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SUPPLEMENT TO COOPERATIVE AGREEMENT NCC1-109

HYPERSONIC NOZZLE DESIGN

by

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SUMMARY

The task reported on here was to investigate possible experimental facilities appropriate to a university environment that can make meaningful contributions to the solution of problems in hypersonic aerodynamics. Needs for the National Aerospace Plane and interplanetary flights with atmospheric aerobraking are used to scope the problem. Relevant events of the past two decades in universities and at the national laboratories are examined for their implications regarding both problems and prospects. Most striking is the emergence of Computational Fluid Dynamics, which is viewed here as an equal partner with laboratory experimentation and flight test in relating theory with reality. Also significant are major advances in instrumentation and data processing methods, especially optical techniques. The direction of the study was guided by the concept of a companion program; i.e., the university effort should complement a major area of endeavor at NASA-Langley. Through this both faculty and student participants gain a natural and effective working relationship. Existing and proposed major hypersonic aerodynamic facilities in industry and at the national laboratories are examined by type; hypersonic wind tunnels, arc-heated tunnels, shock tubes and tunnels, and ballistic ranges. Of these the free piston tunnel and shock tube/tunnel are most appropriate for a university. One strong reason for this is the fact that these devices can be scaled to a manageable size while still giving meaningful flow speeds and enthalpies. The general elements of a program are accordingly outlined in terms of principal faculty investigators, laboratory space, supporting staff, instrumentation, data processing, computation and cost range. The focus of the effort is on high enthalpy, high speed flows in various working gases in the continuum and transition flow regime leading toward rarefied gas dynamics. The 'companion' program is suggested to be the NASA-Langley CFD program including Direct Simulation Monte Carlo techniques.

BACKGROUND

Future space missions call for air breathing propulsion to high altitudes in leaving Earth and high speed aerobraking and maneuvering in the upper atmospheres of planets to assure gravitational capture. Experimental data to refine mission plans and to define vehicle designs are needed in many areas.

This study focuses on laboratory experimental facilities appropriate to a university environment that would yield useful new information in the general area of high speed, high temperature aerodynamics. The prospects for initiating such work are strongly conditioned by events of the last two decades. In the post-Apollo era many facilities were shut down, mostly at the expense of research as distinct from applications testing. For an eleven year period no significant new interplanetary spacecraft were launched. With reduced activity in both fields and 'relevance' the key word in national policy on research grants and contracts, university programs dwindled. Students perceived few opportunities in high speed gas dynamics so enrollments and course offerings shrank dramatically. Many faculty shifted to other fields. These events created the current bimodal age distribution in faculty ranks and national laboratory engineering staff.

Universities at which experimental aerodynamic facilities were shut down also lost most of the shop and operating staff so vital to running a productive research program. Some moved elsewhere, others have retired. Because starting up a major new laboratory facility requires several years, new young faculty may perceive too great a risk in embarking on such a path on their own. Therefore a decision to undertake the development of a major experimental project must have the combined support and commitment of a group of faculty of varied rank in order to create and maintain the essential staying power.

Equally dramatic to the decline of high speed gas dynamics has been the ascendance of new technologies in optics, electronics, computers and computational methods. New laboratory equipment, particularly in the areas of instrumentation and data reduction, has raised the data rate, sensitivity, and cost to levels undreamed of 20 years ago. Similarly, the design of facilities and their controls are now very different. Access for optical observations, remote TV monitors, and robotics are rapidly changing the working relationship between investigator and his facility. For example, key results from an experiment can be obtained almost immediately from sample computer printouts or graphical displays. For quasi-steady flow facilities the operating conditions may be tuned during a run; for highly transient processes instrument and data recording response times are orders-of-magnitude shorter. Such increased time resolution yields a good match with some of the powerful time-marching computational methods now available.

Computational Fluid Dynamics has emerged as an equal partner with laboratory experimentation and flight test in relating theory with reality. While some view CFD as a replacement for laboratory experimentation, a more prudent course is to take full advantage of their complementary features. CFD results may guide experimental plans on where and when to look for particular flow features, while measurements may detect processes not written into a code. For example the omission from a combustion code of an intermediate species such as the hydrogen dioxide negative ion can not be corrected by the code itself. Conversely, when the species is included the CFD output can guide the experimentalist on what concentration to try to detect.

CFD code validation is recognized as a major new stimulus for experimental research. Progress has been such that codes can yield results on problems far outside the range of present test capabilities even though the conditions are well within the range of future space mission design needs. In lieu of trying to simulate all the important parameters simultaneously, a hopeless task anyway, new experimental facilities must be developed that are capable of producing conditions that clearly include the important phenomena in various combinations. The exact flight values may not even be required; only the presence of the phenomena for verification of a CFD code when applied to the same situation. This prospect adds a new dimension to facility definition and design, especially at universities, where considerations of size, noise, power requirements, and safety may place severe limitations on experimental equipment. If phenomena can be studied, though not at the full conditions wanted, then CFD methods may be able to make up for the difference. Whether the same logic can be applied to major new test equipment at the national laboratories is another matter.

