Characterizing Heat Transfer Induced by Additively-Manufactured Surface Roughness

Significance of Research. The purpose of this research is to analyze the heat transfer effects of additively-manufactured surface roughness on internal channel fluid flows. This research is relevant to the energy industry because many complicated components of cooling systems are made using additive manufacturing. Additionally, the US Department of Energy's Transformational Challenge Reactor (TCR) program uses additively-manufactured cooling channels for their reactor. Weinmeister et al. [1] tested cooling channel geometries in order to optimize heat exchange rates in the gas-cooled reactor core. However, further research is required to characterize the heat transfer effects of defects caused during the additive manufacturing process. Parts made through additive manufacturing are subject to many imperfections because the internal surfaces cannot be easily post-machined [2]. Extensive research has been done to study flow effects such as turbulence caused by surface roughness (Figure 1) and physical effects such as reduced fatigue life caused by surface roughness and sub-surface defects [2,3]. While sub-surface defects may also affect heat transfer, the scope of this research will focus primarily on the effects of surface roughness.

The additive manufacturing process causes surface roughness of different magnitude and distribution depending on the parameters of the manufacturing process. First, surface roughness can vary due to the build orientation of the object being manufactured. Figure 2 shows surface topography maps and surface roughness values for test specimens built at different orientations. The surfaces prone to the greatest surface roughness are surfaces requiring support structures during the manufacturing process (Figure 2a, Side 4), surfaces in a downskin orientation (Figure 2b, Side 2), and surfaces aligned away from the gas flow direction (Figure 2c, Side 3) [3]. Second, surface roughness can vary due to the spacing and arrangement of parts during the additive manufacturing process. Figure 3 shows how parts manufactured more closely together are prone to greater fluctuations in relative roughness. This higher surface roughness occurs due to heat accumulation during the Electron Beam Melting (EBM) process of powder-bed additive manufacturing [4]. Lastly, surface roughness can vary due to the primary processing parameters of laser powder-bed additive manufacturing. Figure 4 shows variations in surface topography due to different settings for laser power and laser speed [5]. Understanding how these distributions of roughness affect heat transfer is crucial.

Objectives – Characterize heat transfer induced by additively-manufactured surface roughness

- Create roughness meshes to represent surface roughness distribution caused by additive manufacturing
- Model heat transfer effects of varying cooling channel conductivities and levels of relative roughness
- Analyze simulations and identify potential manufacturing parameters for heat transfer optimization
- Present findings at a research conference and publish findings in a scientific journal

Plan to Meet Objectives. The effect of surface roughness on flow-driven heat transfer in a channel can be quantified by observing the variation of Nusselt number (Nu) with change in the Reynolds number (Re) of the flow, the Prandtl number (Pr) of the fluid, the Peclet number (Pe) of the channel, the relative roughness, and the roughness distribution. For the current proposal, we will focus on the effect of varying Peclet numbers and surface roughness properties, keeping the other properties constant. Computational fluid dynamics (CFD) meshes for smooth-channel flows will be adapted to match the distinct surface roughness distributions found in additive manufacturing, and the Reynolds and Prandtl numbers will be kept constant. Control simulations will be run on smooth channel cases with three Peclet numbers to represent varying conductivities of the metals the channel is made from. Simulations will also be run with three variations of relative roughness for each of the three Peclet numbers. The model will be implemented using the open-source, highly-scalable, high-order spectral element method (SEM) based incompressible Navier-Stokes solver, Nek-5000 [6]. Nek-5000 allows the algorithm to be scaled efficiently to run on peta-scale supercomputers [7]. These CFD simulations will be run in the Center for High Performance Computing (CHPC) at the University of Utah.

Research Timeline. The research will be performed over three semesters. During Spring 2022, I will learn the SEM solver, Nek-5000, and set up the governing equations for the analysis. I will run the three smooth channel case simulations and adapt the existing roughness meshes to match the additive manufacturing surface roughness distribution. During Fall 2022, I will analyze the smooth cases and begin to run the nine rough case simulations. During Spring 2023, I will analyze the rough cases, and I will prepare to present the findings at the USU Student Research Symposium and at Utah Research on Capitol Hill. I will also seek opportunities to publish the findings in scientific journals, such as the Journal of Fluid Mechanics and the International Journal of Heat and Mass Transfer.

