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Flow and heat transfer measurements in swirl tubes with one and multiple tangential inlet jets for internal gas turbine blade cooling

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ABSTRACT

In this paper, we present a detailed experimental and numerical study of the flow phenomena and the heat transfer in swirl tubes with one and multiple tangential inlet jets. Such tangential jets induce a highly 3D swirling flow and an enhanced turbulence in the tube, increasing the convective heat transfer. Thus, a swirl tube is considered as an effective cooling method for technical applications with high thermal loaded components like gas turbine blades.

The flow field, the heat transfer and the pressure loss are examined in a swirl tube with three different inlet jet configurations with one (MI1), three (MI3) or five (MI5) tangential inlet jets in axial direction. For this purpose, we measured the flow field via stereo-PIV (Particle Image Velocimetry) and the heat transfer by applying a transient technique using thermochromic liquid crystals for several Reynolds numbers. The numerical simulations are performed via Detached Eddy Simulation.

The PIV results reveal a complex axial velocity changing after each inlet due to the additional mass flow. Two main structures occur in the swirl tube with five inlet jets: a vortex in the tube center in a wave-like form and large spiral vortices around the tube axis especially near the inlet jets. In the inlet region(s) the highest heat transfer occurs and decreases continuously until the next inlet or towards the tube outlet for the swirl tube with one inlet. The swirl tubes with multiple inlets show lower maximum heat transfer rates compared to the swirl tube with only one inlet due to lower inlet jet velocities. However, the heat transfer distribution is more homogeneous over the entire tube length at a much lower pressure loss. The homogeneous heat transfer can be explained by two mechanisms. At the inlets, the tangential jets impinge onto the concave wall and cause an enhanced convective heat transfer correlating with large spiral vortices. Secondly, the axial velocity becomes stronger further downstream after each inlet jet and causes an enhanced heat transfer between the inlet jets.

The thermal performance parameter for all investigated swirl tube configurations is in the same order of magnitude. Thus, all swirl tube configurations are suitable for cooling. If one is interested in a maximum heat transfer paid by a high pressure loss, the swirl tube with one inlet is the best choice. If a lower but more homogeneous heat transfer with a low pressure loss is desired, one should choose the swirl tube with multiple inlets.

1. Introduction

Major development goals for gas turbines used for propulsion and power generation are to increase the thermal efficiency, which can be achieved by operating the gas turbines at increasingly higher pressures and temperatures. These conditions result in temperatures well above the melting temperature of the blade material, which requires the development of more efficient internal turbine blade cooling strategies (Han et al., 2012). Currently different cooling techniques are investigated like rib turbulators, pin fins, jet impingement, swirl tubes and dimples (Ligrani et al., 2003; Weigand et al., 2011). Here swirl cooling tubes and dimples show a promising cooling performance as they promote a high turbulent mixing in the near wall region and provide high heat transfer enhancement capabilities.

A swirl tube consists of a tube with one or more tangential inlet jets, as shown in Fig. 1, which induce a strong swirling flow circumferentially, enhancing the turbulent mixing near the wall and therefore improves the wall heat transfer significantly. Due to the complex swirling flow coupled with high turbulence, the understanding of the flow and heat transfer characteristics in a swirl cooling system remains a

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Nomenclature

c, c_p	heat capacity, J kg^{-1} K^{-1}
$\tilde{d}$	DES limiter
d	wall distance, m
D	tube diameter, m
f	friction factor, $= \Delta p/(1/2\,\rho \overline{U}_z^2)\,D/L$
h	heat transfer coefficient, W m^{-2} K^{-1}
k	thermal conductivity, W m^{-1} K^{-1}
L	length, m
$\dot{m}$	mass flow rate, kg s^{-1}
Nu	Nusselt number, $= h\,D/k$
Pr	Prandtl number
r, ϕ, z	cylindrical coordinates
Re	Reynolds number, $= \overline{U}_z\,D/\nu$
p	pressure, N m^{-2}
q	dynamic pressure, N m^{-2}
S_{ij}	strain rate, s^{-1}
t	time, s
T	temperature, K
$\overline{U}_z$	bulk velocity (axial), m s^{-1}
u, U_i	velocity, m s^{-1}
x, y, z	cartesian coordinates
Γ	thermal diffusivity, m^2 s^{-1}
Δ	grid spacing, m
η	Kolmogorov length scale, m
Θ	dimensionless temperature
ν	kinematic viscosity, m^2 s^{-1}
ρ	density, kg m^{-3}
τ	shear stress, N m^{-2}
ω	vorticity, s^{-1}
Ω_{ij}	rotation rate, s^{-1}

Indices

$()^+$	dimensionless
$\overline{()}$	filtered
$\langle()\rangle$	averaged
0	initial
f	fluid
in	inlet
r	radial
ref	reference
t	turbulent
w	wall
z	axial
ϕ	circumferential

challenging subject.

