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Numerical predictions of augmented heat transfer of an internal blade tip-wall by hemispherical dimples

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ABSTRACT

The heat transferred to the turbine blade is substantially increased as the turbine inlet temperature is increased. Improved cooling methods are therefore needed for the turbine blades to ensure a long durability and safe operation. The blade tip region is exposed to very hot gas flow, and suffers high local thermal loads due to the external tip leakage flow. A common way to cool the tip is to design serpentine passages with 180° turn under the blade tip-cap taking advantage of the three-dimensional turning effect and impingement. Increased internal convective cooling is therefore required to increase the blade tip lifetime. In this paper, augmented heat transfer of a blade tip with internal hemispherical dimples has been investigated numerically. The computational models consist of two-pass channels with 180° turn and arrays of dimples depressed on the internal tip-cap. Turbulent convective heat transfer between the fluid and dimples, and heat conduction within dimples and tip are simultaneously computed. The inlet Reynolds number is ranging from 100,000 to 600,000. Details of the 3D fluid flow and heat transfer over the tip-walls are presented. Comparisons of the overall performance of the models are presented. It is found that due to the combination of turning impingement and dimple-induced advection flow, the heat transfer coefficient of the dimpled tip is up to two times higher than that of a smooth tip with less than 5% pressure drop penalty. It is suggested that the use of dimples is suitable for augmenting blade tip cooling to achieve an optimal balance between thermal and mechanical design requirements.

1. Introduction

With the increase of the turbine inlet temperature of gas turbines, the heat transferred to the blade is increased. This indicates that the turbine blade inlet temperature may exceed the material melting temperature. As a result, turbine blades must be cooled for a safe and long-lasting operation. Various internal and external cooling techniques are employed to decrease the blade material temperature below the melting point. Fig. 1 depicts typical cooling techniques for internal and external zones. The leading edge is cooled by jet impingement with film cooling, the middle portion is cooled by internal serpentine ribbed-turbulators passages, and the trailing edge is cooled by pin-fins with ejection. In internal cooling, the relatively cold air, bypassed/discharged from the compressor, is directed into the hollow coolant passages inside the turbine blade. In external cooling, the bypassed air is ejected through the small holes, which are located in the turbine blade discretely. Most recent developments in the increase of the turbine inlet temperature have been achieved by better cooling of the turbine blade and improved understanding of the heat transfer mechanisms in the turbine passages. Several publications reviewing the gas turbine heat transfer and cooling technology research are available [1–4].

Cooling of the blade should include the cooling of all regions exposed to high temperature gas and thermal load. Among these regions, the blade tip area is one, particularly for high pressure turbines. Gas turbine blades usually have a clearance gap between the blade tip and the stationary casing or the shroud for the blade rotation and for its mechanical and thermal expansion. The hot gas leaks through the gap because of the pressure difference between the pressure side and suction side. The hot leakage flow increases the thermal load on the blade tip, leading to high local temperature. It is therefore very essential to cool the turbine blade tip and the region near the tip. However, it is difficult to cool such regions, and seal against the hot leakage flow. The blade tip operates in an environment between the rotating blade and the stationary casing, and experiences the extremes of the fluid-thermal conditions within the turbine [5,6]. A very common way to cool the blade tip is to adopt internal cooling by designing serpentine (two-pass, three-pass or multi-pass) channels with a 180° turn/bend inside the blade (as shown in Fig. 2). Taking the advantage of impingement and turning effects, the tip can be cooled to some certain extent. However, in order to augment forced convection,

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Nomenclature

A	wall surface area
D	dimple print diameter
D_h	hydraulic diameter
f	Fanning friction factor
H	dimple height
h	heat transfer coefficient
k	turbulent kinetic energy
Nu	Nusselt number
p	pressure
P	pumping power
Pr	Prandtl number
q_w	wall heat flux
Re	Reynolds number, $Re = \rho\ u_i\ D_h/\mu$
S	spanwise/transverse dimple pitch
T	temperature
u_i	inlet velocity
X	streamwise/longitudinal dimple pitch

Greek symbols

ε	rate of energy dissipation
Γ	production rate of k
Δp	pressure drop
μ	fluid dynamic viscosity
ρ	fluid density
λ	fluid-thermal conductivity

Subscripts

0	fully-developed flow channel
ave	averaged/overall
d	dimple
i	inlet
o	outlet
s	smooth-tip channel
w	wall

