NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT 1161

AVERAGE SKIN-FRICTION DRAG COEFFICIENTS FROM TANK TESTS OF A PARABOLIC BODY OF REVOLUTION (NACA RM-10)

By ELMO J. MOTTARD and J. DAN LOPOSER

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Langley Field, Va.
National Advisory Committee for Aeronautics

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Conduct, under unified control, for all agencies, of scientific research on the fundamental problems of flight
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SUMMARY

Average skin-friction drag coefficients were obtained from boundary-layer total-pressure measurements on a parabolic body of revolution (NACA RM-10, basic fineness ratio 15) in water at Reynolds numbers from \(4.4 \times 10^6\) to \(70 \times 10^6\). The tests were made in the Langley tank no. 1 with the body sting-mounted at a depth of two maximum body diameters. The arithmetic mean of three drag measurements taken around the body was in good agreement with flat-plate results, but, apparently because of the slight surface wave caused by the body, the distribution of the boundary layer around the body was not uniform over part of the Reynolds number range.

INTRODUCTION

Skin-friction-drag data obtained at high Reynolds numbers in subsonic flow is, at the present time, confined mainly to the results of tests of flat plates. Skin-friction data obtained at high Reynolds numbers from tank tests of a body of revolution would be useful both hydrodynamically and aerodynamically. Such data would make it possible in many instances to estimate the error incurred by using flat-plate data in calculating the skin-friction drag of curved surfaces, such as ship hulls and submerged bodies. The data could be obtained at Reynolds numbers ordinarily obtained in air with supersonic flow and could therefore be used in conjunction with the results of tests of missiles in the same Reynolds number range in order to help evaluate the effect of Mach number on the skin-friction coefficient.

Because of the need for skin-friction coefficients for a curved body at high Reynolds numbers in subsonic flow, skin-friction coefficients were obtained on a parabolic body of revolution (NACA RM-10, basic fineness ratio 15) in water at Reynolds numbers from \(4.4 \times 10^6\) to \(70 \times 10^6\) (4.9 fps to 78 fps). The skin-friction coefficients were obtained from measurements of the total pressure through the boundary layer by the use of the boundary-layer momentum theorem. Measurements were made at the 69.4 percent station (based on the length of the basic shape) at three radial positions around the model. In the transition range of Reynolds number (from \(1.1 \times 10^6\) to \(8.9 \times 10^6\)), a dye was injected into the boundary layer and the flow was observed on the upper surface of the model.

SYMBOLS

- \(A\): skin area from nose to measuring station, sq ft
- \(C_f\): average skin-friction drag coefficient
- \(\bar{\delta}\): boundary-layer thickness, ft
- \(\Delta p\): static pressure on body minus static pressure in free stream
- \(g\): acceleration due to gravity, 32.2 ft/sec^2
- \(h\): depth below water surface, ft
- \(\mu\): absolute viscosity, slugs/ft·sec
- \(\eta\): static pressure, lb/sq ft
- \(\Pi_t\): total pressure inside boundary layer, lb/sq ft
- \(\Pi_t^*\): total pressure just outside boundary layer, lb/sq ft
- \(q\): free-stream dynamic pressure, lb/sq ft
- \(R\): Reynolds number based on axial distance from nose to measuring station
- \(r\): radial distance from body axis, ft
- \(r_a\): radial distance from body axis to skin, ft
- \(\rho\): density, slugs/cu ft
- \(s\): distance along surface from nose, ft
- \(t\): time, sec
- \(\tau_w\): wall shearing stress, lb/sq ft
- \(\tau_{w_{av}}\): average wall shearing stress, lb/sq ft
- \(u\): velocity inside boundary layer, fps
- \(U_s\): velocity just outside boundary layer, fps
- \(V\): free-stream velocity, fps
- \(x\): axial distance from nose, ft
- \(y\): distance normal to skin, ft

Subscript:
- \(\max\): maximum value

ANALYSIS

Average skin-friction drag coefficients were obtained from rake surveys of the total pressure through the boundary layer and calculated values of the pressure distribution. The average skin-friction coefficient ahead of a measurement station is

\[ C_f = \frac{\tau_{w_{av}}}{q} = \frac{2\pi}{qA} \int_0^x \tau_{w_{av}} dx \]

Momentum theory is used to evaluate the integral \(\int_0^x \tau_{w_{av}} dx\).
The first and second terms on the right-hand side of equation (5) represent the total momentum loss in the boundary layer as measured by the rake. The third and fourth terms on the right-hand side account for the momentum change in the boundary layer due to pressure gradient. A linear variation of \( \int_0^z \left(1 - \frac{v}{U_b} \right) dy \) with \( z \) was assumed in order to evaluate the importance of the third term. The third term was found to contribute less than 1 percent of the total and was therefore neglected. The fourth term was likewise neglected since it contributed even less than did the third term.

In the computations made in order to obtain the skin-friction coefficients, equations (6) were used to evaluate the terms on the right-hand side of equation (5), which was integrated graphically in order to obtain the value of \( \int_0^z \tau wy \, dx \) required for the solution of equation (1).
Figure 1.—General arrangement of model and apparatus. (Dimensions are in feet.) Body-profile equation: $r_w = 0.5 - 0.00889(7.5-x)^2$.

