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Impingement jet array heat transfer with small-scale cylinder target surface roughness arrays

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ABSTRACT

The present investigation considers special small-scale roughness patterns on impingement target surfaces to increase surface heat transfer augmentation levels of impingement jet array cooling. Utilized are three different heights of cylinder small roughness elements, which are mounted on three different test surfaces. The cylinder-shaped roughness is small-scale because diameter is 7.5 percent and maximum height is 25 percent of impingement hole diameter. Associated results are compared with spatially-averaged Nusselt number ratio distributions measured on target surfaces with triangle small roughness, or rectangle small roughness. Data are obtained for impingement jet Reynolds numbers of 900, 1500, 5000, and 11,000. Nusselt number variations for the small cylinder roughness show different trends with streamwise development and changing roughness height, compared to target plates with small rectangle roughness and small triangle roughness. In general, this is because roughness elements which contain surface shapes with sharp edges generate increased magnitudes of vorticity with length scales of the order of the roughness element diameter. Such generation is not always present in an abundant fashion with the small cylinder roughness because of the smooth contours around each roughness element periphery. Such effects are illustrated by several data sets, including Nusselt numbers associated with the small cylinder roughness with a height of 0.250D at a turbulent Reynolds number of 11,000.

1. Introduction

Impingement cooling is used for a variety of hot-section gas turbine components when substantial cooling and heat transfer augmentation levels are required. The present investigation considers special target surface roughness patterns to increase surface heat transfer augmentation levels of impingement cooling. Three different heights of small cylinder roughness elements arranged into a dense pattern along the test surface are employed. Associated Nusselt number data from these tests are compared with results obtained with target surfaces with arrays of rectangle small roughness, and with results obtained with target surfaces with arrays of triangle small roughness.

A number of recent investigations consider impingement heat transfer augmentation and improvement by means of target surface roughness, rib turbulators, pin fins, other surface texture alterations. However, only few existing investigations consider arrays of roughness elements, with individual sizes which are significantly smaller than impingement hole diameter. Of these studies, the most significant are described by Xing and Weigand [1], Xing et al. [2], Xing and Weigand [3], and Nakamata et al. [4]. Considered in these investigations are rib roughened plates with different crossflow schemes [1], micro-rib roughened plates with different crossflow schemes [2], and micro-dimpled plates with different crossflow schemes [3]. The recent investigation described by Nakamata et al. [4] is important because the effects of roughened elements and cooling hole shape on impingement cooling effectiveness are considered. Round impingement hole configurations utilize a target plate with ribs, a target plate with dips, a target plate with dimples, and a target plate with bumps. A racetrack-shaped impingement hole configuration utilizes a target plate with bumps. This last arrangement gives the highest impingement cooling effectiveness. The investigators also indicate that the dips and dimples perform better than the ribs and bumps, when surface configurations are compared.

The present investigation considers the effects of special cylinder-type roughness patterns on target surfaces to increase surface heat transfer augmentation levels of impingement jet array cooling. Tests are performed at impingement jet Reynolds numbers of 900, 1500, 5000, and 11,000. Of particular interest are line-averaged and spatially-averaged impingement surface Nusselt numbers, as these vary with jet Reynolds number, with streamwise location, and with the height and shape of roughness elements.

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Nomenclature

A	impingement hole area
A_{ht}	heat transfer area on the target plate
C_D	impingement flow discharge coefficient
D	diameter of an individual impingement hole
H	height of roughness element
k	ratio of specific heats
k_a	air thermal conductivity
L	length of roughness element
$\dot{m}$	impingement air mass flow rate
M_a	impingement air flow Mach number
M_i	impingement air flow ideal Mach number
N	number of impingement holes
Nu	local Nusselt number
$\overline{Nu}$	line-averaged Nusselt number
$\overline{\overline{Nu}}$	spatially-averaged Nusselt number
$\overline{\overline{Nu}}_o$	spatially-averaged Nusselt number, baseline with smooth target surface
P_a	impingement air static pressure
P_t	impingement air stagnation pressure
Q	total power provided to the thermofoil heater
q_{cb}	convection heat flux from back side of the target plate
q_{cf}	convection heat flux from front side (or impingement side) of the target plate
q_{rb}	radiation heat flux from back side of the target plate
q_{rf}	radiation heat flux from front side (or impingement side) of the target plate
R	ideal gas constant
Re_j	impingement air flow Reynolds number
T_b	local temperature on the back surface of the polystyrene target plate
T_i	impingement air ideal static temperature
T_j	impingement air static temperature
T_{oj}	impingement air stagnation temperature
T_{tc}	local thermocouple temperature between the heater and the polystyrene target plate
T_W	heater adjacent to the impingement air
u_a	impingement air velocity
W	width of roughness element
x	streamwise coordinate
y	spanwise coordinate
z	normal coordinate
X	streamwise distance between centerlines of adjacent impingement holes
Y	spanwise distance between centerlines of adjacent impingement holes
Z	distance between target plate and impingement hole plate
ρa	impingement air static density
μ	absolute viscosity

