University of Stuttgart
Germany

October 07-08 2021

High Performance Computing in Science & Engineering – 24th Results and Review Workshop of the HLRS

# Numerical Investigation of the Flow and Heat Transfer in Convergent Swirl Chambers

Florian Seibold[1] and Bernhard Weigand[1]

[1]Institute of Aerospace Thermodynamics (ITLR), University of Stuttgart

## Introduction

In modern gas turbine engines, the maximum turbine entry temperature is well above the material's melting point. Therefore, efficient cooling techniques are required. Swirling flows in vortex chambers are a promising method for internal cooling of the turbine blade leading edge.

An axisymmetric vortex breakdown can occur in swirling flows, which is defined by a stagnation point followed by an axial flow reversal [1]. This phenomenon represents a subcritical flow state since disturbances can propagate upstream and downstream. Hence, conditions from the tube outlet can affect the vortex chamber flow field. In contrast, a supercritical state is evident in the absence of vortex breakdown. Then, disturbances can only propagate downstream [2] yielding a robust flow field that is insensitive to the conditions at the chamber outlet [3].

The present investigation analyzes the impact of convergent tube geometries on the flow field and heat transfer in swirl chambers.

## Numerical Methodology

In total, five geometries were investigated with different area ratios $A_{out}/A_0$ (see Fig. 1 and Tab. 1). The hyperbolic tube enforced a linear increase of the local Reynolds number $Re = \overline{u}_z D/\nu$.

All simulations were conducted for an inflow Reynolds number of $Re_0 = 10{,}000$ and a dimensionless swirl number of $S_0 = \dot{I}_\varphi / R\dot{I}_z = 5.3$. The latter represents the ratio of circumferential momentum flux $\dot{I}_\varphi$ to axial momentum flux $\dot{I}_z$.

The open source code OpenFOAM 6 was used for computation. All simulations were executed as compressible Delayed Detached Eddy Simulations (DDES) [5] in combination with the Spalart-Allmaras model [6]. The hybrid DDES approach applies a Reynolds-Averaged Navier Stokes (RANS) model close to the wall and a Large Eddy Simulation (LES) in the free stream. The numerical mesh consisted of a structured O-grid with $16.5 \cdot 10^6$ hexahedral cells. The boundary conditions are listed in Tab. 2. A detailed validation based on mean velocities and turbulence quantities was provided in [4,7].

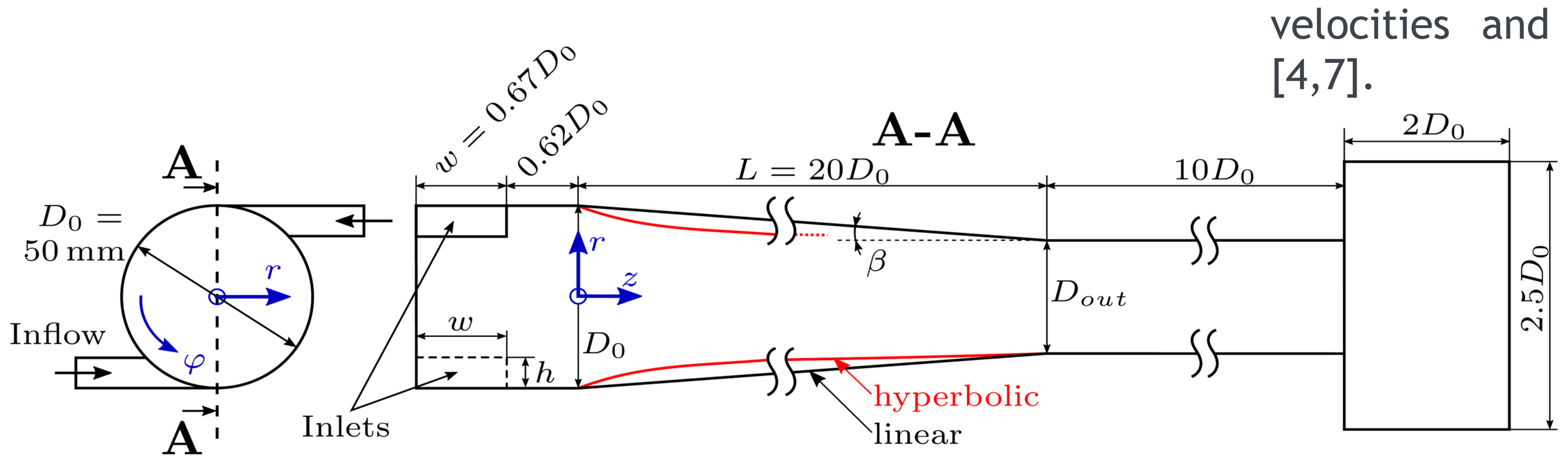

Fig. 1: Computational domain [4]

