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THE TURBULENT BOUNDARY LAYER ON A POROUS PLATE: EXPERIMENTAL HEAT TRANSFER WITH UNIFORM BLOWING AND SUCTION

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Abstract—There exists a need for additional experimental work in the field of heat transfer through a turbulent boundary layer with blowing and suction. An apparatus has been constructed which allows the determination of Stanton number to within 0·0001 units over most of the range between the asymptotic suction layer and the apparent "blow off" of the boundary layer.

Data are presented for the case of uniform blowing and suction, constant free stream velocity, and essentially constant properties. Stanton numbers ranged from 0·0080 (asymptotic suction layer behavior; blowing fraction of −0·00765) to a value of 0·0001 (near "blow off"; blowing fraction of +0·00955). The Reynolds number range is $1{\cdot}3 \times 10^5$–$2{\cdot}3 \times 10^6$. Tabular and graphical results are presented.

NOMENCLATURE

B,	blowing parameter, $B = \dot{m}''/GSt$;
c,	specific heat of the fluid;
c_f,	friction factor;
G,	free stream mass velocity, $G = \rho U_\infty$;
i,	enthalpy;
$\dot{m}''$,	mass flux through the plate surface (positive into the main stream);
P,	pressure;
Pr,	Prandtl number;
$\dot{q}''$,	heat flux at the surface of the plate;
Re_x,	Reynolds number based on free stream conditions and distance from the virtual origin;
St,	Stanton number;
St_0,	Stanton number which would have been observed at the same x-Reynolds number had there been no blowing or suction, all other factors remaining the same;
T,	temperature;
U_∞,	free stream velocity;
u^+,	dimensionless velocity, $u^+ = u/[U_\infty\sqrt{(c_f/2)}]$;
y^+,	dimensionless distance from the wall, $y^+ = (y/\nu)U_\infty\sqrt{(c_f/2)}$;
x,	distance from the virtual origin.

Greek symbols

ν,	kinematic viscosity;
θ,	enthalpy thickness of boundary layer;

Subscripts

w,	refers to value on fluid side of interface: solid–fluid;
T,	refers to condition of transpiration flow in the chamber beneath the porous plate. Note: This is not synonymous with the T-state used by Spalding and others;
p,	refers to the plate.

INTRODUCTION

IT MAY appear, at first glance, to be somewhat late to be experimenting on such a basic problem as heat transfer through a turbulent boundary layer with uniform blowing (or suction), uniform surface temperature, and uniform free-stream velocity. Most present analytical and experimental research deals with massive blowing, surface catalycity, blowing with reacting boundary layers and other topics similarly advanced. It might be assumed that the basic problems have been thoroughly studied, and that a satisfactory collection of experimental data is available.

This does not appear to be the case. Review of the literature shows only three investigations which report local values of Stanton number with uniform blowing or suction: Mickley *et al.* [1], Pappas and Okuno [2], and Torii *et al.* [3]. A fourth investigation, Romanenko and Karchenko [4], reported values of St/St_0 as a function of blowing but not the values of Stanton number themselves. (The St_0 symbol refers to the value of Stanton number which would have been measured at the same x-Reynolds number had there been no blowing, all other conditions remaining fixed.) The domains of these investigations are shown in Fig. 1 in terms of the ranges of x-Reynolds numbers and blowing fractions covered by the individual studies. The reported data from these studies are collected in Fig. 2 for comparison.

Examination of the data in Fig. 2 shows that while the present collection serves to establish the major trends, it is not sufficiently coherent to use as a proving ground for theories differing from one another in detail. The data, considered either separately or together, display an unsatisfactory amount of scatter, and no definitive statement can be made regarding the variation of Stanton number with blowing. There are further problems: most of the data shown in Fig. 2 are from the pioneer study of Mickley *et al.* (1954). This has long been regarded as the basic experimental study in this field, and is the only one of the three studies which covered blowing and sucking over any appreciable range of conditions. The validity of these data was questioned, in 1957, by Mickley himself, in a second report (Mickley and Davis [5]). Mickley's second study did not report any heat-transfer data, focusing entirely on the hydrodynamic problem.

It is historically evident that theoretical progress in the study of turbulent boundary layers has always followed—never led—the experimental effort. Thus, if the theoretical treatment of the turbulent boundary layer with

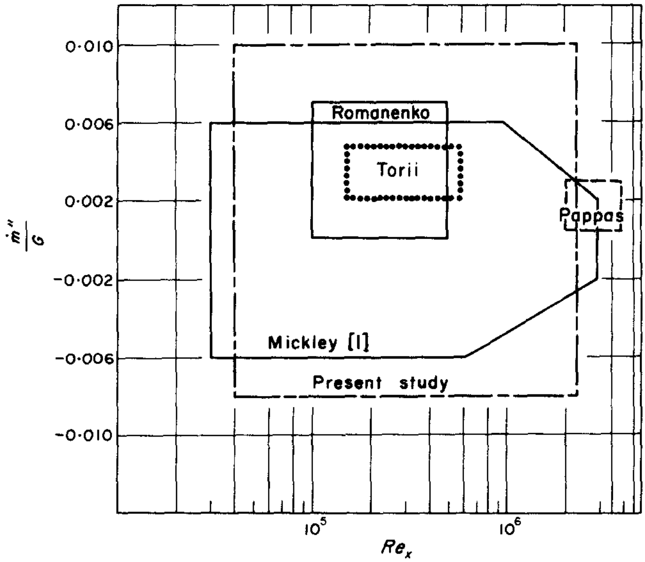

FIG. 1. Summary of experimental domains: five investigations.

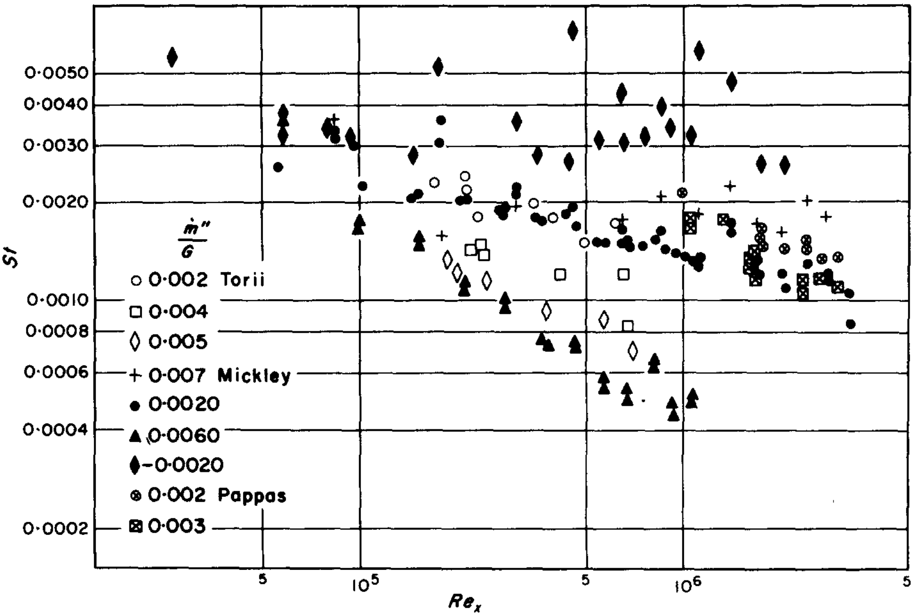

FIG. 2. Summary of reported Stanton number data with uniform blowing: three investigations.

blowing is to be improved, there must exist a satisfactory collection of accurate data. The work reported here is the result of the first phase of a research program aimed at satisfying this need.

OBJECTIVES OF THE PRESENT WORK

In broad terms, the objectives of the work reported here were two-fold:

(1) To develop an apparatus capable of accurate evaluation of the heat-transfer behavior of a turbulent boundary layer under a variety of boundary conditions: free-stream velocity variations, mass diffusion, arbitrary variations of local blowing fraction, and arbitrary variations of surface temperature or surface heat flux.

(2) To investigate the most basic of the heat-transfer problems (uniform free-stream velocity, uniform blowing fraction, and uniform surface temperature) over a wide range of blowing and suction values.

THE EXPERIMENTAL APPARATUS

The Stanford Heat and Mass Transfer Apparatus is a two-story test facility, with the operating controls and heavy hardware on the ground floor, and the test section on the second floor of a 15-ft high tower. A photograph of the test section is shown in Fig. 3. The objective of the apparatus is to provide and control three main systems: main air stream over the test plate, transpiration air flow through the test plates, and electric heater power to the test plates. These functions are accomplished by the systems shown schematically in Fig. 4. The test section consists of two fixed side walls, an adjustable top cover, and the test plate assembly which forms the bottom surface. The test plate assembly is 96-in long in the flow direction, and is divided into twenty-four segments, each of which is as shown in Fig. 5. The working surface, the porous plate at the top, is supported on thin webs of insulating material which reduce heat transfer between the plate and the aluminium base casting below. A porous pre-

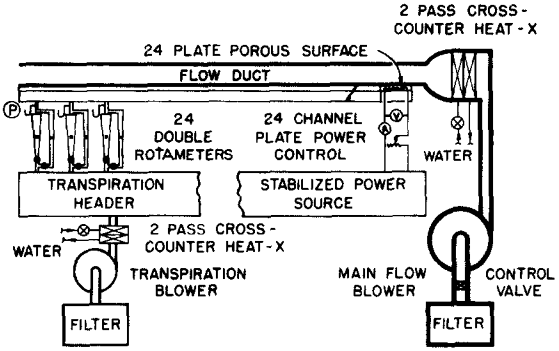

FIG. 4. Flow schematic.

