NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3562

VARIATION OF BOUNDARY-LAYER TRANSITION WITH HEAT TRANSFER ON TWO BODIES OF REVOLUTION AT A MACH NUMBER OF 3.12

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Washington
September 1955

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SUMMARY

An investigation was made at a Mach number of 3.12 to determine the effects of heat transfer on boundary-layer transition. Data were obtained for a cone cylinder and a parabolic-nosed cylinder at Reynolds numbers up to 12×10^6 based on body length. The results show that cooling the cone-cylinder model to a wall-to-free-stream static-temperature ratio of approximately 1.4 increased the transition Reynolds number from a value of about 2.0×10^6 at equilibrium to 10.6×10^6. For temperature ratios less than 1.4, the boundary-layer flow was laminar over the entire model. The rapid increase of transition Reynolds number with small reductions in temperature ratio near 1.4 indicated that temperature ratios slightly lower may result in a laminar boundary layer for very high Reynolds numbers. For the parabolic-nosed body, the transition Reynolds number was about twice that of the cone-cylinder model over the temperature range investigated.

INTRODUCTION

One of the most serious problems confronting today's designers of supersonic vehicles is the large temperature rise associated with frictional heating. This difficulty is not only important with respect to maintaining structural integrity, but also with respect to meeting the necessary requirements for human comfort. Thus, even though some relief can be expected through radiative cooling, designs must incorporate some form of temperature control for continuous flight at high supersonic speeds.

The amount of cooling required will depend largely on the extent to which the boundary-layer flow is laminar or turbulent. Theoretical analyses (refs. 1 and 2) indicate that the stability and extent of the laminar flow may be increased by removing heat. In fact, theory shows that by removing a sufficient amount of heat, the laminar flow may be completely stabilized for all Reynolds numbers and a specified Mach number

range. As a result, a marked effect of surface cooling on the location of transition from laminar to turbulent flow is expected. Experimental data (ref. 3) have demonstrated the effectiveness of cooling in delaying transition at a Mach number of 1.61. However, little experimental data are available concerning this phenomenon at higher Mach numbers and in the temperature range which theory (ref. 2) predicts would provide complete laminar boundary-layer stability. A summary of factors other than surface temperature affecting the extent of the laminar boundary layer may be found in reference 4.

An investigation has been initiated at the NACA Lewis laboratory to evaluate the effects of heat transfer on several bodies of revolution at a Mach number of 3.12. The models were either preheated to a maximum wall-to-free-stream static-temperature ratio of 4.4 or precooled to a minimum temperature ratio of 0.70. This value of 0.70 falls in the region of infinite laminar stability to small disturbances as predicted by reference 2. The experimental transition results obtained from a cone cylinder and a parabolic-nosed cylinder at zero angle of attack and for Reynolds numbers up to 12×10^6 based on model length are included herein.

SYMBOLS

The following symbols are used in this report:

C_p pressure coefficient, $\frac{p - p_0}{q_0}$

c_p specific heat of skin material, Btu/(lb)(°F)

h local heat-transfer coefficient, Btu/(sec)(sq ft)(°F)

p local static pressure

p_0 free-stream static pressure

q_0 free-stream dynamic pressure

Re free-stream Reynolds number

Re_t transition Reynolds number, $\frac{u_0 x_t}{\nu_0}$

T_e equilibrium wall temperature, °R

T_w wall temperature, °R

T_0 stagnation temperature, $^{\circ}R$

t time, sec

t_0 free-stream static temperature, $^{\circ}R$

u_0 free-stream velocity

w specific weight of wall material, lb/cu ft

x axial distance, in.

ν_0 free-stream kinematic viscosity

Subscripts:

i zero time

t transition

x based on axial distance

APPARATUS AND DATA REDUCTION

The investigation was conducted in the Lewis 1- by 1-foot supersonic wind tunnel, which operates at a Mach number of 3.12. This tunnel is a continuous flow, nonreturn type operating at inlet pressures of 6 to 52 pounds per square inch absolute. The stagnation temperature of the inlet air may be varied from approximately 50° to 170° F. These conditions yield a range of free-stream Reynolds number per foot of 1×10^6 to 8×10^6. For this Reynolds number range, the corresponding axial turbulence intensity measured ahead of the nozzle throat at a Mach number of 0.12 is approximately 1.0 to 0.5 percent (ref. 5). The tunnel stagnation dew point was about -35° F at all times.

Sketches of the models investigated and their instrumentation schedules are presented in figure 1. Each model was constructed of K-monel with a wall thickness of 1/16 inch. In an effort to minimize surface roughness as a variable, the surface of each model was ground and polished until the maximum roughness was less than 16 microinches. Each model was instrumented with calibrated copper-constantan thermocouples.

The theoretical wall-pressure distributions for the two models are presented in figure 2. These were calculated using the second-order

theory reported in reference 6. The cone-cylinder model had a very strong favorable pressure gradient at the juncture between the cone and the cylinder. The parabolic cylinder, however, had a favorable pressure gradient over the first 58 percent of its length. Both models have a small adverse gradient over the cylindrical section.

Preheating or precooling of the test model was accomplished by enclosing the model in a set of shoes (fig. 3(a)) and passing hot air or liquid nitrogen into the shoes and over the model surface. The fluid used to precool (or preheat) the model was exhausted through the base of the shoes. Photographs of the cone-cylinder model with shoes along tunnel wall and in place are given in figures 3(a) and (b), respectively. The shoes could be operated while the tunnel was running. For any given test, the shoes were placed over the model after the desired tunnel conditions had been reached. The model was then precooled (or preheated) by passing liquid nitrogen (or heated air) through the retraction struts. Once the desired wall temperature was obtained, the shoes were snapped back against the tunnel walls by means of air cylinders (fig. 3(b)). The transient temperature distributions were then obtained with a multiple-channel recording oscillograph. Temperatures obtained in this manner are believed to be accurate within $\pm 2^{\circ}$ F. 3674

Local heat-transfer coefficients were found from the equation

$$c_p w \frac{dT_w}{dt} = h(T_e - T_w) \tag{1}$$

Implicit in the use of equation (1) are the assumptions that the heat losses due to conduction and radiation are small. These effects were calculated and found to be negligible.

