ENGINEERING TRANSACTIONS • Engng. Trans. • 46, 3–4, 243–250, 1998
Polish Academy of Sciences • Institute of Fundamental Technological Research
10.24423/engtrans.640.1998

EXPERIMENTAL RESEARCH ON STABILITY AND TRANSITION IN HIGH-SPEED WAKES
PART 1. RESEARCH ON THE TRANSITION POSITION IN SUPERSONIC AND HYPERSONIC WAKES, AND THE EFFECTS OF TEMPERATURE AND OTHER FACTORS

V. I. LYSENKO (NOVOSIBIRSK)

The development of disturbances in a supersonic wake (free viscous layer and regular wake) behind a flat plate, both in linear and in nonlinear phases of development was investigated. The influence of several factors (Mach and Reynolds numbers, temperature factor, thickness of a plate, length of its stern) on the wake stability was studied.

1. Introduction

Research on the flow in a wake behind an object is an important problem of aerodynamics. The base drag of bodies of revolution at supersonic speeds can make up to 30% of their complete drag (and particularly for cones – up to 50%; Mihalev [1]; Kovenya and Lebedev [2]), i.e. to determine the aerodynamics of the flying apparatus. In addition, the value of the base drag can increase by more than 100% at laminar and turbulent regimes (Mihalev [1]).

The problem of transition from the laminar flow to the turbulent one in wakes and jets is of great practical significance for decreasing the noise generation in the jets of rocket and aircraft engines, at the supersonic burning, for improvement of the mixture of fuel and oxidizer flows inside the chamber of combustion of the hypersonic flying apparatus.

However, not many experimental researches were done so far on the stability of a wake at supersonic flow speeds (similar research in a boundary layer are more numerous – see, for example, Lysenko [3]; Lysenko and Maslov [4]; and many others), though such papers as Behrens [5], Behrens and Ko [6], Behrens *et al.* [7], Demetriades [8 – 10], McLaughlin [11], McLaughlin *et al.* [12] became classical.

The present paper is devoted to an experimental research on the stability and transition in a high-speed wake behind a flat plate.

2. Equipment and experimental technique

The experiments are carried out in the hotshot tunnel "Transit" at the free stream Mach numbers $M_\infty = 4, 5$ and 7 in the large range of unit Reynolds number $Re_\infty = (40 - 150) \cdot 10^6$ m^{-1}. A symmetric flat plate of 108 mm length and 10 mm thickness was used, having the nose in the form of a wedge with the half-angle of bevel 14° as a test model. The plate stern was blunt (was beveled at the right angle). The plate was fixed rigidly to the lateral walls of the wind tunnel's test section and was exposed at zero angle of attack. By changing the temperature (heating) of air in stilling chamber, the experiments were performed at different values of the temperature factor (wall-to-adiabatic wall temperature ratio) $\overline{T}_w = 1, 0.85, 0.8$ and 0.6.

To fix the transition position in the wake and in the boundary layer of the plate, a Pitot tube was used, with the sizes of the totalhead-tube reception aperture of 0.3 mm height and 1.3 mm width (external sizes of the tube were 0.4 mm and 1.4 mm), and diameter of the reception aperture of static-pressure probe of 0.3 mm, the induction probes DMI, dialog-computer complex DVK-2M and the high-speed digital system of registration "Spectrum-2". To define the position of the boundary layer transition, the location of the totalhead tube on the model surface was changed along the longitudinal coordinate x, and the position of transition was defined in the classical way (considering the change in the probe signal, depending on the change of speed profiles at transition of a laminar boundary layer to the turbulent one; the position of the end of a transitional zone was accepted as the position of transition). To determine the location of transition in a wake, the position of the total head tube along the wake longitudinal axis had to be varied, and the beginning of the essential growth of signal of the probe, connected with the change of speed profiles at transition of a laminar wake to turbulent one (decreasing Mach-number defect), was accepted as the beginning of transition (also according to the classical method – see, for example, McLaughlin *et al.* [12]).

3. Results

In Fig. 1 the scheme of the flow around the model in the experiments carried out is shown, and the results are presented in Fig. 2. Here $\overline{x}_t = x_t$ (mm)/108 is nondimensional longitudinal coordinate of transition. The curve $M = 0$ corresponds to the position of the critical point of the wake (the curve was obtained by approximation of the experimental points at $M_\infty = 4$ and 5).

