CHAPTER 3

Recent Developments in Impingement Array Cooling, Including Consideration of the Separate Effects of Mach Number, Reynolds Number, Temperature Ratio, Hole Spacing, and Jet-to-Target-Plate Distance

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Abstract

Presented are data that illustrate the effects of Mach number, Reynolds number, temperature ratio, hole spacing, and jet-to-target-plate distance on surface Nusselt numbers produced by an array of jets impinging on a flat plate. The local and spatially averaged Nusselt numbers, and local and spatially averaged recovery factors are unique because: (i) data are obtained at constant Reynolds number as the Mach number is varied, and at constant Mach number as the Reynolds number is varied, (ii) data are obtained at constant Reynolds number and constant Mach number, as the temperature ratio is varied, (iii) data are obtained at constant temperature ratio, Mach number, and Reynolds number, as the impingement hole spacing is varied, (iv) data are obtained as the jet-to-target-plate distance is varied as Reynolds number, Mach number, hole spacing, and temperature ratio are constant, and (v) data are given for jet impingement Mach numbers up to 0.74, and for Reynolds numbers up to 60,000. Also included are crossflow-to-jet mass velocity ratio data and discharge coefficient data. Impingement hole spacings are $5D$, $8D$, and $12D$ in the streamwise and spanwise directions, with jet-to-target-plate distances of $1.5D$, $3D$, $5D$, and $8D$. Local spatially resolved and spatially averaged Nusselt numbers, measured using infrared thermography and energy balance techniques, show strong dependence on the impingement jet Reynolds number for each situation as the jet Mach number is maintained constant. Nusselt numbers show negligible variations with Mach number, between $Ma = 0.1$ and $0.2$, however, data taken at Mach numbers greater than approximately $0.25$ (as the Reynolds number is held constant)
show that Mach number has a significant impact on local and spatially averaged Nusselt numbers. This Mach number dependence changes with hole spacing, with greater Nusselt number increases with the less dense impingement arrays. These variations are described using new correlations, which account for the effects of Mach number for all three impingement hole spacings. In regard to the effects of temperature ratio, at constant Reynolds number of 18,000, and constant Mach number of 0.2, experimental results show that local, line-averaged, and spatially averaged Nusselt numbers decrease as the $T_{wa}/T_j$ temperature ratio increases. This is believed to be due to the effects of temperature-dependent fluid properties, as they affect local and global turbulent transport in the flow field created by the array of impinging jets. Data, which illustrate the effects of jet-to-target plate distance on the heat transfer from an array of jets impinging on a flat plate, are presented for a Reynolds number $Re_j$ of 8,200. Jet-to-target plate distances $Z$ of $1.5D$, $3.0D$, $5.0D$, and $8.0D$ are employed. Steamwise and spanwise hole spacings are $8D$. Local and spatially averaged Nusselt numbers show important dependence upon normalized jet-to-target plate distance, especially for smaller values of this quantity.

**Keywords:** Impingement cooling, turbulence jets, impingement jet array, heat transfer augmentation.

### 1 Introduction

Exposure to hot gasses or hot liquids generates undesirable heat in a wide range of applications. Impingement cooling is an attractive method for the removal of these heat loads because of its relative high effectiveness. The main objective of impingement cooling is maximum heat removal with minimal coolant mass flow rates. To achieve this, jets of impinging fluid are frequently delivered by orifices integrated into internal structures within the component in need of heat removal. In the example of cooling leading edge regions of turbine blades and vanes, the impingement air enters the leading edge cavity from an adjacent cavity through a series of crossover holes on the partition wall between the two cavities. The crossover jets then impinge on the concave leading-edge wall and then exit either through film cooling holes, or though exit passages, which lead to another part of the airfoil. Spanwise lines of impingement jets are produced with this arrangement, which direct cooling air on high external heat load regions, such as the stagnation region [1]. Impingement cooling is also often used to cool parts of the combustor in gas turbine engines, including combustion chamber liners, transition pieces, and splash plates. In each case, impinging jets can be used individually or in arrays [2].

The effects of changing impingement plate geometric and configuration parameters, as well as physical parameters in flows with low Mach numbers, incompressible conditions, and relatively low speeds are considered in a variety of existing publications. The effects of Reynolds number and streamwise/spanwise hole spacing in low-speed impingement cooling are addressed by Kercher and Tabakoff [3] and Chance [4]. Metzger *et al.* [5] and Chupp *et al.* [6] address heat transfer with a semi-circular concave region with a line of circular jets impinging on the apex addressing the effects of target spacing, hole spacing, and jet Reynolds
number. The influences of crossflow on a single line of jets is examined by Metzger and Korstad [7], showing that target spacing, jet Reynolds number, and the relative strengths of the jet flow and the crossflow influence heat transfer on the target wall. In another paper, Metzger et al. [8] present heat transfer characteristics measured on a target surface beneath a two-dimensional array of impinging jets also in low-speed flow that indicate in-line jet impingement hole patterns that provide better heat transfer than staggered arrangements. Florschuetz et al. [9] includes data on channel crossflow mass velocity and jet mass velocity (where ratios range from 0 to 0.8), in addition to a correlation with gives Nusselt number dependence on these parameters, as well as on jet impingement plate geometry, Prandtl number, and Reynolds number. Different crossflow schemes on impingement heat transfer in low-speed flows are considered by Obot and Trabold [10] who arrive at the conclusion that for a given crossflow scheme and constant jet diameter $d$, higher heat transfer coefficients are obtained as the number of jets over a fixed target area increases and that progressively lower performance is obtained as the crossflow is restricted to exit through two opposite sides, and then, through one side of the passage between the impingement hole plate and the target plate. Bunker and Metzger [11] present detailed local heat transfer distributions due to line jet impingement for leading edge regions, both with and without film extraction effects. Fox et al. [12] examine the effects of unsteady vortical structures on the adiabatic wall temperature distribution produced by a single impinging jet. Bailey and Bunker [13] investigate impingement arrays with inline jets in a ‘square array’, with different axial and lateral jet spacings and relatively low Mach numbers. Included are correlations developed from these data, which extend the range of applicability of the correlations presented by Florschuetz et al. [9]. Other recent studies considered the effects of jet impingement on a leading edge/concave wall with roughness [14], and the effects of jets with mist and steam on a concave target surface [15]. Parsons et al. [16, 17], Parsons and Han [18], Epstein et al. [19], and Mattern and Hennecke [20] show that rotational effects are important for jets impinging on flat surfaces at relatively low Reynolds numbers. However, there is little or no information available at higher jet Reynolds numbers and jet rotation numbers on concave surfaces relevant to engine conditions. Thus, it is evident that, aside from a few investigations, most of the impingement data from the open literature are obtained on flat, smooth surfaces. Brevet et al. [21] employ flat plates to consider one row of impinging jets in a test section with low speed, incompressible flow in which the spent air is again constrained to exit in one direction. Effects of impingement distance, Reynolds number, and spanwise hole spacing on Nusselt number distributions lead to recommendations for optimal $Z/d$ values of 2 to 5, and optimal spanwise hole spacings of 4 to 5 hole diameters. Brevet et al. [22] describe recovery factors and Nusselt numbers measured on a flat target surface beneath a single, compressible impingement jet. These authors have the distinction of separating the effects of Mach number and Reynolds number. Data sets with different Mach numbers and constant Reynolds number are obtained using different impingement hole plates with different hole diameters. They conclude that, increasing the Mach number (as the Reynolds number is constant) improves impingement heat transfer significantly for jet Mach numbers greater than 0.2.
Other recent studies by Lee et al. [23], Garimella and Nenaydykh [24], and Shuja et al. [25] address the effects of nozzle geometry on heat transfer and fluid flow, whereas Siba et al. [26], Chung and Luo [27], and Abdon and Sundén [28] use experimental and numerical approaches to consider the influences of turbulent impingement jets. In another numerical investigation, Tong [29] investigates the hydrodynamic and heat transfer behavior of circular liquid jets. Laschefski et al. [30] also use a numerical approach to investigate of heat transfer produced by rows of rectangular impinging jets. Seyedein et al. [31] report heat transfer characteristics from confined multiple turbulent impinging slot jets, and Rhee et al. [32] describe heat transfer, mass transfer, and flow characteristics from arrays of effusion holes.