In planning and designing major new, 'full-scale', test facilities the concept of a companion program at an appropriate university offers advantages. Most experienced experimentalists agree that once the minimum critical conditions for studying a given phenomenon have been met, then the number of tests that can be made per day or per month, say, varies inversely with some large power of the facility dimension. A six inch diameter shock tube can be fired several times a day whereas a similar six foot tube might be fired only once a week or month. This size-rate relationship has led to some very effective symbiotic working relationships. The writer participated in such an arrangement while at the Princeton Shock Wave Laboratory. The partners with large scale equipment were the Aberdeen Proving Ground for study of shock diffraction around obstacles, and AVCO-Everett and GE-MSVD laboratories for the study of vibrational relaxation and dissociation in gases. A current example is the arrangement between Cal Tech and Rocketdyne. A medium-sized Stalker tube will be put on top of the GALCIT building while Rocketdyne will acquire a extremely large Stalker tube for hypervelocity model testing.

EXPERIMENTAL NEEDS

The range of flow conditions to be encountered by the National AeroSpace Plane and the Mars missions envisaged in the President's policy statement on future interplanetary flights to Mars and return exceed anything previously encountered by Apollo, Mariner-Viking or Scramjets. The high speed gas dynamics problems may be described in four somewhat inter-related groups; hypervelocity high enthalpy aerodynamics, supersonic combustion for propulsion, non-continuum gas dynamics, and hypersonic boundary layers including transition and separation. Both fundamental property data and useful phenomenological information for engineering design are needed.

Atmospheric entry speeds at Mars are in the range 6-10 km/sec for Hohmann ellipse and Sprint missions. For Earth return the range is 11.6-14.5 km/sec, higher than for lunar return. In both cases the first atmospheric pass must reduce the spacecraft speed to less than planetary escape speed. Little work has been done on the high enthalpy gas dynamics of the Martian atmosphere; 95.7% CO_2, 2.7% N_2, 1.6% Argon. Radiation energy transport is likely to be significant along with convection in the shock layer. Accordingly fundamental property data on reaction rates, electronic and vibrational band radiation strengths, and transport coefficients for the species mixtures encountered will be needed as inputs to CFD codes. Methods for handling both continuum flows and transition to to rarefied or free-molecule flows must also be provided with such data, most of it experimentally measured or verified.

Within the NASP propulsion system a supersonic turbulent flow is desirable to augment diffusion mixing of fuel and oxygen. The goal of keeping the combustion section short calls for a good understanding of wall boundary layers, heat transfer, and control of flow separation at conditions not easily met in ground-based facilities. Fundamental work on elements of the full-scale problem can yield results of value in verifying CFD codes developed for performance analyses.

The low flight path angles for satisfactory atmospheric entry corridors and the horizontal take-off of the NASP mean that future vehicles will spend much longer times in that range of altitude densities between the limits of continuum flow theory and free molecule flows, with possible maneuvering requirements as well. For vertical rocket launch and steep re-entry angles as encountered by ballistic missiles this transition region around Knudsen Number = 1 was not of very significant duration. The data base developed in the '50's and '60's must now be extended. At the higher Mach numbers for space flight the field of rarefied gas dynamics, or flow transition, offers fresh prospects for research, but some new measurement techniques will also be required for independently determining the thermodynamic state and velocity fields at these low densities.

In contrast to the desirability of having the internal flow turbulent, a laminar external flow on the NASP and on the aerobrakes for atmospheric entry could reduce the heating problem. Boundary layer transition and separation at very high Mach numbers needs attention. Some of these effects should be studied in wind tunnels of M=20 and above. Paradoxically, the behavior of boundary layers at these speeds is needed to design the tunnels. A boot-strap process is evidently called for. One example of the complexity of the external flow fields expected is shock wave impingement caused by protuberances. These may be control surfaces, engine inlet air scoops, or structural support struts. Both tunnel and flight tests at supersonic speeds show a complex interaction between shocks, separating boundary layers on the main body, and an intricate pattern of horseshoe vortices under the separation streamline. Very large increases in heating on both the parent body and on the protuberance are observed. Without careful provision for the inclusion of these flow phenomena in a code, it very well might not invent them.

The general picture given by this brief discussion identifies major problem areas as being high enthalpy gas dynamics, high Mach number external aerodynamics, transition to rarefied flows, and the structure of hypersonic boundary layers including laminar-to-turbulent transition and separation. Both basic property data and overall flow phenomena are of interest. The next section of this report discusses the status and future facility requirements.

MAJOR FACILITIES

The limits of aerodynamic testing capabilities are set in general by those of a relatively small number of major facilities located in various national laboratories and a few private firms. The requirements of Reynolds and Mach number simulation dictate resort to test sections of either very large cross-section or very great lengths (e.g., wind tunnels, ballistic ranges). Supporting these are a much larger number of research and test facilities spread widely through public and private laboratories, with a few that have survived in universities. While much attention is now justifiably focussed on defining major equipment upgrading and new facility requirements, some careful effort is also needed to re-equip academic institutions for meaningful experimental work. The reason for this is compelling. All of the engineers, scientists, and skilled technicians who will step into the positions being rapidly vacated by old members of the First Space Age are now, or will be, passing through these institutions. Some must be intrigued by experimental work and given the chance to learn its art and science.

