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JET ARRAY IMPINGEMENT HEAT TRANSFER CHARACTERISTICS

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Two-dimensional arrays of circular air jets impinging on a heat transfer surface parallel to the jet orifice plate are considered. The jet flow, after impingement, is constrained to exit in a single direction along the channel formed by the jet orifice plate and the heat transfer surface. In addition to the crossflow which originates from the jets following impingement, an initial crossflow is present which approaches the array through an upstream extension of the channel (fig. 1). The configurations considered are intended to model the impingement cooled midchord region of gas turbine airfoils in cases where an initial crossflow is also present (fig. 2). A major objective is determination of the effect of initial crossflow air temperature relative to jet array air temperature on impingement surface heat fluxes.

Earlier work in this NASA sponsored project was directed at modeling uniform arrays in cases where an initial crossflow is not present. In those cases, referred to here as noninitial crossflow geometries, there was an endwall or upstream edge to the channel positioned one-half a streamwise hole spacing upstream of the first spanwise row of holes in the array. Note that with the initial crossflow geometry (fig. 1), the special case of zero initial crossflow ($m_c = 0$) is identical to the noninitial crossflow case except for the presence of the upstream channel endwall in the latter case.

In this extended abstract, nomenclature and definition of parameters is first indicated for the more general initial crossflow case. Then the main features of the prior noninitial crossflow studies are briefly summarized. The current status of the initial crossflow work is then discussed.

Consider a uniform rectangular array of circular jet orifices with an inline hole pattern (figs. 1 and 3). Consider further the heat flux, q, at the impingement surface, averaged across the span, but resolved in the streamwise direction to a region of width x_n, centered opposite an arbitrary spanwise row of holes within the array at location x. It is desired to express q as a function of parameters associated with the entire array. Assume constant fluid properties, negligible viscous dissipation, a uniform impingement surface temperature, T_s, an adiabatic jet orifice plate surface at the jet exit plane, and a fully developed channel flow at the entrance to the array (x = 0) with a mixed-mean temperature T_c. Then, at the specified x

$$q = f\,(\underbrace{m_j,\ m_c}_{\text{flow}},\ \underbrace{T_j,\ T_c,\ T_s}_{\text{temperature}},\ \underbrace{x_n,\ y_n,\ z,\ d,\ L}_{\text{geometry}},\ \underbrace{\mu,\ k,\ c_p}_{\text{fluid}})$$

or in one possible dimensionless form, at x/L,

$$\frac{q\cdot d}{k(T_s-T_j)} = f[m_c/m_j,\ \overline{Re}_j, (T_c-T_j)/(T_s-T_j),\ x_n/d, y_n/d, z/d,\ L/x_n,\ Pr]$$

In this form the dependent parameter, which has the form of a Nusselt number, incorporates a heat transfer coefficient defined as $q/(T_s-T_j)$ with the jet temperature T_j as the characteristic fluid temperature. With this definition the Nusselt number is not independent of the temperature differences of the problem, since it still depends on the initial crossflow temperature ratio $(T_c-T_j)/(T_s-T_j)$. In spite of the restrictions imposed, there are still eight independent dimensionless parameters, nine including the specified x/L. Note that one of these is L/x_n which is just the number of spanwise rows in the array.

Still considering q in terms of parameters associated with the entire array, an alternate formulation is

$$q = f(m_j, m_c, T_{aw}, T_s, x_n, y_n, z, d, L, \mu, k, c_p)$$

where

$$T_{aw} = f(m_j, m_c, T_j, T_c, x_n, y_n, z, d, L, \mu, k, c_p)$$

Then in dimensionless form

$$Nu = \frac{q \cdot d}{k(T_s-T_{aw})} = f(m_c/m_j, \overline{Re}_j, x_n/d, y_n/d, z/d, L/x_n, Pr) \tag{1}$$

and

$$\eta = \frac{T_{aw}-T_j}{T_c-T_j} = f(m_c/m_j, \overline{Re}_j, x_n/d, y_n/d, z/d, L/x_n, Pr) \tag{2}$$

This formulation, employing the adiabatic wall temperature, has the advantage that the heat transfer coefficient, $q/(T_s-T_{aw})$, and Nusselt number are rendered independent of the temperature differences of the problem. But, unless $T_c=T_j$, the additional dependent parameter η is also needed. This Nusselt number and the corresponding η are a function of seven independent dimensionless parameters, eight including the specified x/L.

At this point the possibility of representing q as a function of parameters associated only with a given spanwise row is considered (fig. 4). Here, it is assumed that the dependence of q on the velocity and temperature distribution at the control surface (channel cross-section) immediately upstream of the row may be represented in terms of a single velocity and a single temperature parameter, denoted by G_c and T_c. Then in dimensionless form one may write

$$Nu = \frac{q \cdot d}{k(T_s-T_{aw})} = f(G_c/G_j, Re_j, x_n/d, y_n/d, z/d, Pr) \tag{3}$$

and

$$\frac{T_{aw}-T_j}{T_c-T_j} = f(G_c/G_j, Re_j, x_n/d, y_n/d, z/d, Pr) \tag{4}$$

In general, of course, q will depend on the velocity and temperature distributions over such a control surface, which, in turn, depend on the history of the mixing jet flows and crossflows upstream of the control surface. However, the above approximation, <u>if shown to be adequate</u>, admits the possibility of applying measurements obtained for uniform array geometries to heat transfer opposite individual rows of nonuniform array geometries.