Although the number of existing impingement cooling studies is considerable, new innovative cooling configurations are being used in gas turbines, which require additional investigation to account for a number of currently unexplored effects and their influence on impingement heat transfer, especially when compressible flow effects are present. Two of the most important of these unexplored areas are the independent effects of Mach number and Reynolds number for an array of impinging jets. The present chapter provides data on these effects for an array of impinging jets in the form of discharge coefficients, local and spatially averaged Nusselt numbers, and local and spatially averaged recovery factors. The data are unique, not only because data are given for impingement jet Mach numbers as high as 0.74 and impingement jet Reynolds numbers as high as 60,000, but also because the effects of Reynolds number and Mach number are separated by providing data at constant Reynolds number as the Mach number is varied, and data at constant Mach number as the Reynolds number is varied. As such, the present impingement jet array study can be considered a continuation of the investigation of Brevet et al. [22] wherein Mach number influences are investigated for a single impingement jet. Also considered is the effect of increasing wall to jet temperature ratio for an array of cool jets impinging on a heated surface with various flow rates of spent air crossflow. The relationship between the degradation of spatially averaged Nusselt number and wall to jet temperature ratio is represented as a correlation. Data are given for six different temperature ratios. Also provided are new, compressible flow impingement heat transfer data, which illustrate the effects of hole spacing at different Reynolds numbers and Mach numbers. Here, hole spacings of $5D$, $8D$, and $12D$ are employed. The thickness of each impingement plate is $1D$, and the spacing between the hole exit planes and the target plate is $3D$. Included are discharge coefficients, crossflow-to-jet mass velocity ratios, as well as line-averaged, and spatially averaged Nusselt numbers. Data are given that illustrate the separate dependences of local and spatially averaged Nusselt numbers on jet Mach number and jet Reynolds number, for different hole jet spacings. Different hole spacings result in different interactions between adjacent jets and between jets and wall boundary layers, which, when coupled with compressibility, give different local Nusselt number dependence on Mach number. Data, which illustrate the effects of jet-to-target plate distance on the heat transfer from an array of jets impinging on a flat plate, are presented for a Reynolds
number $Re_j$ of 8200. Jet-to-target plate distances $Z$ of 1.5$D$, 3.0$D$, 5.0$D$, and 8.0$D$ are employed, and the streamwise and spanwise hole spacing is 8$D$. Associated local and spatially averaged Nusselt numbers show important dependence upon normalized jet-to-target plate distance, where local variations result from the competing influences of individual jet shear layers, and vortices generated by Kelvin–Helmholtz instabilities.

2 Experimental Apparatus and Procedures

2.1 Impingement flow facility and impingement array plates

Schematic diagrams of the 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, and with configuration as shown in Fig. 1a, is open to the laboratory air at its inlet and exit. Depending upon the required flow conditions, one of two blowers is employed. For the lower Reynolds numbers investigated, a New York Blower Co. 7.5 HP, size 1808 pressure blower is employed. For higher Reynolds numbers, a DRUM Industries, 50 HP, D807

![Figure 1: Impingement investigations experimental facility [33–42]. (a) Component arrangement for Mach number, Reynolds number, and hole spacing investigations. (b) Component arrangement for temperature ratio investigations.](image-url)
pressure blower is employed. In each case, the air mass flow rate provided to the test section is measured (downstream of whichever blower is employed) using an ASME standard orifice plate, flow-mounted calibrated copper-constantan thermocouples, and Validyne DP15 pressure transducers (with diaphragms rated at 13.8 or 34.5 kPa) connected to DP10D Carrier Demodulators. The blower exits into a series of two plenums arranged in series (the upstream plenum is 0.63 m to a side and the downstream plenum measures 0.63 × 0.77 × 0.77 m). A Bonneville cross-flow heat exchanger is located within the plenum, which is farther downstream. 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 [33–42].

This pipe then connects to the 0.635 × 0.635 m side of a plenum, as shown in Fig. 2. Upon entering this plenum, the air first encounters a flow baffle used to distribute the flow, a honeycomb, and other flow straightening devices. These are followed by the impingement plenum (or upper plenum, located below the honeycomb and flow straightening devices) whose top dimensions are 0.635 m and 0.635 m, and whose height is 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 [33–42]. The plenum is thus designed so that different impingement plates can be installed at this location using a 9.5 mm thick polyurethane gasket and ¼ in SAE J429 Grade 5 bolts. Figure 3 shows the test plate configurations, which are employed [37]. Here, each impingement plate is arranged with multiple rows of holes in the streamwise direction, arranged so that holes in adjacent rows are staggered with respect to each other. With this

![Figure 2: Impingement flow facility test section, including impingement plenum, and impingement channel [33–42].](image)
Figure 3: Impingement test plate configurations [37]. (a) $X/D = Y/D = 5$. (b) $X/D = Y/D = 8$. (c) $X/D = Y/D = 12$. 
arrangement, multiple holes are located in each streamwise row. The spacing between holes in the streamwise direction \( X \) is then either 5\( D \), 8\( D \), or 12\( D \), and the spanwise spacing between holes in a given streamwise row \( Y \) is also either 5\( D \), 8\( D \), or 12\( D \). The thickness of each impingement plate is 1\( D \). The spacing between the hole exit planes and the target plate is denoted \( Z \) and is equal to 3\( D \). Note that the coordinate systems employed are also shown in Fig. 3. The impingement cooling flow, which issues from these holes, is contained within the channel formed by the impingement jet plate and the target surface, as shown in Fig. 2, and is constrained to exit in a single direction, which, here, is denoted as the \( x \)-direction. This channel is called the lower plenum. As different plates are employed with different sized impingement holes, this is accomplished using different polycarbonate spacers, which are exactly 3\( D \) in height, and are sealed in place around three sides of the impingement channel. Plates with different impingement hole diameters are used to provide data at a variety of Mach numbers and Reynolds numbers. In all cases, all impingement passage dimensions are scaled relative to impingement hole diameter. Specific hole sizes, mass flow rates, and pressure levels are employed so that data are obtained at different Mach numbers as the Reynolds number is constant, and at different Reynolds numbers as the Mach number is constant [33–37].

When temperature ratio effects are considered, the facility arrangement, shown in Fig. 1b, is employed. In order to obtain different \( T_{wa}/T_j \) temperature ratio values, the impingement air is circulated in a closed loop, and cooled to temperatures as low as \(-80^\circ C\) using liquid nitrogen in two different Bonneville heat exchangers located two different plenums. In order to avoid formation of frost from water vapor initially contained in the air, which passes and circulates in the facility, it is first cooled to a temperature of approximately 0\(^\circ\)C for a period of at least one hour. This results in condensation of portions of the water vapor, which is initially contained within the air stream. As the facility is cooled to even lower temperatures, this water is then frozen at locations, which do not inhibit the passage of the impingement air throughout vital internal components of the facility. The frozen water is collected into trap areas, deliberately designed for this purpose. This approach serves to dry the air somewhat before air temperatures below 0\(^\circ\)C are utilized [36].

2.2 Discharge coefficient measurement and determination

The discharge coefficient is determined using

\[
C_D = \frac{\rho \mu_s}{\rho \mu_i}
\]  

The first step in determining the ideal impingement mass flux \( \rho \mu_i \) is obtaining an ideal impingement Mach number \( M_i \) using

\[
\frac{P_o}{P_s} = \left[1 + M_i^2(k - 1)/2 \right]^{k/(k-1)}
\]

Next, impingement ideal static temperature \( T_i \) is determined using \( T_{oj} \) the ideal Mach number \( M_j \), and the appropriate ideal gas isentropic relationship. Impingement
ideal static density is given by \( \rho_i = \frac{P_i}{RT_i} \), and impingement ideal velocity is given by \( u_i = M_i (kRT_i)^{1/2} \). Note that, in most cases, discharge coefficients are determined, which are based on \( P_a \), the spatially averaged static pressure at the exits of the impingement holes. In some other cases, local discharge coefficients for different impingement holes located along the length of the plate are determined, which are based on measurements of local static pressure measured at different surface pressure taps located along the exit side of the impingement plate [33, 34, 37].

2.3 Local recovery factor measurement

After the static temperature and stagnation temperatures of the impingement air are determined, the local surface recovery factor is determined at different target surface locations using

\[
RF = \frac{(T_{AW} - T_j)}{(T_{\infty} - T_j)}
\]  

(3)

Here, \( T_{AW} \) represents the local adiabatic surface temperature, which is present with zero heat flux on the target surface. Note that some small variations of local adiabatic surface temperature \( T_{AW} \) and local recovery factor \( RF \) are present due to streamwise and spanwise conduction along the test surface, but these are minimized by the use of the polycarbonate target plate, and are included in the estimates of experimental uncertainty values for these two quantities. As tests are conducted and data are acquired, the impingement air jet stagnation temperature is maintained at or very near to the laboratory ambient temperature level \( T_{oj} = T_{ambient} \). This is accomplished using liquid nitrogen in the Bonneville heat exchanger to cool the impingement air to the appropriate level as it passes through the facility. This thermal condition, \( T_{oj} = T_{ambient} \) is then maintained for both the Nusselt number experiments and the recovery factor experiments to provide an appropriate basis of comparison between the data obtained from these two different types of experiments [33, 34]. Because of the spatial uniformity within the impingement supply plenum, and because multiple thermocouples are employed for its measurement, magnitudes of \( T_{oj} \) are representative of the spatially averaged impingement air stagnation temperature.

