INVESTIGATION OF THERMAL AND FLUID FLOW CHARACTERISTICS OF AM SURFACES WITH DIFFERENT SCAN ORIENTATIONS THROUGH CFD AND EXPERIMENTS

by

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ABSTRACT

KULDEEP MANDLOI. Investigation Of Thermal and Fluid Flow Characteristics of AM Surfaces with Different Scan Orientations through CFD And Experiments
(Under the direction of DR. HARISH CHERUKURI)

Additive manufacturing (AM), specifically laser powder bed fusion (LPBF), holds considerable significance across diverse industries such as tool and die making, IC manufacturing, medical implants, electronic cooling, and aerospace sectors due to its ability to produce components with intricate internal and external geometries. This stands in contrast to traditional manufacturing methods that impose limitations on the complexity of part designs. Notably, there is a growing interest in using AM for the production of components with intricate cooling channels featuring complex surface topographies designed to enhance thermal performance. While conventional machining methods can address the roughness of external surfaces, they fall short when it comes to treating internal channels, especially when these dimensions are at a millimeter or submillimeter scale. AM emerges as a promising alternative with the potential to overcome this limitation. To ensure the successful industrial adoption of AM for parts requiring sophisticated cooling channels, it becomes imperative to comprehend the relationship between the as-built surface finish and heat transfer. In LPBF, numerous build parameters, such as part orientation during the build, significantly impact the final part surface topography and, consequently, heat transfer. Existing literature, exemplified by Moody's diagram, simplifies the treatment of surface roughness. However, powder bed fusion processes generate intricate surfaces characterized by strong anisotropic features, spatter, and surface defects, all of which have the potential to influence heat transfer and fluid flow. This research primarily focuses on investigating the effects of AM roughness characteristics, including scan orientations, density of spatter deposits, sizes of spatter, amplitudes, wavelengths, etc., on heat transfer from corresponding AM surfaces and pressure drop across cooling channels. The study employs both numerical and experimental approaches. Computational Fluid Dynamics (CFD) models for mini-channels using StarCCM+ were developed, integrating roughness data from real AM surfaces. CFD simulations for the entire system model and modeling of mini-channels with different wavy surfaces aided in establishing suitable dimensions for experimental setups and determining the Reynolds numbers necessary for relevant experiments. An exchangeable experimental setup was developed based on CFD findings, and AM parts with critical scan orientations (0°, 45°, and 90°) were fabricated, subsequently machined to fit into the setup. In addition, a smooth-surfaced Inconel part served as the baseline control condition. Comparative analysis of CFD and experimental results across different Reynolds numbers validated the findings, revealing significant differences in Nusselt numbers and pressure drops among various AM surfaces. The surface with a 90° scan orientation demonstrated superior heat transfer performance based on nominal build conditions. Building upon these outcomes, further investigation into the effects of 90° weld tracked surfaces in a circular form was conducted. Two aluminum (Al-6061) channels—one with a smooth surface and the other with internal threads mimicking artificial waviness similar to an AM surface with a 90° scan orientation to the fluid flow direction—were conventionally manufactured. Both CFD and experimental investigations were conducted for different mass flow rates. The results indicated that artificial waviness had a substantial impact on heat transfer, resulting in high cooling efficiency. The Nusselt number was approximately three times larger for various flow conditions compared to the smooth channel. However, intentionally structured surfaces also led to larger pressure drops, potentially necessitating additional pumping power depending on the specific application.

DEDICATION

I would like to dedicate my PhD dissertation to my beloved son Chitrarth, my wife Garima, my brother Aman and my parents Mr. Ramesh Chandra Mandloi and Mrs. Asha Mandloi. This venture would not have been possible without their unconditional love, care, and support.

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TABLE OF CONTENTS

LIST OF FIGURES

Article 1: CFD and experimental investigation of AM surfaces with different scan orientations

Article 2: Numerical and experimental investigation of heat-transfer and fluid-flow characteristics of Al-6061 mini channels with a structured vs. smooth internal surface

Article 3: Experimental Investigation of thermal and fluid-flow performance of Inconel-625 AM surfaces with different scan orientations and verification through CFD modeling using sand-grain roughness model.

LIST OF TABLES

Article 3: Experimental Investigation of thermal and fluid-flow performance of Inconel-625 AM surfaces with different scan orientations and verification through CFD modeling using sand-grain roughness model.

LIST OF ABBREVIATIONS

Abbreviation	Definition
ρ	Density of fluid (kg/m^3).
A_c	Cross sectional area of the channel (mm^2)
A_s	Surface area (mm^2)
B	Channel width (mm)
D_H	Mean hydraulic diameter (mm)
F	Friction factor.
H	Heat transfer coefficient (w/m^2-K)
I	Current (Amp)
K_f	Thermal conductivity of water (w/m-K)
L_{ch}	Channel length (mm)
L_0	Overall length (mm)
Nu	Average Nusselt number.
Ω	Ohm
Q	Heat input (w)
q”	Heat flux (w/m^2)
R	Resistance (Ω)
Re	Reynolds number
STD	Standard Deviation
T_m	Bulk mean temperature (c)
T_s	Interface surface temperature (c)
T_{out}	Surface average outlet temperature (c)
μ	Dynamic viscosity (N-m/s)

v	Mean velocity (m/s).
u*	Friction velocity (m/s)
V	Voltage (volt)
ΔP	Pressure drop (kPa)
Ω	Turbulent frequency
EXP	Experimental
CFD	Computational fluid dynamics
CSI	Coherence scanning interferometry
RMS	Root mean square
S_a	Mean of roughness height
S_q	RMS of roughness heights
S_z	Distance from peak to valley
k_s	Sand-grain roughness height
s_p	roughness slope
s_k	skewness
k_u	kurtosis
Sg	Sand-grain
Inclin	45° Inclined tracked surface
IWP	45° Inclined tracked surface with particles
Paral	Parallel tracked surface
PWP	Parallel tracked surface with particles
Smth	Smooth surface
SWP	Smooth surface with particle
Trans	Transverse tracked surface
TWP	Transverse tracked surface with particles

ρ_p	Particle density (number of particles/mm^2)
P_{ch}	Perimeter of channel (mm)

INTRODUCTION

This study centers on elucidating the influence of fluid flow and heat transfer characteristics on additive manufacturing (AM) surfaces, with a specific focus on scan orientation, as well as the position and distribution of spatter deposits. The primary aim is to establish the correlation between pertinent surface specifications and heat transfer phenomena.

Numerous Computational Fluid Dynamics (CFD) models for mini-channels were developed using Star CCM+, leveraging roughness data extracted from real AM surfaces. These surfaces exhibited diverse characteristics, including various wavy patterns and variations in scan orientations. Simplified geometric models, derived from measured surface topographies, were created to streamline computational processes. Pressure drops across mini-channels and Nusselt numbers (Nu) were determined and scrutinized for a range of surface topographies under both laminar and turbulent flow conditions.

In the experimental realm, AM surfaces with critical orientations (0°, 45°, and 90°) were fabricated, and an experimental setup was devised for a comprehensive investigation. Additionally, an Inconel part with a smooth surface was machined to serve as a baseline control condition. The research findings have been disseminated across multiple articles. Article-1 concentrated on numerical explorations, specifically employing simplified models of AM surfaces. The outcomes derived from Article-1 serve as the groundwork for subsequent experimental investigations. Article-2 delved into both CFD and experimental aspects, involving the fabrication of conventional aluminum channels with varied surface features. The findings underscored the substantial influence of deliberately designed surface features on heat transfer, although accompanied by a simultaneous increase in pressure drop.

Article-3, however, provides a more detailed examination, explicitly integrating both CFD and experimental investigations to explore the effects of AM scan orientation on heat transfer and fluid flow characteristics. This article comprehensively discusses the development of the experimental setup, encompassing AM sample preparation, sensor calibration, and uncertainty analysis. Moreover, it incorporates surface characterization and the utilization of a sand-grain roughness model for CFD simulations.

Collectively, these articles encapsulate the entire hypothesis and its validation through diverse investigative methods. Their comprehensive nature positions them as potential components of a doctoral dissertation, offering a holistic exploration of the subject matter.

ARTICLE 1

CFD and experimental investigation of AM surfaces with different build orientations

- Introduction and literature review

To adopt additive manufacturing (AM) for parts having complex cooling channels, an understanding of the relationship between the as-built surface finish and heat transfer need to be developed. In laser powder bed fusion (LPBF, one of the AM techniques), there are several build parameters (e.g., part orientation during the build) that affect the final part surface topography and hence heat transfer[1]. Many studies have been carried out to investigate the effect of AM process variables on the surface roughness. Delgado et al [2] investigated the effects of build orientation (the orientation of the normal to the built surface) on surface roughness and dimensional tolerance for LPBF parts. He showed that build angles extensively affect the roughness of AM parts compared to other process parameters. However, this study is limited to two build angles only. In addition to that Fox et al [3] investigated the effects of built orientation on surface roughness in more detail. They varied the orientation of the built surface to the Z-axis of the build chamber and position within the chamber. To understand the relationship between topographies of real AM surfaces and their effects on heat transfer, surfaces with different orientations were fabricated using LPBF and analyzed [3]. Other authors examined the effects of roughness of AM parts over heat transfer. Snyder et al [4], investigated the effects of build directions on surface roughness of AM parts and its further effects on heat transfer. For this study, the authors built test coupons with different build angles and developed an experimental set-up. From this study the author showed that build direction affects the heat transfer and pressure drop. Kandilkar et al [5] also studied the effect of surface roughness on pressure drop in microchannels. They suggested that the maximum profile peak height (Rp) and mean spacing of profile elements(RSm) correlates with the friction factor. In addition, some authors also quantified the performance of micro channels with rough surfaces by defining evaluation factors. In this regard, Yuan Xing et al equation (9) [6] have defined the thermal performance to evaluate the performance of circular rough micro-channels. However, these studies are limited to channel geometries only and a detailed investigation of the effects of built orientation (including the effects of spatter deposits with waviness) only on heat transfer and fluid flow have not been explored. In this study we focus on the orientation of weld tracks relative to the flow direction. This orientation can be realized in the AM parts built through adjustments to part orientation within the build chamber [1]. We also introduce a new performance factor that captures both the thermal and hydraulic characteristics of a channel which vary with the roughness and orientation of the AM channel relative to the flow direction. Simplified surfaces were developed for use in computational fluid dynamics(CFD)simulations and were based on measured surface topographies from prior work by the authors [1]. The simplifications were necessary to reduce the computational overhead and meshing issues associated with the modeling of real surfaces (i.e., surfaces with a wide range of spatial wavelengths present). Also, to better model AM surfaces, a unique approach to treating particles/spatter deposits (e.g., ejecta from the melt pool, partially melted powder particles, etc.) and their distribution has been adopted in this study. This framework was used to analyze heat transfer in terms of Nusselt number (Nu), pressure drop (ΔP) and the new performance factor (PF), while separating the effects of track orientation and particles/spatter. CFD simulations for different flow conditions (e.g., laminar, and turbulent) and quantities of heat supplied were performed using the commercial CFD software, STAR-CCM+. The CFD simulations also informed the design of the experimental set-up for the validation of computational results. The experimental set-up is designed to analyze the effects of having one AM surface of the four surfaces of a cooling channel. This allows variation in weld track orientation and the effect of the wide range and complexity of topographies, commonly seen on as-built AM surfaces, to be explored.

