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AN INEXPENSIVE SUPERSONIC WIND TUNNEL FOR HEAT-TRANSFER MEASUREMENTS

PART II—RESULTS FOR A LAMINAR BOUNDARY LAYER BASED ON A TWO-DIMENSIONAL FLOW MODEL FOR THE ENTRANCE REGION OF A TUBE

BY

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AN INEXPENSIVE SUPERSONIC WIND TUNNEL FOR HEAT-TRANSFER MEASUREMENTS

Part II - Results for a Laminar Boundary Layer Based on a Two-Dimensional Flow Model for the Entrance Region of a Tube.

By

Joseph Kaye[1] and George A. Brown[2]

SUMMARY

Reliable experimental data on local heat-transfer coefficients for supersonic flow of air in a round tube are reanalyzed in detail with the aid of an approximate two-dimensional flow model. The results are compared with similar results based on a one-dimensional flow model and with the theoretical predictions for supersonic flow over a flat plate and for flow in the entrance region of a tube when a laminar boundary layer is present.

The two-dimensional flow model yields a better understanding of the phenomena which occur for diabatic supersonic flow of air in a round tube than that obtained with the aid of the one-dimensional flow model. The two-dimensional flow model shows that the core Mach number is nearly constant along the length of test section for a range of values of the inlet diameter Reynolds number. For a laminar boundary layer, the values of the local Stanton number agree within a few per cent with the theoretical values for plate flow at the largest values of the inlet diameter Reynolds number.

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NOMENCLATURE

a - inside radius of pipe
A - cross-sectional area, $\pi D^2/4$
A' - heat-transfer area, $\pi D \Delta L$
c_p - specific heat at constant pressure
c_w - discharge coefficient of nozzle
D - inside diameter of pipe
g - acceleration given to unit mass by unit force
G - flow per unit area, w/A
h - coefficient of heat transfer, $q/A'(t_w - t_{aw})$
k - ratio of specific heats
L - distance from end of curved contour of nozzle
M - Mach number, $V/\sqrt{gkRT}$
n - summation index, Eq. (15)
Nu_L - length Nusselt number, hL/λ
p - static pressure
q - net rate of heat transfer
R - perfect-gas constant
Re_D - diameter Reynolds number, $DG/\mu g$
Re_L - length Reynolds number, $LG/\mu g$
St - Stanton number, $h/c_p G$
t - temperature, deg F
T - temperature, deg F abs
V - velocity
w - mass rate of flow
ρ - density
μ - viscosity
λ - thermal conductivity
δ - thickness of boundary layer

Superscript * refers to throat of supersonic nozzle where $M = 1$.

Subscripts:

aw - adiabatic wall conditions
b - boundary layer
c - isentropic core
j - station numbers
o - hypothetical entrance plane of the tube, where the boundary layer is of zero thickness
ob - stagnation conditions in boundary layer
oc - stagnation conditions in core
oi - upstream stagnation conditions
r - atmospheric conditions
s - isentropic conditions
w - wall conditions
∞ - free stream conditions for flat-plate flow

INTRODUCTION

An inexpensive steady-state supersonic wind tunnel has been designed for accurate measurements of local heat-transfer coefficients. It consists of a convergent-divergent nozzle which delivers dry air at supersonic speeds to a test section, one-half inch in diameter and 30 to 50 diameters in length. The various test apparatus and the measurements obtained therefrom have been described previously in detail (1).* Sufficient measurements have been made to demonstrate their reliability when a laminar boundary layer exists in the test section for adiabatic and diabatic supersonic flow. The heat-transfer data were first analyzed (1) with the aid of a simple one-dimensional flow model, abbreviated hereafter as 1-DFM, but it was shown that this model is not fully adequate to explain, interpret, and correlate these measurements.

The value of these measurements of local heat-transfer coefficients would be considerably enhanced if they could be compared with similar measurements for other types of supersonic flow with a laminar boundary layer, such as plate flow, cone flow, etc. One reason for subjecting the data given in (1) to further analysis and computation is to lay the foundation for such comparisons. A second reason is that accurately measured values of local heat-transfer coefficients for supersonic flow with a laminar boundary layer are practically nonexistent so that further analysis of tube-flow data might produce information useful to the designer of devices moving at supersonic speeds. A third reason for using a more complicated flow model to reanalyze the same data is to provide the experimenter with a better phenomenological explanation of the processes which occur in supersonic flow in the entrance region of a tube. The two-dimensional flow model, abbreviated hereafter as 2-DFM, will be used in this paper to analyze and interpret some selected values of the data given in (1).

The analysis of supersonic flow in the inlet region of a tube can be accomplished, on the one hand, in an extremely simple fashion, such as with the aid of the 1-DFM, and on the other hand, in an extremely difficult fashion, such as by investigation of the partial differential equations of energy, momentum, and continuity. Although both of these methods of analysis have been used in the present research program, an intermediate type of analysis is used here to obtain results close to those based on the most exact analysis. This 2-DFM should be considered to represent closely the actual supersonic flow phenomena in the tube.

The 2-DFM is used here only for supersonic flow in the entrance region of a tube with a laminar boundary layer originating at tube inlet. Experimentally it has been found possible to maintain a laminar boundary layer over the entire length of test section by careful control of the inlet conditions. Independent measurements of the velocity and temperature profiles of the tube flow for these inlet conditions have confirmed the existence of this laminar boundary boundary layer. In the previous paper (1) certain values of the tube inlet conditions were selected to present the data for a laminar boundary layer. In

*Numbers in parentheses refer to the Bibliography at the end of the paper.

the present paper, the same values of these inlet conditions are selected to present the results of computation based on the 2-DFM. Comparisons of the results based on the 1-DFM and on the 2-DFM, for the same original data, will be given here. The results based on the 2-DFM will also be compared with theoretical solutions for plate flow and for tube flow.

ASSUMPTIONS FOR TWO-DIMENSIONAL FLOW MODEL WITH HEAT TRANSFER

The 2-DFM arbitrarily divides the supersonic flow in the entrance region of a tube into two parts, a laminar boundary layer and a central core of fluid, as shown in Fig. 1. The laminar boundary layer originates near the tube inlet and grows in thickness by transference of mass from the central core. This 2-DFM is consistent with Prandtl's concept of the boundary layer since it is assumed that both the viscous and thermal effects are concentrated in the boundary layer, and that both are negligible in the core region, i.e., the fluid remaining in the central core undergoes an isentropic process. The basic soundness of this 2-DFM has been conclusively demonstrated by means of accurately measured velocity profiles at various positions along the test section of Fig. 1, for both adiabatic and diabatic flow (2, 3), and also by means of unpublished recently measured temperature profiles.

The present paper deals with a simplified version of the actual 2-DFM in that the actual velocity and temperature profiles are represented by simple approximations for both the laminar boundary layer and the core. The boundary-layer thickness is assumed to be the same for both the velocity and thermal boundary layers. This thickness is arbitrarily taken to correspond to that thickness at which the local velocity in the boundary layer equals 99 per cent of the mean velocity in the core. These simplifications are shown in Fig. 1. They were introduced mainly to reduce the computational time since it was found, after considerable study, that the use of these simplified velocity and temperature profiles yielded results nearly identical to those obtained using a non-linear velocity profile but requiring considerably greater computational time.

The following assumptions are made in the analysis of the 2-DFM:

1. A laminar boundary layer, in which both the viscous and thermal effects are predominant, exists for supersonic flow in the entrance region.

2. The air which remains in the central core undergoes an isentropic change of state from an upstream stagnation state to the static pressure measured at a given section.

3. The properties in the central core of fluid are assumed to be uniform at a given section.

4. The static pressure is assumed to be uniform across each section of the tube.

5. Air is a perfect gas with a constant value of the ratio of specific heats ($k = 1.40$) over the range of temperature under consideration.

6. The laminar boundary layer has a linear distribution of velocity which is further approximated by an average velocity in the boundary layer equal to one-half the core velocity, as shown in Fig. 1.

7. The stagnation temperature of the central core is assumed to be constant at all sections, equal to T_{oc}, whereas the stagnation temperature of the boundary layer is assumed to be uniform at a given section but variable from section to section.

8. The flow is adiabatic up to the tube inlet where the heat transfer originates.

ANALYSIS OF SIMPLIFIED TWO-DIMENSIONAL FLOW MODEL WITH HEAT TRANSFER

The following relations hold at each section of the flow in the tube shown in Fig. 1.

Continuity: $w = w_b + w_c$ (1)

Continuity: $w_c = \rho_c V_c A_c$ (2)

Continuity: $w_b = \rho_b V_b A_b = \rho_b V_b (A - A_c)$ (3)

Geometry: $A_c = \pi \left[(D/2) - \delta \right]^2$ (4)

Geometry: $A = A_b + A_c$ (5)

Equation of state: $p = \rho_c R T_c$ (6)

Equation of state: $p = \rho_b R T_b$ (7)

Definition: $M_c^2 \equiv V_c^2 / gkRT_c$ (8)

Assumption: $V_b = V_c/2$ (9)

The following relations hold between the upstream stagnation state and a state in the core at any tube section:

Isentropic: $p_{oi}/p = (\rho_{oi}/\rho_c)^k$ (10)

Isentropic: $T_{oi}/T_c = (p_{oi}/p)^{(k-1)/k}$ (11)

Isentropic: $T_{oi} = T_{oc}$ (12)

Isentropic: $c_p T_{oc} = c_p T_c + V_c^2/2g$ (13)

Definition: $c_pT_{ob} \equiv c_pT_b + V_b^2/2g$ (14)

Application of the energy equation for steady flow to a control volume which encloses the fluid between the upstream stagnation region and any tube section j yields

$$(1/2)q_j + \sum_{n=1}^{n=j-1} q_n = w_{cj}\,(c_pT_{cj} + V_c^2/2g) + w_{bj}\,(c_pT_{bj} + V_b^2/2g) - wc_pT_{oi}. \quad (15)$$

The summation in Equation (15) starts at the first station at which heat transfer data were measured. This first station for test combinations C and D is described in reference (1).

The additional relations used in this analysis are as follows: The condition for choked flow of air through the supersonic nozzle yields

$G_s^* = (w/A^*)_s = 0.5318\ p_{oi}/\sqrt{T_{oi}}$ (16)

Definition: $c_w \equiv (w/A^*)/(w/A^*)_s$ (17)

Assumption: $T_{aw}/T_{oi} = 0.940$ (18)

Definition: $h \equiv q/A'\ (t_w - t_{aw})$ (19)

Definition: $Nu_{Dc} \equiv hD/\lambda_c$ (20)

Definition: $Nu_{Lc} \equiv hL/\lambda_c$ (21)

Definition: $St_c \equiv h/c_p\rho_cV_c$ (22)

Definition: $Re_{Dc} \equiv \rho_cV_cD_c/\mu_cg$ (23)

Definition: $Re_{Lc} \equiv \rho_cV_cL/\mu_cg$ (24)

Method of Computation

A sample calculation is given in the Appendix.

RESULTS

General

The original measurements of heat-transfer coefficients for supersonic flow obtained with test combinations C and D, comprising four runs with the former and thirteen runs with the latter, are given in detail in (1). These data have been selected for those stagnation conditions where a laminar boundary layer is present over most of the test section. Hence, the method of computation outlined above for the simplified 2-DFM should be applicable for these seventeen runs. In view of the large amount of calculation involved, however, only seven runs have been studied in detail by means of the simplified 2-DFM, namely six and one from test combinations C and D, respectively.

The results for six runs made with test combination D are given in Figs. 2 to 7, inclusive. Six charts were found necessary to present these results in sufficient detail because they are sensitive to small changes in the value of the inlet diameter Reynolds number. The results for one run made with test combination C are given in Fig. 8. One run was selected here mainly to reduce the total computational time and to show the effect of a shorter test section on the data. On each of these seven charts the calculated quantities based on one flow model are plotted without reference to the quantities calculated from the other flow model. Thus, in the curve of Mach number versus length Reynolds number, the values of Mach number and Reynolds number are taken from either the 1-DFM or from the 2-DFM.