The start of transition is usually associated with an abrupt increase in the local heat-transfer coefficient from a laminar to the higher turbulent value (fig. 4(a)). Associated with this abrupt increase in the local heat-transfer coefficient are (1) a sudden increase (for the cooled model) in the time rate of change of temperature (fig. 4(b)) and (2) a sharp decrease (for the heated model) in the axial temperature distribution (fig. 4(c)). For this investigation, the sudden increase in the time rate of change of temperature was generally chosen as the start of transition, since it required the least number of computations. However, for the heated model case, this change in the time rate of change of temperature was not apparent and the location of transition was found from the local heat-transfer coefficients. Both of these methods were checked by plotting the axial temperature distributions.

RESULTS AND DISCUSSION

The effect on transition of surface cooling or heating is summarized in figure 5 for two bodies of revolution. Cooling the cone-cylinder surface to a temperature-difference ratio of -0.45 increased the transition Reynolds number from a value of approximately 2×10^6 at equilibrium to 10.6×10^6. This value of 10.6×10^6 corresponds to the highest available Reynolds number and the last thermocouple location. Heating the model surface to a temperature-difference ratio of approximately 0.53 decreased the transition Reynolds number from about 2.0×10^6 at equilibrium to 0.86×10^6. Between the extreme heating and cooling values the variation appears to be continuous and uniform. The rate of change of the transition Reynolds number with temperature-difference ratio is much larger for cooling than for heating. The transition Reynolds number variation presented in figure 5 was obtained by varying stagnation temperature and stagnation pressure. Yet, for the same model, substantially a single curve is obtained. Thus, it appears that Reynolds number, and not, for example, density level, is the important parameter characterizing boundary-layer transition.

The cold-wall data obtained from the parabolic-nosed model exhibit the same general trend as those of the cone-cylinder model. More importantly, however, the data demonstrate the effect of a favorable pressure gradient (fig. 2). For a given temperature-difference ratio, the transition Reynolds number for the parabolic-nosed model is approximately twice that for the cone-cylinder body. This is not surprising, since two-dimensional stability theory predicts that a favorable pressure gradient increases the boundary-layer stability and, consequently, less cooling is required (refs. 4 and 7).

At the highest Reynolds number per foot, turbulent flow was indicated by the data recorded at the last thermocouple on the parabolic-nosed model. This result may be spurious since data on the cone-cylinder showed laminar flow at the same point. Perhaps extraneous effects such as tunnel disturbances or local surface abrasions initiated this early transition.

A comparison of the experimental transition Reynolds number with the theoretical stability calculations for a cone (converted from flat-plate values by Mangler's transformation) is given in figure 6. For temperature ratios greater than about 1.7, the observed transition Reynolds number is considerably higher than the theoretical Reynolds number for initial instability. This behavior is as expected, because the theoretical minimum critical Reynolds number indicates when disturbances will first be amplified, and not when transition occurs.

For temperature ratios below 1.7, the theory predicts that two-dimensional disturbances are never amplified; the flow is thus stable for all Reynolds numbers, and transition would not be expected. The experimental results, however, indicate that the temperature ratio for

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which transition is delayed to very high Reynolds numbers is 1.4, rather than 1.7. The difference between these values may be accounted for, in part, by including three-dimensional disturbances in the stability analysis. For example, computations made in reference 8 at a Mach number of 4.0 indicate that all three-dimensional disturbances, except those having direction angles larger than 74.3°, are stabilized at a temperature ratio of 1.474. The estimated minimum critical Reynolds number for the latter disturbances was found to be approximately 10^{12}. Consequently, from a practical standpoint, a temperature ratio of 1.474 would stabilize the boundary layer at a Mach number of 4.0. It is expected from the analysis of reference 8 that the theoretical stabilizing temperature ratio for a Mach number of 3.12 would be slightly less than 1.474; therefore, the experimental value of 1.4 appears to be in fair agreement with theory. 3674

SUMMARY OF RESULTS

An investigation of the effects of heat transfer on boundary-layer transition on two bodies of revolution at zero angle of attack and for Reynolds numbers up to 12×10^6 based on model length has given the following results:

1. Cooling the cone-cylinder model to a wall-to-free-stream temperature ratio of 1.4 increased the transition Reynolds number from a value of approximately 2×10^6 at equilibrium to 10.6×10^6. For a wall-to-free-stream temperature ratio below approximately 1.4, results indicate that perhaps the laminar boundary layer would be stable for very high Reynolds numbers.