Results based on an extensive series of tests for a range of uniform array geometries in noninitial crossflow configurations using air as the working fluid are reported in tabular and graphical forms in references 1, 2 and 3 in terms of the parameters of equation (1), except for m_c/m_j which is not a relevant parameter in noninitial crossflow cases. Results were obtained for every geometry tested with Nu resolved in the streamwise direction to at least x_n, and in most cases to $x_n/3$. Correlations, in algebraic form, for Nu (resolved to x_n) expressed in terms of parameters associated with a single spanwise row as in equation (3), are reported in references 4 and 5. In these references, a theoretically based flow distribution model is also presented and validated by comparison with measured flow distributions for these noninitial crossflow cases. The validated flow model was used in developing the correlations referred to above. Results for nonuniform arrays in noninitial crossflow configurations have also been obtained and compared with the uniform array data and the correlation based on that data (ref. 6). Examples are shown in figure 5.

One of the more extensive prior heat transfer studies of two-dimensional arrays of circular jets was reported in reference 7. The studies completed under the present project go substantially beyond prior work, and provide a much more complete understanding of the problem as well as needed design information. The main features of the present project which had not been addressed in prior work may be summarized as follows: (1) streamwise spatial resolution of at least x_n for all geometries tested; (2) observations of ''damped'' periodic streamwise variations of heat transfer coefficients along entire array with spatial resolution of $x_n/3$; (3) detailed verification of validity of geometric scaling; (4) rectangular arrays, i.e., not restricted to $x_n/y_n = 1$; (5) staggered as well as inline hole patterns; (6) correlation for streamwise local application developed in algebraic form; (7) nonuniform as well as uniform array geometries tested; (8) experimentally validated theoretical flow distribution model developed for both uniform and nonuniform array geometries; (9) applicability of uniform array data and correlation to nonuniform arrays examined; (10) effect of confined crossflow on jet orifice discharge coefficients; (11) effects of initial crossflow rate and temperature, currently in progress, discussed further below.

An example of heat transfer characteristics with initial crossflow, specified in terms of array parameters as in equations (1) and (2), is shown in figure 6 for the B(5,4,3)I geometry (i.e., B-size plenum, $x_n/d=5$, $y_n/d=4$, $z/d=3$, Inline hole pattern). The corresponding flow distribution is shown in figure 7. Additional such results are reported in reference 6.

Nusselt numbers specified in terms of parameters at an individual spanwise row, as in equation (3), are illustrated in figure 8. The presence of initial crossflow extends the data point range of G_c/G_j beyond the maximum values existing for the noninitial crossflow (or essentially identical zero initial crossflow) cases. The B(5,4,2)I geometry (upper plot in fig. 8) clearly shows that a minimum value of Nu may occur at a certain G_c/G_j. A point is reached where the jet no longer effectively impinges on the surface, but the Nusselt number increases with the increasing crossflow velocity. The prior noninitial crossflow correlation (refs. 4 and 5) though shown extrapolated beyond the range of G_c/G_j on which it was based, appears to be reasonably consistent with the data points until the increase in Nusselt number begins, except for several data points from the first and second spanwise rows of the array.

Dimensionless adiabatic wall temperatures specified in terms of parameters at an individual spanwise row, as in equation (4), are illustrated in figures 9 and 10. In figure 9, $T_{m,n}$, the mixed-mean total temperature, was used as the characteristic crossflow temperature, T_c, immediately upstream of a given row. Figure 10 shows data for the same cases, but with $T_{aw,n-1}$, the adiabatic wall temperature opposite the row immediately upstream of the row in question, used to represent T_c. It is not clear at this writing whether either of these approaches will prove to be of general utility over a range of geometries. This question is currently being studied. In some instances the dimensionless adiabatic wall temperature at the first row or two, like the Nusselt number, clearly does not follow the general trend of the data points. This is because the relationship between q and T_s at the impingement surface opposite a given row clearly must depend on the details of the velocity and temperature distributions over the channel cross-section immediately upstream of the row. These distributions at downstream rows may differ considerably from those at the first several rows of an initial crossflow array, and their effects cannot necessarily be represented accurately by a single crossflow velocity and a single temperature parameter.

