FINAL TECHNICAL REPORT

ON

AEROPHYSICAL ASPECTS OF GAS AND PLASMA FLOWS

AF-AFOSR-77-3303

1 APRIL, 1977 - 31 JANUARY, 1982

by

I. I. Glass

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AIR FORCE OFFICE OF SCIENTIFIC RESEARCH (AFFL)
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Chief, Technical Information Division

31 MARCH, 1982
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1) **Abstract**

We have provided the only significant experimental and analytical data on pseudo-stationary oblique-shock-wave reflections in monatomic (Ar), diatomic (O$_2$, N$_2$, air), triatomic (CO$_2$) and polytomic (SF$_6$) gases in the form of isopycnics and shock Mach number - wedge angle ($M_s$, $\theta_w$) - plots of value to the military (AFWL, DNA, ARO, BRL, NSWL, DRES, etc.), industry (R & D Associates, Physics International, NASA, etc.) and universities. Our laboratory results have been invaluable to field experiments and to computational fluid dynamicists. The latter have had to develop new, improved codes to match our accurate experimental data.

Our results on the production of neutrons and $\gamma$-rays by explosive-driven implosions in D$_2$ have now been published. They have attracted an international interest. The method provides a simple means of studying fusion plasmas at extreme temperatures and pressures as well as solid-phase transitions from carbon to diamond and other new materials.

The reports on the dynamics of dusty-gas flows produced by shock waves are "best-sellers" and are out of print. We hope to test our analyses in our new 10cm x 20cm dusty gas shock tube built for this purpose during the year with funds from the Canadian Defence Research Establishment Suffield (DRES). The analytical and experimental data has important applications to combustion, dust explosions, damage from blast waves and cosmic gasdynamics.

Our extensions of the random choice method (RCM) have aided us (and others) greatly in analyzing explosion-implosion dynamics, detonations, dusty-gas flows, and viscous heat-conducting vibrationally-excited shock-wave transitions in air for weak spherical N-waves.
The virtue of this method is that it does not suffer from artificial viscosity (implicit or explicit) smearing of shock waves and contact surfaces. If some method could be found to apply RCM to pseudo- and non-stationary flows, it would revolutionize computational shock fluid dynamics.

Our analytical work on swirling turbulent combustion flows has progressed very well. Experimental data are now being accumulated using laser Doppler anemometry (LDA). This work is not only of interest to researchers in various establishments (including AFOSR) but to industry as well. In this regard, we have received some financial support from Canadian Pratt and Whitney to set up the LDA equipment.

2) Research Objectives

The research objectives are to make significant advances in the field of "Aerophysical Aspects of Gas and Plasma Flows", useful to the varying supporting agencies and to research and development in industry. Our objectives have been met to a large extent. This statement can be verified from our numerous publications in distinguished journals and by our peers in the field internationally.

3) Detailed Summary and Perspectives

Although the phenomenon of oblique-shock-wave reflections has been known for a long time, it is only within the period of this Grant that order and understanding has been brought to this subject. Once and for all, we have shown that the domains and boundaries of regular (RR), single-Mach (SMR), complex-Mach (CMR) and double-Mach reflections (DMR) can be plotted as a function of the initial conditions, namely, shock wave Mach number $M_s$ and wedge angle $\theta_w$ -plane, for a perfect gas. If real-gas effects take place then the initial temperature $T_0$ and pressure $P_0$ must
be added. The results for argon (monatomic gas) are shown in Fig. 1. It is seen that the analysis is good and agrees with experiment for a perfect gas in the range tested for $M_s < 10$. The results for air, $N_2$ and $O_2$ (diatomic gases) appear in Fig. 2. It can be seen that the agreement with a perfect gas in this case is quite good except for the SMR+CMR transition line. The experimental data consists of our own work and from others. Figure 3 shows the results for $CO_2$ (a triatomic linear molecule). Again the data agree well with analysis in the range $1 < M_s < 10$.

These two-dimensional data along with interferometric plots of lines of constant density (isopycnics) have formed the basis for testing the validity of several computational methods of predicting the flow quantities. So far, the computational schemes are quite good for predicting shock shapes and wall-density distributions but poor for giving results on isopycnic shapes and distributions. These disagreements are being investigated by many government, university and industrial establishments in a number of countries. Undoubtedly better computational procedures will evolve in the near future.

The foregoing laboratory results have been successfully applied by AFWL, DNA and BRL among others to predict shock-wave configurations and pressure loadings in field tests on vehicles and missile sites.