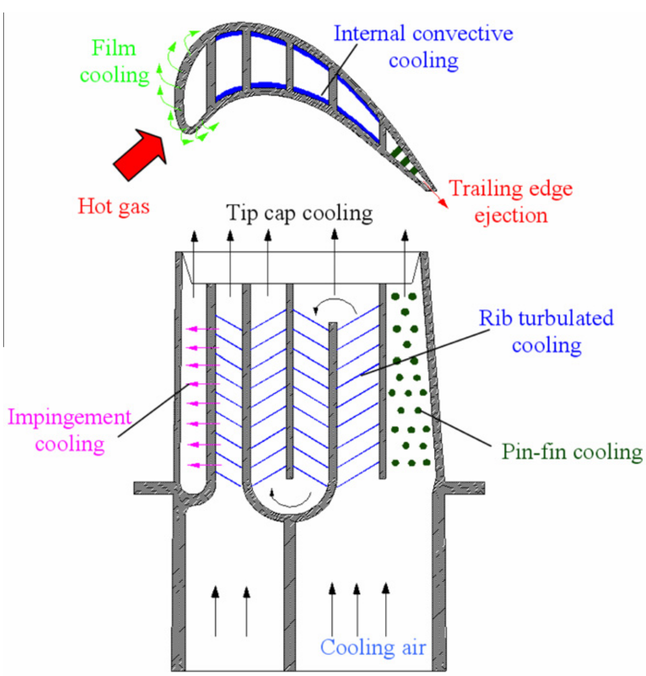

Fig. 1. Typical cooling techniques for a blade.

advanced methods of enhancing the internal convective cooling for the tip region are required to improve the blade life and reliability.

A recent investigation of turbulent heat transfer by Son et al. [7] presented particle image velocimetry (PIV) experiments to study the correlation between the high Reynolds number (Re = 30,000) turbulent flow and the wall heat transfer characteristics in a two-pass square channel with a smooth wall and a 90° rib-roughened wall. The results of the PIV measurement results showed that the flow impingement is the primary factor for the two-pass square channel heat transfer enhancement rather than the flow turbulence level itself. Besides, the secondary flow characteristics were correlated with the wall heat transfer enhancement for smooth and ribbed wall two-pass square channels. Al-hadhrami and Han [8], Fu et al. [9], and Liu et al. [10] and reported heat transfer coefficients and friction factors in two-pass rectangular channels with rib turbulators placed

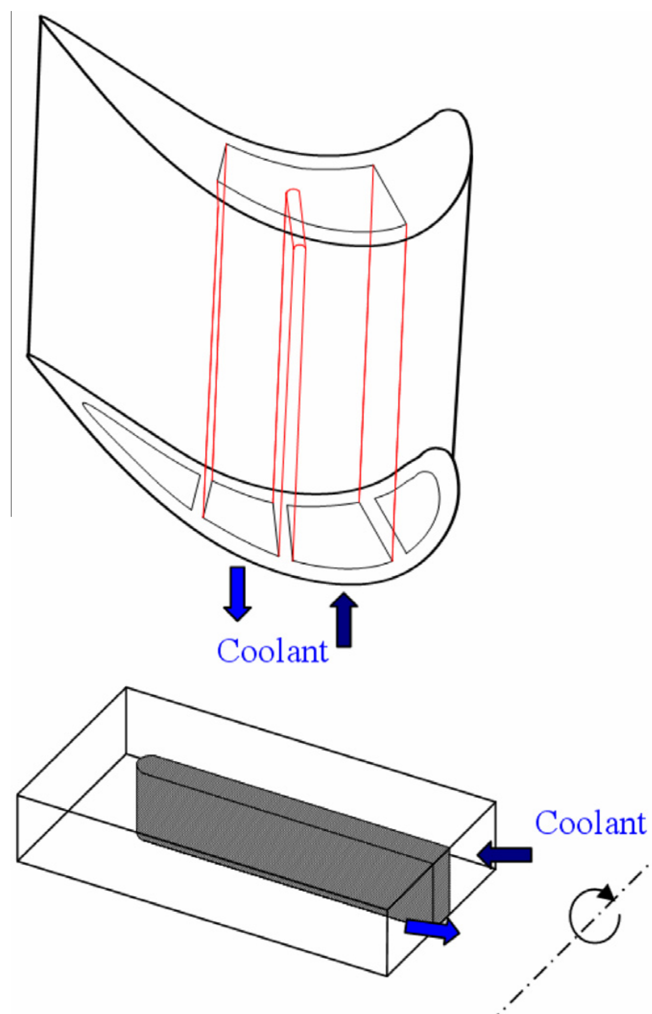

Fig. 2. A typical serpentine passage inside a blade.

on the leading and trailing surfaces. Five kinds of ribs were considered: 45° angled, V-shaped, discrete 45° angled, discrete V-shaped and crossed V-shaped. It was found that due to the turning effect,