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NOMENCLATURE (includes symbols not explicitly defined in text or figures)

C_D = jet plate discharge coefficient
c_p = constant pressure specific heat
f = friction coefficient
G_c = crossflow mass velocity based on channel cross-sectional area
G_j = jet mass velocity based on jet hole area
h = heat transfer coefficient at impingement surface, $q/(T_s-T_{aw})$
k = thermal conductivity
m_c = initial crossflow rate
m_j = total jet flow rate
μ = dynamic viscosity
Pr = Prandtl number
q = heat flux at impingement surface
Re_j = jet Reynolds number, $G_j d/\mu$
T_{aw} = adiabatic wall temperature (with subscript n, denotes location opposite spanwise row number n)
T_c = characteristic temperature of initial crossflow or of crossflow within array depending on context
T_j = characteristic temperature of jet flow
$T_{m,n}$ = crossflow channel mixed-mean temperature upstream of spanwise row n
T_s = heat transfer surface temperature

Superscript

(—) = overbar refers to mean value over jet plate

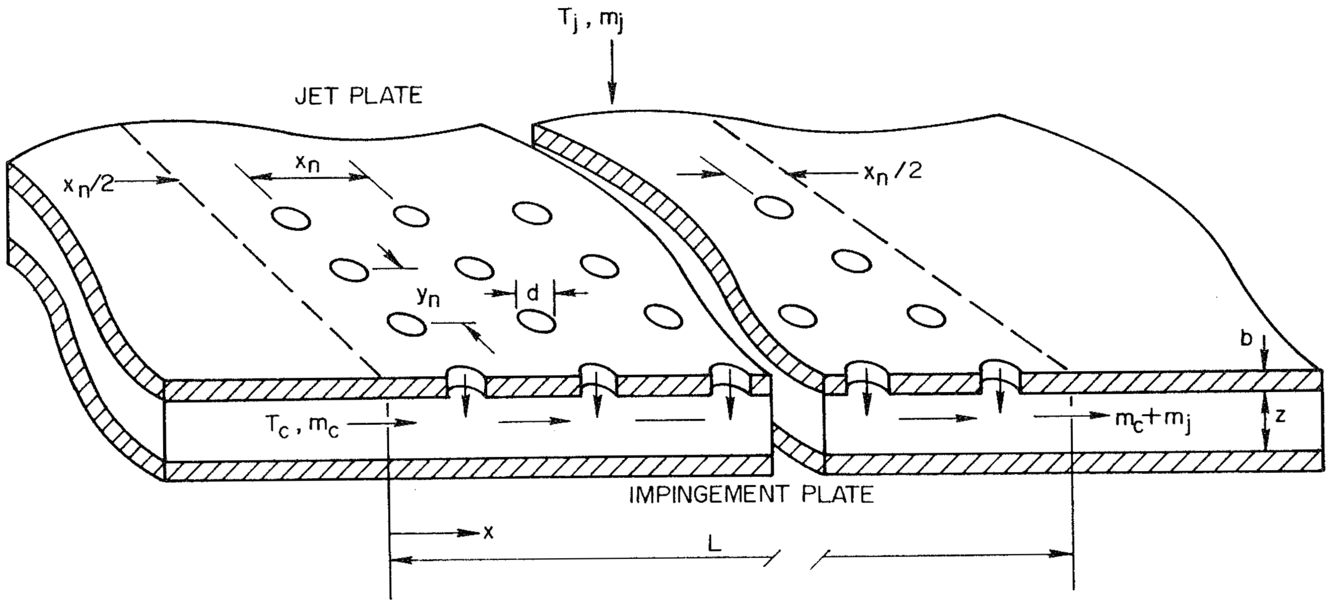


Figure 1. Basic test model geometry with initial crossflow.

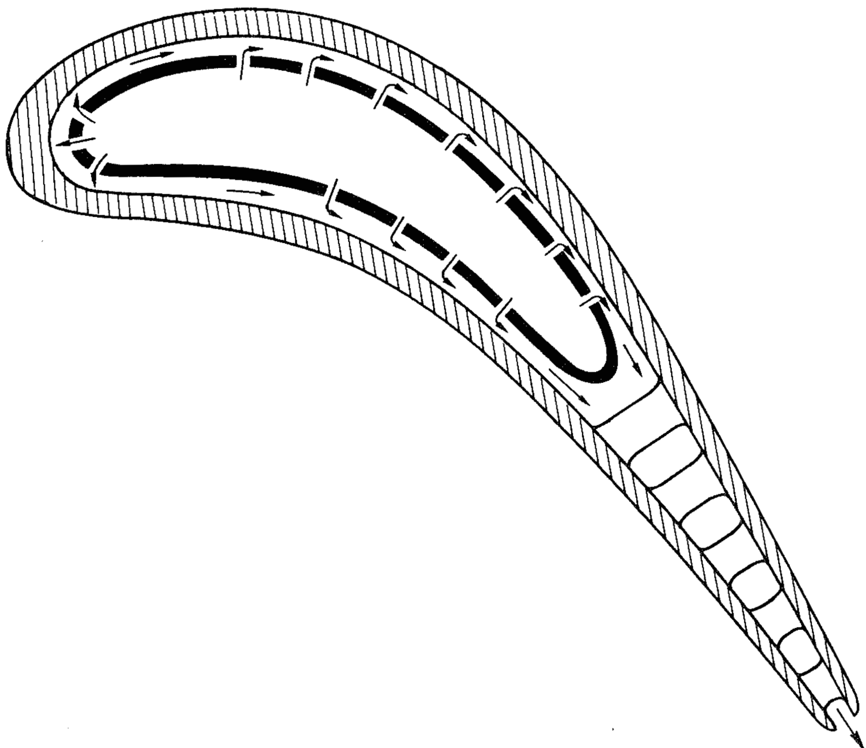
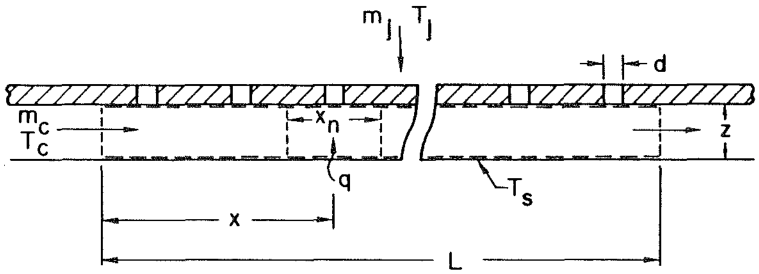


