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Report on the Seventh International Shock Tube Symposium

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The Seventh Shock Tube Symposium was held 23–25 June 1969 in Toronto, Canada. Sponsored by the University of Toronto Institute for Aerospace Studies and the United States Air Force Office of Scientific Research, the meeting drew nearly 300 attendees from some 20 countries. Of the 40 invited and contributed papers, several described new shock-tube techniques while the majority presented recent experimental results and related theory in the fields of shock structure, atomic and molecular physics, radiation, plasma flows, shock waves in solids, and boundary layers. This report summarizes the principal advances presented and attempts a projection of future directions in shock-tube research. The full proceedings will be published by the University of Toronto Press; the programme was published in the Bulletin of the American Physical Society, June 1969, p. 754.

1. History and background

In a span of somewhat less than 25 years, shock-tube research has taken its place as an important contributor to progress in the physical sciences. Although the spectrum of problems investigated by shock-tube methods is a rather broad one, the unifying feature of the method itself has provided a common interest for many scientists and research engineers all over the world. The biennial International Shock Tube Symposium now serves as the principal vehicle for reporting developments in the field, presentation of new ideas and interaction among investigators from widely dispersed research centres. These meetings are concerned with all aspects of shock-tube research; sessions include material on experimental methodology as well as the physical problems to which shock-tube techniques are applied.

It is only recently that the Shock Tube Symposia have taken on an international character along with a definite schedule. The first meeting in this series was held at the Massachusetts Institute of Technology in 1957 under the sponsorship of the Air Force Special Weapons Group. Subsequent meetings were held in other shock-tube research centres such as Albuquerque, New Mexico and Palo Alto, California. Attendance at these early meetings was good, as were many of the papers. However, the organization and planning were not formalized for purposes of providing regularly scheduled meetings.

In 1965 a group at the U.S. Naval Ordnance Laboratory assumed responsibility for organizing a fifth Shock Tube Symposium. The planning was put on a broader base and announcements and invitations were sent to research centres in many countries. Several hundred people participated in that symposium. There was a general air of excitement about newer developments and a feeling that the Shock Tube Symposium was a particularly useful vehicle for workers in that field. At the banquet associated with the meeting, Dr H. Schardin, the well-known German experimental gas dynamicist, who was also an official of the Bonn government, proposed that Germany would be pleased to serve as the host country for the sixth International Shock Tube Symposium two years hence and invited all to come. Dr Schardin died later that year, but his associates continued with the plans for that meeting, partly out of respect to his memory. Accordingly, the Sixth Symposium was held in Freiburg-im-Breisgau, Germany. It, too, was a highly successful meeting and the papers presented there have appeared recently as a supplement to the *Physics of Fluids* for May 1969.

The Seventh Symposium, hosted by the University of Toronto and its Institute for Aerospace Studies, was then the third of the broadly based, international meetings in this series, and it is the proceedings of that meeting with which we are here concerned. The meeting took place during the three-day period of 23–25 June 1969 at the University of Toronto. Principal sponsors were the University of Toronto Institute for Aerospace Studies and the U.S. Air Force Office of Scientific Research. The Symposium was co-sponsored by the Canadian Association of Physicists, the Canadian Aeronautics and Space Institute, the German Physical Society, the American Physical Society and the American Institute of Aeronautics and Astronautics. The international flavour of the meeting was evidenced by the fact that the Advisory Committee included scientists from nine countries.

2. Summary of the programme

The programme opened with a commemorative talk honouring the 70th anniversary of the first paper to be published on shock tubes. The Paul Vieille Lecturer, Abraham Hertzberg, noted the ensuing forty-year interval until shock tube experimentation was again undertaken in 1939. In the context of current concern with the social implications of scientific research, it is of interest to recall that the motivation for Payman and Shepherd's major work during the 1930's had to do with protection of miners against mine blasts. Hertzberg then described the pioneering work by Bleakney and colleagues which developed the shock tube into a tool useful for quantitative research and recalled his own visit to Princeton in 1946 which led directly to building a shock tube at Cornell. The subsequent evolution of the instrument for investigations in many branches of science makes a fascinating story. Best known are key contributions to the data needed for design of re-entry vehicles and to the properties of gas plasmas applicable to energy conversion. This year also marks another significant event in the pageant of shock-tube history, the retirement from active teaching and research at Princeton of Walker Bleakney.