Each of the seven charts presents the Mach number, boundary-layer thickness ratio, local length Nusselt number, and local Stanton number. For the 2-DFM, the Mach number, Nusselt number, and Stanton number are based on properties of the central core of fluid. The local Nusselt and Stanton numbers are, in reality, average values over the short length of flow of two or four pipe diameters. In the discussion of these seven charts, the value of the inlet diameter Reynolds number chosen for identification corresponds to that computed by means of the 2-DFM.

Each of the seven charts contains a comparison of the results based on the 2-DFM with the theoretical predictions of supersonic flow with a laminar boundary layer on a flat plate and with the theoretical predictions for tube flow for constant values of the viscosity and the thermal conductivity. The former predictions are taken from van Driest (4) and the latter from Toong (5). This type of comparison of results based on the 2-DFM with predictions for plate flow and for tube flow should be regarded as a temporary expedient until exact solutions for tube flow and accurate experimental data for plate flow with adverse pressure gradients are available.

Results for Test Combination D-Mach Number

Fig. 2 presents the results based on the simplified 2-DFM for the lowest value of the inlet diameter Reynolds number, namely, 33,000. The Mach number based on the 2-DFM decreased only from 2.7 to 2.1 along the length of the test section whereas that for the 1-DFM decreases from 2.1 to about 1.2. This same type of behaviour of the Mach numbers for the two flow models is found also in Figs. 3, 4, 5, 6, and 7. In Fig. 7, the Mach number based on the 2-DFM decreased only from 2.65 to 2.50 over 50 diameters of length of flow. This constancy of the Mach number based on the 2-DFM supports the contention that this type of test section is, in reality, a useful and inexpensive type of steady-state supersonic wind tunnel. The 2-DFM shows that the core Mach number does not vary as much as that indicated by the 1-DFM and that the value of the core Mach number is significantly greater than the corresponding value based on the 1-DFM. Independent measurements of velocity and temperature profiles at several stations near the tube exit lead to calculated values of the core Mach number which agree, within one per cent, with the values of the core Mach number based on the 2-DFM.

Boundary-Layer Thickness

The boundary-layer thickness at any section in the tube is defined by Equation (4) for the 2-DFM. It should be noted that this thickness is taken arbitrarily as zero in the 1-DFM. For the smaller values of the inlet diameter Reynolds number, namely from 33,000 to 72,000 in Figs. 2, 3, and 4, this ratio increased from about 20 per cent at tube inlet to about 40 to 50 per cent at tube exit. For the larger values of Reynolds number, namely from 88,000 to 115,000 in Figs. 5, 6, and 7, this ratio increases from about 10 per cent at tube inlet to about 25 per cent at tube exit. Such behaviour of the thickness ratio could be interpreted in two ways. Either the laminar boundary layer does not fill the tube at exit and a fully developed flow pattern is not attained for this entrance type of flow, or for the flow length of 50 diameters the supersonic flow is, in reality, one corresponding to a fully developed flow but with a velocity profile which is quite different than that for fully developed incompressible flow in a round tube. Additional experimental data on velocity profiles for several stations near the tube exit are needed before these views can be resolved.

The thickness ratio for tube flow based on the 2-DFM can be compared with a similar ratio derived for the thickness of a laminar boundary layer of a compressible fluid flowing on a flat plate for zero pressure gradient. The theoretical results of Howarth (6) lead to the following equation for the thickness ratio,

$$(\delta/a) = 10.4(L/D)(1 + 0.0795\, M_c^2)/(Re_{Lc})^{1/2}. \qquad (25)$$

Here the thickness corresponds to that value at which the local velocity in the boundary layer on the flat plate is 99 per cent of the free stream value. The values of the thickness ratio based on the 2-DFM are slightly larger than those based on Equation (25) for values of the diameter Reynolds number from

33,000 to 72,000, but both sets of values are in excellent agreement over the entire length of the test section for Reynolds numbers from 88,000 to 115,000. This excellent agreement should be considered as somewhat coincidental for the following reasons:

1. The zero of the length measurement for the tube flow should be the origin of the boundary layer where its thickness is zero, but the actual zero has been arbitrarily taken to be at the end of the curved contour of the nozzle. The effects introduced by this error should disappear by the middle of the test section.

2. The Howarth formula is restricted to zero pressure gradient whereas a finite adverse pressure gradient exists in the tube flow. The smallest pressure gradient is found, however, at the largest value of the inlet diameter Reynolds number, and for this case, the agreement between thickness ratio based on the 2-DFM and on the Howarth formula is the best.

3. At the lowest values of the diameter Reynolds number, namely at 33,000 to 72,000, some evidence exists that separation of the laminar boundary layer probably occurs in the presence of the adverse pressure gradient. Such separation would probably result in a thickening of the laminar boundary layer and cause its calculated thickness based on the 2-DFM to be greater than that indicated by the Howarth formula. Such a thickening calculated on the basis of the 2-DFM, can be seen in Figs. 2, 3, and 4.

Stanton Number

The local heat-transfer coefficients based on the 2-DFM are shown in Figs. 2 to 7 for test combination D in the form of the local Stanton and local length Nusselt numbers. Comparison of the Stanton numbers shows that the major effect of shifting from the 1-DFM to the 2-DFM is to decrease the calculated values of the Stanton numbers and simultaneously to increase the corresponding values of the length Reynolds number. In Fig. 2, for a diameter Reynolds number of 33,000, the first six values of the Stanton number lie within an average deviation of less than 10 per cent from the theoretical solution for tube flow, the remaining eight values fluctuate about a mean value, and the fluctuations begin at a length Reynolds number based on the 2-DFM of 600,000. Similar fluctuations are evident in the values of the Stanton number based on the 1-DFM and are discussed in (1). A similar process of levelling-off of the values of the Stanton number with fluctuations about a mean value is evident in Figs. 3 and 4 at larger values of the diameter Reynolds number.

Figs. 2 to 7 indicate that as the value of the diameter Reynolds number increases from 33,000 to 115,000 the values of the Stanton number based on the 2-DFM move from below the lower line for the tube solution to almost perfect agreement with the theoretical plate-flow solution, shown in Fig. 7. The discrepancies between the values of the Stanton number and the tube solution should not be considered significant at present, since this tube solution is based on the assumption of constant viscosity and thermal conductivity; work is in progress to obtain tube solutions for variable values of these properties. The discrepancies between the values of the Stanton number and the flat-plate solution, especially at the smaller values of the diameter Reynolds number should not be considered significant for two reasons. First, the plate-solution is based on zero pressure gradient but the data were taken with an adverse pressure gradient in the tube; note that the best agreement between the tube-flow data and the flat-plate solution occurs for the smallest value of the adverse pressure gradient in the tube. Second, at the smallest values of the diameter Reynolds number, there is some evidence of separation of the laminar boundary layer so that one would expect some deviations from the theoretical solution for plate flow in which separation effects were neglected.

Nusselt Number

The values of the local length Nusselt number based on the 2-DFM and on the 1-DFM are also shown in Figs. 2 to 7. The main reason for including the Nusselt number is to compare the value of plotting the calculations in different ways. All the conclusions reached so far with the aid of the curves of Stanton number are also evident from examination of curves for the Nusselt number, except that the levelling-off of the Stanton numbers in Figs. 2, 3, and 4 is almost completely masked in the sharply rising values of the Nusselt number at the same length Reynolds number. This masking is a result of using the tube length as a multiplicative factor in the Nusselt number.

Transition

The transition from a laminar to a turbulent boundary layer is clearly evident in Figs. 5, 6, and 7, occurring as a very sharp rise in value of the Stanton or Nusselt number. On the basis of the 2-DFM, this sharp rise occurs at values of the length Reynolds number of 4,000,000, 4,500,000 and 4,500,000 in Figs. 5, 6, and 7, respectively. These values of the length Reynolds number at the start of transition are in good accord with values given in the literature for transition of a laminar boundary layer on a flat plate with zero pressure gradient.

Results for Test Combination C - Effect of Shorter Test Section

The results of using the 2-DFM for calculation of one run with test combination C are shown in Fig. 8. The value of the inlet diameter Reynolds number is 127,000, which corresponds to the highest value for test combination D shown in Fig. 7. Hence the effect of a shorter length of test section may be obtained by comparison of these two figures. Fig. 8 shows that the value of the Mach number, based on the 2-DFM, remains nearly constant. The boundary layer thickness ratio increases from 10 per cent at inlet to about 20 per cent at exit, thus duplicating the behaviour of the boundary-layer thickness ratio of test combination D in Fig. 7. This ratio in Fig. 8 also agrees well with that computed by the Howarth formula.

The values of the local Stanton and local Nusselt numbers based on the 2-DFM, shown in Fig. 8, agree within a few per cent with the values based on the theoretical predictions for plate flow, in the region where a laminar boundary layer is present. The value of the length Reynolds number at transition from a laminar to a turbulent boundary layer lies between 3,000,000 and 4,000,000; this agrees well with the values observed for transition in the longer test section of test combination D. The main effect of the shorter length of test combination C is that the rise in values of the Stanton or Nusselt numbers during transition is never as spectacular as that found in test combination D.

PREDICTION OF DIABATIC SUPERSONIC FLOW IN A TUBE

The 2-DFM provides a means of predicting the flow behaviour for diabatic supersonic flow in the entrance region of a tube if a laminar boundary layer exists. In essence, this method of prediction was confirmed when test combination D was designed to be 50 diameters long instead of 30 for the previous test combination C. The analysis for prediction for diabatic flow is obtained by rearrangement of the basic equations given above but will be omitted here for lack of space. The analysis based on the 2-DFM is also being used to design new test sections for adiabatic and diabatic flow with an inlet Mach number near 5.

CONCLUSIONS

An approximate and simplified two-dimensional flow model for the entrance flow region of a tube yields results which are in agreement with theoretical predictions for tube flow and for plate flow with zero pressure gradient. This flow model yields a better understanding of the phenomena which occur in diabatic supersonic flow of air in a round tube than that obtained with the simple one-dimensional flow model and eliminates the inadequacies of the latter model.

The Mach numbers based on the 2-DFM are significantly larger and much more nearly constant along the test section than those based on the 1-DFM.

The thickness of the laminar boundary layer based on the 2-DFM increases slowly from tube inlet to exit but does not fill the tube cross section at exit. These values of the thickness are in good agreement with those calculated from Howarth's results.

The values of the local Stanton number based on the 2-DFM agree best with the theoretical predictions for tube flow and deviate most from those for plate flow at the lowest value of the diameter Reynolds number, namely, 33,000.

But the reverse is true at the highest value of the diameter Reynolds number, namely, 127,000 for test combination C, and 115,000 for test combination D. The agreement between measured tube values and predictions for plate flow for zero pressure gradient for these last two values of the diameter Reynolds number is within a few per cent. The values of the local Nusselt number based on the 2-DFM behave similar to the Stanton numbers in comparisons with the theoretical predictions for tube flow and plate flow but are of less value in understanding and interpreting the phenomena.

The effect of varying the length of test section from 30 to 50 diameters on the results based on the 2-DFM is negligible, except that the shorter length does not delineate transition as clearly.

The transition from a laminar to a turbulent boundary layer for diabatic supersonic flow in a tube is clearly evident in the sudden and very sharp rise of the values of the local Stanton number. The values of the length Reynolds number at the start of the transition are in excellent agreement with similar data for a laminar boundary layer on a flat plate.

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APPENDIX

CALCULATED RESULTS BASED ON TWO-DIMENSIONAL FLOW MODEL

This appendix contains the results based on the 2-DFM for seven runs, of which six were made with test combination D and one with C. The summary of the large amount of computation based on the 2-DFM is given in Table 1. The values given in Table 1 are based on calculations made with five or six significant figures throughout. A sample calculation is given here, in part, to indicate the method, for Run No. B-1. The original data for Run No. B-1 are taken from Table 5 of reference (1).

