Experimental investigation of the thermal performance in additively manufactured mini channels

Anna Nyhlén, Mats Kinell and Karl-Johan Nogenmyr
Siemens Energy AB, Finspong, Sweden
mats.kinell@siemens-energy.com

Abstract. With recent advances in robustness and design predictability of additive manufacturing (AM), this production method has taken its first steps towards implementation in heavy duty industrial applications such as gas turbines and heat exchangers. Among the benefits of using AM, the most important may be the significant higher degree of freedom in design than when using conventional manufacturing methods. In order to take advantage of these new possible solutions and to consider the surface roughness that arises from AM, it is necessary to have reliable correlations for pressure losses and heat transfer. In this study, the thermal performance for additively manufactured circular channels in Inconel 939 using the Selective Laser Melting (SLM) process are experimentally investigated.

1. Introduction
Almost 100 years ago, Nikuradse [1] performed experimental studies to examine the correlation between the pressure losses for pipe flow due to surface roughness and Reynolds number. Sand grains were applied to pipes and the roughness was characterized by using the average-sand-grain diameter compared to the diameter of the pipe. This translated to the relative roughness parameter ($\varepsilon/d_h$) which is still used as a reference in friction factor measurements today. Many years later, Huang et al. [2] experimentally investigated pipes with large relative roughness, $\varepsilon/d_h \approx 0.42$, and observed the effect of relative surface roughness on the transition flow regime. He found that by increasing $\varepsilon/d_h$, the transition from laminar to turbulent occurred at lower Reynolds numbers. With the increased use of additive manufacturing (AM) in industrial applications it is necessary to examine the pressure losses and heat transfer correlations experienced due to the surface roughness that arises from AM. Under the guidance of Prof. K. Thole, Pennsylvania State University, several studies have been published on this topic e.g. Stimpson et al. [3] who performed experimental studies on channels manufactured by direct metal laser sintering (DMLS) using a cobalt-chrome-molybdenum-based superalloy (CoCr) powder. The study showed that the friction factor increased significantly for AM materials compared to smooth channel data as well as an enhancement in heat transfer. The thermal performance of an AM geometry is highly dependent on the material and the printing parameters. These variables affect the obtained surface roughness which interacts with the flow in a way that at today’s date is not fully clarified. Mazzei and co-workers [4] attempted to numerically model this interaction using a high roughness model implemented in a commercial code and applying experimental data to calibrate the CFD parameters. Although promising results were obtained, especially for the friction factor, more work is required for numerically reliable predictions. Therefore, experimental investigations are necessary for additively manufactured geometries when the material or the printing parameters are changed. The present study examines test channels manufactured in Inconel 939. The properties of IN939 makes it suitable for high temperature environments such as e.g. industrial gas turbines.
2. Test setup and methodology

The test object was mounted in a copper cylinder that was insulated and heated up by electrical surface heaters. The copper cylinder ensures that a uniform temperature was achieved around the outer wall of the test object. A thin layer of thermal conductive paste was applied between the test object and the copper cylinder and between the copper block and the heaters to ensure contact. The test object was then subjected to an air flow of constant mass flow. Air temperature and pressure measurements were made at the inlet and the outlet of the test object. These measurements, together with the measured hydraulic diameter $d_h$, was used to evaluate the heat transfer and pressure loss in the test object. The experimental set up is shown in Figure 1 and Figure 2.

The Darcy friction factor is commonly used for presenting pressure losses in channels and defined as

$$ f_d = \frac{\Delta p}{d_h} \frac{2}{L \rho u^2} \quad (1) $$

Here, $\Delta p$, $d_h$, $L$, $\rho$ and $u$ denote pressure difference between the inlet and outlet of the channel, hydraulic diameter of the channel, length of the channel, density of the medium and flow velocity, respectively. The results are generally plotted in a Moody diagram together with the theoretically determined

$$ f_d = \frac{64}{Re} \quad (2) $$

which represents the fully developed laminar flow and the White-Colebrook equation

$$ \frac{1}{\sqrt{f_d}} = -2 \log_{10} \left( \frac{\varepsilon}{3.7d_h} + \frac{2.51}{Re\sqrt{f_d}} \right) \quad (3) $$

that yields the friction factor for fully developed turbulent flow as a function of the Reynolds number and the relative roughness, $\varepsilon/d_h$. Here, the Reynolds number was evaluated with the hydraulic diameter as the characteristic length.

The Nusselt number is the non-dimensional representation of the heat transfer and was evaluated by assuming axisymmetric temperature distribution in the test object. Based on numerical investigation, this is a valid assumption as long as the test object as well as the flow channel are circular. Discretization along the flow direction and solving for local values of air and wall temperature, the air outlet temperature is obtained and compared to the measurement. This is repeated for different channel heat
transfer coefficients until the difference between calculated and measured outlet temperature is less than 0.1K. The resulting average wall temperature is then used to calculate the Nusselt number.

3. Test objects
For the circular Nickel alloy channels, the design diameter was 0.75 and 1.5mm whereas the aluminum test object had a design channel diameter of 1.5mm. The length of all test objects was 45mm. At the present state of additive manufacturing, design and printed dimensions may not be identical. Therefore, a microscope was used to determine the actual dimensions of the test objects, Figure 3, Figure 4, Figure 5 and Table 1, which were used in the calculations. Further, based on the magnified pictures of the channels, it is evident that a significant surface roughness is present for Inconel 939 compared to the smooth aluminum channel.

| Material     | \( d_h \) (design) [mm] | \( d_h \) (measured) [mm] | \( L/d \) (design) |
|--------------|-------------------------|---------------------------|-------------------|
| aluminum     | 1.5                     | 1.670                     | 30                |
| Inconel 939  | 1.5                     | 1.517                     | 30                |
| Inconel 939  | 0.75                    | 0.7625                    | 60                |

Table 1. Geometrical properties of the test objects.

