Effective Reynolds Numbers for Heated Spheres and Cylinders

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Theme

THE change in aerodynamic drag on spheres and circular cylinders during laminar-turbulent transition is a well-known phenomenon. The effects of a heated surface on transition have been studied extensively for flat plates, as have the effects of a heated flow on a cool surface. The purpose of this investigation was to examine the variation in aerodynamic drag on high temperature spheres and cylinders as they cooled in a room temperature flow and to attempt to correlate the results with the classical understanding of laminar-turbulent transition as a function of Reynolds number.

Contents

Tests were conducted on stainless steel sphere and circular cylinder models in the 6′ × 6′ VPI Stability Wind Tunnel. The spheres tested were 2.57 in. in diameter and the cylinders were 7.36 in. in diameter and 16.53 in. in length. Tests were made with smooth surfaces and with diamond pattern knurled roughness depths of 2.5, 5, and 10 mils. The cylinder was tested with its axis perpendicular to the flow and at angles of 15, 30, and 45° from the perpendicular. The models were heated to temperatures of 1600°F for the cylinder and 1000°F for the sphere and then allowed to cool in the room temperature flow at chosen values of freestream Reynolds number up to 1.2×10^6 while drag forces and model temperature were monitored. Heating was accomplished by use of infrared gas process burners placed around the models. Data from the tests was reduced to coefficient form for analysis.

Before testing the heated models, complete tests were run with the model at room temperature in order to acquire base data for comparison with the heated tests. Results of the unheated tests compared well with the published data for similar cylinder geometry and roughness[1] when support interference was considered.

Figure 1 shows the data from some of the heated cylinder tests when the cylinder was perpendicular to the flow ($\alpha = 0°$) and with a freestream Reynolds number of 10^6 for various surface finishes. These are typical of the results of the tests which generally showed a high drag coefficient at high temperature and a transition to a lower C_D at some lower temperature. The effect of increased surface roughness was to increase the low temperature drag and shift the transition region toward higher temperatures. The effect of freestream Reynolds number was to shift the transition to lower temperatures as Re_∞ was reduced. The effect of changing the angle of attack of the cylinder was to smooth the slope of the C_D change where transition occurred and to reduce the difference between the low and high temperature drags as α was increased.

The data behaves like the reverse of a traditional C_D vs Re_∞ plot for the unheated cylinders. At a high wall temperature (T_W) the C_D is the same as was produced by the unheated laminar boundary layer. As T_W is lowered the C_D indicates a transition to a turbulent boundary layer. It is evident that an increase in T_W produces a boundary-layer behavior similar to that occurring with a decreasing Reynolds number.

In an attempt to correlate the temperature induced aerodynamic behavior with Reynolds number, Eckert's reference temperature (T^*) for boundary layers was used, where the freestream temperature is assumed to be the adiabatic wall temperature,

$$T^* = (T_W + T_\infty)/2$$

Using T^* an "effective" Reynolds number (Re^*) can be calculated:

$$Re^* = \frac{\rho^* V_\infty L}{\mu^*}, \text{where } \rho^* = \rho(T^*) \text{ and } \mu^* = \mu(T^*)$$

Hence, during a constant Re_∞ test run Re^* increases as model temperature decreases. The data can then be plotted as C_D vs Re^* and, if Re^* is effective in accounting for the flow behavior, these plots should coincide with unheated cylinder C_D vs Re_∞ plots for the same surface roughness and angle of attack. Figure 2 shows a comparison of heated and unheated data based on the effective Reynolds number for three different roughnesses. The comparison, while not exact, does seem to confirm the concept of Re^*.

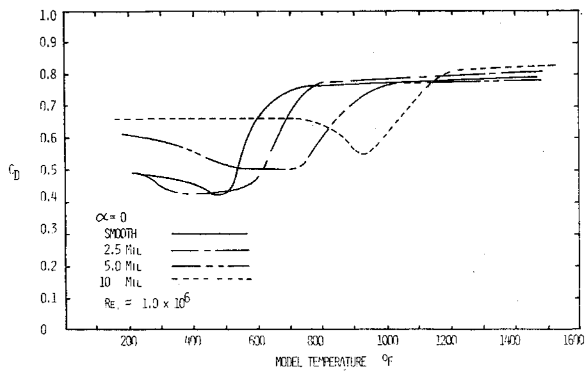

Fig. 1 Effect of wall temperature on cylinder drag coefficient.