Figure 2. Impingement cooled airfoil - midchord jet arrays subject to initial crossflow.



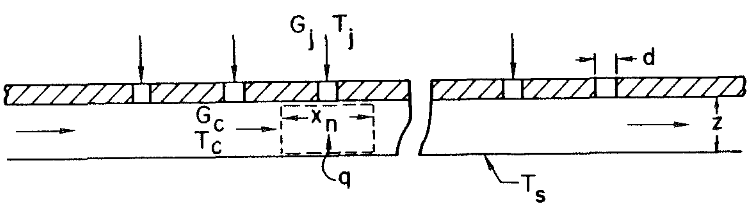
CONSIDER AT SPECIFIED x

$$q = f(\underbrace{m_j, m_c}_{\text{FLOW}}, \underbrace{T_j, T_c, T_s}_{\text{TEMPERATURE}}, \underbrace{x_n, y_n, z, d, L}_{\text{GEOMETRY}}, \underbrace{\mu, k, c_p}_{\text{FLUID}})$$

THEN POSSIBLE DIMENSIONLESS FORM AT SPECIFIED x/L IS

$$\frac{q \cdot d}{k(T_s - T_j)} = f\left[m_c/m_j, \overline{Re}_j, (T_c - T_j)/(T_s - T_j), x_n/d, y_n/d, z/d, L/x_n, Pr\right]$$

Figure 3. Possible formulation of streamwise resolved impingement surface heat transfer characteristics in terms of array parameters.



CONSIDER

$$q = f(G_c, G_j, T_{aw}, T_s, x_n, y_n, z, d, \mu, k, c_p)$$

WHERE

$$T_{aw} = f(G_c, G_j, T_j, T_c, x_n, y_n, z, d, \mu, k, c_p)$$

DIMENSIONLESS FORM

$$\frac{q \cdot d}{k(T_s - T_{aw})} = f(G_c/G_j, Re_j, x_n/d, y_n/d, z/d, Pr)$$

$$\frac{T_{aw} - T_j}{T_c - T_j} = f(G_c/G_j, Re_j, x_n/d, y_n/d, z/d, Pr)$$

Figure 4. Possible formulation of streamwise resolved impingement surface heat transfer characteristics in terms of individual spanwise jet row parameters.

