Numerical study of laminar forced convection heat transfer in a rough mini-channel fabricated by Additive Manufacturing

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Abstract. This study investigates laminar convective heat transfer of water flowing in a mini-channel with a rough surface fabricated by Laser-based Powder Bed Fusion (L-PBF) technology. A Gaussian model was used for generating random roughness, and then the three-dimensional numerical simulation was performed in ANSYS-Fluent 19.1. The numerical results indicated a more than double increase in the Nusselt number of rough channels than that of smooth ones with a marginal pressure drop penalty compared to smooth channels, showing the potential benefits of using rough channels fabricated by L-PBF for heat transfer applications.

1. Introduction

Additive Manufacturing (AM) is a fast-growing fabrication method that creates three-dimensional objects by adding layer upon layer of material. AM techniques have been exploited by various sectors, such as aerospace, automotive, medical and fluid process engineering. Of the techniques used for metal fabrication, Laser-based Powder Bed Fusion (L-PBF) makes it possible to create complete devices in one single manufacturing operation, which has accelerated over the past few decades.

Surface roughness plays a crucial role in transport phenomena, including heat and momentum transfer [1]. Several factors related to AM processes result in irregular roughness on the surface of the parts fabricated by the AM. A heat transfer enhancement of as much as 73% over roughened surfaces fabricated by the L-PBF technique compared to that of smooth surfaces was reported by Ventola et al. [2]. In an experimental study, Stimpson et al. [3] showed that surface roughness brings about a substantial increase in heat transfer coefficient and pressure drop in rectangular channels fabricated by L-PBF. They reported that augmentation of the Nusselt number is not proportional to the rise in the friction factor, especially in channels with small hydraulic diameters.

L-PBF technologies are also well-known for their ability to fabricate free-form objects with almost any desirable configuration. Many researchers have employed this capacity to create non-traditional cooling channels with enhanced thermal performance. In this regard, Kirsch and Thole [4,5] studied the wavy channels fabricated by L-PBF. They observed that a considerable pressure loss accompanies the heat transfer enhancement in rough wavy channels compared to the straight channel.

Accurate prediction of flow and heat transfer in additive manufactured channels requires the inclusion of the effect of the surface roughness in the computational investigations. Hanson et al. [6] simulated turbulent convective heat transfer in turbine’s cooling channels fabricated by L-PBF using grid-resolved roughness generated by a simplified Fourier series. Manavi and Kenig [7] performed a numerical study of convective heat transfer in a microchannel fabricated by AM. They used a 3D
scanner to create the geometry of rough surfaces in microchannels. Recently, Urcia and Kinzel [8] used a Discrete Element Rough Model (DERM) for the computational study of turbulent convective heat transfer in the turbine’s cooling channels. They reported a large discrepancy between DERM and experimental data, indicating a need for improvement in the DERM correlations.

AM is expected to open a new era in the design of heat transfer devices in the next few years. Understanding the hydrothermal characteristics of flow additive manufactured channels is a substantial field of study currently under-investigated, and thus, of significant interest in terms of further consideration. This paper investigates the Computational Fluid Dynamics (CFD) study of fully developed laminar convective heat transfer in a cooling mini-channel with a rough surface fabricated by L-PBF. This work can potentially contribute to electronics cooling, heat exchangers, and conformal cooling channels.

2. Roughness model
The surface roughness can be characterized by the root-mean-square roughness ($R_{rms}$) as well as either skewness ($s_k$) or the kurtosis ($k_u$) [9]. The skewness indicates the departure of roughness elements from symmetry, while kurtosis represents the sharpness of the roughness profile. A Gaussian surface with any root-mean-square roughness has $s_k = 0$ and $k_u = 3$. Ventola et al. [2] characterized five different rough surfaces fabricated by DMLS and observed that all five surfaces represent near Gaussian surfaces. Therefore, a Gaussian model is employed to create a rough surface in the mini-channel in this study.

The rough surface is created using the following steps:
1. Create a Gaussian random heightmap, $z(x, y)$ with $x$ and $y$ being the streamwise and spanwise using the method described by Patir [10].
2. Generate a surface mesh for the rough surface using the heightmap (performed in MATLAB).
3. Export the mesh surface in an STL file (triangular surface mesh).
4. Import the STL file in CAD software and generate the CAD model.