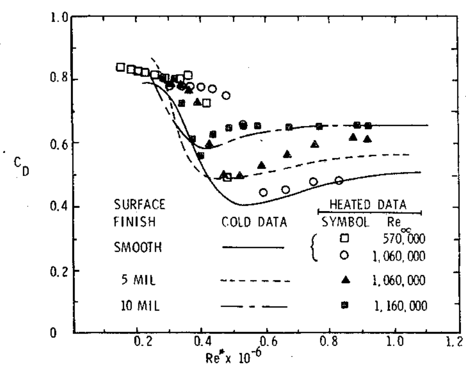

Fig. 2 Comparison of heated and unheated C_D based on Re^*.

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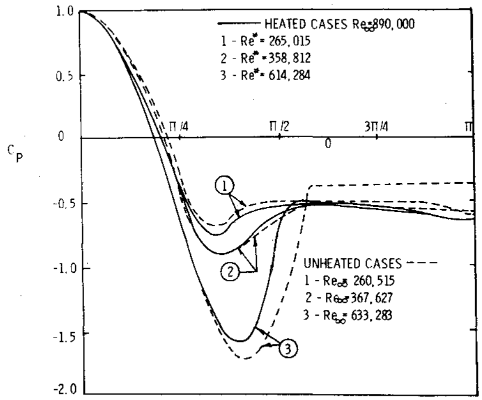

Fig. 3 Pressure distribution comparisons.

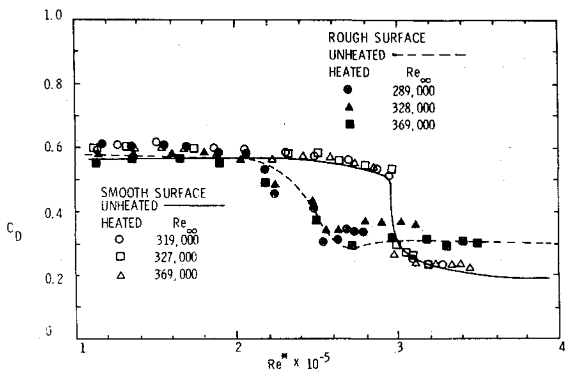

Fig. 4 Sphere data comparison.

To further verify the validity of Re^* tests of pressure coefficients around the cylinder were conducted. If the phenomenon observed is indeed a temperature-induced reverse transition from laminar to turbulent flow which can be explained in terms of an effective Reynolds number, the resulting pressure distribution around the cylinder at a given Re^* on the hot body should match that for an unheated cylinder at the same freestream Reynolds number value. Tests were run on the heated and unheated cylinders in the $\alpha=0$ position with Re_∞ held at 890,000 for the heated case while pressures were measured as the model cooled. The distributions were compared using Re_∞ for the unheated model and Re^* for the heated case and are shown in Fig. 3. The comparisons are seen to be quite good, confirming the fact the concept of an "effective" Reynolds number (Re^*) can indeed be used to predict the flow around, and aerodynamic forces on, a cylinder with a hot surface.

Since a sphere is more sensitive to transition than a cylinder, a comparison of heated and unheated data for a sphere based on Re^* which gave results as good as those for the cylinder should prove the concept of an effective Reynolds number. Figure 4 shows the results of the sphere tests for two different roughnesses. As in the case of the cylinders no correction has been made for mounting sting interference so the C_D values are slightly higher than those in the literature; however, the point to be noted is that the comparisons of hot data plotted vs Re^* with unheated sphere C_D vs Re data are even better than those seen for the cylinder.

It is seen that increasing the model surface temperature has profound effects on the behavior of the boundary layer of spheres and cylinders. An effective Reynolds number, Re^*, can be calculated using Eckert's boundary-layer reference temperature. As T_W increases, Re^* decreases and can result in laminar boundary-layer behavior even though freestream Re may be quite high. The Re^* values accurately determine the C_D characteristics of the sphere or cylinder. Thus, in order to find C_D for a heated sphere or circular cylinder at any temperature, one can calculate Re^*, then use the C_D found for that same value of Re_∞ in tests of an unheated body for the same surface finish and angle of attack.

It is felt that since the concept of an effective Reynolds number (Re^*) based on Eckert's boundary-layer reference temperature is accurate in predicting the pressure distributions and aerodynamic behavior about the classic shapes of a circular cylinder and sphere where laminar-turbulent transition and their influence on separation are known to be most pronounced, the Re^* should be a useful parameter for use in the prediction of other boundary-layer dependent phenomena on the other shapes for heated bodies.

Acknowledgment

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References

[1]McKinney, L. M., "Effects of Fineness Ratio and Reynolds Number on the Low-Speed Crosswing Drag Characteristics oon Circular and Modified-Square Cylinders," NASA TN D-540, Oct. 1960.