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# Effects of spent air removal scheme on internal-side heat transfer in an impingement-effusion system at low jet-to-target plate spacing

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ABSTRACT

Present study reports detailed measurements of heat transfer coefficient for jet impingement in an impingement-effusion system at low jet-to-target plate spacing. The heat transfer coefficients were measured experimentally by transient liquid crystal thermography. Heat transfer experiments were carried out at three jet Reynolds numbers – 3500, 6000 and 9000. The jet plate featured 8 × 9 circular jets with normalized streamwise $(x/d_j)$ and spanwise $(y/d_j)$ spacing of 6. The configurations are divided into two segments based on the characteristics of target surface. The first target surface was smooth without effusion holes, and the second target surface was smooth with effusion holes. The arrangement of effusion holes was staggered with respect to jet plate and the ratio of effusion hole diameter to jet hole diameter was unity. For the smooth target surface without effusion holes, three crossflow schemes were studied – minimum, intermediate and maximum. For the smooth target surface with effusion holes, four different crossflow schemes were studied – zero, minimum, intermediate and maximum. Interesting heat transfer characteristics are reported for different crossflow schemes as it was found that low $z/d_j$ (=1) played an important role in the spent air removal from the system. Discharge coefficient of jets is also reported for wide range of plenum pressure ratio. Also reported are the pumping power requirements for each configuration across full range of flow conditions. It has been found that the minimum crossflow scheme (with and without effusion holes) has been the most efficient configuration and the maximum crossflow scheme with target surface without effusion holes has been the least efficient configuration.

## 1. Introduction

Jet impinging has been widely used for applications requiring high rates of heat removal. Some of the common applications of jet impingement can be found in gas turbine blade leading edge, electronic cooling, combustor liner cooling, food processing industry, etc. Over the past few decades, several studies have been carried out to understand jet impingement heat transfer under various conditions. Jet impingement heat transfer depends upon several parameters, such as, spanwise and streamwise spacing between jets, jet-to-target plate spacing, nozzle contouring, crossflow (spent air) removal scheme, roughness of target surface and initial crossflow. Earlier studies on jet impingement were focused on single jet, in order to establish standard definitions of heat transfer coefficient for jet impingement systems. Goldstein and Behbahani [1] studied heat transfer characteristics of single jet with and without crossflow. The authors established fundamental definition of heat transfer coefficient for jet impingement. They also provided definitions of recovery factor and emphasized on the accurate knowledge of adiabatic wall temperature in the determination of heat transfer coefficient. Viskanta [2] described the fairly complex fluid dynamics peculiar to jet impingement. The author concluded that thermal boundary layer is thinnest near the stagnation region and hence will have maximum heat transfer compared to other radially outboard locations. More details about research on jet impingement prior to 1992 can be found in the review paper by Jambunathan et al. [3].

Impingement/Effusion systems have also been widely studied. Some of the important studies carried out prior to 2005 has been listed from [4–9]. Andrews et al. [4] reported overall heat transfer coefficient for impingement/effusion system using a transient cooling technique. The authors found that the heat transfer coefficient for impingement/effusion system on the effusion inner wall was higher than the impingement alone case by 30% to 45%. The reason accounted for higher heat transfer was due to the pressure loss from the effusion walls. Dabagh et al. [5] studied the effects of number of impingement holes and pressure loss on heat transfer coefficient in an impingement/effusion cooling system. The

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**Nomenclature**

| | |
|---|---|
| c | specific heat capacity of target surface |
| $c_p$ | specific heat capacity at constant pressure |
| $c_v$ | specific heat capacity at constant volume |
| $C_d$ | discharge coefficient |
| $d_j$ | diameter |
| G | mass flux |
| h | heat transfer coefficient (W/m$^2$ K) |
| $H_{ref}$ | hue value to be tracked |
| $k_f$ | thermal conductivity of air at film temperature |
| $k_t$ | thermal conductivity of clear acrylic |
| M | jet exit Mach number |
| $\dot{m}$ | mass flow rate |
| N | number of holes |
| $Nu_{d_h}$ | Nusselt number (based on jet hydraulic diameter) |
| $p_{m,abs}$ | absolute ambient pressure |
| $p_{r,m}*$ | absolute plenum pressure to absolute ambient pressure ratio |
| $R_a$ | universal gas constant |
| $Re_j$ | average jet Reynolds number (based on hydraulic diameter of jet) |
| t | time taken to reach $T_{tlc}$ |
| $t_{target}$ | thickness of the target plate made of clear acrylic |
| T | temperature |
| $T_m$ | mainstream temperature |
| $T_{tlc}$ | temperature of target wall corresponding to $H_{ref}$ |

