International Journal of Heat and Mass Transfer 128 (2019) 54–65

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Heat transfer and pressure loss characteristics in a swirl cooling tube with dimples on the tube inner surface

Yuyang Liu [a], Yu Rao [a,*], Bernhard Weigand [b]

[a] School of Mechanical Engineering, Shanghai Jiao Tong University, Dongchuan Road 800, Shanghai 200240, China
[b] Institute of Aerospace Thermodynamics (ITLR), University of Stuttgart, Pfaffenwaldring 31, Stuttgart 70569, Germany

ARTICLE INFO

Article history:
Received 18 April 2018
Received in revised form 12 July 2018
Accepted 22 August 2018

Keywords:
Gas turbine
Heat transfer
Numerical calculations
Swirl cooling
Multiple inlet jets
Dimples

ABSTRACT

This paper presents a numerical study of heat transfer and pressure loss characteristics in a swirl cooling tube with five tangential inlet jets and with dimples on the tube inner surface. The swirl tube has a length of 20 times the tube diameter, and the Reynolds number based on the tube diameter ranges from 10,000 to 40,000. Polyhedral meshes as well as the SST $k-\omega$ turbulence model were chosen for the numerical calculations. A swirl cooling system with a smooth tube was investigated as baseline, and comparatively with dimples on the tube inner surface. The results showed different swirling flow and heat transfer patterns in the swirl tubes. Dimples on the tube inner surface can reduce the wetted-area averaged heat transfer coefficient on the tube inner surface. However, the total heat transferred in the dimpled swirl cooling tubes can be increased by up to 7.2% due to the increased heat transfer area and the interactions between the swirling flow and the dimpled wall. On the other hand, the pressure loss in the dimpled tube can be appreciably reduced by up to 17.6% compared with that of the smooth swirl tube. Detailed flow interactions between the jets, the tube wall and the dimples are illustrated to explain the heat transfer change and pressure loss reduction mechanisms.

1. Introduction

In order to improve the thermal efficiency of gas turbines, the turbine inlet temperature is designed far beyond the melting point of metal materials. High-efficiency cooling strategies are urgently needed to maintain or extend the service life of engine components. The leading edge of turbine blades suffers from the highest gas temperature and gas velocity. Hence, more attention should be paid to the leading edge cooling strategy. By producing strong circumferential swirling flow, swirl cooling is very efficient in achieving high heat transfer rates [1,2]. Compared to impingement cooling, the swirling flow can drastically increase heat transfer rates by about 20% over the major heat transfer enhancement area and uniforms the heat transfer distribution [2,3]. Fig. 1 shows a typical structure of swirl cooling with multiple tangential inlet jets pertinent to the turbine leading edge.

Since Kreith and Margolis [4] came up with the first idea of swirl cooling, subsequent researches continuously improved the heat transfer performance of the swirl cooling system. The influence of many factors such as the working medium [5], the jet number, spacing and angle [6–8], the tube shape [9,10] as well as the Reynolds number and temperature ratio [11–13] have been extensively investigated. Kreith and Sonju [14] experimentally studied the decay of a tape-induced fully developed turbulent swirl flow through a pipe. It was observed that the turbulent swirl flow decays to about 10–20% of its initial intensity in a distance of about 50 times the pipe diameter, and the decay is more rapid at small Reynolds numbers. Rao et al. [15] experimentally and numerically investigated a swirl cooling chamber with one and five tangential jets. Comparisons have been done for equal mass flow rates and equal inlet jet Reynolds numbers as well as equal pumping power. The results showed that the heat transfer patterns of these two configurations are substantially different and the case with five inlet jets results in higher Nusselt numbers for the same pumping power. Biegger and Weigand [16] conducted flow measurements by using Particle Image Velocimetry (PIV) and heat transfer experiments by using transient Thermochromic Liquid Crystal (TLC) to investigate the influence of outlet geometries of a swirl tube. The results showed that the outlet redirection has no significant influence on the flow field and heat transfer coefficients. The fluid mechanics and heat transfer characteristics in swirl tubes with tangential jet injections were experimentally studied by Chang and Dhir [17]. The experiments were conducted with six tangential jet injectors with inside diameter of 22.23 mm. They found that the

* Corresponding author.
E-mail address: yurao@sjtu.edu.cn (Y. Rao).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.08.097
0017-9310/

