AIAA JOURNAL
Vol. 31, No. 1, January 1993

Technical Notes

TECHNICAL NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes cannot exceed 6 manuscript pages and 3 figures; a page of text may be substituted for a figure and vice versa. After informal review by the editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Unit-Reynolds-Number Effects on Boundary-Layer Transition

Kenneth F. Stetson* and Roger L. Kimmel†
Wright Laboratory,
Wright-Patterson Air Force Base, Ohio 45433

Discussion

NUMEROUS wind-tunnel experiments[1,2] with sharp plate and cone models have documented the result that the transition Reynolds number is dependent upon the unit Reynolds number of the wind tunnel. With a few exceptions, it has been found that increasing the unit Reynolds number increases the transition Reynolds number and this result has generally been referred to as "the unit-Reynolds-number effect."‡ These flow situations are presumed to involve similar boundary-layer profiles and for such cases stability theory has not provided an explanation for the transition Reynolds number changing with changes in the unit Reynolds number.

Because these examples were almost exclusively encountered in wind-tunnel experiments and because of the possibility that wind-tunnel freestream disturbances were responsible, there has been uncertainty as to whether or not the unit-Reynolds-number effect existed in flight situations. Potter[4,5] performed extensive ballistic range experiments to investigate the unit-Reynolds-number effect in the free-flight range environment. Potter's conclusions were that a unit-Reynolds-number effect did exist in the ballistic range data. In fact, the increases in transition Reynolds number with increases in unit Reynolds number were even larger in the ballistic range than in wind tunnels. However, there were differences in Mach number and surface cooling between the ballistic range and wind-tunnel data. Also, the large differences in unit Reynolds number could be significant. If it were possible to obtain ballistic range data at the lower unit Reynolds numbers of wind tunnels, the comparison might be different. Potter found that none of the range-peculiar conditions could offer an explanation for a unit-Reynolds-number effect on transition.

The purpose of this Note is to point out that a specific aspect of the unit-Reynolds-number-problem—that recent wind-tunnel data[6] indicate that planar boundary layers have a greater variation of transition Reynolds number with unit Reynolds number than conical boundary layers. Another significant finding, which very likely is relevant to the above issue, is that conical and planar boundary layers can have different dominant instability phenomena. Cone-planar unit-Reynolds-number differences were evident, but not discussed, in the transition correlations of Pate.[2] Pate's correlations showed a steeper slope for the planar transition Reynolds number vs unit-Reynolds-number data for all Mach numbers between 3 and 8.

Figure 1 is taken from a recent comparison of planar and conical boundary-layer transition at a Mach number of 8 (planar data were obtained with a hollow-cylinder model).[6] The points shown are transition Reynolds numbers based upon the average location of transition onset, defined as the local minimum in the heat transfer rate data. The cone model, with a nosetip radius of 0.002 in. (0.0051 cm), was believed to provide representative "sharp cone" data. The hollow-cylinder model had an average leading-edge radius of 0.002 in. (0.0051 cm). The boundary-layer development characteristics on hollow-cylinder and flat-plate configurations and the practical limitations on model construction make it very difficult to avoid some bluntness effects on such configurations. As a check, the hollow-cylinder transition data of Fig. 1 were compared with data[7] obtained with another hollow cylinder with a smaller leading-edge radius [0.0003 in. (0.00076 cm)] tested in the same wind tunnel and the agreement was excellent. Potter and Whitfield[1] discussed the bluntness issue and collected considerable data on the effects of leading-edge geometry upon transition on flat plates and hollow cylinders. The hollow-cylinder unit-Reynolds-number variation shown in Fig. 1 agrees with previously obtained data from this wind tunnel, including Potter and Whitfield data[1] extrapolated to zero leading-edge radius. Therefore, it appears that both slopes in Fig. 1 were not significantly influenced by bluntness. The most striking features of the Fig. 1 data are the steeper slope of the planar data and the fact that the curves cross. The conical transition Reynolds numbers are only larger than planar at low unit Reynolds numbers. At a unit Reynolds number of 3×10^6/ft (9.84×10^6/m), the planar transition Reynolds number was significantly larger than the conical transition Reynolds number. The reason for these different unit-Reynolds-number effects cannot be explained at this time; how-

