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# HEAT TRANSFER TO A STRONGLY ACCELERATED TURBULENT BOUNDARY LAYER: SOME EXPERIMENTAL RESULTS, INCLUDING TRANSPIRATION

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**Abstract**—Heat transfer experiments have been carried out in air on a turbulent boundary layer subjected to a strongly accelerated free-stream flow, with and without surface transpiration. Stanton number, mean temperature and mean velocity profiles, and turbulence intensity profiles were measured along the accelerated region. The tests were conducted with favorable pressure gradients denoted by values of the acceleration parameter $K\left(=\frac{\nu}{U_\infty^2}\frac{dU_\infty}{dx}\right)$ of $2{\cdot}0 \times 10^{-6}$ and $2{\cdot}5 \times 10^{-6}$. The blowing fraction, $F(=\rho_0 V_0/\rho_\infty U_\infty)$, ranged from 0·0 to 0·004. The flow was incompressible ($U_{\infty,\max} = 86$ fps) with a moderate temperature difference, 25°F, across the boundary layer.

The primary objective of the program was to obtain detailed heat transfer data in strong accelerations and to provide a base for future prediction procedures. A secondary objective was to determine whether re-laminarization of the boundary layer occurs at $K = 2{\cdot}5 \times 10^{-6}$.

The experimental results demonstrate that the Stanton number, as a function of enthalpy thickness Reynolds number, falls increasing below the behavior observed in unaccelerated flow as $K$ is increased, with or without blowing. The profile traverses show that, at the end of acceleration, the boundary layer is still fully turbulent.

Further heat transfer results are presented which illustrate the effects of various conditions at the start of acceleration (notably the thickness of the thermal and hydrodynamic layers) and step-changes in blowing within the acceleration region.

## NOMENCLATURE

$C_f$, surface shear stress coefficient $(=\tau_0/(\frac{1}{2}\rho_\infty U_\infty^2))$;

$c_p$, specific heat;

$F$, mass flux ratio $(=\rho_0 V_0/\rho_\infty U_\infty)$;

$h$, surface heat transfer coefficient;

$K$, acceleration parameter $\left(=\frac{\nu}{U_\infty^2}\frac{dU_\infty}{dx}\right)$;

$Re_H$, enthalpy thickness Reynolds number $(=\Delta_2 U_\infty/\nu)$;

$Re_M$, momentum thickness Reynolds number $(=\theta U_\infty/\nu)$;

$R_t$, turbulent Reynolds number $\left(=\frac{y\sqrt{(\tau_t/\rho)}}{\nu}\right)$;

$St$, Stanton number $(=h/c_p\rho_\infty U_\infty)$;

$T^+$, normalized temperature in inner region coordinates $(=\bar{T}U_\tau/(StU_\infty))$;

$U, V$, mean velocity components in stream-wise and normal directions;

$U^+$, normalized streamwise velocity $(=U/U_\tau)$;

$U_\tau$, shear velocity $(=\sqrt{(\tau_0/\rho)})$;

$x$, denotes streamwise direction;

$y$, denotes normal direction;

$y^+$, inner region normal coordinate ($= yU_\tau/\nu$).

Greek letters

$\Delta_2$, enthalpy thickness

$$\left( = \int_0^\infty \frac{U}{U_\infty}\left(\frac{T - T_\infty}{T_w - T_\infty}\right) dy \right);$$

$\nu$, kinematic viscosity;

$\rho$, density;

$\tau$, shear stress;

$\theta$, momentum thickness

$$\left( = \int_0^\infty \frac{\rho U}{\rho_\infty U_\infty}\left(1 - \frac{\rho U}{\rho_\infty U_\infty}\right) dy \right).$$

Subscripts

$H$, denotes energy;

$\infty$, denotes free-stream;

$M$, denotes momentum;

0, denotes wall;

$t$, denotes turbulence.

## INTRODUCTION

THE PURPOSE of this paper is to present experimental results for heat transfer processes in turbulent boundary layers under the influence of a strong free-stream acceleration. This work is part of a series of experimental investigations which have been conducted on the Stanford Heat and Mass Transfer Apparatus and have been reported in a series of papers [1–7]. Kays [8] has summarized the most significant results and conclusions coming from these investigations.

In the final stage of this program, an extensive experimental investigation was carried out on the turbulent boundary layer with a strong free-stream acceleration, approaching relaminarization. It is the intent of the present paper to present selected experimental results for the thermal boundary layer from this most recent program in a form useful for comparison with the results of turbulent boundary layer prediction schemes.

Specifically, the objectives of this paper are:

1. To present Stanton number data for three transpiration rates ($F$ = 0·0, 0·002 and 0·004) with a strong constant-$K$ acceleration, $K = 2{\cdot}5 \times 10^{-6}$, and for the case of zero transpiration ($F$ = 0·0) with an additional, but lower, acceleration, $K = 2{\cdot}0 \times 10^{-6}$. These data, and the Stanton number data described below, include the unaccelerated regions which occur both before and after the acceleration region.
2. To present Stanton number data with a strong constant-$K$ acceleration, $K = 2{\cdot}5 \times 10^{-6}$, which show the response of the turbulent boundary layer to changes in initial conditions and boundary conditions, specifically the initial ratio of the thermal and hydrodynamic integral parameters, and to steps in blowing at the wall.
3. For each of these seven cases, to present initial temperature and velocity profiles to provide starting data for prediction methods.

## PREVIOUS EXPERIMENTAL FINDINGS

It has been well established that the Stanton number markedly decreases in strongly accelerated flows. Early experimental evidence suggested that a fundamental change in structure, perhaps relaminarization of the turbulent boundary layer, occurred under these conditions. This phenomenon was first discussed by Moretti and Kays [9] in relation to heat transfer and by Launder [10] and Schraub and Kline [11] from a hydrodynamic viewpoint.

More recently, Boldman *et al.* [12] and Back *et al.* [13] reported surface heat transfer and profile data for maximum values of $K$ up to $30 \times 10^{-6}$ and $8 \times 10^{-6}$, respectively. In both papers, heat transfer rates considerably below expected magnitudes for turbulent flow were found for levels of $K$ above 2–3 $\times 10^{-6}$. Caldwell and Seban [14] present similar experimental results for a range of $K$ from $5 \times 10^{-6}$ to $12 \times 10^{-6}$. In all three studies, the acceleration parameter $K$ varies rapidly throughout the region of acceleration and the boundary layer is in a non-equilibrium state.

Experimental results for surface heat transfer of a boundary layer in accelerated flow with transpiration have been reported by Thielbahr, Kays and Moffat [6]. This study was carried out over a range of the acceleration parameter, $K$, from $0{\cdot}57 \times 10^{-6}$ to $1{\cdot}45 \times 10^{-6}$, and a range of the transpiration parameter, $F$, from $-0{\cdot}004$ (sucking) to $+0{\cdot}006$ (blowing).

In those tests, and in the experimental tests reported in this paper, emphasis was placed on maintaining, within the acceleration region, a constant positive value of the acceleration parameter, $K$, a constant transpiration parameter, $F$, and a constant surface temperature, $T_0$. With these conditions it can be shown (see, for example, [6]) that the momentum boundary layer tends towards a constant momentum thickness Reynolds number, and this state is said to denote the "asymptotic" boundary layer, which is a particular type of equilibrium turbulent boundary layer. This boundary layer is characterized by complete hydrodynamic similarity and a constant skin friction coefficient $C_f/2$.

## TEST APPARATUS

The boundary layer was formed on the lower surface of a rectangular channel having initial cross-section dimensions of 6 in. high by 20 in. wide. The entire channel is 8 ft in length. The region of acceleration, extending over a distance of 20 in. begins 16 in. downstream of a $\frac{1}{16}$ in. high, $\frac{1}{4}$ in. wide flat boundary layer trip. The height of the upper wall of the duct can be varied to achieve the desired free-stream velocity; in the experiments described here a linear variation of the wall was utilized in order to achieve a constant value of the acceleration parameter $K$.

To illustrate the experimental setup and the free-stream conditions for an acceleration of $K = 2{\cdot}5 \times 10^{-6}$, Fig. 1 presents a typical setting of the upper wall, and the variations of free-stream velocity and $K$ through the region of acceleration.

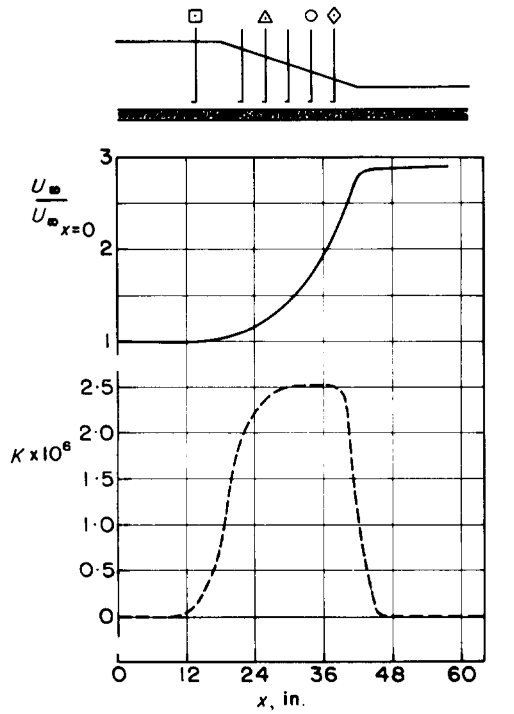


FIG. 1. Traverse locations and typical velocity distribution in the test apparatus for a strong acceleration.

