International Journal of Heat and Mass Transfer 62 (2013) 668–679

Contents lists available at SciVerse ScienceDirect

International Journal of Heat and Mass Transfer

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

Cooling performance analysis of steam cooled gas turbine nozzle guide vane

Wei Wang, Jianmin Gao, Xiaojun Shi, Liang Xu *

State Key Laboratory for Manufacturing Systems Engineering, Xi'an Jiaotong University, No. 28, Xianning West Road, 710049 Xi'an, Shaanxi, PR China

ARTICLE INFO

Article history:
Received 7 January 2012
Received in revised form 12 October 2012
Accepted 20 February 2013
Available online 12 April 2013

Keywords:
Cooling effectiveness
Steam cooling
Convection cooling
Gas turbine
Guide vane

ABSTRACT

As a new kind of advanced cooling technique, steam cooling has been applied in modern high temperature gas turbine blade cooling for improving the turbine efficiency. The superheated steam is selected as coolant to replace traditional compressor air as closed loop steam cooling for the internal convective cooling. This paper experimentally and computationally investigates the cooling performance of internal steam convective cooling in a nozzle guide vane with five smooth radial cooling ducts. Experiments are conducted on a linear turbine cascade at exit Mach numbers of 0.9, and exit Reynolds number of 1.2×10^6. Temperature and static pressure on the cooled vane surface are measured at the mid span for a range of coolant-to-mainstream temperatures ratio and coolant-to-mainstream mass flow ratio. The numerical investigations using the conjugate calculation technique are also performed to predict the complex three dimensional flow and heat transfer. The k–ω based Shear–Stress-Transport (SST) model is selected as the turbulence model. It can be found that the numerical results of vane temperature are underestimated compared with experimental data, especially at the trailing edge. The coolant steam has much higher cooling effectiveness than air, about 12%. The cooling effectiveness at the vane middle chord region is much higher than that at the leading and trailing region, by approximately 50% and 20%, respectively, which will lead to great temperature gradient and thermal stresses at the leading and trailing region. Therefore, more complicated cooling configuration besides convective cooling may be necessitated for this vane.

1. Introduction

To improve the overall cycle efficiencies of gas turbine engines, it is necessary to raise the inlet temperatures and compressor pressure ratio. However, highly efficient gas turbine engines are expected to continue operating at temperatures much higher than the allowable metal temperature of the turbine airfoils, especially the first stage nozzle guide vanes which are exposed to the high-temperature main gas flow. Consequently, effective cooling technique of the airfoils is one of most important part in the thermal design of airfoils.

The conventional internal convection cooling is accomplished by routing the bypassed compressors air as coolant through several internal cooling paths. For many years, numerous investigations for convection cooling have been performed on pipes, square and rectangular multi-pass channels, mainly about the analysis of flow and heat transfer characteristics and geometry modification of rib tabulators which are cast on the internal surface of channels for enhancing the heat transfer performance. Han et al. [1–3] have made the most systematic studies, and have developed the semi-empirical formulas of internal convection heat transfer coefficients from the above investigations. For the external (gas-to-wall) heat transfer coefficient, several experimental studies have been performed in transonic cascade that investigate the effects of exit Mach number, exit Reynolds number, T_w/T_g and freestream turbulence on the surface heat transfer distribution over a turbine blade. Hylton et al. [4] made systematic experimental investigations on aerodynamic (surface velocity) and heat transfer distributions over the surfaces of the Mark II and C3X airfoils, as well as the effect of cascade Ma, Re, and inlet turbulence level changes on the location of transition or separation (as indicated by the heat transfer distribution). Wedlake and Brooks [5] made a series of tests on an annular cascade of nozzle guide vanes and measured the local heat transfer rates and aerodynamic data around the blade surface an on the end walls. Giel et al. [6] examined the effect of strong secondary vertical flows, laminar-to-turbulent transition, shock impingement, and increased inlet turbulence on the airfoil surface heat transfer. They concluded that the effect of Reynolds number was to move the transition locations and the turbulence grid increased leading edge heat transfer and moved the transition locations forward.

As a numerical method for heat transfer evaluation, conjugate heat transfer calculations technique (CCT) has become more

* Corresponding author. Tel.: +86 13572833967.
E-mail address: xuliang@mail.xjtu.edu.cn (L. Xu).

0017-9310/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2013.02.080

important recently, and the numerical calculation efficiency and precision have been improved continuously. In recent years, several authors have tried to use conjugate calculations of heat transfer around the nozzle and heat conduction within its solid body. Many researchers have investigated coupled conjugate heat transfer analysis of turbine systems. Bohn et al. [7] developed a code named CHT-Flow which is a conjugate fluid flow and heat transfer solver. They have published several papers describing it and its application in gas turbine blades and vanes [8–10]. York and Leylek [11] presented a complete 3D conjugate heat transfer simulation on C3X turbine blade and compared the results with the data of Hylton et al. [4]. They simulated the two cases for different Mach numbers and their results showed a very good agreement with the experimental results. Han et al. [12] used hybrid unstructured prismatic grids for conjugate heat transfer prediction in arbitrarily shaped internally cooled configurations.

