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EFFECT OF ADDITIVELY MANUFACTURED SURFACE ROUGHNESS ON PERFORMANCE OF A RIB/DEFLECTOR COOLING CHANNEL

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1. INTRODUCTION

Gas turbines operate at their maximum efficiency when the turbine inlet temperature is the highest possible before structural damage is caused. In most gas turbines the operating temperatures are far above the permissible metal temperatures. Therefore, there is a critical need to cool the turbine blades for safe operation. Internal cooling mechanisms use cold air from the engine's compressor to extract heat from the blade material before it is channelled out at the blade tip. This incurs a loss in the thermal efficiency and power output of the engine, so there is great interest in optimising the cooling potential of this air flow [1].

Additive Manufacturing (AM) is the latest frontier in manufacturing engineering. It has a wide range of benefits and millions of dollars have been invested into its development. One area that shows promise as an application for AM is gas turbine cooling channels. In this case the parts are small and highly sensitive to roughness effects and manufacturing defects, so thorough analysis of the effects of AM techniques is invaluable to its future success. A cooling channel with ribs and deflectors will be analysed numerically using ANSYS Fluent under different surface roughness parameters and its performance evaluated within the range of Reynolds number; 8,000 to 24,000.

One of the most common AM techniques in aerospace applications is Direct Metal Laser Sintering (DSML). In this process layers of metal powder are microwelded together with a high-power computer controlled laser. The build is then brushed, heat treated and deburred to remove excess powder. However, this process won't always remove every imperfection. Stimpson et al. [2] revealed that powder particles sintering or partially melting to the surface can cause significant roughness effects.

2. ROUGHNESS CORRELATION FOR CFD SIMULATION

Most experimental studies in this field quantify surface roughness with arithmetic average height, R_a, while most computational solvers quantify surface roughness with equivalent sand grain height, k_s. Therefore it is essential to identify an appropriate relationship between these two values, in order to simulate accurately with considering the additive manufacturing techniques. Four different k_s/R_a relationships (listed in Table 1) were tested and compared, originating from Stimpson et al. [2], Bammert and Sandstede [3], Schaffler [4] and Kilpatrick and Kim [5]. The CFD model validation and the evaluation of roughness correlations were carried out for the additively manufactured channel flows [2]. In the experiments, five rectangular channels were manufactured using DMLS. The hydraulic diameter and the roughness of the channel are D_h = 406 μm and R_a = 10.3 μm. The simulations were conducted with varying Reynolds number from 3,600 to 10,000 at room temperature. For heat transfer coefficient measurements, a constant wall heat flux of 50,000 W/m^2 was used. The k-ω SST turbulence model was selected based on the previous study [5]. The mesh of total 345,600 elements was selected through the grid independence study. It was found that the relationship of $k_s = 8R_a$ proved most appropriate as seen in Figure 1 and the simulations were validated against the experimental data. Therefore, this roughness correlation has been used for the rest of the analysis.

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Table 1: The k_s/R_a relationships tested

	Correlation	Resultant k_s (m) for $R_a = 1.03\times10^{-5}$
Stimpson et al. [2]	$\frac{k_s}{D_h} = \frac{18R_a}{D_h} - 0.05$	1.651e-04
Bammert and Sandstede [3]	$k_s = 2.2{R_a}^{0.88}$	8.989e-05
Schaffler [4]	$k_s = 8.9R_a$	9.167e-05
Kilpatrick and Kim [5]	$k_s = 8R_a$	8.240e-05