2.4 Local Nusselt number measurement

The power to the thermofoil heater, mounted on the target plate, is controlled and regulated using a variac power supply. Energy balances, and analysis to determine temperature values on the two surfaces of the target plate, then allow determination of the magnitude of the total convective power (due to impingement cooling) for a particular test. To determine the surface heat flux (used to calculate heat transfer coefficients and local Nusselt numbers), the total convective power level, provided by the particular thermofoil heater employed, is divided by the single surface area of this heater, denoted \( A_{ht} \). The target plate is mounted to allow for thermal expansion as it is maintained completely flat. Each target plate employed
is comprised of a 0.0003 m thick etched foil heater (encased within capton), and a 0.00131 m thick polystyrene plate.

One step in this procedure utilizes a one-dimensional conduction analysis, which is applied between the surface within the target plate where the thermocouples are located (between the heater and the polystyrene target plate), and the ambient air environment behind the target plate. This is used to determine $T_{b\zeta}$, the local temperature on the back surface of the polystyrene target plate, adjacent to the surrounding ambient air environment. Also required for this analysis is $T_{tc\zeta}$, the local temperature within the target plate between the heater and the polystyrene plate, which is determined from thermocouple measurements. With these temperatures known, the radiation heat flux and the convection heat flux from the back side of the target plate, $q_{rb}$ and $q_{cb}$, respectively, are determined together using an equation of the form

$$q_{rb} + q_{cb} = h_{loss}(T_b - T_{ambient})$$  \hspace{1cm} (4)

where $h_{loss}$ is assumed to be equal to 15 W/m²K [21]. This value is employed because it provides a good estimate of the combined radiation and convection heat losses from the back of the target plate. The radiation heat flux $q_{rf}$ on the front (or impingement side) of the target plate is determined using

$$q_{rf} = \frac{1}{1 - \varepsilon_f} - 1\vert 1 - \varepsilon_f \vert^{-1}(T_W^4 - T_{ambient}^4)$$  \hspace{1cm} (5)

With this approach, the radiation heat flux is determined for an arrangement with multi-reflection between two infinite plates where each has a uniform temperature. $\varepsilon_f$ and $\varepsilon_{inf}$ are assumed to be equal to 0.9 for all conditions investigated. This approximate approach works well since $q_{rf}A_{h_0}$ is generally only 3%–6% of $Q$, the total amount of power provided to the thermofoil heater. Note that $T_W$, the local target surface temperature on the surface of the heater adjacent impingement air, must be known to determine $q_{rf}$. Because of the inter-dependence of $T_W$, $q_{rf}$, and $q_{cf}$ (the convection heat flux from the front side or impingement side of the target plate), an iterative procedure is required to determine these quantities. The next part of this procedure uses a one-dimensional conduction model for the heater, which includes source generation of thermal energy, to provide a relation between $T_{Wf}$, $T_{tc\zeta}$, and $q_{cf}$. Also included in the analysis is thermal contact resistance between the internal thermocouples and the adjacent heater.

The convection heat flux from the front side (or impingement side) of the target plate is then given by

$$q_{cf} = Q / A_{h_0} - q_{rf} - q_{rb} - q_{cb}$$  \hspace{1cm} (6)

The local Nusselt number is then given as

$$Nu = q_{cf}D / ((T_W - T_{cf})\alpha)$$  \hspace{1cm} (7)

Modified local Nusselt numbers are also determined, which are based on the $(T_W - T_{oj} \ast)$ and the $(T_W - T_{AW})$ temperature differences. The determination of these parameters is discussed later in the present chapter.
Spatially resolved temperature distributions along the target test surface are determined using infrared imaging in conjunction with thermocouples, energy balances, digital image processing, and \textit{in situ} calibration procedures. These are then used to determine spatially resolved surface Nusselt numbers. To accomplish this, the infrared radiation emitted by the heated interior surface of the channel is captured using a Thermacam PM390 Infrared Imaging Camera, which operates at infrared wavelengths from 3.4 to 5.0 µm. Temperatures, measured using the calibrated, copper-constantan thermocouples distributed along the test surface adjacent to the flow, are used to perform the \textit{in situ} calibrations simultaneously as the radiation contours from surface temperature variations are recorded.

This is accomplished as the camera views the test surface from behind, as shown in Fig. 2. In general, at least six thermocouple junction locations are present in the infrared field viewed by the camera. The exact spatial locations and pixel locations of these thermocouple junctions and the coordinates of the field of view are known from calibration maps obtained prior to measurements. During this procedure, the camera is focused, and rigidly mounted and oriented relative to the test surface in the same way as when radiation contours are recorded. Voltages from the thermocouples are acquired using apparatus that are described elsewhere [33–37]. With these data, gray scale values at pixel locations within images from the infrared imaging camera are readily converted to local Nusselt number values. Because such calibration data depend strongly on camera adjustment, the same brightness, contrast, and aperture camera settings are used to obtain the experimental data. The \textit{in situ} calibration approach rigorously and accurately accounts for these variations.

Images from the infrared camera are recorded as 8-bit gray scale directly into the memory of a Dell Dimension XPS T800r PC computer using a Scion Image Corporation Frame grabber video card, and Scion image v.1.9.2 software. One set of 15–20 frames are recorded at a rate of about one frame per second. All of the resulting images are then ensemble averaged to obtain the final gray scale data image. This final data set is then imported into Matlab version 6.1.0.450 (Release 12.1) software to convert each of 256 possible gray scale values to local Nusselt number at each pixel location using calibration data. Each individual image covers a 256 × 256 pixel area [33–42].

3 Experimental Results and Discussion

The results, which follow, are presented in five parts. First, crossflow mass velocity-to-jet mass velocity ratio data and discharge coefficient data are presented for three different impingement jet hole spacing arrangements. Second, experimental measurements, which illustrate the separate effects of Reynolds number and Mach number on impingement array heat transfer, are given, including spatially resolve measurements of Nusselt numbers, as well as surface recovery factors. Third, results, which illustrate the influences of temperature ratio, are presented and discussed. In the fourth part, effects of spacing of the holes within an impingement array are considered and discussed. Finally, in the fifth part, effects of jet-to-target-plate distance are addressed.
3.1 Crossflow mass velocity-to-jet mass velocity ratio and discharge coefficients

Figure 4a shows several examples of the ratio of crossflow mass velocity-to-jet mass velocity as it varies with hole row number for hole spacings of $5D$, $8D$, and $12D$. This ratio is only as high as about 0.48 at the end of all rows of holes when $X/D$ and $Y/D$ are both equal to 5.0. Here, data from the present study show

![Figure 4a](image)

Figure 4: (a) Crossflow-to-jet mass velocity ratio with row number for hole spacings of $5D$, $8D$, and $12D$ and (b) discharge coefficient variations with $Re_j$ for hole spacings of $5D$, $8D$, and $12D$ at constant Mach number 0.2 [37].
reasonably good agreement with the correlation of Florschuetz et al. [9]. Note that, $Gc/Gj$ values are lower for $12D$ hole spacing than for $8D$ hole spacing, with $5D$ having the highest values when compared at a particular value of $x/D$ [37].

Discharge coefficients represent average values for all of the impingement holes on a particular test plate, and are presented in Fig. 4b. Here, all discharge coefficients are based upon $Pa$, which is the ambient pressure measured at the exit of the impingement flow facility. From Fig. 4b, it is apparent that discharge coefficients decrease slightly as the Reynolds number increases, provided the Mach number is 0.2, and the spacings of holes within the impingement array are maintained constant [37].

3.2 Separate effects of Reynolds number and Mach number on impingement array heat transfer

The discussion, which follows, includes consideration of different methods to determine the local Nusselt number, including consideration of local variations of recovery factor and local variations of surface adiabatic temperature.

