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OVER FORTY YEARS OF CONTINUOUS RESEARCH
AT UTIAS
ON NONSTATIONARY FLOWS AND SHOCK WAVES

by

I. I. Glass

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SUMMARY

Analytical and experimental research on nonstationary shock waves, rarefaction waves and contact surfaces has been conducted continuously at UTIAS since its inception in 1948. Some unique facilities were used to study the properties of planar, cylindrical and spherical shock waves and their interactions. Investigations were also performed on shock-wave structure and boundary layers in ionizing argon, water-vapour condensation in rarefaction waves, magnetogasdynamic flows, and the regions of regular and various types of Mach reflections of oblique shock waves. Explosively-driven implosions have been employed as drivers for projectile launchers and shock tubes, and as a means of producing industrial-type diamonds from graphite, and fusion plasmas in deuterium. The effects of sonic-boom on humans, animals and structures have also formed an important part of the investigations. More recently, interest has focussed on shock waves in dusty gases, the viscous and vibrational structure of weak spherical blast waves in air, and oblique shock-wave reflections. In all of these studies instrumentation and computational methods have played a very important role. A brief survey of this work is given herein and in more detail in the relevant references.

CONTENTS

1. INTRODUCTION

The actual research on shock tubes and supersonic wind tunnels was initiated by Dr. G. N. Patterson when he envisioned and planned the then Institute of Aerophysics in 1948, even though it was not actually available until 1949, and opened officially in 1950 [1]. He became its Founder and first Director. His first three students in the shock-tube field, Bitondo [2-4], Glass [3,5] and Lobb [2,6,7], were initially guided by his analysis of shock-tube flows [8] for the design of their facilities and appropriate experiments.

Since this survey is confined to nonstationary flows, it will not be possible to include references to many other gasdynamic flows which were studied then and subsequently throughout the decades by members of the staff and students alike. Dr. Patterson's interests later centred on kinetic theory [9,10], and when I obtained my Ph.D. in 1950, I assumed responsibility for research and development in nonstationary flows. The present survey then deals with the analytical, numerical and experimental studies in this field from 1948 until the present day.

It should be noted at the outset that this survey is not meant to be exhaustive as far as references are concerned or in the details of the various researches. Here and there a reference from sources other than UTIAS will be called up to assist the reader. Consequently, I hope that many authors will forgive me if their names do not appear and the readers for the brevity of this presentation. The choice had to be arbitrary in order to fit the limitations of this review.

2. THE FIRST TEN YEARS, 1948-1958

Analytical and experimental work in this decade centred mainly on one-dimensional flows in shock tubes induced by shock waves and rarefaction waves. The various interactions of these waves as well as those with contact surfaces were also of considerable interest. It was soon realized that the diaphragm-breaking process was far from ideal [2,7,11]. This had a serious effect on the flow quality behind the contact region, which originated in the driver section of the shock tube, and was disturbed and made turbulent by the remaining jagged edges of the diaphragm. Consequently, the predicted high Mach number in this cold gas was not achieved [6,12]. On the other hand, the flow Mach number in the region compressed by the shock wave in the channel was in quite satisfactory agreement with analysis at the lower shock strengths [7,12].

As for the velocity of the shock wave, it was found that it attenuated [11-13] with distance from the diaphragm, increasing shock Mach number, and lowered channel pressures for a given shock-tube cross-section. The attenuation increased with decreasing cross-sectional area. Some early analyses [14-16] showed that the sidewall boundary layers induced by the shock wave and rarefaction wave were responsible for the shock-wave attenuation. In addition, the boundary layer caused the contact surface to accelerate [11] so that the testing time in the hot region was limited and it was not possible to increase it by going to a longer channel, as inviscid analysis predicted. This situation also caused flow gradients in the hot region, which meant that gasdynamicists, physicists and chemists had to take these deviations into account in analysing their test results for perfect and imperfect gases with vibrational, dissociational or ionizational excitations.

Subsequently, the shock tube became one of the most versatile and economical test facilities for universities, government, and commercial institutions alike. It soon evolved into several hybrids of shock tunnels, expansion tubes and multidiaphragm shock tubes designed to provide high-stagnation temperature and high-Mach number test conditions useful for re-entry heat-shield design of space capsules which were then under development.

At UTIAS, however, some emphasis was placed on wave interactions such as the refraction of a shock wave at a contact surface [3,4,17] and through a gas layer. This work also showed that a shock wave may be tailored through refraction such that only a Mach wave is reflected from the contact surface. This idea led to the reflected shock wave, tailored-interface, shock-tunnel operation, thereby providing a constant-pressure high-enthalpy reservoir of gas for expansion through supersonic or hypersonic nozzles [18,19]. It was also surmised that a layer of gas, such as hydrogen or helium, might provide a protective barrier for attenuating blast waves. However, it was soon noted that the subsequent overtaking of the transmitted shock wave by the refracted shock wave would quickly diminish the attenuation [17,20] and increase the pressure ratio across the transmitted wave to nearly the original shock strength incident on the layer of helium.