Several comprehensive surveys and need studies of hypersonic facilities have been made in recent years. References to a number of these is given at the end of this section. Here only a brief outline of new directions will be given in order to set the context for suggesting appropriate companion programs at the university.

Hypersonic Wind Tunnels

High pressure gas is heated and expanded through a nozzle to achieve a uniform flow in the test section of Mach 5 to 18 with air or nitrogen. Other working gases are used for special purposes. With aerobraking in the Mars atmosphere as a strong candidate for future interplanetary flights, new hypersonic nozzles designed for either pure carbon dioxide or a mixture simulating the actual Mars atmosphere will be needed. Such experiments were made in the late '60's using a model Jovian atmosphere for design of the Galileo probe. The main advantages of such conventional tunnels are the purity and uniformity of the flow, the large test volume available for models, and the relatively long testing times; seconds to hours. The enthalpy of the working fluid is limited to that of the supply. To establish useful flows at M=18 and above, supply conditions necessary are T=3000-4000 F and P=10,000-30,000 psi in nitrogen, plus a large vacuum exhaust. These preclude siting such tunnels on campuses for reasons of safety, cost and noise. Boundary layers prevent satisfactory scaling to small, easily manageable sizes.

Arc-heated tunnels

High enthalpy levels can be achieved by direct arc heating of the working fluid. The art of designing such tunnels has reached a high level and number of arc-heaters are in regular use. Inherent to such devices is the loss of very uniform flow and some contamination of the working fluid. The most effective use is in materials testing where temperatures and heat transfer rates expected in flight are well simulated over areas of a square foot or more. Something of an international competition is under way for building a major multi-megawatt arc tunnel. Scaling down is feasible for these systems so a university with a very large program in coupon-sized material testing might justify an arc-tunnel.

Shock Tubes and Tunnels

A large variety of highly useful adaptations to the basic shock tube have appeared since Walker Bleakney showed in the '40's and '50's its value as a research and testing device. By attaching a nozzle to the end wall of a shock tube, a high enthalpy shock tunnel is obtained; albeit with a short flow time. There are a large number of such devices in use throughout the world as witnessed by the papers at the 17th International Symposium on Shock Tubes & Waves (1989); 160 papers from 18 countries. Explosives, combustible mixtures, and condenser-driven arc discharges have been used to raise enthalpy levels and the introduction of free pistons has greatly widened the range of accessible test conditions. The transient nature of the flow in this group limits test times to milliseconds or less, but speeds, temperatures and enthalpies in the desired range are obtainable. Advances in instrumentation and data processing and recording rates have greatly increased the potential of such facilities. Offsetting the disadvantage of short flow test times is a major reduction in the need for high temperature materials (except for nozzle throat sections), leaving a wide selection of strong, tough materials for construction available.

Two variants of shock-tunnels appear to have favorable scaling features in the sense that similar high enthalpy, high speed flows are generated by facilities of different physical sizes, the main difference being only in flow time and test section volume. One is the "Stalker" tube or free piston shock tunnel and the other is the shock tube/tunnel. Three new free piston shock tunnels are being built for Cal Tech, General Applied Science Laboratories, and Rocketdyne. Abstracts of five papers on free piston shock tunnels from the recent 17th shock tube symposium are reproduced as Appendix A of this report. CALSPAN is working toward evolution from their current shock tube/tunnels to gain increased flow times.

Ranges

The ballistic range is an outgrowth of cannon technology and has in turn fed back fresh ideas to the problem of ever-higher launch speeds. The range is unique in providing free flight of a model through a quiescent atmosphere whose composition and thermodynamic state can be selected independently of the launching system. Ranges are necessarily long, the models small and without on-board instrumentation and are usually demolished while coming to rest. Many of the same methods for launching models and for generating very strong shock waves are practical; high pressure gases of low molecular weight, explosive gas mixtures, and electric discharges. Also, rail guns use magnetic forces for accelerating a model and simultaneously maintain its linear motion. Several promising new concepts for obtaining flight speeds in the range of 10 km/sec have emerged from recent studies. Electric induction is being evaluated at NASA Langley and a method for using a gaseous detonation wave riding with a projectile, the RAM accelerator, is being developed by Dr. Abe Hertzberg at the University of Washington. His concept sidesteps one of the oldest problems facing designers of launchers that produce very high projectile speeds. As a projectile gains speed, it tends to run away from the source of energy accelerating it. The rocket partially solved this problem by carrying the propellant along, but at the expense of having to accelerate some of the propellant too. The use of electro-magnetic fields sidestepped that problem and introduced others. The RAM idea distributes the energy source along the flight path and by suitable interaction with the flow causes the projectile to release energy at its rear. Successive compartments with differing reactive gas mixtures are envisioned as solving the old problem of running away from the energy source. Since this promising concept is still in the experimental phase, progress should be watched until practical feasibility is established. The abstract of Dr. Hertzberg's recent lecture on the status of RAM research is also included in Appendix A.

