JET ARRAY IMPINGEMENT FLOW DISTRIBUTIONS AND HEAT TRANSFER CHARACTERISTICS - EFFECTS OF INITIAL CROSSFLOW AND NONUNIFORM ARRAY GEOMETRY

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SUMMARY

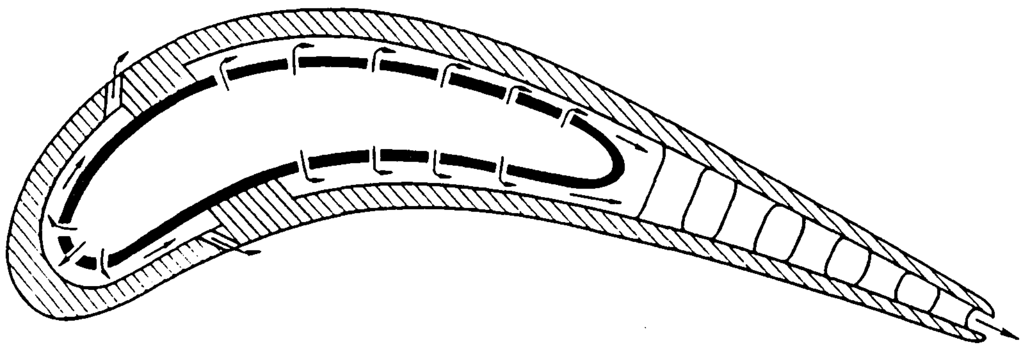
The work reported on is divided into two major parts, each of which represents an extension of work completed in earlier phases of an overall investigation. The overall investigation was directed toward the determination of flow distributions and heat transfer characteristics for two-dimensional arrays of circular air jets impinging on a surface parallel to the jet orifice plate. The configurations considered were intended to model those of interest in current and contemplated gas turbine airfoil midchord cooling applications. The geometry of the airfoil applications considered dictates that all of the jet flow, after impingement, exit in the chordwise (i.e., streamwise) direction toward the trailing edge. The accumulated flow from upstream jet rows in the array acts as a crossflow to downstream rows. In some cooling schemes an initial crossflow arising from air used to cool the leading edge approaches the midchord jet array. The temperature of this initial crossflow air can be several hundred degrees higher than the cooling air introduced to the jet array.

The early work in the study dealt with arrays of uniform geometries not subject to an initial crossflow. These arrays had streamwise hole spacings of 5, 10, and 15 hole diameters, spanwise hole spacings of 4, 6, and 8 diameters, and jet exit plane-to-impingement surface spacings (channel heights) of 1, 2, and 3 hole diameters, with 10 spanwise rows of holes. Spanwise averaged heat transfer coefficients, resolved in the streamwise direction, were measured and correlated in terms of individual spanwise row jet and crossflow velocities, and in terms of the geometric parameters. These results were reported in detail in two previously published NASA reports.

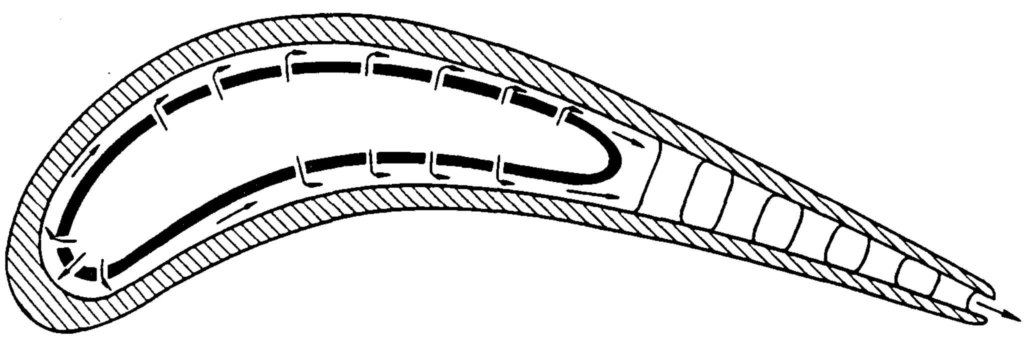
Part I of the present study deals with experimental results for the effects of an initial crossflow on both flow distributions and heat transfer characteristics for a number of the prior uniform array geometries. Heat

transfer coefficients and adiabatic wall temperatures resolved to one streamwise hole spacing were determined for ratios of the initial crossflow-to-total jet flow rate ranging from zero to unity. The adiabatic wall temperatures depend on the relative flow rates and relative characteristic temperatures of both the jet air and the initial crossflow air, as well as on the geometric parameters. Both Nusselt number profiles and dimensionless adiabatic wall temperature ("effectiveness") profiles were determined and considered in relation to the flow and geometric parameters. For some conditions "effectiveness" profiles cover nearly the entire range between zero and unity, and Nusselt numbers at upstream rows are reduced significantly compared with zero initial crossflow values, even for initial crossflow-to-total jet flow ratios as small as 0.2. Special test results which showed a significant reduction of jet orifice discharge coefficients owing to the effect of a confined crossflow were obtained, and a flow distribution model which incorporates those effects was developed.