3. Numerical model
The geometry of the numerical model is a single mini-channel with a rectangular cross-section in which only the bottom surface of the channel is rough, as shown in Figure 1. The channel has a height of 1 mm and a width of 2 mm, while the length of the channel is 8 mm. The thickness of the channel walls is defined as 0.5 mm on each side. The rough surface has $R_{rms} = 21 \mu m$, $s_k = -0.075$ and $k_u = 2.990$, which is very close to the Gaussian surface.

![Figure 1. Geometry and temperature contours for Re=1600](image1)

![Figure 2. Validation of CFD](image2)

Three-dimensional steady-state Navier-Stokes and Energy equations for laminar convection heat transfer were solved numerically. The Finite Volume Method (FVM) implemented in ANSYS-Fluent 19.1 was used to simulate the mini-channel heat transfer and fluid flow. The working fluid is water, while the material of the channel’s body is AlSi10Mg [11], which is a common material in the fabrication of heat exchangers by AM. The domain was considered periodic in the x-direction, which
guarantees a fully developed flow condition. The symmetric boundary condition was applied to the sidewalls of the channel, while the top wall of the channel was assumed to remain adiabatic. A constant heat flux of 20 W/cm² was applied to the bottom wall of the channel. The average inlet temperature of the fluid was defined as 300 K, and the flow Reynolds number varied between 200 to 1600.

The numerical code was validated with the experimental data of Moharana et al. [12]. Good agreement between numerical results and experimental data was achieved, as shown in Figure 2. Several grid resolutions were compared, and a computational grid with 1500000 cells was sufficient for this study since doubling the number of cells showed less than 1 % change in the Nusselt number.

4. Results and discussion

Figure 3 compares the numerical results of the Nusselt number (Nu) and pressure drop per unit length ($\Delta p/L$) of a rough mini-channel fabricated by L-PBF with a smooth mini-channel produced by conventional machining methods. Both the Nu and $\Delta p$ increase with increasing the Reynolds number. For a low Reynolds number, the difference between the Nusselt number of the rough channel and that of the smooth channel is negligible. However, as the Reynolds number increases, this difference becomes more pronounced, with the rough channel providing higher Nu numbers. However, the difference between pressure drops associated with rough and smooth channels is marginal irrespective of Reynolds number.

![Figure 3. Variation of Nusselt number and Pressure drop with Reynolds number](image3.png)

![Figure 4. Variation of heat transfer coefficient along the channel at Re=600 & 1600](image4.png)

Figure 4 shows the variation of the convective heat transfer coefficient along the centerline of the channel for Reynolds numbers 600 and 1600. Since the flow is fully developed, the convective heat transfer coefficient of the smooth mini-channel is almost constant in the flow direction. However, the convective heat transfer coefficient of the rough channel fluctuates due to disturbance caused by the roughness structure. This fluctuation behaviour can be explained using the inset illustrated in Figure 1. The low-velocity flow recirculation in the roughness valley [13] increases the thermal boundary layer (larger thermal resistance between the surface and the bulk flow), resulting in a reduction in the heat transfer coefficient. However, the flow acceleration over the roughness peaks [13], as shown in Figure, reduces the thermal boundary layer (smaller thermal resistance between the surface and the bulk fluid), leading to heat transfer enhancement. Figure 4 shows that, for Re=600, the heat transfer coefficient of the rough channel oscillates around a reference value almost equal to the average heat transfer coefficient of the smooth channel. However, for Re=1600, the heat transfer coefficient of the rough channel fluctuates around a reference value larger than the heat transfer coefficient of the smooth channel, resulting in higher heat transfer between the rough surface and fluid.

5. Conclusion

This study investigated the three-dimensional CFD simulation of convective heat transfer of laminar fully developed flow in a rough mini-channel fabricated by AM. Simulation results demonstrated that
the recirculation and acceleration of flow in the roughness valleys and over the roughness peaks led to enhancement and reduction of the heat transfer coefficient over peaks and valleys of roughness, respectively. This phenomenon caused the heat transfer coefficient of the rough channel to fluctuate around a reference value. For Re=400, this reference value is almost equal to the heat transfer coefficient of the smooth channel, while this reference value became more than double the heat transfer coefficient of the smooth channel. The results demonstrated that under constant Reynolds number, the difference between pressure drop of rough and smooth channels is marginal, which makes the rough channels favourable for enhanced heat transfer applications. These findings demonstrate promises in the fabrication of artificial roughness (see Ventola et al. [2]) by AM to enhance heat transfer in laminar flows. The method presented in this study can also be further deployed for the prediction and optimization of rough cooling channels used in applications such as conformal cooling channels and thermal management systems.

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