Three limitations to present ranges are the small size of models that can be launched, a lack of on-board instrumentation, and difficulty in recovering models fired at high speeds for re-use. Solution of the first problem will probably be found in gradually stepping up the physical size of ranges; admittedly a brute force method but feasible in concept. This helps in overcoming the second problem since both mass and volume of the models would make on-board instruments easier to design. Getting the data out over a laser link is one possibility under study. Another is to record it for later recovery, implying solution of the third problem. Fresh ideas are sorely needed.

The current state of knowledge would seem to preclude universities from constructing really useful ranges, although research on the problems just discussed is certainly warranted.

A UNIVERSITY EXPERIMENTAL PROGRAM

A number of challenging problems areas in experimental hypersonic aerodynamics are open for university-based work with facilities capable of achieving meaningful flow conditions and at the same time satisfying limitations set by constraints on what is appropriate to the campus environment. In addition to recommending a specific type of facility, this section will address the equally vital questions of laboratory location, the principal investigators, supporting staff, instrumentation, and data reduction and processing.

The review of major new facility needs on the national level identified some types of equipment that can be scaled, in the sense that a desired flow velocity or enthalpy level can be obtained without the need for extremely high supply pressure (up to 30,000 psi), great size (diameter of many feet or length of several hundred feet), or megawatts of electrical power. The transient flow devices based on the shock tube, free piston and shock/tunnel, meet this scaling criterion. Their size and complexity is also appropriate in giving a relatively short turn-around time between test runs. Control of the purity of the working fluid and uniformity of the flow, though necessarily for very short run times, is also a positive feature. We therefore propose to proceed along this path; a shock/tunnel or free piston tunnel operating at moderate to low pressure levels is the preferred candidate device. High enthalpy, high speed flows in the continuum and transition to rarefied regime will characterize the program. For this to be a companion program to much larger 'full-scale' facilities at the national laboratory is not a requirement. Instead the companion program may be the third number of the trio of current methods, for CFD program at NASA-Langley including of course the promising new approach using Direct Simulation Monte Carlo techniques.

Principal Investigators

Earlier some reasons were given for forming a loosely associated group of faculty that includes both young Assistant Professors and more senior tenured individuals. At present the individuals active in experimental fluids research include two assistant and one associate level professors, while Dr. J. N. Perkins and this writer are experimentalists but no longer active in the laboratory. The faculty team should also include at least one person active in CFD. Therefore the minimum conditions for providing the necessary staying power in creating a new, significant facility are met in principle.

In practice the principal investigators must have a strong sense of identification with the facility and its program; i.e., they must be intimately involved in designing the main equipment, selecting instrumentation, and planning the research tasks. Without such personal commitment nothing much of value will transpire. Any facility is worth what it cost, and more, only so long as the investigators and staff are actively using it. When they go home at night the equipment value drops to the market price of scrap metal and second hand electronics and the next morning, almost miraculously, recovers its full worth when the people return to work. This is why the detailed selection and design must be left somewhat open until a core group is identified to pursue the goal of building an experimental hypersonics program at NCSU.

Laboratory Space

North Carolina State University is in the process of building up the Centennial Campus, dedicated to graduate research. Two programs are already housed in the first building and the College of Textiles will move into its new quarters next year. Space in a second research building has been allocated for use by the Mars Mission Research Center. This building, which is scheduled for completion in about a year, also has laboratory space that may be suitable for experimental hypersonics. Another possible location is on the lands west of the campus where other programs in energy and mechanics have recently built dedicated laboratories. Either location can meet the needs of the proposed program.

Staff

Both mechanical and electronic technicians will be needed to set up, help calibrate, run and maintain the facility. They will be an integral part of the team, also involved in training the graduate students in some of the realities of experimental life. Both the Department of Mechanical and Aerospace Engineering and several of the Centers and Programs in the College now have such individuals. Addition of such staff and access to good machine and electronics shops is another vital ingredient.

Instrumentation, Data Processing and Computation

Referring again to the earlier discussion on developments in experimental techniques, much reliance on advances in optical measurement methods and very fast electronic circuitry is clearly going to be integral to the effective use of transient flow devices, especially in the low density region where classical pitot and hot wire performance deteriorates. From recent experience in upgrading old facilities we may expect the cost for instrumentation to actually exceed that of the flow facility itself. Further, it will be prudent to build into the program plan provisions for regular additions or replacements of measuring instruments as the technology in the field gallops forward.

Signal conditioning, high speed data recording, and data processing are regarded as an integral part of the instrumentation package. Dedicated desk top PC's and access lines to larger general purpose computers should also be treated as part of the facility but the main frame computers will presumably be university or NASA services.