- Modeling of AM surfaces

In CFD, modeling of roughness using a ‘sand-grain’ model is a commonly known technique [7]. In this approach, the profile Root Mean Square (RMS) value of roughness (S_q) is used to estimate the roughness heights (Ks see figure 1 in [7]) of spherical grains and represents the roughness as spherical grains. However, this model assumes an isotropic, statistically stationary surface topography [8], which does not describe LPBF AM surfaces because of the large dynamic range of surface variability and presence of spatter deposits. Therefore, we developed an approach which can represent the variabilities (e.g., build orientations, distribution, and modeling of particles with different heights) of AM surfaces in a more realistic and specific way. Our approach is based on characterization of significant changes in topography with build orientation [9]. In this work, several characterization techniques (using focus variation microscope) were used to understand the effect of build orientations on surface features. Key characteristics of that work were the area scale [10], amplitude-wavelength content, and positions of partially-melted powder particles on the surface [1]. Therefore, AM surfaces were modeled by acquiring the roughness data from the LPBF AM surfaces with different build orientations. The methodology to model AM surfaces is depicted in Figure 2. To model the AM surfaces, mean (RMS) dimensions (wavelength = 30 µm and amplitude = 150 µm) of measured surfaces have been used. According to build orientations, three critical surface patterns (weld tracks parallel to the flow, weld tracks transverse to the flow, weld tracks inclined to the flow) are modeled and a smooth surface is modeled as a reference surface to compare the difference in terms of heat transfer and pressure drop. Figure 1. (a) Meshing of modeled AM surfaces with spatter deposits.(b)Grid independence analysis. 3 Surf. Topogr. Metrol. Prop. 11 (2023) 034001 K Mandloi et al In this approach, spatter was also modeled separately and then both surface area and hydraulic diameters were calculated.

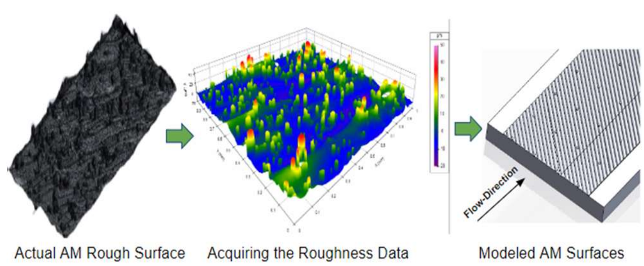

Fig.2 Modeling of AM surfaces.

- CFD results

CFD results for the characterization of heat transfer and fluid flow have been evaluated in terms of three parameters: the Nusselt number, Nu, the pressure drop ΔP, and the performance factor PF, and these are discussed in subsections.

- Characterization of heat transfer

The effects of AM surface roughness on heat transfer were studied using the average Nusselt number, *Nu,* given by [10]. Figures 5 and 6 show the CFD simulation results of Nu for various channels for both turbulent and laminar flow conditions, respectively. The simulations show that the Nu changes with build orientation, with transverse weld track orientation (Trans) performing the best for turbulent flow (Fig. 5 of Article:1). Figure 5 also shows that the effects of spatter deposits are minimal for transverse (Trans vs. TWP) and inclined (Inclin vs IWP) track surfaces while it has a greater impact on parallel (Paral vs. PWP) track and smooth (Smth vs SWP) surfaces. As the Reynolds number decreases and flow becomes laminar, the addition of tracks without particles reduces Nu (Smth vs. Paral vs. Trans vs. Inclin in Fig. 6 of Article:1), presumably due to stagnation of fluid in the valleys of the weld tracks. We also find that the addition of particles for laminar flow improves heat transfer for all the cases compared to the same geometry without particles. The particles create wakes that improve diffusion and mixing among adjacent fluid layers, increasing convective heat transfer.

Fig. 5 Nu for turbulent flow (Re =4000) conditions. See the nomenclature section for interpretation of the horizontal axis labels.

To highlight the role of surface texture more clearly, we look at the percent change in the Nusselt number by using the smooth surface without particles (Smth) as a reference. This is shown for the turbulent flow condition in Fig. 7 of Article:1 (notice the zero percent value change for Smth). The figure has been divided into two regions (light blue and light yellow) to highlight the surface feature dominating the heat transfer characteristics observed for turbulent flow (track orientation vs. particles).

Fig. 6 Nu for laminar flow (Re =1000) conditions. See the nomenclature section for interpretation of the horizontal axis labels.

We see that the presence of particles alone for turbulent flow causes an 18% increase in the Nusselt number for the smooth (SWP) surface (yellow region). The parallel tracks alone increase Nu by 4% but it jumps to 17% with the addition of particles (PWP). Thus, the addition of tracks parallel to the flow increases heat transfer, but the addition of particles increases heat transfer more significantly. The blue region highlights the channel behavior with the addition of tracks at an angle to the flow (transverse and inclined). In contrast, here we see a significant improvement caused by the track orientation alone (28% for Trans and 25% for Inclin). The addition of particles only slightly changes these numbers and interestingly slightly reduces heat transfer compared to what is seen with adding particles to smooth and parallel conditions. As seen in Fig. 6, when the mass flow rate is low and the flow becomes laminar, an AM surface texture has a quite different effect. With laminar flow, the addition of tracks, regardless of their orientation, consistently reduces the percentage change in Nu (Fig. 8 of Article:1) because, as discussed above, the stagnation of the fluid in the track valleys effectively reduces the hydraulic diameter of the channel. The addition of particles counters this with generation of wakes that improve diffusion and mixing among adjacent fluid layers, increasing Nu.

- Effect of surface area on heat transfer

As roughness increases, surface area also increases and according to classical literature, heat transfer is directly proportional to the surface area [5]. Figure 7 of Article:1 also shows the percentage increase in surface area with the addition of particles and tracks, with tracks having a larger percent area increase. If the surface area effect dominated, we would expect the percentage change in Nu to track the percentage change in surface area, and this is not the case. In the turbulent limit, the added mixing (or diffusion) within adjacent layers of fluid caused by the particles and tracks appears to play a more significant role than the increased surface area alone would predict. In the laminar flow limit, the percentage change in the Nusselt number likewise does not track with surface area, again suggesting the impact of the surface texture on the flow also dominates the heat transfer characteristics.

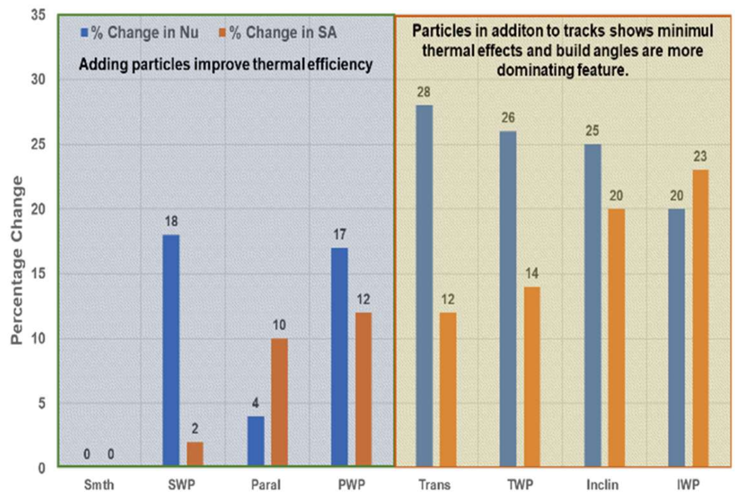

Fig.7 Effects of surface characteristics on percentage change in Nu and surface area for turbulent flow (Re =4000) conditions.

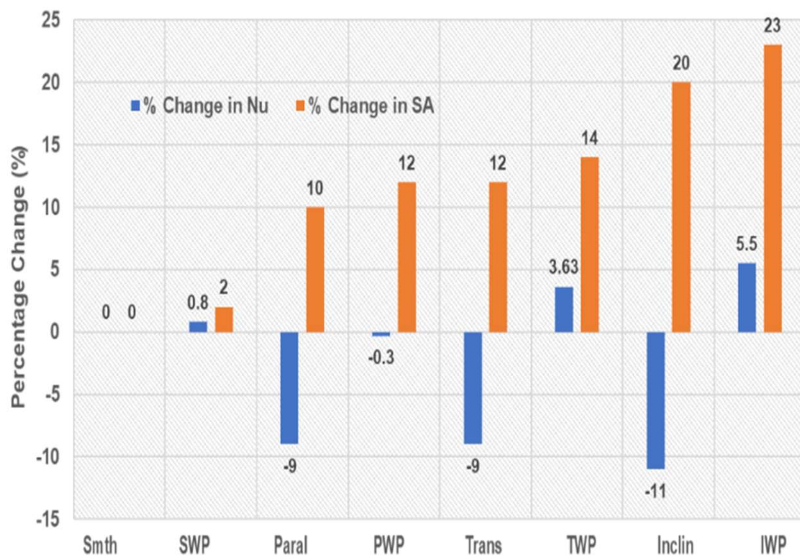

Fig.8 Effects of surface area on heat transfer for laminar flow (Re =1000) conditions.

- Characterization of fluid flow

To characterize the fluid flow due to the effects of roughness, results have been evaluated in terms of pressure drop and the friction factor. Here the pressure drop is defined as the difference between inlet and outlet surface average pressure.

For both turbulent and laminar flow, the pressure drop increases with added surface texture (Fig. 9 and 10 of Article:1), and the amount depends on the track orientation and particle details. While the trends are similar for turbulent and laminar flow, the highest pressure drop is at a different condition for turbulent (highest at TWP) vs laminar (highest at Inclin) flow, indicating the difference in diffusion among fluid layers in the two flow conditions is important.

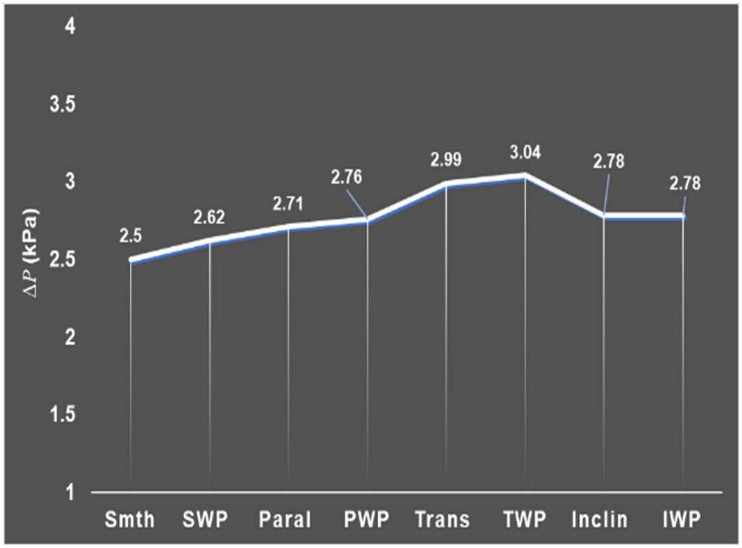

Fig. 9 Pressure drop for ***turbulent flow*** (Re =4000).