The values are summarized as follows:

G^*_s = 46.73 lbm/sec ft^2

$(Re^*_D)_s$ = 92,765

c_w = 0.967

w^*_s = 0.01837 lbm/sec

w = 0.01777 lbm/sec

A = 0.1978 in.^{2} = 0.001373 ft^2

From Table 30 of the "Gas Tables" (7), corresponding to the value of (p/p_{oi}) of 0.04601 for the fourth station, it is found that

M_c = 2.655

T_c/T_{oi} = 0.4149

T_c = $(T_c/T_{oi})\,T_{oi}$ = 0.4149 (570.88) = 236.9^o F abs

For the core,

$$\rho_c = \frac{p_{oi}\,(p/p_{oi})}{RT_c} = \frac{14.479 \times 0.04601 \times 144}{53.342 \times 236.9} = 0.007645 \text{ lbm/ft}^3$$

$$V_c \equiv M_c \sqrt{gkRT_c} = 2.655 \sqrt{32.174 \times 1.400 \times 53.342 \times 236.9} = 2003 \text{ ft/sec}$$

$$G_c \equiv \rho_c V_c = 0.007645 \times 2003 = 15.31 \text{ lbm/(sec ft}^2)$$

For the boundary layer,

V_b = $V_c/2$ = 1002 ft/sec

From Equations (1), (2), (3), (7), (12), (13), (14), and (15)

$$A_c = \frac{q_j/2 + \sum_{n=1}^{n=j-1} q_n + wc_p\,(T_{oi} - V_b^2/2gc_p) - (pV_b c_p A)/R}{G_c c_p\,(T_{oi} - V_b^2/2gc_p) - (pV_b c_p)/R}$$

$$q_j/2 + \sum_{n=1}^{n=j-1} q_n = q_4/2 + q_3 = 0.001482 + 0.011486 = 0.012968 \text{ Btu/sec}$$

$$(T_{oi} - V_b^2/2gc_p) = (570.88 - 1002 \times 1002/2 \times 32.174 \times 778.3 \times 0.2399)$$

$$= 487.4\ ^{\circ}\text{F abs}$$

$$wc_p\,(T_{oi} - V_b^2/2gc_p) = 0.01777 \times 0.2399 \times 487.4 = 2.077 \text{ Btu/sec}$$

$$G_c c_p\,(T_{oi} - V_b^2/2gc_p) = 15.31 \times 0.2399 \times 487.4 = 1791 \text{ Btu/sec ft}^2$$

$$pV_b c_p/R = 14.479 \times 0.04601 \times 144 \times 1002 \times 0.2399/53.342 = 435.1 \text{ Btu/sec ft}^2$$

$$pV_b c_p A/R = 435.1 \times 0.001373 = 0.5976 \text{ Btu/sec}$$

$$A_c = \frac{0.012968 + 2.077 - 0.5976}{1791 - 435.1} = 0.001101 \text{ ft}^2$$

$$A_b = A - A_c = 0.001373 - 0.001101 = 0.000272 \text{ ft}^2$$

$$w_c = G_c A_c = 15.31 \times 0.001101 = 0.01687 \text{ lbm/sec}$$

$$w_b = w - w_c = 0.01777 - 0.01687 = 0.000902 \text{ lbm/sec}$$

$$\delta/a = 1 - (1/a)\sqrt{A_c/\pi} = 1 - (24/0.5018)\sqrt{0.001101/\pi} = 0.1045$$

From Equations (3) and (7)

$$T_b = pV_b A_b/Rw_b = 14.579 \times 0.04601 \times 144 \times 1002 \times 0.000272/53.342 \times 0.00090$$

$$= 547.3\ ^{\circ}\text{F abs}$$

$$\rho_b = \frac{p_{oi}\,(p/p_{oi})}{RT_b} = \frac{14.579 \times 0.4601 \times 144}{53.342 \times 547.3} = 0.003308 \text{ lbm/ft}^3$$

$$G_b \equiv \rho_b V_b = 0.003308 \times 1002 = 3.314 \text{ lbm/sec ft}^2$$

The remaining quantities are calculated as follows:

$$T_{aw} = (T_{aw}/T_{oi})\,T_{oi} = 0.940 \times 570.88 = 536.6 \ {}^{o}\text{F abs}$$

$$h \equiv q/A'\,(t_w - t_{aw}) = 974.7/(672.2 - 536.6) = 7.19 \text{ Btu/hr } {}^{o}\text{F ft}^2$$

$$hD/\lambda_c \equiv 7.19 \times 0.5018/12 \times 3600 \times 0.1942 \times 10^{-5} = 43.0$$

$$hL/\lambda_c \equiv (hD/\lambda_c)\,(L/D) = 43.0 \times 4.484 = 193$$

$$h/c_pG_c \equiv 7.19/0.2399 \times 15.31 \times 3600 = 5.44 \times 10^{-4}$$

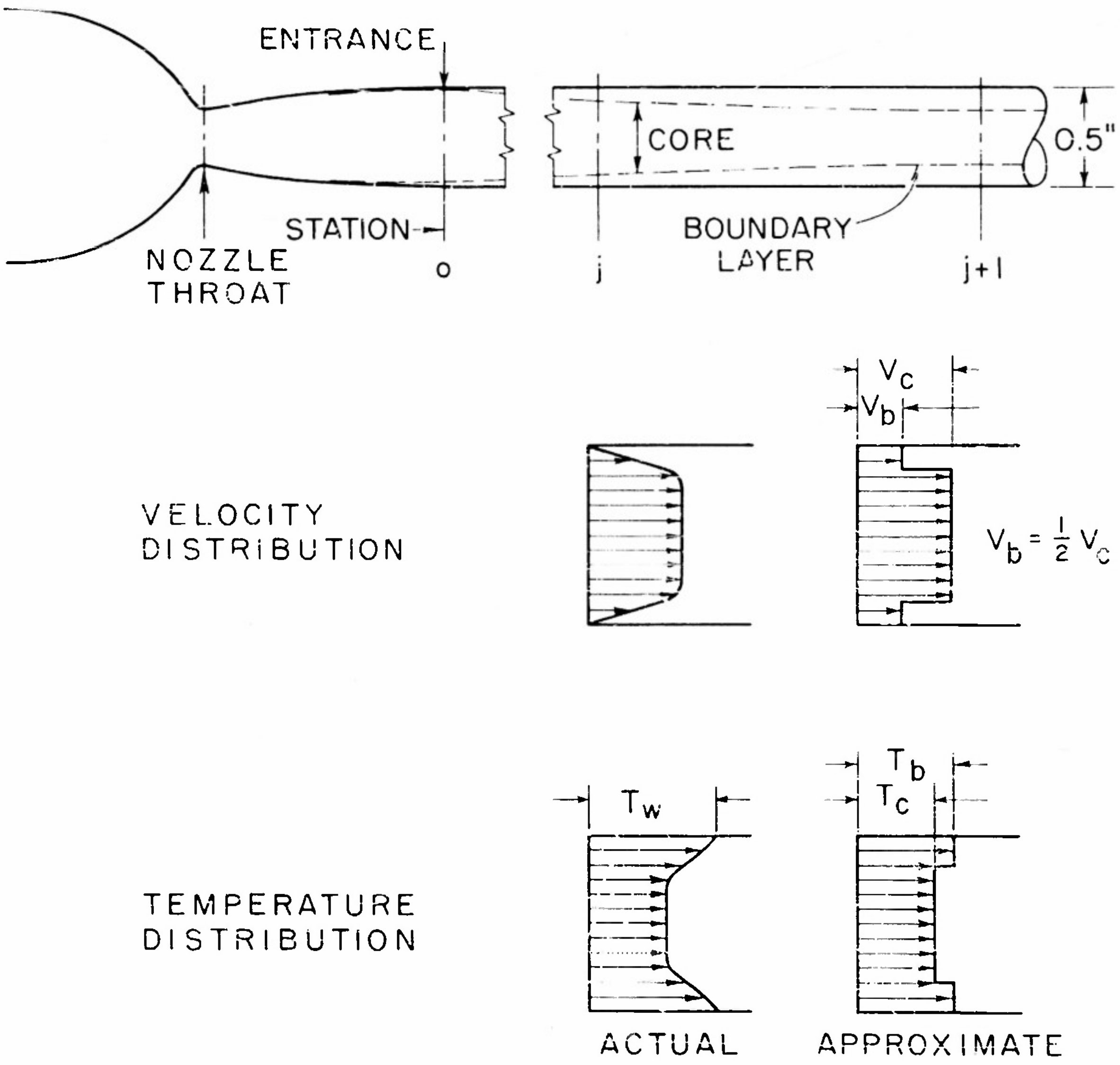
$$Re_{Lc} \equiv \frac{G_c D\,(L/D)}{\mu_c} = \frac{15.31 \times 0.5018 \times 4.484}{12 \times 0.620 \times 10^{-5}} = 463{,}000$$

The calculations are continued by repeating the above steps for Station numbers 5, 6, 7, etc.

