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Numerical investigation of flow and heat transfer in a swirl tube

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ABSTRACT

A swirl tube is a promising cooling method for heavily thermally loaded parts like turbine blades due to the additional circumferential velocity and therefore improved turbulent mixing of the fluid. However, the flow and the heat transfer in such a swirl tube are quite complex and not yet fully understood. To gain understanding of the flow structure and the cooling capability, we simulated a swirl tube via Detached Eddy Simulation (DES) and compared it to own experimental data. The numerical method was validated with DNS literature data simulating a turbulent channel flow with a temperature gradient.

DES and experiments agreed well for the mean velocity profile. The heat transfer coefficients are underestimated by the simulation near the inlet, but show an agreement further downstream. The results show that the flow field is characterized by a vortex system around the tube axis. Near the tube wall we observed an axial flow towards the outlet with a high circumferential velocity component. In contrast, the vortex core consists of an axial backflow. Additionally, turbulent structures showed double helix vortices especially in the inlet region. Furthermore, heat transfer results elucidate the highest Nusselt numbers at the swirl inlet which are up to eight times higher compared to a smooth tube. The heat transfer then decreases towards the tube exit due to the decay of circumferential velocity and becomes more uniform, but is still higher than the heat transfer in a smooth tube. The circumferential velocity with strong gradients in the wall region is the major mechanism for the high heat transfer in the swirl tube.

1. Introduction

For higher efficiencies of modern gas turbines the combustion temperature is raised over the last decades and the blades of the first turbine stage are exposed to extremely high temperatures, which are above the melting temperature of the blade material. For a reliable long term operation the turbine blades need to be cooled. Different cooling techniques like impingement cooling or turbulators are investigated in the last decades to enhance the internal convective heat transfer (see e.g. Ligrani et al. [1], Weigand et al. [2]). One sophisticated method for leading edge turbine blade cooling is a swirl chamber shown in Fig. 1. However, the complex flow and the heat transfer in such a system are far from being completely understood. A swirl chamber consists of a tube with one or more tangential inflow ducts, which induce a highly 3D swirling flow. The increased turbulence and the high velocity gradients close to the wall enhance the heat transfer.

In 1959 Kreith and Margolis [4] proposed that turbulent swirling flow in tubes enhances the heat transfer about four times compared to an axial flow. In the 1980s British and Ukrainian scientists investigated swirling flows for turbine blade cooling known as “vortex technologies”. The first patent about a cyclone cooling in an airfoil was published in 1988 (UK patent). These studies are summarized by Khalatov et al. [5]. The fluid mechanics and the heat transfer in swirl tubes with tangential injection are experimentally studied by Chang and Dhir [6]. They conclude that the high axial velocity near the wall and the enhanced turbulent mixing are the major mechanisms of the high heat transfer. The use of swirl chambers for internal turbine blade cooling is investigated by Glezer et al. [7, 8]. They examined the influence of system rotation on the heat transfer for real application usage for a representative Reynolds number of 20,000 based on the channel diameter. They conclude that Coriolis forces play an important role in enhancing the internal heat transfer. Ligrani et al. [9], Thambu et al. [10] and Hedlund et al. [11, 12] carried out several investigations of swirling tube flows induced by two axial displaced tangential wall jets and one radial outlet. The heat transfer is measured using infrared