It is worth noting that the overtaking of two shock waves provides the ideal shock-tube problem after their interaction, that is, a shock wave and a centred rarefaction wave which are separated by a perfect contact surface. A near-perfect shock-tube problem can also appear at the refraction of a shock wave at an air/helium interface, with a very well defined centred rarefaction wave. Breaking a diaphragm in a shock tube does not produce a centred wave. The tail of the wave is usually obscured in schlieren or shadow photographs, showing that sharp gradients are absent. However, the head of the wave is always visible and provides a gasdynamic means of measuring very accurately the speed of sound in gases [21a]. It is worth noting that only the equilibrium sound speeds were measured from the first characteristic line, even in CO_2-carbon dioxide [21b], and SF_6-sulfurhexafluoride [21c], as it was not possible to produce an ideal centred wave where the frozen precursor might have been observed [see 52a] near the origin.

Additional interactions were studied, such as the head-on collision of shock waves [22] and of shock and rarefaction waves [22,23]. In the former case, again a perfect contact surface is formed. The head-on collision of two shock waves also provides a means of studying reflected shock waves without wall-effects by using two shock waves of equal strength. Very high temperatures with real-gas effects can be obtained in this manner. If a wall is used for reflection, the tailored-interface technique mentioned above can be used to provide a gas with very high escape speed, which is also useful for molecular-beam studies.

One-dimensional refractions of rarefaction waves at contact surfaces [24,25] were also investigated analytically and experimentally using hot-wire anemometry and piezo-pressure gauges. This study showed that rarefaction-wave profiles did not agree with one-dimensional theory and were very much weaker than predicted for a given diaphragm pressure ratio, especially for stronger waves [25]. The so-called Riemann invariants were also not satisfied [12]. Nevertheless, the rarefaction waves as produced agreed reasonably well with the refraction analysis. It can be stated that the various one-dimensional wave interactions studied analytically were verified by experiment. However, in the case of strong shock waves, real-gas effects had to be considered to improve the agreement with analysis [12,22].

With the construction of a 23-cm diameter field-of-view Mach-Zehnder interferometer [26], many worthwhile problems could now be investigated where quantitative density distributions were important for an understanding of the flows involved. This made it possible to study the transition through a contact front developed in a supersonic nozzle [27]. It was shown that it had a density profile resembling a shock-wave transition. The spiral vortex [28] produced by the diffraction of a plane shock wave over a sharp plate was another interesting problem for optical study, especially with the interferometer. It has since been investigated by other researchers in greater detail. The interactions of plane shock waves with plane wire screens [29] and plane and oblique perforated plates [30,31] was also a fruitful area of interest. Transmitted and reflected shock waves were formed which were separated by the screen or plate and a contact region. If the flow through the screen or plate was choked then a second, upstream-facing shock wave was formed near the screen or plate similar to the flow development in a nozzle. Since the screen or perforated plate produces a new transmitted shock wave and contact region, it is possible to obtain density and pressure measurements behind the new shock wave from measurements of the shock speed and contact surface speed in the (x,t)-plane, using a rotating drum camera. This method is useful for perfect gases. However, for real gases, neither the pressure nor particle velocity is very sensitive to changes in initial pressure for a given shock speed. Consequently, this is not a precise method of measuring real-gas properties behind strong shock waves. There is little doubt that direct measurements of pressure, density and temperature are required in such cases.

The interaction of a plane strong shock wave with a steady magnetic field [32] is not unlike the interaction with a wire screen. If argon is used as the test gas for example, then it ionizes and the axial components of the ponderamotive force produced in the gas when it interacts with the magnetic field also gives rise to a transmitted and reflected shock separated by a contact surface. A secondary upstream-facing rarefaction wave can also occur. The wave systems are limited by the initial conditions such that all waves may not always occur. A current flow is also produced at right angles to the flow velocity and magnetic field vectors. In essence, this is the principle of all magnetogasdynamic electric-power generators.

It is also worth noting that some theoretical work on various aspects of the collision and penetration of two rarefaction waves [33], and the overtaking of shock waves by rarefaction waves [34], and vice versa [35], were also completed. Although these are interesting problems, they were not investigated experimentally. In the case of the overtaking problems, simplifying assumptions were made by neglecting secondary characteristics resulting from the interaction. This would limit the analyses to weak rarefaction waves.