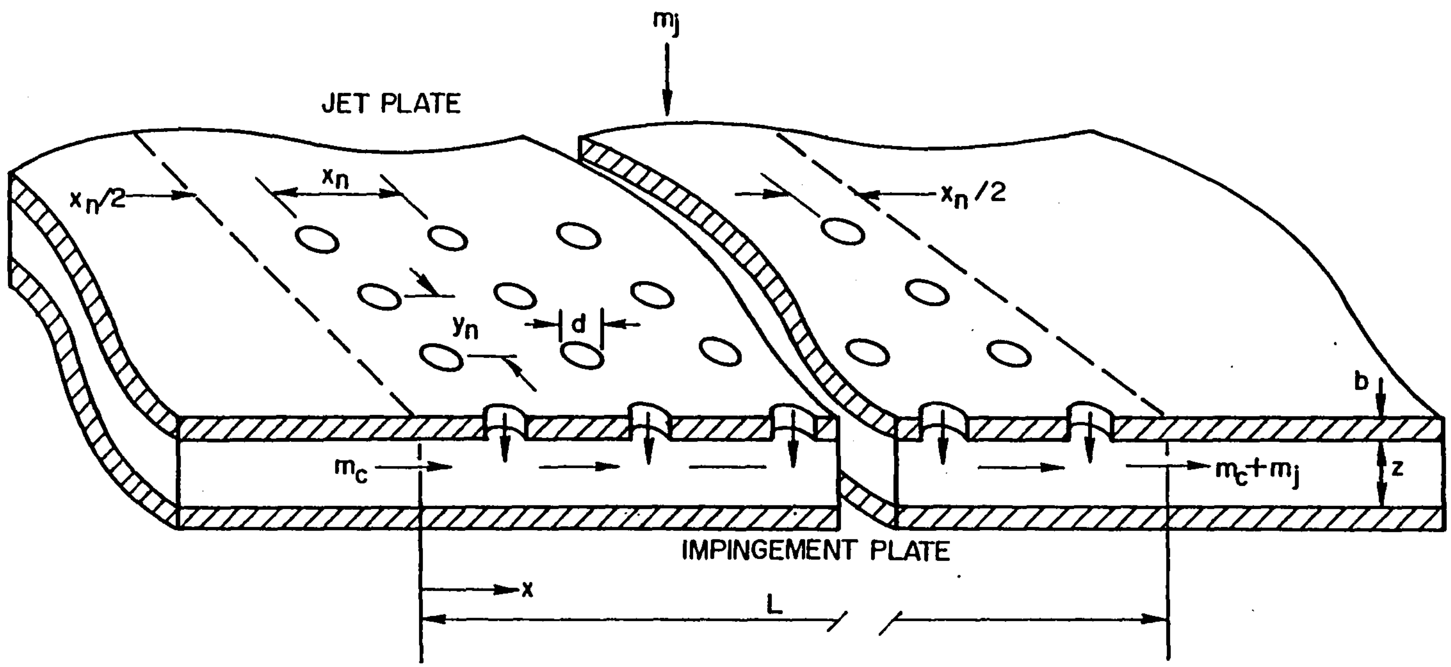
Part II deals with experimental results for the effects of nonuniform array geometries on flow distributions and heat transfer characteristics for noninitial crossflow configurations. The nonuniform arrays are comprised of two different regions each of which has a uniform geometry. Either hole spacing or hole diameter has a different value in the two regions. The previously developed flow distribution model for uniform arrays was extended to nonuniform arrays and validated by comparison with the measured flow distributions. The validated flow distribution model was then employed to compare the nonuniform array streamwise resolved heat transfer coefficient data with the previously reported uniform array data and with the previously developed correlation based on the uniform array data. It was found that the uniform array results can, in general, serve as a satisfactory basis from which to predict heat transfer coefficients at individual rows of nonuniform arrays. However, significant differences were observed in some cases over the first one or two rows downstream of the geometric transition line of the nonuniform array. For practical purposes the "entrance" or "adjustment" length for a downstream region could be considered as requiring from zero to at most two jet rows, depending on the particular case.