The subject of very strong shocks was a major theme running throughout the programme. A number of novel means for generating shocks with speeds greater than Mach 10 were discussed by various authors while others presented many new results obtained from tubes operating up to and in this range. It became clear that testing time is an important consideration about which too little systematic information has been available. By testing time one means that interval of time between passage of a shock front and the occurrence of an appreciable change in the uniformity of flow conditions. Obviously the useful testing time depends to some extent upon the problem being studied as well as on the shock tube configuration employed. The more significant processes which limit testing time are arrival of the driver gas interface and related diffusion phenomena, catch-up of rarefaction waves, boundary layer growth on tube sidewalls and radiative cooling. In general the observed testing time for all kinds of shock tubes is approximately half that calculated using plane flow assumptions in the range of Mach 10 shocks. The useful time decreases rapidly for stronger shocks.

Among the special features of shock-tube flow discussed were fully turbulent boundary layer growth behind strong shocks, bifurcation of reflected shocks interacting with the wall boundary layer, the possible importance of Taylor instability at the driver-gas interfaces and vortex formation behind a sharp corner.

High explosive drivers for shock generation are continuing to receive significant attention both for use on shocks in gases, where this technique competes with various electromagnetic schemes, and for generating shock waves in solids where it is the only technique available for obtaining any significant condensation. For those who quail at inclusion of techniques which obliterate the entire apparatus in the roster of shock tubes, one of the invited speakers pointed out with great care and persuasive eloquence that no problem of logic exists. The notion of 'tube' is merely symbolic in such cases, and the fact that a plane wave is generated holds the central concern. Further, new configurations have been developed in which the destruction is limited to the driver section which can be designed as a rather inexpensive replacement cartridge.

The problem of shocks in solids is of quite a different sort from that for gases, both in terms of complexity and current interest. In gases the same equation of state usually applies to both the upstream and downstream flows. Even when this is not strictly true, as with ionizing or reacting gases, the Boltzmann equation still provides an underlying theoretical unity. For solids, however, interatomic forces provide the microscopic mechanism for momentum and energy transfer. The fund of basic understanding is not yet sufficient to yield a set of generally useful dynamic properties like viscosity and conductivity which permit comparatively easy macroscopic interpretation. Consequently two complementary lines of investigation are active in solid shock research, one from a continuum mechanics viewpoint and the other looking at lattice dynamics. A natural intersection between those primarily interested in the mechanics of materials with solid state physicists and geophysicists has obviously begun and should yield substantial progress during the next decade if the present pace of activity is kept up.

One session of seven papers dealt with plasmas in shock tubes. The interaction of fields and plasmas has been studied in two ways: time varying fields applied to the generation and acceleration of plasmas, and moving plasmas interacting with quasi-stationary fields. Despite inclusion of the Langmuir probe among the second group, it seems that substantially broader theoretical understanding has been obtained in the area of plasma generation and acceleration than in plasma flows interacting with fields and solid bodies. Two such problems receiving attention in the programme were collisionless shocks and interaction of an incident shock tube flow with an electromagnetic field.

Another full session was devoted to contributions in chemical kinetics. Many fast gas reactions can be studied by using a shock wave to deposit energy into a gas in a (nearly) instantaneous fashion, followed by time-resolved observations of the resulting changes in population. Both reaction rates and energy levels can be deduced from suitable spectroscopic or interferometric measurements. The classic example of the latter was the unambiguous determination that the higher dissociation energy of 9·76 ev for N_2 is the correct value of the two indicated from spectroscopic measurements. Despite nearly 20 years of intensive work many puzzling questions continue to provide vitality to chemical kinetic studies in the shock tube.

3. Areas of current emphasis and future directions for shock-tube research

The matter of testing time arose frequently throughout the Symposium and will continue to have a major influence on shock-tube technology. Currently, useful running times range from a few microseconds for the small very high performance devices to well over a millisecond for large shock tubes. Since the fraction of theoretical running time actually obtained appears to decrease with increasing shock strength a better understanding of starting mechanisms and flow stability is clearly important to realization of the full potential of shock tube performance. The desired testing time depends, of course, on the characteristic times for the phenomena being studied. In past years significant increases in running time were achieved in shock tunnel operation by 'matching' the cold flow behind the interface to the shocked gas conditions and by using splitter plates to slice off the tube wall boundary layers. Perhaps some comparably ingenious ideas will be forthcoming to increase the duration of nearly constant conditions behind very strong shocks.

