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Lester Lees, et al

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Lester Lees

Toshi Kubota

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13. ABSTRACT

This report summarizes the following theoretical and experimental investigations:
A. Hypersonic and Rarefied Gas Flows; Wakes behind a two-dimensional blunt body, Wakes behind two-dimensional slender bodies, Linear and nonlinear stability of laminar wakes, Separated and reattaching flows ~~at hypersonic~~ speeds, Viscous flow past a slender yawed cone, Viscous flow around a sharp expansion corner, Laminar and turbulent boundary layers with strong blowing, Supersonic turbulent mixing layer and Kinetic theory description of rarefied gas flows.
B. Flow of Ionized Gases; Theory of weakly ionized gases, Low-intensity discharge transverse to a hypersonic stream, Arc-heated wind tunnel, Collision-free plasmas, and Non-equilibrium phenomena in low-density arc jets.

14. KEY WORDS

Hypersonic Gas Flows
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STATEMENT OF PROBLEM STUDIED

Our work under this contract covered the following theoretical and experimental investigations:

A. Hypersonic and Rarefied Gas Flows

1. Wakes at hypersonic speeds

    1-1. Wakes behind a two-dimensional blunt body

    1-2. Wakes behind two-dimensional slender bodies

    1-3. Linear and nonlinear stability of laminar wakes

2. Separated and reattaching flows at hypersonic speeds

3. Viscous flow past a slender yawed cone

4. Viscous flow around a sharp expansion corner

5. Laminar and turbulent boundary layers with strong blowing

6. Supersonic turbulent mixing layer

7. Kinetic theory description of rarefied gas flows

B. Flow of Ionized Gases

1. Theory of weakly ionized gases

2. Low-intensity discharge transverse to a hypersonic stream

3. Arc-heated wind tunnel

4. Collision-free plasmas

5. Non-equilibrium phenomena in low-density arc jets

RESULTS AND CONCLUSIONS

Wakes Behind Blunt and Slender Bodies at Hypersonic Speeds

When we began our investigation more than twelve years ago, virtually no measurements existed of mean flow, laminar-turbulent transition, or turbulent structure in the wake behind a body at high speeds, and our study of wakes at hypersonic speeds began with the following questions:

(1) Are vortices shed periodically behind a bluff body in a certain Reynolds number range, as at low speeds?

(2) Does the observed inherent stability of a laminar boundary layer at high supersonic speeds persist in the wake?

(3) What is the effect on spreading rates and wake structure of the hot cone of gas that has traversed the strong portion of the bow shock?

(4) If turbulent fluctuations are observed in the wake, is there also a strong component of radiated energy, as found by other people from turbulent boundary layers at hypersonic speeds?

In order to answer some of these questions we conducted experimental and theoretical investigations on the wakes behind blunt and slender bodies at hypersonic speeds. Our findings are briefly summarized in the following subsections.

1.1. Wake behind a Circular Cylinder

A systematic experimental study of the two-dimensional wakes behind circular cylinders of 0.1, 0.2 and 0.3 inch diameter was conducted by T. Kubota and J. F. McCarthy in the GALCIT hypersonic tunnel at Mach number of 5.8 for Reynolds number in the range of 6,000 to 80,000. Static pressure, total pressure and total temperature were measured throughout the cylinder wake, and other flow properties were computed from these measurements. This study defined the characteristics of the mean flow in the near-wake from the wake neck to a distance of about 50 diameters downstream, such as the wake growth rates, the velocity and temperature profiles for laminar and turbulent wakes, and the transition from laminar to turbulent flow. T. Kubota extended linear laminar-wake analysis of to compressible flow with arbitrary pressure gradients in order to provide a check for the experiment. (McCarthy, Ph.D. Thesis, 1962; McCarthy and Kubota, AIAA Journal, 1964)

By using McCarthy's mean flow data, Kingsland's measurements of diffusion in the wake, and the hot-wire measurements of Demetriades we were able to correlate the location of laminar-turbulent transition in the inner viscous wake behind a circular cylinder. (Demetriades and Gold, ARS Journal, 1962).

Later W. Behrens conducted an experimental investigation of wakes far downstream of a small circular cylinder in the Mach 6 wind tunnel. He discovered from his hot-wire survey of the wake that at low Reynolds numbers the inner wake (wake resulting from the boundary layer and base flow) remains steady laminar flow but the outer wake (the entropy layer produced by the strong portion of the bow shock) is unstable and leads to non-steady oscillatory flow. (Behrens, Ph.D. Thesis, 1966; AIAA Journal, 1968). This outer wake instability was confirmed later by Kubota's numerical solution of the linear inviscid stability equations. (Kubota and Behrens, AIAA Journal, 196).