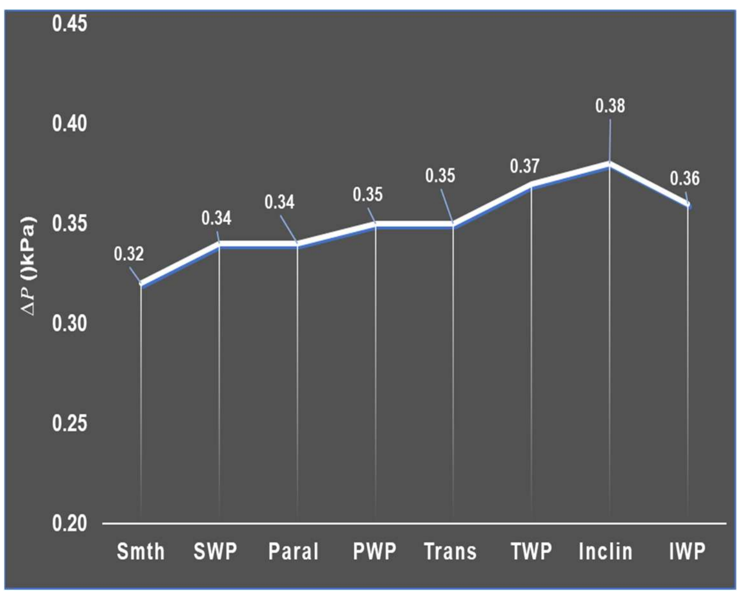

Fig.10 Pressure drop for ***laminar flow*** (Re =1000).

- Effect of surface area over pressure drop

From the literature [5], it has been suggested that roughness increases the interface (fluid-solid) surface area, and this causes higher resistance in the direction of fluid flow, thus leading to increased pressure drop. This would suggest pressure drop should track with increasing surface area which is a measure of increasing roughness. Again, this is not directly the case. For turbulent flow (Fig. 11 of Article:1) pressure drop tracks with increasing roughness (added surface area) but departs from this trend for the inclined tracks with and without particles. For laminar flow (Fig. 12 of Article:1) pressure drop tracks with roughness but clearly departs from the trend for the inclined with particle geometry. This suggests that the details of the fluid mixing given the texture geometry and the flow condition are important for predicting the pressure drop.

- Comparison of CFD and Experimental Results

Validation of CFD results has been done by performing various experiments with different inlet temperatures and heat inputs at different flow conditions with the smooth Inconel-625 channel. Both experimental and CFD results are discussed in the following subsections.

- Results with different inlet temperatures

For the preliminary investigation, experiments were performed without the heat supply but with different inlet temperatures (20°C, 25°C and 30°C) at laminar flow conditions. These results were then compared with CFD results (shown in Fig. 20 and 21 of Article:1).

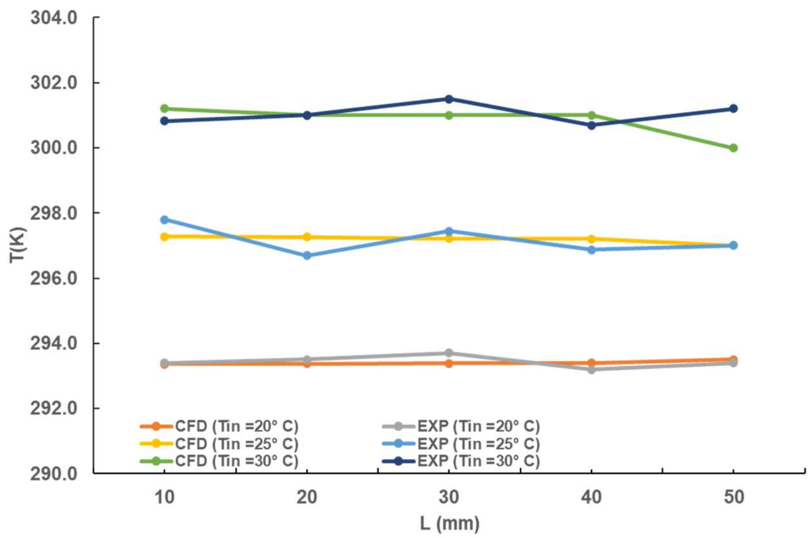

Fig. 20 Temperature along the length of the channel for different inlet temperatures (Re=1000).

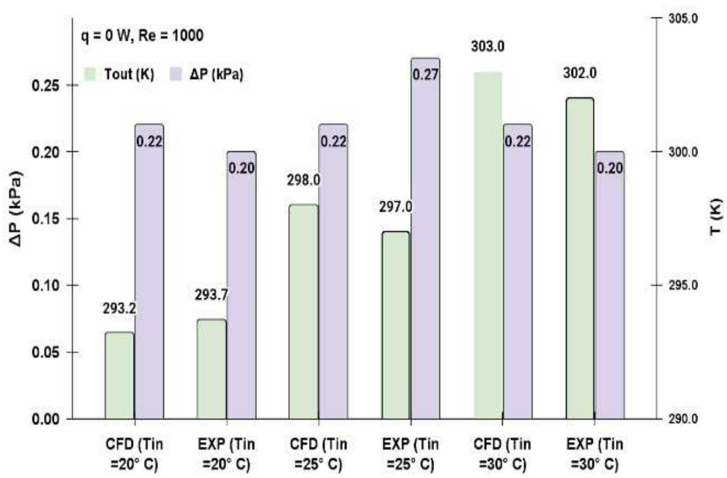

Fig. 21 Outlet temperatures and pressure drop for different inlet temperatures and no heat input (Re=1000).

In Fig. 20 of Article:1, temperatures are plotted along the length of the channel and in Fig.21 of Article:1, outlet temperature and pressure drop have been plotted for different inlet temperatures without heat input. We see from the experiment that the temperature repeatability is on the order of ±0.2°. From this limited sampling, we estimate the experimental pressure drop is 0.22 ± 0.02 kPa on average over these temperature conditions compared to the constant CFD pressure drop of 0.22 kPa for all temperatures.

- Results with constant heat supply

Experiments were performed with constant heat inputs and at different Reynolds numbers using smooth Inconel parts. In Fig. 22-25 of Article:1, experiments were performed at two different flow conditions (laminar and turbulent) and two heat inputs (q"=50.258W and 85.57W).

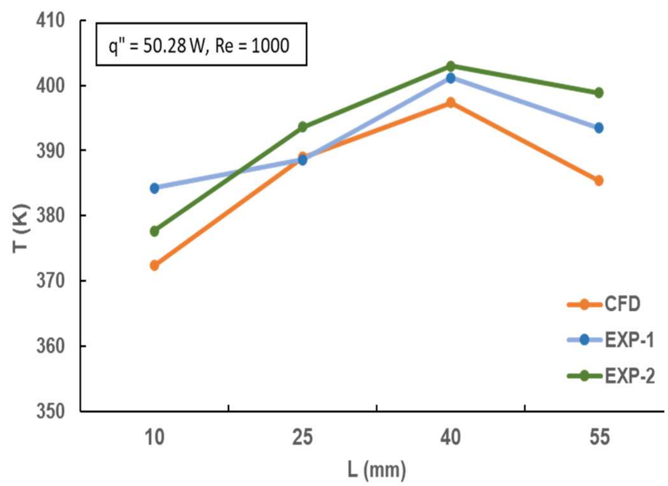

Fig. 22 Temperature along channel length for a constant heat input of 50.28 W (Re=1000).

For repeatability tests, the same experiments were performed at two different times. From Fig.22-25 It can be observed that CFD results are in good agreement with experimental results however the gap between CFD and experimental results increased compared to the results shown in Fig.20-21 of Article:1.

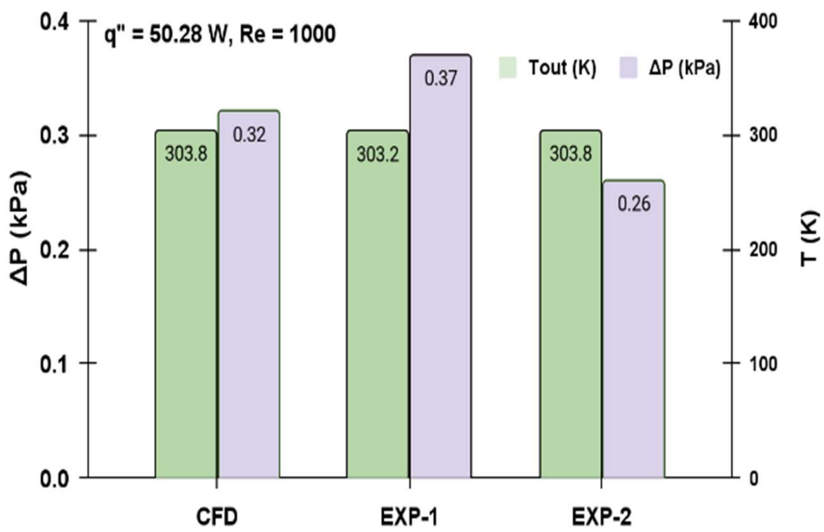

Fig. 23 Results for constant heat input (Re=1000).

The differences we observe between CFD, and experimental results is considered small in the CFD community [10-11], given the challenges of estimating many realistic experimental parameters for the CFD simulations and the many sources of uncertainty in the experiments.

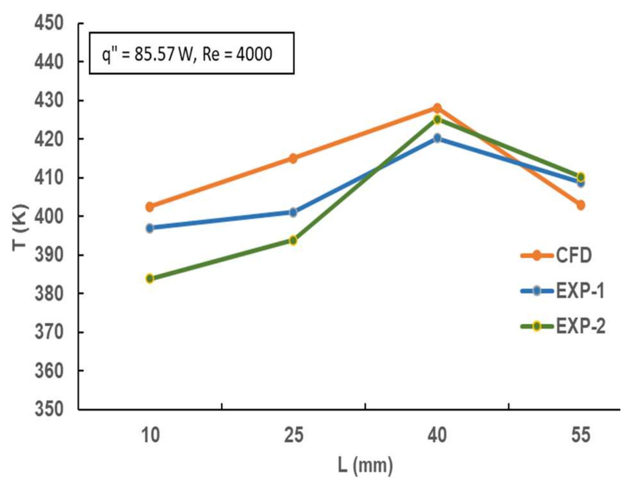

Fig. 24 Temperature along channel length for constant heat input (Re=4000).

A detailed uncertainty analysis is underway to establish a quantitative comparison. Preliminary estimates suggest the experimental uncertainty in the heat supply and the location of the temperature readings are significant and reasonably account for the observed differences with simulation.

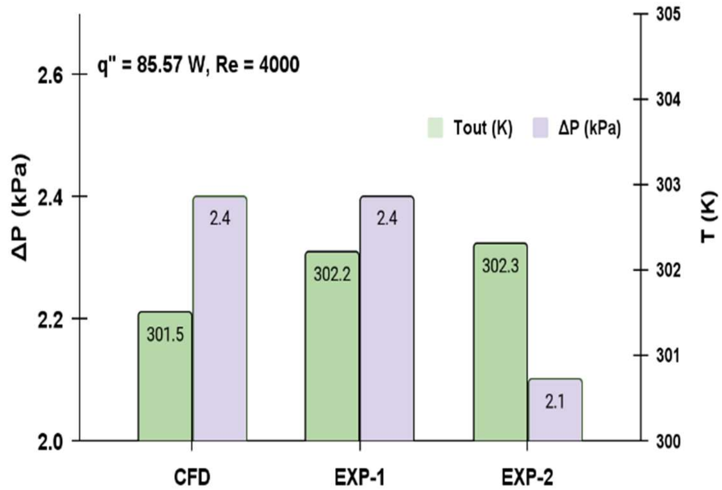

Fig.25 Results for constant heat input (Re=4000).