Cost, Time, Duration

Preliminary estimates on program cost, time to start up, and duration of the project are given in this section. These are based partly on information from the first reference on hypersonic facilities cited earlier, the SAB report, and on informal discussions with a number of people working in the field now. Intermediate-sized free piston shock tunnels and shock tube/tunnels both are in the range $300,00-$500,000. Selection, design, fabrication and installation will require about two or three years, a period compatible with the university's research building plans. Considering that graduate students typically need two years to complete an experimental Masters' thesis and perhaps three or four more for a Ph.D., the minimum duration of a viable program is seen to be a decade. To the extent that commitments can be made, then, the principal elements of a ten year funding plan should be developed. The useful life of the facility will of course extend well into the 21st century.

INFORMATION SOURCES ON HYPERSONIC TEST FACILITIES

"Requirements for Hypersonic Test Facilities", U.S. Air Force Scientific Advisory Board. 2 vols. May 1989.

"The Ballistic Range and Aerothermodynamic Testing", A. W. Strawa, G. T. Chapman, T. N. Canning and J. O. Arnold. AIAA-88-2015. 1988.

"Ballistic Range Technology", ed. by T. N. Canning, A. Seiff and C. S. James. AGARDograph No. 138. August 1970.

Other sources:

Facilities brochures of NASA and other National labs.

Proceedings of the International Symposia on Shock Tubes and Waves. Published biennially.

Minutes of the biannual meetings of the Supersonic Tunnel Association. Distributed to members and not for attribution.

APPENDIX A

Abstracts of papers on the Stalker tube and RAM accelerator given at the 17th International Symposium on Shock Waves and Shock Tubes July, 1989, Lehigh University, Bethlehem, PA.

Papers will appear as AIP Conference Proceedings: Current Topics in Shock Waves early in 1990.

TH 13:50 GA Recent developments with free piston drivers.
Nev I R.J. Stalker

RECENT DEVELOPMENTS WITH FREE PISTON DRIVERS

R.J. Stalker

The University of Queensland

In a brief historical review, it is seen that the development of free piston drivers for shock tubes and shock tunnels has taken place in two "waves". The first wave occurred in the 1960's with construction of a small free piston shock tube at the National Research Council, Ottawa, Canada, followed by others in Australia, England, the U.S.A. and Japan. Of these, only the Australian and Japanese developments survived.

For many years, the major Australian free piston shock tunnel was T3, in Canberra. This was brought into operation in 1968 and operated in parallel with a somewhat smaller, high performance, free piston shock tube, D.D.T. These facilities were notable for the high shock speeds which followed from the high temperatures generated in the driver gas, and they were used extensively for research into hypervelocity aerodynamics and fundamental high temperature gas physics.

The second wave may be said to have begun in 1983, when construction of free piston shock tunnel T4 was initiated in Brisbane, Australia. This facility was engendered from a need to raise operating pressure levels, after shock reflection, at the entrance to the hypersonic nozzle at the downstream end of the shock tube. Operation of previous free piston shock tunnels had shown that, as test section velocities were increased, these pressure levels fell well below expected values. An investigation by Page and the author showed that this pressure loss effect could be avoided by using a long compression tube, and this feature has been incorporated in all of the "second wave" facilities. Because of this, stress wave phenomena, and related fatigue life considerations, come to dominate the design of these facilities. Also, where they are housed within existing buildings, special problems arise in accommodating them.

The new shock tunnels, which are following on from T4, all involve an increase in shock tube diameter. This is because the test time in a reflected shock tunnel is limited by the shock boundary layer interaction which follows shock reflection at the downstream end of the shock tube, a process which causes early driver gas contamination of the test gas. Increasing the shock tube diameter delays this contamination, thereby increasing the test time, and allowing larger aerodynamic models to be tested.

The largest of the new free piston shock tunnels is the RHYFL facility, which is being acquired by Rocketdyne. With a 200 mm shock tube diameter, this facility is expected to yield test times which, as indicated by tests in T4, are sufficient to allow testing of scramjet combustion chambers and exhaust nozzles of a size which approaches full scale.

Free piston drivers also are being applied to expansion tubes. Although expansion tubes involve the use of small aerodynamic test models, they are able to produce a test flow with much lower levels of free stream frozen dissociation than in a shock tunnel. They were widely investigated in the 1960's, with disappointing results. Only the facility at NASA Langley Research Centre was shown to produce a useful test flow, and this was limited to one stagnation enthalpy. Recent further investigations of a small expansion tube have shown that a free piston driver allows a range of useful test conditions to be produced, and that it also allows higher stagnation enthalpies to be achieved. This has led to relocation of the NASA Langley expansion tube to General Applied Science Laboratories, where it is to be fitted with a free piston driver.

These new facilities have a vital role to play in generating the new knowledge needed for efficient flight at speeds up to Earth orbital velocity.

NUMERICAL SIMULATION OF A FREE-PISTON SHOCK TUNNEL

Yves BURTSCHELL, Pierre COLAS, Pierre GUBERNATIS,
David ZEITOUN, Michel IMBERT, Lazhar HOUAS
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The paper describes completely a numerical simulation of the processes encoutered (fig.1) in a free piston shock tunnel[1].