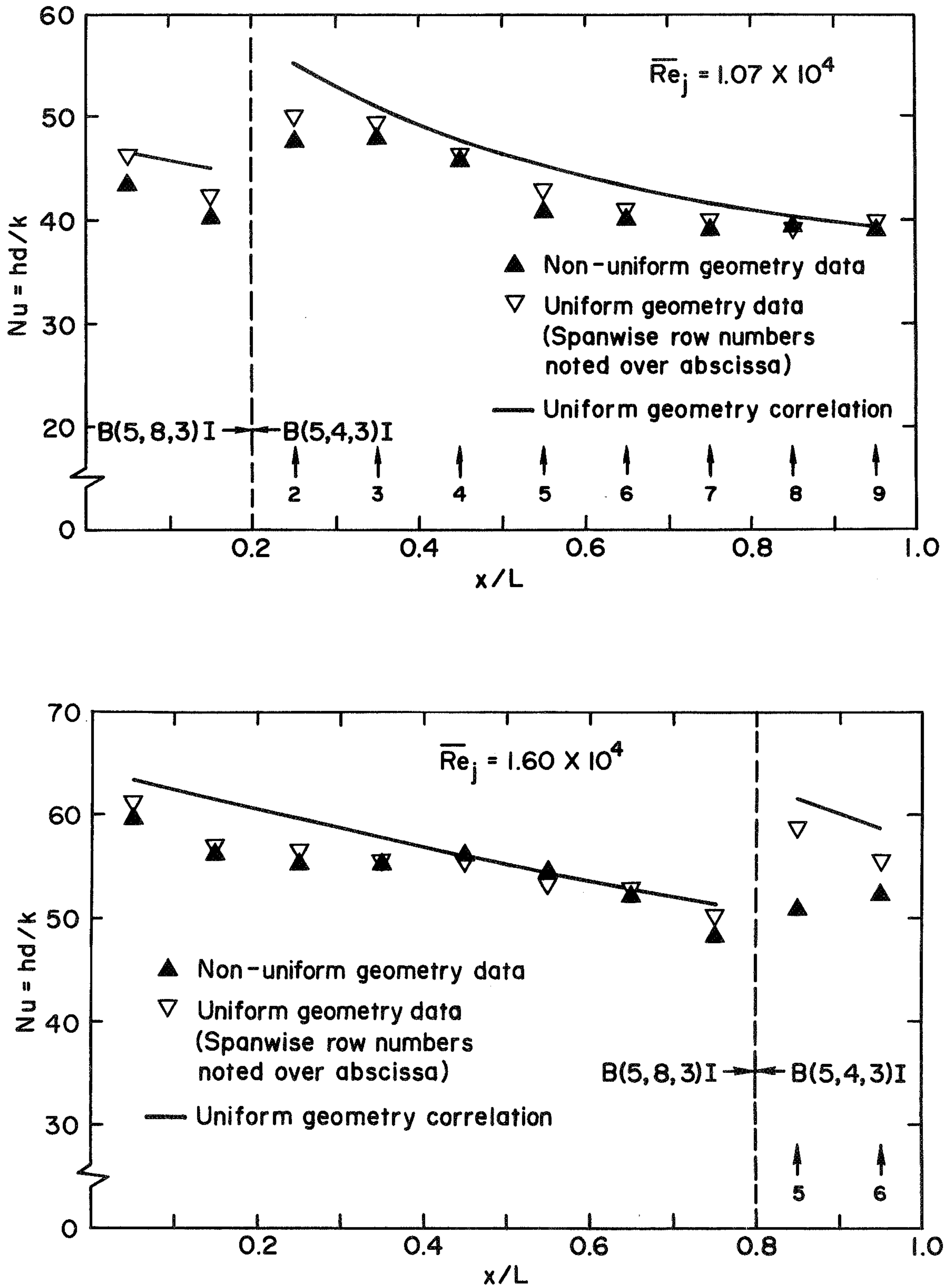


Figure 5. Examples of nonuniform array geometry Nusselt numbers compared with uniform array data and correlation.

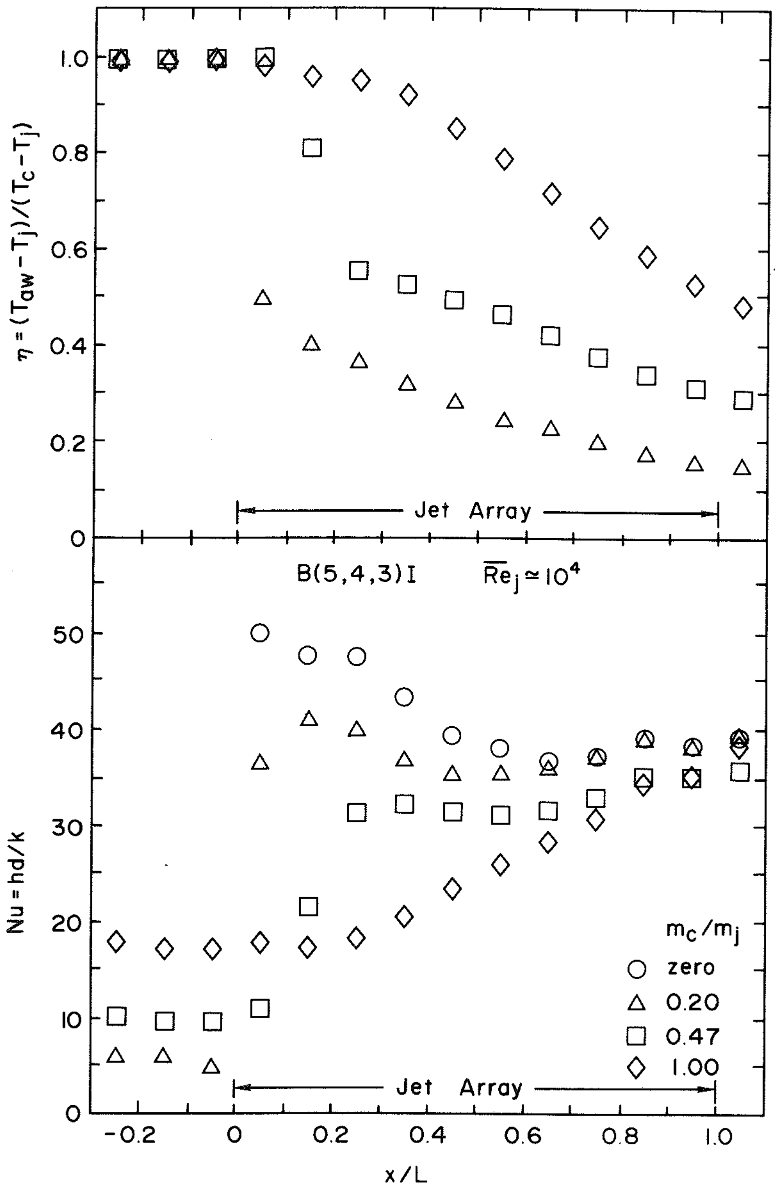


Figure 6. Examples of streamwise profiles of initial crossflow Nusselt numbers (Nu) and dimensionless adiabatic wall temperatures (η) specified in terms of array parameters.

