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Local end-wall heat transfer enhancement by jet impingement on a short pin-fin

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ABSTRACT

A short pin-fin array has been used to improve the internal cooling characteristics at the trailing edge of some gas turbine blade designs. In such a cooling scheme, the pin-fin array that is sandwiched by the turbine blade's inner surfaces, experiences a uniform-like coolant stream. The local elevation of internal heat transfer especially on the end-walls (i.e., inner blade surfaces) at the trailing edge is achieved predominantly by horseshoe vortex-type secondary flows whose fluidic behavior has been well established. A modification to this cooling scheme has been made by introducing a blockage upstream, causing multiple jets to impinge on the pin-fins – the blockage jets. Previous studies on the internal cooling scheme employing the blockage jets have assumed that the end-wall flow topology is similar to that formed by the horseshoe vortex-type secondary flows due to similar local heat transfer distributions. However, there is no detailed and sufficient acknowledgement made of the lack of an approaching boundary layer. Therefore, the present study experimentally investigates local heat transfer around a single short pin-fin subjected to a fully turbulent jet impingement simulating the blockage jet impingement and demonstrates that the end-wall flow topology loosely resembles that formed by a horseshoe vortex system and is strictly different, depending on the distance between the jet exit and the pin-fin, relative to the length of the jet's potential core.

1. Introduction

The trailing edge of a gas turbine blade such as that shown in Fig. 1(a), particularly suffers from inadequate internal and external cooling because of aerodynamic design constraints that require a thin trailing edge [1]. Amongst other internal cooling augmentation designs, the insertion of an array of short pin-fins as shown in Fig. 1(b), has been widely adopted. In most designs, the pin-fin array is subjected to a "uniform-like" coolant stream. Using this augmentation, the increase in heat transfer over that of an empty channel is known to be due to two primary factors [2]. Firstly, the pin-fins enlarge the surface area, compared to an empty internal cooling passage at the trailing edge. Secondly, the boundary layer separates from the end-wall around each pin-fin due to an adverse pressure gradient. As a result, horseshoe vortex-type secondary flows (or simply called "horseshoe vortices") are formed around each pin-fin [3]. The horseshoe vortices then act to increase the turbulence intensity and to promote flow mixing due to the vortical flows in the vicinity of the end-wall surfaces.

In some other gas turbine blade designs, a modification to the pin-fin cooling augmentation has been made through the implementation of perforated plates (the so-called "blockages") placing upstream of the pin-fins. These blockages create concentrated jets to impinge on the pin-fins as illustrated in Fig. 1(c), termed "the blockage jets." From previous studies [4,5], the use of the blockages increases heat transfer that takes place at the trailing edge, compared to that without the blockages. The study by Moon and Lau [4] observed the increased heat transfer at the blockages without a pin-fin array downstream. On the other hand, the numerical simulation by Hong et al. [6] focused on heat transfer at the blockages with a pin-fin array downstream but neglected their effects on the pin-fin array. Kan et al. [5] numerically examined heat transfer around an array of pin-fins but only briefly mentioned the end-wall flow patterns where the stream-lines were noted as pointing out radially from the pin-fin leading edge and the horseshoe vortices were not significant. The flow topology elsewhere, away from the pin-fin leading edge, was overlooked and, furthermore, heat transfer differences with the uniform stream and the jet impingement were not linked to the flow topologies. While there was a difference in heat transfer, a possible increase of 20–50% for the jet impingement [5], the fluidic mechanisms responsible for these differences, specifically relating to the end-wall flow topology, have been ignored.

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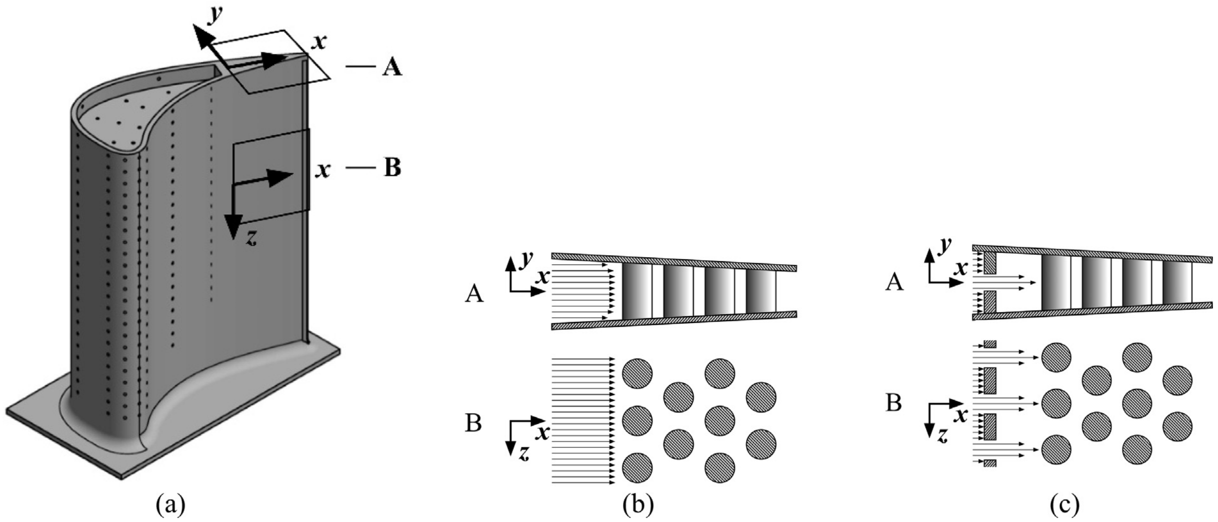

Fig. 1. Internal cooling of a high pressure (HP) gas turbine blade: (a) A CAD design of a HP gas turbine blade, (b) schematics of internal cooling configuration at the trailing edge, employing a pin-fin array subjected uniform-like coolant stream, and (c) schematics of internal cooling configuration at the trailing edge, employing a pin-fin array subjected the blockage jets.

