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Research paper

Effect of discrete-hole arrangement on film-cooling effectiveness for the endwall of a turbine blade cascade

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HIGHLIGHTS

- Film cooling in a turbine cascade endwall with discrete holes was investigated.
- Two different discrete-hole configurations have been considered.
- The adiabatic film-cooling effectiveness was measured by liquid crystal thermography.
- Maps of effectiveness were used to compare the performance of two hole arrangements.
- Effectiveness was selectively averaged in regions at the largest heat transfer need.

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ABSTRACT

This paper investigates film cooling in a turbine cascade endwall for two discrete-hole configurations using liquid crystal thermography. The discrete holes, arranged in rows aligned in the pitchwise direction, gave rise to relative maxima of film-cooling effectiveness downstream of each row, followed by a marked decrease of effectiveness along the gap between adjacent rows of holes. This resulted in a not efficient coverage of the endwall surface, with succession of over- and under-cooled regions. The redesign of discrete-hole configuration, based on knowledge of the heat transfer coefficient map on the endwall without film cooling, enabled the redistribution of the coolant to provide a better coverage of the endwall and a significant increase of the area-averaged film-cooling effectiveness.

1. Introduction

Film cooling has been widely used in high-performance gas turbine to protect turbine blades and endwalls from being damaged by hot gases [1]. It is based on the introduction of a secondary fluid (the coolant) through injection holes or slots placed in the blade and endwall material to form a protective layer between the surface and the hot mainstream gas.

Endwall film cooling and associated heat transfer are strongly influenced by the secondary flow effects. Thus, locating film-cooling holes requires a deep understanding of secondary flow behaviour and associated heat transfer. Blair [2] was the first to measure the film-cooling effectiveness and convective heat transfer coefficient distributions on the endwall of a large-scale turbine vane passage. A cooling slot upstream of the passage channel leading edge was employed and results, obtained from several thermocouples embedded in the wall material, were presented for a range of blowing ratios. One of the key findings was that the effectiveness distributions showed extreme variations across the vane passage with much of the coolant from the upstream injection slot being swept across the endwall toward the suction side corner. Takeishi et al. [3] measured the film-cooling effectiveness distributions on the blade and endwall surfaces of a low speed, fully annular, low aspect ratio vane cascade, using surface-mounted thermocouples. Film-cooling holes were placed on the model vanes and on the inner and outer endwalls. They found that passage secondary flows strongly affect heat transfer and film cooling on the suction surface of the vane and the endwalls. Film-cooling performance for injection through discrete holes in a turbine blade endwall was investigated by Jabbari et al. [4] by using a mass transfer technique based on ammonium–diazo-paper. Visualization experiments revealed the paths and interaction of the jets, which changed with blowing and density ratios. Friedrichs et al. [5–7] conducted aerodynamic and film-cooling measurements for

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a cascade endwall; the ammonia and diazo technique was employed to measure the film-cooling effectiveness. They indicated a marked influence of the secondary flows on the film cooling and, at the same time, an influence of the film cooling on the secondary flows. An improved endwall film-cooling configuration was tested experimentally and results were compared with those obtained for a baseline cooling configuration, consisting of rows of holes at four axial positions [7].

More recently, Kost and Nicklas [8] and Nicklas [9] investigated the aero-thermal behaviour of a transonic cascade with endwall film cooling. Similar investigations, but on different endwall cooling schemes, were also performed by Knost and Thole [10,11]. In Refs. [8–11], a combination of cooling from an upstream slot with film-cooling holes in the passage of the vane was considered; film-cooling effectiveness results were obtained by using the infrared thermography as diagnostic tool.

Significant improvement can be achieved in cooling characteristics of the film by using cooling holes with appropriately designed expanded exits, which are able to provide better lateral coverage and better centreline effectiveness. Barigozzi et al. [12] and Colban et al. [13] experimentally studied (by liquid-crystal and infra-red thermography, respectively) the effect of fan-shaped film-cooling holes for a vane endwall. Fan-shaped holes were found to give a superior cooling performance compared to that of cylindrical holes, but with the drawback of increased manufacturing cost and difficulty, particularly for the vane platform region.

The aim of the present study is to investigate the film-cooling effectiveness improvement gained by the re-design of the cooling configuration, based on knowledge of the heat transfer coefficient map with no film cooling measured in Ref. [14], without introducing any larger complexity in the real machine manufacturing (hence avoiding fan-shaped holes, for example, or very expensive micro-holed surfaces).