- Conclusion

Numerical investigation of fluid-flow and heat-transfer characteristics of various modeled AM surfaces were carried out for both laminar and turbulent flow conditions. For the validation of numerical (CFD) results, experiments were performed with smooth Inconel parts for different flow conditions and heat inputs. CFD results were in reasonable agreement with experimental observations, given large uncertainties in a few experimental parameters. A detailed uncertainty analysis is underway. The CFD results show that the track orientations of AM surfaces, and spatter deposits are the most dominating features of AM surfaces and the surface area impact on heat transfer is minimal in all the cases for both laminar and turbulent flow conditions. Under turbulent flow conditions, transverse track alignment shows highest efficiency in terms of the Nusselt number and adding particles improves heat transfer efficiency for smooth and parallel tracked surfaces in the turbulent limit. However, when the flow becomes laminar, opposite behavior of modeled AM surfaces was observed and surfaces show downside effects in terms of Nu . The next experimental steps include estimating uncertainty contributions and measurement of surface roughness characteristics with actual non-smooth AM surfaces are underway.

ARTICLE 1: REFERENCE LIST

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ARTICLE 2

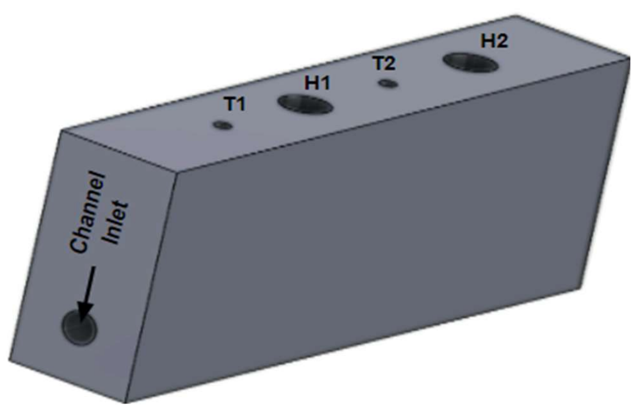
Numerical and experimental investigation of heat-transfer and fluid-flow characteristics of Al-6061 mini channels with a structured vs. smooth internal surface.

- Introduction and literature review

Cooling channels play a vital role in the cooling process of various industrial processes and there is always an interest in improving their performance. Several extensive research studies have been carried out to improve the cooling performance of the mini/micro-channel heat-exchangers and many advances have been realized [1]. However, there are research gaps that have not been explored yet such as the optimization of the internal surface geometries. In this regard, Kandilkar et al. [2] determined that surface roughness affects pressure drop in microchannels. They correlated the friction factor with the mean spacing of profile features (R_{Sm}) and the maximum profile peak height (R_p). In addition, Fox et al. [4] explored the effects of build angles on surface topography for additively manufactured (AM) cooling channels. In that study to explore the relationship between surface topographies and heat transfer, surfaces were built with AM track orientations at angles of 165° to 45° in increments of 15° to the fluid flow direction (referred to as the scan orientation). Also, Mandloi et al. [5-6] extended the work and carried out a computational fluid dynamics (CFD) analysis of AM surfaces with different scan orientations. They investigated the effects of the AM surface topography with different scan orientations on Nusselt number (Nu) and pressure drop. They further investigated the performance of each AM surface by defining a performance factor which is a combination of Nu and the friction factor. From that study they found that the AM surface performance varies with the flow condition, and it is not always the case that rough surfaces increase heat transfer. In addition, they found that the change in the surface area due to the surface texture had a minimal effect on the thermal performance and the impact of the surface geometry, scan orientation and particle distribution, on the flow were the dominant influencers. They showed that thermal performance can be increased by optimizing the scan orientation. In addition, Jacob et al.[1] investigated the effects of build angles of AM surfaces on heat transfer. To investigate such effects, they fabricated test coupons with different scan orientations. The experiments showed that thermal performance of AM cooling channels can be improved by optimizing the scan orientations. Liu et al. [7] fabricated internal cooling channels via both selective laser melting and conventional drilling. They performed various experiments and concluded that the cooling performance of the SLM-fabricated cooling channels was poorer than that of the drilled channels due to the presence of spatter deposits and a loose layer on the SLM-fabricated surface. However, this study was limited in the size scales investigated. Wang et al. [8] carried out 2-D CFD simulations of converging-diverging channels with symmetric internal wavy surfaces. They analyzed the effects of the wavy surfaces on the skin friction coefficient and Nu for different Reynolds (Re) and Prandtl Numbers (*Pr*). They concluded that the heat transfer was not enhanced significantly with a small amplitude-to-wavelength ratio and a significant amplitude-to-wavelength ratio was required for a significant impact on the heat transfer. This study was limited to 2-D and a more general conclusion requires a thorough 3-D investigation. In this paper, we report on 3-D CFD and experimental investigations of Al-6061 channels with different internal surface geometries. One channel has a smooth internal surface and the other has artificial waviness in the form of internal threads. Here, the screw thread serves as an internal waviness (structured) texture similar to the AM weld tracked surfaces with the 90° scan orientation to the flow in previous studies [5-6], without the complexity of spatter particles. Both CFD and experimental results show that the channel with internal threads (the internal waviness) has a higher heat transfer and higher cooling efficiency in terms of Nusselt Number for various flow conditions. This study complements the research underway by the same authors on heat transfer and fluid flow properties of AM surfaces with different scan orientations [5-6,10].

- Fabrication of Al Channels

The methodology to model and fabricate structured internal surfaces for this study is inspired from the three dimensional tessellated surfaces shown in Fig. 8 of reference 9. The tessellated surface texture is similar to internal threads. Our goal was to investigate the effects of such surfaces for heat transfer. Therefore, we modeled and fabricated two separate channels of Al-6061, one with a smooth internal surface and another with internal threads. For the smooth Al channel, a 4 mm hole was created by drilling and sanding (using 1200 grit sandpaper), resulting in a root-mean-square areal topography (RMS) of 1.25 μm as measured with an interference microscope Zygo ZeGage™ Pro HR (using a default 3x3 low pass denoising filter). The abrasive processing results in a low amplitude axial lay. CFD simulation geometries with pictures of the experimental channels are shown in Fig. 1(a-c). The structured channel was fabricated using a M4x0.7 tap to generate internal threads. The same dimensions were used for the CFD simulations. To accommodate sensors such as pressure measuring lines, temperature sensors, and cylindrical heaters, extra holes were created and also considered for the CFD models (see Fig. 1 of Article:2).



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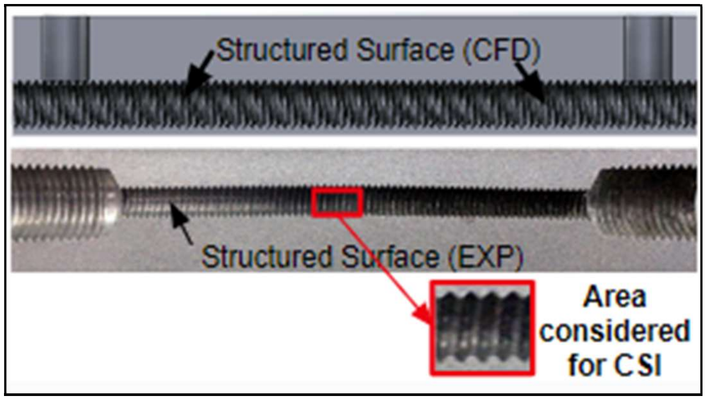

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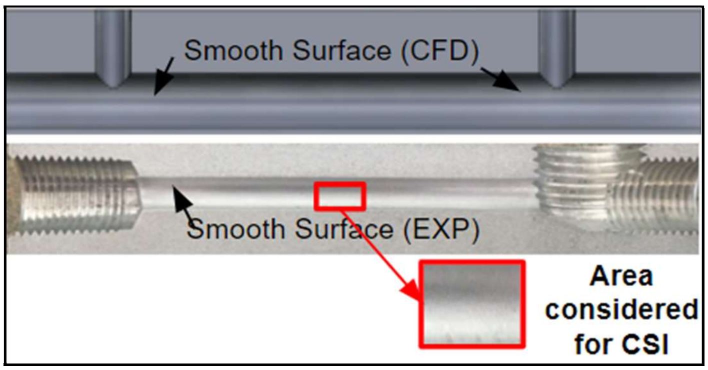
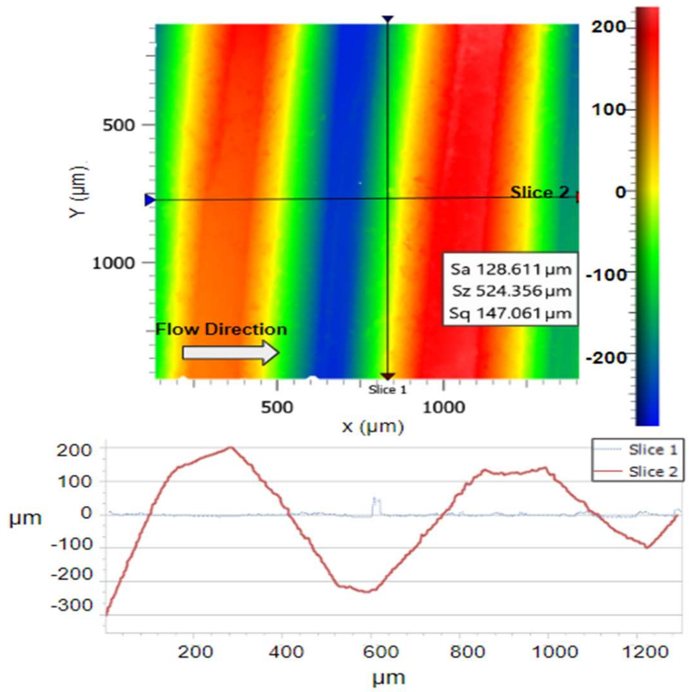


(c)

Fig.1 (a) CAD model of Al-6061 Channel, (b)CAD model (top) and half sectioned fabricated Al part with internal threads (bottom), (c) CAD model and half sectioned fabricated Al part (Smooth surface)

For the areal measurements, similar AL channels were fabricated, and half sections were made as shown in Fig.1(b-c). The surface characterization of the internal surface of channels was done using a Zygo ZeGage™ Pro HR coherence scanning interferometer (CSI) with a 5.5X objective (NA: 0.15). Measurements were taken for both smooth and the threaded channels and area measured are shown in Fig.1(b-c) of Article:2. The cylindrical form was removed, and surface profiles were vertically and horizontally extracted as shown in Fig.2 (a-b). Also, plots below the surface represent topographic height in x and y directions.



