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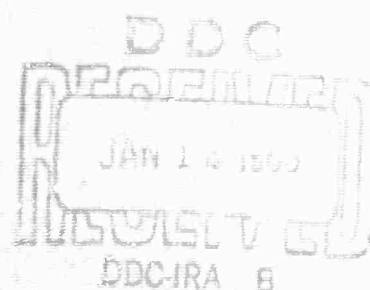
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Semi-Annual Technical Summary Report
Contract DA 04-495-AMC-458(Z)



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RE-ENTRY PHYSICS RESEARCH
SEMI-ANNUAL TECHNICAL SUMMARY REPORT

prepared by

HELIODYNE CORPORATION
Los Angeles, California 90064

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prepared for

ADVANCED RESEARCH PROJECTS AGENCY

under ARPA Order 360
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U.S. ARMY MISSILE COMMAND
Redstone Arsenal
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SUMMARY

This report describes the re-entry physics research activities at the Heliodyne Corporation under Contract DA-04-495-AMC-458(Z) during the time interval of 12 June to 31 December 1964. Investigations were conducted in the following areas: mixing and chemical reactions in turbulent wakes; stability of two-dimensional and axi-symmetric laminar wakes; the influence of non-adiabatic collisions in the vibrational and dissociative relaxation of a high temperature gas; analyses of optical scintillation data from re-entry field tests; and shock tube investigations of the spectroscopic and electromagnetic properties of ablation product/air mixtures.

The individual research topics are described in the following pages in the form of abstracts from completed reports, or progress reports on continuing activities.

MIXING AND FLUCTUATIONS IN A TURBULENT WAKE^{*}

by

Andrew P. Proudian

The structure of turbulent wakes of hypersonic bodies is argued to be largely controlled by the combined action of relatively large scale random convective motions, which introduce inhomogeneities in the wake core, and of molecular diffusion aided by turbulent distortions of fluid elements. A previously developed mathematical model representing turbulent wake mixing in terms of a mixing lag is discussed and qualitatively justified in terms of the above described mixing mechanism, and somewhat generalized. Numerical predictions for the magnitude and variation of mass density fluctuations in a relatively low speed wake are obtained by solving a simplified set of equations, in which the lag is represented by an effective mixing boundary, and are in encouraging agreement with the general magnitude and trend observed experimentally, although firm experimental measurements are lacking to-date.

^{*} Abstract of Heliodyne Research Report 8, dated December 1964

ANALYSIS OF PARTIAL WAKE MIXING AND APPLICATION TO REACTING NON EQUILIBRIUM WAKES*

by

A. Proudian and A. Widawsky

The description of the mean properties of turbulent hypersonic non-equilibrium wakes in terms of partial mixing of ingested fluid by the growing turbulent core is analyzed. A formulation of the conservation equations for wake mixing is developed which avoids internal inconsistencies in the specification of each fluid portion present in some existing treatments. The problem of representing the important effects of statistical fluctuations in mixing in the conservation equations for the mean wake properties is briefly discussed. The conservation equations in the case of negligible dynamic interaction between the mixed and unmixed fluids and in the limit of sudden mixing are integrated to determine mean wake properties, particularly electron densities and their fluctuations, for a blunt body case of importance. The sudden mixing limit is argued to be a reasonable first approximation to turbulent wake mixing. The application of the results to the prediction of radar backscatter from turbulent underdense wakes is discussed.

* Abstract of Heliodyne Research Note 16, dated December 1964

ANALYSIS OF SCHLIEREN MEASUREMENTS*

by

Andrew Proudian

The Schlieren measurement of gas density fluctuations in a turbulent wake has been analyzed in terms of the relative importance of bulk and surface refractive effects. The results indicate that surface effects are almost always important and may even be dominant in the observed results. This conclusion appears to cast some doubt on the validity of the interpretations placed by Clay, et al, of Lincoln Laboratory on their observed results. A more careful analysis of the bulk and surface refraction is required in order to arrive at a definite conclusion.

