Heliodyne Corporation

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

RE-ENTRY PHYSICS RESEARCH

FINAL TECHNICAL SUMMARY REPORT

prepared by

HELIODYN   PORATION
Los Angele.., California 90064

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prepared for

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U.S. ARMY MISSILE COMMAND
Redstone Arsenal
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SUMMARY

This Final Technical Summary report describes the research activities at the Heliodyne Corporation in the field of re-entry physics for the period starting 12 June 1964 and finishing 11 June 1965. The research work described herein was supported under ARPA Order No. 360, Contract DA 04-495-AMC-458(Z), monitored by the U.S. Army Missile Command at Redstone Arsenal. Studies were performed under this contract in the following areas: (a) two-dimensional and axisymmetric laminar wake stability, (b) mixing and chemical reactions in a non-equilibrium turbulent wake, (c) analyses of the properties of schlieren records of turbulent wakes, (d) analyses of molecular transition probabilities in high temperature gas kinetic collisions, (e) analyses of shock wave structure in a particle-gas dispersion, (f) analyses of the rate of burnup of particles behind a moving normal shock wave, (g) development of a powder injection shock tube facility, (h) experimental measurements of the rate of burnup of teflon particles behind a normal shock wave in argon, (i) absorption spectra in shock heated teflon/argon and teflon/nitrogen mixtures, (j) experimental measurements of the electrical conductivity of air and air plus teflon mixtures, and (k) analyses of optical scintillation data from re-entry vehicle tests. In the following section, abstracts of reports completed during the current contract period are presented, and a brief description is given of work that is continuing under Contract DA 01-021-AMC-12727(Z).

STABILITY OF DUST LADEN TWO-DIMENSIONAL LAMINAR WAKES*

by

Ali Hasan Nayfeh

The stability of two-dimensional compressible dusty wakes is investig...ed. 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.

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*Abstract of Heliodyne Research Report 6, dated October 1964

STABILITY OF DUST LADEN AXISYMMETRIC LAMINAR WAKES*

by

Ali Hasan Nayfeh

The stability of dust laden axisymmetric laminar wakes is investigated and a single equation for the amplitude of the pressure disturbance is derived. The stability problem is reduced to solving a complicated eigenvalue problem. The solution is sought by perturbing the dust-free problem for small mass fraction of dust to gas. As in the two-dimensional case, the problem is of the singular perturbation type due to a non-uniformity of the straightforward perturbation expansion far away from the wake axis. A second-order, uniformly valid, solution is obtained. As in the two-dimensional case, the results show that the effect of the dust can be stabilizing as well as destabilizing, depending on the size of the dust particles and their distribution. For small particle size, the dust is destabilizing. As the particle size increases, the destabilization effect increases to a maximum and then decreases to zero. As the particle size increases further, the dust will have a stabilizing effect. The magnitude of the amplification or damping factor depends on the wave velocity, velocity defect, and temperature excess at the wake axis.

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.

A GENERALIZATION AND EVALUATION OF THE PARTIAL MIXING MODEL FOR TURBULENT REACTING WAKES AND WAKE-LIKE FLOWS[*]

by

Andrew P. Proudian

The so-called partial mixing model previously formulated to describe mixing in turbulent wake flows describes the turbulent wake in terms of a mixed and an unmixed fluid component, in which mixing of a given fluid element entrained into the turbulent part of the flow occurs after a prescribed mixing lag ζ. The partial mixing formulation is generalized in the present paper to allow for a range of values for the mixing lag ζ for fluid elements ingested at a given downstream station and to allow for momentum exchange between the mixed and unmixed fluid elements in the wake. It also accounts in part for the influence of the turbulent core on the inviscid flow field around it, by requiring that the pressure in the wake be continuous across the core boundary.

The role of statistical correlation terms in the mean conservation equations of the partial mixing model is analyzed, and it is shown that such terms are probably negligible for the quasi one-dimensional model presently used.

The important assumption of the partial mixing model that microscopic mixing in the turbulent core is a 'sudden' process is semi-quantitatively justified for the high Reynolds number flows to which the model is intended to apply.

APPLICATION OF PARTIAL MIXING MODEL TO THE PREDICTION OF ELECTRON DENSITY FLUCTUATIONS IN THE TURBULENT WAKE OF THE MARK 6 RE-ENTRY VEHICLE. A COMPARISON WITH EXPERIMENT AND WITH OTHER PREDICTIONS. (U)[*]

by

Andrew P. Proudian

The variation of wake properties with downstream distance, principally the mean value and root mean square deviation of electron density are predicted for the Mark 6 re-entry vehicle at an altitude of 100,000 feet. The prediction is based on a so called partial mixing model of the turbulent wake. Pure air chemistry and zero angle of attack have been assumed. The predictions of the variation of absolute root mean square electron density fluctuation with downstream distance appear to be in quite good agreement with data deduced from experimental cross section measurements. The agreement obtains over the entire wake length considered (about 8000 feet), and for both C-band and UHF data. The results are tentatively construed as indicating that spatially resolved measurements of radar cross section in the far wake can serve for discrimination, at least for blunt bodies. Inconsistencies in the results of an earlier theoretical prediction by Hayes and Lin[4], based on a similar wake model, are also discussed.