The results obtained show that the conditions (laminar, transitional or turbulent) of the boundary layer at the end of the plate affects (through change of

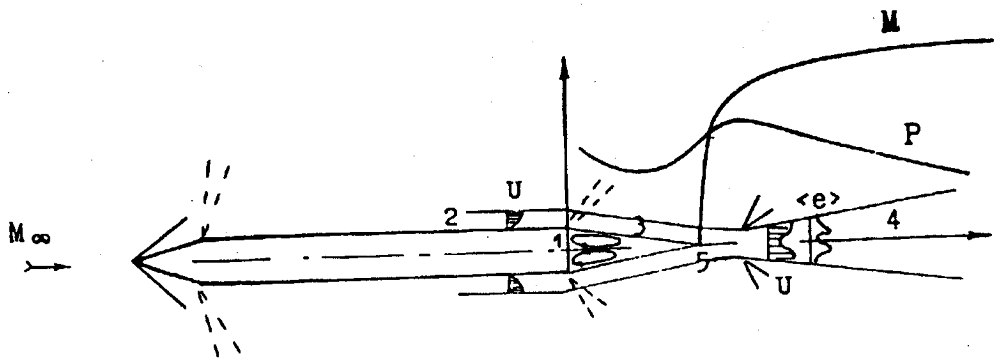

FIG. 1. Diagram of the model flow: 1 – plate end, 2 – boundary layer, 3 – free viscous layer, 4 – wake, 5 – critical back point.

profiles of speed and other parameters, and also at the expense of change of the level of disturbances) the position of the wake transition, though the processes of turbulization (in particular, amplification of disturbances) can occur simultaneously both in a boundary layer and in a wake (because of appropriate instabilities of that boundary layer and the wake). The author has the impression that by decreasing Re_1, the boundary layer at the end of the model remaining turbulent, the beginning of the wake-transition could be near the critical back point (somewhere in the region of the wake throat), and as soon as Re_1 has met the requirements of the transitional condition of the boundary layer, the beginning of transition in the wake started moving away from the critical back point (in accordance with decreasing Re_1). Incidentally, if in the case of the transitional boundary-layer condition the stabilizing effect of the boundary layer on the wake has an effect through the change of profiles of speed and other parameters, in the case of the laminar boundary-layer condition the stabilization occurs by means of reducing the disturbance amplitudes.

It is also shown that compressibility (the increase of Mach number) has a stabilizing influence on the wake. For $\mathrm{Re}_{1\infty} \approx 60 \cdot 10^6\ \mathrm{m}^{-1}$ with consecutive increasing M_∞ from 4 up to 5 and from 5 up to 7, the position of transition (also consecutively) moved away from the model end. A similar withdrawal of transition in a wake was observed in the wind tunnel T-325 (these results will be shown in Part 2, Fig. 1). The obtained results correspond to the papers: MIHALEV [1]; WEN [25]; LYKOUDIS [26]; LEGNER and FINSON [27]; ROSHKO and FISHDON [28]; DEMETRIADES [9], in which the increase of Reynolds number of transition in a wake was found to follow the increase of the Mach number.

Besides, it was found that reduction of the temperature factor at $\mathrm{M}_\infty = 4$ and $\overline{T}_w > 0.8$ stabilizes the boundary layer and, as a consequence of it, the near wake (at least, it is true for the range of Re_1, at which the condition of the mo-