2. For the range of temperature ratios investigated the effect of the favorable pressure gradient on a parabolic-nosed body was approximately to double the transition Reynolds number obtained for a cone-cylinder model.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, July 11, 1955

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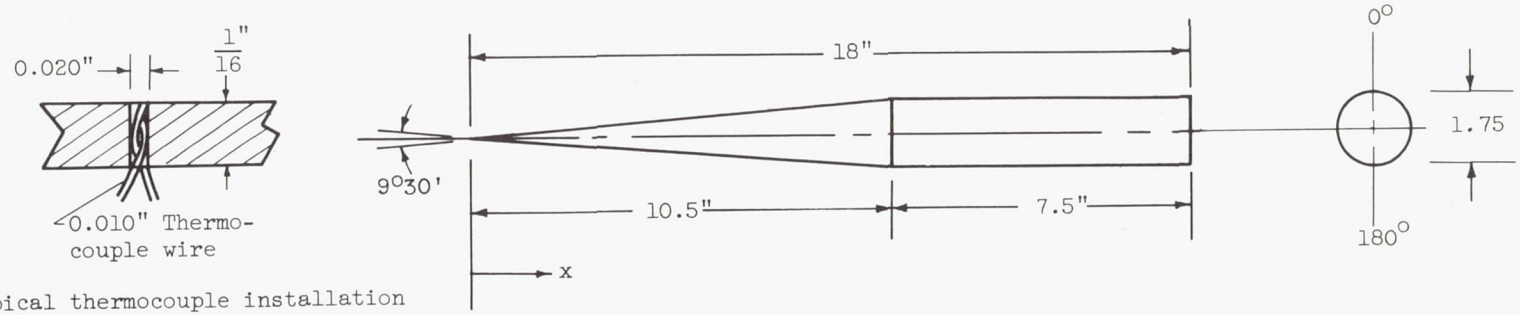
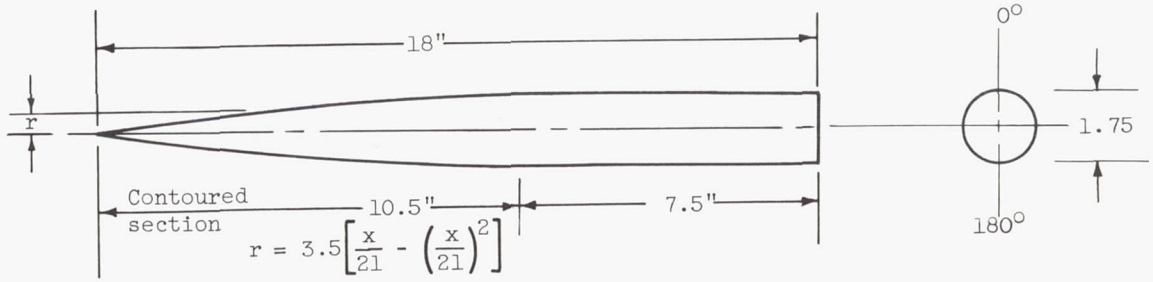


Thermocouple locations at axial distance, x, in.														
2.0	3,0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	10.62	11.50	12.50	13.62	14.75	16.00

(a) Cone-cylinder model.



Thermocouple locations at axial distance, x, in.														
1.0	1.5	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.5	14.0	16.0

(b) Parabolic-cylinder model.

Figure 1. - Details of models and thermocouple locations.

