International Journal of Heat and Mass Transfer 97 (2016) 224–231

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Heat transfer in a rectangular duct with perforated blockages and dimpled side walls

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ARTICLE INFO

Article history:
Received 31 July 2015
Received in revised form 15 December 2015
Accepted 25 January 2016

Keywords:
Heat transfer
Gas turbine blade
Trailing edge cooling
Compound cooling
Perforated blockages

ABSTRACT

Heat transfer and pressure drop in a duct with three serial perforated blockages equipped with staggered jets were experimentally investigated. Eight types of jet holes and three types of side walls, including dimpled walls, were tested. For heat transfer measurements, the transient liquid crystal technique was used. Reynolds numbers based on the hydraulic diameter of the duct and inlet velocity ranged from about 10,000–30,000. Experimental results showed that the Nusselt number ratios decreased as the Reynolds number increased, and the friction factor ratios increased as the Reynolds number increased. The heat transfer coefficient and the pressure loss were strongly affected by the number and the configuration of jets. Compared to the smooth side wall case, the cases with dimpled side walls showed large increases in heat transfer with slight increments in pressure loss. Therefore, it was determined that the thermal performance factor could be enhanced by up to 25% by using a dimpled side wall in the duct with perforated blockages.

1. Introduction

Modern gas turbines are designed to allow for turbine inlet temperatures that exceed allowable material temperatures in order to improve turbine performance and power output. High temperature combustion gas and complex flow phenomena near the blade aggravate the heat transfer problem of the gas turbine blade. As such, various cooling techniques have been applied to blade cooling designs. Fig. 1 shows commonly used internal cooling techniques for a gas turbine blade. Impingement cooling, rib turbulated cooling, dimple cooling, and pin-fin cooling techniques have been widely applied to gas turbine cooling designs, and many studies have been conducted in order to improve the heat transfer performance of those techniques [1].

Some researchers have proposed new concepts with respect to internal cooling techniques for the blade trailing edge. For example, Moon and Lau [3] investigated the pressure drop and heat transfer on a rectangular duct with two perforated blockage configurations. They showed that the number of walls and the configuration of holes did not significantly affect the heat transfer augmentation level. Lau et al. [4] investigated the heat transfer for the flow moving through blockages with holes in an internal cooling passage near the trailing edge region by using naphthalene sublimation. They studied the effects of inlet and exit geometry configurations and showed that the effects of the entrance channel and exit slot geometries were not significant to the average heat (mass) transfer or the distribution of the local heat (mass) transfer. Saha et al. [5] looked at the heat transfer and friction factor of a converging matrix structure with orthogonal ribs representing a gas turbine blade trailing-edge cooling passage. They showed that the matrix structure could result in an averaged Nusselt number enhancement factor of 3–4. Armellini et al. [6] and Coletti et al. [7] conducted experimental and numerical investigations of a trapezoidal cross-section model simulating a trailing edge cooling cavity with one rib-roughened wall and crossing jets. The interaction between the jets and ribs increased the heat transfer coefficient on both the bottom and upper wall. Shin and Kwak [8] measured the heat transfer coefficient in a turbine blade internal cooling passage model with five types of blockages. They showed that staggered impingement jets increased the heat transfer. However, the pressure drop also increased greatly. They concluded that the thermal performance for the perforated blockage could be improved by optimizing the hole shape. Kan et al. [9] investigated the combined effects between perforated blockages and pin fins in a cooling passage. Six different blockage configurations were investigated using both experimental and numerical methods. They showed that the hole-to-channel area ratio is the most important factor for heat transfer enhancement. Smaller area ratio cases showed larger heat transfer enhancements and larger pressure

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.01.081
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Nomenclature

D_h	hydraulic diameter, mm
f	friction factor
h	heat transfer coefficient, W/m^2 K
k	thermal conductivity, W/m K
p	pressure, pa
Pr	Prandtl number of air
Re	Reynolds number
T	temperature, °C or K
t	transient time, s
α	thermal diffusivity of blade material, m^2/s

Subscripts

0	for fully developed turbulent flow in a smooth duct
i	initial condition
m	mainstream
w	wall of test surface

drops. Ahn et al. [10] studied the turbulent forced convective mass transfer downstream of blockages with round and elongated holes in a rectangular channel using naphthalene sublimation. They investigated the effects of the hole aspect ratios, for each hole-to-channel area ratio, on the exposed channel wall. They found that the elongated holes showed a higher overall mass transfer on the channel wall than the round holes. Chung et al. [11] investigated the effects of the array pattern, hole size, and hole direction for the heat transfer and pressure loss on the side wall of a rectangular channel. They showed that the proposed inclined holes array presented improved cooling performance over a conventional configuration.

