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Research Paper

# Effects of wall curvature and streamwise pressure gradient on film cooling effectiveness

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## HIGHLIGHTS

- Film cooling with streamwise pressure gradient on curved walls was investigated.
- The effects of wall curvature are opposite for high or low momentum ratios.
- The critical momentum ratio increases with an increase in favorable pressure gradient.
- Effects of streamwise pressure gradient and wall curvature should not be neglected.

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ABSTRACT

As the load of a modern turbine is increasing, the turning angle and the flow acceleration is increasing. The effects of streamwise pressure gradient (SPG) and wall curvature on film cooling performance are becoming more and more important. Film cooling effectiveness with those two effects was investigated experimentally and numerically. Flow on the concave wall has an unstable effect and increases the turbulence intensity which leads to a faster dissipation and wider lateral spreading. With these two opposite effects, there is a critical point that when the momentum ratio is smaller than the certain value, film cooling effectiveness is highest on concave wall and the rank is opposite when the momentum ratio is larger than the value. The critical momentum ratio is 0.6 with nonaccelerated main flow for all density ratios. For the cases with different SPG, the critical momentum ratio still exists, while the value increases with stronger favorable pressure gradient and ranges from 0.55 to 0.75 in the present research. The film cooling performance with different SPG and wall curvature is quite different from the flat wall case and thus these effects should be taken into consideration in gas turbine film cooling design.



## 1. Introduction

In modern gas turbine design, higher turbine inlet temperature is desired as to increase the efficiency and output of the machine. The hot gas path components must be cooled actively. Film cooling is one of the most important and commonly used cooling technologies.

Film cooling has been widely studied in the past 40 years. Most of them were conducted on flat plat test rigs. The review by Bogard and Thole [1] summarized plenty of geometries and flow parameters influencing film cooling performance, including blowing ratio, density ratio, and the two factors that we mainly focus on in this paper of wall curvature and streamwise pressure gradient (SPG). As the capability of aerodynamic design and optimization of turbine airfoil increases, the interaction between film cooling jet and turbine main flow becomes more and more significant. The film cooling performance in turbine environment differs from that in the flat plate condition. Wall curvature and streamwise pressure gradient are two important characteristics of the turbine main flow.

A brief review of researches on the effects of SPG on film cooling performance is given below while some of the conclusions are contradictory. Slot injection studied by Hartnett et al. [2] shows that favorable pressure gradient (FPG) decreases film cooling effectiveness. Escudier and Whitelaw [3] found that adverse pressure gradient (APG) has a relatively small influence on slot film cooling. Launder and York [4] reported that strong FPG improves film cooling effectiveness while reduces the lateral spreading simultaneously. Teekaram et al. [5] has investigated both slot and hole injection. The results show that SPG has little effect on slot injection while for hole injection, FPG increases cooling effectiveness under large blowing ratios. Yang et al. [6] found that the effect of SPG on cooling effectiveness is complicate and is different under

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**Nomenclature**

| | |
|---|---|
| $C$ | oxygen concentration |
| $D$ | hole diameter |
| $DR$ | density ratio $\rho_c/\rho_\infty$ |
| $K$ | acceleration parameter |
| $L$ | hole length |
| $LI$ | light intensity |
| $M$ | blowing ratio $\rho_c V_c/\rho_\infty V_\infty$ |
| $Ma$ | Mach number |
| $P$ | pressure |
| $(P_{O2})$ | partial pressure of oxygen |
| $r$ | radius of curvature of the curved wall |
| $Re$ | Reynolds number |
| $S, R, Z$ | streamwise, wall normal and spanwise direction in curved wall case |
| $T$ | temperature |
| $Tu$ | turbulence intensity |
| $u$ | velocity component in streamwise direction |
| $V$ | velocity magnitude |
| $W$ | molecular weight |
| $X, Y, Z$ | streamwise, wall normal and spanwise direction in flat wall case |
| $\alpha$ | inclined angle |
| $\eta$ | film cooling effectiveness |
| $\nu$ | kinematic viscosity |
| $\rho$ | density |

*Subscripts*

| | |
|---|---|
| 0 | reference |
| aw | adiabatic wall |
| c | coolant condition |
| d | hole diameter |
| mix | mixture condition |
| r | recovery |
| $\infty$ | main stream condition |