3.2.1 Determination of spatially averaged adiabatic surface temperature, $T_{oj}^*$

To determine an appropriate reference temperature for the determination of heat transfer coefficients and Nusselt numbers, the convective heat power from the impingement side of the target plate $q_{cf}$ is determined as it varies with $(T_w - T_{oj})$ [33, 34]. Data are obtained at three different temperature differences. The largest temperature difference employed is always less than 30°C to avoid variations of measured Nusselt numbers with variable property effects. Such convective heat power data then vary linearly with $(T_w - T_{oj})$. Such linear data are extrapolated to the $q_{cf} = 0$ axis to determine $(T_w - T_{oj}^*)$. Note that the convective power is the value for the entire target plate. Consequently, the magnitude of $T_{oj}^*$ is spatially averaged over the target plate heat transfer area, and as such, is the spatially averaged adiabatic surface temperature for the entire heated portion of the target plate at a particular experimental condition. Consequently, all Nusselt number data are obtained at three different values of $(T_w - T_{oj})$ to provide a means to determine the magnitude of $T_{oj}^*$ for each experimental condition. All Nusselt numbers are then determined using

$$ Nu = \frac{q_{cf} D}{(A_w(T_w - T_{oj}^*)\alpha)} $$

3.2.2 Nusselt number variations with Mach number and Reynolds number

Local spatially resolved surface Nusselt number distributions for $Re_j = 60,000$ and $Ma$ values from 0.16 to 0.74 are shown in Fig. 5a–e. The different views of the test surface in the different parts of this figure are due to different infrared camera views of the target plate as impingement plates with different sized holes are employed on the opposite side. Note that, regardless of the Mach number, the qualitative distributions of local Nusselt number produced by each impingement
jet are similar, with good periodic repeatability in the spanwise direction for each streamwise row of impact locations. This includes local distributions associated with each impingement impact area at different spanwise locations in each streamwise row [34].

Figure 5a–e also shows that only one local maximum value is present in the \( Nu \) distribution underneath each jet. In general, magnitudes of these local jet maxima underneath the different impingement jets decrease as the flow develops in the streamwise direction and \( x/D \) increases, for particular \( Ma \) and \( Re_j \) values. This trend is also illustrated by local Nusselt number data presented as they vary with \( x/D \) for each \( y/D \) location. Another important conclusion, apparent from the results given in Fig. 5a–e, is that local maximum \( Nu \) values generally increase somewhat at each \( x/D \) and \( y/D \) surface location, as Mach number increases, provided the Reynolds number is held constant. A similar conclusion is also reached as the Reynolds number increases, provided the Mach number is held constant [34].

Figure 5: Spatially resolved distributions of surface Nusselt number for \( Re_j = 60,000 \) and \( Ma \) values of: (a) 0.16, (b) 0.21, (c) 0.38, (d) 0.63, and (e) 0.74 [34].
Corresponding line-averaged Nusselt number data as they vary with \( x/D \) are shown in Fig. 6, also for \( Re_j = 60,000 \) and \( Ma \) values of 0.16, 0.21, 0.38, 0.63, and 0.74. These data are also obtained by line-averaging over \( y/D \) values from \(-8.0\) to \(+8.0\). Here, streamwise variations of line-averaged Nusselt numbers are evident. Figure 6 shows that local maximum line-averaged Nusselt number values have the same approximate streamwise spacing as the streamwise spacing of the holes located on the impingement jet plate. Associated local maximum values here generally decrease at successive \( x/D \) locations for each value of impingement Mach number, \( Ma \). In most cases, line-averaged Nusselt number values increase at each \( x/D \) location as \( Ma \) increases. Exceptions to this trend are exhibited by the \( Ma = 0.21 \) data, which show higher peak values (compared to data measured at lower Mach numbers), near the \( x/D = 16 \), \( x/D = 24 \), and \( x/D = 32 \) locations [33, 34].

### 3.2.3 Comparisons of spatially averaged Nusselt numbers with existing correlations, and a new correlation to account for Mach number effects

Spatially averaged Nusselt numbers are compared with the correlation of Florschuetz et al. [9], as shown in Fig. 7a and b. Each data point in these figures, from the present investigation, is determined by averaging local Nusselt number data over \( y/D \) values from \(-8.0\) to \(+8.0\), and over an \( x/D \) range of \( 8.0 \) (or \( x/D = -4.0 \) to \( x/D = +4.0 \)) relative to the centers of the nominal jet impact locations (which correspond to the \( x/D \) centers of the impingement plate holes). The first of these figures shows \( Ma = 0.10 \) data for \( Re_j \) values of 5,200, 6,400, and 8,200.
Here, data from the present study show reasonably good matches to the correlation values from Florschuetz et al. [9] for all of these experimental conditions. Figure 7b presents the present spatially averaged data for $Re_j = 60,000$ and $Ma$ values of 0.16, 0.21, 0.38, 0.63, and 0.74. In this figure, the experimental data associated with $Ma = 0.16$ and $Ma = 0.21$ are in good agreement with values from the Florschuetz et al. [9] correlation. The present data then deviate from this correlation by larger amounts as the impingement Mach number increases further, with the largest deviation evident for $Ma = 0.74$. In general, the trends, shown by
the data in Fig. 7b, are qualitatively consistent with results from Brevet et al. [22] for a single impingement jet.

The variation of spatially averaged Nusselt numbers with Mach number is shown in Fig. 7c. These data are given for specific $x/D$ values, and for specific values of the impingement Mach number. The correlation equation, which best represents these data, is given by

$$\frac{Nu}{Nu_{ref}} = 1.0 + 0.325M_a^{1.55}$$

(9)

As such, this correlation equation is valid for $Re_j = 60,000$, $0.21 \leq Ma \leq 0.74$, $X/D = 8$, $Y/D = 8$, $Z/D = 3$, and $20 \leq x/D \leq 60$ [34]. Equation (9) thus provides a means to determine Nusselt number data for compressible flows at elevated Mach numbers, relative to values from the Florschuetz et al. [9] correlation.

### 3.2.4 Recovery factor data

Recovery factor data provide information on the variation of adiabatic surface temperature over the test surface. Recovery factor data are important because they provide a means to account for local variations of adiabatic surface temperature $T_{AW}$. Local RF values are occasionally greater than 1.0 because the dynamic temperature ($T_{oj} - T_j$) within the denominator of eqn (3) is based upon overall, average impingement jet kinetic energy. Examples are shown in Fig. 8a–c for $Re_j = 60,000$ and $Ma = 0.74$. The contour plot data in Fig. 8a show higher values of recovery factor RF beneath and in the vicinity of impact locations of the impingement jets. This is because $T_{oj} = 23.27^\circ C$, which is approximately equal to $T_{ambient}$ for these tests, which gives $T_j$ equal to $-6.16^\circ C$. As a result, there is heat transfer to the impinging air streams from the surrounding air, an effect that is enhanced by the families of vortices associated with the jet, and the enhanced mixing and entrainment they produce of surrounding fluid to the jets [12]. Nearby jet impact locations, values of RF continue to be relatively high and in general, greater than 1.0, especially on the spanwise sides of impact locations. However, values are occasionally less than one at upstream and downstream locations. Such local variations and the quantitative variations associated with them are further illustrated by the local RF data presented as it varies with $x/D$ for $y/D = 0$, 4, and 8 in Fig. 8b, and as RF varies with $y/D$ for $x/D = 32$, 48, and 56 in Fig. 8c. Note that values of $T_{AW}$, determined from RF data and spatially averaged over the test surface, approximately match magnitudes of $T_{oj}$ for most all experimental conditions where these data are measured [34].

### 3.2.5 Nusselt number data corrected using local recovery factors

The local and line-averaged Nusselt number data presented in Fig. 9a–c are based on the difference between the local, spatially varying measured surface temperature $T_W$, and the local adiabatic surface temperature $T_{AW}$, determined from recovery factor data, as shown in Fig. 8a. This is accomplished by correcting local Nusselt number values using the equation

$$Nu_c = \frac{Nu(T_W - T_{oj}* / (T_W - T_{AW})$$

(10)
Figure 8: Recovery factor data for $Re_j = 60,000$ and $Ma = 0.74$. (a) Local surface recovery factor distribution. (b) Local surface recovery factor data as it varies with $x/D$ for $y/D = 0, 4,$ and $8$. (c) Local surface recovery factor data as it varies with $y/D$ for $x/D = 32, 48,$ and $56$ [34].
Recall that $T_{oj}^*$ represents the adiabatic surface temperature, spatially averaged over the test plate. The results, as shown in Fig. 9a–c, are given for $Re_j = 60,000$ and $Ma = 0.74$. A comparison of Fig. 9a with results presented in Fig. 5e then shows that local corrected Nusselt numbers $Nu_c$ based on local $(T_w-T_{AW})$ (i.e. Fig. 9a) have slightly higher peaks than local $Nu$ values based on $(T_w-T_{oj}^*)$ (Fig. 5e).