*Abstract of Heliodyne Research Memorandum 8, dated October 1964

STABILITY OF DUST LADEN TWO-DIMENSIONAL LAMINAR WAKES*

by

Ali Hasan Nayfeh

The stability of two-dimensional compressible dusty wakes is investigated. An equation is derived for the amplitude of the pressure disturbance. The solution of this equation is sought by perturbing the dust-free solution for small mass fraction of dust to gas. The straightforward perturbation expansion is not uniformly valid far away from the wake axis. A second-order uniformly valid solution is obtained. The results show that the dust can be stabilizing as well as destabilizing, depending on the size of the particles and their distribution. For a uniform distribution of dust and for very small particle size, the dust has a destabilizing effect. As the dust size increases, the destabilizing effect increases to a maximum, and then decreases to zero. As the particle size increases further, the dust will have a stabilizing effect. The quantitative stabilizing or destabilizing effect of the dust depends on the velocity defect and temperature excess at the wake axis.

* Abstract of Heliodyne Research Report 6, dated October 1964

STABILITY OF DUST LADEN AXI-SYMMETRIC LAMINAR WAKES*

by

Ali Hasan Nayfeh

In order to investigate the stability of dusty axi-symmetric laminar wakes, a single equation for the amplitude of the pressure disturbance is derived. The stability problem is converted into finding the eigenvalues (wave number, complex wave velocity) and the eigenfunctions of a complicated eigenvalue problem. Thus, the solution is sought by perturbing the dust-free solution. The straightforward perturbation expansion breaks down far away from the wake axis. A uniformly valid second order expansion is obtained, and the characteristic equation for the eigenvalues is derived. Thus, the analytical analysis is completed.

For a Gaussian mean flow model, the eigenvalues and amplification factor will be obtained. The effect of dust on the position of the transition point behind a body will be investigated.

* Summary of continuing work

HIGH TEMPERATURE MOLECULAR COLLISIONS^{*}

by

A. Proudian and I. Tannenbaum

Calculations of the rates of dissociation and vibrational transitions in gases at several thousand degrees Kelvin have been undertaken in the preceding period. The objective of the calculations has been primarily to include the effects of the higher energy molecular collisions which become important at high temperatures in determining the population of the various molecular vibrational levels, and indirectly affect the state of a high temperature non-equilibrium gas. Those collisions particularly affect the population of the higher vibrational levels, which dominate the dissociation process. Previous calculations of coupled dissociation and vibrational relaxation have used models of molecular collisions which are largely adiabatic in nature, and which do not strongly allow multiple quantum transitions, in contrast to the present model which assumes that impulsive collisions dominate the relaxation process, particularly insofar as the upper vibrational levels are concerned.

The study of the coupled dissociation-vibrational relaxation problem requires the determination of transition probabilities in impulsive collisions, together with the solution of a set of so-called Master Equations describing the relaxation process. The present approach to the computation of the transition probabilities has been to assume that the inter-molecular forces are large compared to the molecular binding forces during the molecular collisions. It has

^{*}Summary of continuing work

also been assumed, (consistently,) that interaction occurs between only one nucleus of each member of a colliding pair of molecules, and that the interaction potential is independent of the position of the "non colliding" nuclei of the colliding molecules. Thus it has been assumed that multiple collisions are not important. The possibility of collision of either member of a molecular pair with either member of the collision partner is then accounted for by simply adding the individual cross sections for each possible collision. The probability of transition from a given state i to a state f of one of the colliding molecules can be equated within the validity of the above stated assumptions, to the probability of transition between free state wave packets with momentum distributions corresponding to the bound states i and f integrated over the range of momenta represented by the bound state. Collisions in which both molecules undergo an internal change are assumed to have a small cross section and are neglected, at least for the present. At present, rotational transitions are also ignored, and the bound state wave functions to be used are based on a Morse intranuclear potential. Only quasi-hard sphere collisions have been considered to date, as the free state scattering amplitudes are then known analytically. The interaction is denoted as quasi-hard sphere rather than simple hard sphere because the radius of the hard sphere is taken to be the classical turning radius for motion in a Morse or Lennard Jones interaction potential. Thus the hard sphere radius is made to depend on the incident energy. This should provide a substantial improvement over a simple, fixed radius hard sphere model. A more realistic potential with adjustable parameters will be developed for use in applications to specific molecules of interest. An optimum

numerical method using the hard sphere amplitudes for computing the transition probabilities is currently being sought.