The main characteristics of the apparatus are determined. The computing methods and the expected results concerning the species concentration and the aerodynamic properties of the hypersonic flow obtained in the test section are presented.

- The one dimensional unsteady flow inside the air tank (1) and in the compression tube (2), as well as the displacement of the piston (3) are treated by a method of characteristics taking into account the section variations.
- Inside the shock tube (4), (incident Mach number between 8 and 13 - air initial pressure between 0.5 and 1.5 bar), the method of characteristics is also used assuming equilibrium for the chemical state of air, (pressure between 100 and 2500 bars and temperature between 2000 and 9000 k).
- Finally, the stagnation conditions in the tailored case (5) are deduced and the flow in the nozzle is computed in the two following ways ; (test section Mach number about 10):
  - A two dimensional implicit unsteady finite volume method of solving the Euler equations is used for high values of the reservoir pressure.
  - A two dimensional explicit unsteady finite difference method is used for solving the complete Navier-Stokes equations for lower pressure regimes. A non-equilibrium air model, previously presented[2], is used in the above calculations.

References:

1 : R.J. Stalker, " A Study of the Free-Piston Shock Tunnel", AIAA Journal, vol. 5, n°12, p. 2160, 1967.

2 : R. Brun, P. Colas, P. Gubernatis, D. Zeitoun," Practical Physico-chemical Models for High Speed Air Flow-Field Computation", to be published in the Journal of Thermophysics and Heat Transfer, 1988.

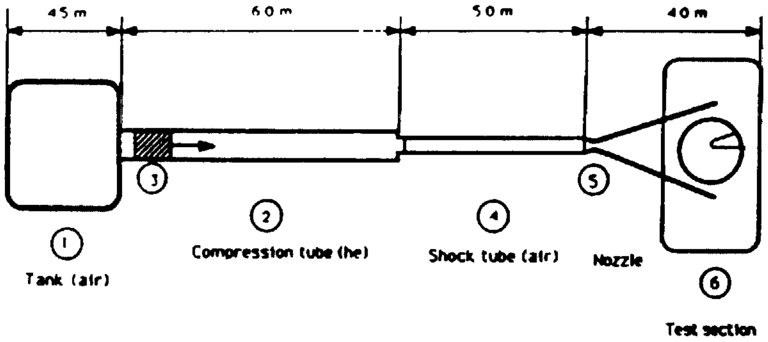

Figure 1: General arrangement

TU 9:50 <u>CC4</u> **Numerical simulation of a free-piston shock tunnel.**
Nov I Y. Burtschell, P. Colas, P. Gubernatis,
D. Zeitoun, M. Imbert, L. Houas and R. Brun

New Generation of Free Piston Shock Tunnel Facilities

by

W.R.B. Morrison*, R.J. Stalker* and J. Duffin**

Recent worldwide interest in the Aerospace plane type of concept has generated a need for more accurate aerodynamic data in the very high enthalpy flow regime. This has been used as an incentive to develop computational fluid dynamics (CFD) capabilities.

Predominantly there are two streams of interest, involving the external aerodynamics of the craft, and the internal flow and combustion problems in scramjet engines. Although CFD methods have had some success in predicting the craft aerodynamics, they are still of very limited use for the combustion problems.

Alternatively, Free Piston Shock Tunnels (FPST) can be used to produce the gas dynamic conditions for both aerodynamic and combustion studies, and gain specific experimental data for flows in the high enthalpy regime. Furthermore they must be used to validate computer codes before the predictions of such codes can be used with confidence in the design situation.

FPST's are the only experimental facilities capable of operating in this regime, producing flows where the major gas dynamic and chemical effects are simulated adequately.

Consequently, a new generation of FPST's have been designed and are being constructed in Australia and the U.S.A. These facilities range in size from shock tube diameters of 76mm to 200mm, with test section diameters from 300mm to 1000mm.

Discussed in this paper are some of the general relationships between facility sizes (such as tube diameters and lengths, and piston mass) and the shock tunnel performance (in terms of test section performance).

An overview of existing FPST's is given, and a comparison of the performance capabilities of both existing and future facilities is presented.

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TU 9:50 Whit **CD4** New generation of free piston shock tunnel facilities.
W.R.B. Morrison, R.J. Stalker and J. Duffin

TRANSIENT PRESSURE MEASUREMENT AT THE END OF A HIGH-ENTHALPY REFLECTED SHOCK TUBE

by

C.M. Gourlay*, B.A. Leslie* and R.J. Stalker**

Ideal one-dimensional theory for reflected shock tubes and tunnels operating in under-tailored mode indicate that a high pressure is expected at the end of the tube behind the reflected shock wave. This theoretically determined pressure is significantly higher than the equilibrium interface, of "plateau" pressure measured over a longer time-scale. Paradoxically earlier measurements (1) of this pressure have failed to register a significant over-pressure. This paper reports recent measurements of the reflected shock pressure with significant over-pressures being recorded. The existence of high pressure levels has important implications in the design of large impulse facilities, such as free-piston driven reflected shock tunnels.