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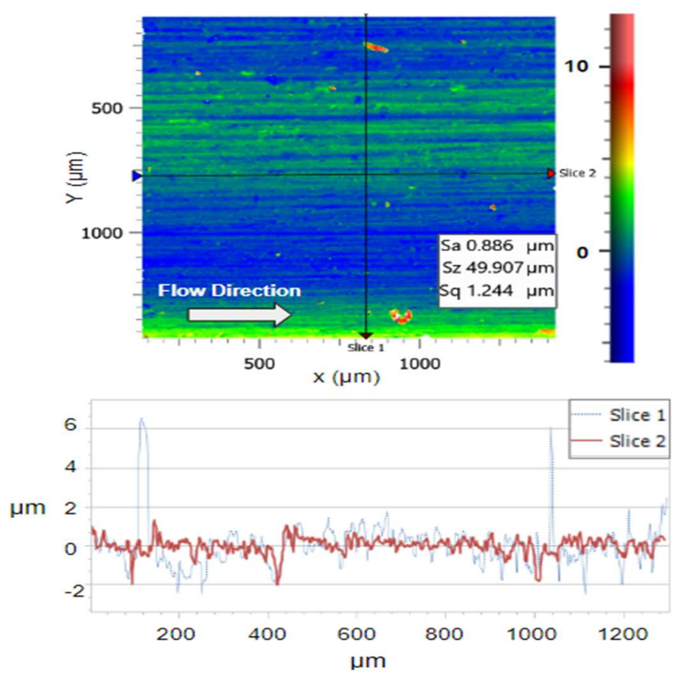
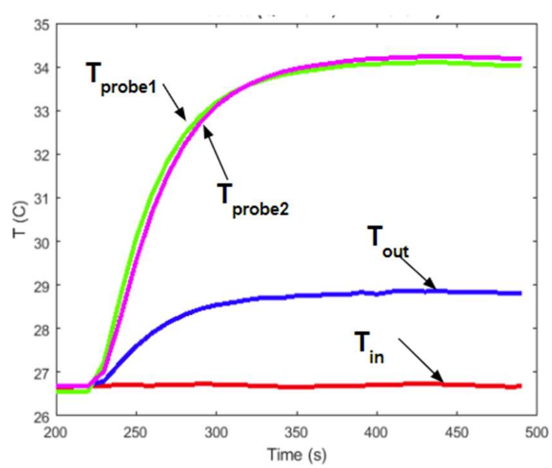


(b)

Fig.2 (a) CSI measurement of half sectioned fabricated threaded Al part (Area: 1.5 X 1.5 mm^2), (b) CSI measurement of half sectioned fabricated smooth Al part (Area: 1.5 X 1.5 mm^2).

- Results

To validate the numerical results, experiments were carried out for the range of Reynolds number (ranging from laminar to turbulent flow conditions) and with constant heat input. Temperature at various locations (such as along the channel length, at inlet and outlet) are plotted in Fig. 13 (a-c) of Article:2 for the channel with structured internal surfaces. All these above mentioned plots represent variation in temperature values from the start of experiments and until the system reaches steady state conditions. Note that the T_{Probe1} and T_{Probe2} are always higher for a smooth channel compared to the structured (rough) one for the same mass flow conditions and heat input. These two temperatures represent the wall temperature at fluid-solid interface and therefore, the bulk mean temperature (T_m) of a smooth channel will also be higher [14] and that too will lead to the higher values of *Nu* for the channel with structured internal surfaces (Eq.1, Fig. 15 of Article:2). The reason for lower wall temperature at fluid-solid interface and so the lower T_m for structured channel is due to increase in thermal diffusion caused by formation of wakes and flow circulation due to roughness (Fig. 8 of Article 2). Note also, that as the mass flow increases, outlet temperatures for all the cases (Fig. 13 (a-c) - Fig. 15 (a-b) of Article 2) decrease due to conservation of energy.



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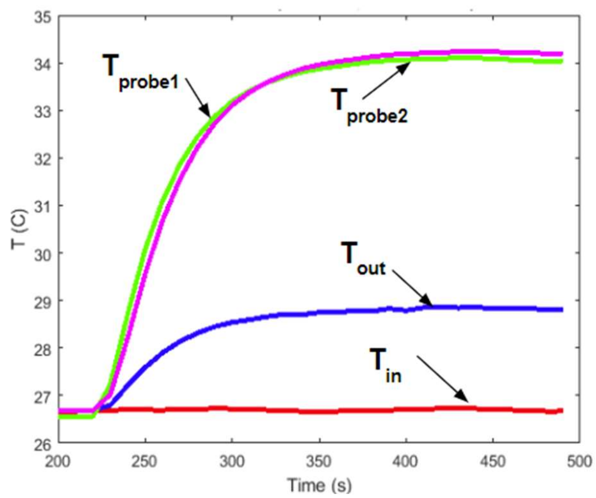

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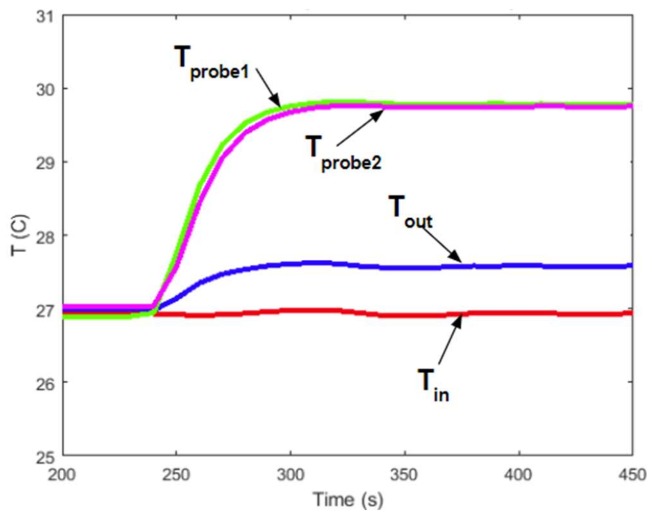

(*C*)

Fig. 14 (a) Temperature at different locations for a structured channel (Re = 1000, Q =26 W), (b) Temperature at different locations for a structured channel (Re = 2500, Q =26 W), (c) Temperature at different locations for a structured channel (Re = 5000, Q =26 W).

- Comparison of Results

For the comparison of CFD and experimental findings, results were plotted in terms of Nu, Pressure drop (ΔP), Friction factor (f) and temperatures at various locations. From Fig. 15 of Article:2, it can be seen that both experimental and CFD results are in good agreement (< 5% difference) with each other and follow the same trend. It can also be noted that the Nu of structured channel increased significantly as Reynolds number increases and both CFD and experimental results agree on this finding.

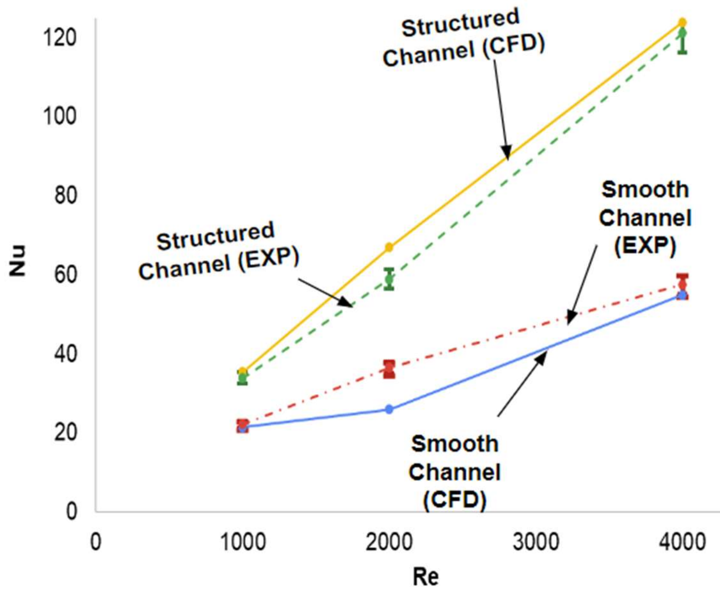

Fig. 15 Nu for different Res (Q =26 W).

However, it is also interesting to note that pressure drop (ΔP) and friction factor (f) of the structured channel also increase drastically (Fig. 15-16 of Article:2) and follow the same trend as of Nu. Therefore, these higher values of ΔP and f may lead to requiring more pumping power depending upon applications. Based on equations 5-7, Fig. 15-16 of Article:2 and Table-2 depict the uncertainties associated with various parameters for different flow conditions for a structured channel. Also, from Fig. 18, it can be seen that both CFD and experimental values of outlet temperature for different Reynolds numbers are in good agreement and justify the previous statement regarding the decrease in Tout with increase in Reynolds number. Also, Figs 18 (a) - 18 (c) of Article:2 depict the temperature along the length of the channel for different flow conditions and with constant heat input (26 W). These plots also verify the statement made in Section 5.2 regarding the importance of wall temperature and its influence on convective heat transfer.

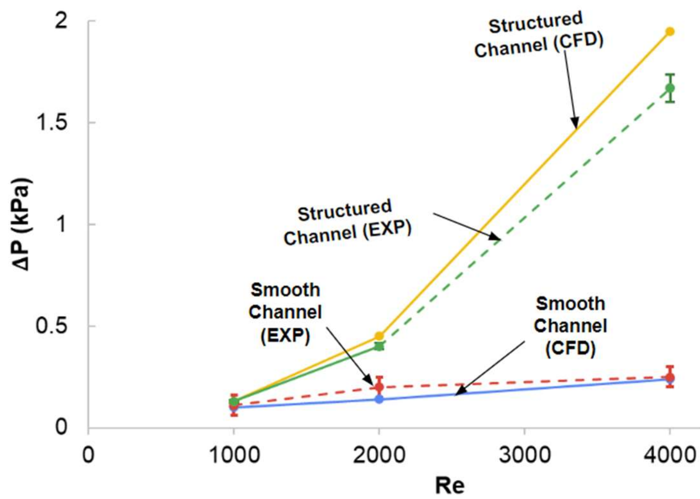

Fig. 16 Pressure Drop (*ΔP)* for different *Res* (Q =26 W).

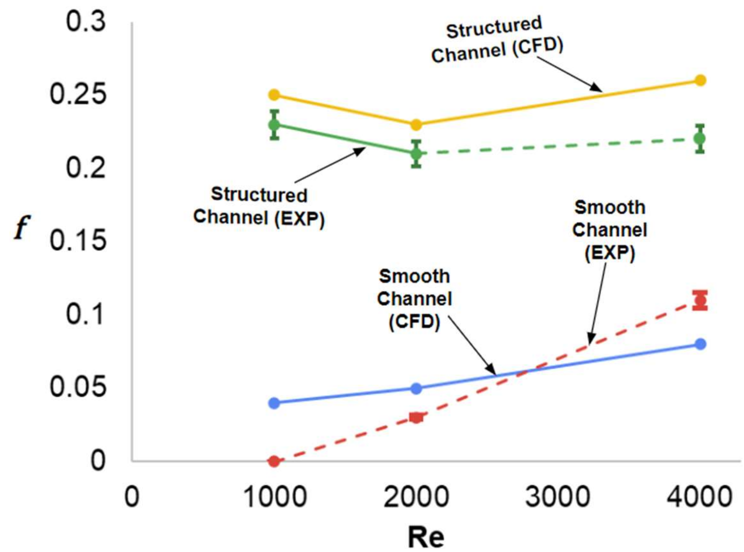

Fig. 17 Friction factor (f) for different *Res* (Q =26 W).

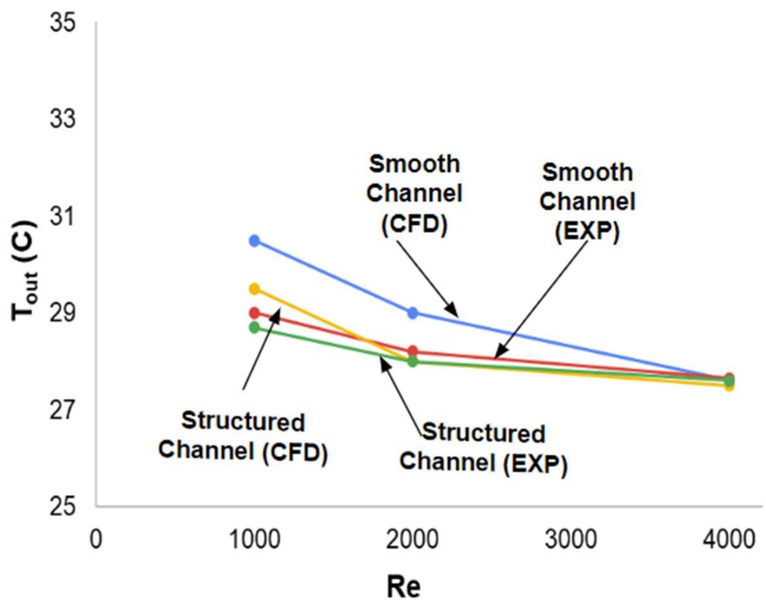

Fig. 18 Outlet Temperature (T_{out}) for different *Res* (Q =26 W).