*Abbreviations*

| | |
|---|---|
| APG | adverse pressure gradient |
| FPG | favorable pressure gradient |
| NPG | wall normal pressure gradient |
| SPG | streamwise pressure gradient |

different free stream turbulence intensities. Ligrani [7] investigated full-coverage film cooling with different FPG and found that film cooling effectiveness increases with larger FPG. Jessen et al. [8] has done PIV measurement on film cooling under APG and found that coolant jet penetrates deeper into the main flow for APG condition. Coletti et al. [9] found that the influence of SPG is complex and it depends on the specific geometry and flow configuration. Konopka et al. [10] conducted a LES simulation on shaped hole film cooling under APG which shows good agreement with PIV result. They found that APG has little effect on cooling effectiveness while a thicker thermal boundary layer was observed off the wall under APG.

All the researches mentioned above are conducted in flat plate test rigs. Investigations on the effects of wall curvature are listed below. Tani [11] found that the turbulence intensity is larger on concave wall and Taylor-Goertler cells is believed to create an unstable flow and increases the turbulence intensity. Mayhew et al. [12] and Saumweber and Schulz [13] investigated the effect of free stream turbulence intensity on film cooling effectiveness and found that the effectiveness increases with elevated turbulence intensity for high blowing ratios and decreases for low blowing ratios. Ito et al. [14] and Schwarz et al. [15,16] measured film cooling effectiveness on convex, flat and concave walls. It is shown in there results that under low blowing ratios, effectiveness is larger on convex wall, while under high blowing ratios, effectiveness is larger on concave wall. Berhe and Patankar [17] did a numerical study on the curvature effects on film cooling effectiveness. They found that the coolant jet is pressed to the surface by wall normal pressure gradient (NPG) and results in a greater cooling effectiveness. Lutum et al. [18,19] studied the effect of FPG on convex surface and found FPG reduces cooling effectiveness. But only one streamwise pressure gradient was investigated in Lutum's study.

No detailed analyses on the effects of SPG and wall curvature both separately and simultaneously are available in the open literature. The present study investigated the film cooling performance with different SPG on both flat, convex and concave wall experimentally and numerically to show the combination of the two effects systematically. The corresponding film cooling effectiveness results and analyses on flat wall are given in a comparison paper [20]. Since the film cooling performance on flat plate is quite different from the case with SPG and wall curvature which is the actual situation in a turbine. The present results are useful in the design of gas turbine cooling system.

## 2. Experimental facilities and procedures

### 2.1. Test facilities

Film cooling experiments were conducted on the low speed film cooling test facility built in Tsinghua University. A schematic of the test rig is shown in Fig. 1. The main flow was supplied by an 11 kW centrifugal blower. The mainstream velocity was measured by a three-hole total pressure probe and a static pressure sensor, and controlled by a valve. The turbulence intensity upstream of the injection point was 2%. $CO_2$ and $N_2$ were used as the cooling gas to achieve a coolant to free stream density ratio of 1.52 and 0.97, respectively. The coolant flow was measured and controlled by a mass flow controller which had an uncertainty of 2%. Film cooling effectiveness was measured by pressure sensitive paint based on mass and heat transfer analogy. More detailed information of the test rig was described by Han [21].

The parameter used to characterize the SPG is the acceleration parameter $K$ defined as:

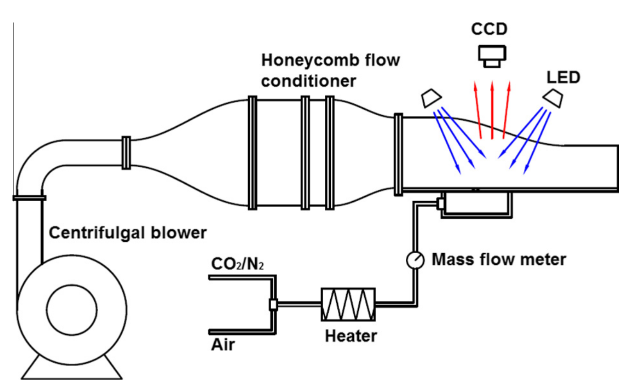


**Fig. 1.** Sketch of the test facility.