The VKI U-Bend Optimization Test Case

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Abstract

This document describes the VKI U-Bend optimization test case which aims at reducing the pressure loss for a typical 180°bend used in serpentine cooling channels of turbine blades. The starting point is a bend composed of two circular arcs and a rectangular cross-section, for which experimental data is available for benchmarking. The flow is incompressible and fully turbulent. The baseline U-bend is characterized with a large separation zone and has a large potential for improvements.

1 The U-Bend Test Case

Internal cooling channels of turbine blades are essential to enable high firing temperatures, and hence high efficiencies. Such cooling channels are characterized by multiple passages of relatively cool air through serpentine ducts. Among the salient features of these cooling passages, the U-bends that connect consecutive passages play a key role, as they represent regions of strong pressure loss, especially for small radius ratio (mean bend radius/duct hydraulic diameter): in this case the bend region can be responsible for up to 25% of the pressure loss in the entire multi-pass cooling system. The optimization of the U-bend shape to minimize pressure losses associated to returning the flow is therefore justified and drew the attention of the internal cooling channels research at the VKI around late 2009.

A typical U-Bend configuration was therefore optimized with engine representative characteristics. The length scale however was chosen to reach good measurement accuracy, resulting in a large scaling up of the geometry compared to the real engine, although keeping the Reynolds number the same. The study which is reported in [2, 1], contains a numerical and experimental part. A baseline shape consisting of two circular arcs is numerically optimized. Subsequently, the baseline and optimized shape are analyzed experimentally and compared to the numerical predictions. Overall a good prediction accuracy was observed, although detailed flow features were not captured by the Reynolds Averaged Navier-Stokes solver.

In a later work, the study was extended to include heat transfer as an additional objective [3]. A multi-objective optimization was carried out, resulting in a Pareto front. The secondary flow motion in the turn, known as a Dean-vortex pair, was identified as the cause for the trade-off between both objectives.

2 Baseline Geometry

A three dimensional view on the baseline geometry is given in Fig. 1. It consists of a circular U-bend with an external radius of $1.26D_h$ and an internal radius of $0.26D_h$. The height and width of the channel are both $1D_h$, resulting in an aspect ratio of 1.0. In Fig. 2 the dimensions of the U-Bend are presented. The (experimental) inlet leg is $23.3D_h$ long to guarantee a fully developed flow at the location of the circular bend. The numerical domain used in the study [2] is only $10D_h$ long, but requires an inlet profile to resemble the longer inlet used in the experimental domain. The hydraulic diameter is $D_h = 0.075\,\mathrm{m}$.

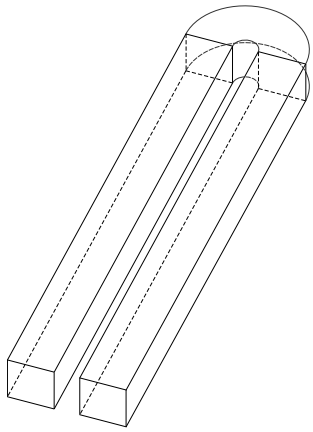

Figure 1: 3D view on the baseline U-bend.

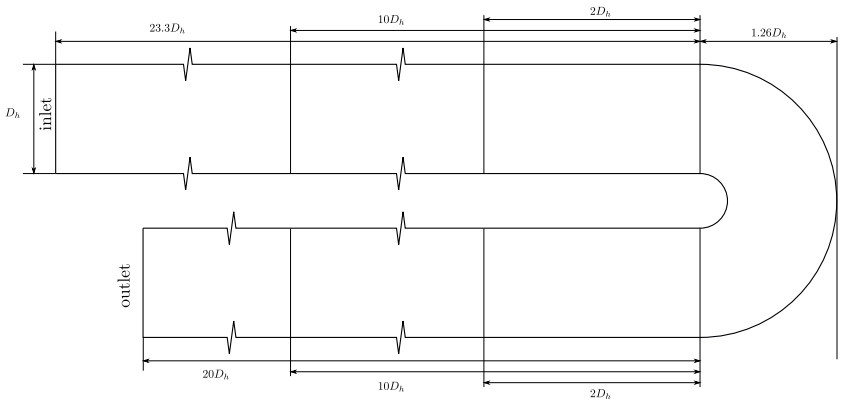

Figure 2: Main dimensions of the U-Bend experimental test case.

3 Experimental campaign

The experimental campaign was performed in atmospheric conditions. The properties of air are listed in Tab. 1. The bulk flow velocity is $U_0 = 8.40\,\mathrm{m/s}$

Name		Value	Unit
Temperature	T	293.15	K
Pressure	P	1.013×10^5	Pa
Density	ρ	1.204	$\mathrm{kg/m^3}$
Viscosity	μ	1.813×10^{-5}	$\mathrm{kg/(s\,m)}$

Table 1: Properties of air at ambient conditions.

leading to a Reynolds number of $Re = 43,830$. The low velocity means that an incompressible assumption can be used to model the flow. The turbulence intensity at the inlet is is 5%.