TABLE 1

CALCULATIONS BASED ON TWO-DIMENSIONAL FLOW MODEL

	Station No.	$\frac{p}{p_{01}}$	M_c	$\frac{T_c}{T_{01}}$	T_c	μ_c	λ_c	V_c	G_c	q	V_b	t_b	G_b	m_r	w_b	$\frac{f}{m}$	Re_{Lc}	T_s	$\frac{q}{A}$	h	$\frac{hD}{\lambda_c}$	$\frac{hL}{\lambda_c}$	$\frac{h}{c_p G_c}$
					°F abs	$\times 10^5$ $\frac{lbm}{sec\ ft}$	$\times 10^5$ $\frac{Btu}{sec\ ft\ °F}$	$\frac{ft}{sec}$	$\frac{lbm}{sec\ ft^2}$	$\times 10$ $\frac{Btu}{sec}$	$\frac{ft}{sec}$	°F abs	$\frac{lbm}{sec\ ft^2}$	$\times 10^2$ $\frac{lbm}{sec}$	$\times 10^2$ $\frac{lbm}{sec}$		$\times 10^5$	°F abs	$\frac{Btu}{hr\ ft^2}$	$\frac{Btu}{hr\ ft^2\ °F}$			$\times 10^4$
Run No. K-23	1	0.03634	2.85	0.3816	214.79	0.565	0.176	2045	17.12	0.392	1022	494.64	3.718	1.819	0.1163	0.121	4.17	672.35	1290	9.00	59.3	195.6	6.09
November 24, 1948	2	.03680	2.84	.3831	215.62	.568	.177	2042	17.27	.284	1021	506.33	3.676	1.815	.1188	.125	6.73	672.39	735	5.52	42.8	226	4.37
t_r = 73.0 °F	3	.03656	2.81	.3885	218.69	.576	.180	2031	17.61	.243	1017	510.51	3.814	1.790	.1400	.144	9.40	672.46	632	5.80	37.5	273	3.77
p_r = 14.628 psia	4	.03856	2.77	.3945	222.04	.584	.182	2023	18.41	.230	1012	512.37	3.959	1.769	.1648	.164	12.2	672.48	755	5.27	33.6	311	3.31
p_{01} = 19.404 psia	5	.04017	2.74	.3992	224.67	.590	.184	2016	18.83	.197	1008	514.69	4.126	1.749	.1846	.179	15.1	672.52	647	4.56	28.4	320	2.77
t_{01} = 103.17 °F	6	.04202	2.71	.4043	227.54	.597	.187	2011	19.41	.189	1004	514.61	4.292	1.726	.2094	.198	18.0	672.44	[illegible]	4.35	26.9	[illegible]	2.48
w_a^* = 0.019939 lbm/sec	7	.04326	2.70	.4076	229.44	.600	.188	2005	19.76	.179	1001	516.11	4.392	1.711	.2235	.208	20.9	672.39	567	4.10	25.3	386	2.40
c_v = 0.970	8	.04417	2.68	.4101	230.83	.605	.189	1997	20.02	.167	999	517.02	4.402	1.688	.2344	.214	23.9	672.47	559	3.83	23.5	406	2.22
w = 0.019341 lbm/sec	9	.04524	2.67	.4129	232.42	.609	.191	1992	20.32	.166	996	518.99	4.549	1.676	.2476	.223	26.8	672.47	546	3.81	23.2	446	2.17
T_{av} = 529.09 °F abs	10	.04555	2.66	.4137	232.87	.610	.191	1991	20.40	.162	996	521.46	4.555	1.694	.2501	.225	29.7	672.47	531	3.70	22.5	478	2.20
	11	.04624	2.65	.4155	233.87	.613	.192	1991	20.59	.172	994	523.16	4.602	1.676	.2579	.230	32.6	672.49	500	3.95	23.9	526	2.22
	12	.04716	2.64	.4179	235.20	.616	.193	1992	20.84	.177	992	524.46	4.673	1.665	.2689	.238	35.7	672.54	589	4.07	24.5	618	2.26
	13	.04755	2.63	.4188	235.74	.617	.193	1989	20.94	.180	991	526.57	4.685	1.662	.2722	.240	38.6	672.40	619	4.32	26.0	706	2.39
	14	.04601	2.66	.4149	233.54	.612	.191	1989	20.53	.223	991	535.24	4.407	1.666	.2482	.227	41.0	672.40	750	5.23	31.7	926	2.95
Run No. B-1	1	0.04337	2.69	0.4080	232.91	0.610	0.191	2015	14.77		1008						0.189						
September 3, 1952	2	.04337	2.69	.4080	232.91	.610	.191	2015	14.77		1008						1.65						
t_r = 83.7 °F	3	.04284	2.70	.4065	232.09	.606	.190	2017	14.66	1.149	1009	521.98	3.258	1.710	0.0669	0.0784	2.38	672.02	5036				
p_r = 14.579 psia	4	.04601	2.66	.4149	236.36	.620	.194	2003	15.31	0.296	1002	537.33	3.314	1.687	.0902	.105	4.63	672.17	915	7.19	43.0	193	5.44
p_{01} = 14.579 psia	5	.04865	2.62	.4216	240.67	.629	.197	1992	15.85	.262	996	546.14	3.491	1.664	.1129	.126	6.02	672.42	795	5.06	34.5	223	4.28
t_{01} = 111.10 °F	6	.05129	2.59	.4280	244.32	.638	.200	1981	16.36	.224	990	544.28	3.673	1.640	.1362	.146	9.09	672.51	735	5.41	31.4	266	3.83
w_a^* = 0.018373 lbm/sec	7	.05260	2.57	.4322	246.10	.642	.202	1975	16.62	.194	987	546.67	3.740	1.639	.1463	.155	11.3	672.57	638	4.69	27.0	283	3.27
c_v = 0.967	8	.05419	2.55	.4349	248.21	.647	.203	1969	16.92	.171	984	547.12	3.837	1.616	.1604	.166	13.6	672.43	561	4.13	23.6	294	2.83
w = 0.017767 lbm/sec	9	.05722	2.51	.4416	252.09	.656	.206	1957	17.48	.152	977	544.11	4.051	1.588	.1887	.187	16.1	672.36	500	3.63	20.7	300	2.44
T_{av} = 536.63 °F abs	10	.06115	2.47	.4501	256.95	.665	.210	1942	18.20	.276	971	539.55	4.331	1.552	.2255	.212	19.9	672.62	470	3.45	19.1	333	2.20
	11	.06438	2.43	.4577	261.30	.678	.214	1929	18.74	.244	964	530.99	4.560	1.517	.2596	.234	24.9	672.37	400	2.95	16.0	344	1.31
	12	.06659	2.42	.4612	263.25	.683	.215	1922	19.14	.247	961	542.52	4.65	1.503	.2740	.244	29.8	672.42	406	2.99	15.1	410	1.61
	13	.06975	2.39	.4673	266.77	.691	.218	1911	19.67	.229	956	540.48	4.655	1.474	.3030	.261	35.0	672.41	377	2.79	14.9	435	1.63
	14	.06910	2.39	.4660	266.05	.689	.217	1914	19.56	.220	957	544.93	4.775	1.483	.2930	.257	39.6	672.31	374	2.76	14.7	492	1.63
	15	.06910	2.39	.4660	266.05	.689	.217	1914	19.56	.224	957	545.66	4.743	1.485	.2912	.256	44.4	672.52	377	2.77	14.8	553	1.64
	16	.06646	2.42	.4609	263.10	.682	.215	1923	19.12	0.423	951	559.32	4.496	1.510	.2610	.240	48.5	672.62	695	5.11	27.6	1241	3.10
	17	.06290	2.45	.4537	258.99	.671	.212	1936	18.50	1.064	968	566.15	4.017	1.560	.2165	.216	52.2	672.07	1782	13.16	72.2	3271	6.43
	18	.06184	2.46	.4515	257.74	.670	.211	1940	18.32	1.631	972	628.32	3.757	1.586	.1900	.206	55.0	671.69	7151				
Run No. B-11	1	0.04474	2.67	0.4225	231.55	0.607	0.190	1994	4.743		997						0.0618						
December 12, 1952	2	.05555	2.53	.4379	246.34	.643	.200	1949	5.411		974						0.570						
t_r = 79.0 °F	3	.05321	2.56	.4325	243.30	.635	.199	1955	5.272	0.7599	979	514.90	1.753	0.4951	0.05427	0.173	0.821	670.79	3332				
p_r = 14.470 psia	4	.05727	2.51	.4413	248.46	.648	.203	1942	5.532	.1019	971	539.45	1.272	.4849	.06209	.197	1.60	671.34	335	2.35	13.42	60.2	4.94
p_{01} = 4.560 psia	5	.07132	2.37	.4703	264.54	.690	.216	1892	6.279	.0934	948	523.92	1.585	.4444	.1055	.232	2.48	670.96	307	2.16	11.60	75.1	3.98
t_{01} = 102.84 °F	6	.08535	2.26	.4951	275.49	.712	.227	1847	6.914	.0642	924	519.37	1.869	.4007	.1492	.353	3.44	671.57	277	1.94	9.92	84.0	3.22
w_a^* = 0.005780 lbm/sec	7	.09011	2.22	.5020	282.82	.720	.231	1833	7.190	.0751	917	520.14	1.955	.3866	.1534	.374	4.32	671.69	262	1.83	9.23	96.6	2.95
c_v = 0.950	8	.09367	2.20	.5074	285.97	.735	.233	1823	7.356	.0734	911	521.12	2.017	.3762	.1717	.389	5.21	671.54	241	1.69	8.62	[illegible]	2.66
w = 0.0054994 lbm/sec	9	.09740	2.17	.5140	289.16	.742	.236	1812	7.514	.0726	904	521.93	2.071	.3612	.1847	.405	6.12	671.47	240	1.68	8.21	120	2.59
T_{av} = 527.78 °F abs	10	.10366	2.13	.5233	294.37	.754	.240	1795	7.750	.1452	893	522.94	2.190	.3461	.2031	.430	7.52	671.67	239	1.67	8.09	141	2.49
	11	.10503	2.12	.5267	296.27	.759	.241	1790	7.879	.1514	894	525.63	2.222	.3411	.2083	.439	9.31	671.35	249	1.75	8.41	[illegible]	2.57
	12	.10772	2.11	.5291	297.62	.761	.242	1784	7.960	.1491	890	528.52	2.213	.3376	.2123	.444	11.1	671.47	245	1.72	8.24	209	2.50
	13	.11126	2.09	.5340	300.40	.768	.244	1775	8.092	.1412	887	530.48	2.291	.3222	.2217	.457	13.1	671.36	232	1.63	7.73	227	2.33
	14	.11246	2.08	.5356	301.30	.770	.245	1771	8.140	.1543	886	533.14	2.300	.3263	.2237	.460	14.8	671.77	247	1.73	8.19	271	2.46
	15	.11263	2.08	.5359	301.44	.770	.245	1771	8.146	.1440	886	535.13	2.290	.3275	.2224	.459	16.5	671.70	237	1.66	7.85	295	2.36
	16	.11209	2.10	.5324	299.45	.765	.244	1777	8.045	.1423	889	540.23	2.250	.3371	.2128	.448	18.2	671.40	236	1.64	7.82	325	2.36
	17	.10533	2.12	.5251	295.73	.757	.241	1786	7.851	.1537	895	546.10	2.126	.3532	.1962	.427	19.7	671.48	253	1.77	8.54	377	2.61
	18	.10209	2.14	.5210	293.09	.751	.239	1799	7.714	.1485	900	554.81	2.041	.3670	.1829	.412	20.6	671.54	2226				
Run No. B-1[illegible]	1																						
December 15, 1952	2																						
t_r = 76.0 °F	3	0.05309	2.56	0.4612	262.67	0.636	0.200	1951	7.530	1.013	9[illegible]	511.65	1.191	0.7145	0.07609	0.169	[illegible]	[illegible]	4457				
p_r = 14.711 psia	4	.05524	2.49	.4460	251.13	.655	.205	1937	[illegible]	0.156	969	532.79	1.9[illegible]	.6935	.0919	.2[illegible]	2.30	671.95	513	3.61	20.4	91.4	5.20
p_{01} = 6.529 psia	5	.06130	2.43	.4546	259.53	.671	.212	1915	8.525	.125	957	529.25	2.0[illegible]	.6670	.1220	.245	3.44	672.90	410	2.89	15.9	[illegible]	[illegible]
t_{01} = 104.06 °F	6	.07132	2.37	.4703	265.12	.687	.217	1894	8.911	112	947	527.05	2.259	.6419	.144	.275	4.63	672.05	367	2.58	13.8	117	3.33
w_a^* = 0.0082790 lbm/sec	7	.07606	2.33	.4790	270.31	.690	.221	1875	9.321	.105	939	526.39	2.392	.6246	.1695	.301	5.84	672.35	344	2.42	12.7	133	3.00
c_v = 0.955	8	.07937	2.31	.4849	273.35	.706	.223	1866	9.559	.098	936	526.69	2.461	.6076	.1832	.320	7.05	672.25	298	2.09	10.9	136	2.53
w = 0.0079064 lbm/sec	9	.08299	2.29	.4906	276.56	.713	.226	1855	9.735	.095	929	526.93	2.569	.5937	.1970	.335	8.29	672.15	312	2.20	11.3	163	2.62
T_{av} = 529.94 °F abs	10	.08494	2.25	.4977	280.57	.723	.229	1845	10.07	.150	922	527.60	2.679	.5759	.2183	.355	10.2	672.27	277	1.95	9.67	172	2.24