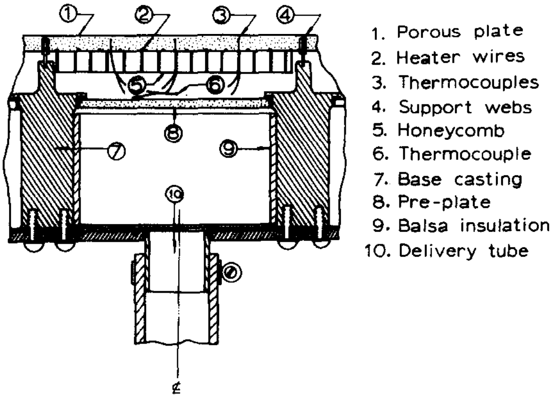

FIG. 5. Cross section view of a typical compartment.

plate, beneath the working plate, serves to even out the distribution of flow in the underbody region. The honeycomb layer attached to the bottom surface of the working plate protects the working plate from lateral gas currents in the underbody region. A lateral current flowing along the unprotected plate would pick up energy, locally cooling the plate, and carry this energy to some other location resulting in a local hot spot. The honeycomb layer has been shown to be effective in preventing this interaction.

The interior surfaces of the casting are insulated to minimize heat transfer between the casting and the transpiration flow. Heat transfer would introduce temperature stratifications with the result that no single measurement of the gas temperature would be representative of its energy content.

The electric heater wires are insulated with Teflon sleeving and cemented into grooves cast into the bottom face of the working plate. An Epoxy cement of high viscosity was selected for this task, to minimize "bleeding" of the cement into voids of the porous plate.

Five thermocouples are imbedded into each porous plate: one on the geometric center of the plate, one three inches to either side, and one each 1·3 in upstream and downstream. This pattern defines the measuring region of the plate, the center 6-in span, and provides means for measuring the temperature distribution in the center span of the plate.

Six of the twenty-four porous plates were glued into each of the four castings which make up the base structure. Alignment of the plates, with one another and with the side rails of the casting, was ensured by clamping the plates and the casting to a precision surface plate during the glueing operation.

The base castings are provided with water passages on their edges, so that the temperature of the casting can be controlled by controlling the temperature of the circulating water.

THE POROUS PLATES

The porous plates used in this apparatus are made of sintered bronze material, using a processing technique developed during the course of this work. They have the characteristics specified in Table 1.

Local permeability was measured using a test fixture which forced a metered amount of air through a circular area of the plate, 0·75 in. in diameter. The resulting pressure drop was used as a measure of the local permeability. Each plate was checked on 1-in centers over its entire area, and no plate was accepted for use in the apparatus if the permeability showed more than 6 per cent variation over the center 6-in span.

The maximum allowable particle size was determined based on the equivalent sand grain roughness correlations of Schlichting [6] and

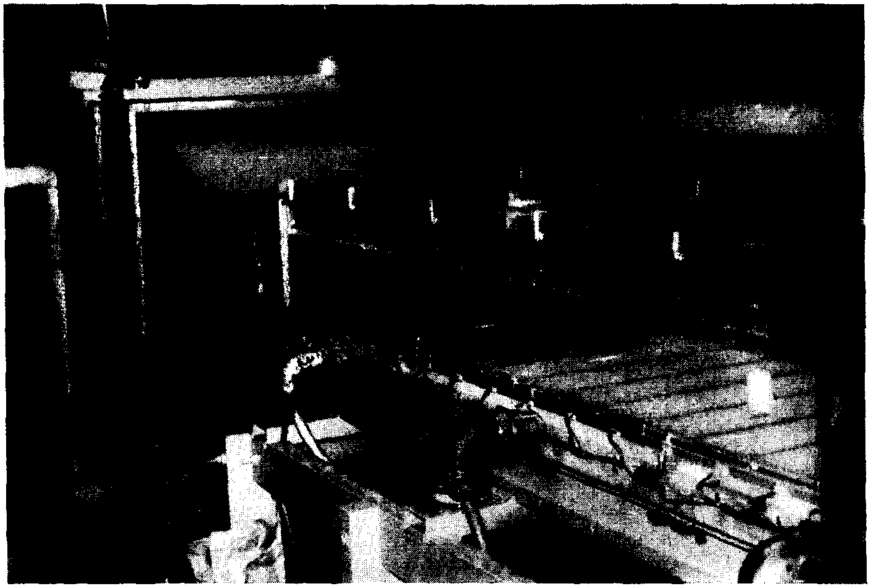

FIG. 3. Photograph of test deck area.

Table 1

1. Overall dimensions	18·0 × 3·975 × 0·25 in
2. Permeability	uniform within ±6 per cent in the center 6-in span
3. Surface roughness	maximum of 200 μ in (RMS) measured with 0·0005 in stylus
4. Thermal conductivity	6·5 Btu/h ft^2°F/ft minimum
5. Surface emissivity	0·37, average
6. Particle shape	spherical (estimated 99 per cent of particles)
7. Particle size	maximum diameter 0·007 in minimum diameter 0·0023 in

the recommendations of Kays [7] regarding the effect of roughness on Stanton number. The criterion chosen was that the roughness effect on Stanton number should be no greater than 5 per cent for velocities up to 100 ft/s for all locations more than one foot down the plate. The present tests were all conducted with the free-stream velocity of about 44 ft/s, well inside the roughness criterion. Future work is planned for higher velocities, however, and freedom from roughness effects will then become important.

The thermal conductivity and the surface emissivity of the plate material were determined by tests conducted in the Stanford Thermosciences Laboratory: these data were necessary to the selection of the plate thickness and heater wire spacing, and to the calculation of the radiation heat loss from the top and bottom surfaces of the plates.

Plate thickness was selected to give 12 in of water pressure drop at maximum transpiration flow (approximately 0·45 ft/s) using the maximum allowable particle size from the roughness criterion. The allowable heater wire spacing was selected analytically so that the top surface of the plate would be uniform in temperature within 0·04 degF.

QUALIFICATION TESTS

The apparatus was subjected to four types of qualification tests: three prior to the data program, and one test applied to the actual data. The three preliminary tests were: energy balances with blowing but no heat transfer, hydrodynamic checks in the boundary layer, and base-line heat-transfer tests.

The energy balance tests were conducted with no main stream flow, and with the test section top cover removed so that the transpiration flow moved directly upwards, in a one-dimensional manner. There was, under these conditions, no heat transfer at the surface of the working plate. All the energy supplied was taken up either by the transpiration flow or by the losses.

The objective of the energy balance tests was to determine whether or not the data reduction program was a valid mathematical model of the test apparatus. Five energy loss mechanisms were recognized, and corrected for in the data reduction program: (1) radiation from the top surface of the plate; (2) radiation from the bottom surface of the plate to the pre-plate and to the casting; (3) conduction between the plate and the casting, through the phenolic support webs; (4) conduction through the stagnant air in the underbody, when there is no transpiration flow; and (5) lateral conduction within the porous plate, due to lateral temperature gradients. The data reduction program includes subroutines for the calculation of each of these losses. Values of the constants required in each of these routines were determined by special "loss tests" aimed at individually measuring the component losses. The total value of all the corrections varies between 5 and 10 per cent of total power supplied, depending on the Reynolds number and the blowing fraction. It also varies from plate to plate, since the local permeability distribution and the local conduction loss paths are somewhat different from plate to plate.

One important result of the energy balance testing was the introduction of the term "effective surface temperature". Use of the "effective surface temperature" corrects for the difference between average plate temperature and the bulk mean temperature of the transpiration flow leaving the surface of the plate. This difference was discovered by a series of energy balance tests in which the transpiration flow was collected and its bulk mean temperature measured above the plate surface using a thermally guarded collecting and mixing chamber. The fluid temperatures were always higher than the average of the five thermocouples imbedded in the plate. Investigations showed that several factors were present: (1) imperfect bonding of the plate thermocouples into their mounting holes had resulted in some thermocouples having substantial conduction errors (approaching 4 per cent); (2) the variations of local permeability introduced variations in local temperature which were coupled to the flow variations thus applying a "weight factor" to the various temperatures; (3) the temperature variations across the center span of the plate, on the order of 1 degF, were such that the geometrically spaced thermocouples were producing a faulty area-average. The overall effect of these three mechanisms was determined by calibrating each plate at several different combinations of blowing and power density. A correction function was then devised which computed the mixed mean fluid temperature from the average temperature of the five plate thermocouples as a function of blowing and power density. This value is used as the "effective plate temperature" in determining the Stanton number. In general, the difference between the measured plate temperature and the corrected "effective plate temperature" is on the order of 0·75 degF.

With the introduction of "effective plate temperature", the energy balances closed within 2 per cent of power, for all cases.

A potential flow region was shown to exist, for all blowing conditions, along the full length of the plate, and to be uniform within ±0·38 per cent in velocity and ±0·25 degF in temperature. The hydrodynamics of the boundary layer were adjusted, by experimentally selecting the boundary-layer trip, until the momentum based virtual origin of the unblown boundary layer coincided with the upstream edge of the porous plate (the location of $x = 0{\cdot}0$). Since the upstream region is not affected by blowing, the conditions at the beginning of the plate should have remained constant throughout the tests. The approach section was insulated, upstream of the plate, so that the thermal boundary-layer thickness was zero at $x = 0{\cdot}0$.

Baseline tests for friction factor and heat transfer were conducted with no blowing, to establish that the apparatus produced acceptable values. Traverses were made of the velocity boundary layer, at several x-Reynolds numbers, down the centerline of the test section and also 3 in to the right and left of the center. These were interpreted using the log-slope method ($k = 0{\cdot}4$) to determine friction factor. Heat-transfer tests were made with no blowing, resulting in Stanton number as a function of x-Reynolds number for the same test conditions used in the velocity traverses. Friction factors were then deduced from the Stanton number data, using $Pr^{-0{\cdot}4}$ as the value of the Reynolds analogy factor.