Tab. 1: Investigated geometries

| $A_{out}/A_0$ | $D_{out}/D_0$ | β [deg] |
|---|---|---|
| 1 | 1 | 0 |
| 1/2 | $1/\sqrt{2}$ | 0.42 |
| 1/3 | $1/\sqrt{3}$ | 0.61 |
| 1/4 | 1/2 | 0.72 |
| 1/4 | 1/2 | hyperbol. |

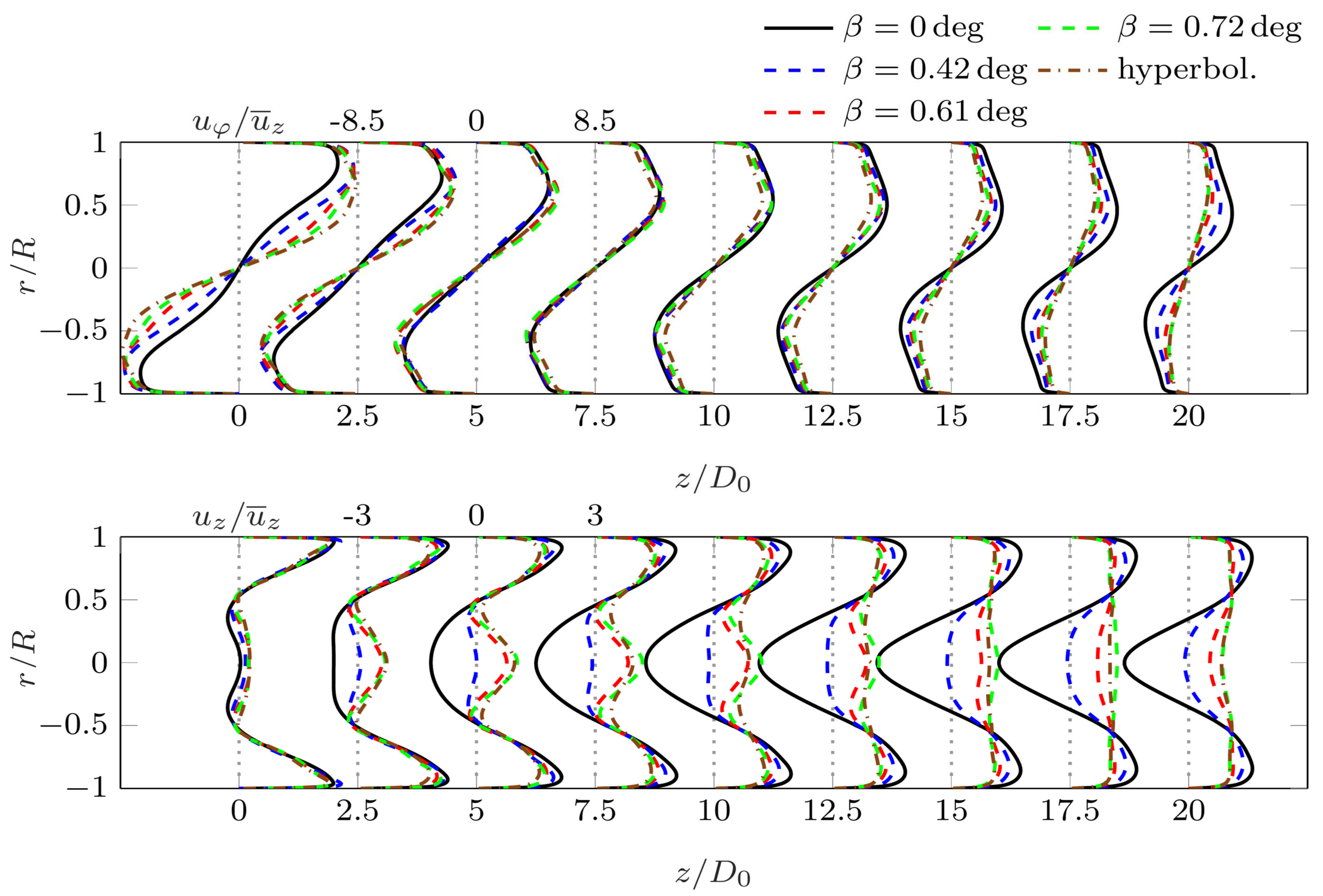

Fig. 2: Circumferential velocity field $u_\varphi$ and axial velocity field $u_z$ scaled by the local axial bulk velocity $\overline{u}_z$