Kreith and Margolis (1959) first proposed that swirling flow induced in tubes can enhance surface heat transfer rates relative to unswirled flows in a heat exchanger application. Recently, a large number of other researchers employed tangential wall jets to induce large-scale swirling flows to enhance the heat transfer rates for gas turbine blade internal cooling. Glezer et al. (1996, 1997, 1998) studied three different configurations based on a swirling flow generated by tangential wall jets for gas turbine blade leading edge internal cooling. The swirl cooling configuration developed in the study demonstrated superior heat transfer rates in comparison with rib turbulated cooling as well as jet impingement cooling. They also showed that system rotation has only a little effect on the heat transfer. Qian et al. (1997) indicated that the swirling flow can drastically increase heat transfer rates by about 20% higher than those generated by impingement cooling. More importantly, swirl cooling produces a more uniform heat transfer distribution on the surface than jet impingement cooling.

Later, Ligrani et al. (1998) and Hedlund and Ligrani (2000) experimentally investigated the flow and heat transfer characteristics in a swirl chamber with two tangential inlet jets displaced axially along the tube. They used the inlet temperature as reference temperature for the heat transfer coefficient and showed that the large-scale swirling and Goertler vortex pairs in the swirl chamber are responsible for the remarkably enhanced heat transfer rates. Khalatov et al. (2000) investigated the heat transfer and pressure loss in a three-pass serpentine cyclone cooling system. They concluded that the cyclone cooling configuration demonstrated a great potential to reach high heat transfer rates in the cooling passages, which was found to be superior compared to rib turbulators. Ling et al. (2006) experimentally studied the heat transfer characteristics of a swirl tube with two tangential inlet jets by using transient liquid crystal thermography with the same swirl tube geometry than Hedlund and Ligrani (2000). Winter and Schiffer (2009) showed that the swirl stabilizes the flow in the cyclone cooling channel, and the system rotation may not have appreciable effects on the flow and heat transfer in the tube.

Recently, Biegger and Weigand (2015) and Biegger et al. (2015) studied the heat transfer and flow structure in a swirl tube with tangential inlet jets at the beginning of the tube by using transient liquid crystal thermography and PIV measurements for the experiments and by conducting Detached Eddy Simulations (DES). They showed that the circumferential velocity has strong gradients in the near-wall region and the helical vortices with enhanced turbulent mixing are mostly responsible for the high heat transfer in the swirl tube. Different outlet boundaries (like a straight outlet, a tangential outlet and a 180° bend outlet) had no severe influences on the flow field or the heat transfer in the swirl tube. This is an important result, because it shows that the

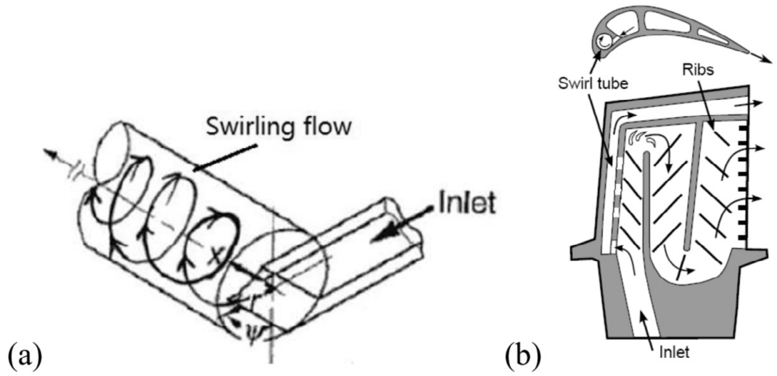

Fig. 1. (a) Tangential jet induced swirling flow in a tube (Ligrani et al., 2003), and (b) swirl cooling for gas turbine blade (Biegger and Weigand, 2015).