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Multiple-jet impingement heat transfer in double-wall cooling structures with pin fins and effusion holes

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ABSTRACT

In a double-wall cooling system with multiple jet impingement the arrangement and size of effusion holes may change flow field and thereby change heat transfer characteristics. This paper stands in the view of internal cooling of turbine blades, and studied multiple-jet impingement heat transfer in double-wall cooling structures with narrow channels with pin fins and different-size effusion holes on the target wall. Five target plates were investigated including flat plate, pin fin plate and three pin fin plates with different-size effusion holes (effusion-to-jet diameter ratio of $D_e/D_j = 0.5,\ 1.0\ and\ 1.5$). Transient liquid crystal thermography experiments were conducted to explore the heat transfer characteristics on these target plates. The ratio of jet-to-plate spacing was fixed to be 1.5 and Reynolds numbers based on the jet diameter range from 15,000 to 30,000. The experimental results showed that the pin fins and effusion holes reduce the crossflow strength in downstream region, improve and uniform heat transfer on the whole target plate obviously. Compared with the flat plate, pin fin plate with effusion holes of $D_e/D_j = 1.5$ has highest averaged Nusselt number on the endwall. Numerical computations were carried out based on the experimental model, which revealed that the total heat transfer quantity on the pin fin plate with effusion holes of $D_e/D_j = 1.5$ can be increased by up to 51% comparing to that of the flat plate. Detailed interactional flow information between the wall jet flow, pin fins and effusion holes is expounded for the heat transfer improvement in the impingement-effusion structures. Moreover, conjugate heat transfer analyses were done to further investigate the overall cooling performance of the impingement-effusion structures.

1. Introduction

Recent advances in gas turbine technology for aerospace propulsion and power generation mainly focus on increasing efficiency as well as maintaining or extending the service life of engine components. One of the important measures relies on the continuing increasing turbine inlet temperature, which is already far above the melting point of the metal material [1]. Therefore more efficient and advanced cooling techniques for turbine blades or combustors are urgently necessitated in order to ensure safe and reliable gas turbine engine operation at elevated gas temperatures. Multiple-jet impingement cooling is one of the most efficient internal cooling techniques for turbine blades, which is mainly due to the very high heat transfer rates achieved by multiple high-velocity jets impinging onto the target plate.

Previous studies of the jet impingement cooling were focused on the influences of jet arrangements and the target wall surface roughness on the heat transfer performance [2–12]. Influences of many parameters such as the geometries of jet holes, jet-to-plate spacing, jet Reynolds numbers, and crossflow effects on the impingement heat transfer on the flat target plate have been intensively studied by Florschuetz et al. [2,3] and reviewed by Han and Goldstein [4] and Weigand and Spring [5]. Spring et al. [6] conducted experimental studies and found that placing ribs between neighbouring two jets can obtain better heat transfer performance under maximum cross flow, which depends on rib configurations on the target wall, and they concluded that the total heat flux can be improved by about 50%. Brakmann et al. [7] conducted an experimental and numerical study and found that arranging dense-cubic micro ribs on the jet plate can improve the total heat transfer by about 42%, while the pressure loss is enhanced by less than 14%. Andrews et al. [8] reported that by keeping the spanwise direction of the ribs on the target wall consistent with the crossflow direction, one can achieve better jet impingement heat transfer performance. Son et al. [9] studied the jet impingement heat transfer on different roughened target surfaces, and showed that employing circular pins and diamond ribs on flat target plate can increase the total heat transfer performance by 22%–35% for a maximum pressure penalty of about 10%. Detailed heat

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Nomenclature

c	Specific heat capacity, $kJ/(kg{\cdot}K)$
D	Diameter, m
H	Jet-to-target plate spacing, m
k	Thermal conductivity, $W/(m{\cdot}K)$
h	Heat transfer coefficient, $W/(m^2{\cdot}K)$
P	Static pressure, pa
P_X, P_Y	Pin Fins' spacing, m
Pr	Prandtl number of the airflow
ΔP	Pressure loss, pa
N	Total time steps number
Re_j	Reynolds number based on jet diameter
Nu	Local Nusselt number
$\overline{Nu}$	Spanwisely averaged Nusselt number
$\overline{\overline{Nu}}$	Globally averaged Nusselt number
Q	Heat transfer quantity from the target plate surface, W
t	Time, s
T	Temperature, K
T_0	Initial temperature, K
$T_{j,i}$	Jet temperature at the time t_i, K
u	Velocity, m/s