- Conclusion

Both experimental and numerical (CFD) investigations have been carried out to analyze the variation in heat transfer and fluid flow characteristics for both smooth and structured Aluminum channels. Both CFD and experimental results show that Nu and ΔP are significantly affected by structured surfaces and enhanced the convective heat transfer. It was also found that as *Re* increases, it increases the Nu with a significant amount and so the heat transfer. Both numerical and experimental results are found to be in good agreement. For the precise analysis of experimental results, uncertainty analysis was also carried out and the parameter values were found to be with less than ±5 percent of uncertainty. Results from this study also helped analyzing the extended work of same authors on AM surfaces with different scan orientations.

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ARTICLE 3

Experimental Investigation of thermal and fluid-flow performance of Inconel-625 AM surfaces with different scan orientations and verification through CFD modeling using sand-grain roughness model.

- Introduction and literature review

The utilization of additive manufacturing (AM) is experiencing significant growth, especially in applications requiring intricate cooling systems, such as those found in gas-turbine engines. Investigating the correlation between the surface topography of AM surfaces with different scan orientations and their impact on heat transfer is essential. Laser powder bed fusion (LPBF) stands out as one of the most prevalent AM techniques, utilizing a laser beam to melt successive layers of metal powder, forming the desired part.

In LPBF, build parameters, including laser scanning speed, material type, laser power, and part orientation, profoundly influence the surface topography of the final product [1]. Numerous researchers, such as Fox et al. [2] fabricated AM surfaces using LPBF. They varied the scan orientation of the surfaces to the Z-axis of the build chamber and position within the chamber and then analyzed the relationship between build orientation and surface. In addition, Delgado et al. [3], have explored the effects of scan orientations on AM surface topography. However, this research has been limited to specific scan orientations, overlooking a comprehensive investigation into the effects of various build orientations on heat transfer and fluid flow characteristics.

Several studies have delved into the effects of AM surface roughness on heat transfer and fluid flow, often focusing on channel geometries. Kandlikar et al. [5], Snyder et al. [4], and others quantified the performance of AM surfaces in terms of heat transfer and friction factor. However, a detailed examination of the effects of scan orientation, including considerations like overlapping weld-tracked orientation, ejecta from the melt pool, partially melted powder particles, and waviness, has been lacking.

Building on the work of Kuldeep et al. [1,7], which involved physically modeling AM surfaces, this current study is an extension incorporating experimental investigations. An exchangeable experimental setup was innovatively designed and developed to quantify the effects of scan orientation on heat transfer and pressure drop under various flow conditions, providing validation for CFD results.

Examining the long history of studying surface topography effects on heat transfer, Moody's chart, based on friction factor calculations, has been a widely used resource since 1994. However, these charts were based on monolayers of sand grains, which do not accurately represent the complexities of actual AM surfaces[11-12]. To address this, an equivalent sand-grain roughness model using parameters like S_q (average roughness) was recommended[13-16].

In this study, the sand-grain roughness model utilizes Rz as a parameter to define the sand-grain roughness size. This modeling approach is an extension of the authors' previous work, where AM surfaces with three critical scan orientations (0°, 45°, and 90°) were fabricated. Additionally, an Inconel part with a smooth surface (with S_q = 5.03 µm, Filter: low pass 100 µm FFT, form removal: cylinder, Area: 4X20 mm and objective: 20X) was machined to serve as a baseline control condition. A noteworthy innovation in this research is the design and development of an exchangeable experimental setup, enabling the quantification of scan orientation effects on heat transfer and pressure drop for various flow conditions, with the added benefit of validating CFD results. The analysis of AM surface roughness effects on heat transfer and fluid flow is conducted in terms of Nusselt Number, pressure drop, and friction factor.

- Fabrication of AM surfaces

AM surfaces with three different scan orientations (0°, 45° and 90°) were fabricated at NIST facility using Laser powder bed fusion (LPBF) process. on an EOS M290 machine using nominal parameters recommended by the machine manufacturer and summarized in Table 1 (from "Surface topography process signatures in nickel superalloy 625 additive manufacturing". For reproducibility and repeatability tests, three samples for each orientation were printed.

Table: 1 Nominal build conditions [24]

Laser power	285 W
Velocity	960 mm/s
Powder	EOS IN625; D50 = 27.1 μm
Layer thickness	40 μm nominal
Step over	110 μm
Stripe width	10 mm

Fig. 1 Fabricated AM parts with different scan orientations.

- Fabrication of resin part using SLA

In order to insulate against heat loss to the environment from the side and upper walls, half of the experimental setup section was produced using Stereolithography (SLA) with Formlab high-temperature resin. This involved utilizing a Formlab SLA 3-D printer to print the components. Figure 2 of article:3 illustrates the entire process, from printing through post-wash steps to the final product.

Fig. 2 3-D printing of resin part through SLA technique.

- Surface roughness characterization

To explore the roughness characteristics of AM surfaces with different orientations, surface roughness characterization was carried out using Zygo ZeGage™ Pro HR coherence scanning interferometer (CSI) with a 5.5X objective (NA: 0.15). The areal measurements were taken from the mid-section of 20X4 mm (shown in Fig. 3) of each AM surface. For the areal measurement, stitching using the adaptive adjust option was used and based on area (20X4 mm) to be measured, a stitch (with 20% overlapping) of 2 rows and 9 columns was configured and the nominal scan length used was 500 µm with scan origin from top (upper limit). To analyze surface characteristics of these surfaces, low pass Fourier filter (100 um) was used, and cylindrical form was removed. and Fig. 4 of Article:3 represents the roughness heights of different surfaces in x and y directions.

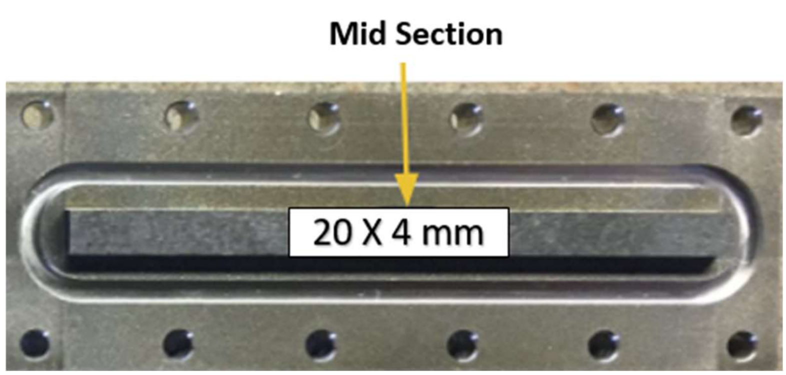


Fig. 3 Area considered for CSI measurements

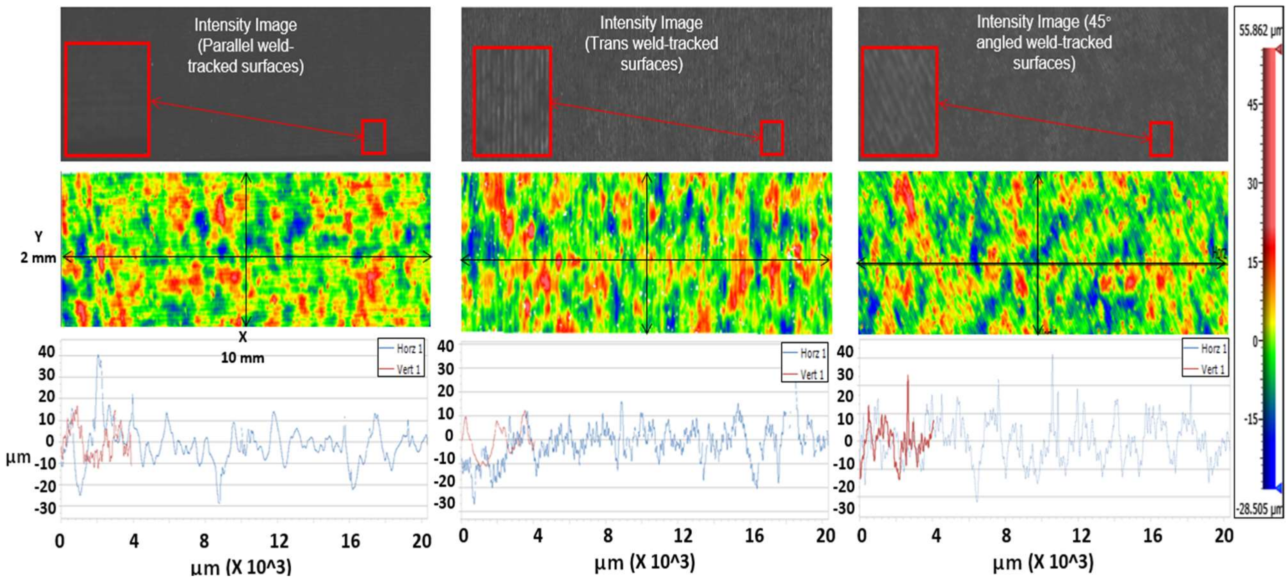
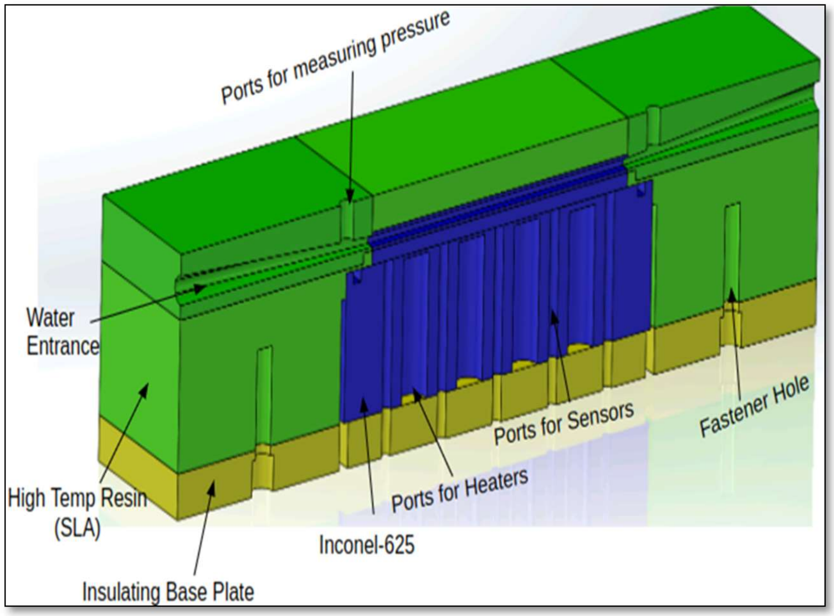


Fig. 4 Areal measurement of AM (0º, 90º and 45º) surfaces (Filter: 100 µm low pass, Form removal: Cylinder).