2. Experimental apparatus and procedures

Presented here are a description of the impingement flow facility, experimental apparatus and configurations, measurement devices, and methods for gathering and analyzing the data. Different rough test plate configurations are also described, along with the impingement hole configuration and impingement cooling passage. Note that portions of the experimental apparatus and procedures are given by Lee et al. [5,6] and by Buzzard et al. [7]. Materials from these references are also included here so that all approach and apparatus details are discussed in a complete fashion.

2.1. Impingement flow facility and impingement plate

Schematic diagrams of the laboratory facility used for heat transfer measurements are presented in Figs. 1 and 2. The facility is constructed of 6.1 mm thick ASTM A38 steel plates, and A53 Grade B ARW steel piping. The air stream through the plenums and channel is drawn from the laboratory atmosphere. To achieve the Reynolds number of the present study, a New York Blower Co. 7.5 HP, size 1808 pressure blower is employed. The air mass flow rate provided to the test section is measured using an ASME standard orifice plate, flow-mounted calibrated copper-constantan thermocouples, and Validyne DP15-20 and DP15-22 pressure transducers (with diaphragms rated at 0.86 and 1.40 kPa, respectively) connected to Validyne Model CD15 Carrier Demodulators. Each of the thermocouples measures recovery temperature, which is used with local velocity magnitude to determine gas static temperature. The blower exits into two plenums arranged in series, where the upstream plenum is 0.63 m in length along each side, and the downstream plenum dimensions are 0.63 m long, 0.77 m tall, and 0.77 m wide. A Bonneville cross-flow heat exchanger is located within each plenum. As the air exits the heat exchanger, and the second plenum, the air passes into a 0.22 m outer diameter pipe, which contains the ASME Standard orifice plate employed to measure the air mass flow rate. This pipe then connects to the 0.635 m by 0.635 m side of a plenum.

Upon entering this plenum, the air first encounters a flow baffle to distribute the flow, and a honeycomb and screens to improve flow spatial uniformity. These are followed by the upper plenum, located below the honeycomb and flow straightening devices (as shown in Fig. 2), with top dimensions of 0.635 m and 0.635 m, and height of 0.40 m. Individual plates with holes used to produce the impingement jets are located at the bottom of this plenum, as shown in Fig. 2. The plenum is thus designed so that different impingement plates can be installed at this location. The present investigation uses one impingement plate.

Fig. 3 shows that the present impingement plate consists of 9 rows of holes in the streamwise direction. The plate is arranged so that holes in adjacent streamwise rows are staggered with respect to each other. With this arrangement, 3 or 4 holes are located in each streamwise row. With this configuration, a sufficient number of impingement holes are included within each streamwise row to provide a representative impingement cooling arrangement. The spacing between holes in the streamwise direction X is 5D and the spacing between holes in the spanwise direction Y is 5D. The thickness of the impingement plate is 1.625D. The spacing between the hole exit planes and the target plate is denoted Z/D, with a value employed in the present investigation of 2.5D. The plate is the same as one plate employed by Lee et al. [5,6].

The impingement cooling flow which issues from these holes is contained within the channel formed by the impingement jet plate and the target surface, and is constrained to exit in a single direction, which here, is denoted as the x-direction. This channel is called the lower plenum or impingement plenum. The impingement plenum channel is made up of a volume of air between the target and jet impingement plate, with 2.5D spanwise margins on each side of the grid of impingement holes. In the present study, the hole diameter size, D, blower, mass flow rate, and pressure