Applied Thermal Engineering 51 (2013) 435–441

Contents lists available at SciVerse ScienceDirect

Applied Thermal Engineering

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

Heat transfer augmentation using a rib–dimple compound cooling technique

Eun Yeong Choi [a], Yong Duck Choi [a], Won Suk Lee [b], Jin Teak Chung [b], Jae Su Kwak [a,*]

[a] School of Aerospace and Mechanical Engineering, Korea Aerospace University, 200-1 Hwajeon-Dong, Deogyang-Gu, 412-791 Goyang City, Republic of Korea

[b] School of Mechanical Engineering, Korea University, 136-713 Seoul, Republic of Korea

HIGHLIGHTS

► Dimple–rib compound cooling technique for internal cooling of gas turbine blade is proposed.
► Detailed heat transfer coefficient and pressure loss measurement results are presented.
► The proposed compound cooling technique showed better thermal performance than rib only or dimpled only cooling technique.

ARTICLE INFO

Article history:
Received 19 March 2012
Accepted 30 September 2012
Available online 8 October 2012

Keywords:
Gas turbine blade cooling
Compound cooling
Dimple cooling
Rib turbulated cooling
Internal cooling

ABSTRACT

Detailed distributions of the heat transfer coefficients in the channel with both angled ribs and dimples were measured using the transient liquid crystal technique. For comparison, heat transfer coefficients for dimpled and angle ribbed channels were also presented. The channel aspect ratio was designed to be 2 and 4 in order to simulate the internal coolant passage of a gas turbine blade. The rib pitch, rib angle, dimple diameter, and dimple center-to-center distance were 6 mm, 60°, 6 mm, and 7.2 mm, respectively. The Reynolds number based on the channel hydraulic diameter ranged between 30,000 and 50,000. Results show that the distribution of heat transfer coefficient was asymmetric due to the secondary flow induced by the angled ribs. Also, dimples fabricated between the ribs increased the heat coefficient with an acceptable increase in pressure drop. Thus, the compound cooling technique with angled rib sand dimples should be considered as a candidate for improving the heat transfer performance of a gas turbine blade internal cooling technique.

1. Introduction

Gas turbine inlet temperature (TIT) has been increased in order to increase the efficiency and power output of gas turbine engines. As a result, the TIT of modern gas turbines began to exceed the permissible operating temperature of gas turbine blade materials. Thus, various cooling techniques have been applied in order to ensure the performance and life of turbine components. With respect to turbine blade internal cooling, a number of techniques have been applied, including rib turbulated cooling, dimple cooling, pin-fin cooling, and jet impingement cooling. A lot of research has been conducted in order to improve the heat transfer performance and pressure drop characteristics of the turbine blade internal cooling technique.

Han et al. [1] showed that heat transfer augmentation using orthogonal ribs and angled ribs were similar, but the pressure loss through the ribbed channel was smaller for the angled rib channel. Park et al. [2] investigated the effects of the rib angle on the heat transfer performance in the channel with various aspect ratios. Their results indicated that the 60° angled rib showed the highest heat transfer augmentation. Kim et al. [3] compared rib turbulated cooling, jet impingement cooling, and dimple cooling techniques in heat transfer augmentation and concluded that the jet impingement cooling technique induced the highest heat transfer coefficient, while the ratio of the heat transfer augmentation to the pressure loss was the highest for the dimpled channel. Ligrani and Blaskovich [4] researched rib, pin-fin, and dimple cooling techniques. Stephens et al. [5] showed that the rib installed on the endwall induces two count-rotating vortices, and the wall heat transfer coefficient is strongly affected by the vortices, of which structure is influenced by the Reynolds number, rib pitch, and rib width to height ratio. Burgees and Nigrani [6] investigated the effect of Reynolds number and dimple depth on the heat transfer in a dimpled channel and showed that the heat transfer augmentation was higher for the case with deeper dimples. Mahmood et al. [7] studied the effect of wall to mainstream temperature ratio in

* Corresponding author. Tel.: +82 2 300 0103.
E-mail address: jskwak@kau.ac.kr (J.S. Kwak).

1359-4311/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.applthermaleng.2012.09.041

Nomenclature

d	dimple depth
D	dimple printed diameter
D_h	channel hydraulic diameter
e	rib height
f_0	friction factor for fully developed turbulent flow in a smooth duct
h	heat transfer coefficient
k	thermal conductivity of the test section
l	rib thickness
Nu	Nusselt number, hD_h/k
p	rib pitch
Pr	Prandtl number
Re_{Dh}	Reynolds number based on hydraulic diameter
S	dimple center-to-center distance
t	transient time
α	thermal diffusivity
ρ_m	density of mainstream fluid

a one side dimpled channel and showed that the heat transfer augmentations became larger as the inlet stagnation temperature to the wall temperature ratio decreased.

Some researchers have tried to combine two cooling techniques in order to enhance the heat transfer performance. Chang et al. [8] studied the compound heat transfer enhancement surface with V-ribs and scales, and showed that the heat transfer coefficient that resulted from using the compound technique was higher than that of the V-ribs only case. Haiping et al. [9] studied the compound heat transfer augmentation technique in combination with the rib and impingement cooling technique.