The following summarizes the results of these qualification tests on the impermeable flat plate:

1. Measured friction factor agreed within 1 per cent of the expected correlation, given by:

$$c_f/2 = 0{\cdot}0295\, Re_x^{-0{\cdot}2}.$$

2. Measured Stanton numbers agreed within 1 per cent of the expected correlation, given by

$$St = 0{\cdot}0295\, Re_x^{-0{\cdot}2}\, Pr^{-0{\cdot}4}.$$

3. Friction factor deduced from log-slope method agreed within 1 per cent of the values deduced from the measured Stanton numbers using the $Pr^{-0{\cdot}4}$ correction.
4. Law-of-the-wall representation was congruent for all velocity traverses past $Re_x = 4 \times 10^5$, including the side traverses, and agreed with Clauser's representation in the log region:

$$u^+ = 5{\cdot}6 \log_{10}(y^+) + 4{\cdot}9.$$

The velocity profiles were interpreted based on two fixed points ($u/U_\infty = 0{\cdot}55$ and $u/U_\infty = 0{\cdot}83$) in an effort to reduce the subjective aspects of choosing the "best" slope through the log region.

The validity of the data with blowing and suction was investigated by a series of boundary-layer energy balances made during the data taking runs. Enthalpy thickness was determined near the beginning and near the end of the porous plate, for each value of blowing and suction, by two independent ways: (1) from temperature and velocity profiles of the boundary layer and, (2) from the two-dimensional energy integral equation of the boundary layer, using the reported values of Stanton number and $\dot{m}''/G$ for each plate segment up to the point in question. The results agreed within 0·0010 ft in most cases, as shown in Fig. 6. This test also places some limits on the possible effects of three-dimensionality on the measured Stanton numbers.

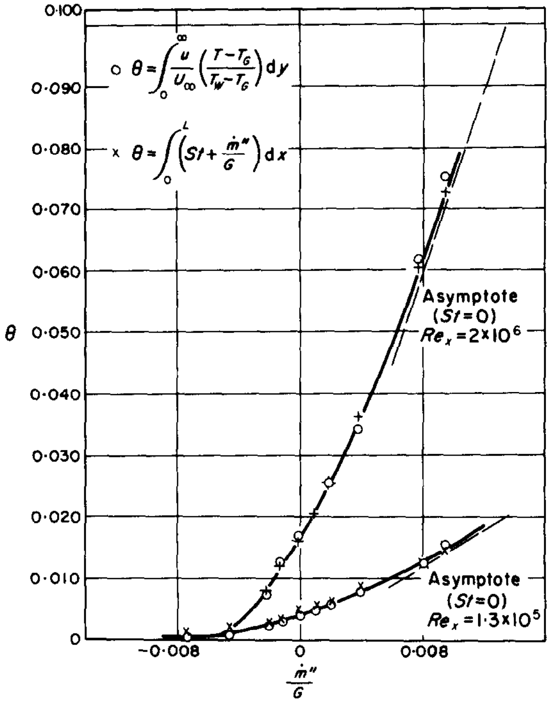

FIG. 6. Comparison of enthalpy thicknesses determined by two methods.

EXPERIMENTAL RESULTS

Figure 7 shows the experimental values of Stanton number as a function of x-Reynolds number for ten different values of blowing fraction. These values are also given in the tabular data section. For each test, the value of the blowing fraction, $\dot{m}''/G$, was held uniform along the entire length of the porous plate. The virtual origin for determining x-Reynolds number was taken to be $x = 0{\cdot}0$, as was shown to be for the case of no blowing. Free-stream velocity was made uniform along the test section by experimentally adjusting the position of the upper wall. This adjustment was made after having established conditions of uniform blowing and uniform surface temperature along the plate. Each blowing fraction was tested at least twice, and most were tested three times. At least two completely independent tests were made for each blowing fraction, to guard against variations in the adjustment of the test rig being incorporated into the results. Experimental Stanton numbers were calculated by the following equation:

$$St = \frac{\dot{q}''}{Gc\,\Delta T}$$

$$= \frac{\text{electric power} - \text{losses} - \dot{m}''(i_w - i_T)}{Gc(T_w - T_G)}.$$

The no-blowing results, $(\dot{m}''/G) = 0$, shown on Fig. 7, are correlated by:

$$St = 0{\cdot}0286\, Re_x^{-0{\cdot}2}\, Pr^{-0{\cdot}4} \text{ (as plotted)}.$$

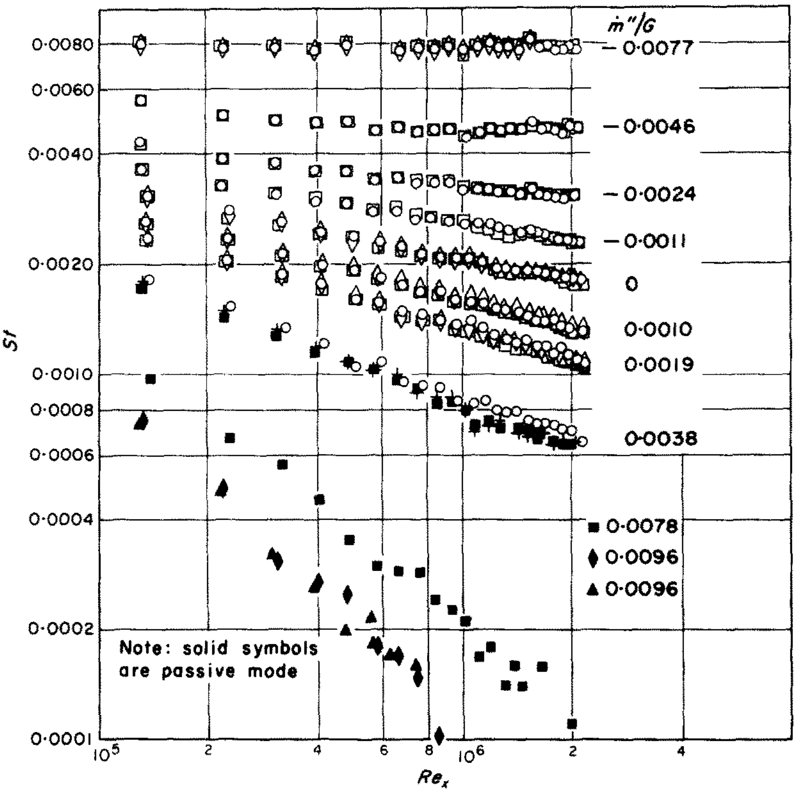

FIG. 7. Stanton number vs. *x*-Reynolds number: summary.

These data were obtained with temperature differences of 21–33 degF. Correction of the data to account for the effect of temperature dependent properties, using $(T_{\text{wall}}/T_{\text{gas}})^{0\cdot4}$, raises the values by approximately 2 per cent yielding a corrected correlation of:

$St = 0{\cdot}0292\, Re_x^{-0\cdot2}\, Pr^{-0\cdot4}$ (experimental values corrected for temperature effects).

These data agree well with the expected correlation for heat transfer from a smooth impermeable plate of uniform temperature to a uniform velocity free-stream, through a turbulent boundary layer:

$St = 0{\cdot}0295\, Re_x^{-0\cdot2}\, Pr^{-0\cdot4}$ (expected correlation).

No attempt was made to apply this temperature ratio correction to the plotted data, or to the tabular data, since the effect of variable properties on heat transfer is not known for the case of blowing or suction.

The Stanton number is seen to decrease with blowing, and increase with suction, as expected. High blowing, $(\dot{m}''/G) \rightarrow 0{\cdot}01$, takes the Stanton number so close to zero that the residual unbalance in the energy accountability would become dominant in fixing the apparent heat transfer. An alternate experimental method was therefore used for the two highest blowing conditions. This alternate method was termed the passive mode. In this mode of operation, the main stream is allowed to run at approximately 90 degF (blower discharge temperature) rather than being cooled before entering the test duct. The transpiration air is held at ambient temperature (about 70°F). An overall temperature difference of about 20 degF is thus available for the experiment. Conduction and radiation losses from the back face of the plate to the casting and preplate are reduced as the blowing increases, because the plate runs more nearly at the temperature of the transpiration flow (as does the casting). The plate temperature becomes more uniform, since local variations in permeability no longer produce local variations in temperature. Somewhat offsetting these advantages is the fact that the Stanton number must be deduced from measurements of very small temperature differences:

$$St = \frac{\dot{m}''c(T_T - T_w) - \text{losses}}{Gc(T_w - T_G)}.$$

The situation is, however, favorable for the accurate measurement of small temperature differences: the surroundings are nearly isothermal and the system can be calibrated in place under operating conditions. Estimates of the uncertainties involved, compared with the energy balance results previously mentioned, indicated that the passive mode should be preferred whenever $\dot{m}''/G$ exceeded 0·004. A series of tests conducted at $\dot{m}''/G = 0{\cdot}004$ showed that the passive mode results were slightly lower than the active mode results, by an amount which qualitatively agreed with the energy balance results for those conditions. Passive mode was used exclusively for the two highest values of blowing, as indicated on Fig. 7.

Stanton number is seen to increase with suction, becoming less dependent on x-Reynolds number. A simple energy balance calculation shows that, in the limit for an asymptotic suction layer, the value of Stanton number must approach $-\dot{m}''/G$. This behavior is shown even more clearly in Fig. 8, which shows the variation of Stanton number as a function of blowing fraction for three constant values of x-Reynolds number. The measured values are seen to approach closely both asymptotic limits: suction and blowing. It would seem safe, for many purposes, to say that $(\dot{m}''/G) = \pm 0{\cdot}01$ defines the boundaries of the asymptotic behavior. Stanton number is nearly zero when $\dot{m}''/G = 0{\cdot}01$, and is nearly equal to $-\dot{m}''/G$ when $\dot{m}''/G = -0{\cdot}01$.