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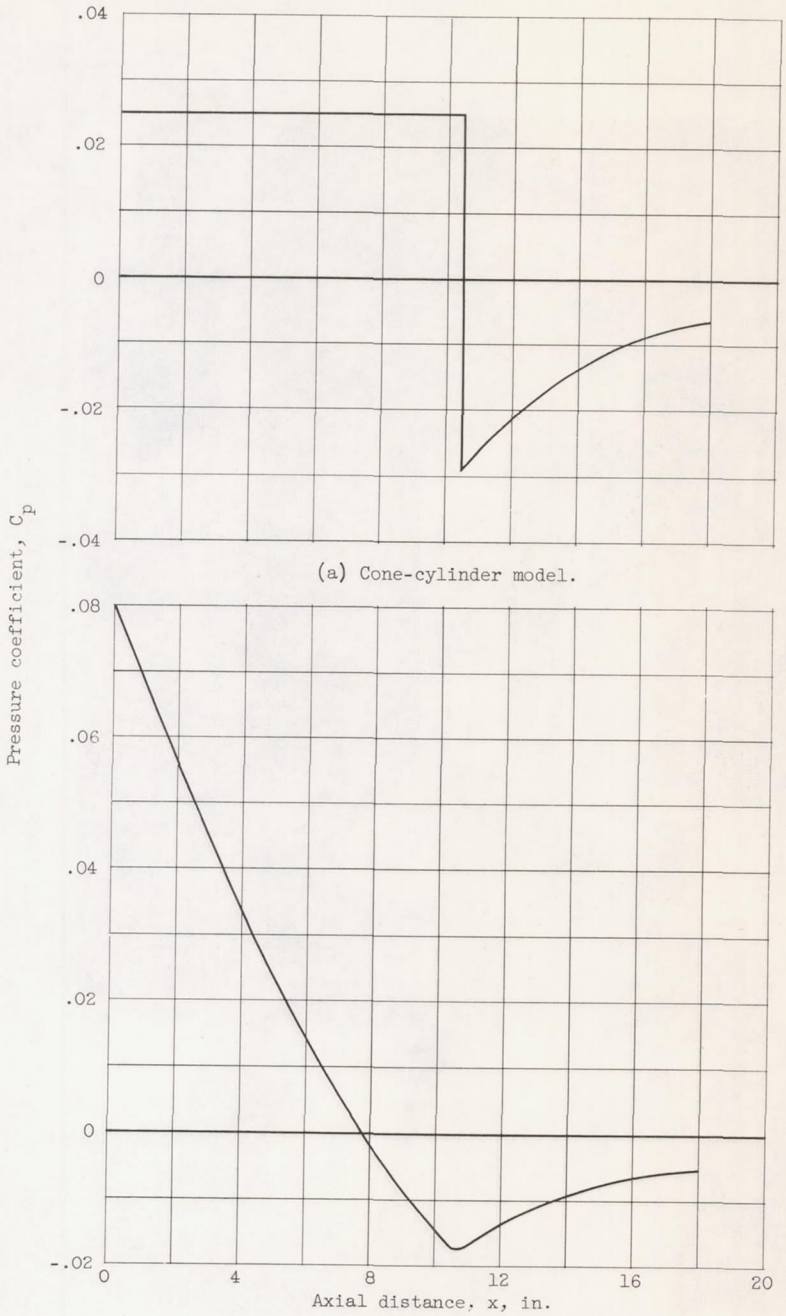
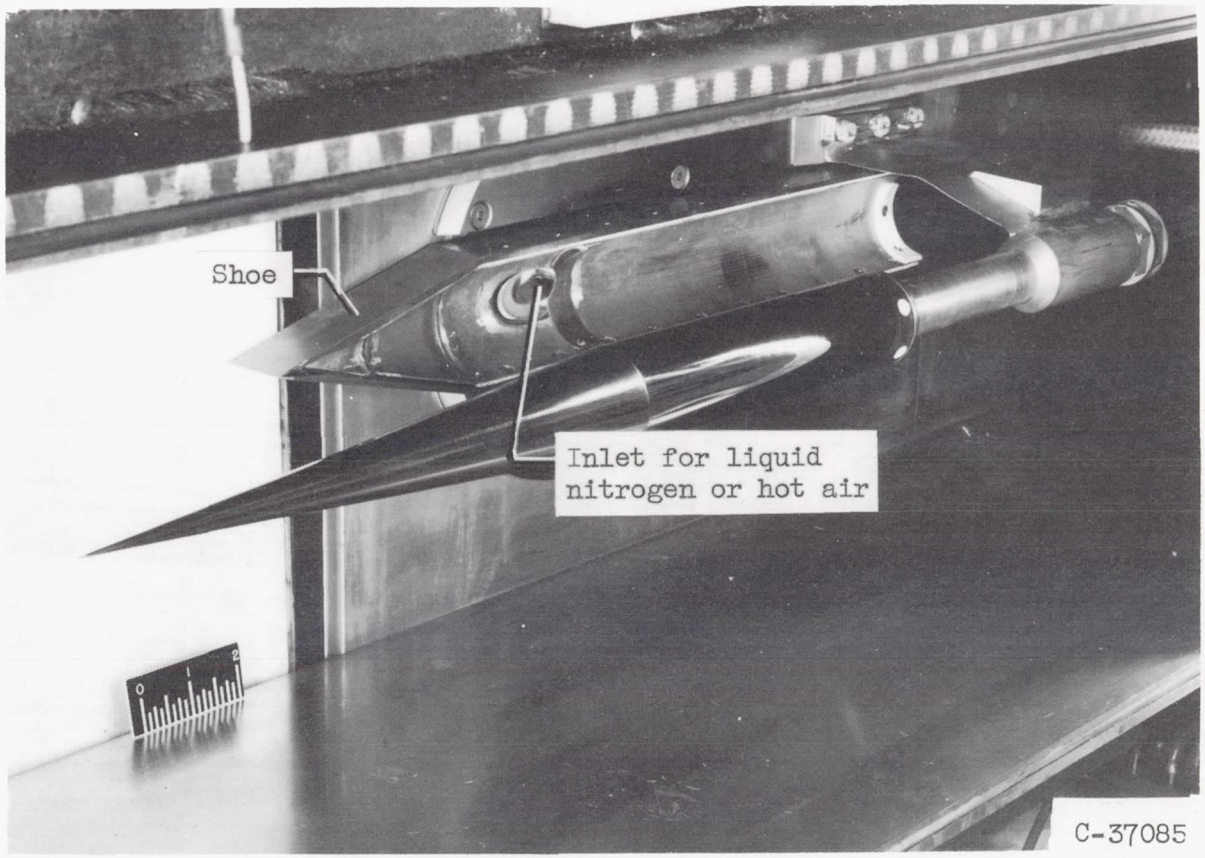


(a) Cone-cylinder model.