The lower wall of the 8 ft channel is comprised of 24 segments of $\frac{1}{4}$ in. thick sintered bronze, allowing for tests with transpiration when desired. Surface temperature is measured by five thermocouples imbedded in the center 6 in. span of each segment. The segments are heated by wires situated in grooves in the bottom surface, spaced close enough together that the top surface temperature perturbation, due to wire spacing, is less than 0·04°F. The heat transfer between the surface and the boundary layer is deduced from an energy balance based on power and temperature measurements in each segment. Mean flow velocity profiles were obtained with a flattened pitot probe, while temperature profiles were measured with an iron–constantan thermocouple with the junction flattened. Turbulence profiles were taken with a 0·0002 in. constant temperature platinum hot wire and a linearized anemometer system. A detailed description of the apparatus and the data reduction method is contained in [15].

Prior to the experiments reported here, an extensive program was undertaken to qualify the test apparatus for use in strong favorable pressure gradients. The low entrance velocities made it necessary to prove the development of a uniform, two-dimensional boundary layer on the wall, and satisfactory energy balances in heat transfer. After some modification to the test rig, the uniformity of the main stream flow and spanwise variations in the boundary layer were found to be within acceptable limits. Transpiration qualification tests, with no main stream flow, were conducted in which the net energy delivered to each plate agreed within about 4 per cent with the measured energy transfer to the transpired air. Surface heat transfer results for the flat plate turbulent boundary layer agree with accepted correlations within 3 per cent. Energy balances between the surface heat transfer data and profile measurements were typically within 10 per cent in the accelerated flows. A more complete discussion of the qualification procedures is contained in [6] and [15].

## EXPERIMENTAL RESULTS

The main purpose of this section is to present Stanton number results to show the significant features of constant-$K$ flows at values of $K$ equal to and above $2{\cdot}0 \times 10^{-6}$. A secondary purpose is to present supporting profile data. The experimental data recorded at the twenty-four segments along the test surface are tabulated for each run in Table 1. Since each plate is 4 in. wide, each Stanton number represents an average over that distance. The enthalpy thickness Reynolds number is generally calculated by

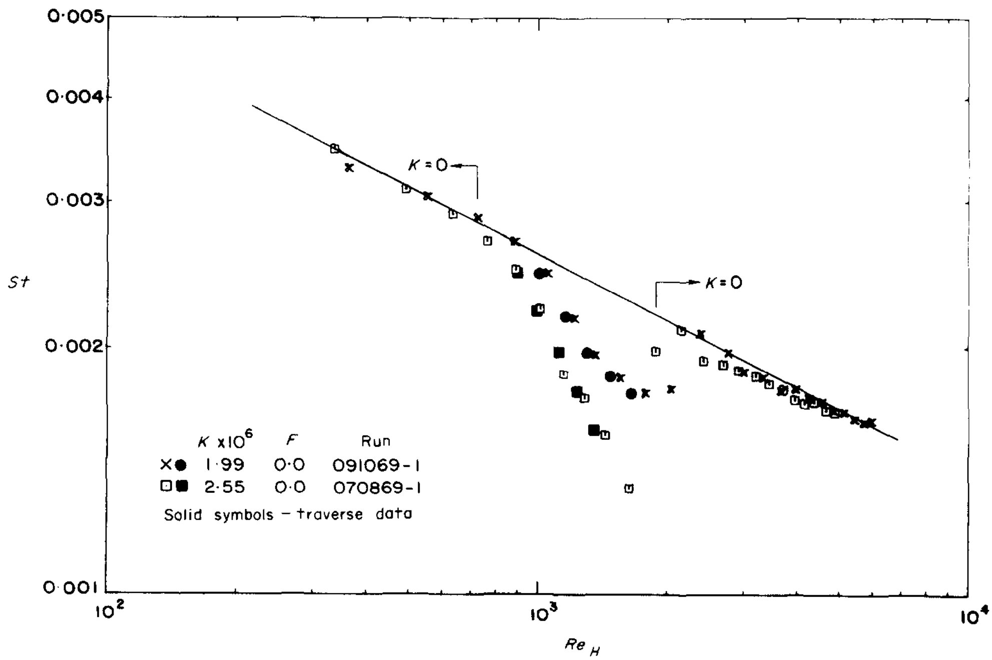


FIG. 2. Experimental results of surface heat transfer in a turbulent boundary layer with a strongly accelerated free-stream flow. ———, Moffat and Kays [1].

*Table 1. Surface heat transfer results*

| $X$(in.) | $U_\infty$(ft/s) | $K \times 10^6$ | $Re_H$ | $St$ | $Re_M$ | $C_f/2$ |
|---|---|---|---|---|---|---|
| | | | Run 091069–1 | | | |
| | $K = 2{\cdot}0 \times 10^{-6}$ nominal; $F = 0{\cdot}0$; $T_\infty = 74{\cdot}4 \pm 0{\cdot}5$°F; $T_0 = 96{\cdot}5 \pm 0{\cdot}3$°F; | | | | | |
| | | | $P = 29{\cdot}83$ in. Hg at exit | | | |
| 6 | 29·6 | 0·01 | 364 | 0·00330 | | |
| 10 | 29·5 | −0·06 | 553 | 0·00304 | | |
| 13·81* | 29·5 | 0·13 | 718 | 0·00284 | 1038 | 0·00231 |
| 14 | 29·2 | 0·13 | 726 | 0·00287 | | |
| 18 | 29·9 | 0·61 | 886 | 0·00268 | | |
| 21·81 | 32·2 | 1·68 | 1006 | 0·00246 | 1064 | 0·00254 |
| 22 | 32·0 | 1·68 | 1054 | 0·00246 | | |
| 25·86 | 36·5 | 2·03 | 1154 | 0·00218 | 942 | 0·00254 |
| 26 | 36·5 | 2·03 | 1213 | 0·00217 | | |
| 29·81 | 42·1 | 1·96 | 1297 | 0·00197 | 804 | 0·00254 |
| 30 | 42·5 | 1·96 | 1367 | 0·00196 | | |
| 33·59 | 50·1 | 2·03 | 1479 | 0·00185 | 747 | 0·00254 |
| 34 | 51·4 | 2·03 | 1561 | 0·00184 | | |
| 37·46 | 62·2 | 2·06 | 1655 | 0·00176 | 677 | 0·00254 |
| 38 | 64·6 | 2·06 | 1781 | 0·00176 | | |
| 42 | 84·0 | 0·85 | 2042 | 0·00178 | | |
| 46 | 86·4 | 0·01 | 2390 | 0·00208 | | |
| 50 | 86·4 | 0·01 | 2765 | 0·00197 | | |
| 54 | 86·4 | −0·01 | 3018 | 0·00187 | | |
| 58 | 86·3 | 0·00 | 3352 | 0·00184 | | |
| 62 | 86·3 | −0·00 | 3690 | 0·00177 | | |
| 66 | 86·3 | 0·01 | 3979 | 0·00178 | | |
| 70 | 86·5 | 0·00 | 4287 | 0·00174 | | |
| 74 | 86·5 | −0·01 | 4601 | 0·00172 | | |
| 78 | 86·4 | 0·01 | 4871 | 0·00168 | | |
| 82 | 86·5 | 0·00 | 5143 | 0·00167 | | |
| 86 | 86·6 | −0·00 | 5434 | 0·00164 | | |
| 90 | 86·5 | −0·01 | 5734 | 0·00162 | | |
| | | | Run 070869–1 | | | |
| | $K = 2{\cdot}5 \times 10^{-6}$ nominal; $F = 0{\cdot}0$; $T_\infty = 72{\cdot}4 \pm 0{\cdot}5$°F; $T_0 = 97{\cdot}4 \pm 2{\cdot}2$°F; | | | | | |
| | | | $P = 29{\cdot}90$ in. Hg at exit | | | |
| 6 | 23·3 | 0·01 | 336 | 0·00348 | | |
| 10 | 23·3 | −0·24 | 492 | 0·00311 | | |
| 13·81 | 23·3 | 0·21 | 624 | 0·00290 | 754 | 0·00250 |
| 14 | 23·2 | 0·21 | 631 | 0·00290 | | |
| 18 | 23·9 | 0·77 | 763 | 0·00269 | | |
| 21·81 | 25·0 | 2·05 | 895 | 0·00248 | 817 | 0·00255 |
| 22 | 25·5 | 2·05 | 886 | 0·00249 | | |
| 25·86 | 28·4 | 2·38 | 990 | 0·00222 | 738 | 0·00260 |
| 26 | 28·7 | 2·38 | 1012 | 0·00223 | | |
| 29·81 | 33·0 | 2·52 | 1120 | 0·00198 | 665 | 0·00260 |
| 30 | 33·5 | 2·52 | 1147 | 0·00186 | | |
| 33·59 | 39·0 | 2·54 | 1236 | 0·00177 | 595 | 0·00257 |
| 34 | 40·3 | 2·54 | 1287 | 0·00174 | | |
| 37·46 | 48·3 | 2·53 | 1345 | 0·00159 | 550 | 0·00248 |
| 38 | 50·6 | 2·53 | 1433 | 0·00157 | | |
| 42 | 65·6 | 1·10 | 1627 | 0·00135 | | |
| 46 | 67·2 | −0·03 | 1878 | 0·00198 | | |
| 50 | 67·2 | 0·01 | 2144 | 0·00210 | | |
| 54 | 67·3 | 0·02 | 2425 | 0·00193 | | |
| 58 | 67·5 | 0·01 | 2701 | 0·00191 | | |
| 62 | 67·6 | 0·01 | 2931 | 0·00188 | | |
| 66 | 67·6 | 0·00 | 3209 | 0·00185 | | |
| 70 | 67·7 | 0·00 | 3449 | 0·00181 | | |