It may be concluded that the studies of diaphragm rupture, the actual wave system in a shock tube, the effects of sidewall boundary layers, various types of wave interactions or shock-wave collisions with screens, perforated plates or magnetic fields have taught us a great deal about one-dimensional nonstationary flows in shock tubes. The agreement with analyses has been quite satisfactory by and large. Researchers using such facilities can apply corrections to deviating flows, whether they be due to inviscid, viscous, or real-gas effects. However, there are still untested analyses that require experimental verification. In addition, there are unanswered questions about actual flows in rarefaction waves, in the cold-flow region, and the entire flow profiles from the head of the rarefaction wave to the shock wave as functions of time. Undoubtedly numerical methods could help in answering some of these questions supported by better experimental data. However, researches probably have more interesting, pressing and challenging current problems to solve and would not be interested in the academic resolutions of old problems; yet this is not always the case, as some recent references indicate. A few examples will be of interest, such as the use of the shock tube for transonic-flow testing of airfoils at high Reynolds numbers [36], the collision of shock waves with screens and honeycombs [37], inviscid-flow and viscous boundary-layer interactions [38], and properties of rarefaction waves and compression waves [39a] and their induced boundary-layer flows [39b]. Many additional examples can be found in journals and Proceedings of the recent Shock Tube Symposia.

3. THE SECOND TEN YEARS, 1958-1968

This period is marked by the extension of the investigations into spherical and cylindrical-shock and blast-wave phenomena in gases and underwater. (It should be noted that a fairly complete picture of what was known during this period about planar flows was summarized in the portion of the *Handbook of Supersonic Aerodynamics on Shock Tubes* [12], which was published in 1959. It soon became out of print. However, photocopies were to be found in many laboratories world-wide and to this day, for example, on a visit to China in 1980, it was ironic to hear it considered as the "bible" for shock-tube research — the term being used by older researchers trained in the West.) Rather simple-type glass diaphragms were utilized for this purpose. Nevertheless, the glass spheres had to be blown carefully by an expert glass blower. The cylindrical diaphragms had optical quality glass discs welded to both ends. The assembly was held between two glass plates to ensure cylindrical flow without end-effects [40].

Our first venture was to study the wave system generated by an exploding pressurized glass sphere [41]. It proved to be a very fruitful avenue of research. Wave-speed schlieren records of the radius-time (r,t)-plane soon showed some remarkable differences with planar shock-tube flows and also similarities. The glass diaphragm-breaking process was similar to that of other diaphragm materials used in a shock tube. Namely, the high-pressure driver-gas was made eddying and turbulent by the glass fragments. Nevertheless, the blast wave soon became spherically symmetrical despite the protuberances in the contact front. As predicted by analysis [43,43] the shock wave and the contact front decelerated and the rarefaction wave head moved at the constant sound speed. In addition, it was clearly shown, for the first time, how the second shock wave, formed at the tail of the rarefaction wave imploded on the origin and reflected. Although the reflected implosion could be seen as a second shock following the main blast wave after the contact front in chemical explosions, the implosion phase was always obscured by the dense gases. Similar results were obtained for cylindrical explosions [44].

Additional interesting applications involved the collision of spherical shock waves [45] and underwater explosions. Unfortunately, glass diaphragms have a limited pressure range in which they can be broken. Consequently it was not possible to study the spherical shock-wave collision problem experimentally over an adequate range. The underwater explosions were more successful from an analytical viewpoint. It was necessary to solve the hydrodynamic shock-tube problem [46] in order to apply the appropriate boundary conditions at the moment of rupture and then continue with the analysis. The agreement of the experiments with this analysis was very satisfactory [47].

Simultaneous with the foregoing studies, the groundwork was being laid for a number of important analytical and experimental investigations. The concept of using explosive-driven implosions as drivers for shock tubes and hypervelocity projectile launchers was taking shape [48-50]. Some of the analytical work was also being done during this period on the nonequilibrium expansion flows of dissociating and ionizing argon around a sharp corner [51, 52]. This was in preparation for conducting several investigations on real-gas effects in the very excellent new shock-tube facility designed, instrumented and tested for this purpose [53]. Concurrently, investigations were performed on magnetohydrodynamic flow in the boundary layer of a shock tube [54]; in a hypersonic shock-tunnel test-section (generously donated by the Cornell Aeronautical Laboratory, Buffalo) which was coupled to an existing UTIAS shock tube [55,56]; and an initial ionization process in strong shock waves produced in hydrogen and helium in a unique electromagnetic-driven implosion shock tube [57].