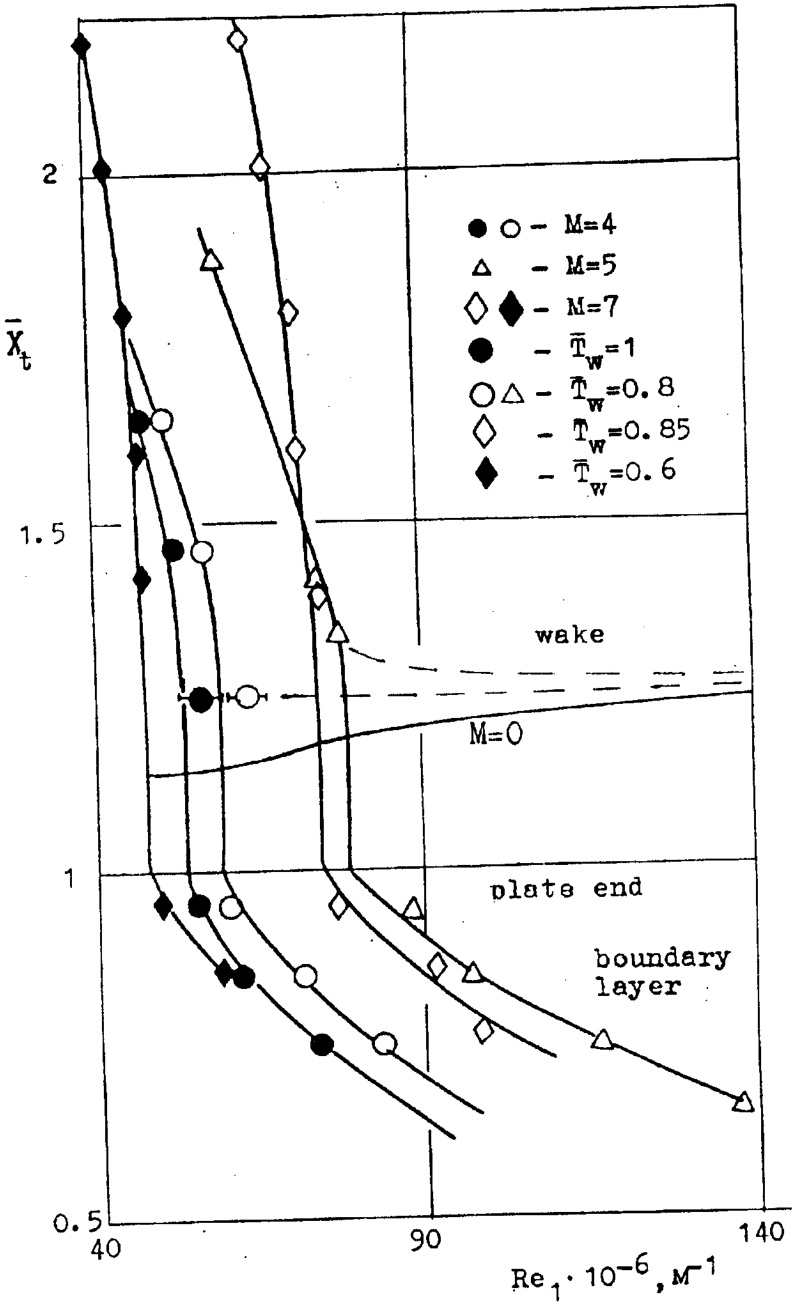

FIG. 2. Nondimensional longitudinal coordinate of transition as a function of unit Reynolds number (●○ – $M = 4$, △ – $M = 5$, ◇◆ – $M = 7$, ● – $\overline{T}_w = 1$, ○△ – $\overline{T}_w = 0.8$, ◇ – $\overline{T}_w = 0.85$, ◆ – $\overline{T}_w = 0.6$.

del-end boundary layer changes), though in case of the laminar boundary layer on the whole plate and large values of $\overline{x}_t$ the situation can become different. At $M_\infty = 7$ and $\overline{T}_w < 0.85$ (when in a boundary layer the transition is determined already by the second unstable mode), the decrease of temperature factor destabilizes both the boundary layer, and the wake. The obtained results do not contradict the theoretical works on stability, in which the decreasing temperature factor destabilizes disturbances of both the first mode in a shear layer (JACKSON and GROSCH [29 – 33]; RAGAB and WU [34]; HEDGE and ZINN [35]; KUDRYAVTSEV and SOLOVYOV [36, 37] and a wake (LEES and GOLD [39]), and of the second mode in a shear layer (RAGAB and WU [34, 40]). However, it is necessary to note that in the paper [40], the influence of cooling of stagnation flow was ambiguous (at $M_1 > 1.5$ it resulted in stabilization of the first mode and destabilization of the second one).

The withdrawal of transition in a wake with decreasing unit Reynolds number was established. A similar influence of Re_1 was observed in the wind tunnel T-325 (these data will be presented in Part 2, Fig 3). Character of the change of dependences of $\overline{x}_t$ upon Re_1, obtained in the wake (reduction of $\overline{x}_t$ with the growth of Re_1) corresponds to the results of the works by MCLAUGHLIN [11] and MCLAUGHLIN *et al.* [12] ($M_\infty = 4.3$), in which it was found, that with the increase of unit Reynolds number, the beginning of transition in the wake moves ahead to the back critical point. A similar result was obtained by PALLONE *et al.* [41] for the hypersonic (6710 m/s) flow speed.

It is also shown that growth of the unit Reynolds number leads to an increase of the longitudinal size of the zone of return currents (in the papers by KOVENYA and LEBEDEV [2] and REEVES and LEES [42] for the laminar wake, similar dependences were obtained). In the experiments carried out, the initial reduction of static pressure was precisely fixed at the movement from the back critical point to the base of the model (with subsequent increase ahead of the model), determining the flow of air into the recirculation zone.