Nomenclature

D	tube diameter, m
D_c	projection diameter of dimple, m
D_d	diameter of dimple, m
H	height of inlet jet, m
H_d	dimple depth, m
h_f	heat transfer coefficient on front half of tube surface, $W/(m^2 \cdot K)$
L	tube length, m
L_j	inlet jets spacing, m
L_d	dimples spacing, m
Nu	Nusselt number
$\overline{Nu}$	circumferentially averaged Nusselt number
$\overline{\overline{Nu}}$	globally averaged Nusselt number
P	static pressure, Pa
ΔP_i	pressure loss for dimpled tube swirl cooling system, Pa
ΔP_s	pressure loss for smooth tube swirl cooling system, Pa
Q_i	heat transferred to dimpled tube, W
Q_s	heat transferred to smooth tube, W
q	heat flux, W/m^2
Re_D	Reynolds number based on tube diameter
S	local swirl number
S_{geo}	geometrical swirl number
u_j	averaged jet velocity, m/s
u_D	averaged velocity at tube outlet, m/s
$V_{i,j}$	flow rate through one jet hole, m^3/s
$\overline{V_i}$	averaged flow rate of five jet holes, m^3/s
w	width of inlet jets, m

Greek symbols

ρ	density, kg/m^3
λ	thermal conductivity of air, $W/(m \cdot K)$
μ	dynamic viscosity, $kg/(m \cdot s)$
ω	non-dimensional vorticity

Subscripts

1	dimple depth of 0.001 m
2	dimple depth of 0.002 m
3	dimple depth of 0.003 m
X	axial direction
r	radial direction
φ	circumferential direction

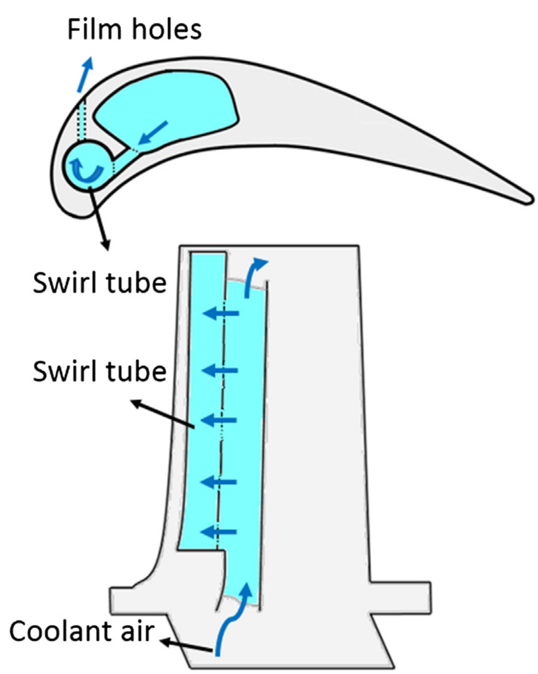

Fig. 1. Schematic of swirl cooling strategy for the turbine leading edge.

high axial velocity near the wall and the enhanced turbulent mixing are the major mechanisms leading to high heat transfer.

Numerical studies have also been published on swirl cooling in smooth tubes [18–22]. Liu et al. [18] investigated swirl cooling of a circular pipe with a single rectangular tangential inlet or two rectangular tangential inlets using numerical calculations. The results showed that the shear-stress transport (SST) $k-\omega$ turbulence model is the best choice based on simulation accuracy. Besides, the influence of the Reynolds number and the ratio of inlet temperature to tube wall temperature were also investigated. The results showed that the heat transfer coefficients of the swirl chamber increase with increasing Reynolds numbers, and increase with decreasing inlet to tube wall temperature ratio. Bruschewski et al. [19] did a LES simulation on the swirling flow heat transfer in a pipe with one unique outlet. Kusterer et al. [20,21] used the SST $k-\omega$ turbulence model to numerically investigate another swirl cooling configuration named Double Swirl Chambers (DSC). The results showed higher heat transfer coefficients for the DSC configuration compared with the single-tube chamber. In particular at the jet inlet regions the DSC configuration has even higher circumferentially averaged heat transfer enhancement by about 41%. Biegger et al. [22] conducted Detached Eddy Simulations (DES) for a single tangential jet swirl cooling system, which agrees well with their experimental data. It has been observed that near the tube wall there is an axial flow towards the outlet with a high circumferential velocity component, and in contrast, the tube core is dominated by backflow. The pressure loss is mainly due to high shear forces between the high circumferential velocity flow and the core flow. With higher circumferential velocity, the pressure loss in the swirl tube will increase dramatically.

To further improve the heat transfer performance and optimize the flow field, it is possible to arrange dimples on the inner surface of the swirl tube. The dimple works as a so called vortex generator which can achieve considerable heat transfer increment with moderate pressure loss [23–26]. However, when dimples are arranged on the swirl tube inner surface, the heat transfer and pressure loss characteristics may be different. In the present paper, the swirl cooling heat transfer and pressure loss performance were studied in a swirl tube with five tangential inlet jets. To characterize the effects of dimples on the swirling flow, four different swirl tubes were investigated, including a smooth swirl tube and three dimpled swirl tubes with different dimple depths. With the dimpled tubes, detailed flow interactions between the jets, the tube wall and the dimples are investigated to explain the heat transfer and pressure loss optimization mechanism in the swirl cooling systems.

2. Computational geometry

The swirl tube geometry from the previous study [15] has been chosen for numerical calculations in order to reasonably validate