*Table 1 (continued)*

| $X$(in.) | $U_\infty$(ft/s) | $K \times 10^6$ | $Re_H$ | $St$ | $Re_M$ | $C_f/2$ |
|---|---|---|---|---|---|---|
| 74 | 67·7 | −0·02 | 3719 | 0·00178 | | |
| 78 | 67·6 | 0·01 | 3957 | 0·00173 | | |
| 82 | 67·7 | 0·01 | 4164 | 0·00171 | | |
| 86 | 67·7 | 0·01 | 4382 | 0·00172 | | |
| 90 | 67·7 | −0·01 | 4670 | 0·00168 | | |
| Run 072769–2 $K = 2{\cdot}5 \times 10^6$ nominal; $F = 0{\cdot}002 \pm 0{\cdot}0001$; $T_\infty = 73{\cdot}31 \pm 0{\cdot}5°F$; $T_0 = 94{\cdot}2 \pm 0{\cdot}4°F$; $P = 29{\cdot}95$ in.Hg at exit | | | | | | |
| 6 | 23·4 | 0·07 | 430 | 0·00276 | | |
| 10 | 23·4 | 0·08 | 651 | 0·00237 | | |
| 13·81 | 23·9 | 0·20 | 835 | 0·00218 | 966 | 0·00190 |
| 14 | 23·5 | 0·20 | 846 | 0·00218 | | |
| 18 | 24·1 | 0·76 | 1050 | 0·00197 | | |
| 21·81 | 26·0 | 1·97 | 1204 | 0·00181 | 1096 | 0·00210 |
| 22 | 25·7 | 1·96 | 1242 | 0·00181 | | |
| 25·86 | 29·4 | 2·46 | 1384 | 0·00167 | 1005 | 0·00210 |
| 26 | 29·1 | 2·45 | 1451 | 0·00157 | | |
| 29·81 | 34·2 | 2·47 | 1582 | 0·00156 | 939 | 0·00210 |
| 30 | 34·0 | 2·47 | 1695 | 0·00141 | | |
| 33·59 | 40·7 | 2·58 | 1864 | 0·00146 | 871 | 0·00210 |
| 34 | 41·1 | 2·58 | 2003 | 0·00148 | | |
| 37·46 | 50·4 | 2·55 | 2109 | 0·00138 | 837 | 0·00210 |
| 38 | 51·7 | 2·55 | 2296 | 0·00141 | | |
| 42 | 67·4 | 1·06 | 2702 | 0·00127 | | |
| 46 | 69·1 | −0·01 | 3172 | 0·00135 | | |
| 50 | 69·0 | 0·01 | 3587 | 0·00125 | | |
| 54 | 69·1 | −0·01 | 4076 | 0·00117 | | |
| 58 | 68·9 | −0·01 | 4547 | 0·00112 | | |
| 62 | 68·8 | −0·01 | 5035 | 0·00111 | | |
| 66 | 68·8 | −0·00 | 5379 | 0·00105 | | |
| 70 | 68·9 | 0·00 | 5788 | 0·00102 | | |
| 74 | 68·8 | −0·01 | 6217 | 0·00097 | | |
| 78 | 68·8 | 0·01 | 6620 | 0·00098 | | |
| 82 | 68·9 | 0·01 | 7067 | 0·00094 | | |
| 86 | 69·0 | −0·00 | 7468 | 0·00093 | | |
| 90 | 68·9 | −0·01 | 7876 | 0·00093 | | |
| Run 083069–1 $K = 2{\cdot}5 \times 10^{-6}$ nominal; $F = 0{\cdot}004 \pm 0{\cdot}0003$; $T_\infty = 72{\cdot}1 \pm 0{\cdot}5°F$; $T_0 = 98{\cdot}8 \pm 0{\cdot}5°F$; $P = 29{\cdot}69$ in. Hg at exit | | | | | | |
| 6 | 23·3 | −0·15 | 538 | 0·00216 | | |
| 10 | 23·4 | 0·17 | 821 | 0·00177 | | |
| 13·81 | 23·6 | 0·45 | 1066 | 0·00154 | 1218 | 0·00130 |
| 14 | 23·5 | 0·45 | 1078 | 0·00151 | | |
| 18 | 24·1 | 0·71 | 1348 | 0·00137 | | |
| 21·81 | 25·7 | 1·92 | 1539 | 0·00127 | 1402 | 0·00145 |
| 22 | 26·0 | 1·92 | 1599 | 0·00119 | | |
| 25·86 | 29·2 | 2·45 | 1814 | 0·00119 | 1290 | 0·00150 |
| 26 | 29·4 | 2·45 | 1876 | 0·00122 | | |
| 29·81 | 33·9 | 2·49 | 2167 | 0·00113 | 1185 | 0·00154 |
| 30 | 34·4 | 2·49 | 2178 | 0·00110 | | |
| 33·59 | 40·4 | 2·54 | 2470 | 0·00108 | 1155 | 0·00158 |
| 34 | 41·6 | 2·54 | 2532 | 0·00107 | | |
| 37·46 | 50·0 | 2·52 | 2862 | 0·00102 | 1109 | 0·00159 |
| 38 | 52·3 | 2·52 | 2959 | 0·00104 | | |
| 42 | 68·2 | 1·09 | 3541 | 0·00091 | | |
| 46 | 7·03 | 0·01 | 4215 | 0·00090 | | |
| 50 | 70·4 | 0·02 | 4929 | 0·00076 | | |

*Table* 1 (*continued*)

| $X$(in.) | $U_\infty$(ft/s) | $K \times 10^6$ | $Re_H$ | $St$ | $Re_M$ | $C_f/2$ |
|---|---|---|---|---|---|---|
| 54 | 70·4 | −0·01 | 5590 | 0·00069 | | |
| 58 | 70·3 | −0·00 | 6248 | 0·00068 | | |
| 62 | 70·3 | 0·00 | 6882 | 0·00060 | | |
| 66 | 70·3 | 0·00 | 7457 | 0·00061 | | |
| 70 | 70·4 | 0·00 | 8102 | 0·00056 | | |
| 74 | 70·3 | −0·01 | 8835 | 0·00053 | | |
| 78 | 70·3 | 0·01 | 9309 | 0·00056 | | |
| 82 | 70·4 | 0·00 | 9945 | 0·00050 | | |
| 86 | 70·4 | 0·01 | 10542 | 0·00052 | | |
| 90 | 70·4 | −0·01 | 11110 | 0·00051 | | |