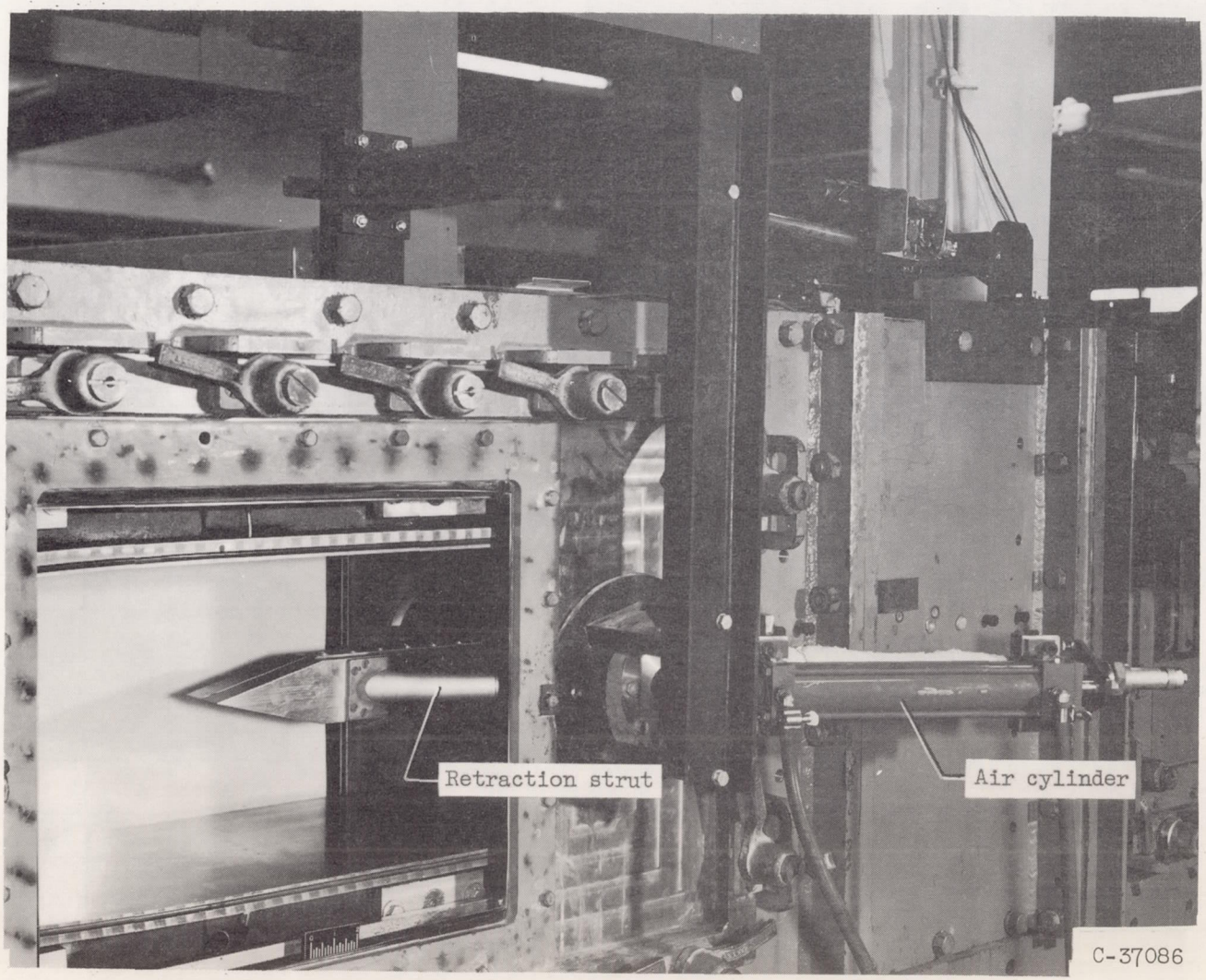
(b) Parabolic-cylinder model.

Figure 2. - Pressure distribution for two bodies of revolution at zero angle of attack.



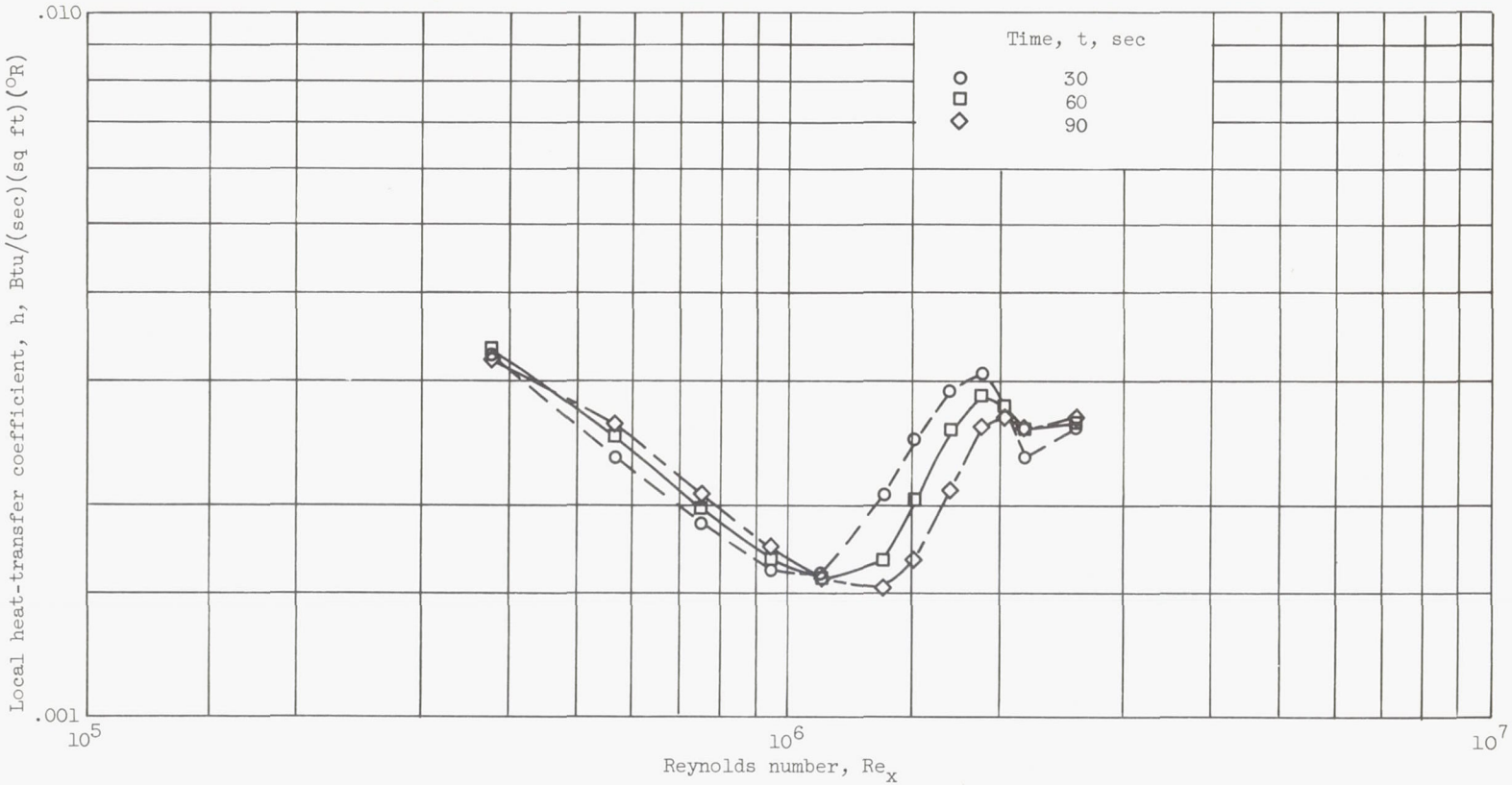
(a) Shoe along tunnel wall.