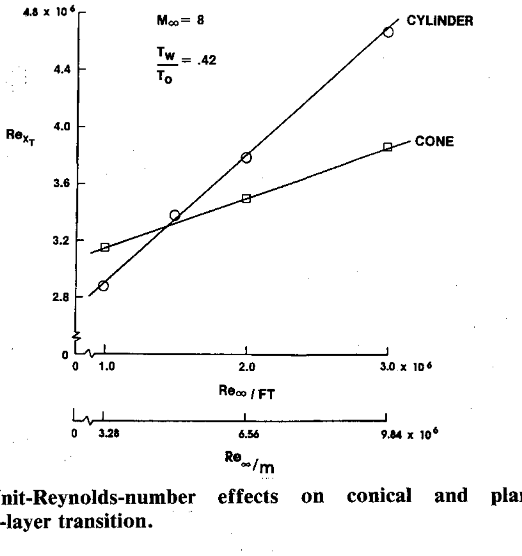

Fig. 1 Unit-Reynolds-number effects on conical and planar boundary-layer transition.

Received Dec. 9, 1991; revision received May 20, 1992; accepted for publication June 2, 1992.

*Aerospace Engineer, High Speed Aero Performance Branch, Flight Dynamics Directorate; currently, Senior Research Engineer, Micro Craft, Inc., P. O. Box 31250, Dayton, OH. Associate Fellow AIAA.

†Aerospace Engineer, High Speed Aero Performance Branch, Flight Dynamics Directorate. Member AIAA.

‡Morkovin[3] has commented that the term should be plural, "effects," since there are undoubtedly several effects associated with a change in unit Reynolds number.

ever, some relevant boundary-layer instability information is available.

Hot-wire anemometry experiments have provided many details of the major disturbances found in planar and conical laminar boundary layers and Ref. 6 contains some pertinent data at a Mach number of 8. These experiments demonstrated that the dominant disturbances in the laminar boundary layer on a sharp cone at zero angle of attack at Mach 8 were second-mode disturbances, the high frequency, acoustical-type disturbances identified by Mack's linear stability analyses.[8,9] Numerical results[10] for the laminar planar boundary layer indicated that second-mode disturbances should also be the major disturbances in the planar boundary layer. However, the hot-wire anemometry data demonstrated that this was not the case. The major disturbances were low-frequency disturbances that were growing in a frequency band that the linear stability analysis indicated should be stable.[6] These Mach 8 planar results appear similar to the flat-plate results obtained by Kendall[11] at Mach numbers of 3.0, 4.5, and 5.6. Kendall reported that "fluctuations of all frequencies were observed to grow monotonically larger in the region of a boundary layer extending from the flat-plate leading edge to the predicted location of instability; i.e., in a region where no growth was expected." This early growth of disturbances was attributed to the strong sound field generated by the turbulent boundary layer on the nozzle wall. Although stability theory predicts that the second-mode instability will be the primary instability at Mach numbers 4.5 and 5.6, Kendall found no evidence to indicate a dominating presence of second-mode waves. However, when testing with a cone model at $M_\infty = 8.5$ ($M_e = 7.7$), second-mode disturbances were the dominant disturbances. Thus, these data (Refs. 6 and 11) indicate that for planar boundary layers between Mach numbers 3 and 8, the major disturbances are low-frequency disturbances that are growing in a frequency band expected to be stable. This situation has never been observed in conical boundary layers.

It is interesting to note that cone transition data obtained in ballistic ranges[4,5] produced a unit-Reynolds-number slope even steeper than the wind-tunnel planar slope. Intuitively, it would seem that the different slopes of the transition Reynolds number vs the unit-Reynolds-number data was a significant point, but at this time one can only speculate as to the causes.

References

[1]Potter, J. L., and Whitfield, J. D., "Effects of Slight Nose Bluntness and Roughness on Boundary-Layer Transition in Supersonic Flows," *Journal of Fluid Mechanics*, Vol. 12, Pt. 4, 1962, pp. 501–535.

[2]Pate, S. R., "Measurements and Correlations of Transition Reynolds Numbers of Sharp Slender Cones at High Speeds," *AIAA Journal*, Vol. 9, No. 6, 1971, pp. 1082–1090.

[3]Morkovin, M. V., "Instability, Transition to Turbulence and Predictability," AGARDograph 236, July 1978.