Previous research has indicated that the angled ribs effectively increase the heat transfer coefficient in a channel, and the dimples show better thermal performance (ratio of heat transfer augmentation to the increase in pressure drop). In this study, a new concept of cooling technique, a rib–dimple compound cooling technique, is proposed, and the detailed heat transfer coefficient measured using the hue detection based transient crystal technique and pressure drop are investigated.

2. Experimental setup

Fig. 1 presents the test apparatus which consists of a Venturi flow meter, a blower ($p_{max} = 4800$ mm H_2O, $Q_{max} = 9.8$ m^3/min), an electrical heater (12 kW), two pneumatic valves, a digital CCD camera (AVT F030C, Stingray), image capturing board (NI PCIe-8255R), DAQ (NI SCIX-1125 and NI PCI-6221). The test section was made of transparent acrylic, and the width of the test section was 100 mm. Two test section heights of 25 mm and 50 mm were tested, and the corresponding hydraulic diameters (D_h) were 0.04 m and 0.067 m, respectively. The corresponding aspect ratios were 2 and 4, respectively. A detailed view of the test section is shown in Fig. 2. Dimples or ribs were fabricated on the bottom plate only. The diameter of the dimples (D), the thickness (l), and height (e) of the ribs were 6 mm, and the ratio of rib thickness to height (l/e) was 1. The rib installation angle with respect to the flow direction was 60° and the pitch (p) between the ribs was ten times the rib thickness, i.e., p/e was 10. The ratio of rib height (e) to the hydraulic diameter (D_h) of the test section was 0.09 or 0.15, depending on the channel height. The dimple depth (d) to the dimple diameter (D) ratio and dimple center-to-center distance (S) to the dimple diameter ratio (D) were 0.191 and 1.2, respectively. The tested Reynolds number based on the channel hydraulic diameter ranged from 30,000 to 50,000.

During the heat transfer measurement tests, in order to achieve a transient test condition, the heated air was bypassed until the air temperature reached a predetermined value. After the air temperature reached the specified value, the air was diverted toward the test section by two pneumatic valves. Then, the color change of the liquid crystals was captured using the digital CCD camera and the captured images were used in order to calculate transient time, which will be discussed later. During the heat transfer test, the mainstream temperature was measured by six T type thermocouples installed upstream and downstream of the test section as shown in Fig. 2. In the heat transfer coefficient calculation, the mainstream temperature at each location was calculated based on the distance between thermocouples and each location.

3. Heat transfer measurement theory

The heat transfer coefficient was measured using the hue detection based transient liquid crystal technique. In this

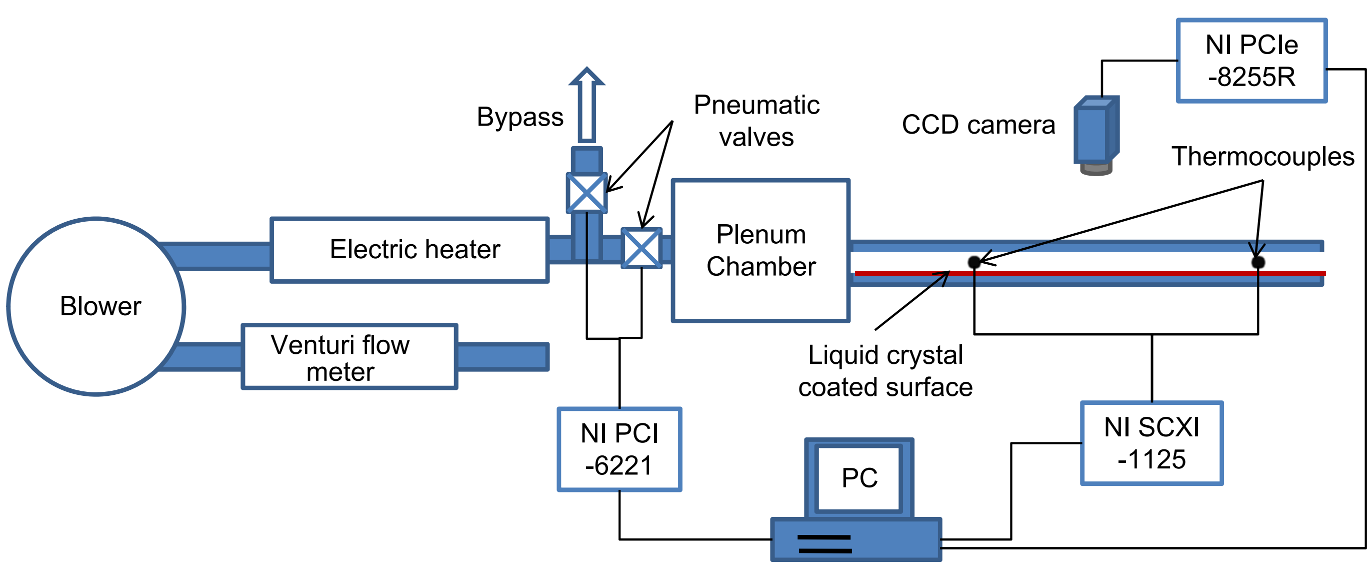

Fig. 1. Experimental setup.