Micro-Xray Tomography Based Pore-scale Simulation of Additively Manufactured Wicks

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WICHITA STATE UNIVERSITY

Motivation and Objectives

- ❑ Fundamental understandings of capillary flow through additively manufactured (AM) wicks with highly non-uniform pore structures are essential to design high heat flux two-phase thermal management systems.
- ❑ Traditional volume-average study is challenging to accurately predict key characteristic of the wicks with highly non-uniform pore structures, e.g., permeability, while experimental characterizations are challenging and expensive.
- ❑ To overcome this challenge, this study examines complex relation between the characteristic capillary flow and non-uniform pore structures using pore-scale computational fluid dynamics (CFD) and micro-X-ray tomography (µCT).

Workflow: From µCT to CFD

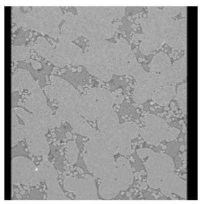

Fig 1. Image 1333 before processing

- ❑ 16-bit µCT images with voxel size ~0.6µm
- ❑ Darker gray: Pores Lighter gray: Solid
- ❑ Contains noise, image border, defects etc.

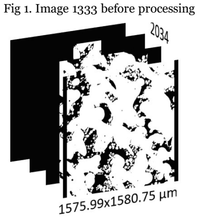

Fig 2. Diagram of processed image stack

- ❑ Defects removed and converted to 8-bit
- ❑ Bilateral filtering
- ❑ Automatic image thresholding
  - Black (0): Pores
  - White (255) : Solid

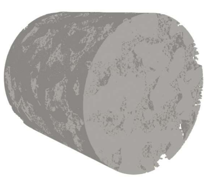

Fig 3. STL model of image stack

- ❑ Surface is reconstructed from image stack and saved as STL
- ❑ STL is decimated while preserving topology

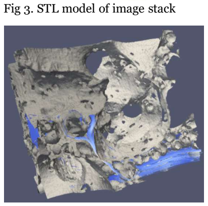

Fig 4. Example of CFD simulation

- ❑ Mesh is generated using snappyHexMesh in parallel
- ❑ Steady state simulation using simpleFoam in parallel

Image Segmentation

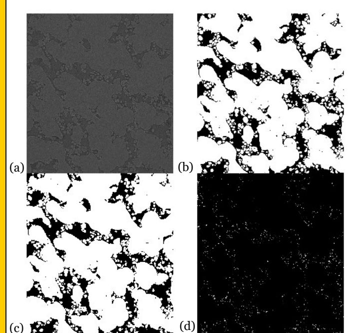

Fig 5. Filtering and thresholding image 1333 (a) original µCT image (b) manually segmented ground truth (c) image segmented automatically using bilateral filter with spatial 30 and range 110 (d) absolute difference between ground truth and automatic segmentation; difference is 2.69%.

- ❑ Successful image segmentation requires filtering and thresholding, and the best tools are bilateral filter and Otsu's thresholding. Parameter sensitivity study was performed on several images and 100 images that was cropped to 400x400µm² and the results are shown in Fig 6. and 7.
- ❑ The local 2-D and global 3-D porosity is compared with a manually segmented dataset and the best was spatial 30 and range 110 (30-110).

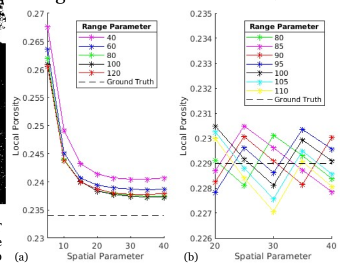

Fig 6. Bilateral filter parameter sensitivity study on image (a) 1333 and (b) 200

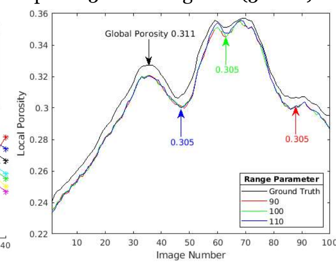

Fig 7. Local and Global Porosity of 400x400µm² image stack using selected bilateral parameter

Mesh Generation

- ❑ The cropped 400x400 µm² image stack is meshed using snappyHexMesh.
- ❑ To reduce the file size, a decimating algorithm is applied, and this study found no changes to porosity or predicted permeability as shown in Fig 8. and 9.