Run 092469–1

$K = 2{\cdot}5 \times 10^6$ nominal; $F = 0{\cdot}0$; $T_\infty = 72{\cdot}9 \pm 0{\cdot}5$°F; $T_0 = 98{\cdot}7 \pm 0{\cdot}4$°F; $P = 29{\cdot}97$ in. Hg at exit

| $X$(in.) | $U_\infty$(ft/s) | $K \times 10^6$ | $Re_H$ | $St$ | $Re_M$ | $C_f/2$ |
|---|---|---|---|---|---|---|
| 6 | 23·2 | 0·13 | 321 | 0·00345 | | |
| 10 | 23·3 | 0·02 | 475 | 0·00315 | | |
| 14 | 23·2 | −0·02 | 621 | 0·00289 | | |
| 18 | 23·1 | −0·05 | 748 | 0·00277 | | |
| 22 | 23·1 | −0·09 | 872 | 0·00269 | | |
| 26 | 23·0 | 0·02 | 992 | 0·00257 | | |
| 30 | 23·2 | 0·07 | 1109 | 0·00244 | | |
| 34 | 23·1 | 0·03 | 1225 | 0·00237 | | |
| 38 | 23·3 | 0·01 | 1329 | 0·00235 | | |
| 42 | 23·1 | −0·08 | 1431 | 0·00232 | | |
| 46 | 23·2 | 0·22 | 1557 | 0·00233 | | |
| 46·76 | 23·5 | 0·22 | 1577 | 0·00242 | 1529 | 0·00210 |
| 50 | 23·3 | 1·42 | 1657 | 0·00230 | | |
| 54 | 23·8 | 0·99 | 1773 | 0·00213 | | |
| 58 | 25·6 | 1·78 | 1866 | 0·00210 | | |
| 58·94 | 26·4 | 1·78 | 1843 | 0·00202 | 1366 | 0·00267 |
| 62 | 29·0 | 2·44 | 1975 | 0·00181 | | |
| 62·86 | 29·7 | 2·44 | 1976 | 0·00187 | 1162 | 0·00264 |
| 66 | 33·6 | 2·48 | 2085 | 0·00171 | | |
| 66·76 | 34·6 | 2·48 | 2040 | 0·00170 | 938 | 0·00257 |
| 70 | 40·5 | 2·64 | 2218 | 0·00150 | | |
| 70·69 | 42·0 | 2·64 | 2169 | 0·00152 | 762 | 0·00243 |
| 74 | 51·2 | 2·55 | 2368 | 0·00134 | | |
| 74·58 | 53·2 | 2·55 | 2261 | 0·00133 | 640 | 0·00217 |
| 78 | 64·0 | 0·73 | 2511 | 0·00118 | | |
| 82 | 64·7 | 0·01 | 2744 | 0·00172 | | |
| 86 | 64·8 | 0·01 | 2979 | 0·00200 | | |
| 90 | 64·7 | −0·01 | 3212 | 0·00192 | | |

Run 100269–1

$K = 2{\cdot}5 \times 10^{-6}$ nominal; $F = 0{\cdot}0$; $T_\infty = 66{\cdot}3 \pm 0{\cdot}5$°F; $T_0 = 88{\cdot}4 \pm 1{\cdot}2$°F; $P = 29{\cdot}80$ in. Hg at exit

| $X$(in.) | $U_\infty$(ft/s) | $K \times 10^6$ | $Re_H$ | $St$ | $Re_M$ | $C_f/2$ |
|---|---|---|---|---|---|---|
| 42 | 23·2 | −0·15 | 167 | 0·00418 | | |
| 46 | 23·2 | 0·02 | 336 | 0·00304 | | |
| 46·76 | 23·5 | 0·02 | 363 | 0·00310 | 1456 | 0·00210 |
| 50 | 23·3 | 0·34 | 480 | 0·00292 | | |
| 54 | 23·7 | 0·88 | 615 | 0·00264 | | |
| 58 | 25·5 | 1·86 | 744 | 0·00251 | | |
| 58·94 | 26·4 | 1·86 | 757 | 0·00243 | 1327 | 0·00267 |
| 62 | 28·7 | 2·27 | 874 | 0·00223 | | |
| 66 | 33·1 | 2·54 | 1007 | 0·00201 | | |
| 66·76 | 34·6 | 2·54 | 1015 | 0·00195 | 895 | 0·00257 |
| 70 | 40·2 | 2·58 | 1153 | 0·00174 | | |
| 74 | 50·7 | 2·53 | 1295 | 0·00153 | | |
| 74·58 | 53·2 | 2·53 | 1372 | 0·00151 | 595 | 0·00217 |
| 78 | 63·5 | 0·73 | 1478 | 0·00136 | | |

*Table 1 (continued)*

| $X$(in.) | $U_\infty$(ft/s) | $K \times 10^6$ | $Re_H$ | $St$ | $Re_M$ | $C_f/2$ |
|---|---|---|---|---|---|---|
| 82 | 64·2 | 0·02 | 1703 | 0·00202 | | |
| 86 | 64·3 | 0·00 | 1960 | 0·00222 | | |
| 90 | 64·2 | −0·02 | 2236 | 0·00209 | | |
| Run 102469–1 | | | | | | |
| $K = 2{\cdot}5 \times 10^{-6}$ nominal; $F = 0{\cdot}0$, $X \leqslant 32$; $0{\cdot}0039 \pm 0{\cdot}0001$, $X > 32$; $T_\infty = 65{\cdot}6 \pm 0{\cdot}5$°F; $T_0 = 89{\cdot}7 \pm 0{\cdot}4$°F; $P = 29{\cdot}99$ in. Hg at exit | | | | | | |
| 6 | 23·6 | −0·30 | 345 | 0·00347 | | |
| 10 | 23·7 | 0·26 | 510 | 0·00313 | | |
| 13·81 | 23·6 | 0·21 | 650 | 0·00292 | 796 | 0·00246 |
| 14 | 23·6 | 0·21 | 656 | 0·00296 | | |
| 18 | 23·9 | 0·69 | 779 | 0·00279 | | |
| 22 | 25·7 | 1·71 | 922 | 0·00251 | | |
| 26 | 29·2 | 2·55 | 1053 | 0·00223 | | |
| 30 | 34·4 | 2·55 | 1186 | 0·00192 | | |
| 34 | 42·1 | 2·64 | 1482 | 0·00086 | | |
| 38 | 54·3 | 2·69 | 1937 | 0·00112 | | |
| 42 | 74·6 | 1·20 | 2608 | 0·00091 | | |
| 46 | 77·6 | −0·01 | 3380 | 0·00093 | | |
| 50 | 77·5 | 0·17 | 4122 | 0·00081 | | |
| 54 | 77·6 | 0·00 | 4829 | 0·00069 | | |
| 58 | 77·5 | −0·00 | 5560 | 0·00070 | | |
| 62 | 77·5 | 0·00 | 6318 | 0·00061 | | |
| 66 | 77·5 | 0·00 | 7078 | 0·00058 | | |
| 70 | 77·7 | 0·00 | 7854 | 0·00057 | | |
| 74 | 77·6 | −0·01 | 8465 | 0·00056 | | |
| 78 | 77·6 | 0·01 | 9201 | 0·00054 | | |
| 82 | 77·7 | 0·01 | 9901 | 0·00054 | | |
| 86 | 77·7 | −0·01 | 10635 | 0·00052 | | |
| 90 | 77·5 | −0·01 | 11372 | 0·00052 | | |
| Run 111369–2 | | | | | | |
| $K = 2{\cdot}5 \times 10^{-6}$ nominal; $F = 0{\cdot}004 \pm 0{\cdot}002$, $X \leqslant 32$; $0{\cdot}0$, $X > 32$; $T_\infty = 68{\cdot}7 \pm 0{\cdot}5$°F; $T_0 = 94{\cdot}3 \pm 1{\cdot}2$°F; $P = 30{\cdot}13$ in. Hg at exit | | | | | | |
| 6 | 23·2 | −0·02 | 478 | 0·00216 | | |
| 10 | 23·2 | 0·25 | 768 | 0·00179 | | |
| 13·81 | 23·3 | 0·23 | 1020 | 0·00156 | 1210 | 0·00130 |
| 14 | 23·3 | 0·23 | 1033 | 0·00155 | | |
| 18 | 23·8 | 0·88 | 1317 | 0·00134 | | |
| 22 | 25·4 | 1·84 | 1572 | 0·00123 | | |
| 26 | 29·0 | 2·59 | 1848 | 0·00117 | | |
| 30 | 34·3 | 2·61 | 2206 | 0·00106 | | |
| 34 | 42·0 | 2·62 | 2476 | 0·00170 | | |
| 38 | 53·8 | 2·62 | 2669 | 0·00147 | | |
| 42 | 72·5 | 1·06 | 2869 | 0·00126 | | |
| 46 | 74·1 | −0·01 | 3083 | 0·00191 | | |
| 50 | 74·0 | 0·01 | 3440 | 0·00181 | | |
| 54 | 74·1 | 0·01 | 3778 | 0·00173 | | |
| 58 | 74·1 | −0·01 | 4040 | 0·00172 | | |
| 62 | 74·0 | −0·01 | 4304 | 0·00168 | | |
| 66 | 74·0 | 0·00 | 4571 | 0·00168 | | |
| 70 | 74·1 | 0·00 | 4827 | 0·00164 | | |
| 74 | 74·1 | −0·01 | 5099 | 0·00163 | | |
| 78 | 74·1 | 0·01 | 5336 | 0·00162 | | |
| 82 | 74·2 | 0·01 | 5587 | 0·00159 | | |
| 86 | 74·2 | −0·01 | 5839 | 0·00160 | | |
| 90 | 74·1 | −0·01 | 6115 | 0·00157 | | |

* At the non-integer values of $X$, the values of $Re_H$, $Re_M$ and $C_f/2$ are evaluated from temperature and velocity profile data. At the plate centerlines, $Re_H$ is obtained by integration of the energy equation along $X$.