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Nomenclature

c, c_p	heat capacity, J kg^{-1} K^{-1}
$\tilde{d}$	DES limiters
D	tube diameter, m
h	height, m
h	heat transfer coefficient, W m^{-2} K^{-1}
$\dot{I}_\phi$	angular momentum, kg m^2 s^{-2}
$\dot{I}_z$	axial momentum, kg m s^{-2}
k	thermal conductivity, W m^{-1} K^{-1}
k	turbulent kinetic energy, m^2 s^{-2}
L	length, m
$\dot{m}$	mass flow, kg s^{-1}
Nu	Nusselt number
Pr	Prandtl number
r	recovery factor
r, ϕ, z	cylindrical coordinates
R	tube radius, m
Re	Reynolds number
p	pressure, N m^{-2}
S	Swirl number
S_{ij}	strain rate, s^{-1}
t	time, s
T	temperature, K
$\overline{V}_z$	bulk velocity (axial), m s^{-1}
v, V_i	velocity, m s^{-1}
w	width, m
α	thermal diffusivity, m^2 s^{-1}
Γ	circulation, m^2 s^{-1}
δ	channel half height
Δ	grid spacing, m
k	isentropic exponent
μ	dynamic viscosity, kg m^{-1} s^{-1}
ν	kinematic viscosity, m^2 s^{-1}
ρ	density, kg m^{-3}
τ	shear stress, N m^{-2}
ω	vorticity, s^{-1}
Ω	angular velocity, s^{-1}
Ω_{ij}	rotation rate, s^{-1}

Indices

$()^+$	dimensionless
$()'$	fluctuation
$\overline{()}$	filtered
$\langle () \rangle$	averaged
0	initial
c	center
f	fluid
geo	geometrical
r	radial
t	turbulent
w	wall
z	axial
τ	friction
ϕ	circumferential

thermography and based on the inlet bulk temperature as reference temperature. They showed flow visualizations and the appearance of different-sized highly interacting Görtler vortex pairs and that the mean heat transfer increases with Reynolds number. The same swirl tube geometry is used by Ling et al. [13]. They investigated the heat transfer applying a transient technique using Thermochromic Liquid Crystal (TLC). The reference temperature for the heat transfer coefficients is also based on the tube inlet temperature.

Winter and Schiffer [14] investigated the effect of rotation on swirl cooling. They conclude that the swirl stabilizes the flow in the channel and that the development of a suction and pressure side is significantly reduced under rotation. The influence of internal swirling flow on the adiabatic film cooling effectiveness of a turbine blade is investigated by Lerch and Schiffer [15]. They showed a higher area-averaged effectiveness on one side of the turbine blades immediately downstream of the cooling holes due to the nonsymmetrical flow structures. The effect comes from the large circumferential velocity, which can influence the inlet flow structure of the film cooling. Marsik et al. [16] investigated the thermodynamic stability condition of swirling flow in a tube. Furthermore, they described the circumferential velocity profile as a solid body vortex in the tube center and as a potential vortex in the outer region.

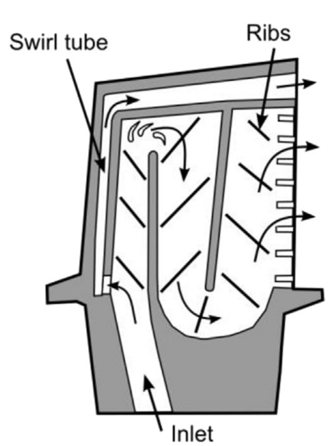

Fig. 1. Turbine blade sketch [3].

In the present paper we investigate the flow field and the heat transfer in a swirl tube to gain understanding of the physical phenomena. We measured the velocity field experimentally via 3C- (3 Components) and tomographic-Particle Image Velocimetry (PIV). The cooling capability is investigated by measuring the surface temperature and the heat transfer coefficients applying the well-established transient TLC method. We simulated the swirl tube via Detached Eddy Simulation (DES) using the open source code OpenFOAM and validated the numerics with DNS literature data simulating a turbulent channel flow with a temperature gradient. The numerical results are compared with experimental data in terms of flow field, swirl number, pressure loss and heat transfer.

The paper is divided into four sections. First we describe the experimental setup, the PIV flow measurements and the heat transfer measurements using the transient liquid crystal technique. Then, the numerical setup is explained regarding the DES method, the computational grid and the boundary condition followed by the validation of the numerics. In the result section we show flow field, pressure loss and heat transfer. Finally, we conclude the paper with a summary.

2. Experimental setup

The experimental apparatus used for the flow and heat transfer measurements at the Institute of Aerospace Thermodynamics