Recently, new concept of closed loop steam cooling has been proposed, which is considered to be promising, since steam has high heat transfer capability, and is easy to be obtained in combined-cycle power plant. Furthermore, using closed loop steam cooling will increase the overall combined cycle thermal efficiency. Because cooling air flows represent a significant portion of the total flow entering the combustor, while the steam, which is extracted from the exit of the HP Turbine, is heated as flowing through the nozzle blades, and then injected into the flow stream entering the IP steam turbine. Jordal and Torisson [13] have shown the benefits of replacing the air-cooling system of the vanes with steam in a closed loop are around 1.5% points. Then Nomoto et al. [14] have performed extensive experimental studies on vane steam-cooling. They arranged 30 straight circular holes in the vanes as cooling path, and pointed out that under the high-pressure steam fluid conditions the inner convection cooling achieves enough cooling efficiency and can replace air-cooling. Bohn and his group [16,17] made systematic experimental and numerical investigation of a steam-cooled vane, which had 22 straight radial cooling passages. The results showed that for this configuration, sufficient cooling can be achieved for the main body of the vane, but high thermal load had been detected in the thin trailing edge region. By application of the Conjugate Calculation Technique (CCT), Kruger et al. [18] have performed a 3-D numerical study of a steam-cooled test vane under realistic operating conditions. The calculations have shown that reaching a comparable cooling potential level using compressor air as cooling fluid demands nearly twice the mass flow needed for steam cooling. But the corresponding cooling efficiency reached with air cooling then is about 10% lower than the expected cooling efficiency for the same cooling fluid mass flow when applying steam cooling. However, all of the above steam cooling studies are based on the cooling configuration of circle holes.

The present investigations, conducted on a vane with hollow rectangular cooling ducts, mainly focus on the evaluation of internal convection steam cooling performance and the comparison of cooling effectiveness between steam cooling and air cooling. Details of thermal load analysis and cooling effectiveness analysis for the test vane are present, including the influence of coolant inlet temperature and mass flow rate on the cooling effectiveness. The measurements results are analyzed and used for the assessments of computational models.

2. Description of analysis

2.1. Experimental apparatus

A schematic of the turbine test facility is shown in Fig. 1, which was described in a previous paper [19]. It mainly consists of a mainstream generator, a plenum, a test section, a control system, a data acquisition system, an exhaust system and the cooling steam and air supply system. The mainstream generator refers to four air compressors connected in parallel and a storage tank. The parallel connected compressors and the AOK Electric Company model ECH 24/26 electric heater with 1700 kW can provide hot gas at a maximum pressure differential of 0.7 MPa, a volume flow rate of 40–150 m^3/min and a maximum temperature of 730 K. This high temperature airstream will be guided through a nozzle into the test section after passing through a plenum chamber and then exhaust into the atmosphere through a pipe equipped with spray desuperheating valve at the end, as is shown in Fig. 1. The plenum chamber is composed of a diffuser, a settling chamber and a contraction section. The settling chamber with a length of 1 m and a cross section of 0.52×0.52 m, has a stainless steel hexagon honeycomb and two damping screens embedded inside, which can lower the turbulence intensity of the gas stream.

The cooling steam supply system, which is also can be seen in Fig. 1, mainly consists of a common electric boiler, a steam superheater, and an exhaust system. The generated superheated steam has a maximum pressure of 1.0 MPa, mass flow rate of l600 kg/h and temperature of 500 K. After coming out of the steam generator, the steam passes through a pipe with a diameter of 5 cm. This pipe is equipped with a flowmeter, a stop valve, a pneumatic gate valve, a control valve to measure and control the pressure and mass flow rate. A stainless steel plenum is connected between the pipe and the vane cooling paths to ensure that the steam entering the vane cooling paths has a sharp contraction entrance condition. The cooling steam flows into the five internal cooling paths from the top of the vane, and at last it is exhausted into the atmosphere through a pipe with a diameter of 5 cm. The cooling air is provided by a small separate compressor rated for a maximum pressure differential of 0.8 MPa and a volume flow rate of 10 m^3/min, and heated by a small electric heater with a power of 33 kW. The cooling air pipe is also equipped with a control valve, a stop valve and a check valve to control the pressure and mass flow rate of the air flowing through the cooling paths.

The test section is a linear turbine cascade with three parallel gas turbine guide vanes embedded in, as is shown in Fig. 2. The vane space is 96.4 mm, and the axial chord is 69.8 mm. All of the vanes have a chord length of 126 mm, and a height of 83 mm. These vanes and their platform are fabricated from stainless steel 304(1Cr18Ni9Ti) with a thermal conductivity of $k = 16.9$ W/(m K). Investigations of cooling performance will be conducted on the center vane. The two outer vanes guide airflow around the inner vane, as is shown in Fig. 2. Thus only the inner vane has hollow cooling configuration with a wall thickness of 6 mm and is internally cooled by air or steam flowing radially through five smooth channels, while the other two adjacent vanes are solid.

All of the heaters and flow pipes are wrapped with insulation to minimize the heat loss.

2.2. Instrumentation

In the whole progress of experiment, the compressors, electric heaters, electric boiler and the desuperheater are continuously monitored and controlled by the control system HollySys PLC, which is integrated of CPU, I/O module, communication module, special function model and back board. This system also implements the control of seven pneumatic valves and two pneumatic gate valves to develop the experiment condition. The PC-based data acquisition equipment Yokogawa Electric Corporation model MX100 is utilized to collect and record pressure and temperature data. It has five modules including 300 channels, of which 230 channels are for the temperature data and 70 are for the pressure data. The data sampling frequency is 100 kHz/channel, and the