COMPARISON WITH THEORY

Theories for predicting the effects of blowing and suction on Stanton number may be divided into two classes: those which directly predict the Stanton number, and those which predict

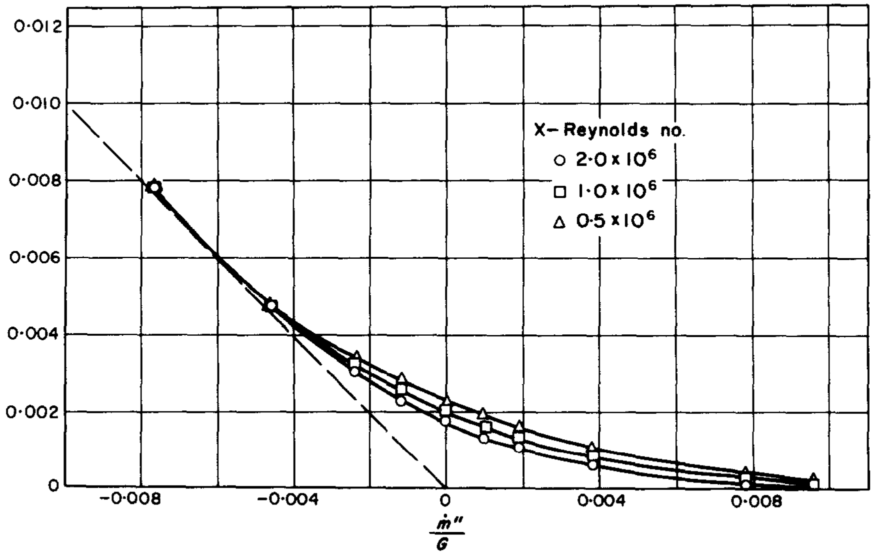

FIG. 8. Stanton number vs. $\dot{m}''/G$ at three x-Reynolds numbers.

Table 2

Run 020467–01			Run 020667–01		
U_∞ = 42·7 ft/s, T_∞ = 64·3°F			U_∞ = 42·9 ft/s, T_∞ = 64·1°F		
P = 30·1 in Hg, T_p = 92·1°F			P = 30·0 in Hg, T_p = 91·9°F		
$Re(x)$	$\dot{m}''/G$	St	$Re(x)$	$\dot{m}''/G$	St
4·42 at +04	−0·00765	0·00934	4·44 at +04	−0·00763	0·00945
1·33 at +05	−0·00740	0·00799	1·33 at +05	−0·00738	0·00820
2·21 at +05	−0·00760	0·00773	2·22 at +05	−0·00758	0·00780
3·09 at +05	−0·00762	0·00769	3·11 at +05	−0·00761	0·00784
3·98 at +05	−0·00756	0·00757	4·00 at +05	−0·00753	0·00766
4·86 at +05	−0·00757	0·00784	4·89 at +05	−0·00755	0·00801
5·75 at +05	−0·00758	0·00751	5·77 at +05	−0·00756	0·00762
6·63 at +05	−0·00766	0·00770	6·66 at +05	−0·00764	0·00786
7·51 at +05	−0·00753	0·00766	7·55 at +05	−0·00751	0·00774
8·40 at +05	−0·00763	0·00783	8·44 at +05	−0·00763	0·00797
9·28 at +05	−0·00754	0·00780	9·33 at +05	−0·00753	0·00793
1·02 at +06	−0·00754	0·00783	1·02 at +06	−0·00751	0·00749
1·11 at +06	−0·00759	0·00808	1·11 at +06	−0·00756	0·00812
1·19 at +06	−0·00750	0·00807	1·20 at +06	−0·00747	0·00814
1·28 at +06	−0·00755	0·00771	1·29 at +06	−0·00753	0·00781
1·37 at +06	−0·00751	0·00781	1·38 at +06	−0·00748	0·00791
1·46 at +06	−0·00754	0·00773	1·47 at +06	−0·00753	0·00783
1·55 at +06	−0·00746	0·00818	1·55 at +06	−0·00744	0·00823
1·64 at +06	−0·00747	0·00766	1·64 at +06	−0·00748	0·00776
1·72 at +06	−0·00756	0·00786	1·73 at +06	−0·00754	0·00786
1·81 at +06	−0·00746	0·00766	1·82 at +06	−0·00744	0·00792
1·90 at +06	−0·00755	0·00770	1·91 at +06	−0·00752	0·00775
1·99 at +06	−0·00752	0·00791	2·00 at +06	−0·00749	0·00797
2·08 at +06	−0·00752	0·00773	2·09 at +06	−0·00749	0·00784

Run 020867–02			Run 020867–01		
U_∞ = 42·6 ft/s, T_∞ = 64·0°F			U_∞ = 42·7 ft/s, T_∞ = 64·0°F		
P = 30·1 in Hg, T_p = 98·5°F			P = 30·2 in Hg, T_p = 98·0°F		
$Re(x)$	$\dot{m}''/G$	St	$Re(x)$	$\dot{m}''/G$	St
4·42 at +04	−0·00466	0·00691	4·45 at +04	−0·00467	0·00701
1·33 at +05	−0·00449	0·00553	1·33 at +05	−0·00451	0·00558
2·21 at +05	−0·00458	0·00508	2·22 at +05	−0·00460	0·00511
3·09 at +05	−0·00463	0·00496	3·11 at +05	−0·00466	0·00498
3·98 at +05	−0·00457	0·00484	4·00 at +05	−0·00457	0·00481
4·86 at +05	−0·00460	0·00489	4·89 at +05	−0·00461	0·00490
5·75 at +05	−0·00459	0·00459	5·78 at +05	−0·00460	0·00463
6·63 at +05	−0·00464	0·00469	6·67 at +05	−0·00464	0·00472
7·52 at +05	−0·00457	0·00460	7·56 at +05	−0·00458	0·00459
8·40 at +05	−0·00460	0·00465	8·45 at +05	−0·00461	0·00471
9·28 at +05	−0·00460	0·00466	9·34 at +05	−0·00462	0·00470
1·02 at +06	−0·00430	0·00442	1·02 at +06	−0·00430	0·00447
1·11 at +06	−0·00431	0·00459	1·11 at +06	−0·00437	0·00455
1·19 at +06	−0·00458	0·00470	1·20 at +06	−0·00458	0·00469
1·28 at +06	−0·00460	0·00465	1·29 at +06	−0·00460	0·00462
1·37 at +06	−0·00457	0·00474	1·38 at +06	−0·00456	0·00467
1·46 at +06	−0·00458	0·00466	1·47 at +06	−0·00459	0·00466
1·55 at +06	−0·00456	0·00490	1·56 at +06	−0·00456	0·00484
1·64 at +06	−0·00455	0·00465	1·65 at +06	−0·00456	0·00464
1·72 at +06	−0·00457	0·00467	1·74 at +06	−0·00457	0·00467
1·81 at +06	−0·00453	0·00461	1·82 at +06	−0·00454	0·00460
1·90 at +06	−0·00455	0·00461	1·91 at +06	−0·00455	0·00461
1·99 at +06	−0·00458	0·00473	2·00 at +06	−0·00458	0·00471
2·08 at +06	−0·00459	0·00475	2·09 at +06	−0·00460	0·00469

Table 2—continued

Run 020667–02

$U_\infty = 42·6$ ft/s, $T_\infty = 64·2$°F
$P = 30·0$ in Hg, $T_p = 92·5$°F

$Re(x)$	$\dot{m}''/G$	St
4·40 at +04	−0·00764	0·00932
1·32 at +05	−0·00738	0·00801
2·20 at +05	−0·00758	0·00770
3·08 at +05	−0·00761	0·00775
3·96 at +05	−0·00755	0·00761
4·85 at +05	−0·00755	0·00795
5·73 at +05	−0·00755	0·00760
6·61 at +05	−0·00765	0·00781
7·49 at +05	−0·00751	0·00766
8·37 at +05	−0·00762	0·00792
9·25 at +05	−0·00753	0·00789
1·01 at +06	−0·00754	0·00776
1·10 at +06	−0·00757	0·00818
1·19 at +06	−0·00751	0·00815
1·28 at +06	−0·00755	0·00777
1·37 at +06	−0·00749	0·00789
1·45 at +06	−0·00754	0·00777
1·54 at +06	−0·00745	0·00820
1·63 at +06	−0·00748	0·00771
1·72 at +06	−0·00755	0·00791
1·81 at +06	−0·00744	0·00771
1·89 at +06	−0·00753	0·00769
1·98 at +06	−0·00779	0·00795
2·07 at +06	−0·00750	0·00778

Run 021367–01

$U_\infty = 41·8$ ft/s, $T_\infty = 64·2$°F
$P = 29·9$ in Hg, $T_p = 92·4$°F

$Re(x)$	$\dot{m}''/G$	St
4·30 at +04	−0·00789	0·00933
1·29 at +05	−0·00762	0·00807
2·15 at +05	−0·00783	0·00775
3·01 at +05	−0·00784	0·00782
3·87 at +05	−0·00775	0·00764
4·72 at +05	−0·00779	0·00799
5·58 at +05	−0·00778	0·00771
6·44 at +05	−0·00791	0·00785
7·30 at +05	−0·00778	0·00782
8·16 at +05	−0·00783	0·00795
9·02 at +05	−0·00778	0·00794
9·88 at +05	−0·00775	0·00791
1·07 at +06	−0·00780	0·00824
1·16 at +06	−0·00774	0·00817
1·25 at +06	−0·00778	0·00782
1·33 at +06	−0·00772	0·00797
1·42 at +06	−0·00779	0·00788
1·50 at +06	−0·00769	0·00835
1·59 at +06	−0·00771	0·00776
1·68 at +06	−0·00777	0·00797
1·76 at +06	−0·00771	0·00775
1·85 at +06	−0·00775	0·00775
1·93 at +06	−0·00776	0·00808
2·02 at +06	−0·00777	0·00785

