Design of a Functionally-Generated 3D Printed Heat Exchanger

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Introduction

Heat exchangers are ubiquitous across many fields of engineering. Moving heat between two fluids without mixing them is a common engineering problem. Many types of heat exchangers exist depending on the needs of the application.

A class of surfaces called the TPMSs (Triply Periodic Minimal Surfaces) hold great potential as heat exchangers. Although discovered in the 19th century, TPMSs were considered mathematical curiosities until the recent advent of 3D printing, which allows engineers to make use of their interesting properties.

Figure 1: A selection of some TPMSs. From left to right: Diamond, Fischer-Koch S (FKS), Gyroid, Lidinoid, Split-P

A TPMS is comprised of a single, continuous curved surface, separating two volumes. Studies have shown that some of these surfaces make for excellent heat exchangers due to their large surface area, natural turbulence promotion, and pressure survivability (owing to lack of corners to concentrate stress) [1][2][3].

A number of TPMSs have been discovered and studied for this purpose and other applications [4]. Each TPMS can be defined by an implicit function of three dimensions. For example, the surface function of a gyroid is:

$$\sin(X)\cos(Y) + \sin(Y)\cos(Z) + \sin(Z)\cos(X) = c$$

where c is a scalar

Methodology

Since conventional CAD software is unable to create TPMSs, and the specialized CAD software that can (e.g. nTop) is prohibitively expensive. a unique workflow was developed:

Python scripts were used to create and modify the TPMS, SolidWorks was used to model additional CAD geometry (e.g. NPT fittings and the heat exchanger shell) and Blender was used to combine meshes using Boolean operations.

In Python, a coordinate system was created in the form of a NumPy meshgrid, a convenient n-dimensional data structure. Each TPMS function was then evaluated over the meshgrid to produce a 3D scalar field. Where the field = c is where the TPMS is defined.

The marching cubes algorithm, as implemented in the scikit-image library, was used to convert the scalar field to an STL. For geometries that made use of an STL file as a sigmoid bound, the pyVista library was used to convert the STL file into a signed distance field within the coordinate system of the TPMS.

Finally, for the CFD analysis, OpenFOAM and Paraview were used to simulate and view the results, respectively.

Results

The TPMS can be functionally modified in several useful ways, all within Python:

- **Volume Gradient** - C can be defined as a function of X, Y, and Z, creating a non-uniform volume. This can transition the TPMS into a solid or open region.

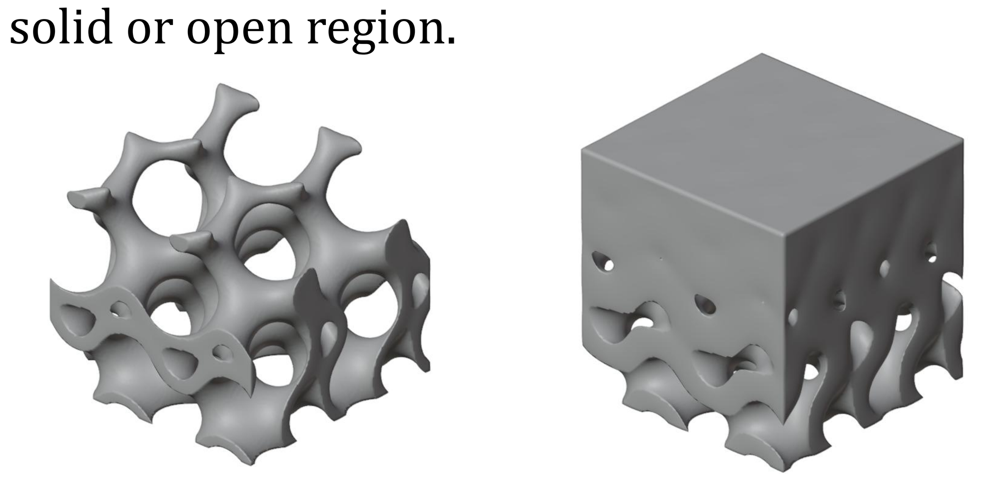

Figure 2: Left: a gyroid transitioning to open space. Right: a gyroid transitioning to closed space.

- **Relative Volume** – The relative volume of the two regions can be altered by using Boolean operations between two TPMSs of different values (below left). This could be potentially useful for heat exchange applications with fluids of different flow rates/specific heats.

