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Conjugate heat transfer on full-coverage film cooling with array jet impingements with various Biot numbers

Eui Yeop Jung [a], Heeyoon Chung [a], Seok Min Choi [a], Ta-kwan Woo [b], Hyung Hee Cho [a,*]

[a] Department of Mechanical Engineering, Yonsei University, 50, Sedamun-gu, Seoul 120-749, Republic of Korea
[b] SUNG IL Co. LTD., Busan 1587-4, Republic of Korea

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ABSTRACT

Total cooling effectiveness was determined on a film cooled surface with staggered array jet impingement cooling at various Biot numbers. Heat transfer experiments were conducted using infra-red thermography for materials of three thermal conductivities: stainless steel ($k = 13.4$ W/m K), Corian ($k = 1$ W/m K), and polycarbonate ($k = 0.2$ W/m K). Conjugated heat transfer was analyzed with the combined effects of conduction through the test plates and convective heat transfer due to the arrayed jet impingement. The inclination angle of the film cooling holes was 35° and that of the jet impingement holes was 90°. The film and jet impingement holes on each plate were arranged in staggered patterns, and the film cooling holes and jet impingement holes were also positioned in a staggered pattern. The jet Reynolds number, based on hole diameter, was 3000 and the equivalent blowing ratio was 0.3. The diameter of the film cooling holes and the jet impingement holes was 5 mm. The distance between jet and film hole plates was varied in the range $1 \leqslant H/d \leqslant 5$. Total cooling effectiveness was measured with and without jet impingement. When jet impingement was added to the internal cooling, the averaged total cooling effectiveness was enhanced about 8.4%. At low Biot numbers, meaning that cooling performance dominated over the conduction effect, the temperature distribution became more uniform due to higher conductive heat transfer. The total cooling effectiveness was strongly related to the Biot number of the plate, and the correlation between total cooling effectiveness at various Biot numbers was determined to predict the total cooling effectiveness in an actual gas turbine engine. The effect of H/d ratio was limited, to within 2.7%.

1. Introduction

The thermal efficiency of a gas turbine is strongly related to the turbine inlet temperature (TIT). To increase the thermal efficiency of a gas turbine system, the TIT has been increased and then it exceeds the melting temperature of the materials in modern gas turbines. For this reason, improved cooling techniques are also required to protect the gas turbine components from the hot combustion gases, such as combined cooling systems with double walls, including full-coverage film cooling with array jet impingements.

As an individual cooling method, film cooling affects external convection significantly because the coolant ejected from a cooling hole protects the external surface directly. There have been several studies aimed at understanding the external convective heat transfer characteristics of film cooling. Various design parameters have been investigated systematically, including hole shape, hole pitch, hole diameter, injection angle, hole arrangements, and blowing ratios [1–6].

In an actual gas turbine, the cooling performance involves the combined convective and conductive heat transfer through the wall, including the effects of the internal cooling system. To investigate the overall heat transfer characteristics around holes, Cho and Goldstein [7–9] measured the heat/mass transfer coefficients at the internal and external walls and inner surface of a circular film cooling hole. Jet Impingement is often used in the internal passages of gas turbine blades to maximize cooling performance. Several investigations of combined cooling systems have been carried out, including film cooling and jet impingement. Cho and Rhee [10] and Rhee et al. [11] measured the local heat/mass transfer coefficients on the inner surface of effusion plate of impingement/effusion cooling system with various H/d values, Reynolds numbers, and hole arrangements. They found that the overall convective heat/mass transfer rates on the internal surface increased about 17% as H/d changed from 5 to 1.

Recently, conjugate heat transfer analyses including external convective heat transfer, conduction through the metal parts, and

* Corresponding author.
E-mail address: hhcho@yonsei.ac.kr (H.H. Cho).

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Nomenclature

d	diameter of injection and film cooling holes (m)	x	streamwise distance from the first row of holes (m)
p	hole spacing (m)	y	spanwise distance from the center of holes (m)
H	gap distance between injection and film cooling plate (m)	Bi	Biot number
t_i	thickness of jet impingement plate (m)	Re_∞	Reynolds number of main flow
t_f	thickness of film cooling plate (m)	Re_{jet}	Reynolds number of jet flow
h_e	external heat transfer coefficient (W/m^2 K)		
k	thermal conductivity of film cooled plate (W/m K)	*Greek symbols*	
T_m	temperature of main flow (K)	ρ_h	density of main flow (kg/m^3)
T_c	temperature of coolant (K)	ρ_c	density of secondary flow (kg/m^3)
T_{aw}	adiabatic wall temperature (K)	$\underline{\emptyset}$	local total cooling effectiveness
T_w	temperature of film cooled plate surface (K)	$\overline{\overline{\emptyset}}$	averaged cooling effectiveness
V_h	main flow velocity (m/s)	η_{ad}	adiabatic film cooling effectiveness
V_c	secondary flow velocity at film cooling hole (m/s)	σ	standard deviation