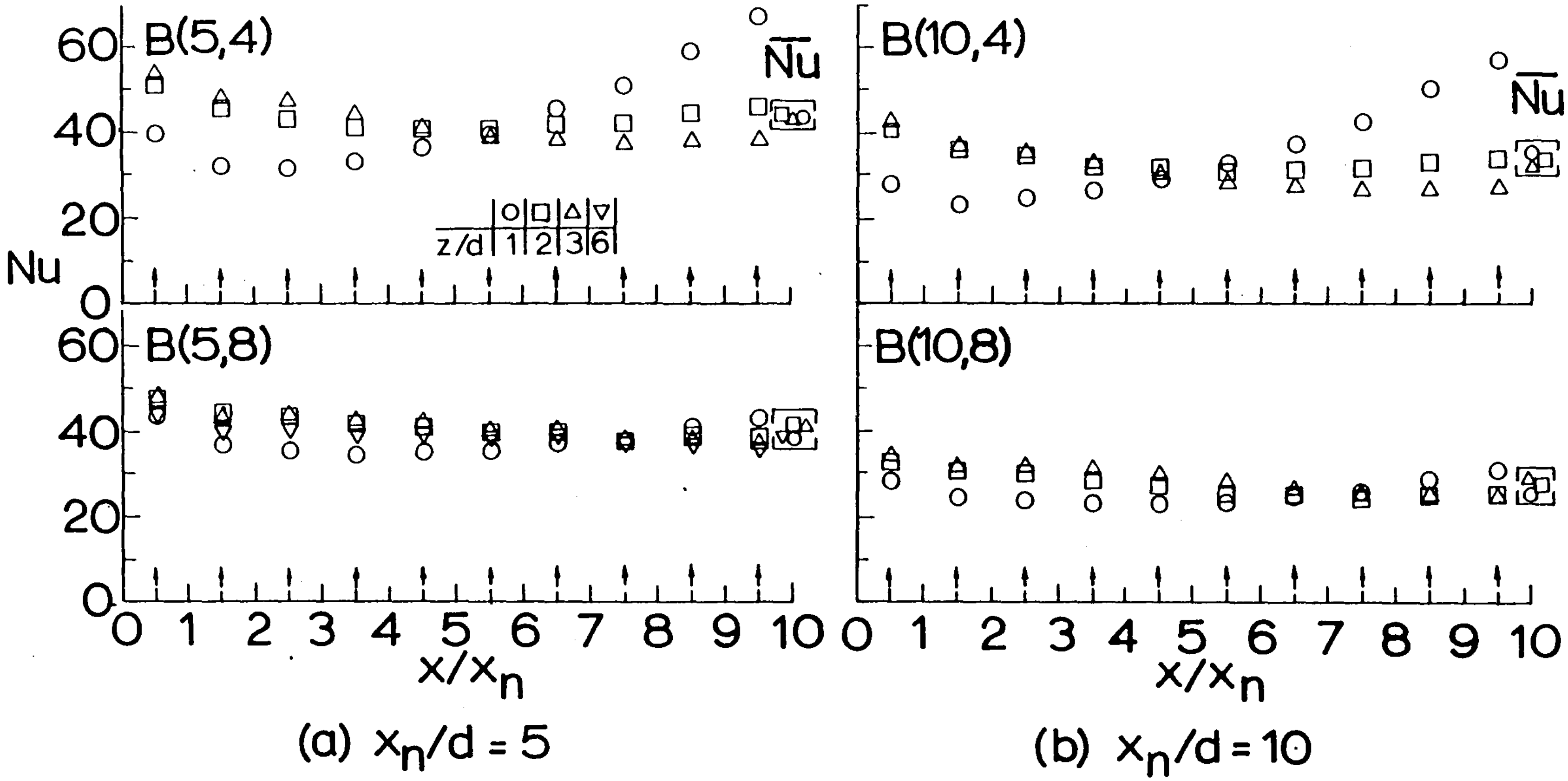
Impingement cooled airfoil - midchord arrays not subject to initial crossflow.



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



Initial crossflow basic test model geometry and nomenclature.



Typical chordwise Nusselt number profiles without initial crossflow

Geometric Parameters and Mean Discharge Coefficients for Jet Plates Tested with Initial Crossflow.

Jet Plate $B(x_n/d, y_n/d)I$	A_o^*	d and b (cm)	N_s	N_s'	$\bar{C}_D$
B(5,4)I(S)	0.0393	0.254	12	18	0.85
B(5,8)I	0.0196		6	9	0.80
B(10,4)I	0.0196	0.127	24	36	0.76
B(10,8)I	0.0098		12	18	0.76

Channel heights, (z/d) = 1, 2, and 3

Fixed Parameters:

Channel width (span), w = 18.3 cm.