AN ANALYSIS OF SCHLIEREN MEASUREMENTS OF GAS DENSITY FLUCTUATIONS IN A TURBULENT WAKE*

by

Andrew P. Proudian and Theodore Azzarelli

The statistical properties of optical ray deflections as measured by a schlieren system are predicted for a turbulent wake. A wake structure consisting of macroscopic fluid elements or blobs of relatively dense fluid embedded in a homogeneous medium is used as the wake model. The autocorrelation function of the optical ray deflections is determined in terms of the statistical properties of individual blobs and of their distribution. It is shown that the autocorrelation function of the deflections is a product of two factors. One is the autocorrelation of the surface element orientations of a blob. The other is the autocorrelation function of the number of intersections of a light ray with the blobs, which can be directly related to the probability distribution of the blobs. The statistical isotropy of ray deflections observed in schlieren measurements implies random orientation or statistical sphericity of the blobs.

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* Abstract of Heliodyne Research Note 18, dated June 1965

MOMENTUM TRANSFER APPROXIMATION FOR THE CALCULATION OF MOLECULAR TRANSITION PROBABILITIES IN HIGH TEMPERATURE GAS KINETIC COLLISIONS[*]

by

Andrew P. Proudian

A straightforward method, the momentum transfer approximation, is proposed for the determination of the probabilities of inelastic (non-electronic) processes in high temperature gas kinetic collisions. The method is based on a very direct transcription of the physical features of high energy impacts into the transition probability formalism, and is closely similar to the Impulse approximation of nuclear physics. The model makes the assumption that the colli .on can be treated as quasi-impulsive, in the sense that the intramolecular binding and motions can be neglected during the collision.

The momentum transfer approximation is applicable to polyatomic as well as diatomic molecules. It permits the computation of simultaneous rotation-vibration transitions, as well as dissociative transitions for any intermolecular interaction potential, and therefore, has wider applicability than most existing quasi-impulsive collision models. It is also significantly simpler in terms of numerical computations, than most existing methods of comparable accuracy.

The momentum transfer approximation is applied in the present paper to preliminary computations of vibrational transition

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probabilities in oxygen, collisions with argon, for temperatures ranging from 4000°F to 22,000°K. The results indicate that multiple quantum jumps are strongly allowed, as expected. The present results are too limited, however, to permit useful comparisons with experiment, or analyses of relaxation of the internal degrees of freedom of shocked gases.

SHOCK WAVE STRUCTURE IN A DUSTY ABLATING GAS*

by

Ali Hasan Nayfeh

The general one-dimensional equations governing the flow of a mixture of a gas and an ablating dust in a constant-area tube are derived taking into account the simultaneous effects of the dust particle drag, convective and radiative heat transfer, and ablation. The pressure, velocity, and temperature in the equilibrium region, i.e., where the dust is completely vaporized, are obtained by neglecting the particle drag, convective and radiative heat transfer. The results show that the driving pressure ratio needed in a shock tube to attain a shock speed of 1.6×10^5 cm/sec in a mixture of argon and 10% mass fraction teflon at room temperature is about 50% more than that needed to attain the same shock speed in pure argon. The effect of the presence of the dust on increasing the driving pressure ratio is in qualitative agreement with observations in Heliodyne's shock tube. These results are encouraging so that the relaxation zone will be constructed in the near future by solving the above mentioned equations.

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*Abstract of Heliodyne Research Note 23, dated June 1965

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

by

W. J. Hooker

Calculations are presented for the trajectories and burnup times of submicron-size particles in a shock tube where the local flow is free molecules with respect to tne particles. Materials ranging in thermodynamic properties from teflon to graphite are treated. It is shown that the burnup times are short compared to characteristic shock tube testing times, and that the small (0.2 micron diameter) particles accelerate to the local free stream velocity almost instantaneously. An operating map is presented for calculating the acceleration time of particles in a shock tube where the local flow is continuum with respect to the particles.

TECHNIQUES FOR PRODUCING SUBMICRON-SIZE
PLASTIC PARTICLES*

by

I. R. Tannenbaum

A brief review of powder technology is presented, covering aspects of interest to the SAPAG project. Included in this portion is a discussion of the method of producing finely divided powders and the possible mechanisms involved in agglomeration. The techniques used in the production of fine powders for use in the SAPAG experiment are described and representative micrographs of powder preparations, as well as number density distributions, are presented and discussed.