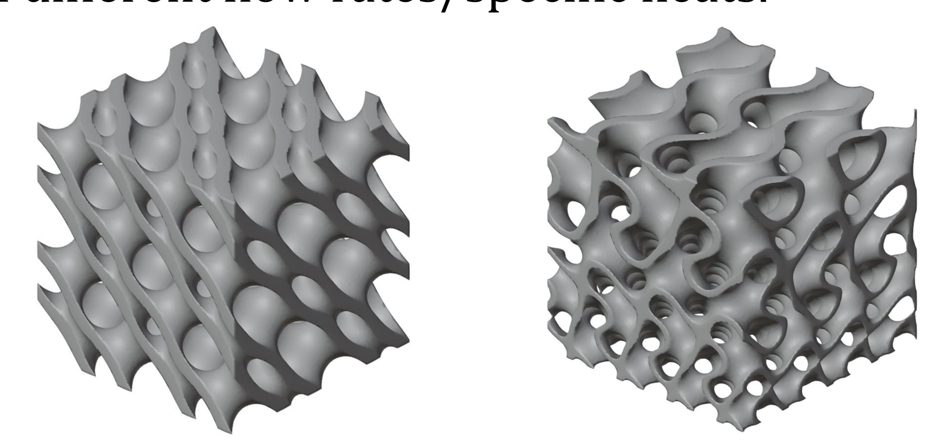

Figure 3: Left: a diamond with two different relative volumes. Right: a gyroid with a cell size gradient.

- **Cell Size Gradient** – Differential equations can be used to create a unit cell size gradient (above right). This could be useful for directing flow.

- **Sigmoid Transition** – Especially useful is the sigmoid function approach, which can be used instead of a Boolean to create smooth transitions between two scalars or scalar fields (below)[5]. This can be used to continuously transition the TPMS mesh into a solid or open region or another scalar field at a specified rate

$$z = 3 \cdot \left(-\frac{6}{1 + e^{-0.08\left(x^2 + \left(y + \frac{\pi}{2}\right)^2 - 48\pi\right)}} + 0.3 \right) - \left(-\frac{5}{1 + e^{-0.08\left(x^2 + \left(y + \frac{\pi}{2}\right)^2 - 36\pi\right)}} + 0.5 \right)$$

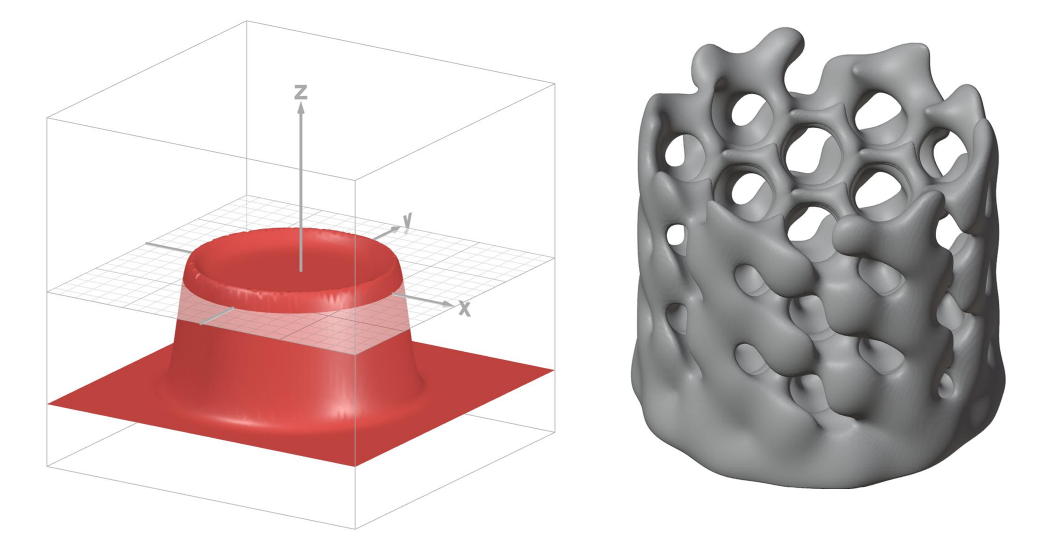

Figure 4: Top: An equation for a cylindrical sigmoid surface (visualized in Desmos). Left: the resulting surface. Right: A gyroid modified with this function.