internal convective heat transfer, were reported, from numerical and experimental studies. Dhiman and Yavuzkurt [12] and Panda and Prasad [13] developed numerical methods in conjugate heat transfer techniques. They reported differences in temperature levels between conjugate and non-conjugate solutions. Their results showed that the spanwise variation in the metal temperature was related to the temperature difference between the main and coolant temperatures and the thermal conductivity of the film cooled plate. Zhang et al. [14] reported a relationship between overall cooling effectiveness and adiabatic film cooling effectiveness. They varied the Biot number of the heat transfer surface, and evaluated the overall cooling effectiveness, numerically. The relationship between the overall cooling effectiveness and the adiabatic film cooling effectiveness was related to the Biot number. Caciolli et al. [15] reported experimental results describing the adiabatic film cooling effectiveness using TLC and PSP methods in multilayer effusion cooling. They sought to evaluate adiabatic cooling effectiveness with a TLC method, considering a one-dimensional conduction model by comparing results measured with the PSP method. McClintic [16] and Dyson et al. [17] analyzed conjugate heat transfer experimentally and suggested a prediction method, assuming a one-dimensional approximation. However, this assumption differs from a real gas turbine blade with its three-dimensional system. It was hard to consider heat transfer near the film cooling hole using the one-dimensional approximation assumption.

In this study, conjugate heat transfer characteristics for full-coverage film cooling with jet impingement cooling, referred to as impingement/effusion cooling, were investigated. We analyzed the contribution of internal convection and conduction to overall cooling performance to understand the heat transfer mechanisms of the combined cooling system. To analyze the influence of internal conduction on total cooling effectiveness, the Biot number was controlled using three materials with different thermal conductivities, in the range from 0.2 to 13.4 W/m K, while maintaining the external convection heat transfer. Additionally, internal impingement heat transfer was considered by changing various gap distances (H/d) in double wall cooling. This manuscript was developed from results described in Turbo EXPO conference GT2015-43810 [18].

2. Experimental apparatus and data reduction

2.1. Experimental facility

Fig. 1 shows a schematic diagram of the closed loop wind tunnel and the secondary flow supply system. The size of the test cross section was 200 × 300 mm^2. The heat exchanger was connected to a constant temperature water bath, and was installed in the wind tunnel to maintain the main flow temperature at 300 K. The velocity was measured using a pitot tube. The temperature was measured using a J-type thermocouple located behind the pitot tube at a distance of 5 cm, which was unaffected by the velocity measurement results. The nominal velocity of the main flow was 34 m/s. The Reynolds number of main flow, based on jet hole diameter was 10,000. The turbulence intensity of the main flow obtained using hot-wire measurements, was 1.5%.

A blower was used to provide a secondary flow, and a heater with a proportional-integral-derivative (PID) controller was used to maintain the secondary flow temperature at 323 K. The heated secondary flow passed through the jet impingement hole, and impinged on the back side of film cooled plate. The impinged flow passed through the film cooling holes and was then ejected into the main flow to form a coolant film. An orifice flow meter was used to measure the mass flow rate of the secondary flow. The secondary flow temperature was measured using a J-type thermocouple located upstream of the jet impingement plate (Fig 1). The secondary flow channel pipe and chamber were covered with an insulator to reduce heat loss and to provide a more uniform temperature. The operating conditions of experiment are summarized in Table 1.

2.2. Test section

The test section of the impingement/effusion cooling system was composed of a full-coverage film cooling plate and a jet impingement plate. Fig. 2 shows top and side views of the full-coverage film cooling plate and the jet impingement plate. The white ellipses show the locations of the film cooling holes, and the blue[1] circles indicate the locations of the projected jet impingement holes. The dimensions of the full-coverage film plate were 240 × 240 mm^2.

The full-coverage film cooling holes consisted of 13 rows of holes, where each row had 12 or 13 holes (Fig. 2). Three different film cooled plates were tested to assess the effects of conductivity: stainless steel (AISI 304, k = 13.4 W/m K), Corian (k = 1 W/m K), and polycarbonate (k = 0.2 W/m K). The jet impingement plate had the same number of holes. Both hole arrays were arranged in staggered pattern, and the film cooling holes and jet impingement holes were located in the staggered pattern. Experiments were carried out with film cooling holes of an inclined angle at 35°. The diameters of both holes were 5 mm, and the pitch-to-diameter ratio (p/d) was 3 in both the streamwise and spanwise

[1] For interpretation of color in Fig. 2, the reader is referred to the web version of this article.