International Journal of Heat and Mass Transfer 97 (2016) 502–510

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Experimental study on heat transfer improvement structures with staggered transverse elongated pedestal array

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ARTICLE INFO

Article history:
Received 17 July 2015
Accepted 10 February 2016

Keywords:
Heat transfer coefficient
Liquid crystal thermometry
Elongated pedestal array
Lumped capacitance method

ABSTRACT

Experiments have been conducted to investigate the overall thermal performance of a rectangular channel implemented with an elongated pedestal array. The staggered pedestals were elongated transversely (perpendicular to flow direction) in order that the jet flow from between the pedestals impinges at the center of the pedestals in downstream row. The average heat transfer of the pedestal and endwall surfaces were measured by the lumped capacitance method and transient liquid crystal method, respectively. The pressure drop across the pedestal arrays was measured. The heat transfer coefficients were measured over the Reynolds number range from 6000 to 25,000. Four test sections were designed to evaluate the effect of geometric parameters, i.e. major axis to minor axis ratio $D/d = 5.0$ and 8.0, $X/d = 0.8$–1.2, $S/d = 1.175$–1.5. Conclusions were drawn as the elongated pedestal array provided considerably high heat transfer enhancement. However, the overall thermal performance was compromised by a very high pressure drop across the pedestal array.

1. Introduction

The hot gas-path airfoil components of modern gas turbine engines operate under hostile environments with temperatures far exceeding the melting temperature of metal. In order to achieve maximum possible thermal efficiency for modern gas turbine engines, the turbine entry temperature will continue to rise to higher levels. To enable gas turbine engines to operate at such high temperatures, effective cooling strategies were required to hot-path components to gain its reliability and durability. The typical cooling technologies for gas turbine engine includes pin–fin, jet impingement and rib-turbulator as internal cooling and film cooling as external cooling.

Pedestal, also known as pin–fin, is widely used in industry, such as electronic component cooling and heat exchangers. It is also a popular and effective means for gas turbine cooling, especially the trailing edge section of the airfoil. It not only offers significant heat transfer enhancement, but also robust structural support for hollow trailing edge regions. Pedestal promotes heat transfer on airfoil walls by disturbing thermal boundary layer development over the surface, increasing the effective heat transfer area and affecting downstream flow turbulence. Detailed description on mechanism of heat transfer enhancement by pedestal could be found in Incropera & Dewitt [1]. Lau et al. [2] observed that pin fins commonly used in turbine cooling have a pin height-to-diameter ratios typically between ½ and 4. Numerous studies have been carried out by scholars from NASA-Lewis (Vanfossen [3], Brigham and Vanfossen [4] and Simoneau and Vanfossen [5]) and Arizona State University (Metzger et al. [6–10]) who made significant contributions on pedestal heat transfer for turbine airfoil cooling. Brigham and Vanfossen [4] investigated the effects of H/d (height-to-diameter ratio) and streamwise pitch variation on array averaged heat transfer. They concluded that streamwise pitch had slight effect on staggered pin–fin array heat transfer. In addition, the results revealed that the Nusselt number is only a function of Reynolds number for $H/d < 2.0$, however, for $H/d > 2.0$, the Nusselt number becomes a function of H/d as well as Reynolds number. An extensive literature survey also including the above studies was presented by Armstrong and Winstanley [11]. In this survey, the effects of pedestal array configuration, spanwise and streamwise pitch, height-to-diameter ratio, channel convergence and flow parameters on heat transfer for both pedestal surface and endwall surface were discussed and concluded. Corresponding empirical correlations of endwall and pedestal surface heat transfer from previous studies were given. They also gave recommendations about the conditions and limitations for using the heat transfer correlations presented by Metzger et al. [7] and VanFossen [3] for short pins and by Faulkner [12] for long pins. An inconsistency of pin heat transfer coefficient versus endwall heat transfer

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.02.025
0017-9310/

Nomenclature

μ	dynamic viscosity	Nu_0	reference Nusselt number
A	area	Re	Reynolds number
Bi	Biot number	S	spanwise pitch
d	diameter/minor axis	T	temperature
D	major axis	t	time
D_h	hydraulic diameter	T_i	initial temperature
H	pedestal height/channel height	T_∞	bulk temperature
h	heat transfer coefficient	T_w	wall temperature
k_{alu}	thermal conductivity of aluminum	Δp	pressure difference
k	thermal conductivity	U_m	mean velocity
L	channel width	U	maximum velocity
l	distance between pressure tapes	X	streamwise pitch
$\bar{m}$	mean mass flow rate	Pr	Prandtl number
m	mass		
Nu	Nusselt number		