Run 020967–01

$U_\infty = 42·7$ ft/s, $T_\infty = 65·3$°F
$P = 30·1$ in Hg, $T_p = 98·5$°F

$Re(x)$	$\dot{m}''/G$	St
4·40 at +04	−0·00242	0·00542
1·32 at +05	−0·00234	0·00426
2·20 at +05	−0·00239	0·00390
3·08 at +05	−0·00241	0·00374
3·96 at +05	−0·00238	0·00359
4·84 at +05	−0·00239	0·00358
5·73 at +05	−0·00240	0·00338
6·61 at +05	−0·00241	0·00343
7·49 at +05	−0·00237	0·00333
8·37 at +05	−0·00242	0·00334
9·25 at +05	−0·00240	0·00331
1·01 at +06	−0·00238	0·00320
1·10 at +06	−0·00240	0·00319
1·19 at +06	−0·00237	0·00320
1·28 at +06	−0·00239	0·00316
1·37 at +06	−0·00238	0·00314
1·45 at +06	−0·00237	0·00306
1·54 at +06	−0·00235	0·00320
1·63 at +06	−0·00231	0·00308
1·72 at +06	−0·00238	0·00310
1·81 at +06	−0·00235	0·00303
1·89 at +06	−0·00237	0·00303
1·98 at +06	−0·00231	0·00308
2·07 at +06	−0·00236	0·00305

Run 020967–02

$U_\infty = 42·3$ ft/s, $T_\infty = 64·1$°F
$P = 30·1$ in Hg, $T_p = 97·5$°F

$Re(x)$	$\dot{m}''/G$	St
4·39 at +04	−0·00244	0·00540
1·32 at +05	−0·00236	0·00427
2·20 at +05	−0·00241	0·00389
3·07 at +05	−0·00243	0·00377
3·95 at +05	−0·00238	0·00362
4·83 at +05	−0·00240	0·00362
5·71 at +05	−0·00242	0·00341
6·59 at +05	−0·00242	0·00346
7·47 at +05	−0·00239	0·00337
8·34 at +05	−0·00240	0·00337
9·22 at +05	−0·00240	0·00333
1·01 at +06	−0·00239	0·00325
1·10 at +06	−0·00241	0·00322
1·19 at +06	−0·00238	0·00323
1·27 at +06	−0·00238	0·00319
1·36 at +06	−0·00239	0·00318
1·45 at +06	−0·00239	0·00315
1·54 at +06	−0·00238	0·00323
1·62 at +06	−0·00233	0·00311
1·71 at +06	−0·00240	0·00312
1·80 at +06	−0·00237	0·00305
1·89 at +06	−0·00233	0·00309
1·98 at +06	−0·00238	0·00307
2·06 at +06	−0·00238	0·00309

Table 2—continued

Run 021067–01

U_∞ = 42·5 ft/s, T_∞ = 64·7°F
P = 30·0 in Hg, T_p = 90·1°F

$Re(x)$	$\dot{m}''/G$	St
4·39 at +04	−0·00118	0·00453
1·32 at +05	−0·00113	0·00364
2·19 at +05	−0·00116	0·00324
3·07 at +05	−0·00117	0·00310
3·95 at +05	−0·00115	0·00297
4·83 at +05	−0·00115	0·00292
5·70 at +05	−0·00116	0·00278
6·58 at +05	−0·00117	0·00283
7·46 at +05	−0·00115	0·00266
8·34 at +05	−0·00116	0·00267
9·21 at +05	−0·00115	0·00261
1·01 at +06	−0·00115	0·00256
1·10 at +06	−0·00116	0·00258
1·18 at +06	−0·00115	0·00257
1·27 at +06	−0·00115	0·00251
1·36 at +06	−0·00114	0·00247
1·45 at +06	−0·00116	0·00244
1·54 at +06	−0·00113	0·00247
1·62 at +06	−0·00112	0·00242
1·71 at +06	−0·00115	0·00238
1·80 at +06	−0·00114	0·00236
1·89 at +06	−0·00114	0·00236
1·97 at +06	−0·00115	0·00232
2·06 at +06	−0·00115	0·00232

Run 021267–01

U_∞ = 42·3 ft/s, T_∞ = 64·9°F
P = 30·0 in Hg, T_p = 89·9°F

$Re(x)$	$\dot{m}''/G$	St
4·36 at +04	−0·00118	0·00456
1·31 at +05	−0·00114	0·00369
2·18 at +05	−0·00117	0·00326
3·05 at +05	−0·00117	0·00315
3·92 at +05	—0·00116	0·00304
4·80 at +05	−0·00116	0·00297
5·67 at +05	−0·00117	0·00283
6·54 at +05	−0·00118	0·00289
7·41 at +05	−0·00116	0·00271
8·28 at +05	−0·00116	0·00272
9·15 at +05	−0·00116	0·00264
1·00 at +06	−0·00116	0·00265
1·09 at +06	−0·00117	0·00251
1·18 at +06	−0·00116	0·00251
1·26 at +06	−0·00116	0·00243
1·35 at +06	−0·00115	0·00240
1·44 at +06	−0·00116	0·00241
1·53 at +06	−0·00114	0·00241
1·61 at +06	−0·00113	0·00236
1·70 at +06	−0·00115	0·00235
1·79 at +06	−0·00115	0·00233
1·87 at +06	−0·00115	0·00233
1·96 at +06	−0·00125	0·00231
2·05 at +06	−0·00120	0·00229

Run 012666–01

U_∞ = 44·5 ft/s, T_∞ = 64·4°F
P = 29·7 in Hg, T_p = 97·0°F

$Re(x)$	$\dot{m}''/G$	St
4·55 at +04	0·00000	0·00413
1·36 at +05	0·00000	0·00308
2·27 at +05	0·00000	0·00279
3·18 at +05	0·00000	0·00259
4·09 at +05	0·00000	0·00244
5·00 at +05	0·00000	0·00236
5·91 at +05	0·00000	0·00229
6·82 at +05	0·00000	0·00222
7·73 at +05	0·00000	0·00213
8·64 at +05	0·00000	0·00210
9·55 at +05	0·00000	0·00207
1·05 at +06	0·00000	0·00207
1·14 at +06	0·00000	0·00202
1·23 at +06	0·00000	0·00191
1·32 at +06	0·00000	0·00193
1·41 at +06	0·00000	0·00190
1·50 at +06	0·00000	0·00190
1·59 at +06	0·00000	0·00187
1·68 at +06	0·00000	0·00188
1·77 at +06	0·00000	0·00183
1·86 at +06	0·00000	0·00180
1·95 at +06	0·00000	0·00185
2·05 at +06	0·00000	0·00181
2·14 at +06	0·00000	0·00182

Run 012166–01

U_∞ = 44·4 ft/s, T_∞ = 65·0°F
P = 29·8 in Hg, T_p = 86·2°F

$Re(x)$	$\dot{m}''/G$	St
4·55 at +04	0·00000	0·00386
1·36 at +05	0·00000	0·00299
2·27 at +05	0·00000	0·00269
3·18 at +05	0·00000	0·00251
4·09 at +05	0·00000	0·00240
5·00 at +05	0·00000	0·00229
5·91 at +05	0·00000	0·00221
6·82 at +05	0·00000	0·00216
7·73 at +05	0·00000	0·00212
8·64 at +05	0·00000	0·00208
9·55 at +05	0·00000	0·00202
1·05 at +06	0·00000	0·00199
1·14 at +06	0·00000	0·00200
1·23 at +06	0·00000	0·00194
1·32 at +06	0·00000	0·00192
1·41 at +06	0·00000	0·00189
1·50 at +06	0·00000	0·00189
1·59 at +06	0·00000	0·00186
1·68 at +06	0·00000	0·00184
1·77 at +06	0·00000	0·00183
1·86 at +06	0·00000	0·00177
1·95 at +06	0·00000	0·00179
2·05 at +06	0·00000	0·00178
2·14 at +06	0·00000	0·00176

Table 2—continued

Run 010667–01

U_∞ = 43·5 ft/s, T_∞ = 62·8°F
P = 30·2 in Hg, T_p = 96·2°F

$Re(x)$	$\dot{m}''/G$	St
4·55 at +04	0·00000	0·00418
1·37 at +05	0·00000	0·00308
2·28 at +05	0·00000	0·00281
3·19 at +05	0·00000	0·00262
4·10 at +05	0·00000	0·00246
5·01 at +05	0·00000	0·00241
5·92 at +05	0·00000	0·00231
6·83 at +05	0·00000	0·00224
7·74 at +05	0·00000	0·00215
8·65 at +05	0·00000	0·00213
9·56 at +05	0·00000	0·00209
1·05 at +06	0·00000	0·00209
1·14 at +06	0·00000	0·00204
1·23 at +06	0·00000	0·00197
1·32 at +06	0·00000	0·00196
1·41 at +06	0·00000	0·00193
1·50 at +06	0·00000	0·00194
1·59 at +06	0·00000	0·00192
1·68 at +06	0·00000	0·00188
1·78 at +06	0·00000	0·00186
1·87 at +06	0·00000	0·00179
1·96 at +06	0·00000	0·00184
2·05 at +06	0·00000	0·00182
2·14 at +06	0·00000	0·00180

Run 012166–02

U_∞ = 44·4 ft/s, T_∞ = 65·0°F
P = 29·8 in Hg, T_p = 86·8°F

$Re(x)$	$\dot{m}''/G$	St
4·55 at +04	0·00000	0·00386
1·36 at +05	0·00000	0·00300
2·27 at +05	0·00000	0·00269
3·18 at +05	0·00000	0·00251
4·09 at +05	0·00000	0·00239
5·00 at +05	0·00000	0·00230
5·91 at +05	0·00000	0·00221
6·82 at +05	0·00000	0·00216
7·73 at +05	0·00000	0·00212
8·64 at +05	0·00000	0·00208
9·55 at +05	0·00000	0·00202
1·05 at +06	0·00000	0·00200
1·14 at +06	0·00000	0·00201
1·23 at +06	0·00000	0·00194
1·32 at +06	0·00000	0·00192
1·41 at +06	0·00000	0·00189
1·50 at +06	0·00000	0·00189
1·59 at +06	0·00000	0·00186
1·68 at +06	0·00000	0·00183
1·77 at +06	0·00000	0·00183
1·86 at +06	0·00000	0·00176
1·95 at +06	0·00000	0·00180
2·05 at +06	0·00000	0·00177
2·14 at +06	0·00000	0·00176