Personal Relationship to Project. The research proposed for this project aligns with my personal goals of using computational methods to simulate real-world problems, especially those problems related to the aerospace and energy industries. I plan to do an internship with Idaho National Laboratories in Summer 2022 to continue researching computational fluid dynamics as it relates to the nuclear industry. I hope to return from my internship with useful experience for the final stages of this research project. I intend to continue studying computational fluid dynamics in graduate level education.

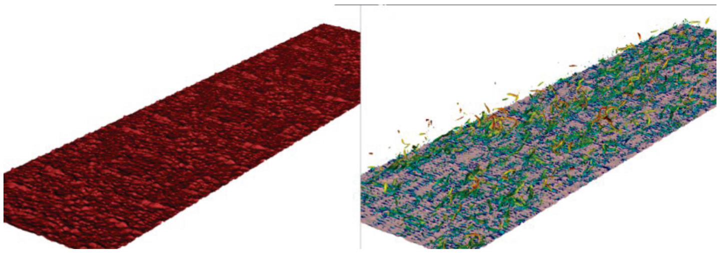

Figure 1. Fully resolved turbulent flow over natural biofilm generated roughness mesh.

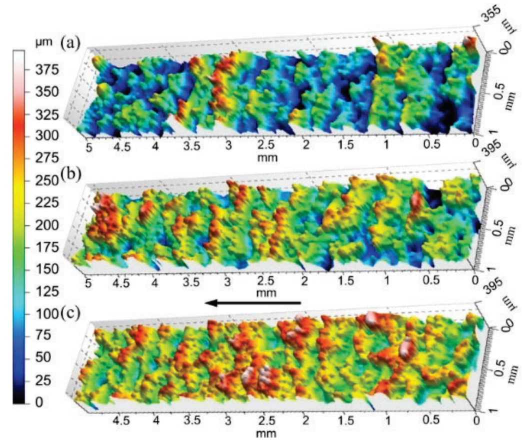

Figure 3. 3D representation of surface roughness at coupons with different spacing distances: (a) 5 mm, (b) 10 mm, and (c) 20 mm [4].

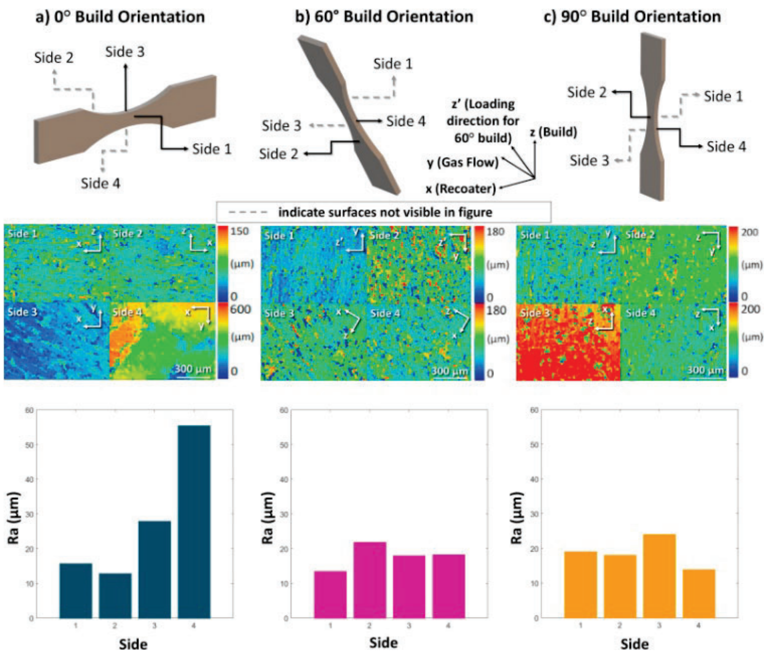

Figure 2. Representative surface topography maps and Ra values for a) 0° build orientation, b) 60° build orientation, and c) 90° build orientation [3].

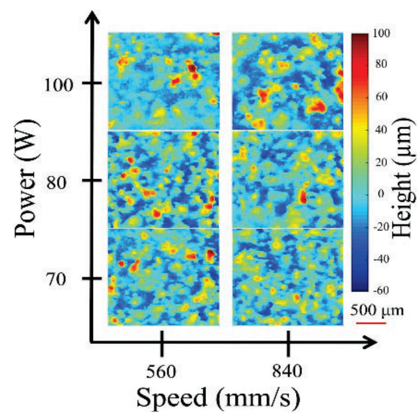

Figure 4. Height maps for different primary parameter settings for laser speed and power [5].

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