Experiments were performed in the 76mm diameter shock tube of the T4 free-piston machine at the University of Queensland. A blanked-off end to the shock tube was manufactured containing a piezo-electric pressure transducer with a frequency response of up to 500 KHz. In previous work (1) the transducers had been mounted on the side-walls of the shock tube close to the reflected end. In these studies the transducer was mounted in the end plate close to the axis of the tube with the transducer face normal to the direction of travel of the shock wave. This location was chosen so as to avoid the jet regions established by the interaction of the reflected shock wave with the tube boundary layer. Data was recorded with a transient digital event recorder. The shock tube was driven by a free-piston driver with a diaphragm rupture at 28 MPA and a volumetric compression radio of 80. The driver gas was helium and the test gas was air. A range of primary shocks speeds from 1700 to 5100 m/s were employed giving enthalpies in the plateau region of up to 30 MJ/kg.

Measurements of the reflected shock pressure gave ratios of peak over-pressure to plateau pressure of more than two. The duration of the high pressure pulse varied from 90 microseconds at a shock speed of 1700 m/s to 50 microseconds at 5100 m/s. The magnitude of the over-pressure, as a function of shock speed, can be predicted well by ideal shock tube theory with real air. However the duration of the pressure pulse cannot be explained by this theory. The measured durations are significantly less than the predicted ones, especially for the lower primary shock speeds.

According to theory the duration of the high pressure region is governed by the time required for the reflected shock to reach the contact surface between the driver gas and the test gas.(2) After this event expansion waves propagate towards the end of the shock tube as the test gas expands to the equilibrium interface. To explain the shorter measured over-pressure pulses it is proposed that the reflected shock wave arrives at the contact surface earlier than expected from theory. Thus the expansion of the test gas commences earlier, and expansion waves arrive at the end of the tube earlier than predicted. A suitable mechanism for the acceleration of the reflected shock wave is found in the bifurcation caused by shock wave boundary layer interaction.(3) The height of the bifurcated foot of the reflected shock wave grows with distance as the shock moves away from the end wall. Initially the bifurcation is small relative to the diameter of the shock tube, and the reflected shock speed is controlled by the normal part of the shock system. However, as the bifurcation grows and occupied a significant part of the cross-sectional area of the

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TH 16:30 **GC5** Transient pressure measurement at the end of a
Nev I high-enthalpy reflected shock tube.
C.M. Gourlay, B.A. Leslie and R.J. Stalker

tube, the reflected shock speed will be controlled by the bifurcated part of the shock system. The increase in shock speed can be qualitatively explained by the increase in pressure ratio across the two oblique legs of the bifurcation as the flow processed by the rear leg is forced to turn more parallel to the shock tube axis.

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A COMPRESSION IGNITION DRIVER FOR A FREE PISTON SHOCK TUNNEL

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A free piston driver for a shock tube or shock tunnel is basically a method for adding energy to the driver gas. Another method involves combustion of a stoichiometric mixture of hydrogen and oxygen in the driver gas immediately before diaphragm rupture. The second method may conveniently be combined with the first by adding the combustible mixture to the driver gas, and allowing it to be ignited by the temperature rise which occurs during the free piston compression process. This paper reports a theoretical and experimental study of such a combination.

Theoretical studies indicate that the gain in driver gas energy achieved by this method does not offer significant increases in shock speed over those achievable without combustion. This is because, except at low compression ratios, the increase in molecular weight of the driver gas more than offsets the gain in temperature occasioned by the additional energy release, to actually reduce the speed of sound in the compressed driver gas.

However, in operating a reflected shock tunnel, the free piston driver suffers from the disadvantage that, as driver compression ratios are increased, severe pressure losses take place which reduce the pressure at the end of the shock tube supplying the flow of test gas through the hypersonic nozzle to the tunnel test section. The use of compression ignition combustion in the driver offers advantages in raising this nozzle reservoir pressure. For example, gains of a factor of 2 or 3 appear theoretically possible at useful nozzle stagnation enthalpy levels.

The experiments were conducted in a free piston shock tunnel with a compression tube 102 mm in diameter and 2.4 m long. The entrance to the shock tube was 38 mm in diameter, and the shock tube was 63 mm in diameter and 4.0 m long.

It was found that compression ignition occurred at a volumetric compression ratio of 10, and was relatively insensitive to variation in pressure levels. The maximum amount of combustible mixture used was limited by the need to limit the rebound of the piston, and by the maximum pressures in the compression tube, but was sufficient to double the energy added to the driver gas.

Tests were conducted at shock speeds of 3.0 ± 0.5 km/sec. It was predicted that shock speeds would vary only by 20% over the range of combustible mixture concentrations used, and the experiments yielded a variation of approximately 30%. Nozzle reservoir pressure gains of a factor of 1.8 were predicted, and up to 1.7 was measured. The nozzle reservoir pressures and shock speeds were higher than predicted for the higher driver gas volumetric compression ratios tested, and lower for the lower volumetric compression ratios.