Run 012766–01

U_∞ = 44·4 ft/s, T_∞ = 65·2°F
P = 29·9 in Hg, T_p = 127·4°F

$Re(x)$	$\dot{m}''/G$	St
4·55 at +04	0·00000	0·00420
1·37 at +05	0·00000	0·00312
2·28 at +05	0·00000	0·00281
3·19 at +05	0·00000	0·00263
4·10 at +05	0·00000	0·00245
5·01 at +05	0·00000	0·00236
5·92 at +05	0·00000	0·00227
6·83 at +05	0·00000	0·00220
7·74 at +05	0·00000	0·00213
8·65 at +05	0·00000	0·00210
9·56 at +05	0·00000	0·00204
1·05 at +06	0·00000	0·00207
1·14 at +06	0·00000	0·00201
1·23 at +06	0·00000	0·00192
1·32 at +06	0·00000	0·00191
1·41 at +06	0·00000	0·00189
1·50 at +06	0·00000	0·00191
1·59 at +06	0·00000	0·00187
1·69 at +06	0·00000	0·00187
1·78 at +06	0·00000	0·00183
1·87 at +06	0·00000	0·00180
1·96 at +06	0·00000	0·00184
2·05 at +06	0·00000	0·00181
2·14 at +06	0·00000	0·00182

Run 010467–01

U_∞ = 44·2 ft/s, T_∞ = 65·2°F
P = 30·0 in Hg, T_p = 98·4°F

$Re(x)$	$\dot{m}''/G$	St
4·57 at +04	0·00099	0·00358
1·37 at +05	0·00099	0·00259
2·28 at +05	0·00099	0·00231
3·20 at +05	0·00100	0·00210
4·11 at +05	0·00099	0·00199
5·02 at +05	0·00099	0·00193
5·94 at +05	0·00099	0·00185
6·85 at +05	0·00100	0·00175
7·76 at +05	0·00099	0·00168
8·67 at +05	0·00099	0·00169
9·59 at +05	0·00099	0·00159
1·05 at +06	0·00098	0·00159
1·14 at +06	0·00098	0·00155
1·23 at +06	0·00100	0·00151
1·32 at +06	0·00099	0·00148
1·42 at +06	0·00099	0·00147
1·51 at +06	0·00099	0·00144
1·60 at +06	0·00100	0·00142
1·69 at +06	0·00099	0·00139
1·78 at +06	0·00099	0·00141
1·87 at +06	0·00099	0·00135
1·96 at +06	0·00100	0·00135
2·05 at +06	0·00099	0·00130
2·15 at +06	0·00100	0·00131

Table 2—continued

Run 123066–01			Run 120866–01		
U_∞ = 44·1 ft/s, T_∞ = 66·1°F			U_∞ = 44·4 ft/s, T_∞ = 65·7°F		
P = 30·0 in Hg, T_p = 98·1°F			P = 30·1 in Hg, T_p = 96·4°F		
$Re(x)$	$\dot{m}''/G$	St	$Re(x)$	$\dot{m}''/G$	St
4·53 at +04	0·00100	0·00353	4·58 at +04	0·00100	0·00369
1·36 at +05	0·00100	0·00258	1·37 at +05	0·00100	0·00266
2·26 at +05	0·00100	0·00233	2·29 at +05	0·00099	0·00241
3·17 at +05	0·00100	0·00213	3·20 at +05	0·00100	0·00217
4·08 at +05	0·00100	0·00199	4·12 at +05	0·00100	0·00204
4·98 at +05	0·00101	0·00192	5·03 at +05	0·00100	0·00199
5·89 at +05	0·00100	0·00185	5·95 at +05	0·00100	0·00192
6·79 at +05	0·00100	0·00177	6·86 at +05	0·00099	0·00184
7·70 at +05	0·00100	0·00169	7·78 at +05	0·00100	0·00175
8·60 at +05	0·00100	0·00168	8·69 at +05	0·00100	0·00174
9·51 at +05	0·00100	0·00161	9·61 at +05	0·00101	0·00166
1·04 at +06	0·00100	0·00159	1·05 at +06	0·00099	0·00166
1·13 at +06	0·00100	0·00153	1·14 at +06	0·00099	0·00160
1·22 at +06	0·00100	0·00150	1·24 at +06	0·00100	0·00154
1·31 at +06	0·00100	0·00147	1·33 at +06	0·00100	0·00155
1·40 at +06	0·00100	0·00144	1·42 at +06	0·00100	0·00150
1·49 at +06	0·00100	0·00146	1·51 at +06	0·00100	0·00149
1·58 at +06	0·00100	0·00141	1·60 at +06	0·00099	0·00146
1·68 at +06	0·00100	0·00139	1·69 at +06	0·00100	0·00146
1·77 at +06	0·00100	0·00141	1·78 at +06	0·00100	0·00147
1·86 at +06	0·00100	0·00136	1·88 at +06	0·00099	0·00143
1·95 at +06	0·00100	0·00136	1·97 at +06	0·00100	0·00137
2·04 at +06	0·00100	0·00132	2·06 at +06	0·00100	0·00135
2·13 at +06	0·00100	0·00131	2·15 at +06	0·00100	0·00134

Run 010367–02			Run 120966–02		
U_∞ = 44·1 ft/s, T_∞ = 63·3°F			U_∞ = 44·4 ft/s, T_∞ = 64·7°F		
P = 30·1 in Hg, T_p = 95·2°F			P = 30·1 in Hg, T_p = 97·5°F		
$Re(x)$	$\dot{m}''/G$	St	$Re(x)$	$\dot{m}''/G$	St
4·59 at +04	0·00192	0·00324	4·60 at +04	0·00385	0·00259
1·38 at +05	0·00191	0·00239	1·38 at +05	0·00384	0·00182
2·29 at +05	0·00188	0·00208	2·30 at +05	0·00385	0·00152
3·21 at +05	0·00192	0·00189	3·22 at +05	0·00382	0·00134
4·13 at +05	0·00189	0·00173	4·14 at +05	0·00382	0·00121
5·05 at +05	0·00188	0·00167	5·05 at +05	0·00385	0·00106
5·97 at +05	0·00188	0·00159	5·97 at +05	0·00381	0·00108
6·88 at +05	0·00191	0·00145	6·89 at +05	0·00381	0·00096
7·80 at +05	0·00190	0·00143	7·81 at +05	0·00381	0·00093
8·72 at +05	0·00190	0·00143	8·73 at +05	0·00381	0·00092
9·64 at +05	0·00189	0·00137	9·65 at +05	0·00382	0·00085
1·06 at +06	0·00191	0·00135	1·06 at +06	0·00381	0·00084
1·15 at +06	0·00188	0·00131	1·15 at +06	0·00381	0·00085
1·24 at +06	0·00189	0·00128	1·24 at +06	0·00382	0·00081
1·33 at +06	0·00191	0·00126	1·33 at +06	0·00381	0·00079
1·42 at +06	0·00190	0·00121	1·42 at +06	0·00381	0·00080
1·51 at +06	0·00190	0·00120	1·52 at +06	0·00384	0·00075
1·61 at +06	0·00191	0·00117	1·61 at +06	0·00382	0·00074
1·70 at +06	0·00189	0·00117	1·70 at +06	0·00382	0·00074
1·79 at +06	0·00189	0·00115	1·79 at +06	0·00381	0·00069
1·88 at +06	0·00190	0·00114	1·88 at +06	0·00381	0·00071
1·97 at +06	0·00190	0·00113	1·98 at +06	0·00381	0·00071
2·07 at +06	0·00185	0·00108	2·07 at +06	0·00384	0·00064
2·16 at +06	0·00192	0·00107	2·16 at +06	0·00383	0·00065

Table 2—continued

Run 120966–01			Run 010367–01		
$U_\infty = 44{\cdot}2$ ft/s, $T_\infty = 64{\cdot}5$°F $P = 30{\cdot}1$ in Hg, $T_p = 97{\cdot}6$°F			$U_\infty = 43{\cdot}5$ ft/s, $T_\infty = 63{\cdot}0$°F $P = 30{\cdot}1$ in Hg, $T_p = 96{\cdot}0$°F		
Re(*x*)	$\dot{m}''/G$	*St*	*Re*(*x*)	$\dot{m}''/G$	*St*
4·57 at +04	0·00191	0·00331	4·54 at +04	0·00194	0·00313
1·37 at +05	0·00190	0·00236	1·36 at +05	0·00194	0·00234
2·28 at +05	0·00190	0·00206	2·27 at +05	0·00192	0·00203
3·20 at +05	0·00191	0·00189	3·18 at +05	0·00194	0·00186
4·11 at +05	0·00189	0·00174	4·09 at +05	0·00192	0·00165
5·03 at +05	0·00192	0·00165	5·00 at +05	0·00193	0·00163
5·94 at +05	0·00190	0·00157	5·90 at +05	0·00191	0·00156
6·85 at +05	0·00191	0·00150	6·81 at +05	0·00194	0·00142
7·77 at +05	0·00192	0·00146	7·72 at +05	0·00193	0·00140
8·68 at +05	0·00191	0·00145	8·63 at +05	0·00194	0·00138
9·60 at +05	0·00193	0·00137	9·54 at +05	0·00194	0·00131
1·05 at +06	0·00190	0·00139	1·04 at +06	0·00194	0·00132
1·14 at +06	0·00190	0·00136	1·14 at +06	0·00191	0·00125
1·23 at +06	0·00194	0·00126	1·23 at +06	0·00194	0·00122
1·33 at +06	0·00193	0·00124	1·32 at +06	0·00194	0·00119
1·42 at +06	0·00193	0·00123	1·41 at +06	0·00191	0·00117
1·51 at +06	0·00191	0·00123	1·50 at +06	0·00193	0·00116
1·60 at +06	0·00192	0·00119	1·59 at +06	0·00193	0·00114
1·69 at +06	0·00187	0·00120	1·68 at +06	0·00191	0·00112
1·78 at +06	0·00191	0·00113	1·77 at +06	0·00193	0·00110
1·87 at +06	0·00191	0·00118	1·86 at +06	0·00195	0·00109
1·96 at +06	0·00192	0·00112	1·95 at +06	0·00192	0·00110
2·06 at +06	0·00186	0·00109	2·04 at +06	0·00188	0·00105
2·15 at +06	0·00191	0·00109	2·13 at +06	0·00195	0·00103