Heat transfer test plate width, 12.2 cm

Heat transfer test plate length, 39.4 cm

Overall channel length, 43.2 cm

Initial crossflow channel length, 26.0 cm

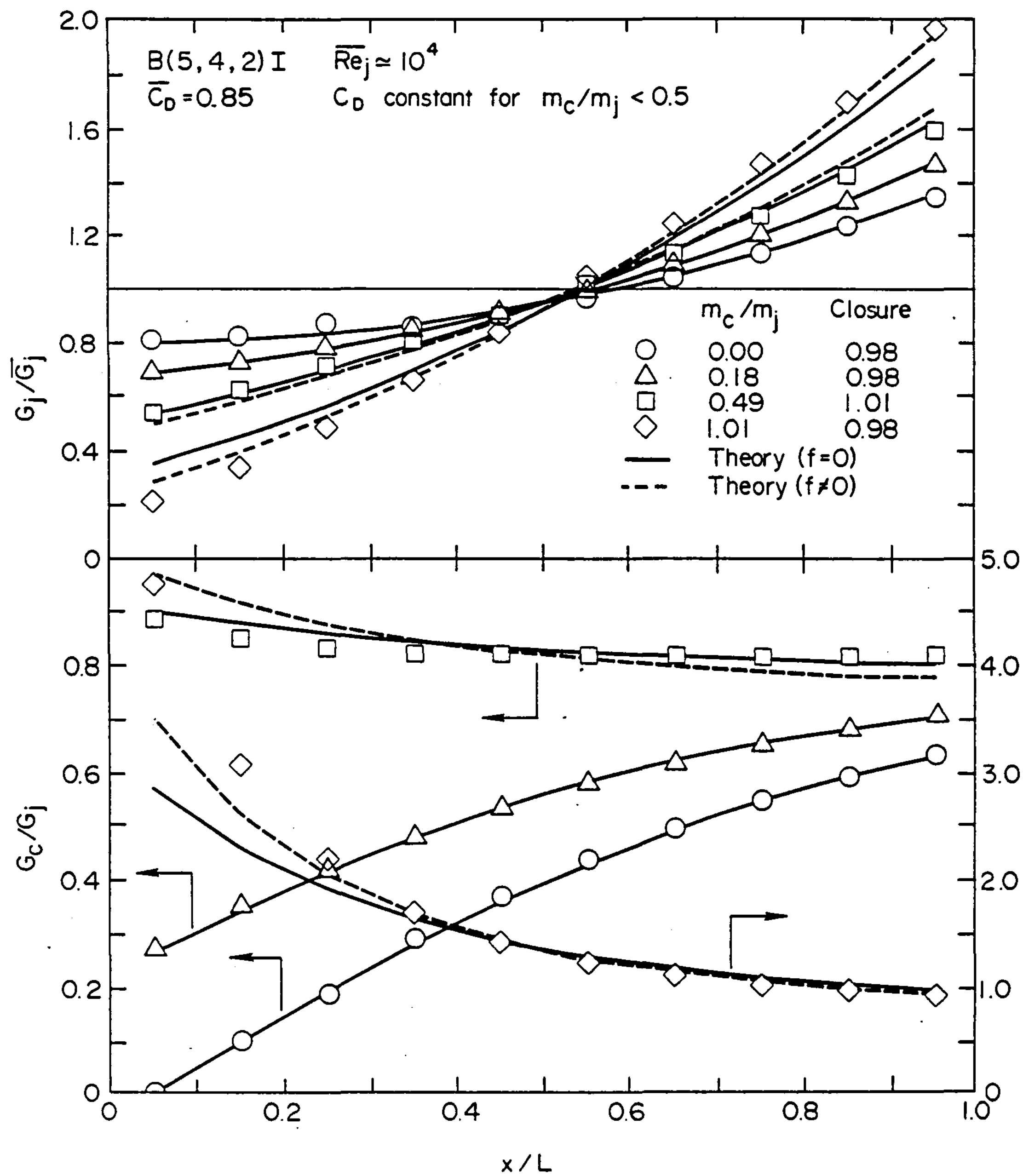
B-size jet array and plenum length, L = 12.7 cm