The location of the static pressure measurements are shown in Fig. 3. A traverse is conducted with a Pitot tube at the center of the duct at a location $16D_h$ downstream of the inlet. Table 2 lists the measured velocity non-dimensionalized by the reference velocity U_0 for different spanwise positions.

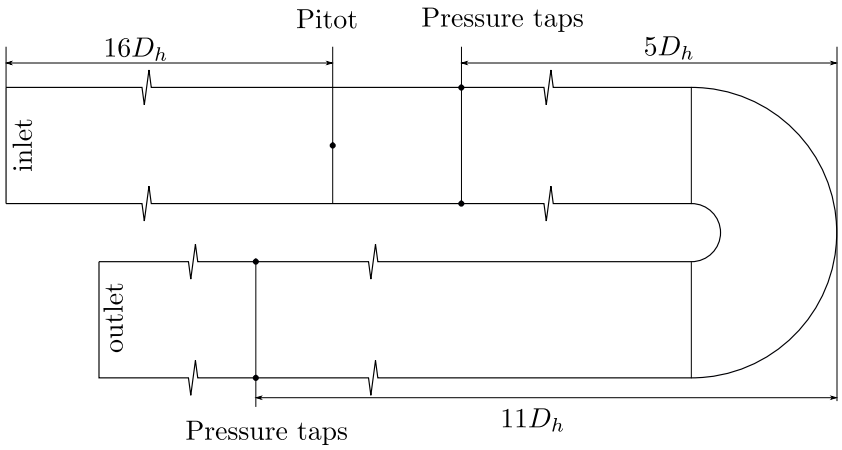

Figure 3: Location of the experimental measurements.

The normalized static pressure drop for the baseline U-bend resulting from static pressure measurements is given by:

$$\Delta P = \frac{P_{s,up} - P_{s,down}}{\frac{1}{2}\rho U_0^2} = 1.03 \pm 0.03 \tag{1}$$

where $P_{s,up}$ is the static inlet pressure at $5D_h$ from the tip of the bend (see Fig. 3), averaged over three measurements from taps drilled in three sides of the channel, and $P_{s,down}$ is the static pressure at $11D_h$ from the tip of the bend averaged in a similar manner.

PIV measurements were performed at the middle height of the channel and at a height $z/D_h = 0.03$. Figure 4 shows the measurements positions. In Fig. 5 the measured velocity is shown at the middle section $z/D_h = 0.5$, while Fig. 6 shows the PIV obtained velocity at $Z/D_h = 0.03$.

U/U_0	z/D_h	U/U_0	z/D_h	U/U_0	z/D_h
0.7452	0.0135	1.1173	0.3309	1.0738	0.8014
0.8302	0.0357	1.1149	0.3489	1.0663	0.8188
0.8527	0.0419	1.1156	0.4103	1.0615	0.8288
0.8833	0.0555	1.1149	0.4246	1.0561	0.8375
0.9098	0.0654	1.1153	0.4637	1.0486	0.8486
0.9187	0.0753	1.1173	0.4737	1.0350	0.8611
0.9329	0.0877	1.1132	0.4948	1.0350	0.8611
0.9452	0.0989	1.1149	0.5121	0.9989	0.8922
0.9649	0.1150	1.1193	0.5382	0.9812	0.9046
0.9901	0.1361	1.1153	0.5655	0.9710	0.9133
1.0125	0.1535	1.1159	0.5904	0.9561	0.9226
1.0234	0.1615	1.1159	0.6028	0.9404	0.9319
1.0346	0.1714	1.1153	0.6313	0.9132	0.9462
1.0425	0.1907	1.1139	0.6661	0.8823	0.9593
1.0513	0.1981	1.1139	0.6810	0.8605	0.9649
1.0724	0.2254	1.1119	0.6959	0.7459	0.9799
1.0819	0.2403	1.1003	0.7269		
1.0928	0.2527	1.0870	0.7468		
1.0938	0.2794	1.0840	0.7692		
1.1081	0.3073	1.0802	0.7834		

Table 2: Measured spanwise velocity profile at location $16D_h$ downstream from the inlet at the center of the duct.

4 Optimization test case

The presented U-bend configuration is optimized for minimized pressure losses with limitations given to the spacial dimensions. The numerical domain for the optimization is reduced with respect to the experimental one to reduce the computational cost.

4.1 Boundary Conditions

The same boundary conditions are applied as for the baseline test case. To reduce the numerical cost, it is suggested to use an inlet and outlet length of $10D_h$ with respect to the center of the arcs of the baseline case, which is considered sufficient for allowing to impose boundary conditions unaffected by the u-bend shape. For the inlet it is recommended to use a velocity profile from the corresponding position of one computation performed on the experimental configuration. For the outlet a constant pressure can be assumed.