*Table 2. Starting temperature and velocity profiles*

| $Y$(in.) | $Y^+$ | $T^+$ | $U^+$ | $\bar{T}$ | $U/U_\infty$ |
|---|---|---|---|---|---|
| | | Run 091069–1; $X$ = 13·81 in. | | | |
| 0·0035 | 2·4 | 3·0 | 2·5 | 0·176 | 0·119 |
| 0·0055 | 3·8 | 4·1 | 3·9 | 0·240 | 0·186 |
| 0·0095 | 6·7 | 5·8 | 6·4 | 0·345 | 0·307 |
| 0·0135 | 9·4 | 7·1 | 8·4 | 0·424 | 0·401 |
| 0·0195 | 13·6 | 8·7 | 10·3 | 0·511 | 0·497 |
| 0·0285 | 20·0 | 10·0 | 11·9 | 0·590 | 0·570 |
| 0·0435 | 30·5 | 11·2 | 13·1 | 0·664 | 0·631 |
| 0·0635 | 44·6 | 12·1 | 14·0 | 0·717 | 0·673 |
| 0·0985 | 69·2 | 13·2 | 14·8 | 0·776 | 0·716 |
| 0·1635 | 115·1 | 14·3 | 15·0 | 0·840 | 0·775 |
| 0·2635 | 185·8 | 15·4 | 17·5 | 0·905 | 0·848 |
| 0·4385 | 309·6 | 16·5 | 19·4 | 0·971 | 0·942 |
| 0·6385 | 451·1 | 17·0 | 20·5 | 0·998 | 0·994 |
| 0·7385 | 521·7 | 17·0 | 20·6 | 1·000 | 0·998 |
| | | Run 070869–1; $X$ = 13·81 in. | | | |
| 0·0035 | 2·0 | 2·4 | 2·1 | 0·143 | 0·105 |
| 0·0055 | 3·1 | 3·4 | 3·4 | 0·200 | 0·165 |
| 0·0075 | 4·3 | 4·3 | 4·6 | 0·247 | 0·225 |
| 0·0105 | 6·1 | 5·4 | 5·8 | 0·320 | 0·288 |
| 0·0155 | 9·0 | 7·0 | 8·0 | 0·410 | 0·397 |
| 0·0225 | 13·1 | 8·5 | 10·0 | 0·497 | 0·500 |
| 0·0305 | 17·8 | 9·8 | 11·3 | 0·564 | 0·565 |
| 0·0405 | 23·6 | 10·7 | 12·4 | 0·621 | 0·616 |
| 0·0585 | 34·2 | 11·8 | 13·3 | 0·681 | 0·667 |
| 0·0835 | 48·8 | 12·7 | 14·2 | 0·735 | 0·709 |
| 0·1185 | 69·4 | 13·5 | 15·0 | 0·781 | 0·749 |
| 0·1685 | 98·8 | 14·4 | 15·9 | 0·832 | 0·794 |
| 0·2685 | 157·8 | 15·6 | 17·3 | 0·900 | 0·868 |
| 0·4185 | 246·3 | 16·7 | 18·9 | 0·963 | 0·954 |
| 0·6185 | 364·2 | 17·3 | 19·8 | 0·996 | 0·998 |
| 0·7185 | 423·2 | 17·4 | 19·8 | 1·000 | 1·000 |
| | | Run 072769–1; $X$ = 13·81 in. | | | |
| 0·0035 | 1·8 | 3·3 | 2·1 | 0·166 | 0·089 |
| 0·0055 | 2·9 | 4·5 | 3·2 | 0·224 | 0·140 |
| 0·0085 | 4·4 | 5·4 | 4·8 | 0·266 | 0·212 |
| 0·0145 | 7·6 | 7·3 | 7·2 | 0·364 | 0·317 |
| 0·0205 | 10·6 | 8·7 | 9·2 | 0·429 | 0·405 |
| 0·0295 | 15·3 | 9·9 | 10·9 | 0·488 | 0·480 |
| 0·0465 | 24·2 | 11·8 | 12·5 | 0·582 | 0·555 |
| 0·0715 | 37·3 | 13·0 | 13·9 | 0·640 | 0·615 |
| 0·1065 | 55·6 | 13·9 | 15·0 | 0·685 | 0·660 |
| 0·1815 | 94·8 | 15·8 | 16·6 | 0·776 | 0·736 |
| 0·3065 | 160·5 | 17·6 | 18·9 | 0·866 | 0·839 |
| 0·4565 | 239·4 | 19·3 | 21·0 | 0·944 | 0·935 |
| 0·6565 | 344·7 | 20·3 | 22·4 | 0·995 | 0·996 |
| 0·7565 | 397·2 | 20·4 | 22·4 | 1·000 | 1·000 |
| | | Run 083069–1; $X$ = 13·81 in. | | | |
| 0·0035 | 1·4 | 2·1 | 1·9 | 0·090 | 0·067 |
| 0·0055 | 2·3 | 3·2 | 3·0 | 0·136 | 0·106 |
| 0·0075 | 3·1 | 3·7 | 4·1 | 0·162 | 0·144 |
| 0·0125 | 5·2 | 5·2 | 6·2 | 0·225 | 0·221 |
| 0·0205 | 8·5 | 7·1 | 9·5 | 0·305 | 0·335 |
| 0·0295 | 12·4 | 9·2 | 11·2 | 0·397 | 0·399 |

*Table 2 (continued)*

| $Y$(in.) | $Y^+$ | $T^+$ | $U^+$ | $\bar{T}$ | $U/U_\infty$ |
|---|---|---|---|---|---|
| 0·0395 | 16·5 | 10·3 | 12·5 | 0·447 | 0·448 |
| 0·0595 | 24·9 | 11·9 | 14·1 | 0·515 | 0·506 |
| 0·0945 | 39·7 | 13·8 | 15·8 | 0·593 | 0·568 |
| 0·1395 | 58·6 | 15·4 | 17·3 | 0·657 | 0·623 |
| 0·2145 | 90·3 | 17·1 | 19·2 | 0·734 | 0·692 |
| 0·3395 | 143·2 | 19·4 | 22·0 | 0·829 | 0·794 |
| 0·4895 | 207·0 | 21·4 | 24·9 | 0·913 | 0·898 |
| 0·6895 | 292·0 | 23·1 | 27·2 | 0·983 | 0·984 |
| 0·9145 | 387·5 | 23·5 | 27·6 | 1·000 | 0·999 |
| | | Run 092469–1: $X$ = 46·76 in. | | | |
| 0·0035 | 1·8 | 1·9 | 2·3 | 0·097 | 0·104 |
| 0·0055 | 2·9 | 2·8 | 3·6 | 0·149 | 0·163 |
| 0·0105 | 5·5 | 4·6 | 5·9 | 0·243 | 0·269 |
| 0·0185 | 9·8 | 6·7 | 8·8 | 0·357 | 0·400 |
| 0·0275 | 14·6 | 8·5 | 10·7 | 0·450 | 0·486 |
| 0·0395 | 21·0 | 9·6 | 12·0 | 0·508 | 0·547 |
| 0·0645 | 34·4 | 11·0 | 13·4 | 0·584 | 0·610 |
| 0·1095 | 58·4 | 12·3 | 14·4 | 0·649 | 0·661 |
| 0·2095 | 111·9 | 13·7 | 15·9 | 0·722 | 0·729 |
| 0·3595 | 192·4 | 15·1 | 17·4 | 0·797 | 0·800 |
| 0·5845 | 313·4 | 16·7 | 19·1 | 0·874 | 0·881 |
| 0·8845 | 475·2 | 18·1 | 20·8 | 0·951 | 0·963 |
| 1·1095 | 596·5 | 18·8 | 21·5 | 0·987 | 0·994 |
| 1·3595 | 731·2 | 19·1 | 21·6 | 1·000 | 1·000 |
| | | Run 100269–1: $X$ = 46·76 in. | | | |
| 0·0035 | 1·9 | 2·3 | 2·3 | 0·154 | 0·104 |
| 0·0055 | 2·9 | 3·3 | 3·6 | 0·223 | 0·163 |
| 0·0105 | 5·7 | 5·1 | 5·9 | 0·342 | 0·269 |
| 0·0165 | 8·9 | 6·9 | 8·1 | 0·465 | 0·371 |
| 0·0245 | 13·4 | 8·5 | 10·1 | 0·569 | 0·462 |
| 0·0335 | 18·2 | 9·6 | 11·4 | 0·643 | 0·521 |
| 0·0455 | 24·8 | 10·7 | 12·3 | 0·716 | 0·569 |
| 0·0705 | 38·5 | 11·8 | 13·3 | 0·790 | 0·617 |
| 0·1155 | 63·2 | 12·9 | 14·4 | 0·863 | 0·666 |
| 0·1805 | 98·9 | 13·7 | 15·4 | 0·916 | 0·713 |
| 0·3055 | 167·6 | 14·5 | 16·8 | 0·964 | 0·777 |
| 0·4805 | 263·7 | 14·8 | 18·3 | 0·988 | 0·847 |
| 0·6805 | 373·6 | 15·0 | 19·6 | 0·995 | 0·912 |
| 0·8805 | 483·5 | 15·0 | 20·7 | 1·000 | 0·962 |
| | | Run 102469–1: $X$ = 13·81 in. | | | |
| 0·0035 | 2·1 | 3·0 | 2·0 | 0·180 | 0·097 |
| 0·0055 | 3·3 | 3·8 | 3·1 | 0·225 | 0·152 |
| 0·0095 | 5·6 | 4·8 | 5·2 | 0·284 | 0·254 |
| 0·0155 | 9·2 | 7·1 | 7·9 | 0·422 | 0·388 |
| 0·0225 | 13·5 | 8·7 | 10·0 | 0·517 | 0·492 |
| 0·0335 | 20·1 | 10·0 | 11·8 | 0·594 | 0·582 |
| 0·0525 | 31·5 | 11·3 | 13·3 | 0·673 | 0·654 |
| 0·0755 | 45·4 | 12·3 | 14·2 | 0·728 | 0·699 |
| 0·1305 | 78·5 | 13·5 | 15·4 | 0·799 | 0·760 |
| 0·2305 | 138·9 | 14·9 | 17·0 | 0·878 | 0·842 |
| 0·3305 | 199·4 | 15·7 | 18·3 | 0·929 | 0·906 |
| 0·4805 | 290·3 | 16·6 | 19·6 | 0·977 | 0·973 |
| 0·6805 | 411·3 | 17·0 | 20·1 | 0·998 | 0·998 |
| 0·8805 | 532·2 | 17·0 | 20·2 | 1·000 | 1·000 |