Greek symbols

ρ	Density, kg/m^3
λ	Thermal conductivity of airflow, $W/(m{\cdot}K)$
μ	Viscosity coefficient, $kg/(m{\cdot}s)$
η	Overall cooling effectiveness

Subscripts

e	Effusion hole
j	Impingement jet
p	Pin fin
z	Vertical coordinate, mm
w	Wall
f	Flat plate
Out	Outlet

transfer data on the smooth and roughened target surface of impingement cooling system was experimentally provided by Ei-Gabry et al. [10]. The test rig was designed to be with crossflow in one direction, and the different jet holes' angels of 30°, 60° and 90° were investigated. Xing et al. [11] showed detailed jet impingement heat transfer distribution on micro-rib structured surface by using the transient liquid crystal thermography method, and their results showed that the overall heat transfer performance on the endwall of the micro-rib roughened plate is always better than the case with flat plate with minimum crossflow scheme. Buzzard et al. [12] investigated the impingement heat transfer on micro pin fin roughened wall, and found that the micro pin fins can significantly improve the overall heat transfer performance of the jet impingement cooling.

Nowadays new casting technologies allow the manufacturing of narrow impingement channels in a double-wall configuration, which shows the potentials of further increasing cooling capabilities of turbine internal flow. An extensive investigation of narrow jet impingement cooling with flat target plates has been recently reported by Terzis et al. [13,14], who used the Particle Image Velocimetry and transient liquid crystal thermography to obtain detailed flow and heat transfer characteristics in the jet impingement systems, and indicated a deep understanding about the effects of near wall flow structures on the convective heat transfer in narrow jet impingement channels with jet-to-plate spacing ratios of 1–3. Moreover, the detailed heat transfer correlations on different surfaces of narrow impingement channel were obtained in their study [15].

It is also noted that a more efficient cooling technology for turbine blades or combustors is the combination of jet impingement with surface roughening elements and external effusion/film cooling. The arrangements of the effusion holes on the target plates may change the flow structure and heat transfer characteristics in the jet impingement cooling system, and limited publications addressed the issues previously. Hong et al. [16] experimentally investigated the jet impingement heat transfer based on heat/mass analogy in a channel with initial cross flow configurations, and the jet-to-plate ratio is 2 and only one jet Reynolds number of 10,000 was investigated. They found that the pin fin positions and the cross flow blowing ratios can influence the jet impingement heat transfer, but didn't show any detailed flow structure in such impingement cooling systems. Cho et al. [17] investigated the effusion hole arrangements on the local heat/mass transfer for an impingement/effusion cooling for jet Reynolds numbers from 3000 to 14,000 by experiments and numerical computations, and they indicated that staggered arrangements of jet holes with effusion holes provide the best thermal performance. Funazaki and Hachiya [18] conducted a

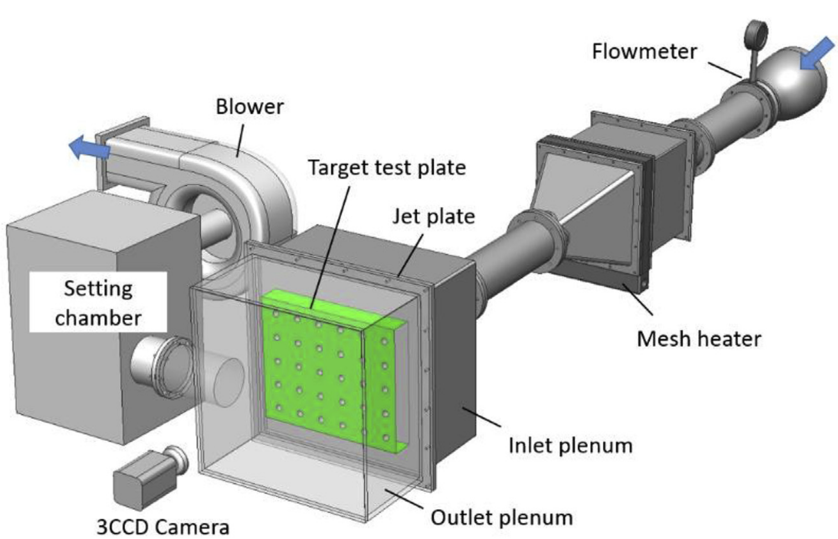

Fig. 1. Schematic of the experimental facility.