Figure 9: Corrected and uncorrected surface Nusselt number data for $Re_j = 60,000$ and $Ma = 0.74$. (a) Local corrected surface Nusselt number distribution. (b) Local surface Nusselt number data as it varies with x/D for y/D = 0. (c) Surface Nusselt number variations with x/D, which are line-averaged over y/D from −8.0 to +8.0 [34].
This trend is also illustrated by the local Nusselt number data presented as it varies with \( x/D \) (for \( y/D = 0 \)) in Fig. 9b, as well as by the line-averaged Nusselt number data given in Fig. 9c. The relative differences between corrected and uncorrected data in these figures are generally quite small because recovery factors in Fig. 8a–c are close to 1.00 with the largest values in the vicinity of 1.03. As a result, spatially averaged Nusselt numbers are approximately the same regardless of whether they are based upon \((T_{W} - T_{AW})\) or \((T_{W} - T_{oj}*)\). Note that local recovery factor \( RF \) values are sometimes greater than 1.0 because a spatially averaged value of \( T_{oj} \) (for all of the impingement array holes) is used determine local \( RF \) magnitudes at all test surface locations [34].

3.3 Effects of temperature ratio on impingement array heat transfer

Figures 10–12 show the effects of \( T_{wa}/T_{j} \) temperature ratio on local and spatially averaged Nusselt number data for \( Re_{j} = 18,000 \) and \( Ma = 0.2 \). These data at different increasing values of \( T_{wa}/T_{j} \) are obtained by decreasing the impingement jet static temperature \( T_{j} \) and increasing \( T_{wa} \), where \( T_{wa} \) is the spatially averaged target wall temperature, and \( T_{j} \) is the impingement jet static temperature.

3.3.1 Local surface Nusselt number variations with temperature ratio

Surface Nusselt number distributions are presented in Fig. 10a–f for \( Ma = 0.20 \), \( Re_{j} = 18,000 \), and \( T_{wa}/T_{j} = 1.06, 1.25, 1.36, 1.48, 1.58, \) and \( 1.73 \). Note that, regardless of the temperature ratio, the qualitative distributions of local Nusselt number produced by each impingement jet are similar, with good periodic repeatability in the spanwise direction for each streamwise row of impact locations. Figure 10a–f also shows that each impingement jet produces only one local maximum value in the \( Nu \) distribution on the target surface beneath each jet. Magnitudes of these local maximum values decrease underneath the different impingement jets with \( T_{wa}/T_{j} \) for the \( T_{wa}/T_{j} \) values investigated, with minor variations between streamwise rows as \( x/D \) increases. Variations with streamwise distance are due to the increasing effect of hot, spent air crossflow, which reduces the effectiveness of the impinging jets. Figure 10a–f also shows that local \( Nu \) values decrease as the temperature ratio increases, with the most noticeable differences evident in peak (or local maximum) values. This is partially because, as temperature ratio increases at constant Reynolds number, the intensity of the impingement jets decreases due to the decreases in both mass flow rate and volumetric flow rate [36].

3.3.2 Spatially averaged Nusselt number variations with temperature ratio

Spatially averaged Nusselt numbers are averaged over an area that extends \( \pm 4 \) diameters from the specified \( x/D \) location and over \( y/D \) data points from \(-8 \) to \( 8 \). This area thus amounts to two complete spatial periods of impingement jet array geometry. Note that spatially averaged target surface temperatures \( T_{wa} \) are determined over the same spatial surface areas.

Figure 11 gives spatially averaged Nusselt numbers at different values of \( T_{wa}/T_{j} \), along with values from the correlation of Florschuetz et al. [9]. There are noticeable
Figure 10: Spatially resolved surface Nusselt number distributions for $Re_j = 18,000$, $Ma = 0.2$, and $T_{wa}/T_j = 1.06$, 1.25, 1.36, 1.46, 1.58, and 1.73 [36].
differences between the present data for $T_{wa}/T_j = 1.06$ and the correlation of Florscheutz et al. [9], which is for a temperature ratio $T_{wa}/T_j$ of approximately 1.1. This is because the experimental conditions for the present data are outside the range of validity of the Florscheutz correlation. In both cases, spatially averaged Nusselt number data points are given for $x/D$ of 32, 40, 48, and 56. For each of these streamwise locations, the results, as shown in Fig. 11, show that area-averaged Nusselt numbers decrease as the $T_{wa}/T_j$ temperature ratio increases up to 1.73, provided the impingement jet static temperature is held constant. Such behavior evidences some deterioration of impingement cooling performance. This is because the variable property effects degrade local turbulent transport. In addition,
the high crossflow temperature relative to jet temperature decreases the effectiveness of the impinging jets, and causes area-averaged Nusselt numbers to decrease with $x/D$ at each $T_{wa}/T_j$ temperature ratio value [36].

### 3.3.3 Spatially averaged Nusselt numbers and the temperature ratio correlation equation

Figure 12 shows Nusselt number ratios $Nu/Nu_{cp}$ as they depend upon temperature ratio $T_{wa}/T_j$ for $Re_j = 18,000$ and $Ma = 0.2$. $Nu_{cp}$ represents the constant property Nusselt number, a condition corresponding with a temperature ratio, $T_{wa}/T_j$, of approximately one. In the present study, a temperature ratio near one (1.06) is used as an approximation for $Nu_{cp}$. The $Nu/Nu_{cp}$ data, as shown in Fig. 12, follow the same trend as shown in Fig. 11, which shows a decrease in Nusselt number as the $T_{wa}/T_j$ temperature ratio increases from 1.06 to 1.73. The correlation equation, which best represents the data shown in Fig. 12, is given by [36]

$$\frac{Nu}{Nu_{cp}} = (T_{wa}/T_j)^{-0.35}$$

This correlation equation is determined for $Re_j = 18,000$, $Ma = 0.2$, $1.060 \leq T_{wa}/T_j \leq 1.73$, $X/D = 8$, $Y/D = 8$, $Z/D = 3$, and $32 \leq x/D \leq 56$. However, eqn (11) is expected to be valid for a wider range of incompressible (or near incompressible) flow conditions, which include $Re_j$ from near 3,000 to about 30,000, $Ma$ from near 0 to approximately 0.25, and a range of $X/D$ and $Y/D$ values in the vicinity of 8.

The Nusselt number variations, which are observed as either $T_{wa}/T_j$ or $T_{wa}/T_j$ varies, are mostly due to variable property effects. Most important are variations of molecular thermal conductivity, absolute viscosity, and static density with spatial location and time, since these changes as static temperature varies with spatial location and time. Note that the contributions of specific heat to Nusselt number variations are less important because of its weak dependence on temperature in gas flows. The effects of conductivity, viscosity, and density variations on local turbulent transport of momentum and heat are complex. For example turbulent transport is generally mostly a result of mixing, collisions, and interactions of different sizes of turbulent eddies. However, ultimately, as molecular scales are approached, thermal transport is due to conduction between adjacent packets of oscillating fluid. In many cases, such molecular conduction provides some restriction on overall magnitudes of turbulent transport, which can be achieved. Such limitations and the associated phenomena and interactions are especially complex in impingement array flows because they involve such a wide variety of phenomena, including jet flows, shear layer interactions, stagnation regions, interactions between adjacent impingement jets, wall-jet interactions, three-dimensional boundary layer development, and interactions between impingement jets and these boundary layers [36].

### 3.4 Effects of hole spacing on impingement array heat transfer

The results, presented in Figs 13–16, illustrate the influences of hole spacing on impingement array surface heat transfer, for different Reynolds numbers and different Mach numbers.
Figure 13: Surface Nusselt number variations which are line-averaged over y/D for one hole spacing in either direction from the origin for constant Reynolds number 30,000 and (a) hole spacing $5D \, Ma = 0.09$, 0.17, 0.30, and 0.38, (b) hole spacing $8D \, Ma = 0.20$, 0.35, 0.45, and 0.59, (c) hole spacing $12D \, Ma = 0.10$, 0.17, 0.38, and 0.45 [37].
3.4.1 Line-averaged Nusselt numbers

Figure 13a–c presents Nusselt numbers that are line-averaged over $y/D$ from $-2.5$ to $+2.5$ for a hole spacing of $5D$, over $-4.0$ to $+4.0$ for a hole spacing of $8D$, and over $-6.0$ to $+6.0$ for a hole spacing of $12D$. Figure 13a–c shows line-averaged Nusselt number comparisons as the Mach number varies at constant Reynolds number for each of the three hole spacings. Here, comparisons at constant $x/D$ and $Ma$ values of $0.1$, $0.17$, $0.30$, and $0.38$ [37].

Figure 14: Hole spacing $X/D = Y/D = 5$ comparison of area-averaged Nusselt numbers with correlation of Florschuetz et al. [9]. (a) Data for $Ma = 0.17$, and $Re_j = 17,300$, $30,000$, and $59,000$. (b) Data for $Re_j = 30,000$ and $Ma$ values of $0.1$, $0.17$, $0.30$, and $0.38$ [37].