*Table 2 (continued)*

| $Y$(in.) | $Y^+$ | $T^+$ | $U^+$ | $\bar{T}$ | $U/U_\infty$ |
|---|---|---|---|---|---|
| | | Run 111369–2: $X$ = 13·81 in. | | | |
| 0·0035 | 1·5 | 2·3 | 1·7 | 0·102 | 0·060 |
| 0·0055 | 2·3 | 3·2 | 2·7 | 0·143 | 0·094 |
| 0·0075 | 3·2 | 3·9 | 3·6 | 0·174 | 0·128 |
| 0·0115 | 4·9 | 5·1 | 5·2 | 0·225 | 0·184 |
| 0·0185 | 7·9 | 7·6 | 8·1 | 0·333 | 0·287 |
| 0·0285 | 12·1 | 9·4 | 10·9 | 0·412 | 0·386 |
| 0·0385 | 16·4 | 10·3 | 12·4 | 0·454 | 0·440 |
| 0·0635 | 27·1 | 12·5 | 14·6 | 0·549 | 0·521 |
| 0·1085 | 46·4 | 14·4 | 16·5 | 0·629 | 0·590 |
| 0·1635 | 70·1 | 16·0 | 18·2 | 0·697 | 0·651 |
| 0·2635 | 113·2 | 18·1 | 20·7 | 0·787 | 0·744 |
| 0·3885 | 167·3 | 20·1 | 23·4 | 0·870 | 0·840 |
| 0·5635 | 243·2 | 21·9 | 26·3 | 0·950 | 0·947 |
| 0·7635 | 329·9 | 23·0 | 27·6 | 0·996 | 0·995 |
| 0·8635 | 373·1 | 23·1 | 27·7 | 1·000 | 0·999 |

integration of the energy equation up to the centerline of each plate, starting with a measured value prior to the acceleration region. An independent method, shown in Table 1 and presented in part of Fig. 2, is to evaluate the enthalpy thickness from profile measurements throughout the acceleration. The degree of agreement between these two methods is a measure of the boundary layer energy balance. The local Stanton number for each profile position is obtained by interpolating on a smooth curve through the data at the plate centerline. In order to provide starting data for investigators interested in attempting to predict the test results, the temperature and velocity profiles, which are taken in the constant velocity region prior to acceleration, are given in Table 2 for each test.

*Effects of strong acceleration, with and without blowing*

The surface heat transfer data, for nominal values of the acceleration parameter $K$ of $2{\cdot}0 \times 10^{-6}$ and $2{\cdot}5 \times 10^{-6}$, with no transpiration, are presented in Fig. 2 in terms of Stanton number and the enthalpy thickness Reynolds number. Boundary layer traverses of mean temperature, mean velocity, and the streamwise fluctuating velocity are presented in Fig. 3. The hydrodynamic data shown there, as well as all the hydrodynamic results discussed in this paper, are taken from the work of Loyd *et al.* [16], who studied the fluid mechanics of strongly accelerated boundary layer flows in parallel with the heat transfer tests discussed here.

A hydrodynamic similarity solution is possible for constant-$K$ turbulent boundary layers, and the mean velocity profiles appear to approach such a similarity condition near the end of acceleration. As expected from the momentum equation, surface skin friction is nearly constant. The turbulence profiles indicate that the intensity of the turbulence is decreasing throughout the accelerated zone. In the outer regions, the last two profiles in the accelerated zone show evidence of similarity. At the end of acceleration, the peak in the streamwise fluctuating velocity normalized by the free-stream velocity, $\sqrt{\overline{u'^2}}/U_\infty$, decreases to about 9 per cent, compared to 11 per cent prior to acceleration. For stronger accelerations, other experimenters have found the peak value to be reduced to 6 per cent [14] and 2 per cent [17].

With a constant wall temperature, a thermal equivalent of the hydrodynamic similarity solution does not exist. The continuous reduction

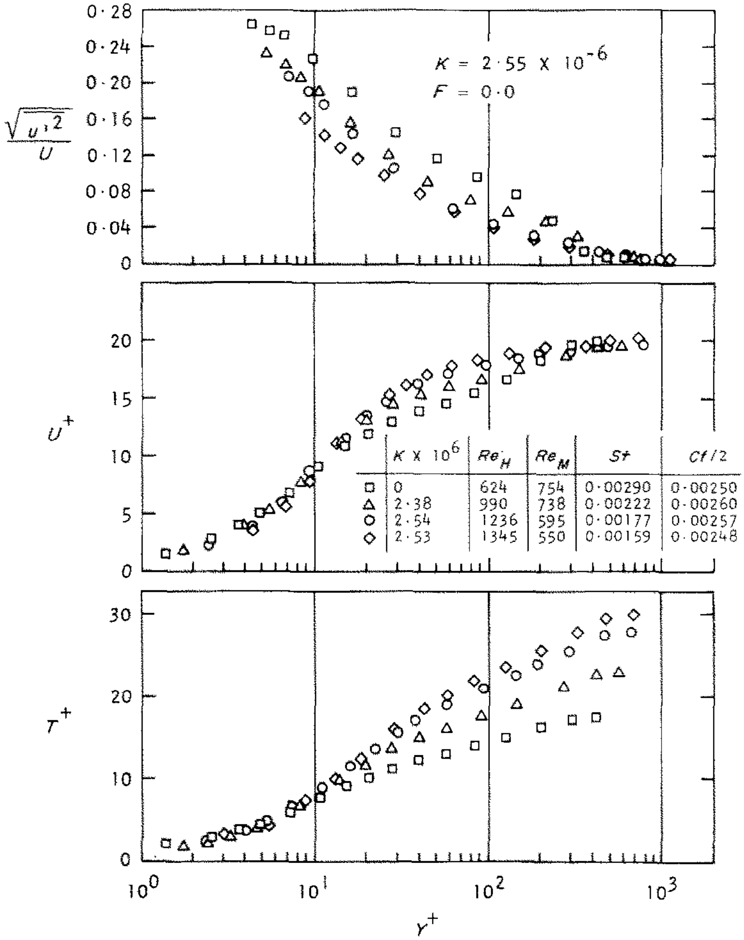


FIG. 3. Traverse data for the unblown turbulent boundary layer at a nominal free-stream acceleration of $K = 2{\cdot}5 \times 10^{-6}$. Traverse symbols correspond to Fig. 1.

in Stanton number through the region of acceleration is reflected in the growth of the temperature profiles in $T^+ - y^+$ coordinates.

Bradshaw [18] has proposed that relaminarization takes place when the maximum value of the turbulent Reynolds number, tentatively defined as $R_t = (y/\nu)\sqrt{(\tau_t/\rho)}$, falls below 30. Applying an integral technique to the hydrodynamic data in Fig. 3, Loyd *et al.* [16] have calculated the total shear stress distribution for the boundary layers in this study. Knowing $\tau$ and the local velocity gradient, the turbulent shear stress $\tau_t$ can be approximately determined. Carrying out this procedure, the maximum values of $R_t$ for the profiles shown in Fig. 3 are, respectively from the start of acceleration, 115, 128, 100 and 68, usually occurring at about $y^+ = 275$. The minimum $R_t$ of 68 suggests, at least according to Bradshaw's criterion, that relaminarization has not taken place.