	11	.08813	2.24	.4996	281.63	.725	.230	1841	10.15	.1[illegible]	9[illegible]	529.54	2.695	.5725	.2182	.359	12.5	672.13	275	1.94	9.51	210	2.21
	12	.09346	2.20	.5050	286.42	.736	.233	1825	10.50	.1[illegible]	913	531.33	2.830	.5504	.2403	.372	15.2	672.10	290	2.12	10.4	255	2.32
	13	.09477	2.19	.5101	287.55	.739	.234	1822	10.58	.177	911	534.11	2.[illegible]	.5466	.2440	.387	17.9	671.75	291	2.05	10.2	299	2.25
	14	.09606	2.17	.5151	290.39	.745	.237	1812	10.79	.178	906	535.79	2.924	.5337	.2569	.405	20.2	671.58	285	2.03	9.99	331	2.18
	15	.09667	2.17	.5160	290.59	.746	.237	1811	10.82	.175	905	538.57	2.923	.5332	.2575	.401	22.7	672.24	288	2.03	9.92	371	2.17
	16	.09441	2.19	.5045	287.[illegible]	.732	.234	1823	10.56	.171	911	544.60	2.734	.5545	.2362	.382	24.7	672.08	282	1.98	9.83	406	2.17
	17	.09394	2.26	.5040	286.03	.737	.234	1826	10.53	.192	912	548.65	2.752	.5585	.2319	.378	27.1	672.14	315	2.22	11.0	499	2.44
	18	.09361	2.20	.5043	286.55	.736	.234	1825	10.52	.493	912	[illegible]	2.7[illegible]	.5643	.2263	.375	[illegible]	672.18	2161				
Run No. B-14	1	0.04931	2.61	0.4232	239.32	0.626	0.196	1980	10.00		990.						0.135						
December 22, 1952	2	.04806	2.64	.4171	235.65	.618	.193	1990	10.47		995.						1.15						
t_r = 67.5 °F	3	.04[illegible]	2.62	.4211	238.11	.623	.195	1983	10.69	1.107	992.	511.42	2.4[illegible]	1.111	0.0830[illegible]	0.130	1.7	671.87	4653				
p_r = 14.858 psia	4	.05347	2.57	.4306	243.00	.636	.200	1966	11.22	0.238	983.	534.96	2.554	1.092	.1023	.158	3.31	672.41	781	5.55	32.3	145	5.73
p_{01} = 9.811 psia	5	.05560	2.53	.43[illegible]	24[illegible]	.64[illegible]	.203	1954	11.63	.1[illegible]	977.	535.21	2.691	1.072	.1214	.181	4.87	672.59	578	4.10	23.5	152	4.08
t_{01} = 105.50 °F	6	.05988	2.50	.4452	251.75	.655	.206	1941	12.03	.152	971.	534.20	2.834	1.055	.1411	.200	6.50	672.33	504	3.56	20.1	[illegible]	1.63
w_a^* = 0.012423 lbm/sec	7	.06331	2.45	.4545	257.[illegible]	.668	.210	1925	12.56	.135	963	531.17	3.039	1.024	.1695	.229	8.23	672.77	445	3.15	17.4	132	2.90
c_v = 0.961	8	.06553	2.43	.4590	259.5[illegible]	.674	.212	1917	12.82	.114	959.	531.46	3.130	1.01[illegible]	.1831	.242	9.91	672.68	375	2.65	14.5	131	2.39
w = 0.011938 lbm/sec	9	.06925	2.39	.4663	263.70	.684	.216	1904	13.24	.111	952.	529.[illegible]	3.296	0.9665	.2070	.263	11.7	672.59	366	2.60	14.0	202	2.27
T_{av} = 531.56 °F abs	10	.07297	2.36	.4733	267.61	.693	.219	1892	13.66	.215	946.	529.75	3.450	.9634	.2304	.283	14.4	672.93	354	2.51	13.3	232	2.12
	11	.07684	2.33	.4804	271.60	.702	.222	1879	14.08	.205	939.	530.54	3.604	.9394	.2544	.303	18.0	672.57	336	2.39	12.5	[illegible]	1.98
	12	[illegible]	2.3[illegible]	[illegible]	[illegible]	[illegible]	.225	1868	14.43	.222	934.	531.73	3.733	.9148	.2751	.319	21.6	672.64	365	2.59	13.4	351	2.08
	13	.08135	2.29	.48[illegible]	276.12	.712	.225	1864	14.55	.196	932.	53[illegible]	3.739	.9137	[illegible]	[illegible]	25.[illegible]	672.09	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	14	.08412	2.27	.4930	27[illegible]	.710	.227	1856	14.03	.200	93[illegible]	535.54	3.[illegible]	[illegible]	[illegible]	.336	[illegible]	671.84	32[illegible]	2.34	11.9	399	1.63
	15	.08467	2.26	.4939	279.30	.720	.22[illegible]	1854	14.09	.196	927.	536.23	3.[illegible]	.9957	.29[illegible]	.33[illegible]	32.3	672.73	322	2.28	11.6	434	1.77
	16	.08309	2.27	.49[illegible]	27[illegible]	[illegible]	.227	1857	14.81	.205	920.	542.10	3.[illegible]	.9[illegible]	.2904	.333	35.7	672.03	337	2.40	12.3	505	[illegible]
	17	.08009	2.29	.4875	275.67	.711	.225	1866	14.56	.246	933.	549.0[illegible]	3.640	.9266	.2673	.31[illegible]	[illegible]	672.56	405	2.87	14.8	672	2.29
	18	.07881	2.31	.4839	273.63	.707	.223	1873	14.28	.642	936.	56[illegible]	3.4[illegible]	.9458	.2450	.306	40.[illegible]	672.91	2817				
Run No. B-15	1																						
December 23, 1952	2	0.04514	2.67	0.4127	233.70	0.612	0.192	1989	12.88		1000						1.42						
t_r = 71.5 °F	3	.04540	2.66	.4133	234.15	.613	.192	1980	12.93	1.242	999.	516.31	2.931	1.429	0.07859	0.103	2.09	671.43	5446				
p_r = 14.712 psia	4	.05003	2.60	.4250	240.72	.629	.197	1978	13.72	0.278	989.	533.02	3.070	1.399	.1036	.135	4.09	672.00	913	6.54	38.5	173	5.52
p_{01} = 12.362 psia	5	.05264	2.57	.4311	244.20	.638	.200	1968	14.14	.203	984.	538.93	3.205	1.380	.1274	.157	6.01	672.05	660	4.79	27.8	180	3.94
t_{01} = 106.77 °F	6	.05517	2.54	.4370	247.55	.645	.203	1957	14.56	.179	979.	538.16	3.348	1.361	.1469	.175	7.99	672.15	589	4.22	24.2	205	3.36
w_a^* = 0.015639 lbm/sec	7	.05818	2.50	.4437	251.32	.654	.206	1946	15.03	.104	973.	536.20	3.523	1.337	.1704	.195	10.0	672.31	539	3.85	21.3	228	1.97
c_v = 0.964	8	.06069	2.48	.4491	255.37	.652	.209	1936	15.42	.141	968.	535.21	3.663	1.318	.1900	.211	12.1	672.21	462	3.31	18.5	230	2.48
w = 0.015076 lbm/sec	9	.06288	2.45	.4536	256.97	.668	.210	1928	15.75	.134	964.	534.05	3.783	1.301	.2071	.225	14.2	672.11	442	3.16	17.5	253	2.33
T_{av} = 532.47 °F abs	10	.06545	2.43	.4589	259.93	.675	.213	1919	16.13	.243	959.	535.32	3.916	1.281	.2268	.240	17.4	672.39	407	2.91	15.9	277	2.09
	11	.07021	2.38	.4682	265.20	.687	.217	1902	16.81	.237	951	533.75	4.176	1.243	.2647	.266	21.9	672.12	389	2.79	14.9	320	1.92
	12	.07328	2.36	.4739	268.46	.695	.219	1892	17.24	.248	946.	[illegible]	4.32[illegible]	1.219	.2932	.282	26.4	672.19	400	2.92	15.5	393	1.96
	13	.07510	2.34	.4772	270.34	.699	.221	1886	17.49	.227	943.	536.55	4.405	1.207	.3010	.291	30.7	671.69	373	2.68	14.1	415	1.78
	14	.07585	2.33	.4786	271.12	.701	.221	1884	17.59	.224	942.	539.26	4.421	1.203	.3048	.294	35.0	672.35	309	2.64	13.6	461	1.73
	15	.07698	2.32	[illegible]	272.26	.703	.222	1880	17.74	.217	940.	541.45	4.460	1.196	.3119	.299	39.4	672.28	356	2.55	13.3	49[illegible]	[illegible]
	16	.07625	2.34	.4768	270.00	.698	.221	1883	17.45	.258	943.	547.86	4.502	1.211	.2909	.288	43.2	672.26	425	3.04	16.0	661	2.02
	17	.07084	2.38	.4694	265.07	.689	.217	1900	16.90	0.560	950.	567.2[illegible]	3.950	1.256	.2518	.264	46.5	672.0[illegible]	921	6.60	35.3	1602	4.52
	18	.06802	2.40	.4641	262.87	.682	.215	1910	16.51	1.012	955.	[illegible]	3.697	1.288	.2191	.246	48.7	[illegible]	4438				
Run No. B-16	1																						
December 24, 1952	2																						
t_r = 76.0 °F	3	0.04506	2.67	0.4124	234.55	0.614	0.192	2004	16.91	1.353	1002	513.77	3.861	1.891	0.0957	0.0977	2.72	211.39	5934				
p_r = 14.660 psia	4	.04729	2.64	.4182	[illegible]	.622	.195	1994	17.42	0.331	997	541.81	3.883	1.876	.1134	.114	5.25	211.96	1087	7.93	47.3	212	5.27
p_{01} = 16.277 psia	5	.04952	2.61	.4237	240.96	.630	.197	1984	17.92	.245	992	542.71	3.978	1.855	.1345	.132	7.71	212.04	865	5.87	34.5	224	3.79
t_{01} = 109.00 °F	6	.05175	2.58	.4291	244.02	.637	.200	1975	18.41	.217	987.	541.80	4.145	1.833	.1565	.148	10.2	212.27	715	5.20	30.2	256	3.27
w_a^* = 0.020552 lbm/sec	7	.05309	2.55	.4341	246.86	.644	.202	1966	18.86	.196	983	540.36	4.304	1.812	.1777	.164	1[illegible].8	212.32	644	4.68	26.9	2[illegible]2	2.88
c_v = 0.968	8	.05589	2.53	.43[illegible]	249.[illegible]	.650	.204	1958	19.28	.170	979	540.07	4.453	1.792	.197[illegible]	.177	15.4	212.22	590	4.00	23.1	[illegible]	2.[illegible]
w = 0.019894 lbm/sec	9	.05779	2.51	.4426	251.82	.656	.206	1951	19.67	.162	976.	539.26	4.593	1.772	.2170	.190	18.1	212.12	531	3.87	21.8	315	2.28
T_{av} = 534.57 °F abs	10	.06045	2.48	.4485	255.08	.663	.209	1941	20.21	.2[illegible]	9[illegible]	538.21	4.7[illegible]	1.765	.2440	.207	22.2	212.34	475	3.46	19.2	336	1.9[illegible]
	11	.06167	2.45	.4553	255.90	.672	.212	1929	20.05	.269	965	537.84	5.018	1.712	[illegible]	.227	27.8	212.12	442	3.22	17.7	378	1.79
	12	.06643	2.42	.4600	262.0[illegible]	.680	.214	1919	21.38	.2[illegible]	960.	538.16	5.205	1.685	.3047	.2[illegible]	33.4	212.21	400	3.35	15.2	462	1.82
	13	.06695	2.40	.4640	263.06	.684	.215	1914	21.68	.254	957.	539.91	5.290	1.676	.3197	.251	39.0	211.92	420	3.05	16.4	483	1.63
	14	.06724	2.41	.4624	262.97	.682	.215	1916	21.53	.258	958.	545.02	5.294	1.682	.3076	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	458	1.66
	15	.06809	2.40	.4641	261.92	.684	.216	1913	21.69	.258	957.	547.80	5.225	1.675	.3140	.250	49.6	212.27	490	3.57	19.2	718	1.90
	16	.06439	2.44	.4565	259.73	.674	.212	1927	20.99	0.745	963.	584.95	4.925	1.723	.2665	.227	53.[illegible]	212.18	1225	8.92	48.8	2018	4.92
	17	.06130	2.47	.4503	256.11	.666	.209	1938	20.38	1.777	969.	604.64	4.316	1.7[illegible]	.2175	.204	58.0	211.54	2921	21.4	119	5373	12.19
	18	.05918	2.4[illegible]	.4458	253.54	.660	.207	1946	19.96	1.599	973	670.81	3.771	1.814	.1751	.186	60.8	211.10	6610				