Downstream exit length, 4.5 cm

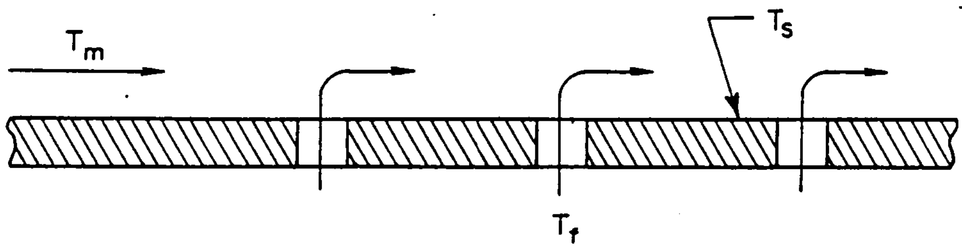
Initial crossflow development length, 24.1 cm

Number of spanwise rows of jet holes, N_c = 10

I = Inline, S = staggered hole pattern

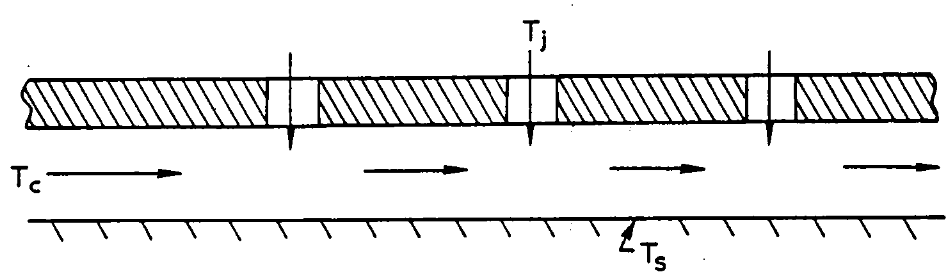


Effect of initial crossflow on jet array flow distribution ($G_j/\overline{G}_j$) and cross-to-jet mass velocity ratio (G_c/G_j) for B(5,4,2)I geometry - experimental data compared with predictive model.



$$q = h(T_s - T_{aw}) \qquad \eta = \frac{T_{aw} - T_m}{T_f - T_m}$$

Film cooling as a three-temperature problem.