Both theory and experiment indicated that significant gains in nozzle reservoir pressure could be obtained with a compression ignition driver. The theory also indicated that these gains could be improved substantially if an early ignition source such as a spark plug, could be used to cause ignition well before the auto-ignition volumetric compression ratio of 10 was reached.

TU 9:30 CC3 A compression ignition driver for a free piston
Nev I shock tunnel.
T. Cain and R.J. Stalker

The Paul Vieille Memorial Lecture

Thermodynamics of the RAM Accelerator

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The ram accelerator, a ramjet-in-tube concept, is under study at the University of Washington. In principle, this device is capable of efficiently accelerating projectiles to velocities up to 10-12 km/sec, utilizing cycles similar to the thermodynamic propulsive cycles which generate thrust in ramjets and scramjets. During the past three years, our group has progressed from proof-of-principle operation to operation at in-tube Mach numbers >7 and velocities >2500 m/sec. The test projectile, which resembles the centerbody of a supersonic ramjet, travels through a tube filled with a premixed combustible gas mixture of fuel, oxidizer and diluent. The tube walls act as the outer shroud of the ramjet. The projectile does not carry any on-board propellant. The energy release occurs in a combustion zone on or behind the projectile and travels with the projectile. Thus, all the energy required to accelerate the projectile is stored within the tube, where it is available as required.

Since ramjets operate most efficiently for a given configuration in a narrow range of Mach numbers, the accelerator tube is partitioned in such a fashion as to control the in-tube Mach number. The efficiency and the thrust level are functions of the pressure and the composition of the mixture in the tube ahead of the projectile. The ballistic efficiency (i.e., the fraction of the available chemical energy converted to kinetic energy of the projectile) can be maintained at high levels, as the projectile velocity increases, by filling the ram accelerator tube with gas mixtures which are distributed along the tube such that their acoustic velocity increases towards the muzzle. In principle, the ram accelerator concept is scalable for projectile masses ranging from grams to thousands of kilograms and has the potential for a number of applications of interest such as hypersonic flow and propulsion studies, hypervelocity impact studies, and the direct launch of metric ton-size vehicles to orbit at low cost.

The initial exploratory studies were previously discussed by the author in a presentation at the 16th International Symposium on Shock Tubes and Waves in 1987. These experiments were carried out using a test facility having a 12.2 m long, 38 mm bore accelerator section, into which projectiles were injected at velocities of 700-1300 m/sec. Excellent agreement was found between the aerothermodynamic calculations and the observed performance. Transition between mixtures with different acoustic speeds was accomplished, allowing the experimental facility to achieve projectile velocities up to 2 km/sec. In addition, the theoretical possibility of operation in combustion modes resembling those of a scramjet was explored.

Since the publication of these results, the facility has been modified to allow us to explore the limits of the performance capabilities of this device, insofar as it is possible in a university environment. It was observed that at velocities above ~1.5 km/sec, the projectile velocity and acceleration would significantly exceed the values predicted by aerothermodynamic theory. This apparent anomaly has proved to be a new mode of operation which has heretofore not been reported. This mode is capable of accelerating the projectile smoothly from velocities below the detonation velocity of the gas mixture to velocities well in excess of the detonation velocity. In a typical case, an experiment was carried out in a methane-oxygen-helium mixture with a detonation speed of 2070m/sec, and a projectile velocity of 2310 m/sec was achieved.

In subsequent work, a propellent mixture was developed using ethylene as the fuel and carbon dioxide as the diluent, having a theoretical detonation speed of 1650 m/sec. Utilizing the accelerator tube as a detonation tube, we were able to verify that the actual detonation speed of this mixture closely matched the theoretical speed. This relatively low detonation speed mixture enabled us to carry out some interesting experiments, in which the projectile was injected at velocities significantly above the detonation speed (e.g., >2000 m/sec) such that the local, in-tube Mach number was approximately 6.8. Continued steady acceleration was observed to Mach numbers of 7.5. This acceleration at velocities significantly above the detonation speed of the gas ahead of the projectile is believed to be a result of shock-induced supersonic combustion. This mode of operation is referred to as "superdetonative."

In view of these interesting findings, a theoretical program was developed at the University of Washington which could partially simulate such superdetonative operation. Due to the complexity of the ethylene-oxygen-CO_2 chemistry involved in the superdetonative experiment, a complete simulation has not yet been attempted. However, a two-dimensional, inviscid CFD model using oxygen and hydrogen, diluted with noble gases, has been used. The model includes full chemical kinetics and has verified that shock-induced combustion zones in the immediate vicinity of the projectile will efficiently accelerate the projectile, with the flow remaining supersonic throughout.

The ram accelerator group at the University of Washington is again in the process of modifying the apparatus to explore higher velocity operation (up to 4 km/sec) in both the transdetonative and superdetonative modes. In addition, the tube will be fitted with a transparent test section to allow observation of the details of the flow phenomena in the combustion region around the projectile. In addition, advanced spectroscopic diagnostic techniques, such as CARS, will be implemented in the future to obtain detailed information on the reacting flow.

M 8:40 AA Thermodynamics of the RAM Accelerator.
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