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Research paper

# Film cooling effectiveness and flow structures for novel upstream steps

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## HIGHLIGHTS

- The film cooling effectiveness of novel upstream steps were investigated.
- The broken normal step along the spanwise increased the film cooling effectiveness.
- A usage the curvature for the step is an effective way to improve the cooling.
- Decreasing the jet vertical velocity component in case of the upstream step.

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## ABSTRACT

In this study, computational simulations were made using ANSYS CFX to predict the improvements in film cooling performance by using novel upstream steps. There are twenty-one novel steps consisting of three groups are tested. The first group consists of a rectangular step with different tilt angles. The second group consists of a normal rectangular step with and without segmentation. The third group consists of curved steps with and without segmentation. Optimizing the curved steps dimensions is performed. The film cooling effectiveness ($\eta$) of twenty-one novel steps were investigated and compared with experiment. Velocity profiles, pressure coefficient profiles and turbulent kinetic energy contours were discussed. Blowing ratios in the range (0.5, 1, 1.5 and 2) were investigated. Results indicate that the best novel step is the curved step with width (W/8) and the average values of film cooling effectiveness is increased to 138.8% compared with the experiment.



## 1. Introduction

Modern gas turbines are designed to run at high turbine inlet temperatures well in excess of current metal temperature limits to improve thermal efficiency and power output [1]. In addition to improved temperature capability materials and thermal barrier coatings, highly sophisticated cooling techniques such as augmented internal cooling and external film cooling must be used to maintain acceptable life and operational requirements under such extreme heat load conditions. Film cooling is the introduction of a secondary fluid (coolant or injected fluid) at one or more discrete locations along a surface exposed to a high temperature environment to protect that surface not only in the immediate region of injection but also in the downstream region and this technique will used in this paper.

Several researches and development activities have proved that using cylindrical holes in film cooling had disadvantages in gas turbine applications due to the jet lift off the surface, particularly at higher momentum flux ratios (~1 and above) leading to the deterioration of the film cooling performance. Therefore, the research for new developments to optimize film cooling performance has been intensified in recent years.

The film cooling performance parameters such as heat transfer coefficient (h) and film cooling effectiveness ($\eta$) to find the net heat flux reduction over blade surface are dependent on the film cooling geometry and the coolant and mainstream flow fields. Some studies have focused only on the heat transfer coefficient enhancement, and others have presented only film effectiveness results and others presented each of these parameters. In this paper adiabatic film cooling effectiveness has been studied.

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### 1.1. A review of studies on film cooling effectiveness

A large number of papers have been published on the topic of shaping the film cooling hole. Shaped holes have been proven to provide the highest adiabatic effectiveness among film cooling configurations as investigated in Saumweber and Schulz [2], Goldstein et al. [3], Sen et al. [4], Thole et al. [5], Laveau and Abhari [6] and Gao and Han [7]. But the Shaped holes are expensive to manufacture. Instead of using holes with shaped exits, Na and Shih [8] have introduced a design concept where an upstream ramp with backward-facing step is positioned directly in front of the cooling exit. Barigozzi et al. [9and10] have shown that an upstream ramp in the front of a cylindrical hole can have a thermal protection improvement. Rallabandi et al. [11] focused on the problem of determining the heat load reduction due to film-cooling holes with an upstream step. But step studies need to determine the heat transfer coefficients in details and to optimize the steps dimensions.

Sister holes another technology investigated by Ely and Jubran [12] to increase cooling effectiveness by reducing pockets of reversed flow.

Nasir et al. [13] investigated triangular tabs that are located along upstream edge of the holes. These tabs increased cooling effectiveness, but this application shown an increase in pressure drop. Certain configurations of cylindrical holes embedded in transverse trenches have been shown to perform similarly to shaped holes, and trenches would be cheaper to manufacture than shaped holes. Several studies have investigated various trench configurations such as Bunker [14], Waye and Bogard [15], Lu et al. [16], Harrison and Bogard [17], Jia et al. [18], Zuniga and Kapat [19].