The flow in the free shear layer and the neck region behind a circular cylinder was defined by Dewey's experimental investigation. By utilizing the hot-wire anemometer at various heating currents, Dewey measured the local total temperature and the local mass flux. Supplemented by total pressure measurements, his results showed that at low Reynolds numbers the penetration of the shear layer into the base flow is extensive and the neck compression region extends for several shear layer thicknesses upstream and downstream of the wake stagnation point, and thus it was shown that except for very high Reynolds numbers the Chapman-Dennison analysis for the base flow is too crude and a more rational approach is needed which incorporates the interaction between the shear layer, the base flow and the external inviscid flow. (Dewey, Ph. D. Thesis 1963; AIAA Journal, 1965). This lead to theoretical investigations by Reeves, Klineberg and Grange supported by OSR, USAF.

These measurements behind an uncooled cylinder were later extended to the wake behind a cooled cylinder by Ramaswamy (Ph. D. Thesis, 1971).

One technique proposed for reducing (or modifying) the electron production in the neck and near-wake is to inject coolant into the base region. This injection has two effects on the flow: (1) The recompression and heating in the neck region is reduced because of the mass addition in the base flow region. (2) A low temperature coolant with a high specific heat mixes with the high temperature gas in the shear layer and reduces the temperature.

The effect of air injection in the base region of a circular cylinder on the wake flow was investigated by Herzog (Ae. E. Thesis, 1964), and the diffusion of foreign gas in the base-flow and the near wake was measured by Collins (Ph. D. Thesis, 1968; Collins, Lees and Roshko, AIAA Journal, 1970).

2. Wakes behind Slender Bodies at Hypersonic Speeds

The flow behind a slender body is different from that behind a blunt body in that the base flow and the near wake are surrounded by high Mach number stream behind a slender body at hypersonic speeds while the base and wake flows behind a blunt body are bounded by relatively low Mach number flow even at hypersonic freestream Mach number. In order to define the flow field behind a slender body, Kubota and Batt conducted measurements of the near-wake flow behind a wedge of 10° half-angle in the Mach 6 wind tunnel for surface temperatures of 0.8 and 0.2 of stagnation temperature. The most striking feature of the flow uncovered by the measurements is that only a small fraction of mass originally contained in the boundary layer enters the viscous recompression region near the axis and most of the flow in the boundary-layer wake is supersonic and nearly inviscid. The base-flow and near-wake region behind a slender body at hypersonic speeds exhibits a two-layer structure: a viscous inner wake and a nearly inviscid, supersonic rotational outer wake of the boundary layer. (Batt, Ph.D. Thesis, 1967; Batt and Kubota, AIAA Journal, 1968). This experiment served as a test case for many numerical solutions of base-flow problems.

These measurements were extended by Wu and Behrens to the case of slender wedges at angle of attack (Wu, Ae.E. Thesis, 1971) and by Hulcher and Behrens to the case of a thin plate at angle of attack (Hulcher, Ae.E. Thesis, 1972; Hulcher and Behrens, Proc. 1972 Heat Transfer and Fluid Mech. Institute).

3. Wake-Flow Stability

In connection with our work on wake flows we investigated theoretically the stability of laminar compressible wakes.

Gold investigated the linear stability theory for both two-dimensional and axially symmetric wake flows. This study showed that the high temperature in the wake associated with high Mach number reduces the amplification rate and has the effect of delaying the transition to turbulent flow. More importantly his investigation showed that axisymmetric wakes are unstable not to axisymmetric perturbations but to non-axisymmetric perturbations and develop into a spiral motion. (Gold, Ph. D. Thesis, 1963; Lees and Gold, AIAA Journal, 1966).

The linear stability theory tells us that unstable small fluctuations are amplified at exponential rates by extracting energy from the mean shear flow. This may be correct when the energy contained in the fluctuations are small, but it is obvious that as the fluctuation intensities increase we have to take into account the effect of the fluctuations on the mean flow. This non-linear stability theory was investigated by Ko and Kubota by using the integral method in which the solutions of stability equations for parallel mean flow were incorporated. A very good agreement with measurements by Sato and Kuriki in low-speed wake was obtained. (Ko, Ph. D. Thesis, 1968; Ko, Kubota, and Lees, Journal of Fluid Mech. 1970). Ko was successful later in extending to compressible axisymmetric wakes (at TRW Systems Group), but our earlier attempt to apply the same technique to mixing layer was met with a certain fundamental difficulty, which needs a further investigation.