4.2 Shape degree of freedom

The baseline arc curves as well as the inlet and outlet legs of a length up to $2D_h$ are allowed to be changed. The shape of the inner and outer curve however needs to remain inside the bounding box shown in Fig. 7, which restricts the length and width of possible changes to account for structural limits. The height of the channel is allowed to change to maximal $0.6D_h$ in both directions measured from

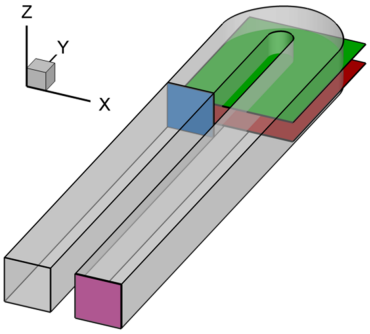

Figure 4: Location of the PIV measurements.

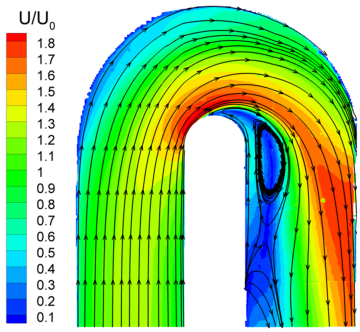

Figure 5: PIV measurements at $z/D_h = 0.5$.

the middle plane of the channel (the plane dividing the height of the baseline channel in half). The distance between both cooling channels is not subject to optimization, as well as the hydraulic diameter.

4.3 Objective

The objective of the optimization is to minimize the total pressure losses between the inlet and outlet of the domain, normalized as follows:

$$Obj = \frac{P_{0,inlet} - P_{0,outlet}}{\frac{1}{2}\rho U_0^2} \tag{2}$$

where the total pressure is mass averaged.

5 Conclusion

The present document describes the setup for an aerodynamic optimization study. Experimental data on a baseline test case is provided to calibrate the CFD model. It is hoped that this document will stimulate the exchange of optimization results on this test case. Authors publishing their results are asked to reference the test case using references [2, 1].

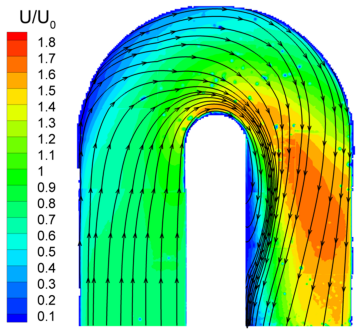

Figure 6: PIV measurements at $z/D_h = 0.03$.

6 References

References

[1] F. Coletti, T. Verstraete, J. Bulle, T. V. der Wielen, N. van den Berge, and T. Arts. Optimization of a U-Bend for Minimal Pressure Loss in Internal Cooling Channels – Part II: Experimental validation. *ASME Journal of engineering for Gas Turbines and Power*, 135:pp 051016, 2013.

[2] T. Verstraete, F. Coletti, J. Bulle, T. V. der Wielen, and T. Arts. Optimization of a U-Bend for Minimal Pressure Loss in Internal Cooling Channels – Part I: Numerical Method. *ASME Journal of engineering for Gas Turbines and Power*, 135:pp 051015, 2013.

[3] T. Verstraete and J. Li. Multi-objective optimization of a U-bend for minimal pressure loss and maximal heat transfer performance in internal cooling channels. In *ASME TURBO EXPO*, San Antonio, USA, June 2013. Paper No. GT2013-95423.

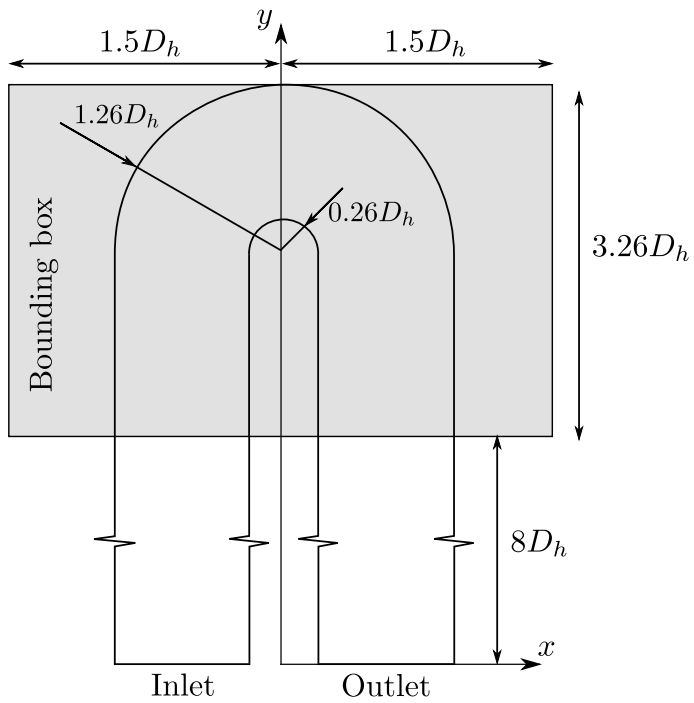

Figure 7: Free space for the shape deformation.