Of interest also is the test time behind the reflected shock, because of the application to shock tunnel flows. Discrepancies between side-wall and end-wall pressure measurements indicate that caution should be used in such studies, particularly when such data is used to determine stagnation data for shock tunnel flows.

Test time becomes particularly critical for very high temperature studies because the contact surface follows the incident shock so closely. Typically, people who employ arc-heated shock tubes are constantly striving for an extra microsecond or so of test time in the flow behind a shock or surrounding a model. The same is true of other exotic types of shock tubes such as electric discharge types, where investigators continue to try specific approaches in the absence of general guidelines. In one study, for example, it was found that shock attenuation, which relates to the testing time problem, could be effectively eliminated in an arc-heated shock tube by use of helium-argon mixtures for the driver gas. In another report on the performance of an electric-discharge shock tube, it was found that induction heating of the downstream gas gave improved flow performance.

Studies of testing time were to some extent part of a more general interest in the design and behaviour of high performance shock tubes. Interest in generating very strong shocks stems from possible applications in atomic and plasma physics experiments, especially where connected with astrophysical problems, thermonuclear work and super-orbital atmospheric penetration. Strong shock waves can be generated in such devices as the free piston and by-pass piston shock tube, the arc-driven shock tube, T-tube and other electric discharge shock tubes, and the implosion driven shock tube, among others. Several of these techniques are not brand new but the continuing development and analysis has improved their capability for quantitative studies. This is especially true of the high-explosive driver methods, but it is also true to a significant extent for the others. In one such study helium was compressed to 3·3 kilobars by a high-explosive formed piston travelling at 6·3 km/sec. The measurements included shock attenuation which was about 1 % per metre at the highest shock speeds. Test times were very short.

The group at Toronto has been pioneering the use of an implosion technique coupled with a suitable drive chamber geometry to obtain shock Mach numbers of 40 in an 8 mm diameter channel at 1 Torr. Shock attenuation in these devices is severe; in the example just quoted the shock decays to Mach 11 in 1·90 m travel. The fact that such devices are now used in conjunction with various laboratory photographic and electronic techniques represents appreciable progress as compared with the early field-type installations for explosively driven shock tubes. More generally, one can say that both electromagnetic and solid explosive driving shock waves appear to hold substantial promise for future work with strong shocks. Despite the large amount of research done during the last 15 years in both these areas, one is left with the uncomfortable feeling that arts and crafts are typical of each forward step and that a science-based technology of strong shock generation is still to come. Fortunately a growing interest in shocks in solids and continuing interest in plasma power generation are keeping this field lively. One is reminded incidentally that remarkably little research on the liquid state has been done with shock waves, suggesting that new results from this field are to be looked for.

A substantial fraction of recent shock-tube research has dealt with the radiation from a shock-heated gas. Several papers at this Symposium indicated that there is continuing interest in that subject. The radiative studies in some cases are used as diagnostic devices for the gas dynamic behaviour, while in other cases the shock tube is employed as a means to obtain specific atomic or molecular parameters. An example of the former is a report by a Japanese group who studied line profile broadening in the reflected region of a T-tube. Good consistency of the temperature and electron density values with the Saha equation was obtained from some helium-hydrogen mixtures. A similar technique was used in another report of the study of relaxation of a hot 'dense plasma focus' used to produce a strong shock in hydrogen. In yet another study, spectroscopic studies were made on air plasmas behind a reflected shock wave in the range around 1 eV and comparison was made between reflected temperature and the gas-dynamic temperature. The reports on radiative shock-tube studies continue to indicate the use of more and more sophisticated techniques and also redundancy to improve precision of the results.

The study of radiative and absorptive behaviour of gases was given a boost by the shock tube for two basic reasons: (1) the shock wave can be made to process the gas so as to produce thermodynamically defined populations of excited states (in contrast say, to a typical discharge tube); and (2) the shock itself serves as an excellent ($t = 0$) co-ordinate for non-equilibrium behaviour involving radiation (except for certain studies where precursors are important). Time-resolved spectroscopy has been developed as a standard technique in many laboratories by now. Studies of radiative behaviour of shock-heated gases have been and will continue to be used for research on transition probabilities, plasma densities, dissociation and ionization energies, inter-particle force laws, activation energies, reduction of ionization potential and gas polarizabilities.