SIMPLIFIED TWO-DIMENSIONAL FLOW MODEL

FIG. 1

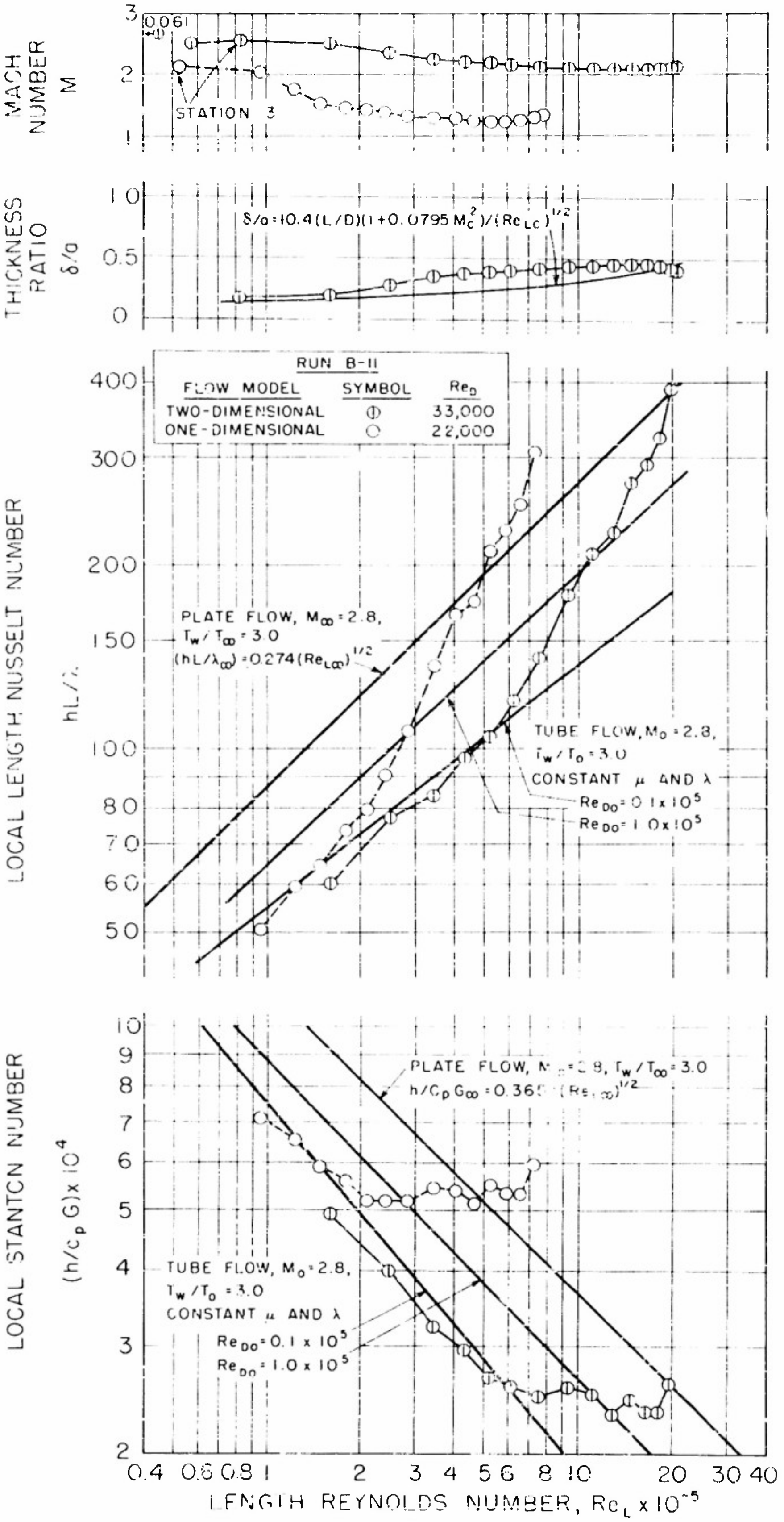
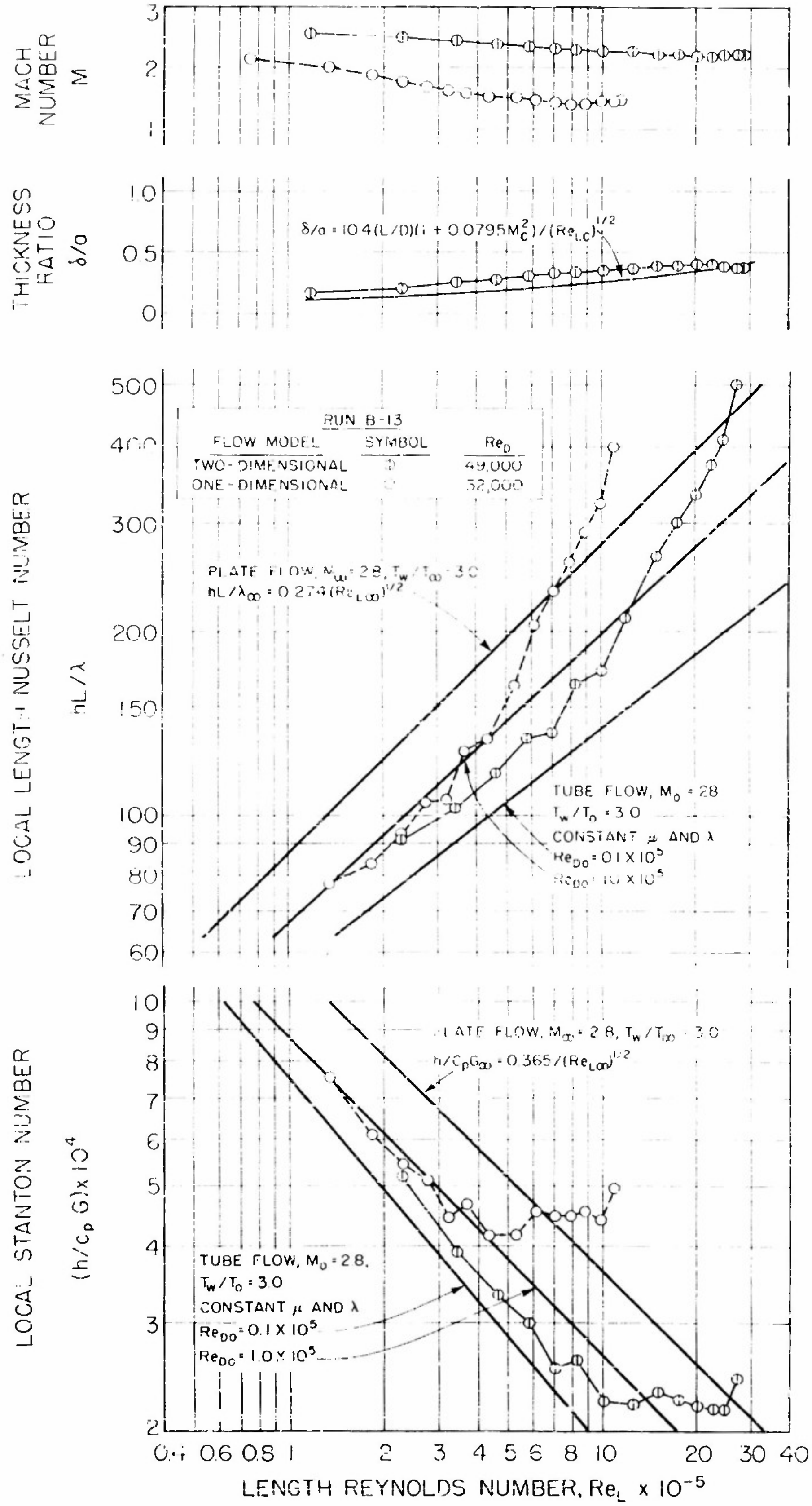

MACH NUMBER M
3
2
1
0.061
STATION 3
THICKNESS RATIO δ/a
1.0
0.5
0
δ/a = 10.4 (L/D)(1 + 0.0795 M_c^2)/(Re_Lc)^1/2
RUN B-11
FLOW MODEL
SYMBOL
Re_D
TWO-DIMENSIONAL
33,000
ONE-DIMENSIONAL
22,000
LOCAL LENGTH NUSSELT NUMBER hL/λ
400
300
200
150
100
80
70
60
50
PLATE FLOW, M∞ = 2.8, T_w/T∞ = 3.0
(hL/λ∞) = 0.274 (Re_L∞)^1/2
TUBE FLOW, M_o = 2.8, T_w/T_o = 3.0
CONSTANT μ AND λ
Re_Do = 0.1 x 10^5
Re_Do = 1.0 x 10^5
LOCAL STANTON NUMBER (h/c_p G) x 10^4
10
9
8
7
6
5
4
3
2
PLATE FLOW, M∞ = 2.8, T_w/T∞ = 3.0
h/C_p G∞ = 0.365 (Re_L∞)^1/2
TUBE FLOW, M_o = 2.8, T_w/T_o = 3.0
CONSTANT μ AND λ
Re_Do = 0.1 x 10^5
Re_Do = 1.0 x 10^5
0.4
0.6
0.8
1
2
3
4
5
6
8
10
20
30
40
LENGTH REYNOLDS NUMBER, Re_L x 10^-5

FIGURE 2



MACH NUMBER M
3
2
1
THICKNESS RATIO δ/a
1.0
0.5
0
δ/a = 10.4(L/D)(1 + 0.0795M$_c^2$)/(Re$_{L,c}$)$^{1/2}$
LOCAL LENGTH NUSSELT NUMBER hL/λ
500
400
300
200
150
100
90
80
70
60
RUN B-13
FLOW MODEL
SYMBOL
Re$_D$
TWO-DIMENSIONAL
49,000
ONE-DIMENSIONAL
52,000
PLATE FLOW, M$_\infty$ = 2.8, T$_w$/T$_\infty$ = 3.0
hL/λ$_\infty$ = 0.274(Re$_{L\infty}$)$^{1/2}$
TUBE FLOW, M$_0$ = 2.8
T$_w$/T$_0$ = 3.0
CONSTANT μ AND λ
Re$_{D0}$ = 0.1 X 10^5
Re$_{D0}$ = 1.0 X 10^5
LOCAL STANTON NUMBER (h/c$_p$ G) x 10^4
10
9
8
7
6
5
4
3
2
PLATE FLOW, M$_\infty$ = 2.8, T$_w$/T$_\infty$ = 3.0
h/C$_p$G$_\infty$ = 0.365/(Re$_{L\infty}$)$^{1/2}$
TUBE FLOW, M$_0$ = 2.8,
T$_w$/T$_0$ = 3.0
CONSTANT μ AND λ
Re$_{D0}$ = 0.1 X 10^5
Re$_{D0}$ = 1.0 X 10^5
0.4
0.6
0.8
1
2
3
4
5
6
8
10
20
30
40
LENGTH REYNOLDS NUMBER, Re$_L$ x 10^{-5}