Figure 3. - Tunnel installation.



(b) Shoes in place.

Figure 3. - Concluded. Tunnel installation.



(a) Local heat transfer coefficients for heated cone-cylinder model; Reynolds number per foot, 2.27×10^6; wall temperature at zero time, 782° R.

Figure 4. - Method of locating transition.

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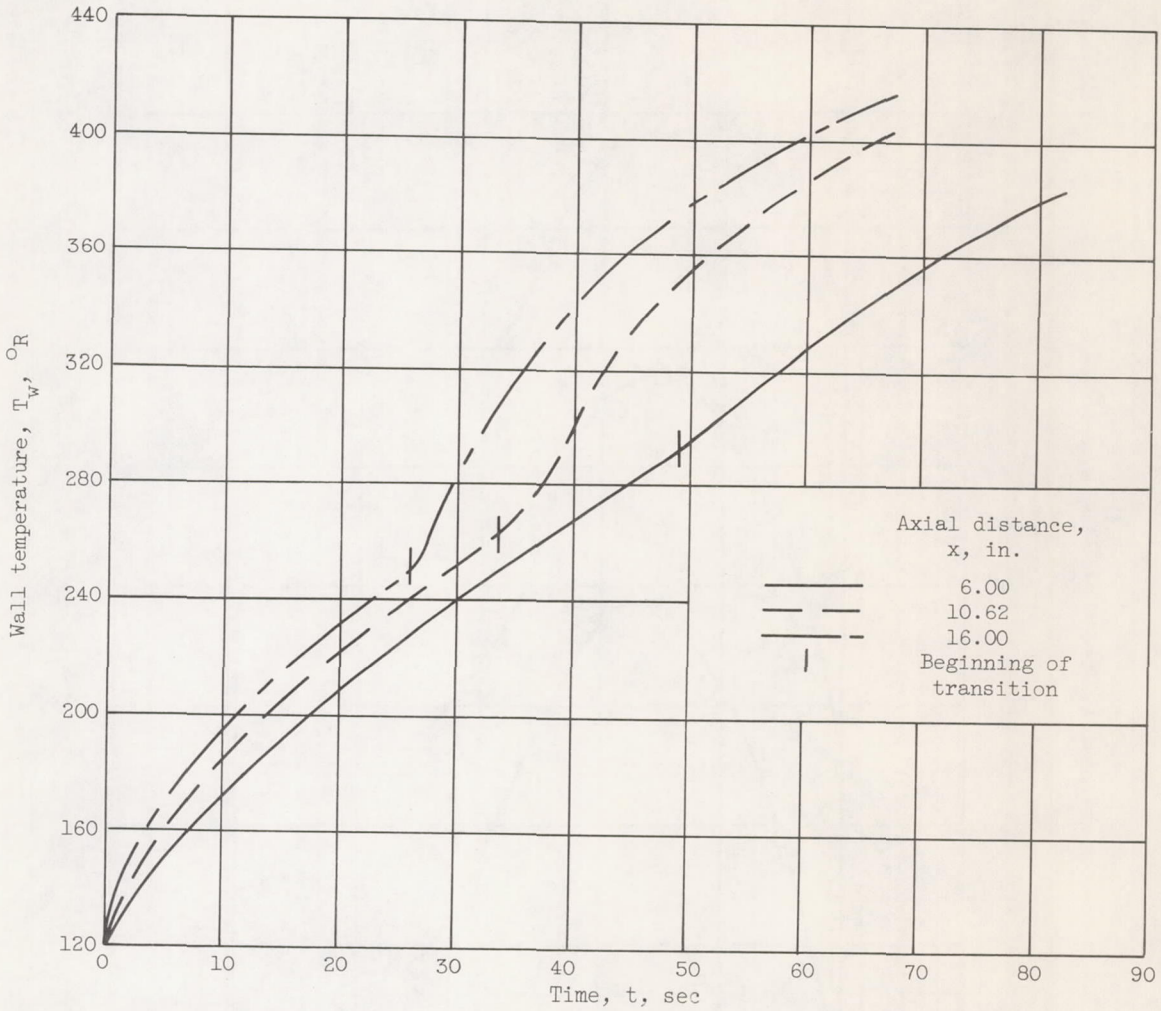
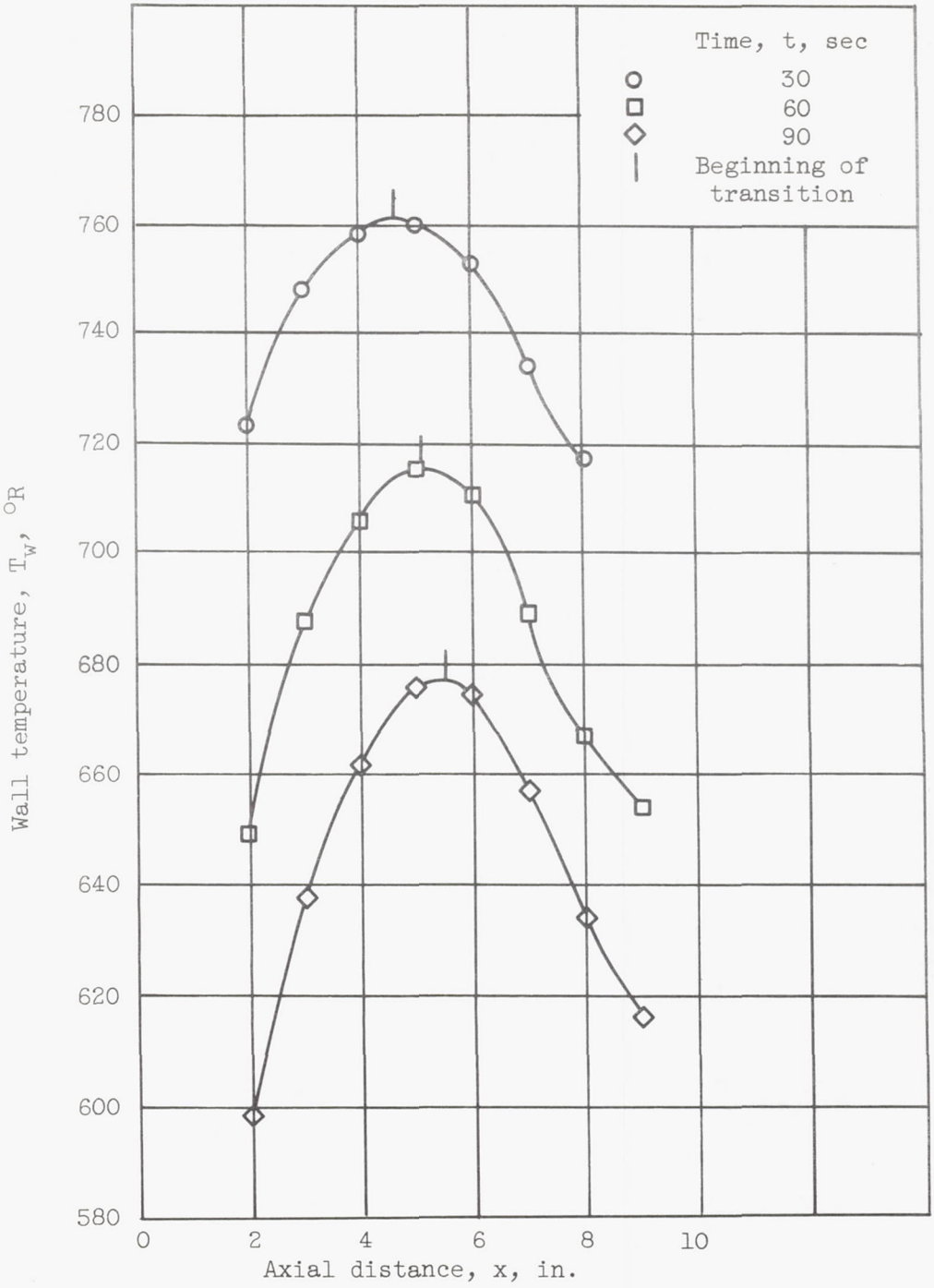