*Greek symbols*

| | |
|---|---|
| ρ | density of clear acrylic |
| γ | $c_p/c_v$ |

*Subscripts*

| | |
|---|---|
| abs | absolute |
| i | initial |
| j | jet |
| m | mainstream |
| w | wall |

authors used computer code to analyze the fluid dynamics in the impingement channel. Their measurements indicated that the interaction between the target and the jet plate resulted in a convective heat transfer to the jet plate and this heat transfer was about half of the convective heat transfer on the target wall. The authors also concluded that increasing the number of impingement holes resulted in decrement in heat transfer coefficient by about 20%. Cho and Rhee [6] investigated the effects of jet-to-effusion plate distance on heat transfer on the effusion inner wall. The authors found high heat transfer region at the stagnation point and at the mid-line between two jets due to secondary flows. In general, for low values of z/d, the heat transfer was higher. In this study, the crossflow was guided through the effusion holes only. Rhee et al. [7] studied the heat transfer in an impingement/effusion system with initial crossflow for a z/d of 2. A mass transfer technique was used to calculate the mass transfer coefficient and then the heat transfer coefficient from the heat-mass transfer analogy. The authors reported shifting of stagnation points due to strong effects of crossflow. One interesting observation from this study was the heat/mass transfer coefficients for impingement/effusion cooling with crossflow were similar to impingement cooling with the same initial crossflow. Ekkad et al. [8] investigated the effect of the presence of film cooling holes on target plate. The authors studied three different crossflow schemes and reported that the presence of film cooling holes helped in the regulation of crossflow but the effect of film holes for maximum crossflow case was not discernable. The heat transfer comparisons in [8] were made with an earlier study carried out by Huang et al. [9].

Rhee et al. [10] carried out experimental and numerical investigation of heat/mass transfer for impingement/effusion system at low jet-to-target plate spacing. The authors reported that strong crossflow effects in the case of impingement alone configuration can be regulated by having effusion holes where all the spent air was forced to pass through the effusion holes. Cho et al. [11] investigated the effects of hole arrangement on local heat/mass transfer in an impingement/effusion cooling system. The authors studied three types of relative arrangement of jet and effusion holes – staggered, shifted in one direction and inline. The authors reported that overall averaged Sherwood number for staggered and shifted arrangement was approximately 70% higher than the in-line configuration.

Post 2005 studies on impingement/effusion cooling have been listed from [12–14]. Hong et al. [12] studied the effects of fin shapes and their arrangements on heat transfer for impingement/effusion cooling system with crossflow. The authors reported that as the crossflow strengthened, the effects of fins became more dominant and resulted in enhanced heat transfer, however, the pressure losses also increased due to increase in the channel blockage ratio due to the addition of the fins. Hong et al. [13] studied heat transfer characteristics of impingement/effusion cooling with rib turbulators under rotating conditions. The authors reported that for leading and trailing edges, the deflection of jets because of crossflow reduced, due to presence of ribs. Hoberg et al. [14] carried out heat transfer measurements for jet impingement arrays with local coolant extraction. Correlations were provided for Nusselt number as function of jet Reynolds number for different cases studied.

Current paper documents detailed study of all the possible crossflow schemes in order to determine a configuration which has highest thermal hydraulic performance. The jet-to-target plate distance was kept low in order to simulate configurations which can be used in double wall cooling arrangements in turbine airfoils where space is one of the major constraints. An interesting way of evaluating efficiency of impingement/effusion cooling system has been shown in the present study by plotting global Nusselt number with the pumping power requirement. Separate effects of crossflow regulation and nature of target surface (with and without effusion holes) have been studied. The present study reports detailed measurements of heat transfer coefficient on target plates, with and without effusion holes. The jet-to-target plate spacing was kept at one jet diameter. For the target plate with no effusion holes, three different crossflow schemes were tested – minimum, intermediate and maximum crossflow. For the target plate with effusion holes, four different crossflow schemes were tested – minimum, intermediate, maximum and zero crossflow. For all the above crossflow schemes, the jet Reynolds number was varied from 3500 to 9000. This study investigates the effect of spent air removal scheme on jet impingement heat transfer in an impingement/effusion system at low jet-to-target plate spacing. Following section documents the details of the experimental setup, data reduction procedure, uncertainty and sensitivity analysis, and result and discussion.