[4]Potter, J. L., "Boundary-Layer Transition on Supersonic Cones in an Aeroballistic Range," *AIAA Journal*, Vol. 13, No. 3, 1975, pp. 270–277.

[5]Potter, J. L., "The Unit Reynolds Number Effect on Boundary-Layer Transition," Dissertation submitted in partial fulfillment of the requirements for the Degree of Doctor of Philosophy, Vanderbilt Univ., Nashville, TN, May 1974.

[6]Stetson, K. F., Kimmel, R. L., Thompson, E. R., Donaldson, J. C., and Siler, L. G., "A Comparison of Planar and Conical Boundary Layer Stability and Transition at a Mach Number of 8," AIAA Paper 91-1639, June 1991.

[7]Donaldson, J. C., private communication, Arnold AFB, TN Calspan Corp., Jan 1991.

[8]Mack, L. M., "Linear Stability Theory and the Problem of Supersonic Boundary-Layer Transition," *AIAA Journal*, Vol. 13, No. 3, 1975, pp. 278–289.

[9]Mack, L. M., "Boundary Layer Linear Stability Theory," AGARD Rept. No. 709, June 1986.

[10]Gasperas, G., "Effect of Wall Temperature Distribution on the Stability of Compressible Boundary Layer," AIAA Paper 89-1894, June 1989.

[11]Kendall, J. M., "Wind Tunnel Experiments Relating to Supersonic and Hypersonic Boundary Layer Transition," *AIAA Journal*, Vol. 13, No. 3, 1975, pp. 290–299.

Near-Wall Two-Equation Model for Compressible Turbulent Flows

H. S. Zhang* and R. M. C. So†
Arizona State University,
Tempe, Arizona 85287
C. G. Speziale‡
ICASE, NASA Langley Research Center,
Hampton, Virginia 23665
and
Y. G. Lai§
CFD Research Corporation,
Huntsville, Alabama 35801

Introduction

DIRECT numerical simulations of compressible turbulent flows, at high Reynolds numbers with all scales resolved, will probably not be possible in the foreseeable future, if ever at all. Therefore, turbulence modeling will continue to play a crucial role in the aerodynamic design of advanced aircraft. In high-speed aerodynamic applications, near-wall turbulence modeling is extremely important for the accurate prediction of crucial design parameters such as the skin friction and heat transfer coefficients. Despite its technological importance, progress in near-wall turbulence modeling has been slow. Many commonly used near-wall models, which contain a variety of ad hoc wall damping functions, are not asymptotically consistent and yield poor predictions even for simple incompressible boundary-layer flows.[1] These deficiencies can be fatal when turbulence models are applied to complex flows where it is necessary to integrate the governing equations directly to the wall. High-speed compressible flows present a whole range of new problems to near-wall turbulence modeling. Shock/boundary-layer interactions with turbulence amplification and flow separation represent but two examples. Two-dimensional equilibrium turbulent boundary layers are less of a problem provided that the external Mach number M_∞ is less than 5. For such flows, it can be argued that the turbulence statistics are only altered by compressibility effects through changes in the mean density—the crux of the Morkovin hypothesis[2] which allows for the use of variable density extensions of existing incompressible turbulence models where explicit dilatational terms are neglected. However, even the ability of these models to reliably predict mean flow properties in two-dimensional equilibrium boundary layers for $M_\infty \geq 5$ has been recently called into question.[3] For nonequilibrium compressible flows involving shocks and hypersonic speeds, the issue of near-wall turbulence modeling is even more unsettled.[4]

This Note makes an attempt to verify that asymptotically consistent near-wall modeling is crucial for the accurate prediction of high-speed compressible flows. This is accomplished by invoking Morkovin's hypothesis[2] in the extension of the recent near-wall k-ϵ model of So et al.[5] to compressible flows. The resulting compressible two-equation model is tested for boundary-layer flows with M_∞ as high as 10 and with wall cooling ratios T_w/T_{aw} as low as 0.3.

Received Dec. 18, 1991; presented as Paper 92-0442 at the AIAA 30th Aerospace Sciences Meeting, Reno, NV, Jan. 6–9, 1992; revision received May 27, 1992; accepted for publication May 30, 1992.

*Graduate Assistant, Mechanical and Aerospace Engineering.
†Professor, Mechanical and Aerospace Engineering. Member AIAA.
‡Senior Staff Scientist. Member AIAA.
§Scientist.