- Experimental setup

To confine the effects of AM surfaces on heat-transfer and flow characteristics, the experimental setup was designed in a manner where the side and upper walls were assumed to be acting like insulating boundaries. The setup was designed and fabricated such that it can facilitate the exchange of AM parts for different experiments. Therefore, it was developed in two halves and then assembled (Fig. 5 of Article:3). One half of this setup is made of Formlab high-temp carbon resin [19] and was fabricated using stereolithography (SLA) and the other half of this setup is an exchangeable one and it is made of Inconel-625 using LPBF technique. The selection of fabrication techniques was based on material type and the complexity of the set-up. The entire assembly of the experimental setup has been discussed in section 3.6.



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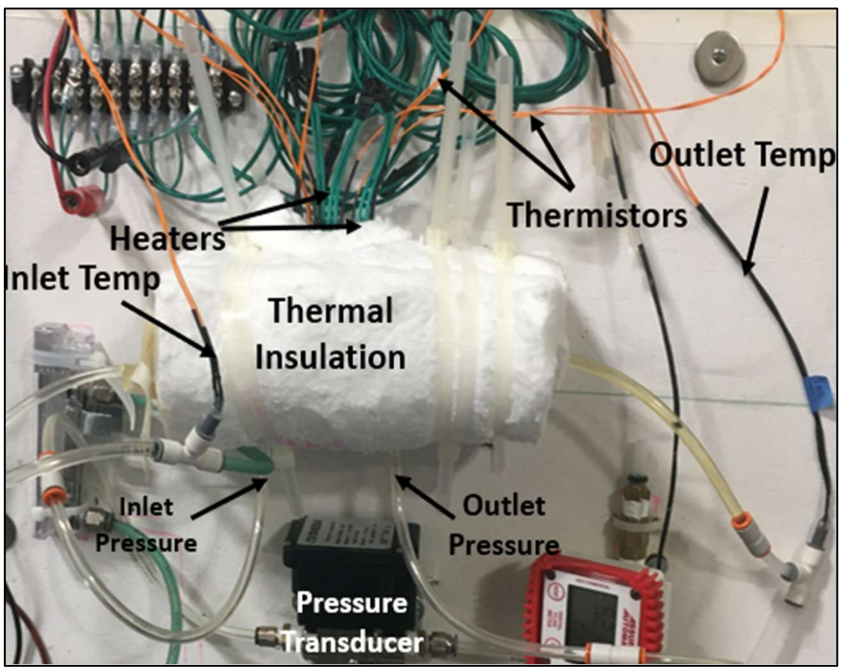


(b)

Fig. 5 (a) Half-sectioned CAD model of set-up, (b) A real experimental set-up.

- Results and discussion

For examining the thermal and fluid-flow characteristics of AM surfaces, results were analyzed in terms of Nusselt Number (*Nu*), pressure drop (ΔP), friction factor (*f*) and outlet temperature (T_{out}). Below equations are used for determining these parameters [22].

$$Nu = \frac{q^{"} .\, \overline{D}_H}{K_f \,.\, (T_s - T_m)}, \qquad (11)$$

$$\Delta P = P_{in} - P_{out}, \qquad (12)$$

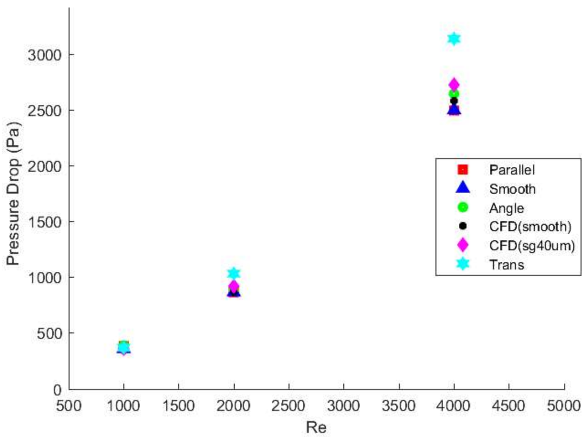
and

$$f = \frac{2 \,.\, \Delta P \,.\, \overline{D}_H}{\rho \,.\, L \,.\, v^2}. \qquad (13)$$

Figures 17-20 present results in terms of ΔP, *f*, *Nu*, and T_{out} for various AM surfaces across different Reynolds numbers, while Figure 21 illustrates the temperature profile along the length of the channels. An observation from Figures 17-20 reveals that the channel with a transversely tracked surface (90° scan orientation) exhibits the highest convective heat transfer (based on *Nu*), accompanied by elevated pressure drop and friction factor. This observation is substantiated by both Computational Fluid Dynamics (CFD) and experimental results.

Conversely, a channel with a 45° oriented AM surface demonstrates optimal values (lower than transverse tracked surface and higher than smooth one) for *Nu* and ΔP across different flow conditions. However, a channel with a 0° scan-oriented surface performs inadequately for all flow conditions, occasionally even worse than the smooth surface. Hence, it is crucial to emphasize that not all AM surfaces can deliver a high rate of heat transfer; rather, it depends significantly on the scan orientation and flow conditions.

Furthermore, these results indicate that the surface with the highest Nu value (90° scan orientation) entails a higher pressure drop, potentially necessitating increased pumping power, contingent on the application scale. Additionally, it was observed that the sand grain model tends to substantially overestimate *Nu* for lower Reynolds numbers.



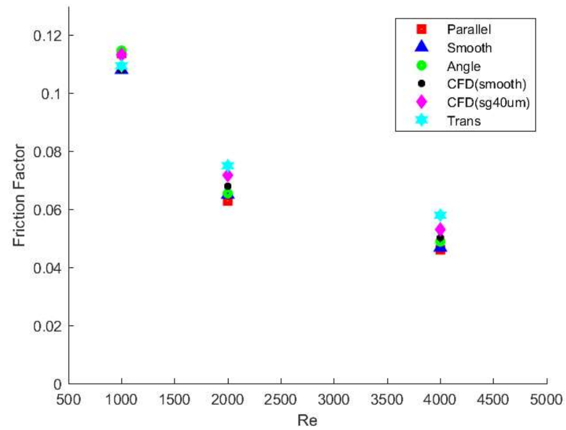
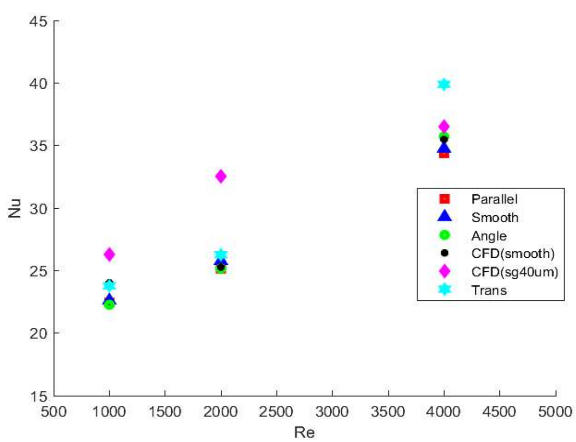


Fig. 17 Pressure drop for different Reynolds Number Fig. 18 Friction factor different Reynolds Number



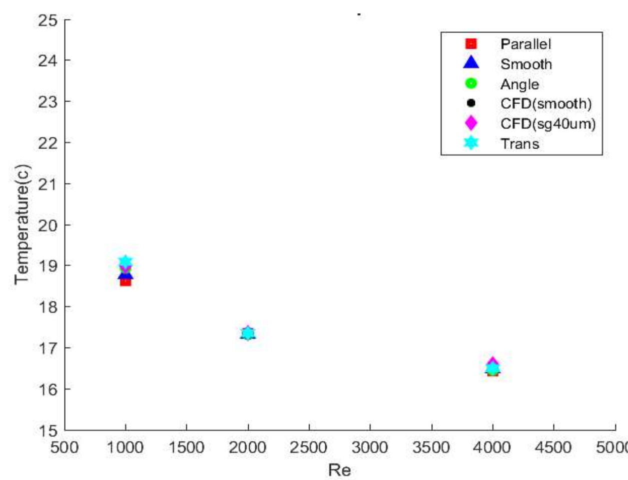
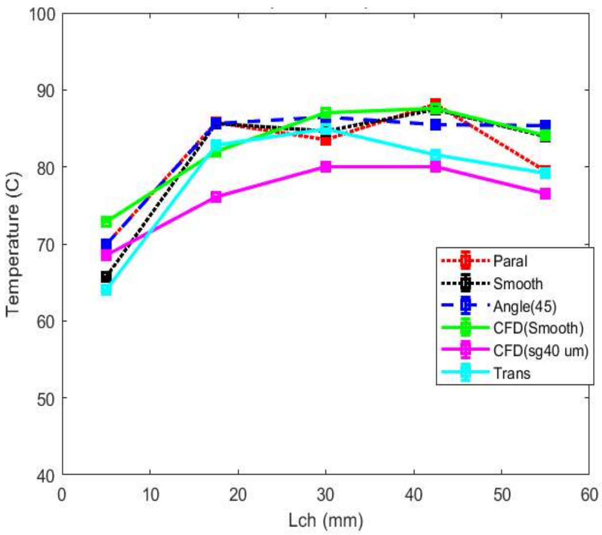


Fig. 19 Nusselt Number for different Reynolds Number Fig. 20 Outlet temperature for different Reynolds Number



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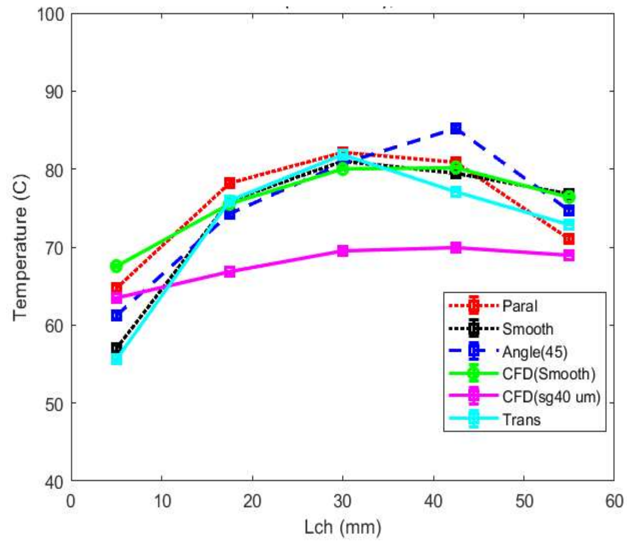

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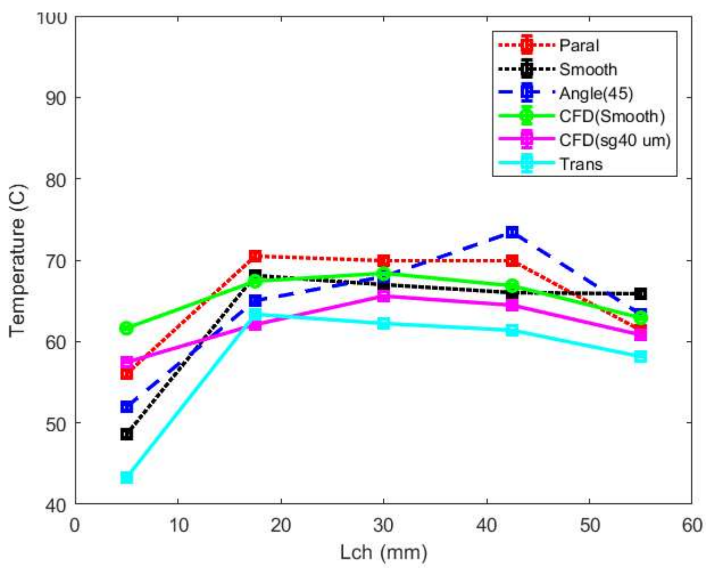

(c)

Fig. 21 (a) Temperature along channel length for Re =1000, (b) Temperature along channel length for Re =2000, (c) Temperature along channel length for Re =4000

- Conclusion

To investigate the correlation between the as-built surface finish of additive manufacturing (AM) surfaces with different scan orientations and their subsequent effects on heat transfer and fluid flow, comprehensive computational fluid dynamics (CFD) and experimental studies were undertaken. In the realm of CFD simulations, a sand-grain roughness model was implemented. Conversely, for the experimental phase, a novel approach was devised, leading to the creation of an adaptable experimental setup. In pursuit of result reproducibility, experiments were iteratively conducted (three times) for each AM part at various intervals. An in-depth Type-A uncertainty analysis was then performed based on the experimental data.