4. CONCLUSIONS

1. The condition (laminar, transitional or turbulent) of the boundary layer at the end of a model exerts the influence (by means of the change of profiles of speed and other parameters, and also at the expense of change of the level of disturbances) on the position of the transition in a wake, though the processes of turbulization can occur simultaneously both in the boundary layer, and in the wake (due to the corresponding instabilities).

2. Compressibillity of the flow (increasing Mach number) stabilizes the wake disturbances - their amplification rates decrease, and the transition moves away from the model.

3. Cooling of a model surface at $M_\infty \sim 7$ exerts a destabilizing influence on the development of disturbances in a wake.

4. With the increase of unit Reynolds number, the beginning of transition in a wake moves forward to the critical point.

References

1. A.N. Mihalev, *Influence of Reynolds number on the parameters of a near – wake behind supersonic cones* [in Russian], [in:] Physical-Gasdynamical Ballistic Researches, Nauka, Leningrad 1980, 88–98.
2. V.M. Kovenya, A.S. Lebedev, *Numerical modeling of viscous separated flow in a near – wake* [in Russian], Zh. Prikl. Mekh. Tekh. Fiz., 5, 53–59, 1989.
3. V.I. Lysenko, *High-speed boundary-layer stability and transition*, Int. J. Mech. Sci., **35**, 11, 921–933, 1993.
4. V.I. Lysenko, A.A. Maslov, *The effect of cooling on supersonic boundary-layer stability*, J. Fluid Mech., **147**, 39–52, 1984.
5. W. Behrens, *Far wake behind cylinders at hypersonic speeds: II. Stability*, AIAA J., **6**, 2, 225–232, 1968.
6. W. Behrens, D.R.S. Ko, *Experimental stability studies in wakes of two-dimensional slender bodies at hypersonic speeds*, AIAA J., **9**, 5, 851–857, 1971.
7. W. Behrens, J.E. Lewis, W.H. Webb, *Transition and turbulence phenomena in supersonic wakes of wedges*, AIAA J., **9**, 10, 2083–2084, 1971.
8. A. Demetriades, *Hot-wire measurements in the hypersonic wakes of slender bodies*, AIAA J., **2**, 2, 245–250, 1964.
9. A. Demetriades, *Transition in two-dimensional wakes*, AIAA J., **16**, 6, 587–591, 1978.
10. A. Demetriades, *Experiments on the free shear layer between two supersonic streams*, AIAA Paper, 710, 8p., 1990.
11. D.K. McLaughlin, *Experimental investigation of the stability of the laminar supersonic cone wake*, AIAA J., **9**, 4, 696–702, 1971.
12. D.K. McLaughlin, J.E Carter, M. Finston, A. Forney, *Experimental investigation of the mean flow of the laminar supersonic cone wake*, AIAA J., **9**, 3, 479–484, 1971.
13. J. Laufer, T. Vrebalovich, *Stability and transition of a supersonic laminar boundary layer on an insulated flat plate*, J.Fluid Mech., **9**, pt.2, 257–299, 1960.
14. A. Demetriades, *An experiment on the stability of hypersonic laminar boundary layers*, J. Fluid Mech., **7**, 385–396, 1960.
15. J.M. Kendall, *Supersonic boundary layer stability experiments*, Aerospace Rep.TR-0158 (S3816-63)-1, **2**, 1967.

16. A.D. Kosinov, A.A. Maslov, *The development of the artificially caused disturbances in the supersonic boundary layer* [in Russian], Izv. Akad. Nauk SSSR, Mekh. Zhid. Gaza, 5, 37–43, 1984.

17. A.D. Kosinov, A.A. Maslov, S.G. Shevelkov, *An experimental research of wave structure of the supersonic boundary layer* [in Russian] Zh.Prikl.Mekh.Tekh.Fiz., 5, 107–112, 1986.

18. A.D. Kosinov, A.A. Maslov, S.G. Shevelkov, *Stability of a supersonic boundary layer after a fan of waves of rarefaction* [in Russian], Zh. Prikl. Mekh. Tekh. Fiz., 3, 113–117, 1989.

19. A.D. Kosinov, A.A. Maslov, N.V. Semionov, S.G. Shevelkov, *Wave structure of artificial disturbances in the supersonic boundary layer on a plate* [in Russian], Zh. Prikl. Mekh. Tekh. Fiz., 2, 95–98, 1990.