Run 122066–01			Run 122066–02		
$U_\infty = 46{\cdot}3$ ft/s, $T_\infty = 88{\cdot}7$°F $P = 29{\cdot}9$ in Hg, $T_p = 76{\cdot}8$°F			$U_\infty = 46{\cdot}1$ ft/s, $T_\infty = 88{\cdot}6$°F $P = 29{\cdot}9$ in Hg, $T_p = 76{\cdot}7$°F		
Re(*x*)	$\dot{m}''/G$	*St*	*Re*(*x*)	$\dot{m}''/G$	*St*
4·40 at +04	0·00383	0·00236	4·38 at +04	0·00386	0·00236
1·32 at +05	0·00380	0·00172	1·31 at +05	0·00383	0·00172
2·20 at +05	0·00382	0·00143	2·19 at +05	0·00386	0·00144
3·08 at +05	0·00380	0·00128	3·07 at +05	0·00383	0·00129
3·96 at +05	0·00381	0·00116	3·94 at +05	0·00385	0·00118
4·84 at +05	0·00381	0·00109	4·82 at +05	0·00383	0·00110
5·72 at +05	0·00380	0·00103	5·69 at +05	0·00383	0·00103
6·60 at +05	0·00383	0·00097	6·57 at +05	0·00386	0·00099
7·48 at +05	0·00382	0·00092	7·45 at +05	0·00384	0·00090
8·36 at +05	0·00381	0·00083	8·32 at +05	0·00384	0·00087
9·25 at +05	0·00381	0·00085	9·20 at +05	0·00384	0·00084
1·01 at +06	0·00379	0·00080	1·01 at +06	0·00383	0·00083
1·10 at +06	0·00380	0·00072	1·10 at +06	0·00383	0·00070
1·19 at +06	0·00379	0·00075	1·18 at +06	0·00382	0·00073
1·28 at +06	0·00379	0·00071	1·27 at +06	0·00383	0·00076
1·36 at +06	0·00378	0·00071	1·36 at +06	0·00383	0·00070
1·45 at +06	0·00381	0·00072	1·45 at +06	0·00384	0·00071
1·54 at +06	0·00382	0·00070	1·53 at +06	0·00384	0·00070
1·63 at +06	0·00380	0·00067	1·62 at +06	0·00382	0·00064
1·72 at +06	0·00380	0·00068	1·71 at +06	0·00382	0·00067
1·81 at +06	0·00380	0·00066	1·80 at +06	0·00382	0·00066
1·89 at +06	0·00380	0·00065	1·88 at +06	0·00383	0·00065
1·98 at +06	0·00382	0·00065	1·85 at +06	0·00384	0·00067
2·07 at +06	0·00381	0·00066	2·06 at +06	0·00385	0·00062

Table 2—continued

Run 121966–02			Run 120966–03		
$U_\infty = 46·1$ ft/s, $T_\infty = 84·9$°F $P = 30·0$ in Hg, $T_p = 69·6$°F			$U_\infty = 44·6$ ft/s, $T_\infty = 64·8$°F $P = 30·1$ in Hg, $T_p = 97·7$°F		
Re(*x*)	$\dot{m}''/G$	*St*	*Re*(*x*)	$\dot{m}''/G$	*St*
4·45 at +04	0·00777	0·00145	4·62 at +04	0·00771	0·00157
1·34 at +05	0·00777	0·00098	1·39 at +05	0·00771	0·00098
2·23 at +05	0·00777	0·00067	2·31 at +05	0·00769	0·00060
3·12 at +05	0·00777	0·00057	3·23 at +05	0·00769	0·00054
4·01 at +05	0·00779	0·00046	4·16 at +05	0·00769	0·00050
4·90 at +05	0·00780	0·00035	5·08 at +05	0·00769	0·00035
5·79 at +05	0·00776	0·00030	6·00 at +05	0·00770	0·00041
6·68 at +05	0·00779	0·00029	6·93 at +05	0·00771	0·00043
7·57 at +05	0·00775	0·00029	7·85 at +05	0·00771	0·00037
8·46 at +05	0·00779	0·00024	8·77 at +05	0·00770	0·00030
9·35 at +06	0·00780	0·00023	9·70 at +05	0·00770	0·00031
1·02 at +06	0·00776	0·00021	1·06 at +06	0·00768	0·00030
1·11 at +06	0·00775	0·00017	1·15 at +06	0·00767	0·00028
1·20 at +06	0·00775	0·00018	1·25 at +06	0·00768	0·00030
1·29 at +06	0·00776	0·00014	1·34 at +06	0·00770	0·00032
1·38 at +06	0·00779	0·00016	1·43 at +06	0·00768	0·00033
1·47 at +06	0·00780	0·00014	1·52 at +06	0·00772	0·00028
1·56 at +06	0·00778	0·00019	1·62 at +06	0·00768	0·00026
1·65 at +06	0·00778	0·00016	1·71 at +06	0·00770	0·00027
1·74 at +06	0·00777	0·00020	1·80 at +06	0·00760	0·00029
1·82 at +06	0·00777	0·00020	1·89 at +06	0·00767	0·00028
1·91 at +06	0·00777	0·00020	1·99 at +06	0·00769	0·00026
2·00 at +06	0·00778	0·00011	2·08 at +06	0·00772	0·00025
2·09 at +06	0·00778	0·00018	2·17 at +06	0·00772	0·00024

Run 121266–02			Run 121366–01		
$U_\infty = 46·3$ ft/s, $T_\infty = 89·9$°F $P = 30·1$ in Hg, $T_p = 72·6$°F			$U_\infty = 44·6$ ft/s, $T_\infty = 66·5$°F $P = 30·1$ in Hg, $T_p = 100·1$°F		
Re(*x*)	$\dot{m}''/G$	*St*	*Re*(*x*)	$\dot{m}''/G$	*St*
4·42 at +04	0·00951	0·00122	4·59 at +04	0·00941	0·00133
1·32 at +05	0·00947	0·00172	1·38 at +05	0·00935	0·00094
2·21 at +05	0·00944	0·00048	2·30 at +05	0·00933	0·00051
3·09 at +05	0·00953	0·00032	3·21 at +05	0·00937	0·00044
3·97 at +05	0·00944	0·00027	4·13 at +05	0·00936	0·00029
4·86 at +05	0·00944	0·00020	5·05 at +05	0·00933	0·00029
5·74 at +05	0·00948	0·00022	5·97 at +05	0·00934	0·00027
6·62 at +05	0·00945	0·00017	6·89 at +05	0·00935	0·00015
7·51 at +05	0·00946	0·00016	7·81 at +05	0·00934	0·00022
8·39 at +05	0·00947	0·00008	8·73 at +05	0·00936	0·00025
9·27 at +05	0·00944	0·00009	9·64 at +05	0·00936	0·00026
1·02 at +06	0·00946	0·00006	1·06 at +06	0·00935	0·00049
1·10 at +06	0·00947	0·00008	1·15 at +06	0·00935	0·00030
1·19 at +06	0·00948	0·00006	1·24 at +06	0·00936	0·00018
1·28 at +06	0·00950	0·00002	1·33 at +06	0·00939	0·00026
1·37 at +06	0·00945	0·00009	1·42 at +06	0·00937	0·00024
1·46 at +06	0·00944	0·00004	1·52 at +06	0·00941	0·00018
1·55 at +06	0·00944	0·00007	1·61 at +06	0·00938	0·00016
1·63 at +06	0·00946	0·00003	1·70 at +06	0·00908	0·00055
1·72 at +06	0·00947	0·00003	1·79 at +06	0·00936	0·00025
1·81 at +06	0·00950	0·00000	1·88 at +06	0·00942	0·00023
1·90 at +06	0·00946	0·00000	1·97 at +06	0·00941	0·00026
2·03 at +06	0·00939	0·00001	2·07 at +06	0·00935	0·00022
2·08 at +06	0·00943	0·00001	2·16 at +06	0·00941	0·00023

Table 2—continued

Run 121966–01

U_∞ = 46·3 ft/s, T_∞ = 89·1°F
P = 30·0 in Hg, T_p = 73·3°F

Re(x)	$\dot{m}''/G$	*St*
4·41 at +04	0·00774	0·00146
1·32 at +05	0·00776	0·00089
2·20 at +05	0·00775	0·00060
3·08 at +05	0·00776	0·00048
3·97 at +05	0·00776	0·00035
4·85 at +05	0·00778	0·00035
5·73 at +05	0·00774	0·00024
6·61 at +05	0·00778	0·00024
7·49 at +05	0·00773	0·00019
8·37 at +05	0·00777	0·00006
9·25 at +05	0·00778	0·00008
1·01 at +06	0·00774	0·00000
1·10 at +06	0·00771	0·00000
1·19 at +06	0·00774	0·00010
1·28 at +06	0·00773	0·00002
1·37 at +06	0·00776	0·00001
1·45 at +06	0·00778	0·00003
1·54 at +06	0·00777	0·00000
1·63 at +06	0·00777	0·00000
1·72 at +06	0·00776	0·00000
1·81 at +06	0·00773	0·00000
1·89 at +06	0·00773	0·00004
1·98 at +06	0·00776	0·00003
2·07 at +06	0·00778	0·00003

