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Efficiency study of a gas turbine guide vane with a newly designed combined cooling structure

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ABSTRACT

Efficient turbine blade cooling structure design with high cooling effectiveness and low cooling loss is essential for improving the efficiency of turbomachines. This paper designs a new cooling structure combining external film cooling and internal convection cooling for a 1/2 scaled down gas turbine vane. The superheated steam replaces the traditional compressor air as coolant for the internal convective cooling. Wind tunnel experiments are conducted on a linear turbine cascade at exit Mach numbers of 0.9, and exit Reynolds number of 1.2×10^6, in order to study the cooling effectiveness of this cooling structure. Then the cooling entropy creation due to inevitable cooling losses (including internal friction and heat transfer losses and external heat transfer and mixing losses) of air cooling and steam cooling is estimated and discussed. It is found that, the cooling effectiveness of the test vane with newly designed cooling structure is high (approximately 0.8) and uniformly distributed. The entropy creation of external air cooling due to external mixing is higher than the heat transfer, and for the steam convective cooling, the entropy creation due to internal friction is much higher than heat transfer in the cooling process.

1. Introduction

Effective cooling technique of airfoils is one of the most important parts in the thermal design of airfoils. Research activities in gas turbine blade cooling began in the early 1970s [1,2]. Researchers have investigated various cooling methods for many years. They can be summarized to two categories: external film cooling and internal cooling. The film cooling methods is being used in many advanced engineering applications and has been studied since 1953 at the Heat-Transfer Laboratory of the University of Minnesota [3]. The publications relating to the film cooling are far too numerous and the known literature consists of nearly 2700 manuscripts [4]. Bogard and Thole [5] have made a review of film cooling through a discussion of the analyses methodologies, a physical description, and the various influences on film-cooling performance. There also have been numerous investigations for internal convection cooling. Han et al. [6] have made the most systematic studies. The research emphasis is the convective heat transfer performance in the cooling passage with rib turbulators, pin fins, dimples, and impinging jets.

However up to now, most published papers have focused on film cooling or internal convective cooling independently. Cooling performance of blade with both external cooling and internal cooling is seldom studied, especially the experimental study. Recently, a promising cooling technology for the vanes using steam was developed. It is found that steam cooling is a very efficient method of cooling since steam has higher heat transfer capability than air. In addition, since the cooling air comes from the compressor, using cooling air represents a significant portion of the total gas flow entering the combustor. Jordal and Torisson [7] have shown that replacing the air-cooling system of the vanes with steam in a closed loop had around 1.5 percentage points increase in thermal efficiency. Nomoto et al. [8] pointed out that under high-pressure steam fluid conditions the inner convection cooling achieves enough cooling efficiency and can replace air-cooling. Bohn and his group [9,10] 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. To evaluate the cooling performance of the internal convection cooling by air and steam, our group [11] have made experimental and numerical study to confirm the cooling effectiveness for a test vanes using a hot wind tunnel. This test vane has five hollow rectangular cooling ducts. Results show that the averaged cooling effectiveness of steam is higher than the air at the same mass flow rate, by about 12%. In addition, the cooling effectiveness at the middle chord region of the vane is much higher

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Nomenclature

A_h	area of film hole
c	vane chord length (mm)
D	Hole diameter (mm)
DR	density ratio (ρ_c/ρ_∞)
H	vane span height (mm)
k	thermal conductivity (W/m K)
L	length of hole (mm)
M	blowing ratio ($M = \rho_c U_c/\rho_\infty U_\infty$)
Ma	Mach number
m	mass flow rates (kg/s)
P	hole pitch (mm)
Q	heat transfer rate
Re	Reynolds number (reference length: chord)
R	gas constant
S	streamwise surface distance from stagnation (mm)
T	temperature (K)
U	fluid velocity (m/s)
X	spanwise distance from film cooling hole (mm)
Z	spanwise distance from bottom of vane (mm)
μ	dynamic viscosity(Ns/m^2)
φ	ejection angle
σ	entropy created per unit mass of mixture
ε	cooling effectiveness
ρ	density (kg/m^3)
η	turbine efficiency