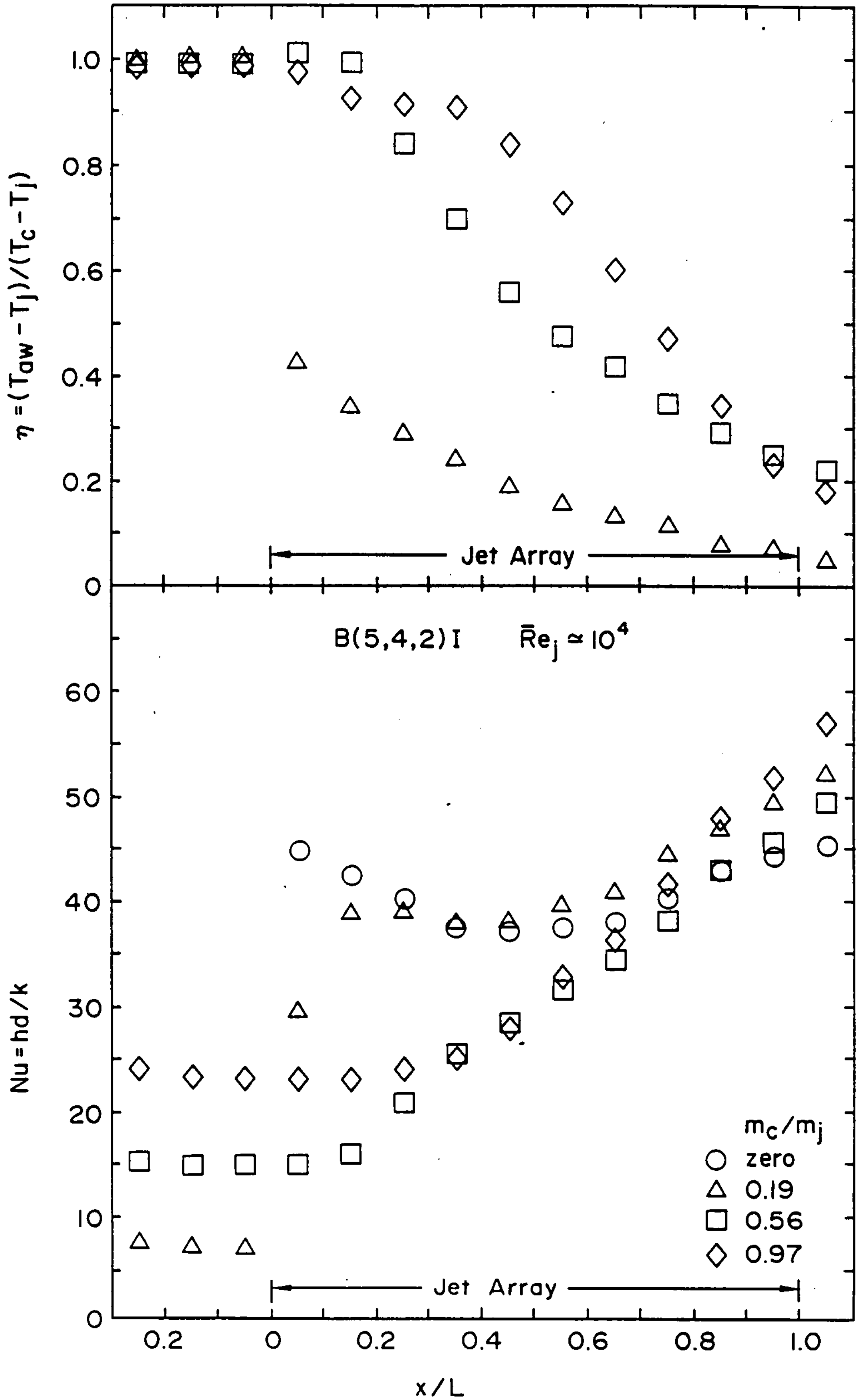


$$q = h(T_s - T_{aw}) \qquad \eta = \frac{T_{aw} - T_j}{T_c - T_j}$$

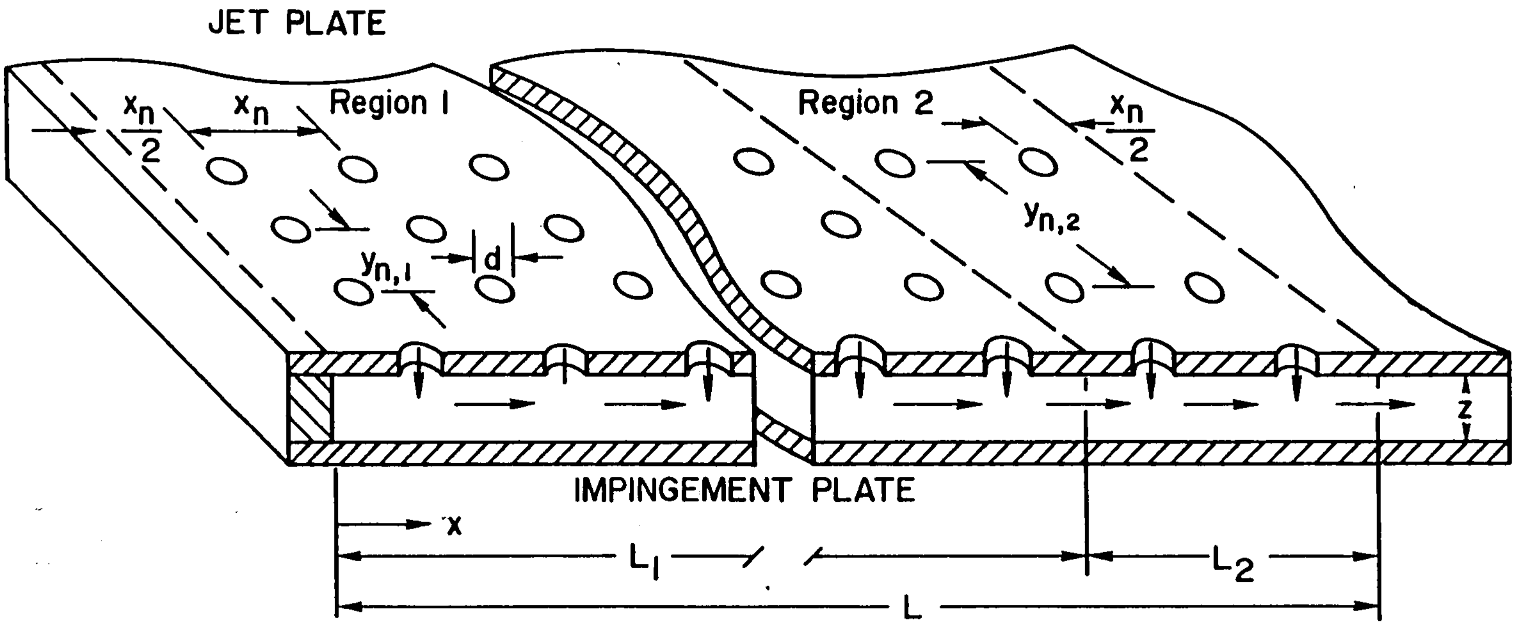
or

$$q = h\left[(1-\eta)(T_s - T_j) + \eta(T_s - T_c)\right]$$

Jet array impingement with initial crossflow as a three-temperature problem.