Supersonic Separated and Reattaching Flows

The flows involving boundary-layer separation still remain unsolved. It is true that we are able to estimate the separation point with given pressure distribution for two-dimensional flows, but it is not possible in many cases to extend the calculation beyond the separation. In the early 60's the importance of interaction of boundary layer and external inviscid flow in determining the pressure distribution and hence the boundary-layer separation and reattachment was recognized, and an approximate analytical method based on the moment-method treatment of boundary layer was proposed for two-dimensional supersonic flows with shallow separated flow. (Lees and Reeves, AIAA Journal, 1964).

Since the Lees-Reeves solution is an approximate solution and it has some difficulties in dealing with highly cooled boundary layers at hypersonic Mach numbers, an experimental investigation was carried out by Lewis on the effect of cooling on separated and reattaching flow in a sharp corner formed by a 10^{o} wedge mounted on a flat plate. For a purely laminar interaction the surface-pressure distribution and the profile shape parameter distribution agree well with the Lees-Reeves-Klineberg theory in the adiabatic case. The pressure distribution near the separation -- the free-interaction region -- is correlated by the scaling suggested by Curle. (Lewis, Ph.D. Thesis, 1967; Lewis, Kubota and Lees, AIAA Journal, 1968).

In Lewis' experiment the wedge was effectively of infinite length -- the trailing edge of the wedge did not have any influence on the separation and reattachment of the boundary layer. Ko and Kubota investigated experimentally and theoretically the effect of shortening the wedge as well as the effect of rounding the concave corner. They were able to obtain good agreement between measurements and theoretical predictions by placing the branch-point singularity of the moment equations of Lees-Reeves-Klineberg formulation. (Ko, Ph.D. Thesis, 1968; Ko and Kubota, AIAA Journal, 1969).

Tyson made a fundamental contribution by investigating the topology of integral curves in the x-M-H plane (streamwise distance - Mach number - shape parameter) of the moment equations for adiabatic wall. Tyson's analysis, together with Kubota's analysis of departure solutions and asymptotic solutions for large X, established the existence and uniqueness of the moment-method solutions applied to supersonic separation problems (Tyson, Ph. D. Thesis, 1967).

Somewhat unrelated to the studies reviewed above, but another class of problems involving separation is the flow around a yawed body of revolution. Earlier Tracy conducted a systematic measurement of flow past a yawed sharp-nosed cone in the Mach 8 wind tunnel. His measurements of surface pressure, surface heat-transfer rates and Pitot pressure distribution at various angles of attack are serving even today (ten years after the experiment) as one of a few test cases detailed enough to check numerical computations.

Viscous Flow Around a Sharp Expansion Corner

For smooth slender bodies in slightly viscous flows the theory of boundary layer is well established. The basic assumption in the theory is that the streamwise variations in the flow are small compared to the transverse gradients in the boundary layer. This assumption breaks down near a sharp leading edge, the trailing edge of a thin plate and a sharp expansion corner. Many practical shapes have a sharp corner such as the junction of a cone-cylinder, the ridge on a double-wedge airfoil, and the corner at the bluff base of a finite cone or wedge.

Puhl carried out measurements of the flow around a corner of 10° half-angle cone and cylindrical aft body. His measurements of surface pressure distribution and total pressure distribution in the boundary layer clearly indicated the inapplicability of conventional boundary layer theory. (Puhl, Ae. E. Thesis, 1965). Tyson studied the flow around a sharp corner by means of the moment method neglecting the transversal pressure gradients and by finite difference solution of the full boundary layer equations including the transverse momentum equation. (Tyson, Ph. D. Thesis, 1967). Victoria extended the flow measurements to a two-dimensional case. He also obtained an analytical solution of the integral moment equations using the method of matched asymptotic expansions (Victoria, Ph. D. Thesis, 1969).

Laminar and Turbulent Boundary Layers with Strong Blowing

The normal injection of gas at a solid wall into laminar or turbulent layer is a very effective means of reducing the amount of heat conducted into the wall, actively employed by pumping the gas through a porous wall, or passively employed by using ablative wall material. When the major portion of heat transferred to the wall is radiation from hot gas outside the boundary layer, the amount of gas injected at the surface could become large compared to the amount required for reducing the convective heat transfer. Fernandez studied the problem of two-dimensional boundary layers with large distributed surface injection. For the case of laminar boundary layer, asymptotic solutions were obtained for large injection based on the fact that in this case the boundary layer may be divided into two regions: an inner region adjacent to the surface where viscous mixing plays a minor role; and a viscous layer where the transition occurs from the inner solution to the inviscid flow outside the boundary layer. For turbulent flow, experiments with uniformly distributed surface injection was performed at a freestream Mach number 2. 6. An unexpected result of the experiment was that the entrainment rate of the turbulent boundary layer approached the value for the incompressible turbulent mixing layers while the entrainment of supersonic turbulent mixing layers decreases rapidly with increasing Mach number (Fernandez, Ph. D. Thesis 1969, Fernandez and Zukoski, AIAA Journal, 1969).