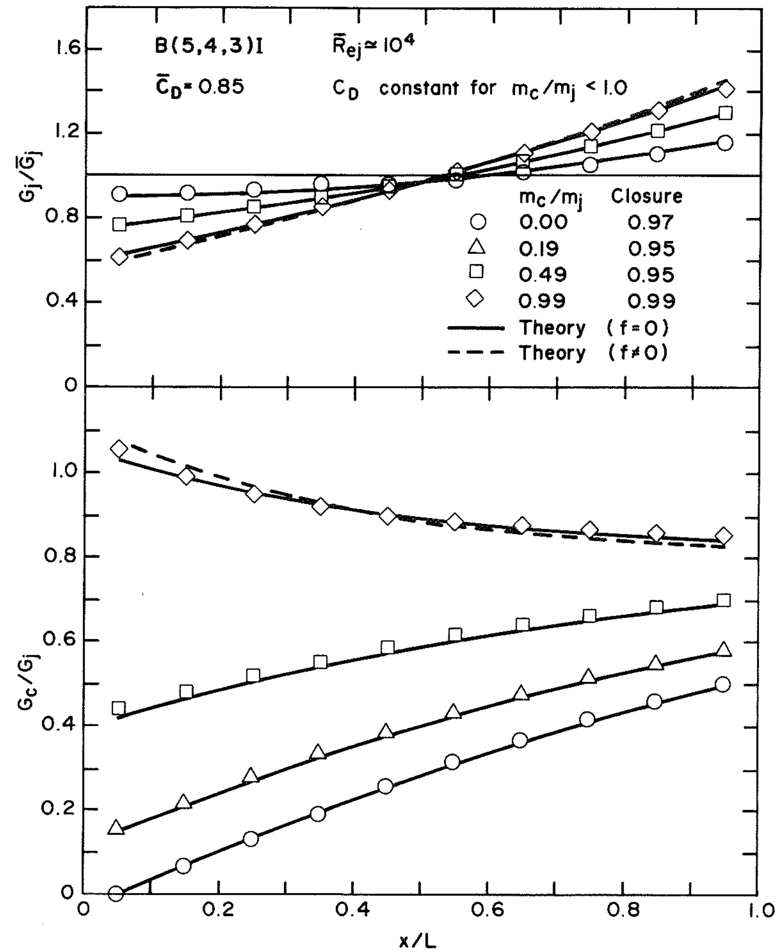


Figure 7. Examples of flow distributions with initial crossflow for array geometry of figure 6.