It is of interest to look at some of the above projects in more detail. The explosive-driven-implosion research and development is of particular importance. It was not only necessary to understand the spherical combustion and detonation processes [50], but also to develop a means of instantly and simultaneously detonating an explosive hemispherical shell in a safe and reusable facility. Some consultation with U.S. and Canadian explosive-research laboratories made it clear that the current thinking was that it was not possible to detonate a solid explosive with a gaseous detonation wave. However, we felt that not enough was known then about the physical processes involved in the microsecond regime during the initiation of a solid explosive and therefore the advice from experts was put aside. A small one-dimensional facility was built to test the initiation of solid explosives by gaseous detonation waves [58]. Many explosives were tried (including some dangerous ones, like lead azide; I am grateful to Dr. R. E. Duff for persuading me by telephone to immediately desist from using such unpredictable and hazardous materials) and PETN was found to be an excellent safe secondary-explosive to be used for making hemispherical shells of explosives to be detonated by the gaseous detonation wave in stoichiometric hydrogen-oxygen mixtures in the reusable hemispherical driver [59]. The implosion on reflection at the geometric centre produced a hot high-pressure plasma useful for driving projectiles, intense shock waves, the creation of diamonds from graphite and producing fusion plasmas in deuterium. This work will be discussed subsequently in more detail.

The explosive-driven implosion chamber was used as a driver for projectiles and shock tubes. A great deal of analytical, design and experimental work was done to predict and verify its performance [60-65]. Although plans were made to build a much larger launcher (from a 5 mm barrel to a 25 mm barrel; from a 100-mm radius hemispherical cavity to a 300-mm radius cavity; from a few hundred-gram PETN-shell to one of many kilograms), it was soon found on the smaller-scale model that there were no projectile materials available that could withstand the enormous plasma base pressures and temperatures developed after reflection of an implosion. Consequently, even though very high velocities (20 km/s) were predicted analytically, no more than 5.4 km/s was actually obtained for an 8-mm dia lexan projectile weighing 0.36 g [66]. It is possible that such problems would not have existed on the projected full-scale launcher. Nevertheless, the very high cost of producing such a large facility, coupled with several uncertainties such as projectile integrity, the large amounts of explosive to be used, consistent focussing of the implosions and safety aspects associated with a facility of this size discouraged its construction.

It is also worth noting that an alternative scheme for producing explosive-driven implosions was tried by directly initiating a 5-mm thick sheet explosive hemispherical shell by using 91 explosive detonators. This meant that all detonators had to fire within a jitter of two or three microseconds — a formidable task. The method did not prove successful and had to be abandoned [67].

In order to prepare for the interferometric studies of nonequilibrium corner-expansion flows of dissociating oxygen and nitrogen, as well as ionizing argon, it became necessary to determine the refractivities of the component gases in the mixtures [68-70]. This was done successfully with considerable accuracy in the 10 cm × 18 cm hypervelocity shock tube by means of the 23-cm dia Mach-Zehnder interferometer. Additional analytical work was also done on such flows with coupled vibrational-dissociational nonequilibrium [71]. An initial investigation on dissociating-oxygen corner-flow did not prove to be definitive in its comparison with analysis [72] and therefore would require additional study.

Some preliminary research was also done on oblique shock-wave reflections at a sharp compressive corner and shock-wave diffraction over a sharp expansive corner [73]. In subsequent years this area of investigation was to lead to some important studies, with significant results.

Interest was also aroused by the possibility of flying a micrometeoroid-impact gauge designed by NASA on one of NASA's or Canada's rocket experiments. This area of research was at that time of much importance. The safety of astronauts and spacecraft under bombardment from micrometeoroid particles travelling at the escape velocity from Earth (11 km/s) up to the escape velocity from the solar system (73 km/s) was still an unsettled question. The gauge was calibrated by dropping glass microspheres under gravity and in a shock-tube flow [74] seeded with the same glass spheres as well as one-micron particles charged electrostatically [75] and accelerated to 7 km/s at the NASA Goddard Space Flight Center. This gauge was not flown on one of the rocket experiments owing to lack of funds and personnel.

4. THE THIRD TEN YEARS, 1968-1978

This decade is marked by efforts to experimentally observe and measure actual and physical properties [76] of the focus of combustion and explosive-driven implosions and to compare them with analytical predictions [77]. Temperatures were measured spectroscopically for combustion runs only [76], and projectile base-pressures were inferred from microwave measurements of the projectile velocity in the launcher barrel

[78]. Spectroscopic temperature and pressure measurements [79,80] were reasonably successful and were improved on subsequently.