FIGURE 3

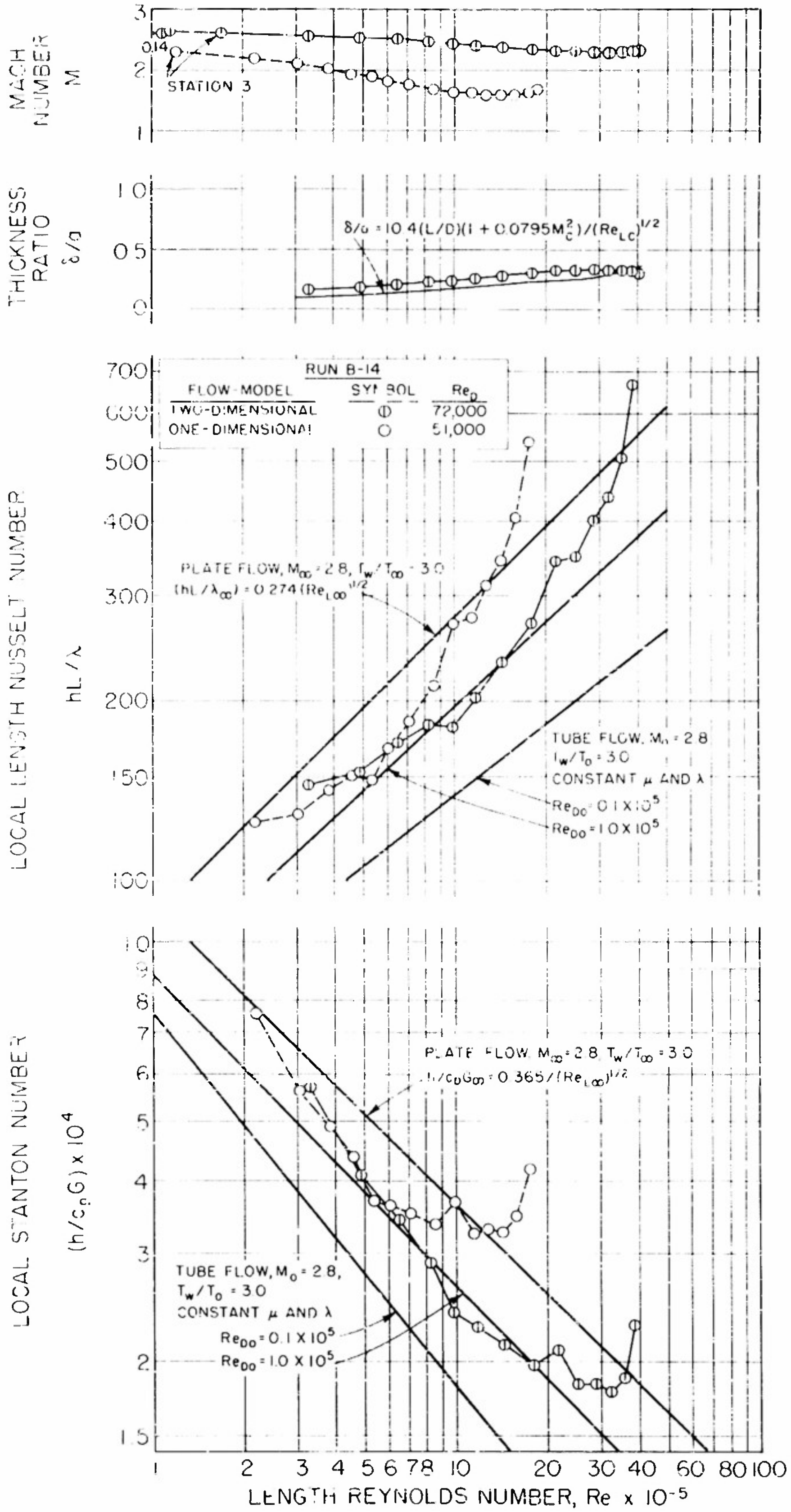

MACH NUMBER M
3
2
1
0.14
STATION 3
THICKNESS RATIO δ/a
1.0
0.5
0
$\delta/a = 10.4(L/D)(1 + 0.0795M_c^2)/(Re_{Lc})^{1/2}$
RUN B-14
FLOW-MODEL
SYMBOL
Re_D
TWO-DIMENSIONAL
Ⓘ
72,000
ONE-DIMENSIONAL
○
51,000
LOCAL LENGTH NUSSELT NUMBER
hL/λ
700
600
500
400
300
200
150
100
PLATE FLOW, $M_\infty = 2.8$, $T_w/T_\infty = 3.0$
$(hL/\lambda_\infty) = 0.274(Re_{L\infty})^{1/2}$
TUBE FLOW, $M_0 = 2.8$
$T_w/T_0 = 3.0$
CONSTANT μ AND λ
$Re_{D0} = 0.1 \times 10^5$
$Re_{D0} = 1.0 \times 10^5$
LOCAL STANTON NUMBER
$(h/c_pG) \times 10^4$
10
9
8
7
6
5
4
3
2
1.5
PLATE FLOW $M_\infty = 2.8$ $T_w/T_\infty = 3.0$
$h/c_pG_\infty = 0.365/(Re_{L\infty})^{1/2}$
TUBE FLOW, $M_0 = 2.8$,
$T_w/T_0 = 3.0$
CONSTANT μ AND λ
$Re_{D0} = 0.1 \times 10^5$
$Re_{D0} = 1.0 \times 10^5$
1
2
3
4
5
6
7
8
10
20
30
40
60
80
100
LENGTH REYNOLDS NUMBER, $Re \times 10^{-5}$

FIGURE 4

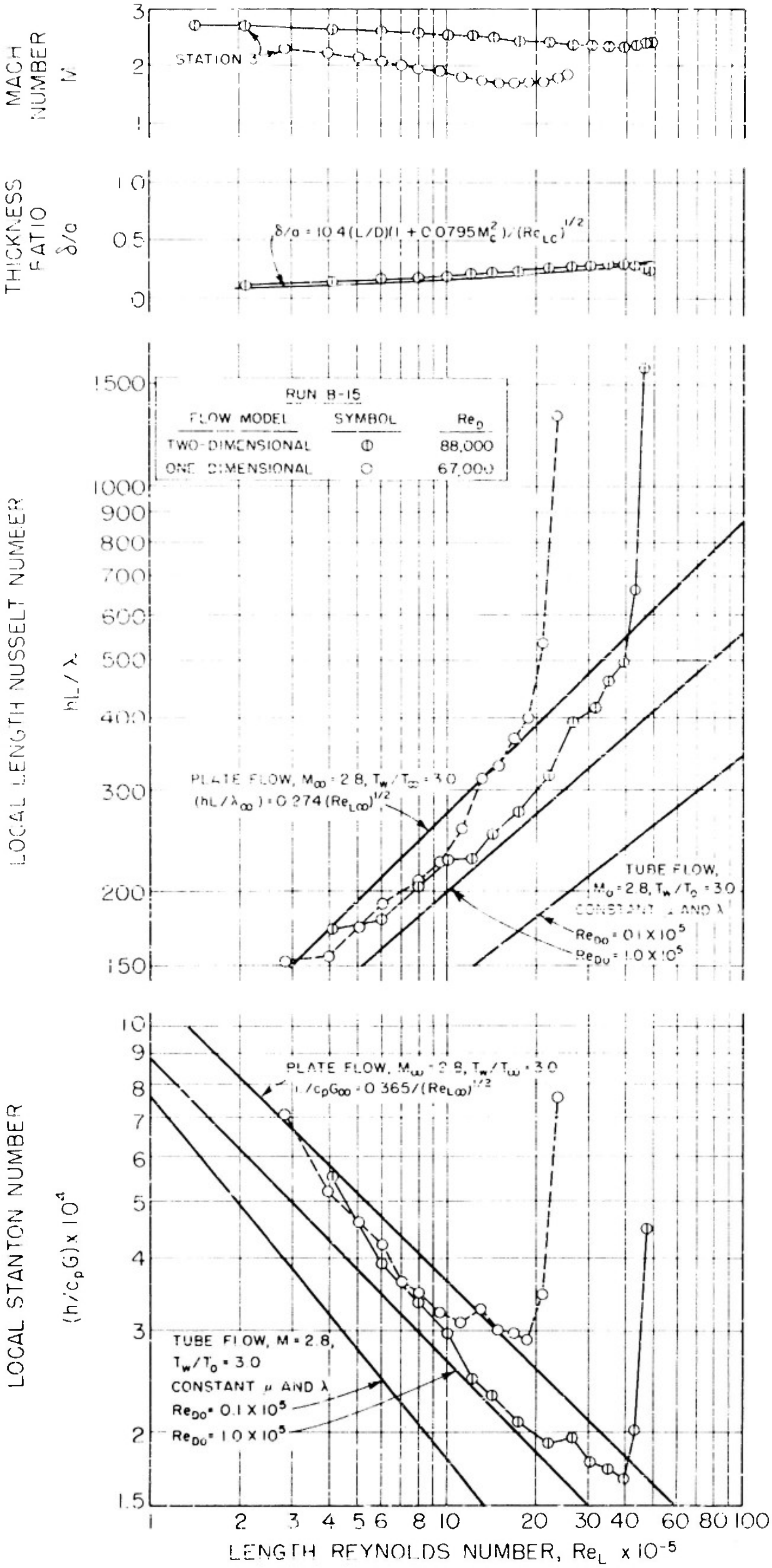

MACH NUMBER M
3
2
1
STATION 3
THICKNESS RATIO δ/a
1.0
0.5
0
δ/a = 10.4(L/D)(1 + 0.0795M_c^2)/(Re_Lc)^1/2
LOCAL LENGTH NUSSELT NUMBER hL/λ
1500
1000
900
800
700
600
500
400
300
200
150
RUN B-15
FLOW MODEL
SYMBOL
Re_D
TWO-DIMENSIONAL
88,000
ONE DIMENSIONAL
67,000
PLATE FLOW, M∞ = 2.8, Tw/T∞ = 3.0
(hL/λ∞) = 0.274 (Re_L∞)^1/2
TUBE FLOW, M0 = 2.8, Tw/T0 = 3.0
CONSTANT μ AND λ
Re_D0 = 0.1 X 10^5
Re_D0 = 1.0 X 10^5
LOCAL STANTON NUMBER (h/cpG) x 10^4
10
9
8
7
6
5
4
3
2
1.5
PLATE FLOW, M∞ = 2.8, Tw/T∞ = 3.0
h/cpG∞ = 0.365/(Re_L∞)^1/2
TUBE FLOW, M = 2.8,
Tw/T0 = 3.0
CONSTANT μ AND λ
Re_D0 = 0.1 X 10^5
Re_D0 = 1.0 X 10^5
1
2
3
4
5
6
8
10
20
30
40
60
80
100
LENGTH REYNOLDS NUMBER, Re_L x 10^-5

FIGURE 5

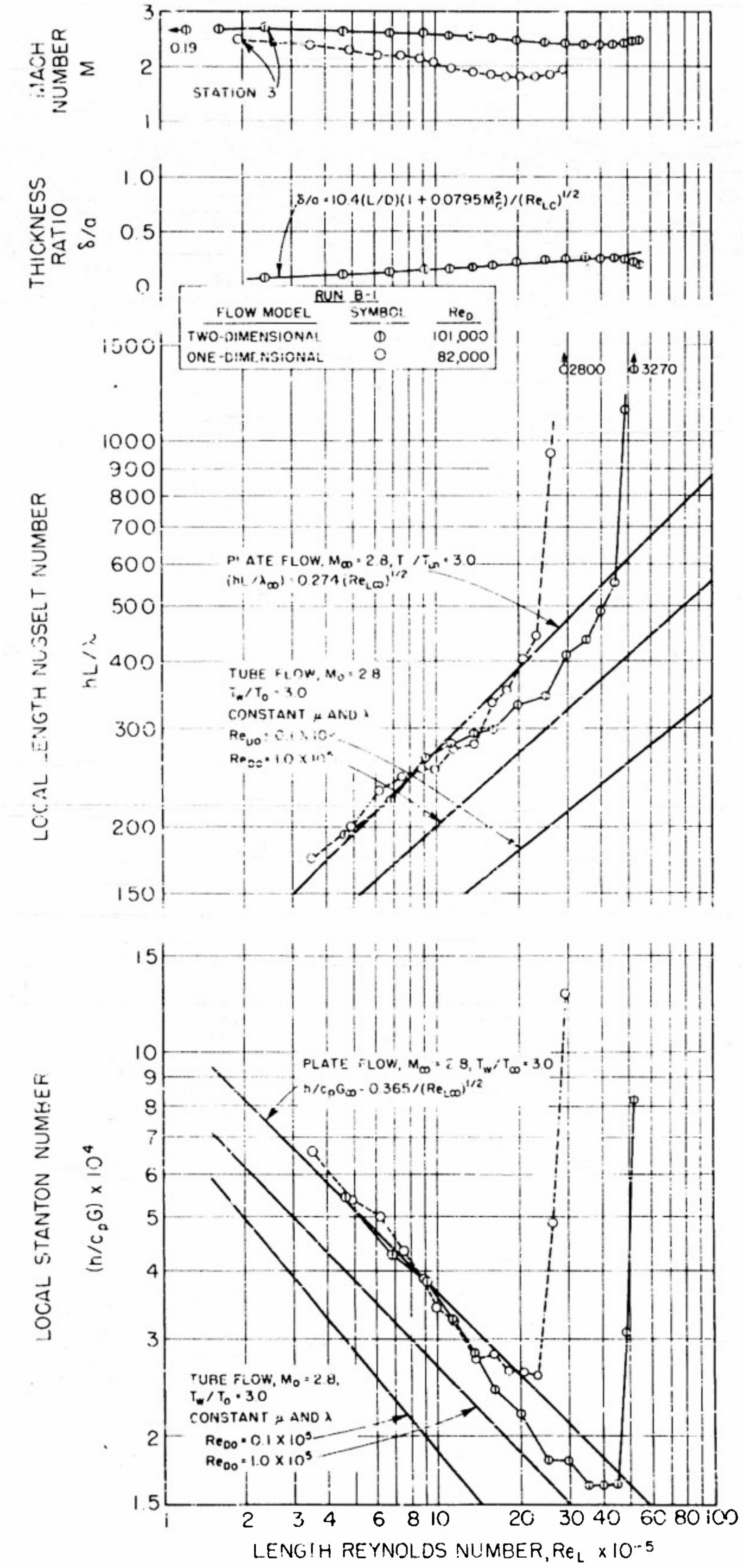

MACH NUMBER M
3
2
1
0.19
STATION 3
THICKNESS RATIO δ/a
1.0
0.5
0
δ/a = 10.4(L/D)(1 + 0.0795M$_c^2$)/(Re$_{LC}$)$^{1/2}$
RUN B-1
FLOW MODEL
SYMBOL
Re$_D$
TWO-DIMENSIONAL
ⵁ
101,000
ONE-DIMENSIONAL
○
82,000
2800
3270
LOCAL LENGTH NUSSELT NUMBER hL/λ
1500
1000
900
800
700
600
500
400
300
200
150
PLATE FLOW, M$_\infty$ = 2.8, T$_w$/T$_\infty$ = 3.0
(hL/λ$_\infty$) = 0.274(Re$_{L\infty}$)$^{1/2}$
TUBE FLOW, M$_0$ = 2.8
T$_w$/T$_0$ = 3.0
CONSTANT μ AND λ
Re$_{D0}$ = 0.1 X 10^5
Re$_{D0}$ = 1.0 X 10^5
LOCAL STANTON NUMBER (h/c$_p$G) x 10^4
15
10
9
8
7
6
5
4
3
2
1.5
PLATE FLOW, M$_\infty$ = 2.8, T$_w$/T$_\infty$ = 3.0
h/c$_p$G$_\infty$ = 0.365/(Re$_{L\infty}$)$^{1/2}$
TUBE FLOW, M$_0$ = 2.8,
T$_w$/T$_0$ = 3.0
CONSTANT μ AND λ
Re$_{D0}$ = 0.1 X 10^5
Re$_{D0}$ = 1.0 X 10^5
1
2
3
4
6
8
10
20
30
40
60
80
100
LENGTH REYNOLDS NUMBER, Re$_L$ x 10^{-5}