Table 1. Decimation parameters and reduction for 30-110 STL.

Decimation Input Parameters	
Target Reduction	0.9
Preserve Topology	Yes
Feature Angle	15
Boundary Vertex Deletion	Yes
Decimation Results	
Original File Size	150 MB
Decimated File Size	50 MB

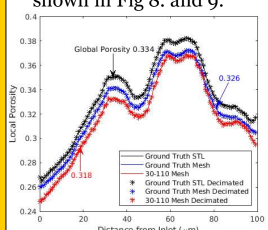

Fig 8. Local and global porosity of ground truth STL, mesh of ground truth STL, mesh of auto-segmented 30-110 STL and effects of decimation

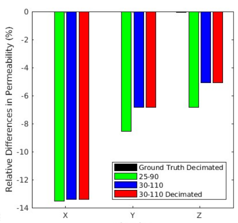

Fig 9. Relative differences in anisotropic permeability of various meshes relative to ground truth simulation

- ❑ A cropped 400µm-cube volume is now analyzed using CFD.
- ❑ Using optimized meshing parameters, the final mesh is created is summarized in Table 2.

Table 2. Mesh information and mesh quality using 30-110 decimated STL

Number of Cells	
Polyhedra Cells	74,891
Hexahedra Cells	2,527,403
Total Cells	2,602,294
Mesh Quality Metrics	
Max Aspect Ratio	4
Non-Orthogonality	Avg/Max 8/48
Max Skewness	3

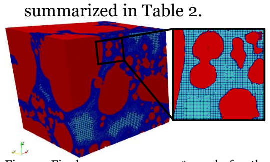

Fig 10. Final 400x400x400µm³ mesh for the fluid (blue) and solid (red) regions

CFD Simulation

- ❑ Steady-state laminar simulation is performed on engine oil at standard sea-level (SSL) condition using simpleFoam.

Table 3. Velocity and pressure boundary conditions

Patch Name	Velocity (mm/s)	Pressure (m²/s²)
Inlet	fixedValue (0.1 0 0)	zeroGradient
Outlet	zeroGradient	fixedValue (0)
Walls	fixedValue (0 0 0)	zeroGradient
Wick	fixedValue (0 0 0)	zeroGradient

Table 4. Fluid Properties

Average Pore Diameter (µm)	70
Density (kg/m³)	850
Viscosity (Pa·s)	0.5
Reynolds Number	0.0001

- ❑ Results are shown for simulation in the *x*-direction, however simulation was also done on *y*- and *z*-directions.

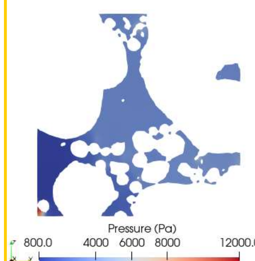

Fig 11. Pressure distribution at the inlet

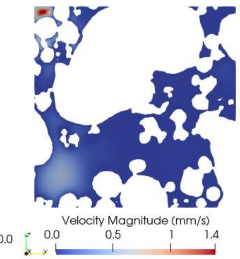

Fig 12. Velocity distribution at the outlet

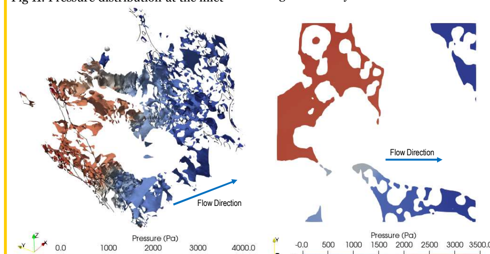

Fig 13. Model simulation of (a) pressure contour (b) pressure distribution at z =1/2 plane along flow direction

400µm-Cube Results and Conclusion

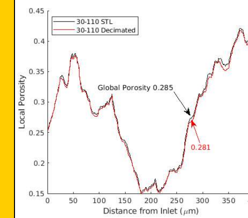

Fig 14. Local and Global Porosity of 400x400x400µm³ volume STL and decimated mesh.

- ❑ To validate the CFD results, Carman-Kozeny relation for perfect sphere particle in packed bed is used to estimate permeability, κ.