An important step was taken to apply the explosive-driven implosions as drivers for shock tubes [81]. A 23-mm shock-tube channel was used instead of a launcher barrel [82]. This proved to be a very worthwhile method of producing very strong shock waves (20 km/s) in air [83]. It also led to the explanation of some anomalous radiation effects in the shock fronts [84], which until then defied a reasonably physical interpretation. One of the reviewers of our paper in complimenting our work noted that this proper explanation had waited for several years and urged us to change our research note to a full paper. Although this was a very useful driver, far more impressive electrical drivers were developed at JPL [85] and NASA Ames [86]. This made it possible to obtain at JPL shock-wave velocities of 45 km/s, with little attenuation in a 15 cm dia channel with a 4-μs test-time. Concurrently, an explosive (Voitenko) driver developed at NASA Ames [87], using 30 kg of explosive (about 300-fold greater than the explosive-driven implosion shock tube at UTIAS) yielded velocities of 70-67 km/s in a 3 cm × 3.1-m long glass tube over a distance of 1 meter in one of the runs (about 3-fold greater than at UTIAS). These experiments had to be done at the Lawrence Radiation Laboratory explosive test site, where the facility was destroyed after each run (except for the instrumentation). This is probably the highest shock-wave velocity obtained, with a modest attenuation, and some test time useful for Jovian entry studies. It should be noted that all of these facilities used very low (0.05 torr ~ 2 torr) channel gas pressures.

Another very important application of the UTIAS Explosive-Driven Implosion Driver was in the production of synthetic diamonds from graphite. By placing graphite in a steel capsule and exposing it to a focussed-implosion and its reflection, thereby generating enormous pressures (megabar range) and temperatures (millions of degrees), the attenuated transmitted shock-wave pressures and temperatures were sufficient to create the phase transition. Industrial-type diamonds of 10-20 μm were produced with a yield of about 5-10% of the original graphite [88]. Although such diamonds had been produced statically and dynamically before, this technique was quite novel and promising for the manufacture of new materials and in the application to problems in solid-state physics.

The process was transferred to 3M Canada Ltd., as it was felt that it could best be developed by an industrial firm with much experience in related areas. As a result a fairly large group was set up by 3M at UTIAS to further develop and extend the work on the production of industrial diamonds. The success of this initial work (diamonds were produced in the first experiment) [88], led to the concept of using the explosive-driven implosions to produce fusion plasmas and neutrons from deuterium-deuterium reactions. Further consideration will be given to the implosion research in the final section.

This period was also productive in analytical and experimental studies of ionizing-argon flows. Definitive interferometric investigations were made of the shock structure of ionizing argon and krypton at nominal shock Mach numbers of 13 and 16 [70,89,90]. It was found that the shock wave developed nonstationary oscillations at the higher Mach numbers (>14). The oscillations were easily removed by adding small amounts of hydrogen (~0.5% of the initial pressure), with the consequent reduction of the overall transition length to about one-third of its pure-gas value. The total plasma density and electron density profiles for pure argon, and with small amounts of hydrogen added as an impurity, agreed well with analysis. Two questions remain unanswered to this day: precisely why only a hydrogen impurity removes the oscillations and why the electron cascade-front, where equilibrium ionization occurs, moves towards the translational front as it approached the wall. Some analytical work has recently appeared, which attempts to explain this phenomenon [91].

At the same time the laminar shock-tube wall-boundary layer and the flat-plate boundary-layer flow in the quasi-steady region were studied in ionizing argon analytically and interferometrically for the same shock Mach numbers as the shock structure [92-95]. (It is worth noting that a wall-boundary-layer study at low shock Mach numbers in air had been done many years earlier [96] using the same Mach-Zehnder interferometer with a smaller rectangular shock tube.) It was shown that the wall boundary layer had a profound effect on the shock structure: the smaller the tube hydraulic-diameter, the thinner the shock structure. This result is of importance when comparing experimentally-measured shock structure with analysis. The properties of both types of boundary layers were compared analytically and experimentally. There certainly are differences between them. A difficulty with any experimental technique is to probe the boundary layer near the wall. Nevertheless, total plasma density and electron-number densities were obtained up to 0.1 mm from the wall. The shock-structure wall-boundary-layer interaction did not appear to affect the flat-plate boundary layer too much at lower shock Mach numbers (~13). However, at higher Mach numbers (~16), radiation losses induced nonuniformities at a given test-section station [45].

Another important area of ionizing-argon flows was the investigation of a quasi-steady corner-expansion [97]. The results agreed reasonably well with an earlier analysis [52c], which was later extended to include radiation losses [98]. Apparently, radiation losses were not too important at the lower shock Mach numbers (where the experimental data was obtained) to affect the corner-expansion. As noted earlier, at higher shock Mach numbers, radiation effects are quite significant and would affect such flows.