Previous research [3,4,8–11] has explored the possibility of improving the thermal performance of the internal cooling with perforated blockages. In this study, a compound internal cooling technique for the turbine blade trailing edge with repeated perforated blockages and dimpled side walls is proposed. Eight types of blockage holes were considered, and two of them were selected to be tested with the dimpled side walls. The effects of the jet hole and side wall configurations on the heat transfer and pressure loss were experimentally investigated.

2. Experimental setup and measurement methods

Fig. 2 shows the schematic of the test setup. The test setup consisted of a blower, a Venturi flow meter, an electrical heater (12 kW), two pneumatic valves with solenoid valves, a plenum chamber, and a rectangular duct with perforated blockages. Air was heated by the electrical heater and bypassed until a predetermined air temperature was reached. Then, the heated air was diverted toward the test section via the two pneumatic valves. A 280-mm wide, 35-mm high duct was connected to the plenum chamber, and three perforated blockages were installed in the duct. Fig. 3 presents a detailed view of the heat transfer measurement region. The heat transfer coefficient was measured on the side walls between the perforated blockages. Liquid crystals (35C1W, Hallcrest) were sprayed on the side wall, and black paint was sprayed over the liquid crystal coating. The color change of the liquid crystals was recorded using a digital CCD camera (AVT Stingray F033C) from the back of the liquid crystal coated surface, as shown in Fig. 2.

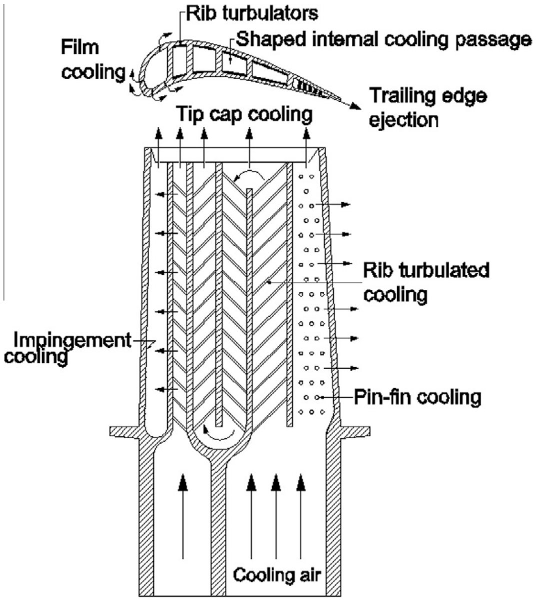

Fig. 1. Commonly used internal cooling techniques for a gas turbine blade [2].

Before conducting the heat transfer tests, the relation between the hue of the liquid crystals and the temperature was calibrated. Black paint and liquid crystals were sprayed on the 5-mm thick aluminum plate, and the temperature of the plate was controlled by a temperature controller. At each temperature step, the hue value was calculated from the color of the liquid crystals. Fig. 4 presents the liquid crystal calibration results.

In order to measure the mainstream temperature for each heat transfer measurement plane, a total of five T-type thermocouples for each measurement plane were installed, as shown in Fig. 3. The pressure drop through the perforated blockages was measured from a total of ten pressure taps installed upstream and downstream of the heat transfer measurement planes.

Fig. 5 presents the perforated blockages used in this study. The configuration of the blockages was selected by referring to results from the authors' previous study [8], in which the case with wider holes and the case with the greater number of holes showed better performance. Each blockage set consisted of three perforated blockages with the same configuration except for the hole locations. Holes for each blockage were fabricated so that the jet from the upstream blockage impinged to the downstream blockage between the jets. Hole sizes were determined so that the flow area for each blockage was the same for all blockages. Table 1 lists the configuration of each perforated blockage.

Fig. 6 shows the three types of side walls considered in this study. Fig. 6(a) shows the smooth side wall, and Fig. 6(b) and (c) show the dimpled cases with 15-mm and 7.5-mm diameter dimples, respectively. For both dimpled cases, the ratios of the dimple depth and dimple-to-dimple distance to the dimple diameter were 0.2 and 1.33, respectively.

The transient liquid crystal technique was used to measure the heat transfer coefficient. For this technique, the test model was assumed to be a one-dimensional semi-infinite model with a convective boundary condition. The governing equation, initial, and boundary conditions are as follows:

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \quad (1)$$