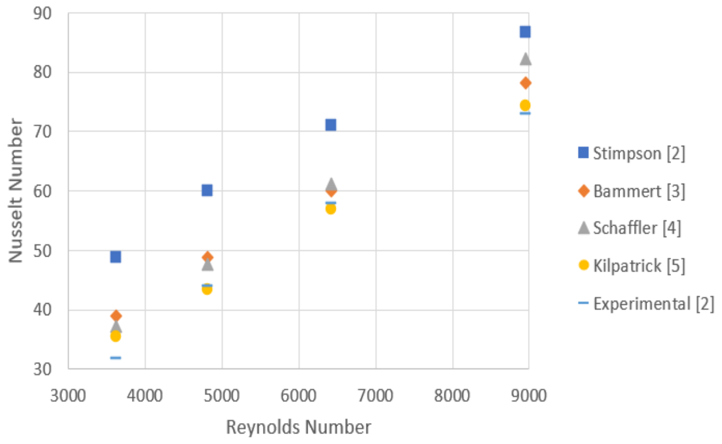


Figure 1: Comparing the roughness relationships against the test data [2]

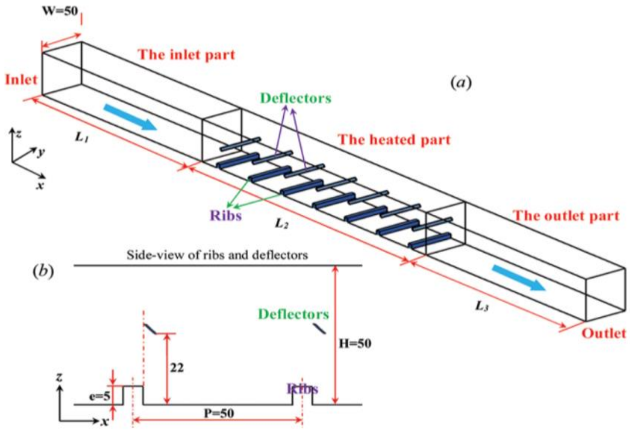


Figure 2: The simulation domain as illustrated by Xie et al. [6]

3. RIBBED CHANNEL WITH DEFLECTORS

The simulation cases of a ribbed channel without deflectors and with deflectors (shown in Figure 2) were analysed and compared against the data from Xie et al. [6]. This computational domain consisted of 391,136 mesh elements with increased density around the rib and deflector geometry. A grid convergence study was carried out to ensure that this resolution is valid. The hydraulic diameter of the channel is 50 mm. Reynolds numbers between 8,000 and 24,000, a typical range for cooling operation in gas turbines, have been considered. Firstly, the domain was assumed completely smooth surfaces and a constant heat flux of 1000 W/m^2 was applied on the ribbed section of the channel. The results of smooth channel are compared against the reference [6] in Table 2.

Table 2: Comparison of thermal performance of the smooth channel against the reference [6]

(a) without deflector

Re	Nu [6]	Nu	Difference
8000	30	39.44	31%
12000	46.63	48.41	3.8%
16000	61.09	61.49	0.7%
20000	76.89	74.25	–3.4%
24000	91.85	86.5	–5.8%

(b) with deflector

Re	Nu [6]	Nu	Difference
8000	36.05	43.9	22%
12000	51.76	57.55	11%
16000	67.84	70.63	4.1%
20000	83.92	83.29	–0.8%
24000	99.24	95.5	–3.8%

Secondly, the surface roughness, R_a, between 5 and 50 μm were applied on the surfaces of the same channels (see Fig. 3) and deflectors, and then the effects of surface roughness will be discussed in terms of the flow behaviours, heat transfer distributions and the overall cooling channel performance. The limitations, possibilities and overall viability of additively manufacturing deflectors in gas turbine cooling will also be evaluated.

4. RESULTS WITH ROUGHNESS

Setup

The turbulence model used is the SST k-ω model at the range of Re values from 8,000 to 24,000 [6]. Following the boundary conditions used by Xie et al. the simulation has a 1000 W/m^2 heat flux in the ribbed middle section, a uniform inlet temperature of 300K, a 5% turbulent intensity velocity inlet, and all other surfaces are assumed to be adiabatic. Stimpson et al. identified that common R_a values found in literature range from 5 to 50 micrometers [2]. Converting to k_s using Kilpatrick's correlation produces a range between 40e-6 m and 400e-6 m.

Results

The numerical results between Re = 8000 and Re = 24000 demonstrate an increase in Nu with surface roughness, becoming more pronounced with increasing Re (Figure 3).