The current formulation of the relaxation equations has been made to correspond to the relaxation of a polyatomic gas behind a normal shock. At present the formulation applies to a system of molecules with only one internal set of energy levels, e. g., the vibrational levels of a diatomic molecule. However, the formulation can be readily generalized to include more than one vibrational mode, or rotational modes.

The formulation applies equally to molecules in an infinite heat bath at a fixed temperature T and to an isolated system of molecules for which T will drop as the gas relaxes.

The key simplifying assumption of previous calculations of coupled dissociation and vibrational relaxation has been that a known form for distribution of the molecules among their vibrational states, generally a Boltzmann distribution corresponding to some temperature T_v , was assumed, and therefore a single parameter, such as T_v , was solved for in order to obtain the vibrational populations. This simplification is not consistent with the present model for transition probabilities and, in fact, the study of the actual distribution is one objective of this study. Thus, the population of each vibrational level must be considered individually, leading to a set of up to fifty or more coupled differential equations to describe the system. Since these cannot be integrated analytically, care must be exercised in selecting a numerical integration scheme which is not prohibitively time consuming. At present, the numerical integration of the relaxation equations is being studied for the simplest

case, which corresponds to coupled vibration-dissociation relaxation of a highly diluted diatomic gas in an infinite monatomic (perfect) heat bath. The initial computations will be performed for an oxygen argon mixture, for which experimental results are available.

The dissociation rates to be used in solving the relaxation equations have not yet been determined. While the impulsive collision model can be applied to predict dissociation probabilities, the criteria for its validity are not well satisfied for dissociation from most of the vibrational levels except for collision energies of perhaps ten volts or so. When numerical results from the collision model for various temperatures are available, it will be possible to choose between using those results and relying on experimental equilibrium rates together with a preferential dissociation model such as that used by Treanor and Marrone, which favors dissociation from higher vibrational levels, and which is consistent with theoretical numerical results such as those of Keck.

It is hoped to compare the results with the experimental studies by K. Wray of relaxation of dilute oxygen in argon behind shocks, and with the theoretical predictions based on the Landau-Teller transition probabilities. If the numerical calculations for the simple cases indicate, as anticipated, a significant change in dissociation rates, the formulation will be generalized to flow situations of interest behind hypersonic shocks and in hypersonic boundary layers, and applied to ablation contaminated flows and, in particular, to the study of the dissociation of important radiating states of excited molecules.

OPTICAL SCINTILLATION ANALYSES*

by

Saul Feldman

Analyses relating the time dependence of passively emitted radiation to significant body parameters of a re-entering vehicle have recently been initiated, and no definite conclusions have yet been deduced.

*Summary of continuing work

A SUMMARY OF CALCULATIONS OF CHEMICAL AND FLUID
DYNAMIC PARAMETERS IN THE SAPAG FACILITY*

by
William J. Hooker

The equations describing the ablation lifetime and trajectory of material particles in a shock tube flow (developed in previous reports on the SAPAG facility) have been re-examined, and programmed for computation on an IBM 7094. Computations have been made of particle burnup times for various materials using real air shock tube properties, and compared with calculated shock tube testing times. In the limit of small relative velocity between the particles and the free stream, simple analytic solutions exist for particle radius and trajectory which are applicable to many physically useful shock tube conditions.

