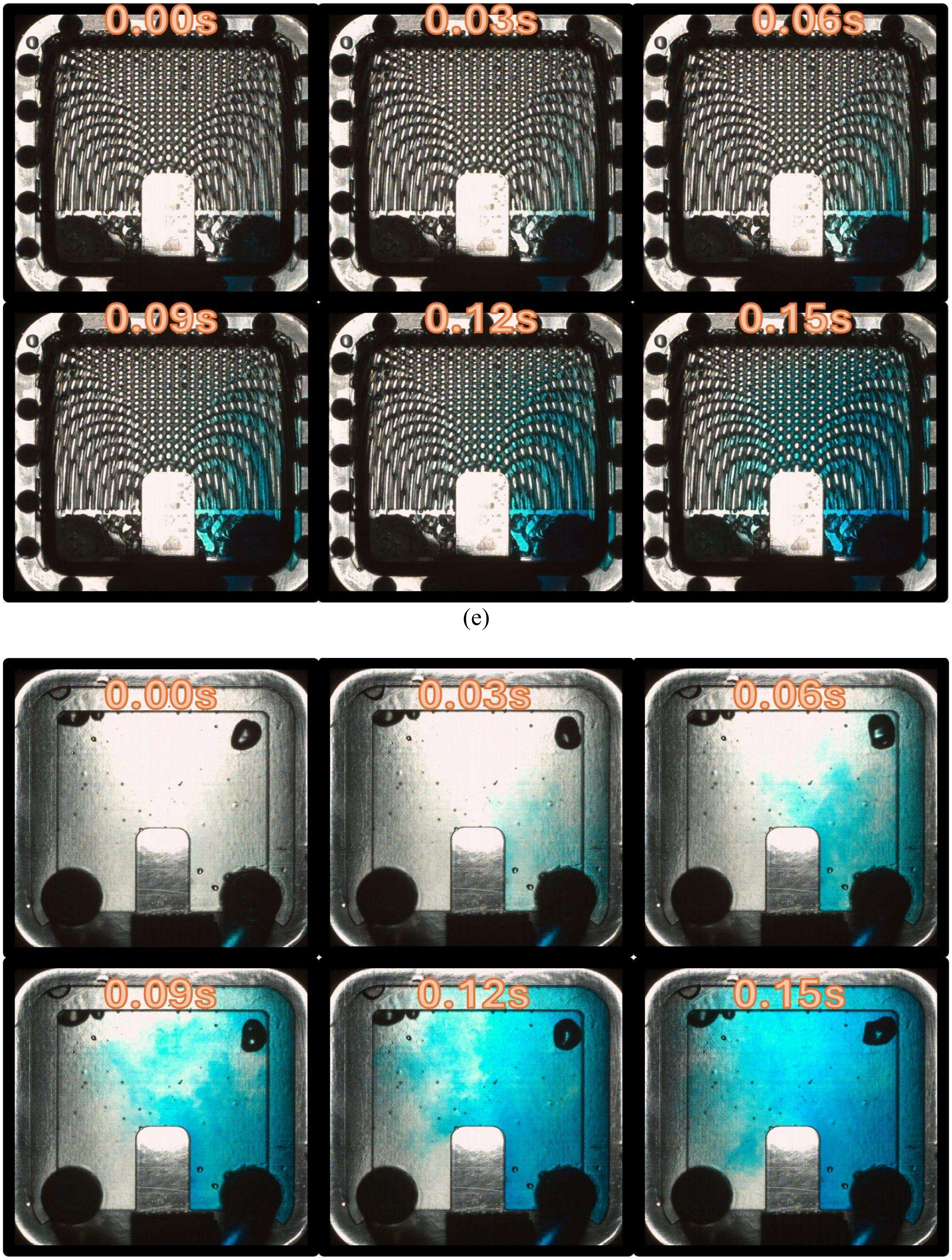

(e)

(f)

Figure 5. High speed camera still images of water dyed blue as it travelled through each of the heat sinks: (a) gyroid; (b) Split-P; (c) Neovius; (d) Lidinoid; (e) field driven gyroid; and (f) a baseline heat sink with no infill

Conclusions

The primary goal of this work was to develop an experimental method for imaging fluid flow in additively manufactured heat sinks, which was achieved using SLA with a clear resin and a high-speed camera. Water dyed blue showed best results and imaging was able to discern fluid flow paths adequately. This work raises several opportunities for future work, including detailed and quantified tracking of the fluid front, as well as validating Computational Fluid Dynamics (CFD) simulations using this experimental technique. With regard to the designs themselves, within the confines of this limited study, the Split-P structure showed good uniformity and high mass flow rate, while the simulation-driven modifications of the gyroid structure conditioned the flow for better coverage and is thus a worthy direction to pursue for further study.

Supplementary Materials

Design files (STL and nTop) of all five heat sinks in this work are available for download at data.mendeley.com with DOI: 10.17632/87gbx4vc9v.1.

Acknowledgements

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