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Figure 13a–c presents Nusselt numbers that are line-averaged over $y/D$ from $-2.5$ to $+2.5$ for a hole spacing of $5D$, over $-4.0$ to $+4.0$ for a hole spacing of $8D$, and over $-6.0$ to $+6.0$ for a hole spacing of $12D$. Figure 13a–c shows line-averaged Nusselt number comparisons as the Mach number varies at constant Reynolds number for each of the three hole spacings. Here, comparisons at constant $x/D$ and $Ma$ values of $0.1$, $0.17$, $0.30$, and $0.38$ [37].
and constant Reynolds number generally show increases of line-averaged Nusselt numbers with Mach number. Line-averaged Nusselt number comparisons as the Reynolds number changes at constant Mach number for each of the three hole spacings show considerable increases with Reynolds number, as well as values that decrease in a periodic fashion with streamwise development as $x/D$ increases. This decrease with $x/D$ is more pronounced for smaller hole spacings due to increased effects of spent air crossflow [37].

Figure 15: Hole spacing $X/D = Y/D = 8$ comparison of area-averaged Nusselt numbers with correlation of Florschuetz et al. [9]. (a) Data for $Ma = 0.2$, and $Re_j = 17,300$, $30,000$, and $59,000$. (b) Data for $Re_j = 30,000$ and $Ma$ values of $0.1$, $0.2$, $0.35$, $0.45$, and $0.59$ [37].
3.4.2 Spatially averaged Nusselt numbers

Figures 14–16 compare measured spatially averaged Nusselt numbers for hole spacings of $5D$, $8D$, and $12D$ with correlation values from Florschuetz et al. [9]. These data are obtained by averaging over areas in the streamwise and spanwise directions, which are the same as the spanwise averaging distance used to obtain the line-averaged data.

Figure 16: Hole spacing $X/D = Y/D = 12$ comparison of area-averaged Nusselt numbers with correlation of Florschuetz et al. [9]. (a) Data for $Ma = 0.2$, and $Re_f = 17,300, 30,000,$ and $59,000$. (b) Data for $Re_f = 30,000$ and $Ma$ values of $0.1, 0.2, 0.35, 0.38$, and $0.45$ [37].

3.4.2 Spatially averaged Nusselt numbers

Figures 14–16 compare measured spatially averaged Nusselt numbers for hole spacings of $5D$, $8D$, and $12D$ with correlation values from Florschuetz et al. [9]. These data are obtained by averaging over areas in the streamwise and spanwise directions, which are the same as the spanwise averaging distance used to obtain the line-averaged data.
Figure 14a shows comparisons for 5D hole spacing at a constant Mach number of 0.17 and $Re_j$ values of 17,300, 30,000, and 59,000. Here, measured and correlation-predicted values [9] are in agreement within 5%–10% for the lower $Re_j$ values. Figure 14b shows the comparison for 5D hole spacing at constant Reynolds number and Mach number values of 0.09, 0.17, 0.30, and 0.38. Here, the two data sets for $Ma \leq 0.2$ show good agreement with Florschuetz et al. [9], with a departure from the correlation that increases with increasing Mach number at each $x/D$ value.

Figure 15a shows the comparison for 8D hole spacing at constant Mach number of 0.20 and $Re_j$ values of 11,100, 13,100, 17,300, 30,500, and 59,000. In all cases, there is good agreement between measured and correlation-predicted values [9]. Figure 15b shows the comparison for 8D hole spacing at constant Reynolds number, and Mach number values of 0.10, 0.20, 0.35, 0.45, and 0.59. Here, as seen for the 5D hole spacing data, the two cases for $Ma \leq 0.2$ show good agreement with Florschuetz et al. [9], with a departure from the correlation that increases with increasing Mach number at each $x/D$ value [37].

Figure 16a shows that, at constant Mach number, data for hole spacing 12D show good agreement with the correlation predicted values [9] for $Re_j = 17,300$. When $Re_j = 30,000$ and $Re_j = 57,000$, measured values are then higher than predicted values. Figure 16b shows that for near-incompressible cases, when $Ma = 0.11$ and $Ma = 0.22$, spatially averaged Nusselt number values are in agreement with each other, but higher than Florschuetz et al. [9] predicted values. These differences are not surprising when one considers that the 12D hole spacing data are outside the range of applicability of the Florschuetz et al. [9] correlation, which does not consider geometries with hole spacing greater than 8D for a staggered array. Area-averaged Nusselt numbers then increase with Mach number at each $x/D$ value, which is consistent with results, presented in Figs 14b and 15b, for the two smaller hole spacings [37].

3.4.3 Correlations to account for compressibility on spatially averaged Nusselt numbers with different hole spacings

Variations due to different impingement jet spacings are, in part, because each jet produced using the larger spacing of $X/D = Y/D = 12$ approximates the behavior of an individual jet. When $X/D = Y/D = 8$ and $X/D = Y/D = 5$, the cumulative effects of induced crossflows partially reduce the effectiveness of each individual jet. However, because the jets are closer together, with greater local influences of surrounding jets, line-averaged and area-averaged Nusselt numbers are generally higher as $X/D$ and $Y/D$ decrease [37].

Of importance to such changes are the vortices which form around the impinging jets, and then interact with each other after they impact on the target surface [12]. Interactions of these jet vortices with the accumulation of crossflows from sequential rows of jets, which are especially apparent in associated data for the 5D and 8D jet spacings, are also important, and generally give general trends of decreasing local and spatially averaged Nusselt numbers with $x/D$. These interactions are tied...
to the unsteady vortex structures and vortex rings, which initially form around the periphery parts of the impingement jets. According to Fox et al. [12], it is the competition between these vortex rings and the associated secondary vortices induced by them, which determine the local stagnation temperature and static temperature distributions on the impingement target plate. The resulting total temperature alterations from these vortices are then also responsible for enhancing the surface heat transfer and the surface Nusselt number distributions. Depending upon the interactions between the primary and secondary vortex rings after they impact and advect along the target plate, different amounts and distributions of surface heating and/or cooling can be produced [12].

Compressibility, even in a mild form, alters these complex vortex interactions. Complications and complexity also result as the compressible vortex rings and the associated secondary vortices from different impingement jets intermingle and interact with each other in a myriad of possible forms and combinations. The results of these interactions are evident in the data presented in Figs 5–16, which show that the associated changes are generally most apparent in local values (i.e with smaller periodic variation with \(x/D\) or \(y/D\)), than values that are line-averaged or area-averaged [37].

Existing correlations for arrays of impinging jets generally do not include compressible flow effects. To resolve this deficiency, spatially averaged Nusselt numbers are compared with the correlation of Florscheutz et al. [9] for \(Re_j = 30,000\) and values of Mach number that range from 0.1 to 0.45. This is accomplished by considering the dependence on impingement jet Mach number \(Ma\), of the ratio of the area-averaged Nusselt number to the area-averaged Nusselt number at the same experimental conditions determined from the Florscheutz et al. [9] correlation. An example of such data is shown in Fig. 7c for \(X/D = Y/D = 8\). As such, the Mach number dependent deviation from Florscheutz et al. is correlated for hole spacings of \(X/D = Y/D = 5\), \(X/D = Y/D = 8\), and \(X/D = Y/D = 12\). For \(X/D = Y/D = 5\), the correlation equation, which best represents these data, is given by

\[
\frac{\overline{Nu}}{\overline{Nu_F}} = 0.95 + 1.2Ma^{1.6}
\]  

(12)

For \(X/D = Y/D = 8\), the associated correlation equation is given by

\[
\frac{\overline{Nu}}{\overline{Nu_F}} = 1.0 + 1.2Ma^{1.9}
\]  

(13)

For \(X/D = Y/D = 12\), the resulting correlation equation is given by

\[
\frac{\overline{Nu}}{\overline{Nu_F}} = 1.1 + 1.2Ma^{2.3}
\]  

(14)

Equation (13) thus provides an alternative to eqn (9) for \(X/D = Y/D = 8\) and a different \(Re_j\) of 30,000. The present data and associated correlations thus provide evidence that these detrimental effects for the smaller hole spacings change as the Mach number increases. The present data thus deviate from the Florscheutz et al. [9] correlation by larger amounts as the impingement Mach number increases, with the largest deviation evident for the highest Mach number, which is considered [37].
3.5 Effects of jet-to-target-plate distance on impingement array heat transfer

The results, as shown in Figs 17 and 18, illustrate the influences of jet-to-target plate distance on impingement array heat transfer.