The transition lines themselves must be fine-tuned in order to improve the agreement between analysis and laboratory experiments. A great deal has already been done in this respect and this will be the subject of future reports under the new Grant AF-AFOSR-82-0096.

The production of fusion plasmas in deuterium cannot be described more simply than in the brief paper in Physics of Fluids by Glass and Sagie, "Application of Explosive-Driven Implosions to Fusion", (Ref. 1). A copy is enclosed. This unique method of producing neutrons, $\gamma$-rays
and solid-phase transitions (graphite to diamond of 10-20\mu m dia) offers simple, new possibilities for many avenues of physical research of interest to industry, universities and the military. As a matter of fact, 3M of Canada, who are interested in industrial diamonds, have taken up our research and development program on the use of explosive-driven implosions to generate diamonds from graphite. Several R & D personnel from 3M are stationed at our Institute pursuing this work. It is an excellent example of technology transfer from a university to industry.

Although the dynamics of dusty-gas flows is of much importance to science, industry and the military, very limited research and development was conducted in the past in this field. In a more practical vein, very little is known about nonstationary drag and heat transfer experienced by individual particles accelerated by shock or blast waves. Neither is it known precisely what impact pressure such flows impose on structures, nor what damage may result to vehicles, hardened missile sites or buildings affected by high-speed high-pressure dusty-gas flows. In order to understand such problems, the two avenues of analysis and experiment have been undertaken. Our analytical work on the flow in a dusty-gas shock tube (Figs. 4 to 6) and the passage of a shock wave through a dusty-gas layer (Figs. 7 and 8) (in great demand internationally), will form the basis for our experimental work. For the latter, we have built and will instrument a 3-3/4 x 8 in. dusty-gas shock tube 60 ft. long, in order to check our analyses by using glass spheres as homogeneous dust in the 10-50\mu m range. Optical methods, laser Doppler anemometry, pressure gauges, impact gauges, heat-transfer gauges and other devices will be used for this purpose. We estimate the dusty-gas shock tube will cost $500,000.00 and it is being supported by Canadian funds. Here
is an excellent example of AFOSR benefits coming from an almost entirely Canadian funded project.

The random-choice method (RCM) of analyzing nonstationary planar, cylindrical and spherical flows with shock waves has proven to be one of the most powerful and accurate computational methods available today. Its power and accuracy lies in the fact that it makes no use of finite difference methods which suffer from an inherent explicit or implicit artificial viscosity that smears shock fronts and contact surfaces in a flow. Instead it solves the Riemann problem at each time step in the numerical analysis in a random fashion. The results provide sharp fronted shocks and contact surfaces. This method has been applied successfully at our Institute to numerous problems such as explosion, implosion and detonation-wave dynamics, nonlinear planar-wave interactions and dusty-gas dynamics. However, we have also succeeded in using the method for spherical N-wave shock-front transitions with viscosity, heat conductivity and vibrational excitation. The N-waves were generated by exploding wires. The explosion process was modelled by considering the N-waves produced by a small pressurized sphere which is suddenly ruptured. The sphere diameters and the initial conditions determine the properties of the N-waves that simulate those actually obtained from exploding wires. Some of the results appear in Figs. 9 and 10. The comparison between analysis and experiment is good. This research will help us understand the properties of N-waves generated in the atmosphere by SST's and will explain the order-of-magnitude discrepancy between measured and predicted risetimes of sonic boom N-waves. The risetime controls the human-startle effect. The shorter the risetime (microseconds), the more annoying is the boom.

So far the RCM has been successful in treating nonstationary one-
dimensional flows. What is required for the treatment of pseudo-stationary two-dimensional oblique-shock-wave reflections or nonstationary spherical shock-wave reflections is a RCM algorithm to handle such complex flows. So far, despite the endeavours of many able computational fluid dynamicists, the search has proved to be very elusive.

The analytical-numerical program with coupled gasdynamic and chemical-dynamic equations of motion to deal with turbulent, swirling, combusting flows has been completed. Now emphasis has been placed on laser Doppler anemometer (LDA) experimentation shakedowns in order to measure the turbulence components and Reynolds stresses at a given station of a combustor. The results can then be used as data input in the analysis for predicting these quantities at any other station downstream. Their new measurements can be made at the predicted stations in order to check the various models of turbulence and the coupled equations of motion.

As a fall out of the LDA work, it has been confirmed that particle size and their velocity can readily be measured to 1%. This will make it possible to measure fuel-spray size and velocity distributions in combustors which is of much importance to the jet-engine industry in the USA and Canada.