20. A.D. Kosinov, A.A. Maslov, S.G. Shevelkov, *Experiments on the stability of supersonic laminar boundary layers*, J.Fluid Mech., **219**, 621–633, 1990.

21. A.D. Kosinov, N.V. Semionov, S.G. ShevelkovG, *Investigation of supersonic boundary layer stability and transition using controlled disturbances*, [in:] Methods of Aerophysical Research, Proc. 7-th Intern. Conference, **2**, 159–166, Novosibirsk 1994.

22. T.R. Troutt, D.K. McLaughlin, *Experiments on the flow and acoustic properties of a moderate Reynolds-number supersonic jet*, J.Fluid Mech., **116**, 123–156, 1982.

23. D.K. McLaughlin, G.L. Morrison, T.R. Troutt, *Experiments on the instability waves in a supersonic jet and their acoustic radiation*, J.Fluid Mech., **69**, 73–95, 1975.

24. S. Martens, K.W. Kinzie, D.K. McLaughlin, *Measurements of Kelvin-Helmholtz instabilities in a supersonic shear layer*, AIAA J., **32**, 8, 1633–1639, 1994.

25. K. -S. Wen, *Wake transition*, AIAA J., **2**, 5, 956, 1964.

26. P.S. Lykoudis, *A review of hypersonic wake studies*, AIAA J. 4, 4, 577, 1966.

27. H.H. Legner, M.I. Finson, *Mach number dependence of laminar near-wake transition for slender cones*, AIAA J., **15**, 3, 417–419, 1977.

28. A. Roshko, U. Fishdon, *About the role of transition in a near wake*, Mechanics, 6, 1969.

29. T.L. Jackson, C.E. Grosch, *Inviscid spatial stability of a compressible mixing layer*, NASA-CR-181671, ICASE Rep. 2, 1988.

30. T.L. Jackson, C.E. Grosch, *Inviscid spatial stability of a compressible mixing layer*, J. Fluid Mech., **208**, 609–637, 1989.

31. T.L. Jackson, C.E. Grosch, *Absolute/convective instabilities and the convective Mach number in a compressible mixing layer*, Phys.Fluids A, **2**, 6, 949–954, 1990.

32. T.L. Jackson, C.E. Grosch, *Inviscid spatial stability of a compressible mixing layer. Part 2. The flame sheet model*, J. Fluid Mech., **217**, 391–420, 1990.

33. T.L. Jackson, C.E. Grosch, *Inviscid spatial stability of a compressible mixing layer. Part 3. Effect of thermodynamics*, J. Fluid Mech., **224**, 159–175, 1991.

34. S.A. Ragab, J.L. Wu, *Linear instability waves in supersonic turbulent mixing layers*, AIAA J., **27**, 6, 677–686, 1989.

35. U.G. Hegde, B.T. Zinn, *Vortical mode instability of shear layer with temperature and density gradients*, AIAA J., **28**, 8, 1389–1396, 1991.

36. A.N. Kudryavtsev, A.S. Solovyov, *Stability of a shear layer of compressible gas* [in Russian], Zh. Prikl. Mekh. Tekh. Fiz., 6, 119 -127, 1989.

37. A.N. Kudryavtsev, A.S. Solovyov, *Stability of a viscous compressible shear layer with temperature leap* [in Russian], Zh. Prikl. Mekh. Tekh. Fiz., 4, 88–95, 1991.

38. L. Lees, *Hypersonic wakes and trails*, AIAA J., **2**, 3, 417–428, 1964.

39. L. Lees, H. Gold, *Stability of laminar boundary layers and wakes at hypersonic speeds. Part 1. Stability of laminar wakes*, [in:] Fund. Phenom. in Hypersonic Flow, 4, 310–337, Cornell Univ. Press, Buffalo, N.Y. 1964.

40. S.A. Ragab, J.L. Wu, *Linear instabilities in two-dimensional compressible mixing layers*, Phys. Fluids A, **1**, 957–966, 1989.

41. A.J. Pallone, J. Erdos, J. Eckerman, *Hypersonic laminar wakes and transition studies*, AIAA J., **2**, 5, 855–863, 1964.

42. B.L. Reeves, L. Lees, *Theory of laminar near wake of blunt bodies in hypersonic flow*, AIAA J., **3**, 11, 2061, 1965.

RUSSIAN ACADEMY OF SCIENCES
INSTITUTE OF THEORETICAL AND APPLIED MECHANICS
Novosibirsk 630090, Russia;
e-mail: gaponov@itam.nsc.ru

Received June 2, 1997; new version May 18, 1998.