In the future, there is likely to be further comparison of computer-simulated spectra with observed spectra of shock-heated gases. Studies of the challenging problem of coupling between gas-dynamic and radiative behaviour are continuing and will provide interesting reports at future meetings. It is expected also that greater spectral coverage will be emphasized. On the long wavelength side, renewed interest in molecular structure and resonant processes in connexion with gas-laser interactions should provide exciting new developments. On the other hand, the work on high energy shocks will require even more attention to studies in the vacuum ultra-violet including the grazing-incidence régime in the hard ultra-violet. It is not unreasonable to expect that such studies will extend ultimately into the X-ray régime.

The study of strong shock waves is, of course, intimately connected with the field of plasma dynamics. The literature is well supplied with studies of shock-heated ionized gases from several points of view which include transport behaviour; non-equilibrium studies in which the two-fluid character of the gas gives rise to unique problems; coupling between shock-heated plasmas and magnetic fields; and interactions of shocked plasmas and electromagnetic radiation. The subject is a difficult one, however, and it can be debated whether the ratio of answers obtained to additional questions raised is greater than unity. Papers in the plasma area presented at the Toronto meeting include studies of the interaction of an ionizing shock with a magnetic field from a non-steady flow point of view, behaviour of a current sheet in a magnetically driven shock tube, study of ionization profiles in the end-wall thermal layer and measurement of plasma parameters by various methods. Two of the papers dealt with the study of collisionless shock waves, a controversial area from both the theoretical and experimental point of view. A major difficulty for the laboratory investigator concerns scaling of the problem if one wishes to relate laboratory results to satellite measurements of the interaction between the solar wind and the earth's magnetosphere. The papers just mentioned represent definite progress over previous studies, and there is clearly the interest and need for continuing work. In another area of plasma dynamics, namely the field of instabilities, relatively little work has been done in shock tubes thus far. There was the feeling at the meeting that shock-tube methods are capable of contributing more to this area in the future. Here again, it is likely that some of these investigations will be performed in conjunction with computer simulation analyses.

There are fashions in physics just as in clothing. The current interest in laser physics has extended to the field of gas dynamics and includes such areas as the use of lasers as light sources for various types of optical studies, the investigation of laser-induced high temperature shock waves and plasmas, the study of plasma parameters by laser scattering, laser-gas interactions to investigate inelastic collisional processes and optically resonant behaviour of shock-tube flows in which population inversions have been obtained. The papers presented at Toronto provided several examples of the use of lasers in connexion with experimental techniques, and included a report on population inversion obtained in shock-induced dissociation. The interest in this field is high and it is to be expected that future shock-tube conferences will devote complete sessions to shock-tube research concerned with lasers and their interactions with shock-heated gases.

One further area of shock-tube research treated extensively at the Toronto meeting was chemical kinetics. Fast chemical reactions have been studied with the aid of shock tubes for almost 20 years. Early work centred on the halides and other molecules exhibiting significant opacity in the visible region of the spectrum. Interferometry, spectroscopy, and fast optical radiation detectors have extended the range of reaction orders and rates that can be studied so that a significant amount of atomic and molecular physics work is now under way along with continuing reaction chemistry research. Several interesting uses have also been made of the rapid cooling rates available in both the one-dimensional and Prandtl–Meyer expansion fans generated in shock-tube flows. Future prospects include the identification of individual transition probabilities through high resolution spectroscopy in the visible region of the spectrum and data on vibration-rotation transitions rates with infra-red measurements. The availability of large capacity computers has also helped extend the useful field of shock-tube experimentation into very complex chemical reactions by enabling investigators to test various hypothetical reaction models against observation, treating rate constants and binding energies as variable parameters.

Finally, the matter of precursors should be mentioned. The term relates to disturbances which precede a travelling shock, generally of substantial strength. Such effects have been found by several investigators and their existence is well established by now. However, the physical model is still a subject of active discussion. Observed precursors include electrons, electromagnetic radiation and electric fields. The most likely mechanism for electron production is photoionization by radiation originating behind the shock. Other mechanisms such as diffusion may play a role in some configurations. Remarks by several speakers together with discussions in the sessions and hallways indicate continuing high interest in the problem. More results should be forthcoming at future meetings in view of the increased activity with high-performance shock tubes.

The participation of many young scientists in the programme and discussions at this meeting, together with the general enthusiasm of all the participants, reflected the feeling that shock-tube research continues to contribute vigorously to the over-all progress of science. Plans for the next international symposium are to meet at the Imperial College of Science and Technology, London, in 1971.