The combined effects of blowing and a strongly accelerated free-stream flow are shown

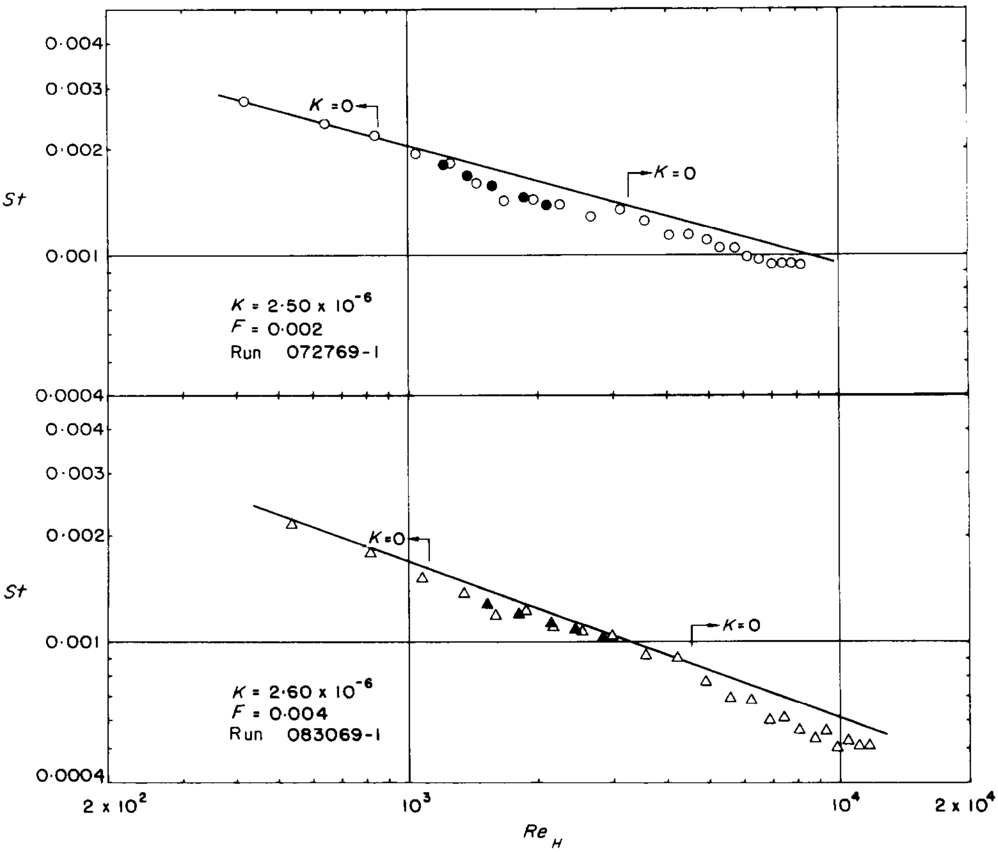


FIG. 4. Experimental results of surface heat transfer in a turbulent boundary layer with blowing, at a nominal free-stream acceleration of $K = 2{\cdot}5 \times 10^{-6}$. ———, Whitten, Moffat and Kays [3].

in Fig. 4. Blowing affects heat transfer to the surface in two ways. First, and most important, the increase in the component of velocity normal to the wall convects energy away from the surface. Secondly, the structure of the sublayer is changed. Physically, the thickness of the laminar-like region near the wall increases, but on the inner region scale, $y^+$, the sublayer becomes thinner. Since acceleration acts to thicken the sublayer, the ultimate size of the sublayer thickness depends on the strength of the blowing and acceleration. The local shear stress and heat flux distributions through the layers are also influenced in an opposing manner by blowing and acceleration.

*Response to changes in initial conditions*

Figure 5 presents the results of three test runs, nominally at $K = 2{\cdot}5 \times 10^{-6}$, which differ only in the thickness of the momentum and thermal boundary layers at the start of the accelerated region. Run 070869, a near-equilibrium run, was previously presented in Fig. 2.

In run 092469, the unaccelerated boundary layer was allowed to develop over a longer distance before the acceleration was imposed.

Run 100269 corresponds in hydrodynamic development to run 092469, but again the thermal boundary layer growth was delayed.

It is apparent that the heat transfer results presented in Fig. 5 are quite dependent on the initial conditions. In nozzle tests, Boldman *et al.* [12] reported that different inlet boundary layer thicknesses produced no appreciable variation in the peak heat transfer coefficient, which roughly corresponds here to comparing the minimum Stanton number in the runs where $\Delta_2/\theta \approx 1$. In the present series of tests, it is possible that the significant inlet condition is the ratio of the boundary layer thicknesses. At the end of the acceleration region the values of the ratio $\Delta_2/\theta$ are, for example, 1·75 and 3·4, respectively, for runs 071569 and 092469. There is no substantial difference in the recovery performance (not shown in Fig. 5) of the four runs, suggesting that it is the inner layer structure which controls the heat transfer behavior throughout the accelerated region. The trends in the reduction in heat transfer give the impression that were the acceleration to continue indefinitely, the Stanton number would asymptotically approach a single functional relationship with the enthalpy thickness Reynolds number. Consequently, it is possible that the different behaviors merely reflect the degree to which each boundary layer is initially out of the equilibrium state associated with the imposed acceleration.

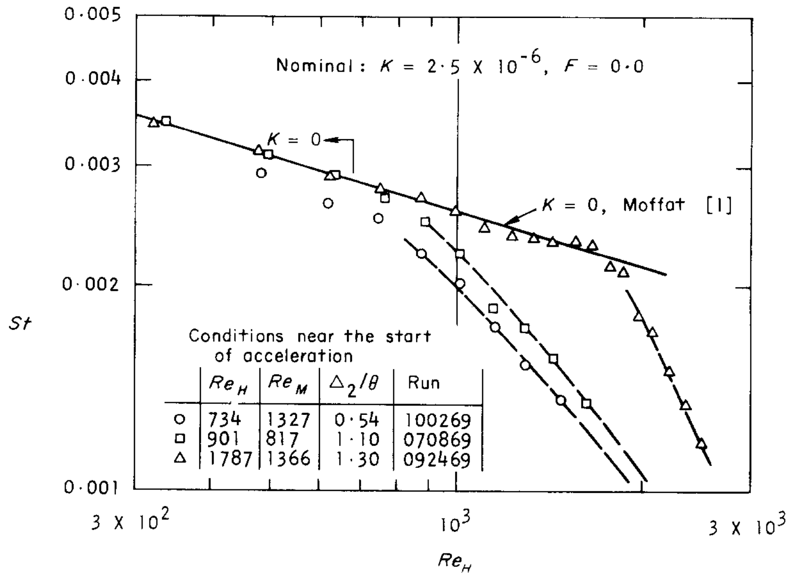


FIG. 5. Experimental results of surface heat transfer at $K \approx 2{\cdot}5 \times 10^{-6}$ with various initial conditions at the start of acceleration (– – – – –, for visual aid only).

Figure 5 demonstrates the danger of identifying relaminarization by the heat transfer behavior, since each test was carried out at a nominal value of $K$ equal to $2{\cdot}5 \times 10^{-6}$. In fact, the steep slope of the Stanton number curve in run 092469 appears very similar to the results of Caldwell obtained at a much stronger favorable pressure gradient (peak $K = 5 \times 10^{-6}$).

*Response to changes in boundary conditions*

Tani [19] summarized the results of several hydrodynamic studies which investigated the response of the turbulent boundary layer to sudden perturbations. In general, the response was nearly instantaneous near the wall, but lagged in the outer regions. For example, a sudden change in pressure gradient immediately imposes a change in $\partial U/\partial x$, resulting in a change in $\partial U/\partial y$, and, consequently, the rate of production of the turbulent energy. A readjustment of the turbulence and shear stress follows. Tani suggests that, near the wall, the scale of turbulence is small enough so that the attainment of local equilibrium is rapid. In the outer regions, however, most of the turbulent energy resides in larger-scale turbulence, which is associated with longer life-times and is responsible for the slower outer region adjustment.

In all the acceleration studies reported here, a near stepwise change in pressure gradient is imposed and removed, respectively, at the start and end of the accelerated region. The behavior in the beginning of the accelerated region

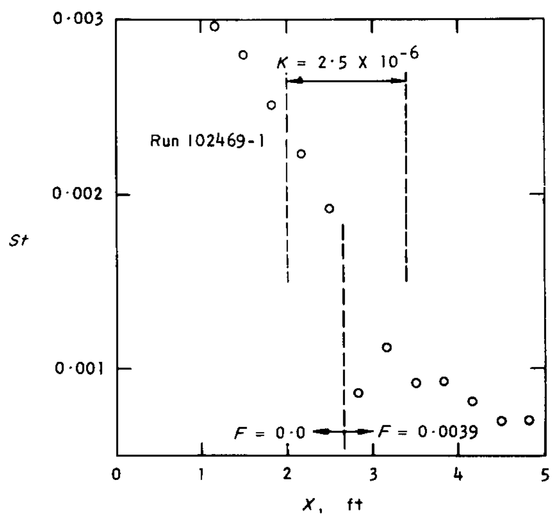


FIG. 6. Experimental data for a step-up in blowing within the accelerated region.

appears to show a substantial lag in the overall response of the boundary layer, while the recovery region, at the end of acceleration, indicates a considerably faster response.