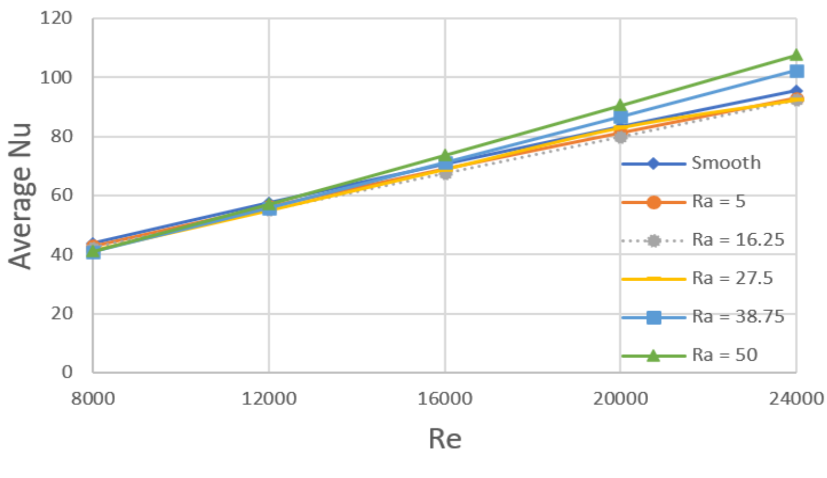
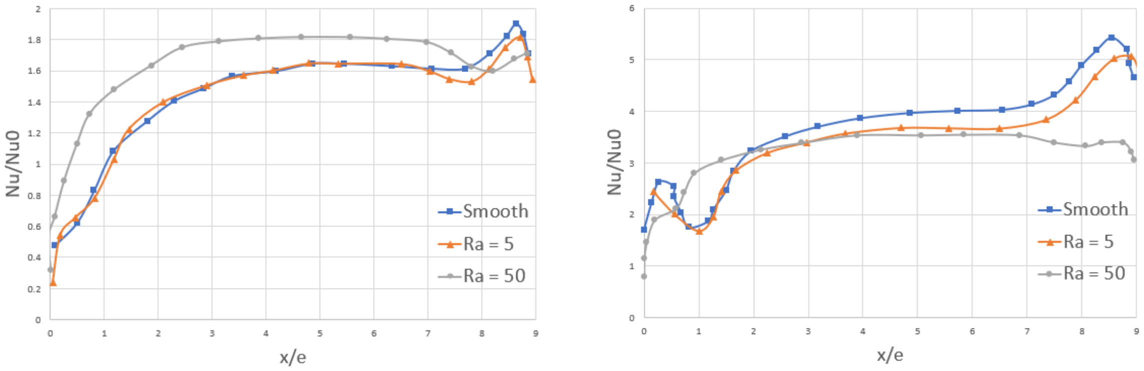


Figure 3: Average Nusselt number for the channel against Reynolds Number

The difference in channel outlet temperature caused by changing roughness was negligible. The Nu distribution between the 5th and 6th rib was observed at different roughness and Re values (Figure 4). Turbulent kinetic energy (TKE) stream contours were captured and demonstrate minimal interaction between the rib and deflector turbulence.



(a) Re = 8000 (b) Re = 24000

Figure 4: Nusselt number distribution between rib 5 and 6 for three different roughnesses

FLOW FEATURE ANALYSIS

As surface roughness is increased the flow demonstrates a larger turbulent wake behind each deflector, and greater turbulent effects. Due to the distance between the ribs and deflectors their turbulent flow features do not interact in an observable manner. The temperature distribution across the channel varied with surface roughness; becoming more evenly spread out across the surface at higher roughnesses. This behaviour was consistent at Re = 8000 and Re = 24000.