Under nominal build conditions, encompassing factors such as laser power, scanning speed, layer thickness, and powder specifications, the findings indicate that track orientations on AM surfaces emerge as the most influential features. Notably, the impact of surface area on heat transfer is minimal for both laminar and turbulent flow conditions. In turbulent flow scenarios, a transverse track alignment demonstrates the highest efficiency in terms of the Nusselt number (Nu). However, as the flow transitions to laminar, many surfaces yield similar Nu values. Specifically, the surface with a 90° orientation, despite achieving the highest Nu under turbulent conditions, exhibits suboptimal performance in terms of pressure drop (ΔP). In contrast, the 45° oriented surface, while having a lower Nu and ΔP compared to the 90° tracked surface, outperforms the 0° tracked surfaces. Both CFD and experimental results align to support these conclusions. Consequently, it is crucial to emphasize that not all AM surfaces possess the capability for high heat transfer rates, and this capability is notably contingent on scan orientation and prevailing flow conditions.

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Below table depicts the overview and findings of each article.

Articles	Overview	Findings
Article-1	• Focused on numerical investigations, specifically utilizing simplified models of AM surfaces. • Modeled AM surfaces with different scan orientations based on surface characterization. • Conducted several CFD simulations to optimize the channel geometry. • The findings from Article-1 lay the foundation for subsequent experimental investigations.	• The surface with a 90° scan orientation demonstrated the highest efficiency in terms of *Nu* under turbulent flow conditions. • Conversely, under laminar flow conditions, the modeled AM surfaces exhibited a contrasting behavior, displaying adverse effects on *Nu*. • The dominating features of AM surfaces, including track orientations and spatter deposits, had the most significant influence, while the impact of surface area on heat transfer was minimal in both laminar and turbulent flow conditions.
Article-2	• To further investigate the effects of scan orientations within a circular geometry, an aluminum channel with	• Both Computational Fluid Dynamics (CFD) and experimental findings indicate a substantial impact of structured

	varied surface features (representing a 90° scan orientation) underwent CFD analysis. • To compare CFD results, a smooth aluminum channel was also modeled, and CFD simulations were executed. • The experimental setup was devised and validated based on the CFD results. • The findings underscored the substantial impact of deliberately designed surface features on heat transfer, accompanied by a simultaneous increase in pressure drop.	surfaces (> 3X) on Nu and ΔP, leading to enhanced convective heat transfer. • The study also revealed that as Reynolds number (Re) increases, there is a notable rise in Nu and subsequent improvement in heat transfer. • The results from both numerical simulations and practical experiments are observed to be in a good agreement.
Article-3	• Offers a more in-depth exploration, explicitly combining both CFD and experimental analyses to investigate the impacts of AM build orientation on heat	• Under turbulent flow conditions, the transverse track (90°) alignment demonstrates optimal efficiency concerning the Nusselt number (Nu). • However, as the flow transitions

	transfer and fluid flow characteristics. • This article thoroughly explores the creation of the experimental setup, covering aspects such as AM sample preparation, sensor calibration, and uncertainty analysis. • Additionally, it incorporates surface characterization and the application of a sand-grain roughness model for CFD simulations.	into a laminar state, numerous surfaces exhibit similar Nu values. Specifically, the surface with a 90° orientation, despite achieving the highest Nu under turbulent conditions, demonstrates suboptimal performance in terms of pressure drop (ΔP). • In contrast, the 45° oriented surface, although having a lower Nu and ΔP compared to the 90° tracked surface, surpasses the 0° tracked surfaces in performance. • Both Computational Fluid Dynamics (CFD) and experimental results substantiate these findings. Consequently, it is imperative to underscore that not all Additive Manufacturing (AM) surfaces possess the same characteristics Consequently, it is crucial to emphasize that not all AM surfaces possess the

		capability for high heat transfer rates, and this capability is notably contingent on scan orientation and prevailing flow conditions.

OVERALL CONCLUSION

In this investigation, both numerical simulations and experimental assessments were undertaken to examine the relationship between characteristics of additive manufacturing (AM) surface roughness (such as scan orientations, spatter deposit density and size, amplitudes/wavelengths, etc.) and their consequential impact on heat transfer and pressure drop across cooling channels. For CFD simulations, surface roughness characterizations of various AM surfaces were performed. Based on these roughness characteristics, simplified versions of the AM surfaces were modeled. Additionally, an analogy was drawn between sand-grain roughness characteristics and transversely tracked AM surfaces (90°). Consequently, a sand-grain roughness model was employed to further analyze the resultant effects of surface roughness. On the experimental front, AM surfaces with three critical orientations (0°, 45°, and 90°) were fabricated, and an adaptable experimental setup was developed for comprehensive investigations. To ensure the repeatability of experimental results, experiments were replicated three times for each AM surface at different intervals, and an uncertainty analysis (type-A) was conducted. The outcomes indicate that track orientations of AM surfaces, and spatter deposits are the most influential features, while the surface area's impact on heat transfer is minimal for both laminar and turbulent flow conditions. Under turbulent flow, a transverse track alignment demonstrates the highest efficiency in terms of the Nusselt number (Nu). However, when the flow transitions to laminar, most surfaces yield similar Nu values. The 90° oriented surface, which exhibits the highest Nu under turbulent conditions, performs poorly in terms of pressure drop (ΔP). In contrast, the 45° oriented surface offers optimal values (between smooth and transverse) for both heat transfer and ΔP. These findings are substantiated by both CFD and experimental results. Building upon these results, an additional investigation into the effects of 90° weld-tracked surfaces in a circular form was conducted. Two aluminum (Al-6061) channels—one with a smooth surface and the other with internal threads mimicking artificial waviness akin to an AM surface with a 90° scan orientation to fluid flow—were conventionally manufactured. Both CFD and experimental investigations were conducted for different mass flow rates. The results indicate that intentional structured surfaces, with artificial waviness, significantly impact heat transfer, resulting in high cooling efficiency with a Nusselt number approximately three times larger for various flow conditions compared to the smooth channel. However, these intentionally structured surfaces also lead to larger pressure drops and may necessitate additional pumping power depending on the application.

In conclusion, it is crucial to note that not all AM surfaces exhibit high heat transfer rates, and this is contingent on scan orientation (based on nominal build conditions) and flow conditions. The future scope of this study involves further exploring the effects of scan orientations in micro/mini-channel heat exchangers.

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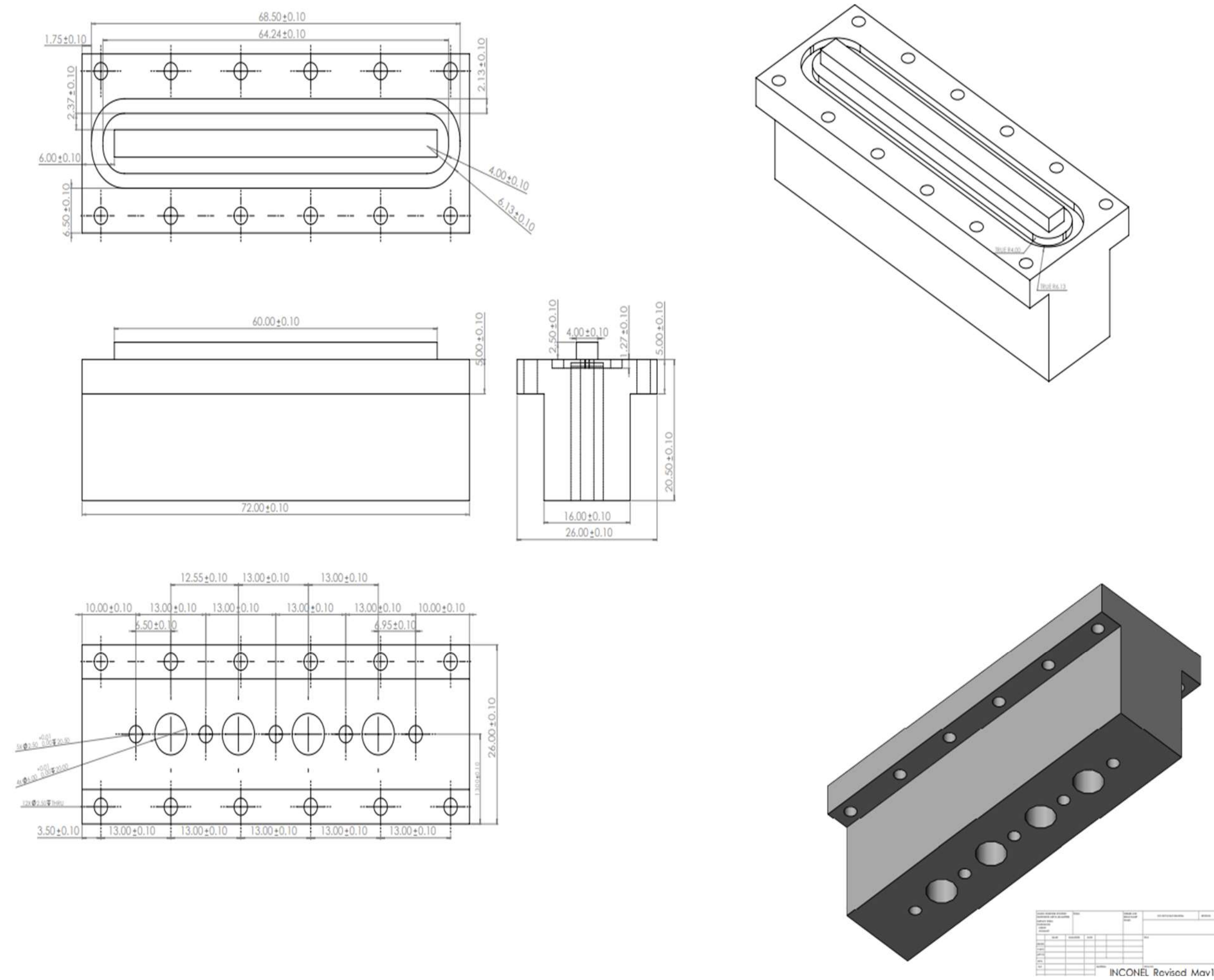
APPENDIX A : 2-D DRAWING OF INCONEL EXCHANGEABLE PART



APPENDIX B: 2-D DRAWING OF AL-6061 PART WITH ARTIFICIAL THREADS