- **Checkerboard** – This technique uses a Boolean combination of two sigmoid-modified TPMSs to gradually transition each fluid region of the TPMS into negative space to avoid the use of baffles and reduce pressure loss.

$$z = \frac{10}{1 + e^{(0.015xy)}} - 5$$

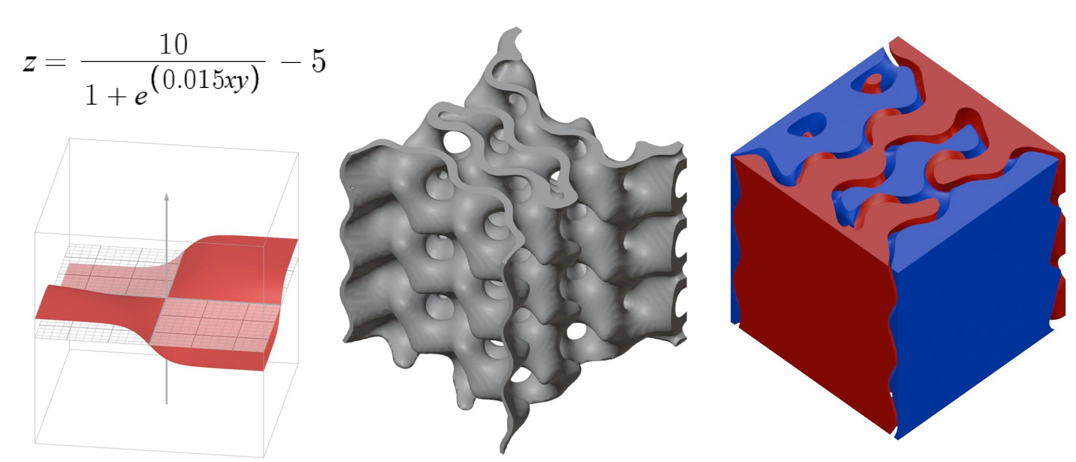

Figure 5: Left: the formula and resulting surface (Desmos). Middle: A gyroid modified with this function. Right: The two resulting separate volumes

The heat exchanger was constructed using a combination of the above mathematical techniques.

1. The heat exchanger shell was modeled in SolidWorks, then exported as an STL
2. The STL was imported into Python and converted into a signed distance (scalar) field. The inside surface was then used as a sigmoid boundary for a TPMS. The "checkerboard" method described above was used to gradually phase in/out each separate fluid region at the inlets/outlets.
3. The resulting STL was imported into Blender, where NPT fittings (modeled in SolidWorks) were joined to the model with Boolean operations.