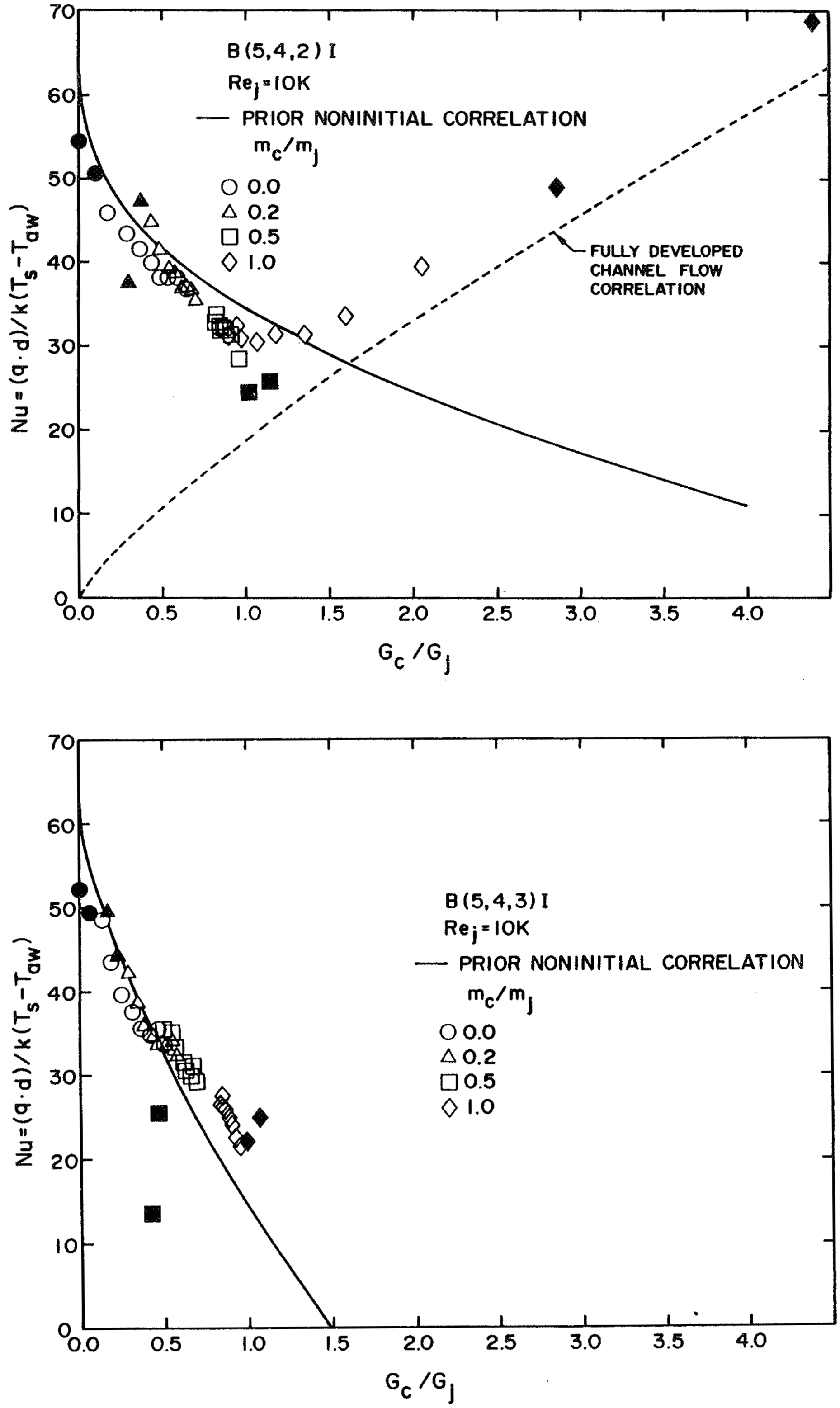


Figure 8. Examples of streamwise resolved Nusselt numbers as a function of individual spanwise row cross-to-jet mass velocity ratios. Solid symbols denote data from first and second upstream rows of array.

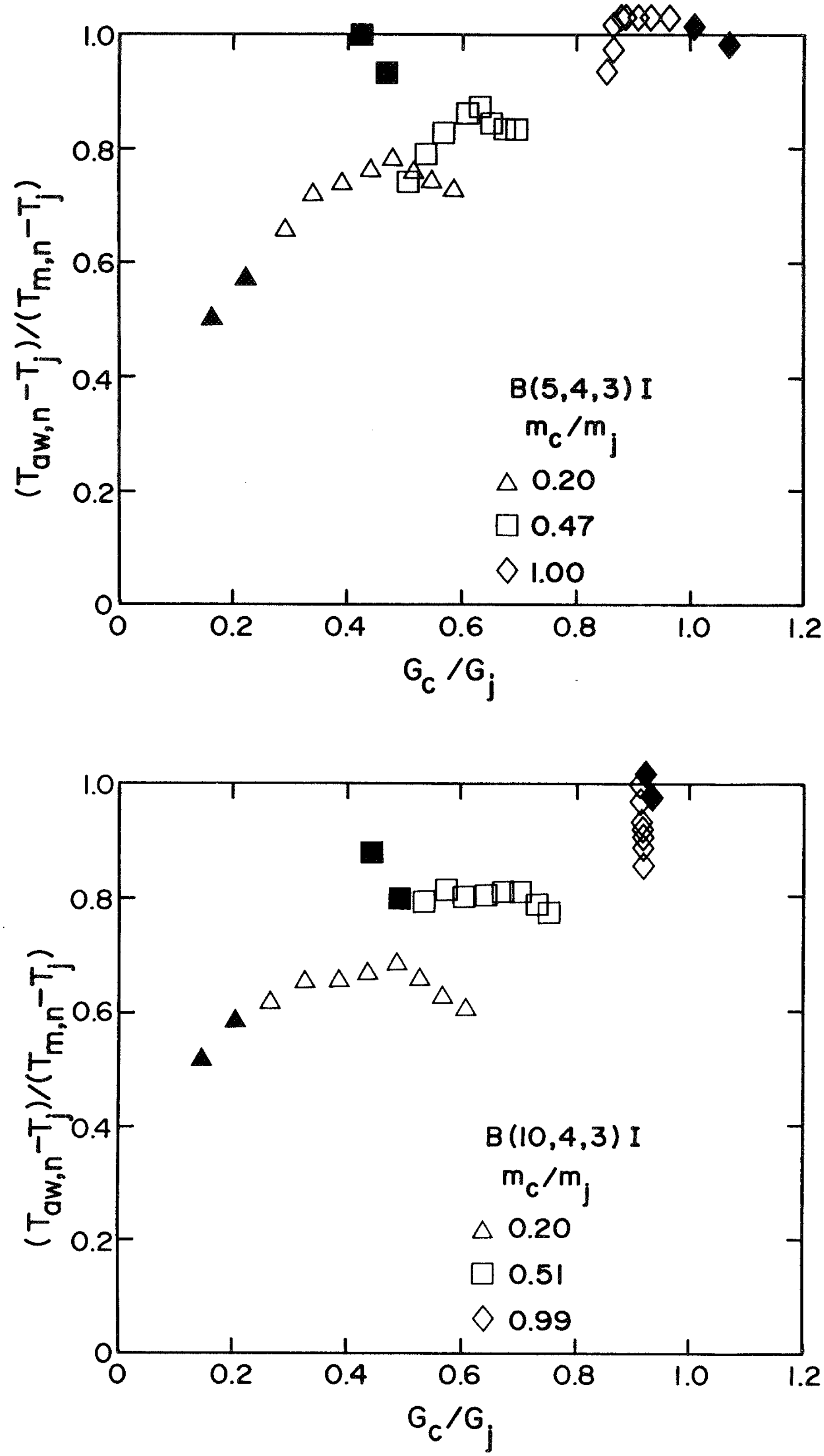
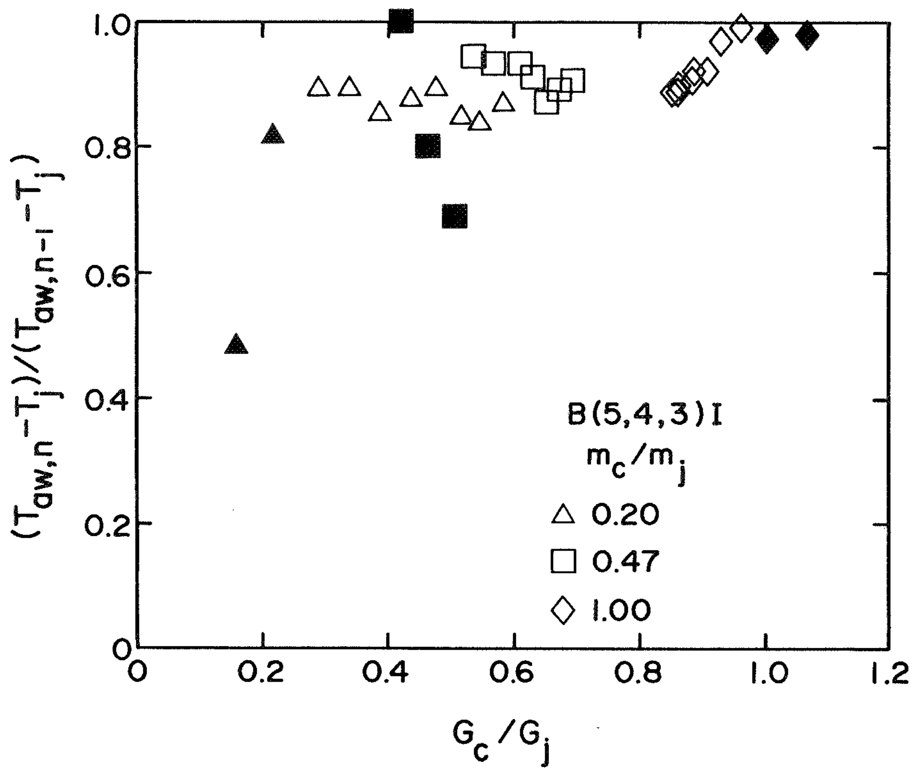