Effect of initial crossflow rate on η and Nu profiles for B(5,4,2)I geometry.



Example of basic test model geometry
and nomenclature for nonuniform array.

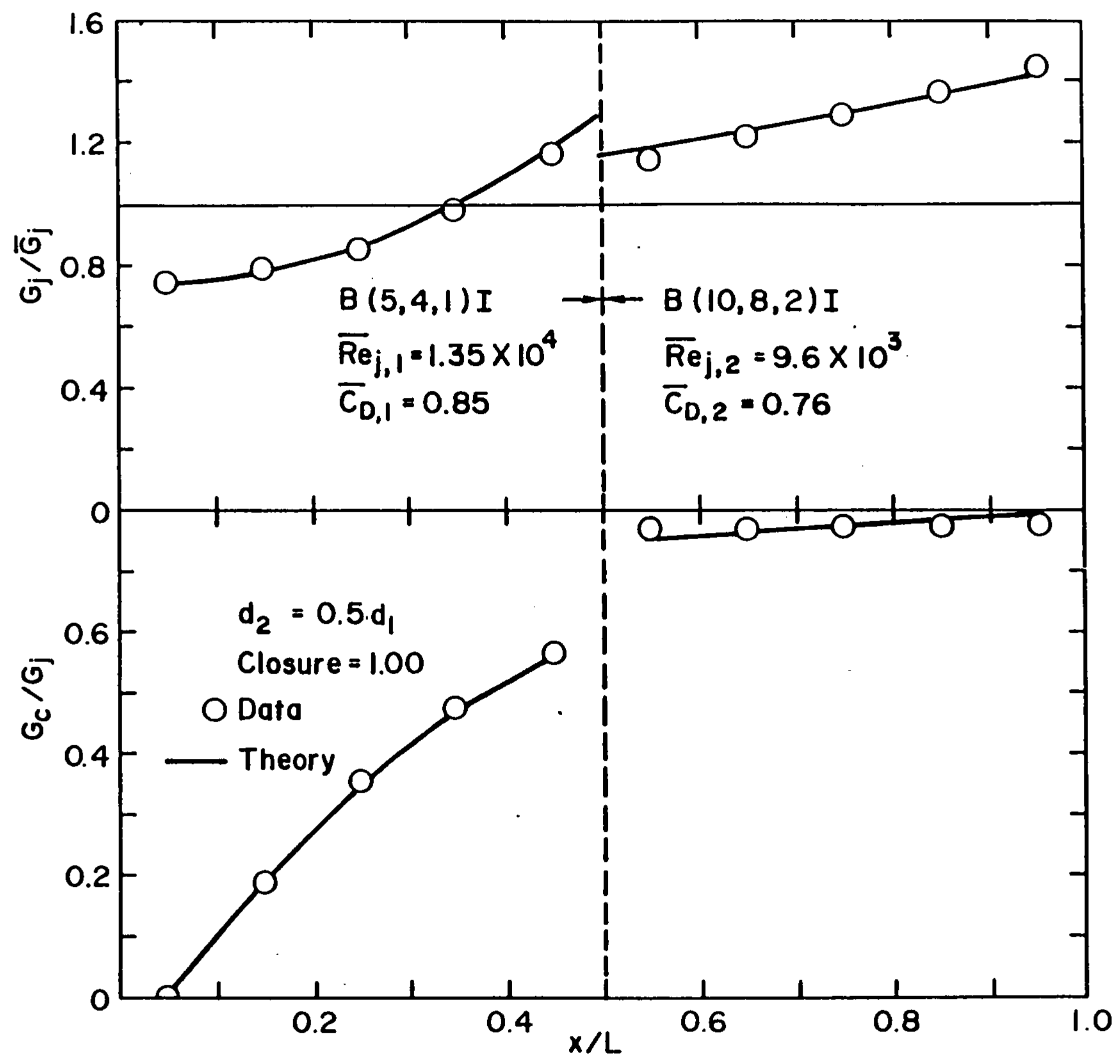
Nonuniform Array Geometries Tested

Nonuniform Parameter	Array Geometry† Region 1	Region 2	Number of Rows Region 1	Region 2	d (cm)	Test Series #
x_n	B(10,8,3)I	B(5,8,3)I	4	2	0.254	1X*
y_n	B(5,8,3)I	B(5,4,3)I	8	2	0.254	2Y*
	B(5,4,3)I	B(5,8,3)I	4	6	0.254	3Y*
	B(5,8,3)I	B(5,4,3)I	2	8	0.254	4Y*
	B(5,4,3)I	B(5,8,3)I	1	9	0.254	5Y*
	B(10,8,3)I	B(10,4,3)I	8	2	0.127	6Y
	B(5,8,2)I	B(5,4,2)I	8	2	0.254	7Y
	B(10,8,2)I	B(10,4,2)I	8	2	0.127	8Y
	B(10,8,2)I	B(10,4,2)I	5	5	0.127	9Y
					d_1(cm)	
d	B(10,8,2)I	B(5,4,1)I	5	5	0.127	1D*
	B(5,4,1)I	B(10,8,2)I	5	5	0.254	2D*