3.5.1 Spatially resolved local Nusselt numbers

Figure 17 presents local Nusselt number comparisons for normalized jet-to-target plate distances \( Z/D \) of 1.5, 3.0, 5.0, and 8.0, as dependent upon \( y/D \) for particular values of \( x/D \), and as dependent upon \( x/D \) for particular values of \( y/D \). These data are presented for an impingement Reynolds number of approximately 8,200. For all conditions examined, lower local values are generally present both at and between jet impact locations as \( Z/D \) approaches 8.0, when compared at

![Graphs showing local Nusselt number variations](image)

Figure 17: Local Nusselt number variations for \( Re_j \approx 8,200 \) for different \( Z/D \) values and \( X/D = Y/D = 8 \). (a) Variations with \( y/D \) for \( x/D = 20 \). (b) Variations with \( x/D \) for \( y/D = 4 \) [42].
the same $Re_j$, $x/D$, and $y/D$. The highest local maximum Nusselt numbers appear to be associated either with $Z/D$ of 3.0 or 5.0. Associated overall local Nusselt number decreases with increasing $Z/D$ (at most all $x/D$ and $y/D$ values) are due to diminished jet coherence, as well as diminished coherence of associated Kelvin–Helmholtz generated vortices, which occur as jet advection distances become larger. However, regardless of the value of $Z/D$, magnitudes of successive local peak Nusselt numbers, at successive jet stagnation point impact locations, generally decrease with $x/D$ for all values of $Z/D$ and impingement Reynolds number, which are considered.

When examined at a particular value of $Re_j$, note that the streamwise locations of local maximum Nusselt numbers shift to larger $x/D$ locations as the normalized jet-to-target distance increases. This is a result of larger advection distances between the impingement hole exits and the target plate, which allow crossflows to exert greater influences in shifting the locations of jet impact stagnation points. The Kelvin–Helmholtz generated vortices, which form in an intermittent fashion around each jet, also play a role in this process, especially as they periodically impact onto the target surface and are then advected in the crossflow direction. Such unsteady vortices are also important in augmenting local Nusselt number values at target surface locations in the near-vicinity of stagnation point locations [38–42].

**3.5.2 Spatially averaged Nusselt numbers**

Spatially averaged Nusselt numbers for a jet hole spacing of $X/D = Y/D = 8$ are presented in Fig. 18. Each spatially averaged value is determined over an area that extends over an $x/D$ range from $-4.0$ to $+4.0$ relative to each streamwise row location, and over a $y/D$ range comprised of one or two complete periods of local spanwise Nusselt number variation. The spatially averaged Nusselt number results, as shown in Fig. 18, are given to illustrate the dependence upon $Z/D$ for an $Re_j$.  

![Figure 18: Spatially averaged Nusselt numbers as dependent upon $Z/D$ for $Re_j \approx 8,200$ and $X/D = Y/D = 8$ [42].](image)
value of 8,200. Important variations with normalized jet-to-target plate distance are apparent. Note that the highest spatially averaged Nusselt numbers are present for $Z/D = 3.0$ and for $Z/D = 5.0$ for $Re_j = 8,200$.

Such changes of local and spatially averaged Nusselt numbers with $Z/D$, and the resulting optimal values, are believed to be a result of the competing influences of two different phenomena: (i) the coherence of individual jets and the strength of adjacent shear layers and (ii) the development and advection of vortices generated by Kelvin–Helmholtz instabilities. The coherence of individual jets and the intensity of the adjacent shear layers are strongest just after each jet emerges from an impingement plate hole. With this situation, maximum local jet velocities are distributed over the central part of each jet, with the largest gradients of velocity present in the thinnest shear layers, which surround each jet. As each jet advects downstream and surrounding fluid becomes entrained to become part of each jet, the local velocity profile becomes more rounded with adjacent shear layer velocity gradients, which are less intense as jet fluid diffuses and advects in lateral directions. If such jets impinge upon a surface, the highest local and spatially averaged surface Nusselt number augmentations are expected to be present just after jets emerge from originating holes, when they are most coherent with the most intense adjacent shear layers.

Another mechanism for local heat transfer augmentation is formation, development, and surface impact of Kelvin–Helmholtz generated vortices. In contrast to the diminishing jet coherence with streamwise development, these vortices continue to develop as they advect in the streamwise direction. Their ability to augment thermal transport is a result of the mixing they induce between the jet and surrounding non-jet fluid. The resulting gradients of density (if the flows are compressible) and stagnation temperature within the vortices are key elements in their capability to augment local heat transfer coefficients and Nusselt numbers [42].

The relative influences of the jet/shear layer coherence and Kelvin–Helmholtz generated vortices are reflected in the $Z/D$ values associated with the highest Nusselt numbers. For higher jet Reynolds numbers $Re_j$, jet/shear layer coherence seems to be more important, since $Z/D = 1.5$ gives optimal surface Nusselt numbers for an impingement array. For lower Reynolds numbers, the Kelvin–Helmholtz vortices have greater influences since $Z/D$ from 3.0 to 5.0 give optimal impingement Nusselt numbers [38–42].

4 Summary and Conclusions

Experimental data, obtained from multiple investigations conducted since 2003, illustrate a variety of influences on impingement array heat transfer, including: (i) the separate effects of Reynolds number and Mach number, (ii) the influences of temperature ratio, (iii) the effects of spacing of the holes within an impingement array, and (iv) effects of jet-to-target-plate distance. As such, data are given for spacings between holes in the streamwise direction $X$ and the spanwise direction $Y$ of $5D$, $8D$, and $12D$. The thickness of each impingement plate is $1D$, and the spacing between the hole exit planes and the target plate is denoted $Z$ and is equal to either $1.5D$, $3D$, $5D$, or $8D$.
Experimental spatially averaged, surface Nusselt number data obtained for a constant impingement Mach number $Ma$ of 0.1, and different Reynolds numbers $Re_j$ from 5,200 to 8,200 show good agreement with the correlation of Florschuetz et al. [9]. Nusselt number data obtained at a constant Reynolds number of 60,000 and different impingement Mach numbers also shows good agreement with the Florschuetz et al. [9] correlation, provided $Ma = 0.16$ and $Ma = 0.21$. Measured spatially averaged results for $Re_j = 60,000$ then deviate from this correlation by larger amounts as the impingement Mach number increases further, with the largest deviation evident for $Ma = 0.74$. A new correlation equation for spatially averaged Nusselt numbers is then presented for this range of Mach numbers. The variations represented by this correlation are due to local Nusselt numbers, which generally increase with Mach number at different $x/D$ and $y/D$ locations, provided $Re_j = 60,000$ and impingement Mach number $Ma$ is greater than 0.25. Local, spatially resolved Nusselt number data also show that only one local maximum value is present underneath each jet, with local peak line-averaged Nusselt number values, which generally decrease with streamwise development at successive $x/D$ locations.

Local spatially resolved Nusselt number data obtained a Mach number $Ma$ of 0.74, and $Re_j = 60,000$ are also corrected to account for local variations of the adiabatic surface temperature, which are determined from local recovery factor data. Local corrected Nusselt numbers, based on local $(T_w-T_{AW})$, then have higher peaks than local Nusselt numbers, which are based upon $(T_w-T_{oj})$. This is because local recovery factor $RF$ data are higher beneath and in the vicinity of impact locations of the impingement jets, with values as large as 1.03.

Data are also provided to illustrate the effects of the ratio of impingement target plate temperature to impingement jet temperature, at constant Reynolds number. The spacing between holes in the streamwise direction $X$ is then 8$D$, and the spanwise spacing between holes in a given streamwise row $Y$ is also 8$D$. The thickness of each impingement plate is 1$D$, and the spacing between the hole exit planes and the target plate is denoted $Z$ and is equal to 3$D$.

Local and spatially averaged Nusselt numbers decrease as the $T_{wa}/T_j$ temperature ratio increases for any particular $x/D$ and $y/D$ location for $Re_j = 18,000$ and $Ma = 0.2$. The spatially averaged Nusselt number decrease is especially substantial as the $T_{wa}/T_j$ temperature ratio increases from 1.06 to 1.73, which evidences some deterioration of impingement cooling performance. The area beneath each impingement jet shows a higher rate of heat transfer than the surrounding areas, which do not have the additional heat transfer benefit associated with perpendicular impinging jets. The effect of increasing temperature ratio is more apparent in the regions under the impinging jets where the heat transfer is noticeably reduced, a contrast from the surrounding areas, which show almost no change. This is believed to be due to variable property effects, which degrade local turbulent transport in the impingement flow as $T_{wa}/T_j$ increases.