Some interesting results were obtained by introducing a step in blowing during acceleration. In Fig. 6 the Stanton number versus axial position along the plate is shown for the case where a stepwise change in blowing from no blowing to $F = 0·004$ is introduced at an axial distance of 32 in. (see Fig. 1). The Stanton number immediately drops to an unusually low value, apparently due to the convective effect of blowing and the thick sublayer resulting from acceleration. It is conjectured that the blowing then acts to thin the sublayer and the behavior is thereafter similar to the results shown in Fig. 4. A similar quick response to a step in blowing was found in run 111369–2 where the blowing is stopped at $x = 32$ in. With the sudden removal of substantial convection away from the wall, but the residual effect of a thin sublayer due to blowing, the Stanton number immediately rises to a high value, then decreases rapidly at a rate reminiscent of run 092469 shown in Fig. 5. The recovery region shows no effects which can be attributed to the wall blowing.

## SUMMARY AND CONCLUSIONS

This paper has presented experimental results for heat transfer in a turbulent boundary layer under the influence of a free-stream acceleration with and without surface blowing. Values of the acceleration parameter $K$ ranged from $2·0 \times 10^{-6}$ to $2·5 \times 10^{-6}$ with the blowing fraction $F$ varying from 0·0 (no blowing) to 0·004. Tabular data, including temperature and velocity profiles in the constant velocity region prior to acceleration, are provided.

It is concluded from this study that (1) a turbulent boundary layer subjected to an acceleration up to $K = 2·5 \times 10^{-6}$ does not relaminarize, (2) the initial thermal condition of the boundary layer markedly influences the surface heat transfer characteristics during acceleration (in practical applications, the length of the acceleration region may never be long enough to remove the effect of the upstream thermal history), and (3) the response of the strongly accelerated turbulent boundary layer to steps in blowing at the wall, on the other hand, is quite rapid, thus displaying the same characteristics as the turbulent boundary layer without acceleration.

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## TRANSFERT THERMIQUE À UNE COUCHE LIMITE TURBULENTE FORTEMENT ACCÉLÉRÉE: QUELQUES RÉSULTATS EXPÉRIMENTAUX, TRANSPIRATION INCLUSE


**Résumé**—Des expériences de transfert thermique ont été menées dans de l'air sur une couche limite turbulente soumise à un écoulement potentiel fortement accéléré avec et sans transpiration superficielle. On a mesuré le long de la région accélérée le nombre de Stanton, les profils de température et de vitesse moyennes ainsi que d'intensité de turbulence. Les essais ont été conduits avec des gradients de pression favorables correspondant à des valeurs du paramètre d'accélération $K = [(\nu/U_\infty^2)(dU_\infty/dx)]$ égales à $2 \times 10^{-6}$ et $2{,}6 \times 10^{-6}$. La fraction de soufflage $F = (\rho_0 V_0/\rho_\infty U_\infty)$ se situe dans le domaine 0,00–0,004. L'écoulement est incompressible ($U_\infty$ max = 26 m/s) avec une différence de température modérée, 14°C, à travers la couche limite.

Le premier objectif du programme était d'obtenir des résultats détaillés de transfert thermique dans de fortes accélérations et de fournir une base pour des méthodes d'estimation ultérieures. Un second objectif était de déterminer si la relaminarisation de la couche limite se produit à $K = 2{,}5 \times 10^{-6}$.

Les résultats expérimentaux montrent que le nombre de Stanton, fonction du nombre de Reynolds basé sur l'épaisseur d'enthalpie, cesse de croître au-dessous du comportement observé dans des écoulements non accélérés quand $K$ est augmenté avec ou sans soufflage. Les profils montrent qu'à la fin de l'accéleration la couche limite est toujours entièrement turbulente.

On présente ensuite les résultats de transfert thermique qui illustrent les effets de conditions variées au début de l'accélération (notamment l'épaisseur des couches thermique et hydrodynamique) et de changements échelons de soufflage dans la région d'accélération.

## WÄRMEÜBERTRAGUNG AN EINE STARK BESCHLEUNIGTE TURBULENTE GRENZSCHICHT: EXPERIMENTELLE ERGEBNISSE MIT WANDAUSBLASUNG

**Zusammenfassung**—In Luft wurden Wärmeübergangsuntersuchungen an einer turbulenten Grenzschicht durchgeführt, die einer starken Beschleunigung unterworfen war, mit und ohne Ausblasen durch die Wand. Stanton-Zahl, mittlere Temperatur- und Geschwindigkeitsprofile sowie die Profile der Turbulenzintensität wurden im Beschleunigungsbereich gemessen. Die Versuche wurden mit geeigneten Druckgradienten durchgeführt, die durch die Beschleunigungsparameter $K$ von $2{,}0 \cdot 10^{-6}$ und $2{,}5 \cdot 10^{-6}$ bestimmt sind $[K = (\nu/U_\infty^2)(\mathrm{d}U_\infty/\mathrm{d}x)]$. Die Reibung $F$ in der Ausblasströmung bewegte sich in einem Bereich von 0,0 bis 0,004 $[F = (\rho_0 V_0/\rho_\infty U_\infty)]$. Die Strömung war inkompressibel ($U_{\infty,\max} = 26{,}2$ m/s) mit einer mässigen Temperaturdifferenz quer zur Grenzschicht von 14 K.

Das erste Ziel des Programms war es, detaillierte Wärmeübergangsdaten bei starken Beschleunigungen zu erhalten und eine Grundlage zu bilden für zukünftige Abschätzungen. Das zweite Ziel war zu bestimmen, ob die Grenzschicht bei $K = 2{,}5 \cdot 10^{-6}$ wieder laminar wird.

Die experimentellen Ergebnisse zeigen, dass die Stanton-Zahl, als eine Funktion der von der Enthalpiedifferenz abhängigen Reynolds-Zahl, immer weiter unter die Werte sinkt, die in einer unbeschleunigten Strömung bei steigendem $K$ beobachtet werden, mit und ohne Ausblasen. Das Querprofil zeigt, dass am Ende der Beschleunigung die Grenzschicht noch voll turbulent ist.

Weitere Ergebnisse zeigen die Abhängigkeit von verschiedenen Bedingungen am Beginn der Beschleunigung (besonders der Dicke der thermischen und der hydrodynamischen Grenzschichten) sowie eine Abhängigkeit von kleinen Änderungen beim Anblasen im Beschleunigungsbereich.

## ПЕРЕНОС ТЕПЛА К ТУРБУЛЕНТНОМУ ПОГРАНИЧНОМУ СЛОЮ ПРИ ГРАДИЕНТНОМ ОБТЕКАНИИ. НЕКОТОРЫЕ ЭКСПЕРИМЕНТАЛЬНЫЕ РЕЗУЛЬТАТЫ, ВКЛЮЧАЯ РЕЗУЛЬТАТЫ ПО ИСПАРЕНИЮ

**Аннотация**—Проведены эксперименты по переносу тепла в турбулентном пограничном слое воздуха в условиях градиентного обтекниая при наличии и отсутствии испарения на поверхности. Вдоль области ускорения проводились измерения значений числа Стантона, профилей средней температуры и средней скорости и профилей интенсивности турбулентности. Опыты проводились при наличии отрицательных градиентов давления, выраженных через значения параметра ускорения

$$K\left(= \frac{\nu}{U_\infty{}^2}\frac{\mathrm{d}U_\infty}{\mathrm{d}x}\right) = 2{,}0\times 10^{-6} \text{ и } 2{,}5\times 10^{-6}$$

Интенсивность вдува $F$ $(= \rho_0 V_0/\rho_\infty U_\infty)$ изменялась в диапазоне 0,0–0,004. Рассматривался случай течения несжимаемой жидкости ($U_{\infty,\max} = 86$ фут/сек) при небольшом перепаде температур (25°) поперек пограничного слоя.

Основная задача сводилась к получению подробных данных по теплообмену при больших ускорениях и обеспечению основы для дальнейших расчетов. Кроме того, ставилась цель определить, происходит ли повторная ламинаризация пограничного слоя при $K = 2{,}5\times 10^{-6}$.

Экспериментальные результаты показывают, что при наличии или отсутствии вдува по мере увеличения $K$ число Стантона в функции числа Рейнольдса для толщины энтальпии прекращает уменьшаться ниже уровня, наблюдаемого при отсутствии ускорения. Распределения профилей показывают, что при прекращении ускорения пограничный слой остаётся полностью турбулентным. Далее приводятся результаты по теплообмену, которые иллюстрируют влияние на них различных условий в начале ускорения (особенно толщина теплового и гидродинамического слоев) и ступенчатых изменений вдува в области ускорения.