A number of analytical and experimental investigations were started on condensation of water vapour cooled by nonstationary rarefaction waves in a shock tube [99-101]. Although the initial work was started in the Fifties in order to see if indeed condensation shock waves do appear in rarefaction waves, it was not until the Seventies that it was shown analytically (using the method of characteristics) that such waves must occur as a result of the release of the latent heat of condensation [99]. The experimental pressure profiles [101] could be explained on either the analytical basis of homogeneous [99] or heterogeneous [100] nucleation. Which model is correct will have to await a future experimental decision. Unfortunately, this interesting work had to be terminated owing to insufficient financial support. It is also worth noting that in the Seventies a number of excellent facilities such as the wave-interaction tube [11], the shock sphere [40] and a new hypersonic shock tunnel [102] had to be abandoned owing to lack of funding in these areas of research.

This period also saw a continuation of the research on oblique shock-wave reflections, which culminated in some significant results. The work initially dealt with a number of considerations of real-gas effects [103]. It was later extended to solve once and for all the problem of: given a sharp compressive corner of angle θ_W in a shock-tube channel at specified initial conditions, what type of reflection will occur when it is hit by a plane shock wave at a specified Mach number M_S? Investigators from a number of countries had tackled this problem since the Forties with only partial success. It was finally solved and verified interferometrically at UTIAS for diatomic [104] and monatomic gases [105]. It was shown that in the (M_S, θ_W)-plane four types of reflections [regular, single Mach, transitional (complex) Mach and double Mach) can occur. Note, although the term complex Mach reflection has been used for many years, there is nothing complex about it. The term *transitional* is much better between regular and double Mach reflections. The regions and their transition boundaries were determined analytically for perfect and imperfect gases, including the effects of equilibrium vibration, dissociation and ionization. Recently, it was found that our interferometric results and the optical data from many other researchers agree best with a perfect-gas analysis as far as the various regions and their transition boundaries are concerned. However, real-gas effects become important immediately after the viscous shock waves. Consequently, some areas bounded by the incident, reflected and Mach-stem shock waves may be in nonequilibrium or may achieve equilibrium, depending on the various relaxation times. Therefore, in analysing the flows, real-gas effects must be considered.

The experimental lines of constant-density (isopycnics) showed that despite the many developments in computational methods, all were not capable of accurately predicting the isopycnics of such nonstationary flows [106]. This is now being addressed by a number of computational centres with increasing accuracy [107,108]. Numerical data can now be compared with the available interferometric data for monatomic, diatomic [104-106] and triatomic [125] gases.

It can be expected that more novel and accurate computational methods will evolve in the near future. Such results would be of much assistance to the experimenter in interpreting his optical data not only in the laboratory but in field trials of spherical blast waves. Numerical time-dependent solutions for such problems are yet to be achieved. Once computer codes are verified experimentally, they can produce far more data on physical quantities than it is possible to measure.

In the late Sixties the supersonic transport (SST) became controversial for a number of reasons. Their possible injurious effects on humans, animals and structures were important considerations for Canada, if overflight laws were to be enacted based on facts. Therefore, a number of Canadian establishments and the University of Toronto contributed to the construction of two simulators: a travelling-wave sonic-boom facility and a loudspeaker-driven booth [109]. A great deal of research was conducted in the areas of psycho-acoustics, human response, effects on animals, structural response and gasdynamic analyses [110-117]. Basically, no effects on humans when subjected to sonic booms similar to SST's were observed as far as heart rate changes, temporary threshold shifts and while driving an arduous automobile course. The structural effects on *aged* panels also were found to be negligible. However, small animals like mice, guinea pigs, chinchillas and Rhesus monkeys did tend to suffer physical damage at the basal turn of the cochlea in the form of bleeding which was absorbed in time (or destroyed hair cells). Sonic-boom rise-time, overpressure-amplitude and frequency of exposure were all important factors affecting the bleeding. However, the scaling laws from small animals to humans are unknown. Nevertheless, caution should be exercised against excessive exposure to superbooms.

Since human-startle effects increase with decreasing sonic-boom rise-time [118], the question arose why actual sonic booms produced by SST's can be 100 to 1000-fold greater than predicted by planar shock wave analysis. Atmospheric turbulence [119], temperature gradients near the ground, microphone-response limitations and vibrational excitation [120] of the oxygen and nitrogen components of air were all blamed. Consequently, this problem was investigated experimentally using exploding sparks and wires [121]. It now appears that vibrational excitation of oxygen can give rise to extended shock-wave transitions at low overpressures (about one-tenth the usual sonic-boom value of 100 Pascals). Small-scale turbulence would not be significant. However, large eddies of the size of the aircraft might well give rise to rounded booms with large rise-times or spiked booms with short rise-times. Both types are observed during any overflight past an array of microphones at different altitudes or on the ground.

5. THE FOURTH TEN YEARS, 1978-1988, AND BEYOND

Some of the problems discussed in the previous section are being continued and extended. New research is being initiated and conducted in new or forthcoming facilities. The following research areas are being pursued at the present time: implosion-wave dynamics, oblique shock-wave reflections, sonic-boom effects and the new areas of turbulent, swirling, combusting flows (although this does not deal with shock-tube flows, it deserves to be mentioned) and shock waves in dusty gases.