THE PREPARATION AND INJECTION OF TEFLON/GAS DISPERSIONS FOR SHOCK TUBE INVESTIGATIONS*

by

Robert R. Holden and W. J. Hooker

A narrative account is presented of the problems associated with the development of the powder injection shock tube facility at Heliodyne Corporation. Techniques for handling and controlling the contamination level of submicron-size powders are described. A discussion is presented of the various stages in the evolution of the presently used powder injection system. Methods for measuring powder concentration distribution are discussed, and the results of independent measurements are shown.
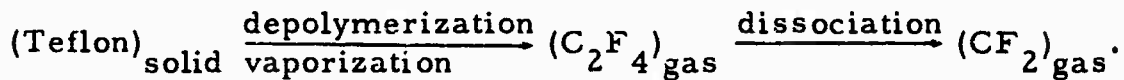

BURNUP RATES OF POWDERS BEHIND A
NORMAL SHOCK WAVE[*]

by

W. J. Hooker and A. L. Morsell

The burnup rate of teflon powders in a shock-heated argon bath has been studied with the use of a shock tube. The rate of disappearance of the ablating particles was monitored by measuring the absorption, at $2536\overset{o}{A}$, of CF_2, which is the end product in the (assumed) reaction

$$(\text{Teflon})_{\text{solid}} \xrightarrow[\text{vaporization}]{\text{depolymerization}} (C_2F_4)_{\text{gas}} \xrightarrow{\text{dissociation}} (CF_2)_{\text{gas}}.$$

The data, which was obtained over the temperature interval of 1600-3100°K, was interpreted to deduce the thermal accommodation coefficient for argon/teflon collisions. The coefficient was found to be of order unity.

THE ABSORPTION SPECTRA OF SHOCK-HEATED TEFLON/ARGON AND TEFLON/NITROGEN MIXTURES[*]

by

W. J. Hooker and R. P. Sellers, Jr.

Absorption spectra have been obtained for the equilibrium products of shock-heated teflon/argon and teflon/nitrogen mixtures. The ultraviolet CF_2 band system has been identified, and its absorption coefficient has been measured as a function of wavelength in the spectral interval 2300-2800$\overset{o}{A}$. The spectral distribution of the CF_2 absorption coefficient has been found to be independent of temperature at 1370 and 2320°K. CF_2 is the only band system observed in absorption for teflon/argon mixtures in the spectral interval 2200-4400$\overset{o}{A}$. By contrast, only the CN violet system is observed for teflon/nitrogen mixtures in the same spectral interval.

ELECTRICAL CONDUCTIVITY OF SHOCK-HEATED AIR AND AIR PLUS TEFLON MIXTURES[*]

by

A. L. Morsell

The electrical conductivities of shock-heated air and air-plus-teflon mixtures have been measured using a method similar to the conducting gas-magnetic field interaction method described by Lin, Resler, and Kantrowitz.[1] All measurements were made for an initial shock-tube pressure of 1 cm Hg. The air-teflon mixture contained about 1 mole percent of teflon. The shock speeds ranged from 2.93 to 5.58 mm/μsec corresponding to temperatures between 3150°K to 6500°K, and conductivities between 0.24 and 111 mhos/m. The electron densities corresponding to these conductivity values range from less than 10^{11} electrons/cm^3 to about 10^{15} electrons/cm^3.

No difference in conductivity between the air and air-teflon mixtures was observed. Except for two conductivity values measured for very low shock speeds, all the measured values differ by less than a factor of two from theoretical values computed for pure air in equilibrium.

STUDIES OF SHOCK-HEATED PARTICLES AND GASES[*]

by

W. J. Hooker, A. L. Morsell, and A. H. Nayfeh

The research work summarized in the Abstracts of Research Notes 17, 19, 20, 21, 23, 24, and 25 will be continued. In addition, independent temperature and pressure measurements will be made on the gas behind the shock wave. These measurements will be correlated with the predictions from a computer program currently under development that accounts for the dominant momentum and energy transfer processes for a shock wave in a particle laden gas. With the means available for measuring and computing the temperature and pressure behind the shock wave, it will be possible to use higher mass loadings of powders in the gas in the shock tube than is presently possible. The optical absorption spectrum of teflon/air mixtures will be studied and the influence of teflon on the conductivity of high temperature air will be further investigated. Where possible, materials obtained from Bell Telephone Laboratories, as used in the Bell Sphere Experiments, will be included for study in this program.

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[*]Summary of continuing work

TURBULENT WAKE STUDIES[*]

by

A. P. Ploudian

The partial mixing model developed under the present contract will be studied further to determine the limits of its applicability, and a comparison with other turbulent wake models will be made. The determination of the mixing rates from a combination of experimental data and further theoretical analysis will be undertaken, and the model will be generalized to include gradual mixing, pressure matching at the boundaries and, if possible, to include radial variations of mean wake properties. A more general numerical code will be written to represent the partial mixing model, and selected numerical computation(s) designed primarily to verify the model will be undertaken.

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[*]Summary of continuing work