The position of the deflector (baseline case with deflector height h = 22 mm) was adjusted by shifting the deflector positions towards the ribs, first by 10 mm (h = 12 mm) and then by 15 mm (h = 7 mm). All boundary conditions remained the same and analysis was performed at Reynolds numbers of 8000, 16000 and 24000. This produced visible flow interaction and a change in thermal performance. The TKE contour exhibits clear delayed boundary layer separation, inducing greater heat transfer (Figure 5). Figure 6 illustrates that flow velocity between the ribs and deflectors is reduced significantly when h = 7mm. Figure 7 demonstrates a significant reduction in turbulent viscosity when h = 12 mm, contributing to the increased heat transfer performance.

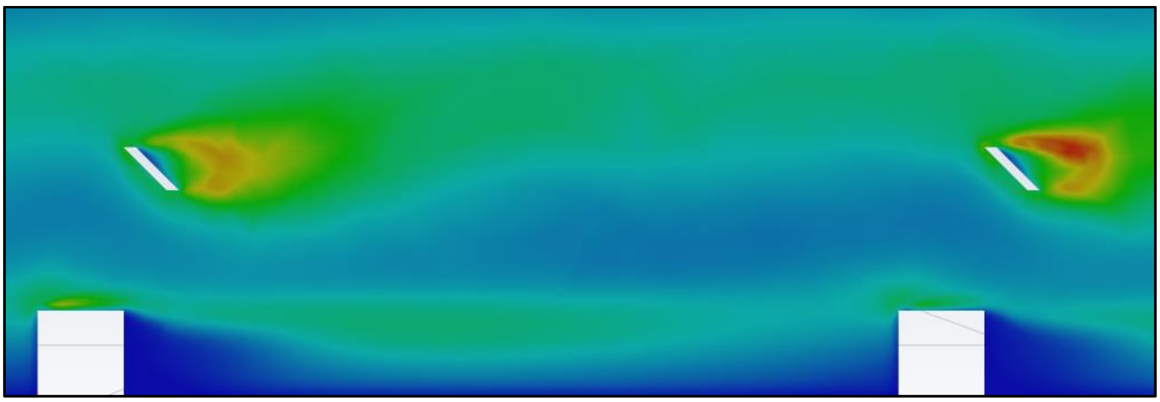


Figure 5: TKE contours between the 5th and 6th rib for h = 12 mm at Re = 16000 for R_a = 50 µm

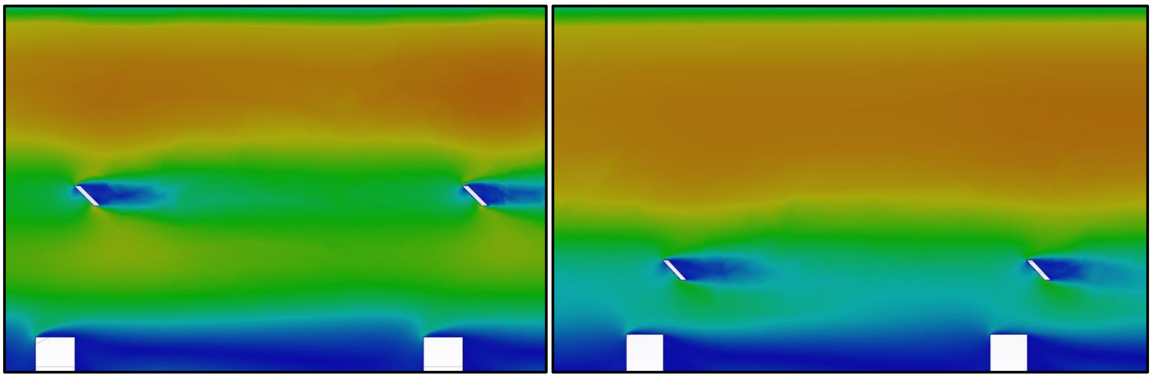


Figure 6: Comparison of velocity for h = 22 mm and h = 12 mm at $R_a = 50$ μm and Re = 16000