(b) Temperature history for cooled cone-cylinder model; Reynolds number per foot, 7.94×10^6; wall temperature at zero time, 120° R.

Figure 4. - Continued. Method of locating transition.



(c) Axial temperature distribution for heated cone-cylinder model; Reynolds number per foot, 2.27×10^6; wall temperature at zero time, 782° R.

Figure 4. - Concluded. Method of locating transition.

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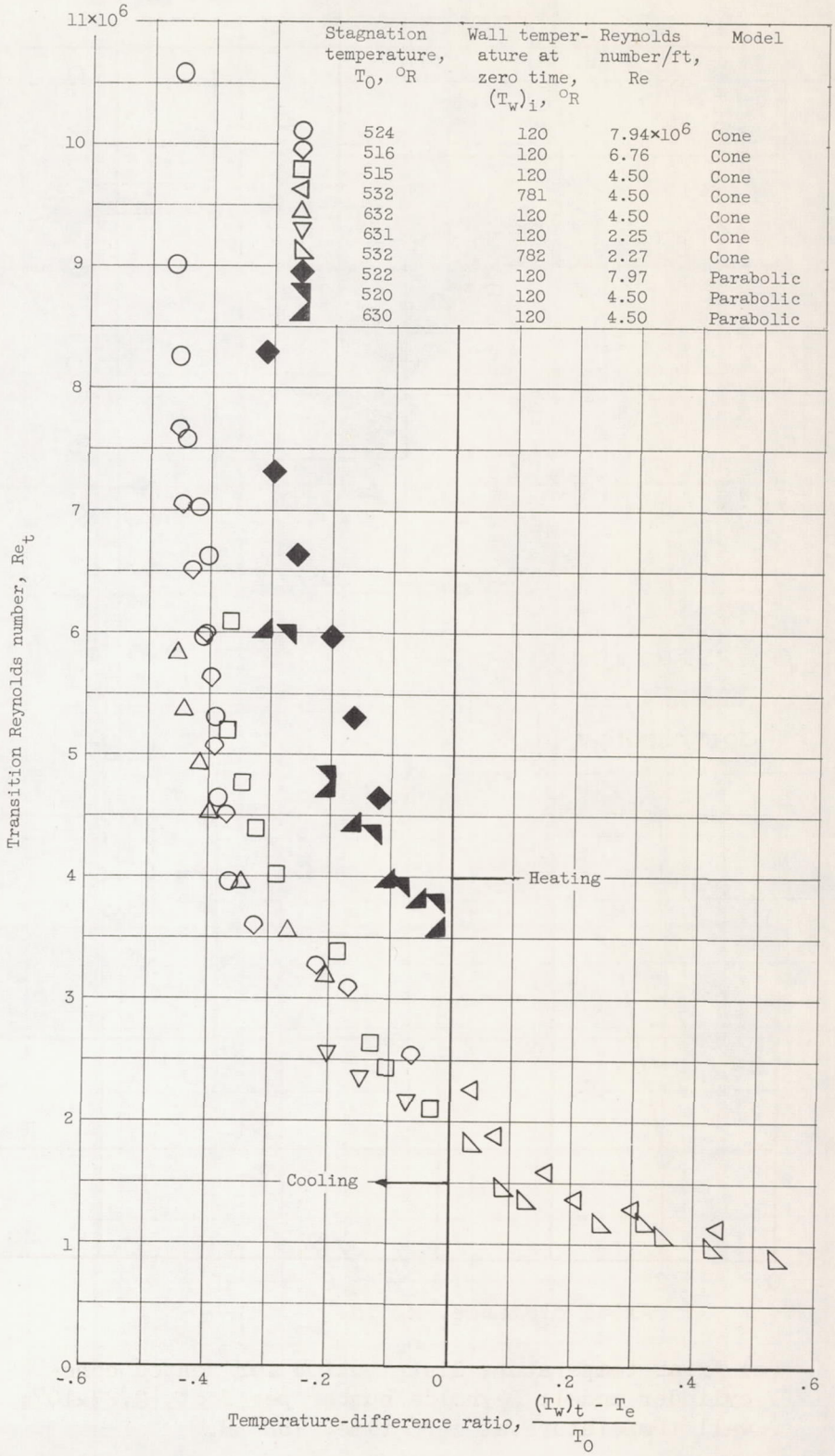