coefficient was found among these early studies. VanFossen [3] suggested that the heat transfer coefficient from the pin surface is about 30% higher than that of the endwall for staggered pin–fin arrays with $0.5 < H/d < 2.0$, $S/d = X/d = 3.46$. Metzger et al. [6] conducted similar experiment for $2.5 < S/d < 3/5$, $1.5 < X/d < 3.5$, $H/d = 1$ and suggested that the pin surface heat transfer coefficient is about double of that for endwall. Furthermore, Al Dabagh and Andrews [13] used a transient heating technique and obtained contradictory results from staggered arrays with $S/d = 2.0$, $X/d = 1.5$ and $H/d = 0.7$, 1.0, 2.2. The results reported that the pin heat transfer coefficient is about 15–35% lower than that of endwall. Chyu et al. [14] suggested that the inconsistency might result from different thermal boundary conditions used for the measurements. Chyu et al. [14] used a naphthalene sublimation method to examine the effect of thermal boundary condition with staggered array of $H/d = 1.0$ and $S/d = X/d = 2.5$. The results illustrated the pin surface heat transfer coefficient is about 10–20% higher than that of endwall. Recently, Chyu et al. [15] conducted an experiment using hybrid liquid crystal technique to explore the effect of height to diameter ratio on heat transfer characteristics of pin fin arrays. The conclusion was drawn that the pin surface heat transfer coefficient is consistently higher than that of endwall, by about 35–70%. Furthermore, Metzger et al. [6] observed that the heat transfer peaked at the third to fifth row and decayed after fifth row which benefits from the interaction between wakes created by upstream pins and obstructions created by downstream pins. Later, Chyu [16,17] used the naphthalene sublimation method to investigate influence of pin-to-endwall fillet and heat transfer performance of four protruding elements (i.e. cube, cylinder, pyramid and hemisphere). Chyu [16] indicated negative influence of fillet to heat transfer. In addition, Chyu and Natarajan [17] have used flow visualization to study the flow behavior near a pin and its mounting surface boundary layer. Most pin fin researches at early stage focused on the determination of heat transfer and pressure loss characteristics of circular pin fin. Nevertheless, there were also some researches based on different pin fin shapes and concepts. Metzger et al. [9] experimentally investigated the heat transfer characteristics of oblong pins with major axis to minor axis ratio of 2 ($D/d = 2$) and various orientations with respect to the main flow. The results indicated that oblong pin fin arrays have higher heat transfer enhancement along with higher level of pressure loss. Kirsch et al. [18–20] further investigated the heat transfer performance of oblong pin fin array which included the heat transfer profile along the mid-span of oblong pin surface. Also, they examined the thermal performance of a circular pin fin array with the second row replaced with oblong pins. Chyu et al. [21] conducted a mass transfer experiment and investigated the thermal performance of square, diamond and circular pin fin arrays with $H/d = 1$, $S/d = X/d = 2.5$ for both in-line and staggered arrays. The results revealed that the square pin fin array provided the highest heat transfer coefficient with moderate pressure penalty. Chyu et al. [21] recommended the square pin fin array as an alternative feature for trailing edge cooling. Uzol and Camci [22,23] used liquid crystal and PIV techniques to examine the heat transfer and flow characteristics of an elliptical pin fin array for $D/d = 1.0$, 1.65, 2.5. The results showed that the wall heat transfer enhancement of circular pin is about 25–30% higher than that of the elliptical pin, but circular pins generate 100–200% more pressure loss. However, Li et al. [24] performed a similar study on elliptical pins using the naphthalene sublimation technique and presented contradictory results, although in a different Reynolds number range. Li et al. [24] conducted the experiment at Reynolds number range of 1000–10,000 and the results given for the elliptic pin had a slightly higher heat transfer coefficient than the empirical correlation suggested by Metzger [6], with much lower pressure drop. Meanwhile, Uzol and Camci [22,23] carried out their experiments in the Reynolds number range of 10,000–47,000. Moon et al. [25] numerically studied heat transfer and pressure characteristics of single fan shaped pin in the Reynolds number range of 5000–100,000. The conclusion was drawn that the maximum heat transfer improvement was about 22.8% higher than circular pin and was found at a Reynolds number of 80,000.

Many comparative studies have been conducted to investigate the effect of pin spacing on the thermal performance of pin–fin arrays. Metzger et al. [6] studied the effects of streamwise spacing by independently varying the streamwise spacing relative to the spanwise spacing and concluded that the closely spaced arrays obtained higher heat transfer than widely spaced arrays. Lyall et al. [26] conducted an experiment to investigate the pin heat transfer and endwall heat transfer in single row of pin–fin and found that the pin heat transfer increased with an increase of spanwise spacing, however, the endwall heat transfer showed a reversed trend with increase of spanwise spacing. Recent research by Lawson et al. [27] has been carried out to determine the independent effects of spanwise and streamwise spacing on heat transfer and pressure loss through a multiple row array of pin–fins. Results indicated that the heat transfer in an array of pin–fins increased with a decrease of spanwise and streamwise spacing. Moreover, the spanwise spacing had a stronger effect than the streamwise spacing on the pressure drop while streamwise spacing had a stronger effect than spanwise spacing on heat transfer. Ostanek and Thole [28] investigated the thermal performance of non-uniform streamwise