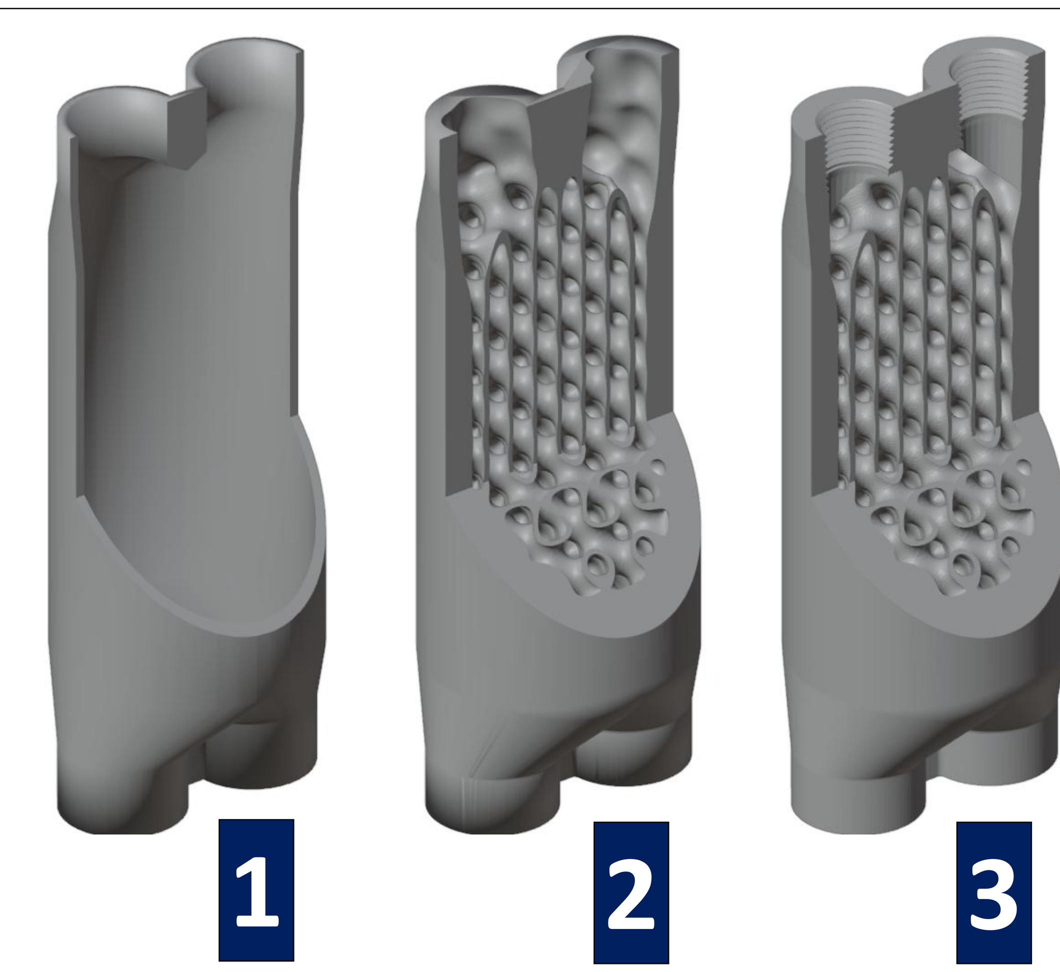

Figure 6: Left: the TPMS heat exchanger at different stages of creation

CFD

An exploratory CFD study was performed for the heat exchanger. A simplified model was imported into OpenFOAM and used in a conjugate heat transfer (CHT) model. This study is a proof of concept and will serve as the starting point for a more rigorous analysis.

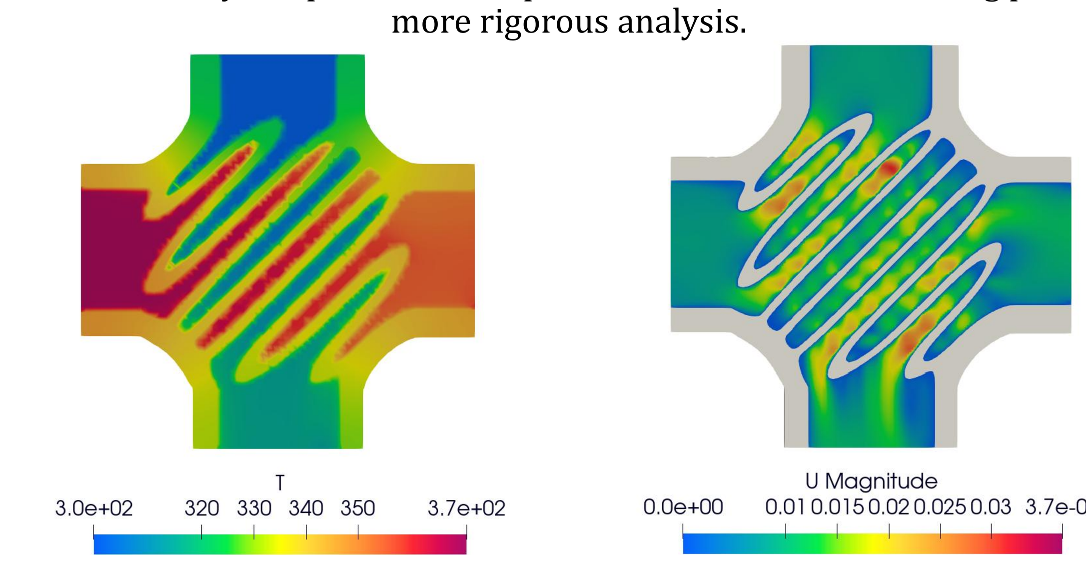

Figure 7: Left: Temperature distribution across the midplane (K). Right: Velocity magnitude (m/s).

Conclusions

This project demonstrates a workflow for the creation and modification of TPMS surfaces in Python. It can also be combined with conventional CAD (e.g. SolidWorks) and mesh editing (e.g. Blender) software to smoothly and continuously combine TPMS surfaces with CAD geometry such as a defined shell and fittings to create a usable product.

This approach is extremely flexible and can be used to create TPMS-based heat exchangers that fit many applications. Iteration for performance can take the form of a combination of CFD and physical testing.

Future Directions

Despite the recent surge of academic interest, TPMSs remain largely unused in industry. This may be due to the specialized software required to model and modify them, or the high entry cost of metal 3D printing. This project also revealed that CFD analysis of TPMSs in heat exchange applications is difficult due to the very large file sizes required to capture their behavior. Nevertheless, CFD remains useful to reduce the time and money spent physically iterating with prototypes, so this approach should be pursued further.

Physical testing of a metal 3D printed heat exchanger should be performed similarly to other examples in the literature. Temperature change, pressure change, and flow rate should be measured for both fluid regions to characterize the heat transfer and pressure loss for a design.

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