Tab. 2: Boundary conditions

| | inlet | wall | outlet |
|---|---|---|---|
| u | $u_{in} =$ const. | $u_w = 0$ | $\partial u/\partial n = 0$ |
| T | $T_{in} = 333K$ | $T_w = 293K$ | $\partial T/\partial n = 0$ |
| p | $\partial p/\partial n = 0$ | $\partial p/\partial n = 0$ | $p =$ const. |

Tab. 3: Globally averaged Nusselt numbers

| β [deg] | 0 | 0.42 | 0.61 | 0.72 | hyperbol. |
|---|---|---|---|---|---|
| num | 140.8 | 122.6 | 103.8 | 102.7 | 105.7 |
| exp | 135.0 | 134.5 | 111.6 | 104.5 | - |

## Results

Convergent swirl chambers impose a flow acceleration in circumferential and in axial direction. The latter causes in increasing local axial bulk velocity $\overline{u}_z$, which is used for scaling in Fig. 2. The circumferential velocity $u_\varphi$ then shows a characteristic flow pattern that is independent of the angle $\beta$. Further, a Rankine vortex is evident, which consists of a solid body rotation in the center and a potential vortex in the outer region. The size of the solid body vortex shrinks towards the outlet. The axial velocity $u_z$ of the constant-diameter tube reveals a pronounced backflow. In contrast, convergent tubes are able to suppress this flow reversal and obtain a supercritical flow that is insensitive to disturbances from downstream. Such a robust state is crucial for a real engine application.

The cooling capability was assessed based on the non-dimensional Nusselt number

$$\mathrm{Nu} = \frac{\left.\frac{\partial T}{\partial n}\right|_w D}{T_w - T_{ref}} = \frac{hD}{k}\,. \qquad (1)$$

The local adiabatic wall temperature $T_{aw}$ was used as reference temperature $T_{ref}$. $T_{aw}$ can be approximated in swirling flows by assuming an adiabatic compression from the centerline to the wall [8]. Experimental data was measured using the transient liquid crystal technique. The complete procedure is described in [7].