2. Experimental facility

The experiments were performed in a blow-down type wind tunnel housing a large-scale high-pressure turbine blade cascade (Fig. 1). An auxiliary apparatus was used to inject a secondary fluid for the film-cooling of the cascade endwall. For practical reasons, the experiments were conducted with a cold air mainstream as primary fluid and a hot "coolant" air flow as secondary fluid according to a common practice followed in similar investigations. The coolant air flow, controlled by a variable speed fan and measured by means of a Venturi flowmeter, was heated by an electric heater and delivered to a plenum located underneath the cascade endwall. This process resulted in temperature differences between the coolant and mainstream in the 9–35 K range.

2.1. Test section and film-cooling geometry

The linear cascade, shown in Fig. 1, is characterized by a blade chord of 312.5 mm, a height of 210.2 mm and a cascade pitch of 339.4 mm. The flow entered at a zero angle. The Zweifel coefficient of the cascade was 1.01. The endwall boundary layer at the cascade inlet was 18 mm thick with a displacement thickness of 2.22 mm, a momentum thickness of 1.92 mm, and a shape factor of 1.16. Fillets with a round profile extending for 10 mm along the endwall and blade surfaces were used for contouring. Since periodicity attainment required at least three passages, cascade consisted of four blades; measurements were performed in the central passage, where the heated endwall was located. The cascade periodicity, imposed by the modification of the flexible tailboards installed at the exit of the external blades, has been then checked by comparing the aerodynamic loadings measured over the two central blades.

The investigated blade cascade has been previously aerodynamically tested without film cooling in Ref. [15]; similarly, endwall heat transfer without film cooling was experimentally studied in Ref. [14]. For the film-cooling experiments, the film-cooled endwall region was made of a 19 mm-thick layer of balsa wood having a low thermal conductivity (=0.065 W/mK), in order to provide a nearly adiabatic surface, suitable to allow adiabatic film-cooling effectiveness measurements.

The endwall regions immediately upstream and in the passage of the cascade featured discrete holes, arranged according to the two different layouts shown in Fig. 2. Regardless of the discrete-hole geometry, all the holes were cylindrical in shape, had a diameter of 5 mm (length to diameter ratio of 7.6) and ejected at a

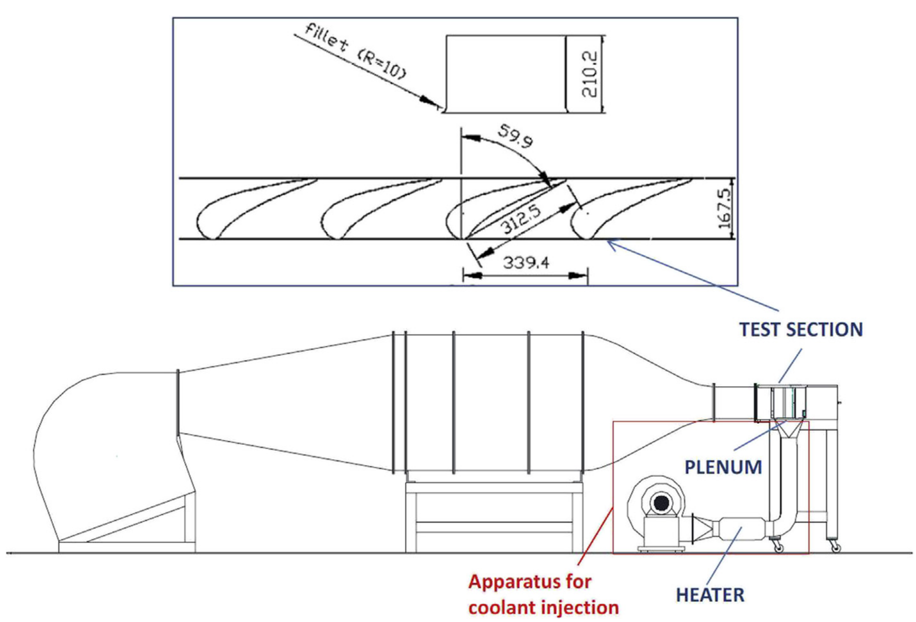

Fig. 1. Schematic of the experimental facility and of the turbine cascade. Dimensions in [mm].