Subscripts

0	total quantities
m	mixing condition
c	coolant
s	steam cooling
f	film cooling
g	external gas stream
t	trailing cooling
i	coolant condition at inlet to blade passages
o	coolant condition at exit from blade
w	wall (outer surface of the blade)

than that at the leading and trailing edge region. This unacceptable thermal load at the leading and trailing edge as well as large thermal stresses may lead to a mechanical failure of the vane. Thus additional research is necessary to optimize the geometric configuration which is efficient, simpler and feasible from manufacturing point of view resulting in better performance.

Cooling can reduce the metal surface temperature, allowing higher turbine inlet temperature and higher turbine efficiency consequently. Unfortunately, it brings inevitable aerodynamic and thermodynamic losses and offsets part of the increased turbine efficiency [12]. First, part of the compressor air will be diverted from the main flow and used for cooling; second, the coolant pressure losses exists in the process of feed, delivery; and third, the mixing of coolant with the mainstream after ejection will reduce the aerodynamic efficiency of the turbine. Loss is usually defined in terms of entropy increase, stagnation pressure and kinetic energy loss. Entropy increase is a more convenient measure for calculating cooling losses. Denton [13] summarized the source of entropy creation: viscous effects in boundary layers, viscous effects in mixing processes, shock waves, and heat transfer across temperature difference. Young and Horiock [14] presented new proposals for defining the efficiency of a cooled turbine. They developed a framework for modeling air-cooled gas turbine cycles and used sample calculations in terms of irreversible entropy creation to illustrate the division and magnitude of the cooling loss. Lim [15] extended the analytical predictions of the entropy generation mechanisms with film cooling flow described by Young and Wilcock [16,17] to include flow ejected at compound angles and uses three-dimensional computational fluid dynamics (CFD) to provide the mainstream flow properties.

Based on the analysis above, this paper develops a combined cooling structure for a 1/2 scaled down gas turbine vane, which combines both the air cooling and steam cooling. Air is supplied for film cooling at the leading and trailing edge, and steam is supplied for the internal convective cooling at the mid region. A wind tunnel laboratory is built up. This experimental rig can offer both air and superheated steam as coolant, and can provide main gas flow with high temperature and pressure to simulate the flow field of a real gas turbine cooling vane. Wind tunnel experiments are conducted on a linear turbine cascade at exit Mach numbers of 0.9, and exit Reynolds number of 1.2×10^6 to confirm the cooling performance and cooling loss.

2. Experimental sections

2.1. Experimental setup

The experimental facility had already been described in a previous paper [18] and its schematic is shown in Fig. 1. It mainly consists of a mainstream generator, a plenum, a test section, a control system, a data acquisition system, an exhaust system and the steam and air coolant supply system. The mainstream generator refers to four air compressors connected in parallel and a storage tank. The parallel connected compressors and electric heater can provide hot gas at a pressure of 188 kPa and a volume flow rate of 100 m^3 per minute at a temperature of 633.15 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. Fig. 2(a) shows the picture of the plenum chamber and test section, and the enlarged view of the test section is shown in Fig. 2(b). 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 inlet turbulence intensity of the gas stream to be about 5%.

The cooling steam supply system mainly consists of a common electric boiler, a steam superheater, and an exhaust system. The 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 air coolant 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. There is also a stainless steel plenum before the cooling air entering the vane cooling paths. All of the heaters and flow pipes are wrapped with insulation to minimize the heat loss.

The test section is a linear turbine cascade with only three parallel gas turbine guide vanes embedded in. It could reach transonic through flow condition and achieve good periodicity. Fig. 3 is the schematic of the test section. These vanes are scaled one-and-half times of a real gas turbine guide vane with a chord length of