Run 121566–01

U_∞ = 46·4 ft/s, T_∞ = 88·5°F
P = 30·1 in Hg, T_p = 71·6°F

Re(x)	$\dot{m}''/G$	*St*
4·44 at +04	0·00955	0·00122
1·33 at +05	0·00950	0·00075
2·22 at +05	0·00950	0·00049
3·11 at +05	0·00949	0·00031
3·99 at +05	0·00950	0·00027
4·88 at +05	0·00950	0·00025
5·77 at +05	0·00947	0·00018
6·66 at +05	0·00949	0·00017
7·55 at +05	0·00949	0·00015
8·43 at +05	0·00952	0·00008
9·32 at +05	0·00951	0·00006
1·02 at +06	0·00951	0·00010
1·11 at +06	0·00951	0·00005
1·20 at +06	0·00956	0·00012
1·29 at +06	0·00953	0·00006
1·38 at +06	0·00952	0·00001
1·46 at +06	0·00956	0·00000
1·55 at +06	0·00950	0·00004
1·64 at +06	0·00956	0·00000
1·73 at +06	0·00952	0·00001
1·82 at +06	0·00956	0·00000
1·91 at +06	0·00954	0·00000
2·00 at +06	0·00950	0·00004
2·09 at +06	0·00953	0·00001

Run 121066–01

U_∞ = 44·3 ft/s, T_∞ = 65·2°F
P = 30·2 in Hg, T_p = 97·0°F

Re(x)	$\dot{m}''/G$	*St*
4·59 at +04	0·00940	0·00127
1·38 at +05	0·00935	0·00087
2·29 at +05	0·00933	0·00050
3·21 at +05	0·00941	0·00036
4·13 at +05	0·00933	0·00028
5·04 at +05	0·00934	0·00024
5·96 at +05	0·00935	0·00054
6·88 at +05	0·00932	0·00022
7·79 at +05	0·00932	0·00025
8·71 at +05	0·00933	0·00027
9·63 at +05	0·00932	0·00020
1·05 at +06	0·00934	0·00032
1·15 at +06	0·00935	0·00026
1·24 at +06	0·00929	0·00020
1·33 at +06	0·00937	0·00022
1·42 at +06	0·00934	0·00023
1·51 at +06	0·00932	0·00020
1·60 at +06	0·00932	0·00019
1·70 at +06	0·00932	0·00027
1·79 at +06	0·00933	0·00032
1·88 at +06	0·00935	0·00025
1·97 at +05	0·00934	0·00026
2·06 at +06	0·00934	0·00023
2·16 at +06	0·00932	0·00022

the change in Stanton number. The former group is typified by Rubesin [8], Kendall *et al.* [9] and Torii [3]. The latter group is represented by Mickley *et al.* [1], Spalding [10], and Kutateladze [11]. The simplest of all theories is one suggested by Mickley, and by Spalding (their analyses differ only in choice of the descriptor for the blowing parameter; the assumptions and results are identical). This can variously be described as a "stagnant film" or a "Couette flow" analysis. The essential features are: (1) the boundary-layer energy equation is reduced to an ordinary differential equation by discarding all x-derivatives; (2) the thickness of the "stagnant film" or the "Couette layer" is assumed to be unaffected by blowing; and (3) the transport mechanisms inside the boundary layer are assumed unaffected by the blowing.

One would be hard pressed indeed to justify these assumptions on any physical grounds and it is easy to see why the later, more mechanistic, analyses were subsequently proposed. Perhaps the most surprising outcome of the present experiments is the demonstration that the Mickley–Spalding theory is by far the most successful in predicting the variation of Stanton number with blowing, for the conditions tested here. It should quickly be added that these results are restricted to the case of uniform blowing along a plate of uniform temperature, with a uniform free-stream velocity above the plate. More advanced theories may be relatively more successful in handling complex cases, variable blowing, variable temperature, etc., but that remains to be seen.

The Mickley–Spalding theory predicts that the variation in Stanton number can be correlated by

$$St/St_0 = \frac{\ln(1 + B)}{B} \text{ where } B = \dot{m}''/GSt.$$

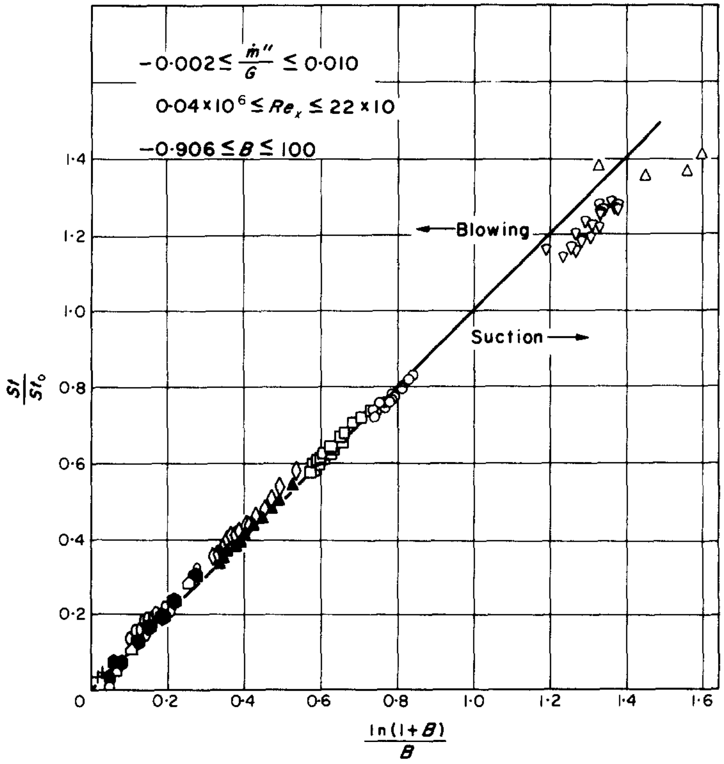

FIG. 9. St/St_0 vs. $\ln(1 + B)/B$.

Figure 9 shows the experimental data plotted in these terms. The region for which St/St_0 is less than 1·0 is the blowing region, the remainder is suction. The agreement between experiment and this elementary theory is extremely good for all values of blowing. The deviation between theory and experiment, at the high suction conditions, represents a 5 per cent shift from predicted values of Stanton number. The behavior of the function ln $(1 + B)$ as B approaches $-1·0$ is such as to greatly amplify any irregularities in the data. No claim can therefore be made, based on these tests, for the accuracy of the Couette flow model for high suction values.

CONCLUSIONS

(1) An apparatus has been constructed which is capable of measuring Stanton number within 0·0001 units over the range of conditions between boundary-layer blow-off and the asymptotic suction layer (roughly between $\dot{m}''/G = 0·01$ and $-0·01$) except for high suction, where the inaccuracy is believed to be on the order of 0·0003 units.

(2) The initial experimental program has been completed, resulting in a set of data describing the variation of Stanton number with blowing (and suction) over the full range of conditions described above, with the blowing fraction uniform along the plate.

(3) The data given in Table 2 show excellent agreement with the theoretical predictions attributable to Mickley [1] or Spalding, i.e.

$$\frac{St}{St_0} = \frac{\ln(1 + B)}{B}.$$

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Résumé—Il existe un besoin pour des travaux expérimentaux supplémentaires dans le domaine du transport de chaleur à travers une couche limite turbulente avec soufflage et aspiration. On a construit un appareil qui permet de déterminer le nombre de Stanton à 0,0001 près dans la plus grande partie de la gamme entre la couche d'aspiration asymptotique et le découlement par soufflage de la couche limite.

Des résultats sont présentés dans le cas d'un soufflage et d'une aspiration uniformes, d'une vitesse de l'écoulement libre constante, et de propriétes essentiellement constantes. Les nombres de Stanton variaient de 0,0080 (comportement de couche d'aspiration asymptotique; soufflage relatif de $-0{,}00756$) à une valeur de 0,0001 (au voisinage du décollement par soufflage; soufflage relatif de $+0{,}00955$). La gamme des nombres de Reynolds allait de $1{,}3 \times 10^5$ à $2{,}3 \times 10^6$.

Les résultats sont présentés sous forme de tableaux et de graphiques.

Zusammenfassung—Es besteht ein Bedarf an zusätzlicher Versuchsarbeit auf dem Gebiet der Wärmeübertragung durch eine turbulente Grenzschicht mit Einblasung und Absaugung. Es wird eine Apparatur entwickelt, welche die Bestimmung der Stanton-Zahl innerhalb von 0,0001 Einheiten im grössten Teil des Bereiches zwischen der asymptotischen Absetzungsschicht und dem scheinbaren "Abblasen" der Grenzschicht gestattet.

Versuchswerte werden angegeben für den Fall gleichmässiger Einblasung und Absaugung konstanter Freistromgeschwindigkeit und im wesentlichen konstanter Stoffwerte.

Der Bereich der Stanton-Zahl erstreckt sich von 0,0080 (asymptotisches Verhalten der Grenzschicht; Ausblasanteil −0,00765) bis 0.0001 (nahe "Abblasen"; Ausblasanteil +0,00955). Die Reynolds-Zahlen umfassen den Bereich von 1,3 × 10^5 bis 2,3 × 10^6. Die Ergebnisse werden in Tabellen und Diagrammen wiedergegeben.

Аннотация—Необходимо проведение дополнительного экспериментального исследования теплообмена при турбулентном обтекании проницаемой пластины при вдуве и отсосе. Создана установка, позволяющая определение числа Стантона до 0,0001 в большем диапазоне изменения интенсивности вдува и отсоса от условий асимптотического отсоса пограничного слоя до «кажущегося отдува» пограничного слоя.

Приводятся данные, полученные при однородном вдуве и отсосе, постоянной скорости свободного потока и постоянных физических свойствах. Числа Стантона изменялись от 0,0080 (асимптотический отсос пограничного слоя при величине параметра отсоса, равной 0,00765) до 0,0001 (вблизи «отдува» при величине параметра вдува — 0,00955). Исследование проведено в диапазоне чисел Рейнольдса от 1,3×10^5 до 2,3×10^6. Результаты представлены графически и даны в таблицах.