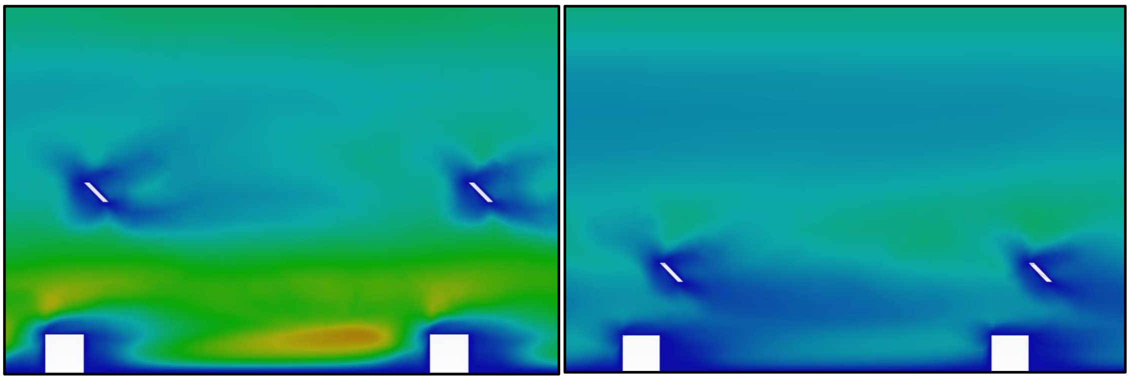


Figure 7: Comparison of viscosity for h =22 mm and h = 12 mm at $R_a = 50$ μm and Re = 16000

The average wall shear stress and pressure drop was measured for each deflector configuration at Re = 16000 and R_a = 50 μm. The average wall shear stress decreases with the addition of deflectors, and decreases further as the deflector is lowered. The pressure drop in the channel increases when deflectors are added, but this effect is less pronounced the lower the deflector is placed. This data suggests that the h = 7 mm deflector has the highest level of thermal efficiency. However the highest Nusselt number is achieved by the h = 12 mm deflector (Figure 8).

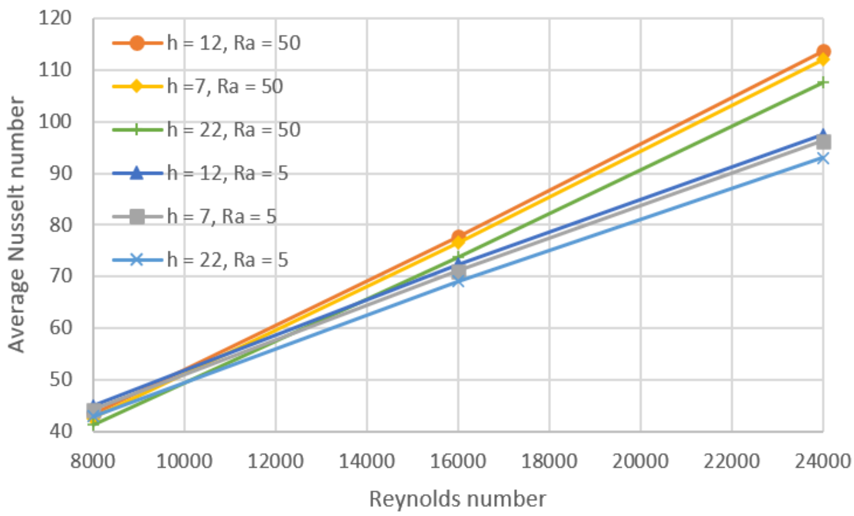


Figure 8: Thermal performance for different rib heights from $R_a = 5$ μm to $R_a = 50$ μm

5. CONCLUSION

The following results were observed:

- Overall temperature change remains the same with varying roughness. The outlet temperature decreases consistently with increasing Reynolds number.
- At certain deflector locations, the interaction of flow features caused by deflectors and ribs was significantly observed. The optimal deflector location for this rough AM channel and deflector shape is demonstrated to be 12 mm from the ribbed wall.
- Deflectors close to the walls of AM ribbed channels demonstrate an overall increase in thermal performance.
- Key parameters (e.g. surface roughness, deflector location) for future AM cooling channel design were identified.

6. REFERENCES

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