Figure 5. - Effect of adding or removing heat on boundary-layer transition.

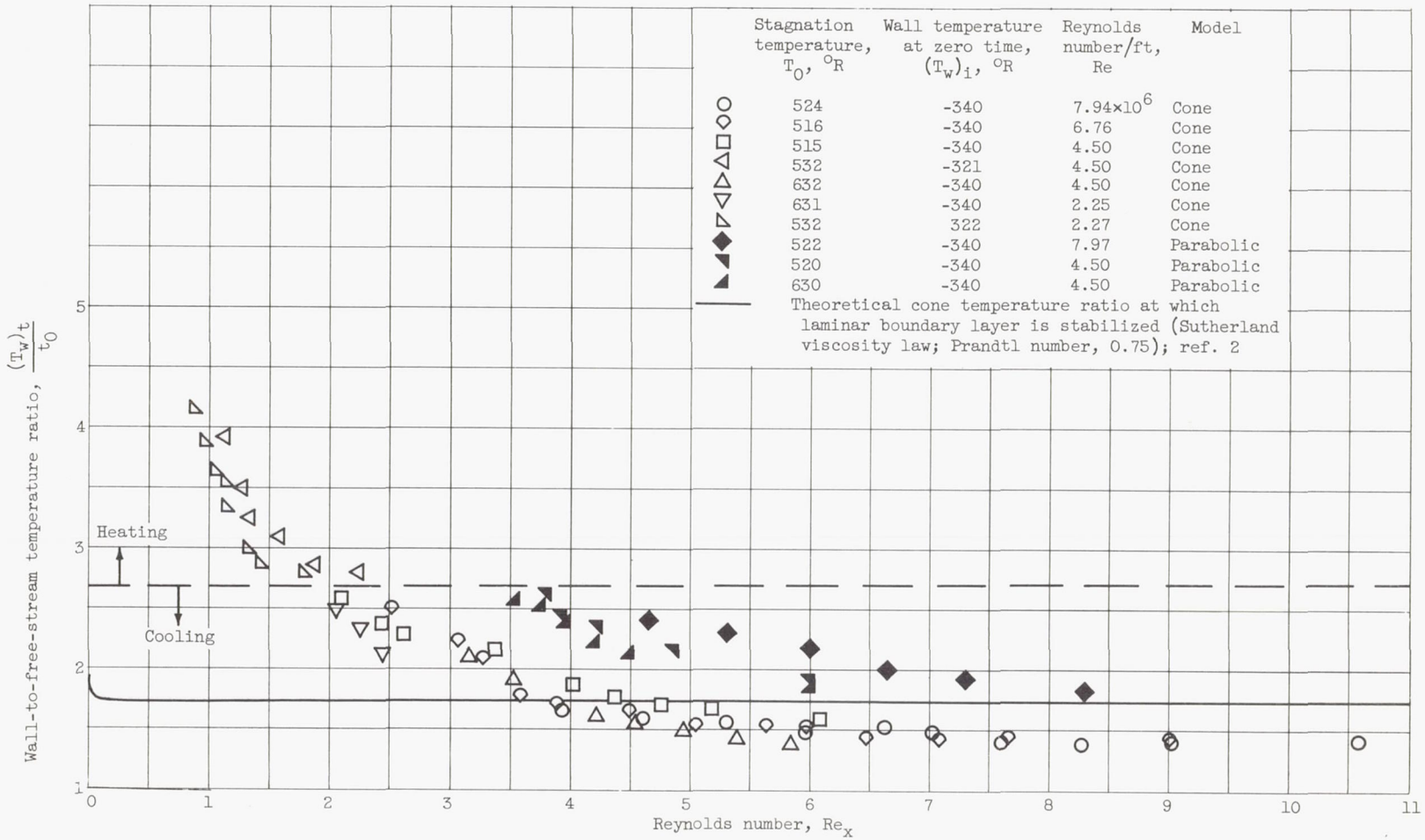

Figure 6. - Comparison of experimental transition Reynolds number with theoretical stability calculation.