The end-wall flow topology around an array of short pin-fins with blockage jets has been overlooked because a similar end-wall flow topology to a horseshoe vortex system has been assumed [5]. For pin-fin aspect (length-to-diameter) ratios less than $H/D = 2.0$, heat transfer is independent of the aspect ratio for the uniform flow case; the end-wall (secondary) flows being the dominant effect [7]. As the pin-fins at the turbine blade trailing edge have low aspect ratios, in practice, of 0.5–4.0 [8–11], the secondary flows formed around such short pin-fins have to be taken into consideration.

After impingement (and stagnation) on to the pin-fin without the end-walls, a wall jet forms on the pin-fin leading edge, moving away from the stagnation point in the plane of symmetry (Fig. 2(a)). This has been shown by Jiao [12] using laser induced fluorescence (LIF) flow images. On the other hand, with the end-walls that laterally confine the jet, the wall jet stagnates on the end-walls before moving upstream as illustrated in Fig. 2(b). On the end-walls, upstream of the pin-fin, there is no apparent approaching stream (or boundary layer flow), moving towards the pin-fin. Kan et al. [5] briefly described the same behavior based on their numerical simulations but did not realize the lack of an approaching boundary layer flow. Without a boundary layer stagnating on the pin-fin and separating from the end-walls, the mechanism for the formation of horseshoe vortices is absent. Based on the conjectured flow topologies in the plane of symmetry in Fig. 2(b), an entirely different end-wall flow topology to that of a horseshoe vortex system is expected.

The end-wall flow topology especially upstream of a pin-fin subjected to an impinging jet should, therefore, not always be expected or assumed to feature horseshoe vortices. Accordingly, the fluidic features responsible for the measured heat transfer values should also not always be attributed to features inherent in a horseshoe vortex system. The present study, therefore, aims to clarify the end-wall flow topology and consequential heat transfer characteristics around a short pin-fin subjected to the fully turbulent round jet impingement that roughly simulates the blockage jet impingement on a short circular pin-fin. Our specific focus is placed on experimentally demonstrating end-wall flow patterns and their effect on heat transfer characteristics around the circular pin-fin with an emphasis on their dissimilar features, if present, to those of horseshoe vortices. To this end, a series of end-wall flow measurements have been conducted around a short circular pin-fin that is subjected both to a fully turbulent uniform-like stream and fully turbulent round jet impingement. The former serves as

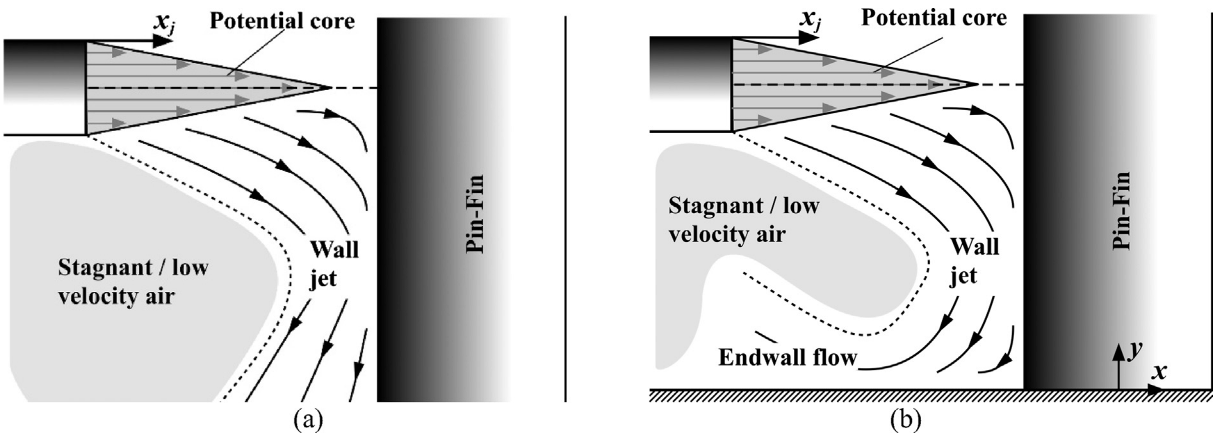

Fig. 2. Flow schematics in the plane of symmetry for a pin-fin subjected to a turbulent jet impingement: (a) For a high aspect ratio pin-fin (produced based on the LIF data from Jiao [12]) and (b) for a low aspect ratio pin-fin with end-wall flow (conjectured based on the impinging round jet on a flat plate with lateral confinement).