*Abstract of Heliodyne Research Note 17, dated January 1965

EXPERIMENTAL MEASUREMENTS IN THE SAPAG FACILITY*

by

W. J. Hooker, A. L. Morsell and I. R. Tannenbaum

The final version of the SAPAG facility has been in operation since October 1964. The basic shock tube has an all-stainless steel driven section of 3" diameter x 20' length, and is terminated with a dump tank. The tube currently is cold gas driven, and shock waves with velocities up to 4.2 mm/ μ sec have been generated in air using a hydrogen driver at 100 atmospheres pressure.

The problem associated with producing powders in the submicron size range, storing them for extended periods of time, and injecting them into the shock tube in a uniform and reproducible manner have basically been overcome. At the present time, powders are being produced that have a particle size distribution such that approximately 94% of the particles are smaller than 0.8 micron diameter and 50% smaller than 0.1 micron, as determined by electron microscopy. Storing of the finely ground powders for periods of time up to six weeks produces no significant change in the particle size distribution.

Whereas previous tests of powder injection uniformity in a glass shock tube produced substantial gradients of powder mass loading in the axial direction, measurements in the present all metal facility show less than a 10% variation from one end of the shock tube to the other, and the reproducibility is better than 10%.

Measurements have been made of the rate of adsorption of water vapor into the surfaces of the finely ground powders used in experiments to date. These tests have shown that for particles prepared under drybox conditions, there is a rapid adsorption in the first few seconds of exposure to a normal room atmosphere, but that the final equilibrium weight of any given sample corresponds to the addition of approximately one molecular layer of water vapor to each particle. For the materials and sizes tested to date, this corresponds to a weight increase of approximately 1%.

*Summary of continuing work.

Extensive investigations have been made of shock wave attenuation along the length of the tube, and testing time at the observation stations. For initial pressures of 1 to 200 mm Hg and for shock velocities from 1.8 to 4.2 mm/ μ sec, the attenuation is less than 5% over the useable length of the tube (approximately the last half). The measured testing times fall approximately half way between the calculated values based upon laminar and turbulent boundary layer flows.

The shock tube has been instrumented with a Jarrell-Ash f/6.3 plate spectrograph, and an EG&G xenon flash lamp for absorption measurements. The flash lamp has a nominal 1/e duration of 10 μ sec and is triggered to flash at a selected time behind the incident shock wave. Emission and absorption spectra have been obtained for shock heated air and teflon, and air and epoxy resin mixtures, using a 10 micron spectrograph slit width (with a basic grating resolution of 20 $\text{\AA}$ /mm). Photomultipliers and infrared detectors with appropriate wavelength interval filters are currently being selected to follow reactions pertinent to each material being tested.

The basic circuitry and configuration of the coil used for electron density measurements in the shock tube have undergone extensive revision. Various coil geometries and circuit elements have been tested from the point of view of basic circuit stability as well as the magnitude of the frequency shift under actual shock tube conditions. At the present time, no single configuration works acceptably over the entire range of electron densities encountered (based upon pure air equilibrium chemistry), and it may be necessary to use selected designs for several overlapping ranges of operation.

A series of test firings into pure air have been run in order to calibrate the electron density measuring coil under the proper conditions of electron density and collision frequency. From the tests, a curve of coil frequency change versus calculated electron density is obtained. Since the data interpretation in this calibration technique requires an equilibrium electron density to be established during the available test time, a nonequilibrium normal shock

code obtained from Cornell Aeronautical Laboratory, Inc. (CAL Report No. QM-1626-A-12(II) "Inviscid, Nonequilibrium Flow Behind Bow and Normal Shock Waves, " by Leonard J. Garr and Paul V. Marrone) has been used to compute the equilibration distance for the test cases of interest. It is anticipated that this computer code, along with the normal shock code obtained from the Los Alamos Scientific Laboratory (Report No. LA-2980, "HUG, A Fortran-FAP Code for Computing Normal Shock and Detonation Wave Parameters in Gases, " by Paul F. Bird, Russell E. Duff and Garry L. Schott), will be extensively used in this measurement program.