Finally, our research and development work in the foregoing areas is continuing in a vigorous manner. Many reports are in preparation in the five major areas considered. Several papers have been sent to distinguished journals. One has already been accepted for publication in the Proceedings of the Royal Society of London and others will follow. Details will be given under Grant AF-AFOSR-82-0096 in the near future.

Dr. I. I. Glass
Principal Investigator
4) Publications 1981-1977


FIG. 1 EXPERIMENTAL VERIFICATION OF OBLIQUE SHOCK-WAVE-REFLECTION REGIONS AND BOUNDARIES IN THE \((M_s, \theta_w)\)-PLANE. PERFECT MONATOMIC GAS \(\gamma = 1.667\), LAW (1970), CMR IN HELIUM (\(\triangleright\)); LAW AND GLASS (1971) CMR IN ARGON (\(\triangledown\)), BAZHENOVA ET AL. (1976) DMR IN ARGON (\(\square\)). PRESENT RESULTS IN ARGON: ■, DMR; ▼, CMR; ▲, SMR; ●, RR.
FIG. 2 EXPERIMENTAL VERIFICATION OF OBLIQUE SHOCK-WAVE-REFLECTION REGIONS AND BOUNDARIES IN THE \((\theta_s, \omega_w)\)-PLANE. PERFECT DIATOMIC GAS \(\gamma = 1.400\). ----- REAL GAS. \(\Delta, \Theta, \text{AIR (DATA FROM SMITH 1945)}\); \(\text{V, A, O, AIR (WHITE 1951)}\); \(\Box, \text{V, A, O, OXYGEN (LAW AND GLASS 1971)}\); \(\blacksquare, \text{V, OXYGEN (BZHENOVA ET AL. 1976)}\); \(\Theta, \text{NITROGEN (BZHENOVA ET AL. 1976)}\); \(\text{V, A, O, NITROGEN (BEN-DOR AND GLASS 1978)}\).
FIG. 3 EXPERIMENTAL VERIFICATION OF OBLIQUE SHOCK-WAVE-REFLECTION REGIONS AND BOUNDARIES IN THE $\left(M_s, \theta_w\right)$-PLANE FOR A TRIATOMIC GAS CO$_2$ $\gamma = 1.290$. $\square$ = RR, $\circ$ = SMR, $\triangle$ = CMR, $+$ = DHR.
Fig. 4  Schematic diagram of flow in a dusty-gas shock tube after diaphragm rupture.

$\mathbf{R}$ = rarefaction wave; $\mathbf{C}^0$ = contact front, $S^0$ = shock front,
$H$ = head, $T$ = tail.
Fig. 5 Flow quantities at \( \tau = 4 \) \((\alpha = 1, P_{41} = 10, d = 10 \text{ m})\).

--- gas, --- particles, ------ frozen flow.
Fig. 6 Variation of shock wave Mach number $M_s$ with diaphragm pressure ratio $P_{41}$. 

- $M_s$ based on frozen speed of sound $a_{1f}$,
- $M_s$ based on equilibrium speed of sound $a_{1e}$.
FIG. 7 SCHEMATIC x-t DIAGRAM OF THE PASSAGE OF A SHOCK WAVE THROUGH A DUSTY-AIR LAYER.

S: INCIDENT SHOCK WAVE, S: TRANSMITTED SHOCK WAVE, C: CONTACT FRONT, S: INDUCED SHOCK WAVE, R: INDUCED RAREFACTION WAVE, CW: COMPRESSION WAVE.
FIGURE 8. Flow quantities at $t = 3.12 \times 10^{-4}$ s ($p_4/p_5 = 5$). (a) Pressure, (b) Mass concentration, (c) Temperature, (d) Velocity. ——— gas, ———— particles. (i) Beginning of formation of a reflected shock wave, (ii) Beginning of formation of a contact region.
Table 1: Initial conditions for computation.

<table>
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<tr>
<th>No.</th>
<th>$P_o$ (K)</th>
<th>$T_i$ (K)</th>
<th>$R_o$ (cm)</th>
<th>$h$ (cm)</th>
<th>$dX$ (cm)</th>
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<tr>
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<td>0.0383</td>
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<td>$O_2 - N_2$, viscous</td>
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<tr>
<td>J</td>
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<td>289</td>
<td>1.15</td>
<td>0.0383</td>
<td>—</td>
<td>perfect, inviscid</td>
</tr>
</tbody>
</table>

Fig. 9: Path of shock front.

$t^* = -\frac{\rho_i c_i}{\rho_o c_o}, R^* = R/R_o$

$\rho_i$: density
$c_i$: speed of sound
$\rho_o$: density
$c_o$: speed of sound
$R_o$: radius of pressurized sphere
Fig. 10a  Risetime as a function of distance (II).