Three aspects of implosion-wave dynamics are of importance at this time. The spectroscopic measurements of temperature at an implosion focus, which is produced by combustion or with explosives, and the application of the Random-Choice Method [122, 123] to analyse the experimental results. The application of explosive-driven implosions to the production of industrial diamonds and other new materials required an improved facility. It was built for this purpose and eliminates a good deal of physical labour through mechanization. The horizontal position of the flat face of the hemisphere during a run has greatly improved the frequency of excellent focussing. The measurement of physical quantities using manganin-wire pressure gauges, X-ray diffraction, electron diffraction and photomicrographs have all proved to be very useful. A model is being developed to explain how dynamic transitions from graphite to diamond can take place in the submicrosecond regime [124]. Additional solid-state problems will be investigated in the oncoming years.

The use of explosive-driven implosions to produce fusion has not been easy, mainly due to lack of financial support and trained personnel. Nevertheless, neutrons and γ-rays have been generated from D-D reactions at the focus in runs of 54-atm stoichiometric deuterium-oxygen ($2D_2 + O_2$) and about 100-g PETN explosive-shells. Similar results have also been obtained by placing a small hemispherical capsule containing 1.2 atm of pure deuterium covered by a metal diaphragm at the implosion focus (similar to a Voitenko compressor [87]). Experts in the field were skeptical if we would obtain neutrons with so little explosive energy. Our prospects for improving this work and to measure the neutron flux and other radiation properties are not good without adequate financial support. Yet our ideas have proved to be sound and they await further developments.

The research on oblique shock-wave reflections in monatomic and diatomic gases has been successfully applied to a triatomic gas such as carbon-dioxide [125], which is already substantially excited at room temperature. Yet the numerous experiments all agree with the (M_s, θ_w)-plot for a perfect gas with $\gamma = 1.29$. Consequently, the shock-wave-reflection process behaves as if the specific heats were frozen in front and immediately behind the shock waves. The flow regions bounded by the shock waves will be in nonequilibrium and if the flow times are long enough equilibrium will finally be attained. The results do not fit the complete vibrational-dissociational-equilibrium model nor any other partial equilibrium model [125]. The research is being continued in air. The early dissociation of oxygen with increasing shock strength compared to nitrogen adds some interesting aspects to this problem. It is, of course, of most interest to experimenters conducting spherical-blast investigations in the field.

It has now been found that some small animals suffer significant hearing impairment (in the entire range or in some part of the high-frequency range) after the blood clots in the cochlea have been absorbed. Since their hearing range far exceeds that of man (mice hear up to 100 kHz), it is at present not known whether humans also suffer losses and for how long at high frequencies (<20 kHz) when chronically exposed to sonic booms [126].

It now appears that the excellent N-waves produced by exploding wires may not be able to exactly simulate SST sonic booms. The Random-Choice Method has been successfully applied to solve this problem by modelling the exploding wire or spark by a blast from a small pressurized sphere. Since this method does not introduce an artificial viscosity it is possible to solve the spherical shock-wave transition [127]. It is thinner than the equivalent plane-wave profile solved by G. I. Taylor [127]. The work on the structural response of a wood-plaster room subjected to sonic boom and its subsequent crack-propagation properties has been completed [128]. The agreement between pressure and strain measurements and analysis was very good. The agreement of the finite-element crack-propagation analysis and (of necessity) one decisive experiment was very satisfactory. The problem of the pressures generated in two interconnecting rooms by a sonic boom is now being investigated analytically and experimentally [137].

The design of thermally efficient combustors with a minimum of pollutants for jet engines and home furnaces is a very important field of research in view of our dwindling fossil fuels. Such flows are usually turbulent, swirling and chemically reacting. It is a difficult problem to model analytically [129]. In order to verify such analysis, it is important to measure the turbulence quantities of the flow. This can be done using laser-Doppler velocimetry. It can also be applied to measure fuel-droplet size and distribution. Such a facility has now been developed and will shortly be applied to verify the analytical work [129]. Hypersonic combustion is another area of interest [130-132].

The structure of moving shock waves in dusty air is of considerable interest. For this purpose the analysis of a dusty-gas shock tube has been completely investigated using the Random-Choice Method [133]. The nonequilibrium-flow profiles from the head of the rarefaction wave to the frozen shock wave were computed, including the shock-front and contact-front transitions. Working curves were determined for frozen and equilibrium shock transitions as functions of the initial conditions, dust concentration and diaphragm-pressure ratio. The regions where only dispersed shock waves eventually occur have also been found. A new 7.6 cm × 20 cm shock tube was constructed [134] to validate the analysis and to conduct many new experiments of current interest to the researcher in the laboratory or on field trials.