	D(15,6,3)I	D(10,4,2)I	5	5	0.254	3D
	D(10,4,2)I	D(15,6,3)I	5	5	0.381	4D

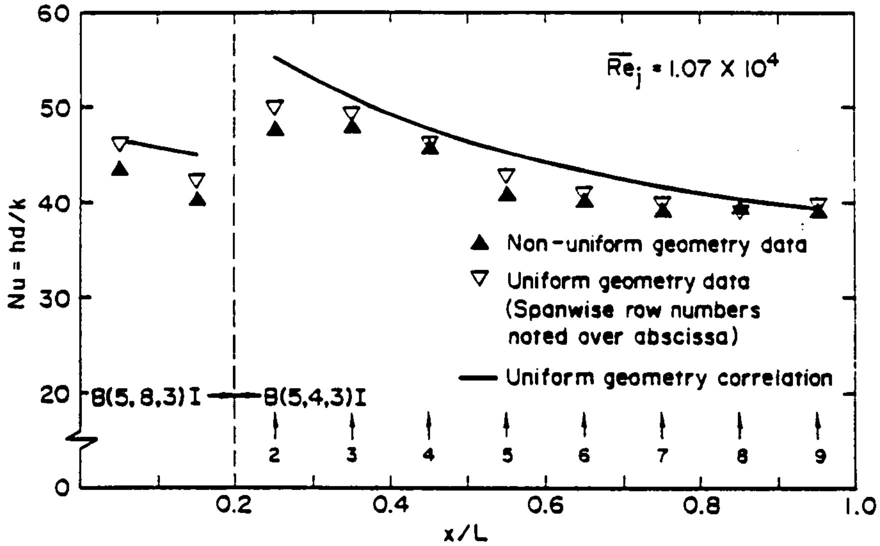
† (x_n/d, y_n/d, z/d)
Prefix designates overall array length: B(L = 12.7 cm), D(L = 38.1 cm)
Suffix designates hole pattern: I = Inline

* Flow distribution (row-by-row) measured in addition to heat transfer coefficients

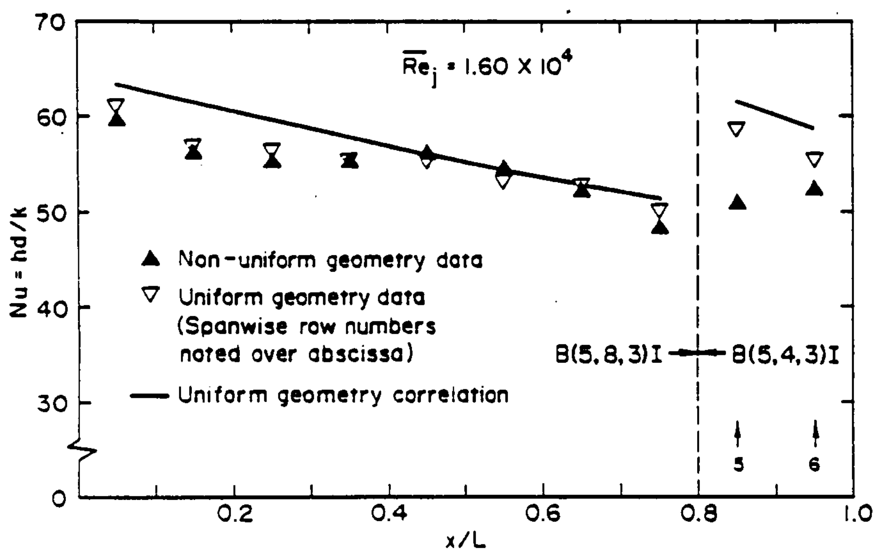
Note: b = d, for Test Series 1X and for 2Y through 9Y
b = largest of d_1 or d_2, for Test Series 1D through 4D



Flow distribution data for nonuniform diameter array compared with theory. Test #2D.



Nusselt number data for nonuniform y_n array compared with uniform array data and correlation. Test #4Y.



Nusselt number data for nonuniform y_n array compared with uniform array data and correlation. Test #2Y.