Figure 9. Examples of dimensionless adiabatic wall temperature as a function of individual spanwise row cross-to-jet mass velocity ratio, using mixed-mean total temperature upstream of row as characteristic crossflow temperature. Solid symbols denote data from first and second rows of array.



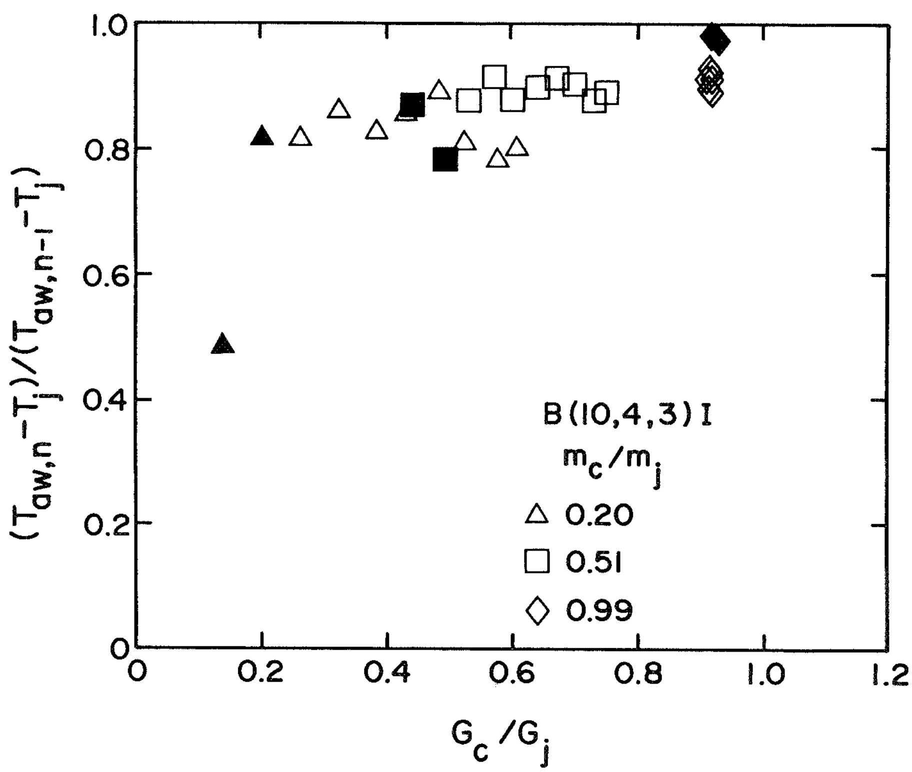


Figure 10. Examples of dimensionless adiabatic wall temperature as a function of individual spanwise row cross-to-jet velocity ratio, using adiabatic wall temperature at upstream row as characteristic crossflow temperature. Solid symbols denote data from first and second rows of array.