  $\kappa_{estimate}$ =1.23e-12 m²

- ❑ From CFD simulation, pressure drop along the wick and average velocity at the outlet allows permeability calculations using Darcy's Law.

Table 5. Average velocity at outlet, pressure drop along wick and permeability estimate in *x*, *y* and *z* directions

Direction	Average Velocity (mm/s)	Pressure Drop (Pa)	κ (m^2)
x	0.025	2704	1.81E-12
y	0.051	6008	1.66E-12
z	0.036	4369	1.63E-12

- ❑ CFD can accurately predict permeability from µCT images and provide detailed view of velocity and pressure distribution along the wick.
- ❑ Future work will estimate permeability of the full stack and compare with experimental results.

Scalability

- ❑ Meshing and simulation scalability is studied using BeoShock High Performance Computing (HPC) at Wichita State University.
- ❑ For meshing, hierarchical decomposition method using 36 cores (1 node) performed best and did not scale well using more than 1 node. For solving, scotch and hierarchical decomposition both scaled well using up to 108 cores (3 node).

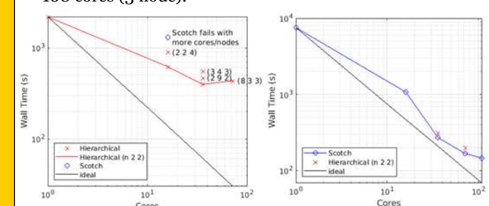

Fig 15. Scaling of scotch and hierarchical domain decomposition method using BeoShock for (a) snappyHexMesh (b) simpleFoam

References

[1] K. Kuhlmann, C. Sinn, J. M. Siebert, G. Wehinger, J. Thöming, and G. R. Pesch, "From MCT data to CFD: An open-source workflow for engineering applications," Engineering Applications of Computational Fluid Mechanics, vol. 16, no. 1, pp. 1706–1723, 2022.

[2] X. Li, F. Wang, G. A. Riley, M. Egbo, M. M. Derby, and G. Hwang, "Integrated Micro X-ray tomography and pore-scale simulations for accurate permeability predictions of porous media," Frontiers in Heat and Mass Transfer, vol. 15, no. 1, 2020.

Acknowledgement

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Slide 1

HG0 [@Ang, Marcus] [@Ahmed, Ikramuddin] What about revising this in the following?
- Fundamental understandings of capillary flow through additively manufactured wicks with highly non-uniform pore structures are essential to design high heat flux two-phase thermal management systems.
- Traditional volume-average study is challenging to accurately predict key characteristic of the wicks with highly non-uniform pore structures, e.g., permeability.
- To overcome this challenge, this study examines complex relation between the characteristic capillary flow and non-uniform pore structures using pore-scale computational fluid dynamics and micro-X-ray tomography.
Hwang, Gisuk,
2023-03-24T05:58:42.992

AM0 0 Yes I think it's okay. In the second point, I think it's good to point out experimental procedures too.
Ang, Marcus,
2023-03-24T15:42:30.161

HG0 1 I agree. I think you can elaborate "while experimental procedure may be expensive" by revising "while experimental characterizations are challenging and expensive". Note that the use of "may be" is not typically an ideal way to

write a technical report since it often weakens your statement.
Hwang, Gisuk,
2023-03-24T20:34:15.170

HG1 [@Ang, Marcus] [@Ahmed, Ikramuddin] I think you can remove this section (and two bullet points). Instead, you can change your section heading (Motivation and Backgrounds) to "Motivation and Objectives". What do you think?
Hwang, Gisuk,
2023-03-24T06:00:52.020

AM1 0 Yes I think that's okay!
Ang, Marcus,
2023-03-24T15:35:53.872

HG2 [@Ang, Marcus] You mean binary?
Hwang, Gisuk,
2023-03-24T06:02:03.362

AM2 0 Yes. But I might remove the term and instead go straight to value of pore and solid. Looking back, I think it may be confusing as binary usually means 0 and 1.
Ang, Marcus,
2023-03-24T15:44:52.715

HG2 1 Sounds good to me.
Hwang, Gisuk,
2023-03-24T20:34:43.171