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A review of gas turbine effusion cooling studies

R. Krewinkel *

Institute of Power Plants, Steam and Gas Turbines, RWTH Aachen University, Templergraben 55, 52055 Aachen, Germany

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ABSTRACT

Effusion-cooling is the next logical step in gas turbine blade cooling. Research on this topic has been done since the early 1950s, but manufacturing and modelling difficulties have prevented its commercial application so far. Still, there is a multitude of scientific publications about most aspects of this technology. Here, an overview over the publications most relevant for engineering uses is provided, with a focus on its application to gas turbine blades. The topics addressed here include the basic geometric and aerodynamic parameters known from film-cooling, but also the thermal conductivity of the base material, simplified approaches for modelling effusion-cooling and finally the application to blades, which incorporates the combination of impingement- and effusion-cooling as well as influences from operation.

Contents

1. Introduction

Modern gas turbines are operated at hot gas temperatures well in excess of the softening temperature of the metallic components in the hot gas path. Therefore different cooling technologies are normally applied, the most advanced of which is film-cooling. The discrete nature of these cooling holes does not provide a closed cooling film over the blade surface and the blade is not adequately shielded from the combustion gases. The required excessive amount of coolant leads the coolant jet to overshoot and induces vortices that can considerably reduce the effectiveness. Only the far field, where the cooling film reattaches to the surface, is cooled properly. With effusion-cooling, however, the jets influence each other, and because of their lower impulse do not overshoot into the main flow but remain within the boundary layer. This

* Address: MAN Diesel & Turbo SE, Steinbrinkstrasse 1, 46045 Oberhausen, Germany. Tel.: +49 2086929277.

E-mail address: robert.krewinkel@man.eu

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Nomenclature

A	area [m^2]
D	hole diameter [m]
H	spanwise hole distance [m]
L	streamwise hole distance [m]
T	temperature [K]
ad	adiabatic
c	cold
d	curvature diameter [m]
h	hot
p	pitch; distance between holes [m]
u	velocity [m/s]
λ	thermal conductivity [W/mK]
ρ	density [kg/m^3]
CFD	Computational Fluid Dynamics
I	Impulse Ratio $\left[\frac{u_c^2 \rho_c}{u_h^2 \rho_h}\right]$
LES	Large Eddy Simulation
M	Blowing Ratio $\left[\frac{u_c \rho_c}{u_h \rho_h}\right]$
PIV	Particle Image Velocimitry
R	Density Ratio $\left[\frac{\rho_{in}}{\rho_{out}}\right]$
TBC	Thermal Barrier Coating
V	Velocity Ratio $\left[\frac{u_c}{u_h}\right]$
α	Inclination Angle of Cooling Hole [°]
η	Cooling Effectiveness $\left[\frac{(T_h - T_w)}{(T_h - T_c)}\right]$

intensifies the tendency of the vortices to reattach to the wall which increases the cooling effectiveness.

It is of paramount significance that effusion-cooling is the result of many subsequent rows of cooling holes. In other words, true effusion-cooling cannot exist after only one or two rows of cooling holes [1]. It seems 7 rows of cooling holes is the minimum for a model that encapsulates all relevant phenomena. Therefore most research on film-cooling cannot provide data that is valid for effusion-cooling. Furthermore, the flow of the coolant through the cooling holes causes convective cooling, the potential of which is utilized far better in the more densely spaced effusion-cooling holes than with film-cooling. This, as well as the cooling in the coolant plenum, can only be properly assessed using conductive materials (as far as blades are concerned) in experiments or conjugate calculations.

The manufacturing costs as well as concerns regarding the reliability of effusion cooling have so far prevented its commercial use in gas turbine blades. In combustor liners, on the other hand, effusion-cooling is much closer to commercial application and most studies therefore focus on this. Hence selected studies of effusion cooling of combustor liners are also included in this overview. Differences like the length-to-diameter ratio of the holes, the hot gas *Ma* and the thermal conductivity of the substrate material exist between blades and liners. Therefore, some results of studies on liners cannot be applied to blades, but some aspects of the cooling, like the development of the cooling film over multiple rows of cooling holes, are not affected by this. Transpiration-cooling (as defined below) s explicitly not part of this review because the manufacturing, the flow through the porous body and the distance to application all differ significantly from effusion-cooling.

The following review is structured according to topics that are the most important for the development and assessment of effusion-cooling. Since some of the larger studies occupy themselves with multiple topics, a certain amount of cross-referencing between sections is unavoidable, although it was attempted to reduce this to a minimum. Within the sections analytical publications are discussed before experimental ones and numerical work is usually discussed last. This by no means intends to be a weighing of the importance or accuracy of the publications. While the evidence in one field may suggest that numerical results do not capture the experimental data correctly (as with turbulence modelling), an exceptionally good agreement between numerics and experiments may be found in other fields. One example for this can be seen from Fig. 5, where experimental (Particle Image Velocimitry), advanced CFD (Large Eddy Simulation) and "simple" CFD (Reynolds-Averaged Navier–Stokes) using a Baldwin-Lomax turbulence model are compared. This suggests that although the detailed flow field may not be captured fully, the results suffice for more general statements on, for example, the temperature distribution.

1.1. Effusion-cooling vs. other cooling techniques

The difference between film- and effusion-cooling lies in the size and number of the cooling holes: Effusion has holes with diameters down to 0.2 mm; their large number causes a very close spacing and therewith an interaction of the coolant jets that does not exist with film-cooling. Associated with these characteristics are differences in the amount of coolant exiting each of the holes as well as its velocity and impulse. The flow through effusion-cooling holes is, due to their small size and the lesser amount of coolant, normally laminar. Typically, the coolant used for both

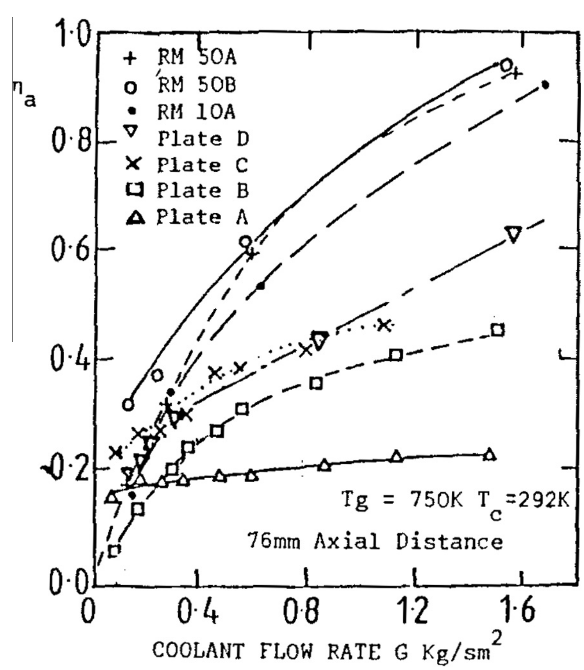

Fig. 1. Comparison of the cooling effectiveness of effusion- and transpiration-cooled plates [3].