4. Results
The experimental set up was benchmarked and verified using the smooth circular aluminum test object with a measured diameter of 1.67mm. The results are presented in Figure 6 and Figure 7 along with the Gnielinski correlation for the Nusselt number and White-Colebrook correlation, \( \epsilon/d_h \approx 0 \), for the friction factor. The Gnielinski correlation is valid for \( 3 \cdot 10^3 < Re < 5 \cdot 10^6 \) for fully developed flow, hence the entrance effects for the aluminum test object were evaluated. Correlations for entrance effects in channel flow was described by Mills [5] and was applied to the Gnielinski equation and is presented in Figure 6 together with the benchmarking results for the Nusselt number. Hence, as seen in Figure 6 and Figure 7, the experimental data for the smooth aluminum channel resembles well to the correlations for smooth channel flow. Further, in Figure 7 the friction factor for circular channels manufactured in Inconel 939 as well as results from [2] is shown. The IN939 test objects as well as the results from Pennsylvania State University, PSU, yield an offset from the laminar line, \( f = 64/Re \), that is larger than for the aluminum one. This behaviour has been reported in other experimental investigations e.g.[2], [6]. If the Reynolds number is further increased, the flow will enter the transitional region where the friction factor increases until it almost becomes constant. Here, the flow is turbulent, and the aluminum channel follows the White-Colebrook/Blasius curve. Even though the absolute roughness is assumed constant for all Inconel 939 test objects, the relative roughness, \( \epsilon/d_h \), will increase with decreasing diameter which, in turn, yields earlier transition to turbulent flow and higher friction factor distributions[2].
The results in Figure 7 for IN939 are obtained using an inlet/outlet loss of 0.5/1.0 dynamic head for turbulent flow and 0.5/2.0 for laminar flow. The test objects from PSU are additively manufactured from a cobalt-chrome-molybdenum-based powder. A comparison is possible by using the arithmetic average roughness, $R_a$, instead of the sand grain roughness, nondimensionalized by the hydraulic diameter. As seen in Figure 7, L-2x-Co and IN939 $d_h = 1.52\text{mm}$ as well as M-2x-Co and IN939 $d_h = 0.76\text{mm}$ yield almost identical friction factor distributions in the turbulent region for similar $R_a/d_h$. $R_a$ is a very incomplete measure of surface characteristics, but when comparing two metal-AM surface with each other, it is still useful, as it can be expected that the shape of the surface topology of the two samples are similar.
The heat transfer results are shown in Figure 8 as the gain of the Nusselt number in the form of $Nu/Nu_0$, where the Gnielinski correlation for smooth channel is used as $Nu_0$. All test objects in the present study experience an increase in $Nu/Nu_0$ with the Reynolds number. IN939 $d_e=1.52$mm and the aluminum, however, eventually reaches a plateau in contrary to IN939 $d_e=0.76$mm which continuously increases until approximately $Re = 25000$ where choking occurs. Higher Reynolds numbers could not be reached for this test sample with the pressures available and, therefore, no plateau could be observed. The results is an example of the potential using AM channels in heat transfer applications -at Reynolds numbers above $10^4$, the enhancement in the Nusselt number for IN939 $d_e=1.52$mm exceeds 100%. Moreover, in Figure 8, results from [3] are included and all except the aluminum test object yield a decrease in $Nu/Nu_0$ as $Re$ increases. Apparently, $R_a/d_h$ does not suffice to predict the heat transfer between the flow and the wall in an additive manufactured mini channel.

5. Conclusions
AM has many advantages and have shown considerable potential being used in industrial applications, including the gas turbine industry. The AM industry is fast paced and studies examining the properties as well as the thermal performance are necessary for successful design solutions.

The test rig and evaluation method were verified using a smooth aluminum channel. The results were in very good alignment to the White-Colebrook correlation for smooth channels and the Gnielinski correlation for fully developed turbulent flow in smooth channels modified for entrance effects.

The Nusselt number and Darcy friction factor were evaluated for two Inconel 939 channels with two different hydraulic diameters: 0.76mm and 1.52mm. The friction factor increased with decreasing hydraulic diameter due to the increase in relative roughness. For the turbulent region, the friction for the AM channels was 3-4 times higher than for the smooth aluminum channel. IN939 $d_e=1.52$mm experienced a higher Nusselt number enhancement than IN939 $d_e=0.75$mm for $Re < 2 \cdot 10^4$. The latter experienced choking at this point and could not reach higher $Re$ whereas the former experienced constant values of $Nu/Nu_0$ for higher $Re$. Both IN939 channels yielded strong heat transfer enhancement and that especially for Reynolds numbers above $10^4$.

Based on the comparison to other published results, the arithmetic average roughness nondimensionalized by the hydraulic diameter may be an appropriate parameter to predict the friction factor for AM mini channels. More experimental data from different materials and printing parameters are, however, necessary to confirm that assumption. The same comparison for the Nusselt number showed that the arithmetic average roughness does not suffice to predict heat transfer.

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