Our experimental research on sonic booms terminated with the researches given in Refs. 135-138 and was finally terminated owing to lack of financial support by the Canadian Transportation Agency, who believed that the SST will not be a problem for Canada, for many years to come. However, analytical work on sonic booms continued to this day, as reported in Refs. 139-141.

Analytical and experimental studies on ionizing shock waves and ionizing boundary layers are reported in Refs. 142-146, and in dusty-gas boundary layers in Refs. 147-149. Additional numerical problems in dusty-gas flows were solved in Refs. 150-156.

The work on shock-wave reflections and refractions has continued to the present day [157-172, 180-182]. Prof. H. M. Glaz [169] has shown that his numerical results do simulate the interferometric data very well. Hence the problem of numerical simulation has been resolved, providing that real-gas effects and viscosity are taken into account.

The research using the explosive-driven implosion facility continued until 1988, with the help of Prof. N. Salansky [see Refs. 173-178], and stopped, owing to a lack of funds and graduate students. It can be summarized that although diamonds were produced in our explosion-driven implosion facility, they were too small to be of commercial interest. The pressure and temperature pulses were too short to allow much diamond growth and often caused reversion to another state of carbon.

We did not have sufficient funds or personnel to develop the proof that we did obtain neutrons at the focus of the implosion. Nevertheless, the facility proved its usefulness for many purposes [179].

At the Eighth Mach Reflection Symposium in July, 1988, I was honoured for my "seminal contributions to theory and experiments revealing the complex nature of oblique shock-wave reflection phenomena", where Dr. George Ullrich and Dr. Heinz Reichenbach gave a brief assessment of my researches. I have retired from active work at UTIAS. However, I am writing a monograph, with my co-author Prof. J. P. Sislian, on "Nonstationary Flows and Shock Waves", based on my over 200 research papers with my students and colleagues. We are hopeful to complete it in 1991, and to have it published. In addition, Prof. Y. Q. Sheng of the Nanjing Aeronautical Institute is assisting us with many solutions of shock-tube-flow problems, which will be used in our monograph.

6. CONCLUSIONS

This brief survey of research on shock tubes and waves at UTIAS over the past 42 years has attempted to give some insight into a unique experience. It is doubtful if any other laboratory has been engaged in this ever-changing field, continuously, over such a lengthy period. A lot of good research and development work was done in a number of specially conceived facilities. It has led to the training of many Ph.D. and Masters graduates, visiting scientists and academics. Numerous UTIAS reports and journal papers were published. The present list of references is by no means complete. Our work over the years has attempted to add to and enlarge mankind's store of scientific and engineering knowledge. The outlook for the future is bright. There are excellent young people world-wide to take over and continue this important work on nonstationary flows and shock waves for many years to come.

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UTIAS Review No. 50
University of Toronto, Institute for Aerospace Studies (UTIAS)
4925 Dufferin Street, Downsview, Ontario, Canada, M3H 5T6

OVER FORTY YEARS OF CONTINUOUS RESEARCH AT UTIAS ON NONSTATIONARY FLOWS AND SHOCK WAVES

Glass, I. I.

1. Nonstationary flows — analyses and experiments
2. Shock wave reflections, refractions, diffractions, interactions
3. Condensation shocks
4. Rarefaction waves
5. Contact surfaces
6. Spherical and cylindrical shock waves and combustion waves
7. Ionizing gas flows and boundary layers
8. Implosions
9. Hypervelocity launchers
10. Dusty-gas flows
11. Sonic boom
12. Interferometry
13. Diamonds from graphite
14. Neutrons and gamma-rays from chemical implosions

I. Glass, I. I. II. UTIAS Review No. 50

Analytical and experimental research on nonstationary shock waves, rarefaction waves and contact surfaces has been conducted continuously at UTIAS since its inception in 1948. Some unique facilities were used to study the properties of planar, cylindrical and spherical shock waves and their interactions. Investigations were also performed on shock-wave structure and boundary layers in ionizing argon, water-vapour condensation in rarefaction waves, magnetogasdynamic flows, and the regions of regular and various types of Mach reflections of oblique shock waves. Explosively-driven implosions have been employed as drivers for projectile launchers and shock tubes, and as a means of producing industrial-type diamonds from graphite, and fusion plasmas in deuterium. The effects of sonic-boom on humans, animals and structures have also formed an important part of the investigations. More recently, interest has focussed on shock waves in dusty gases, the viscous and vibrational structure of weak spherical blast waves in air, and oblique shock-wave reflections. In all of these studies instrumentation and computational methods have played a very important role. A brief survey of this work is given herein and in more detail in the relevant references.

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