Figure 2.—Model mounted on towing support.
Cross section of model at rake station, front view

<table>
<thead>
<tr>
<th>Distance</th>
<th>Rake 1</th>
<th>Rake 2</th>
<th>Rake 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.055</td>
<td>0.050</td>
<td>0.050</td>
</tr>
<tr>
<td>B</td>
<td>.380</td>
<td>.360</td>
<td>.335</td>
</tr>
<tr>
<td>C</td>
<td>.675</td>
<td>.655</td>
<td>.630</td>
</tr>
<tr>
<td>D</td>
<td>1.775</td>
<td>1.760</td>
<td>1.735</td>
</tr>
<tr>
<td>E</td>
<td>3.025</td>
<td>2.510</td>
<td>2.490</td>
</tr>
</tbody>
</table>

Figure 3.—Arrangement and configuration of total-pressure rakes. (Dimensions are in inches except as noted.)

Figure 4.—View of model at rake station.
PROCEDURE

The data were taken during the constant-speed interval of the test run after the pressures had reached an equilibrium value.

In the low-speed range, the flow was made visible by injecting a thin dye stream into the boundary layer. At Reynolds numbers where the boundary layer was not completely turbulent, initial turbulence in the tank was minimized by scheduling the runs in order of increasing speed and allowing a 25-minute idle period before each run.

The alignment of the model with the direction of motion was checked during the test runs and found to be within $\pm \frac{1}{4}$°.

In order to minimize corrosion of the aluminum skin of the model by the salt water in which it was tested, the model was taken out and washed with fresh water at the end of each day's testing and was polished before again being put into the water.

RESULTS AND DISCUSSION

Typical velocity profiles are shown in figure 5. The agreement of the results from the two outside tubes shows that they are both outside the boundary layer. The average skin-friction coefficients as obtained by the use of equation (5) at the three radially spaced measurement stations are plotted against Reynolds number in figure 6. An indication of the repeatability of the final results can be obtained by comparing data points from runs made at similar Reynolds numbers.

Included in figure 6 is the Schoenherr line which represents the average value of the skin-friction coefficients from most of the available flat-plate skin-friction data for fully turbulent flow. (Schoenherr's skin-friction formulation is explained in refs. 4 and 5.) The agreement between experimental skin-friction coefficients measured at the three rake stations and those predicted from the Schoenherr line is good at low and high Reynolds numbers. At intermediate Reynolds numbers (corresponding to velocities in the region of the maximum velocity of propagation of waves in the tank at the test water level) the skin-friction coefficients differ for the different rakes with an apparent increase in skin-friction coefficient with an increase in depth at the measuring station. Such a trend would occur if the entire boundary layer were being swept downward by a very slight vertical component of flow, such as might exist if the surface disturbance which accompanied the model had its trough located above the measuring station. Wave measurements at Reynolds numbers from $4.4 \times 10^6$ to $12 \times 10^6$ showed that the trough of the wave was indeed located above the rake station. The maximum depression of 1.1 inches at the rake station occurred at a Reynolds number of $8.9 \times 10^6$. Apparently, large errors can result from only small amounts of cross flow if only one rake is used on this type of body.

The arithmetic mean of the average skin-friction coefficients from the three rakes is plotted against Reynolds number in figure 7. It is seen from this plot that not only the coefficients at low and high Reynolds numbers agree with those predicted from the Schoenherr line but also the mean of the three rather widely different coefficients obtained at the intermediate Reynolds numbers agrees well with the Schoenherr line value.

At Reynolds numbers low enough for the laminar region on the model to extend aft of the dye orifices, the extent of the laminar region was clearly indicated by the dye stream. The length of the laminar region at various Reynolds numbers is tabulated thus:

<table>
<thead>
<tr>
<th>Reynolds number, $R$</th>
<th>Length of laminar region in percent of total length from nose to rake station, $\frac{x}{L}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1.1 \times 10^6$</td>
<td>$&gt;100$</td>
</tr>
<tr>
<td>$2.2$</td>
<td>$66$</td>
</tr>
<tr>
<td>$4.4$</td>
<td>$27$</td>
</tr>
<tr>
<td>$6.6$</td>
<td>$24$</td>
</tr>
<tr>
<td>$8.9$</td>
<td>$&lt;1.6$</td>
</tr>
</tbody>
</table>

Figure 5.—Variation of the nondimensional velocity ratio with distance normal to the skin.
The data plotted in reference 5 indicate the Reynolds number of transition for flat plates in water to be about $3 \times 10^5$. In the present investigation, the flow was observed over the upper surface only and the flow on the bottom may have been different because of the wave accompanying the model; a direct comparison with the flat-plate data, therefore, is not possible.

CONCLUDING REMARKS

For a streamline body of revolution with a basic fineness ratio of approximately 15 (NACA RM-10), the average skin-friction drag coefficient for the forward 69 percent of the basic body in incompressible flow was very nearly the same as that for flat plates.

The distribution of the boundary layer around the body was apparently affected by a very small cross component of flow over part of the Reynolds number range.

LANGLEY AERONAUTICAL LABORATORY,
NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS,
LANGLEY FIELD, VA., OCTOBER 8, 1952.
REFERENCES