Fig. 10b  Comparison of pressure profiles (II).

E : $R = 19$ m, $(\Delta p)_{max} = 6.33$ Pa, $t_e = 16.78 \mu$sec, $t_s = 69.37 \mu$sec

F : $R = 19$ m, $(\Delta p)_{max} = 6.0$ Pa, $t_e = 7.7 \mu$sec, $t_s = 66.3 \mu$sec
Application of explosive-driven implosions to fusion

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Our explosive-driven implosion facility was used to produce hemispherical implosions in a stoichiometric mixture of deuterium-oxygen. A high-resolution scintillator detection system measured neutrons and γ rays resulting most likely from the fusion of deuterium.

I. INTRODUCTION

The Institute for Aerospace Studies hemispherical implosion chamber is a unique device for producing explosive-driven implosions which are stable and well-focused at the geometric center in a safe and reusable facility.1 It has been used as a driver for launching hypervelocity projectiles,1 to generate intense planar shock waves,1 and to produce diamonds from graphite.1 In the present study it was utilized to bring about fusion in a deuterium-oxygen plasma.

II. EXPERIMENTAL EQUIPMENT

The implosion chamber (Fig. 1) consists essentially of two massive mating steel plates. The rear plate contains a 20-cm diam hemispherical cavity. Into it is fitted an explosive package consisting of a copper liner to which is bonded a shell of supertine PETN secondary explosive (of about 3 mm in thickness weighing 97 g and releasing about 0.6 MJ of energy for the case reported). The front plate contains an exploding nickel wire (0.13-mm diam×1-mm long) and the gas inlet and outlet. Both plates are fastened together by 32 bolts. The hemispherical cavity is filled with a stoichiometric mixture of deuterium-oxygen (in this case about 55 atm releasing about 0.4 MJ of energy). The gas is detonated at the geometric center by the exploding wire. The gaseous detonation wave instantly and simultaneously explodes the PETN on impact, thereby generating a well-focused implosion wave. This wave reflects at the geometric center, leaving a small pocket of plasma at extreme pressure (megabars) and temperature (millions of degrees) in which a deuterium fusion reaction occurs. To our knowledge this is the most direct method of initiating fusion using only chemical energy. We have tried other indirect methods to obtain fusion, where a small capsule containing deuterium was placed at the focal point of the implosion. One of these was successful and provided almost identical results, thereby lending support to the simple direct technique. Details can be found in Ref. 5.

The detection system for sensing neutrons and γ rays (produced by the neutrons and their interactions with the steel implosion chamber) consists of two scintillator-

footnotes:

1 On sabatical leave from the Nuclear Research Centre, Beersheba, Israel.

FIG. 1. Schematic of implosion-chamber facility and scintillator detectors.
rays than the direct neutrons from the implosion focus. Owing to the large attenuation of the inelastically scattered neutrons, the phenomenon is spread out and delayed as recorded in Fig. 2(b).

IV. DISCUSSION AND CONCLUSIONS

A consideration of the plasma parameters shows that the peak temperatures may be obtained at a radius of about 10 μm with an ion density of about 5x10^2 ions/cm^3. The implosion time is then about 10^-10 sec. Although radiation and conduction heat losses are significant, they would allow temperatures to be reached up to a few keV.

Discussions of different work, with greater complexity, to produce neutrons in deuterium by explosive means can be found in Ref. 5, as well as some considerations of the possibilities of scaling the present apparatus to obtain thermonuclear fusion. Here, we have shown that neutrons and γ rays can be obtained from nuclear reactions by very direct means from an explosive-driven hemispherical-implosion focus in D_2-O_2 mixtures. There is little doubt that temperatures in the keV range were reached thereby approaching thermonuclear fusion conditions. Much work remains to determine the details of the physical properties of such plasmas and the resulting nuclear collision processes.

ACKNOWLEDGMENTS

We wish to thank Dr. A. K. Kudian for his assistance in designing the detection system and Dr. Alan Entenberg of the Laboratory for Laser Energetics, University of Rochester, for calibrating the system.

The financial assistance received from the Natural Sciences and Engineering Research Council of Canada, the University of Toronto Connaught Fund, and the U.S. Air Force under Grant AF-AFOSR-77-3303 is acknowledged with thanks.

FIG. 2. Oscilloscope record from detector No. 1. (a) Without fusion, 2H_2O mixture at 27.2 atm and 127 g PETN explosive. (b) With fusion, 2H_2O mixture at 54.4 atm and 97 g PETN explosive. (i) arrival of implosion and beginning of events, (ii) ignition noise.