FIGURE 6

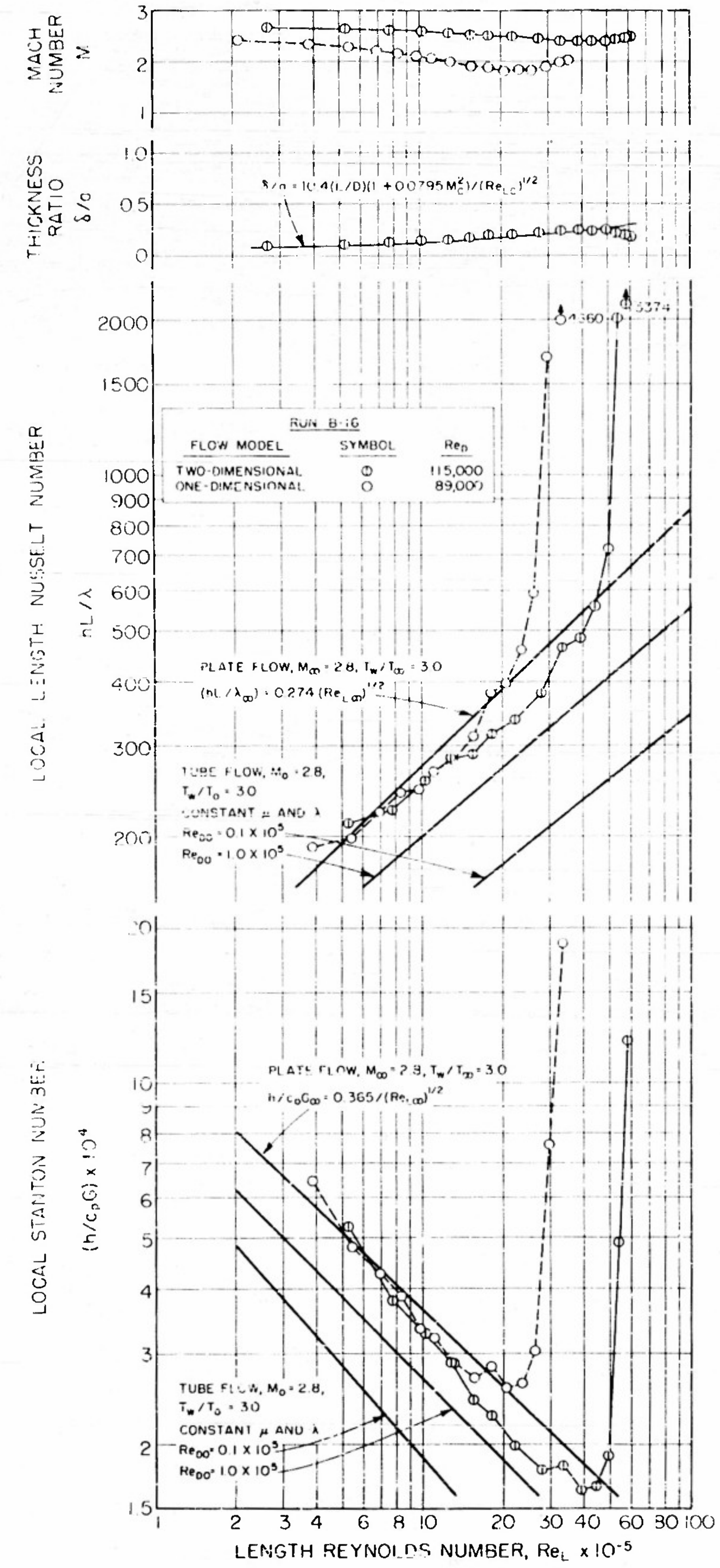

MACH NUMBER
M
3
2
1
THICKNESS RATIO
δ/a
1.0
0.5
0
δ/a = 10.4(L/D)(1 + 0.0795 M$_c^2$)/(Re$_{Lc}$)$^{1/2}$
LOCAL LENGTH NUSSELT NUMBER
hL/λ
2000
1500
1000
900
800
700
600
500
400
300
200
4360
5374
RUN B-16
FLOW MODEL
SYMBOL
Re$_D$
TWO-DIMENSIONAL
Φ
115,000
ONE-DIMENSIONAL
○
89,000
PLATE FLOW, M$_\infty$ = 2.8, T$_w$/T$_\infty$ = 3.0
(hL/λ$_\infty$) = 0.274 (Re$_{L\infty}$)$^{1/2}$
TUBE FLOW, M$_0$ = 2.8,
T$_w$/T$_0$ = 3.0
CONSTANT μ AND λ
Re$_{D0}$ = 0.1 X 10^5
Re$_{D0}$ = 1.0 X 10^5
LOCAL STANTON NUMBER
(h/c$_p$G) x 10^4
20
15
10
9
8
7
6
5
4
3
2
1.5
PLATE FLOW, M$_\infty$ = 2.8, T$_w$/T$_\infty$ = 3.0
h/c$_p$G$_\infty$ = 0.365/(Re$_{L\infty}$)$^{1/2}$
TUBE FLOW, M$_0$ = 2.8,
T$_w$/T$_0$ = 3.0
CONSTANT μ AND λ
Re$_{D0}$ = 0.1 X 10^5
Re$_{D0}$ = 1.0 X 10^5
1
2
3
4
6
8
10
20
30
40
60
80
100
LENGTH REYNOLDS NUMBER, Re$_L$ x 10^{-5}

FIGURE 7

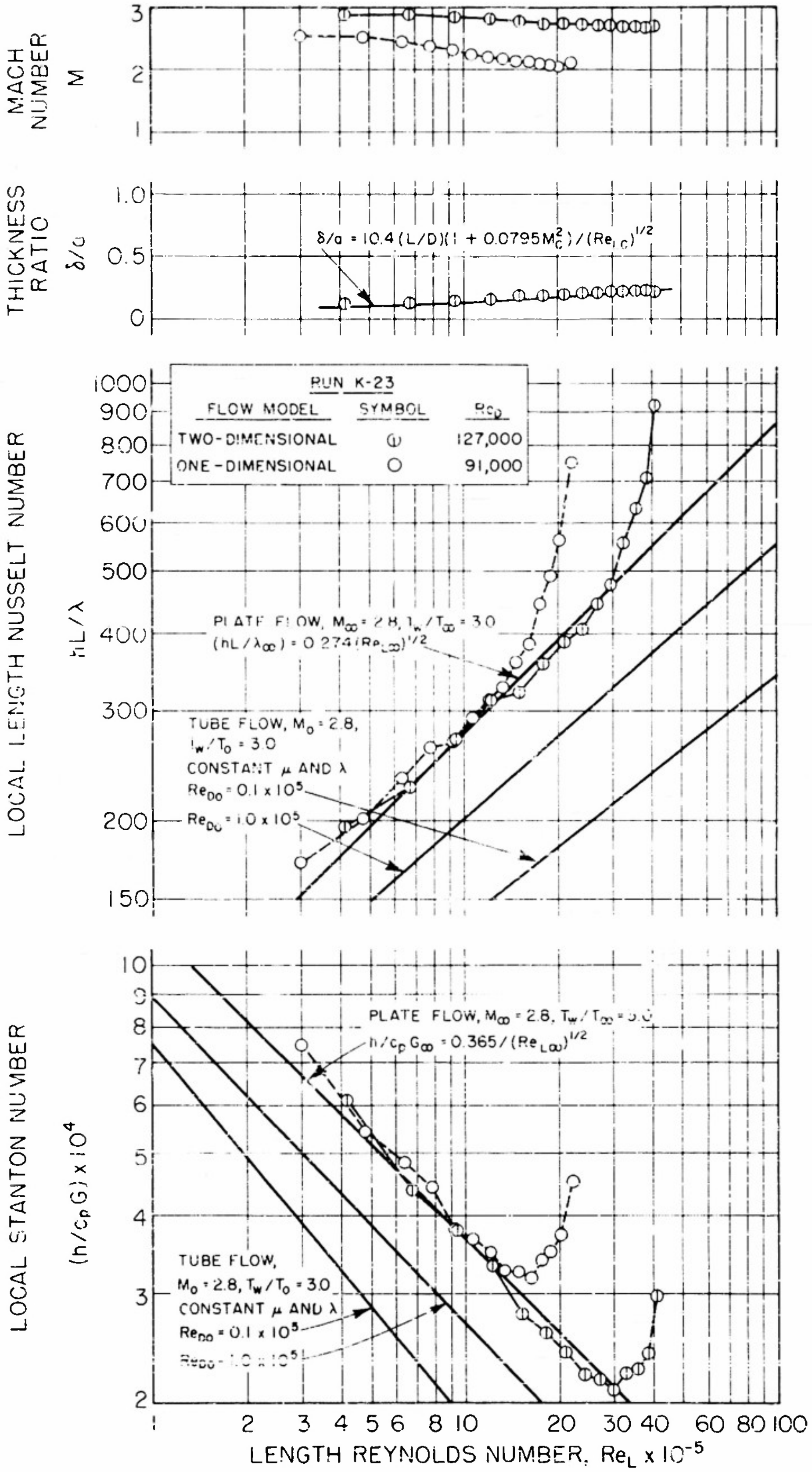

MACH NUMBER M
3
2
1
THICKNESS RATIO δ/a
1.0
0.5
0
δ/a = 10.4 (L/D)(1 + 0.0795M_c^2)/(Re_L,c)^1/2
LOCAL LENGTH NUSSELT NUMBER hL/λ
1000
900
800
700
600
500
400
300
200
150
RUN K-23
FLOW MODEL
SYMBOL
Re_D
TWO-DIMENSIONAL
⌀
127,000
ONE-DIMENSIONAL
○
91,000
PLATE FLOW, M∞ = 2.8, T_w/T∞ = 3.0
(hL/λ∞) = 0.274 (Re_L∞)^1/2
TUBE FLOW, M_0 = 2.8,
T_w/T_0 = 3.0
CONSTANT μ AND λ
Re_D0 = 0.1 x 10^5
Re_D0 = 1.0 x 10^5
LOCAL STANTON NUMBER (h/c_p G) x 10^4
10
9
8
7
6
5
4
3
2
PLATE FLOW, M∞ = 2.8, T_w/T∞ = 3.0
h/c_p G∞ = 0.365/(Re_L∞)^1/2
TUBE FLOW,
M_0 = 2.8, T_w/T_0 = 3.0
CONSTANT μ AND λ
Re_D0 = 0.1 x 10^5
Re_D0 = 1.0 x 10^5
1
2
3
4
5
6
8
10
20
30
40
60
80
100
LENGTH REYNOLDS NUMBER, Re_L x 10^-5

FIGURE 6

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