Supersonic Turbulent Mixing

Spurred by Fernandez' findings we embarked on a critical examination of supersonic turbulent mixing layers. We set up a nearly ideal turbulent mixing layer between Mach number 2.5 stream and "quiescent" air in our supersonic wind tunnel. Our measurements included not only the mean flow properties but also the statistical properties of fluctuating quantities. The significance of carefully conducted detailed measurements in supersonic turbulent mixing layers becomes apparent if one observes that the recent trend in the predictive methods for turbulent shear flows is to include more of the physics of turbulence than do the methods based on mixing length or eddy viscosity models. The two-dimensional mixing layers, aside from their increasing technical importance, have the advantage from the turbulence physics point of view that there are no solid walls present so that the direct effects of molecular transport is not important. A disadvantage is that its study in the laboratory is difficult compared to other free mixing flows, which is reflected in the discrepancies in the experimental data existent for two-dimensional supersonic mixing layers.

Our first study in the Mach 2.5 mixing layer conducted by Kubota and Ikawa is nearly completed, and the results will be presented in Ikawa's Ph.D. thesis in the near future.

Other problems

In addition to the studies reviewed above, we are conducting an experimental study of flow-induced cavity oscillations and a study of low-speed wakes behind self-propelled bodies. These are at a preliminary stage at present and will be continued under new contracts.

Kinetic Theory Description of Rarefied Gas Flows

Since it is next to impossible to solve the Maxwell-Boltzmann equation exactly, in 1959 Lees proposed an approximate method based on Maxwell's moment equations incorporating approximate distribution functions to describe the rarefied gas flows from the free-molecule flow regime to the continuum-flow regime.

Wu applied the method to the problem of the flow generated by a step-function increase in the temperature of an infinite plate. The equations were linearized for a small temperature rise, and she was able to obtain closed form solutions which described the transition of the flow from the nearly-collision-free regime to the Navier-Stokes-Fourier regime. (Wu, Ph.D. Thesis, 1963).

Brinker applied the method to the flow outside a sphere at arbitrary Knudsen number: the heat-flux from a slightly heated sphere at rest in an infinite gas; the velocity field and drag of a slowly moving sphere in an unbounded space; the velocity field and torque on a slowly rotating sphere. Singular aspects of the moment method encountered in the last two problems lead to a formal criterion for a "well-posed" moment system, and the previously unanswered question of just how many moments must be used in a specific problem was clarified to a great extent. (Brinker, Ph.D. Thesis, 1969).

Flow of Ionized Gases

Our effort in this area was focused on: the theory of weakly ionized gases and electrogasdynamics in order to understand the added effects of electromagnetic forces on gas flows (Demetriades and Hill, J. Appl. Phys., 1965); construction of an arc-jet wind tunnel and measurements in highly ionized, supersonic argon free jet (Witte, Ph. D. Thesis, 1967; Witte, Kubota and Lees, AIAA Journal, 1969); theoretical and experimental studies of thermally non-equilibrium gas flows in low density arc jets (Cassady, Ph. D. Thesis, 1970; Cassady and Lees, AIAA Journal, 1972). A novel analogy of a flow in cosmic scale with hypersonic flow past a body was made by Lees in his paper on the interaction between the Solar-plasma wind and the geomagnetic field in an attempt to describe the geomagnetic cavity surrounding the earth and its long tail extending into the interplanetary space. (Lees, AIAA Journal, 1964).

PARTICIPATING PERSONNEL

Clark B. Millikan
Lester Lees
Wilhelm Behrens

Anthony Demetriades
George Bienkowski

Forbes C. Dewey
Harris Gold
Richard R. Tracy
Ying-Chu Lin Wu
Robert T. Herzog
Andreas Puhl
John E. Lewis
Richard G. Batt
Thomas J. Tyson
Arvel B. Witte
Chia-Chun Chao
F. L. Fernandez
Denny R. S. Ko
Donald J. Collins
Gary D. Brinker
Keith J. Victoria
Philip E. Cassady
M. A. Ramaswamy
Jiunn-Jenq Wu
Gregory Hulcher
Robert L. Gran

Paul E. Baloga (Engineer)

Truus Van Harreveld (Mathematician)

Gerrit Van Halewijn
San Roman
Jacob Van Dijk
} (Junior Engineers)

Geraldine Van Gieson
Virginia Conner
} (Secretaries)

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