New experimental data are additionally provided when flows are compressible, as the jet hole spacing is varied for Reynolds numbers from 17,300 to 60,000, and for Mach numbers as high as 0.45. The spacings between holes in the streamwise direction $X$ are then 5$D$, 8$D$, or 12$D$, and the spanwise spacings between holes in a
given streamwise row $Y$ are also $5D$, $8D$, or $12D$. The thickness of each impingement plate is $1D$, and the spacing between the hole exit planes and the target plate is denoted $Z$ and is equal to $3D$. These data are given for an array of impinging jets in the form of ratios of crossflow mass velocity to jet mass velocity, discharge coefficients, line-averaged Nusselt numbers, and spatially averaged Nusselt numbers.

Measured Nusselt number data for each of the three hole spacing configurations show strong dependence on Mach number, for Mach numbers greater than about 0.25, as Reynolds number is held constant. The correlations developed from these experimental data show that increasing the Mach number improves heat transfer for each geometry to differing degrees, with the strongest Mach number dependence for the $X/D = Y/D = 12$ array. When the impingement jet Mach number is less than about 0.25, local, line-averaged, and area-averaged data show strong Reynolds number dependence, but almost no dependence on Mach number for each jet spacing arrangement. Each jet produced using $X/D = Y/D = 12$ approximates the behavior of an individual jet, whereas the influences of surrounding jets, including the cumulative-induced crossflows and interactions of jet-induced vortex structures become more pronounced when $X/D = Y/D = 8$ and when $X/D = Y/D = 5$. The present experimental data also show that spatially averaged Nusselt numbers are generally higher for smaller hole spacings than for more sparse arrays when compared at the same streamwise location. In addition, the $12D$ jet spacing area-averaged Nusselt number data show the least variation with $x/D$ while the $5D$ jet spacing shows the largest. Corresponding periodic line-averaged Nusselt number data show that values decrease significantly at successive $x/D$ locations for $X/D = Y/D = 5$, whereas $X/D = Y/D = 12$ periodically varying data are approximately invariant with $x/D$.

Experimental results are also presented that illustrate the effects of jet-to-target plate distance on the heat transfer from an array of jets impinging on a flat plate. Considered is a Reynolds number $Re_j$ of 8,200. Non-dimensional jet-to-target plate distances $Z/D$ are 1.5, 3.0, 5.0, and 8.0, and normalized streamwise and spanwise hole spacings, $X/D$ and $Y/D$, respectively, are both 8.0. Experimental results also illustrate important variations of local, and area-averaged Nusselt numbers with normalized jet-to-target plate distance, especially for smaller values of this quantity. As such, the highest Nusselt numbers generally appear to be associated either with $Z/D$ of 3.0 or 5.0 for $Re_j$ of 8,200. Associated overall and local Nusselt number changes with $Z/D$ (at most, all $x/D$ and $y/D$ values) are due to the competing influences of jet/shear layer coherence, and Kelvin–Helmholtz generated vortices. In general, the former are believed to be more influential for smaller jet advection distances, whereas the latter are likely more important as jet advection distances become larger.

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played vital and important roles in obtaining the results, which are presented, especially in regard to the detailed and meticulous experimental procedures that were employed to obtain results of excellent quality.

**Nomenclature**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>Impingement hole area ($m^2$)</td>
</tr>
<tr>
<td>$A_{cross}$</td>
<td>Exit channel cross-sectional area ($m^2$)</td>
</tr>
<tr>
<td>$A_{ht}$</td>
<td>Heat transfer area on the target plate ($m^2$)</td>
</tr>
<tr>
<td>$C_a$</td>
<td>Impingement air flow sonic velocity (m/s)</td>
</tr>
<tr>
<td>$C_i$</td>
<td>Impingement air flow ideal sonic velocity (m/s)</td>
</tr>
<tr>
<td>$C_D$</td>
<td>Discharge coefficient</td>
</tr>
<tr>
<td>$D$</td>
<td>Diameter of an individual impingement hole (m)</td>
</tr>
<tr>
<td>$G_c$</td>
<td>Crossflow mass velocity (kg/m$^2$ s)</td>
</tr>
<tr>
<td>$G_j$</td>
<td>Jet mass velocity (kg/m$^2$ s)</td>
</tr>
<tr>
<td>$h_{loss}$</td>
<td>Heat transfer coefficient for convection and radiation loss on back side of target plate (W/m K)</td>
</tr>
<tr>
<td>$K$</td>
<td>Ratio of specific heats</td>
</tr>
<tr>
<td>$\dot{m}$</td>
<td>Impingement air mass flow rate (kg/s)</td>
</tr>
<tr>
<td>$\dot{m}_c$</td>
<td>Crossflow air mass flow rate (kg/s)</td>
</tr>
<tr>
<td>$M_a$</td>
<td>Impingement air flow Mach number</td>
</tr>
<tr>
<td>$M_i$</td>
<td>Impingement air flow ideal Mach number</td>
</tr>
<tr>
<td>$N_u$</td>
<td>Local Nusselt number</td>
</tr>
<tr>
<td>$N_{uc}$</td>
<td>Corrected local Nusselt number</td>
</tr>
<tr>
<td>$\bar{N}_u$</td>
<td>Line-averaged Nusselt number</td>
</tr>
<tr>
<td>$\overline{N_u}$</td>
<td>Spatially averaged Nusselt number</td>
</tr>
<tr>
<td>$N_{up}$</td>
<td>Constant property spatially averaged Nusselt number</td>
</tr>
<tr>
<td>$N_{ur}$</td>
<td>Spatially averaged Nusselt number from Florschuetz [9] correlation</td>
</tr>
<tr>
<td>$P_a$</td>
<td>Impingement air static pressure (Pa)</td>
</tr>
<tr>
<td>$P_i$</td>
<td>Impingement air ideal static pressure (Pa)</td>
</tr>
<tr>
<td>$P_{oj}$</td>
<td>Impingement air stagnation pressure (Pa)</td>
</tr>
<tr>
<td>$Q$</td>
<td>Total power provided to the thermofoil heater (W)</td>
</tr>
<tr>
<td>$q_{rf}$</td>
<td>Radiation heat flux from front side (or impingement side) of the target plate (W/m$^2$)</td>
</tr>
<tr>
<td>$q_{rb}$</td>
<td>Radiation heat flux from back side of the target plate (W/m$^2$)</td>
</tr>
<tr>
<td>$q_{cf}$</td>
<td>Convection heat flux from front side (or impingement side) of the target plate (W/m$^2$)</td>
</tr>
<tr>
<td>$q_{cb}$</td>
<td>Convection heat flux from back side of the target plate (W/m$^2$)</td>
</tr>
<tr>
<td>$R$</td>
<td>Ideal gas constant (J/kg K)</td>
</tr>
<tr>
<td>$Re_j$</td>
<td>Impingement air flow Reynolds number</td>
</tr>
<tr>
<td>$RF$</td>
<td>Recovery factor</td>
</tr>
<tr>
<td>$T_{ambient}$</td>
<td>Ambient static temperature (K)</td>
</tr>
<tr>
<td>$T_b$</td>
<td>Local temperature on the back surface of the polystyrene target plate (K)</td>
</tr>
<tr>
<td>$T_w$</td>
<td>Local target surface temperature on the surface of the heater adjacent impingement air (K)</td>
</tr>
</tbody>
</table>
$T_{AW}$  Local adiabatic target surface temperature (K)
$T_{wa}$  Spatially averaged target surface temperature, surface of the heater adjacent to the impingement air (K)
$T_i$  Impingement air ideal static temperature (K)
$T_j$  Impingement air static temperature (K)
$T_{oij}$  Impingement air stagnation temperature (K)
$T_{oij}^{*}$  Corrected impingement air stagnation temperature to give zero spatially averaged surface heat flux (K)
$T_{tc}$  Local thermocouple temperature between the heater and the polystyrene target plate (K)
$u_a$  Impingement air velocity (m/s)
$u_{crossflow}$  Crossflow air velocity (m/s)
$u_i$  Impingement air ideal velocity (m/s)
$u_{jet}$  Jet air velocity (m/s)
x  Streamwise coordinate (m)
y  Spanwise coordinate (m)
z  Normal coordinate (m)
$X$  Streamwise distance between centerlines of adjacent impingement holes (m)
$Y$  Spanwise distance between centerlines of adjacent impingement holes (m)
$Z$  Distance between target plate and impingement hole plate (m)

Greek symbols

$\alpha$  Air thermal conductivity (W/m$^2$ K)
$\rho_a$  Impingement air static density (kg/m$^3$)
$\rho_i$  Impingement air ideal static density (kg/m$^3$)
$\mu$  Absolute viscosity (kg/m s)
$\sigma$  Boltzmann constant
$\varepsilon_f$  Emissivity of the front surface of the target plate
$\varepsilon_{inf}$  Emissivity of a plate located opposite to the target plate

References