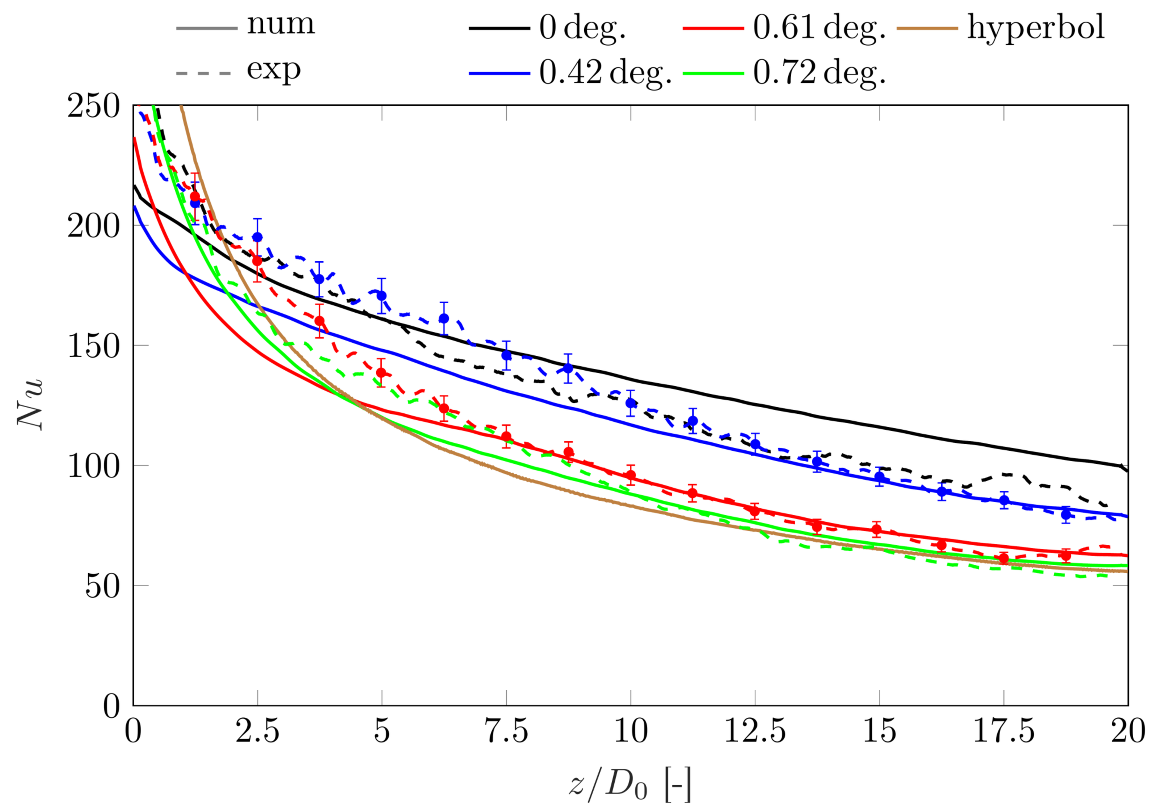

Fig. 3: Circumferentially averaged Nusselt numbers

Figure 3 illustrates local Nusselt numbers and Tab. 3 provides its global values. These results show overall good agreement with experimental data. Further, the heat transfer decreases as $\beta$ increases. This drop is mainly caused by the varying tube diameter $D$ in Eq. (1) and hence does not indicate a degression of the heat transfer coefficient $h$. Consequently, the tube surface significantly affects the Nusselt number values.

## Usage of Computational Resources

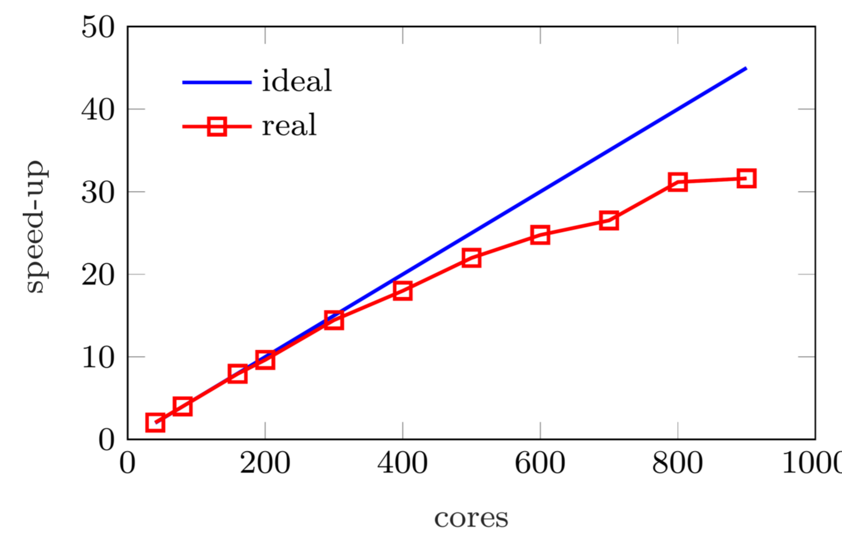

Fig. 3: Scaling of the numerical setup on the FH2 platform at the Steinbuch Center of Computing (SCC)

Figure 3 presents a speed-up analysis of the numerical setup. Based on these results, a parallelization of 660 cores (25,000 cells/core) was selected yielding an overall computation time of 18 to 36 days.

## Summary & Conclusion

Various swirl tubes with converging cross-section were investigated numerically for $Re_0 = 10{,}000$ und $S_0 = 5.3$. Convergent swirl tubes imposed a flow acceleration in circumferential and axial direction. The characteristic pattern of the circumferential velocity was not affected herby. The axisymmetric vortex breakdown was suppressed by converging geometries yielding a robust flow state that is insensitive to disturbances from downstream. Furthermore, heat transfer investigations showed overall good agreement with experimental data. A significant drop in Nusselt numbers was evident in all convergent geometries and the varying tube diameter was identified as main factor for this decline.

## Contact

Institute of Aerospace Thermodynamics (ITLR)
University of Stuttgart
Pfaffenwaldring 31, 70569 Stuttgart, Germany
e-mail: florian.seibold@itlr.uni-Stuttgart.de

## References

[1] Escudier, M. P. and Keller, J. J., AIAA J. 23 (1985) 111-116.
[2] Benjamin, T. B., J. Fluid Mech. 14 (1962) 593.
[3] Bruschewski, M., Grundmann, S. and Schiffer, H.-P., Int. J. Heat Fluid Flow 86 (2020) 108670.
[4] Seibold, F. and Weigand, B, Int. J. Heat Fluid Flow 90 (2021) 108806
[5] Spalart, P. R., Deck, S., Shur, M. L., Squires, K. D., Strelets, M. K. and Travin, A., Theor. Comput. Fluid Dyn. 20 (2006) 181-195.
[6] Spalart, P. and Allmaras, S., La Rech. Aèrosp. 1 (1994) 5-21.
[7] Biegger, C. Sotgiu, C and Weigand, B., Int. J. Therm. Sci. 96 (2015) 319-330.
[8] Kobiela, B., Ph.D. thesis, University of Stuttgart (2013).

Deutsche Forschungsgemeinschaft
German Research Foundation

Institute of Aerospace Thermodynamics