Rhee et al. [20] conducted an experimental study to measure the local film-cooling effectiveness and the heat transfer coefficient for four different cooling hole shapes such as a straight rectangular hole, a rectangular hole with laterally expanded exit, a circular hole and a two-dimensional slot are tested. The results showed that the rectangular holes provide better performance than the cylindrical holes. For the rectangular holes with laterally expanded exit, the penetration of jet is reduced significantly, and the higher and more uniform cooling performance is obtained even at relatively high blowing rates. The reason is that the rectangular hole with expanded exit reduces momentum of coolant and promotes the lateral spreading like a two-dimensional slot.

The above review revealed that the development of film cooling has aimed at producing high film effectiveness and low heat transfer coefficient, with uniform protection of the surface, using

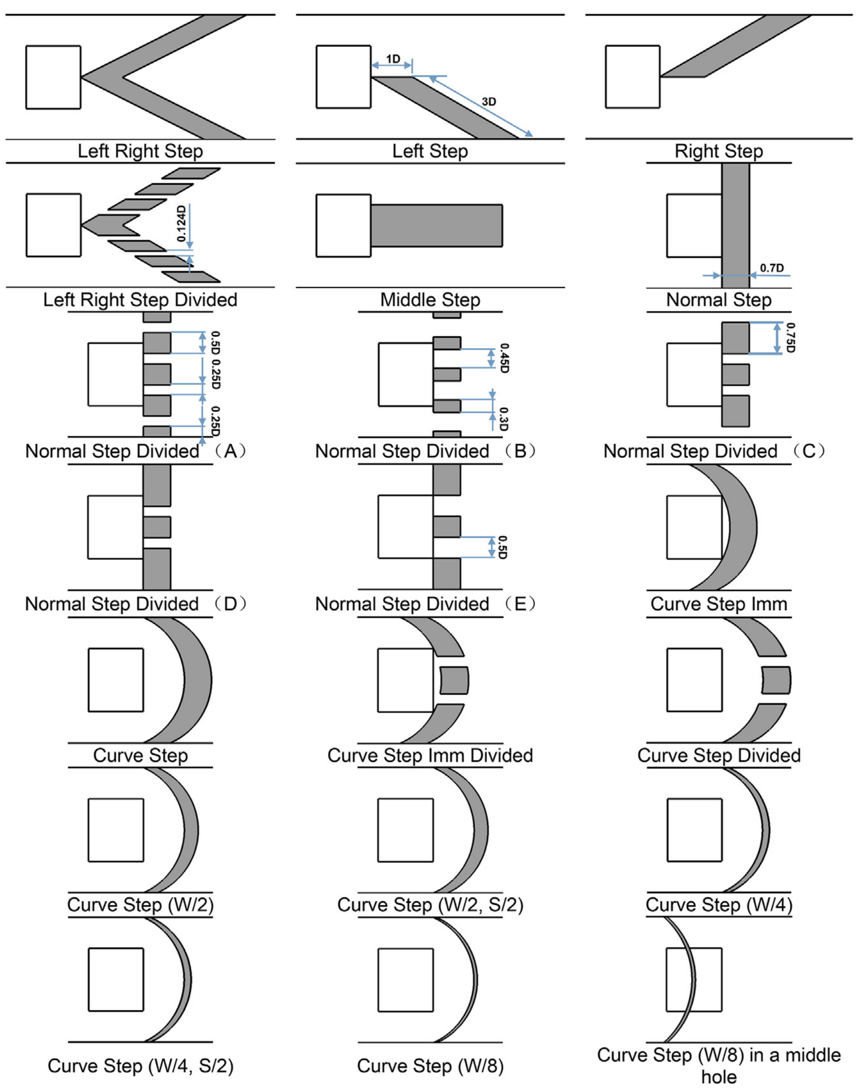


**Fig. 1.** All configurations under tested.