Memorandum M-669

Hypersonic Test Facility Delft
HTF-Delft

May 1993

W.J. Bannink / P.G. Bakker

TU Delft
Faculty of Aerospace Engineering
Laboratory of High Speed Aerodynamics

Delft University of Technology
Hypersonic Test Facility Delft
HTF-Delft

W.J. Bannink / P.G. Bakker
1. Introduction

In the USA, Europe, CIS and Japan research is going on in a number of projects which are incorporated in technology programs aimed at the development of hypersonic vehicles. These programs are concerned with re-entry vehicles such as the Space Shuttle, HERMES, BURAN, HOPE, as well as single or two stage airbreathing systems of horizontally starting and landing vehicles like NASP, HOTOL, SÄNGER, etc. The latter category is intended to soar into a low orbit after a cruise flight at a Mach number which could vary from 4 to 15 dependent on the propulsion system. The research projects have in common, that strong viscous and high-temperature effects are involved. Both phenomena have a significant influence on the mechanical quantities (pressures, forces) and the thermodynamic quantities (heat fluxes, heat loads). The subject of the combined action of aerodynamics and thermodynamical real gas effects belongs to the field of aerothermodynamics.

In general the aerodynamicist does not care much about temperatures, heat fluxes, heat loads; he provides force and moment measurements on so called 'cold' models in the wind tunnel. Until recently also experimental hypersonic flow research was limited to the study of flow along 'cold' models, whereas in theoretical work mostly adiabatic walls were assumed.

Due to a number of difficulties that occurred in real flight of the Space Shuttle program [1],[2], the necessity of taking into account the aerothermodynamic phenomena was felt seriously. Also the coupling of various effects, that are in itself different, could not be neglected any more. In this respect we might think of:
- thickness of the viscous layer along the surface of the vehicle;
- status of the viscous layer ( laminar or turbulent);
- interaction effects (shock/vortex/viscous layer);
- emissivity of the surface (radiation cooling);
- surface temperature and surface heat flux.

All these aspects are valid for the external flow past the vehicle fuselage and/or wing as well as for the internal flow in the inlet, combustion and nozzle modules.

Depending on the flightpath of the vehicle, the above mentioned coupling may also exist between groups of phenomena. During re-entry in the atmosphere, maximum heat loads usually occur at heights of about 50 km to 70 km, there the surface flow is still laminar. It is well above altitudes where airbreathing propulsion is applied and where the surface flow is mainly turbulent, so there will be consequences for the propulsion system (RAM and/or SCRAM).

The designer of hypersonic vehicles will be confronted with several fundamental problems:
- insufficient understanding of the above mentioned phenomena and effects;
- insufficient understanding of the coupling between the phenomena;
- limitations on experimental ground-simulation facilities;
- limitation on computing resources;
- limitations on computer codes, in particular regarding their flow physical and thermodynamic modelling.

With respect to the last item it is evident that there is an urgent need for an adequate validation of computational results even for simple cases. However, then we fall back on the experimental limitation. There exists a close relation between the aerothermodynamic properties of the gas and the thermal status of the vehicle surface. If we confine ourselves to very simple, though from a standpoint of validation also necessary problems, we may in an interaction procedure between theory and experiment deliver a very valuable contribution by performing appropriate tests. By this we mean: use the particular capability of a testing facility to simulate certain flow phenomena as a starting condition for a computational flow problem; make a validation of numerical results on the basis of the experimental results obtained in the facility. In this way it seems possible to obtain computer codes that derive their predicting capabilities from well simulated flow models in ground facilities.

This memorandum is organized as follows: Section 2 goes into the aerothermodynamic design philosophy seen against the background of the fore mentioned fundamental design problems. Section 3 mentioned the requirements put to hypersonic facilities for the simulation of specific flow conditions. In section 4 is pointed out how the Faculty of Aerospace Engineering of the University of Technology Delft will contribute to hypersonic testing. For this purpose a Ludwieg tube type of facility was selected that has recently been designed and built in Germany. This facility meets a number of requirements demanded for simulation of certain aspects of the external flow past hypersonic vehicles for not too high free stream Mach numbers (see section 3). Also the excellent suitability is brought up of this particular type of Ludwieg tube for educational purposes at a university. As will be seen the facility is especially designed for operation and use in a university laboratory.

Finally the financial consequences are discussed together with the prospect to bear the expenses if the facility would be realized at the Faculty of Aerospace Engineering.

2. Aerothermodynamics: from model to physical reality.

More than classical aerodynamics, hypersonic aerodynamics has to cope with the difficulty, attached to all ground facilities, to simulate simultaneously a number of similarity parameters: Mach number, Reynolds number, Stanton number, total enthalpy, etc.. The current procedure to cope with this difficulty is the use of so called transfer models. This are in fact scaling laws and/or computational methods in aerothermodynamics by means of which the flow simulation (often on a small scale with limited similarity of one or only a few parameters) made in a wind tunnel is extrapolated to real flight and real geometry.

Despite the success of the application of aerothermodynamics on existing Space Shuttle designs (and possibly also the Russian Buran) the present transfer models are not sufficiently developed to meet the requirements of future designs of hypersonic vehicles
[1]. This statement may be supported by the following facts [3],[4]:

- The next generation of hypersonic vehicles will consist of airbreathing systems where the engine is integrated in the vehicle geometry (integrated system). The flightpaths are low orbits. From an aerothermodynamic viewpoint the flow past the vehicle is for the major part of the flight trajectory dominated by viscous effects. Along the entire vehicle up to the propulsion system at the rear part there exists a thick turbulent boundary layer, the transition from laminar to turbulent flow is located in the nose area. Therefore, the designer has to take account of the integration of the propulsion system (forebody, inlet, engine, nozzle, expansion part) in this thick layer with relatively a strongly reduced kinetic energy. Yet he is asked for a design delivering a sufficient net thrust.

- Transfer models demand a good data base, at present almost completely based on wind tunnel results; if computational results are used they ought to be validated. If the experimental facility does not meet the (aerothermodynamical) design requirements this facility will in general not be suitable for validation of the computational transfer models either. To break out of this vicious circle one could think of carrying out detailed measurements on a small scale experimental hypersonic model from which real flight data exists in real flight. Such a solution is extremely expensive and will probably only be applied in the final stage of a large technological project [4].

- In addition to the similarity parameters a relation has to be given containing the wall temperature. Since the wall temperature is one of the unknowns of the problem, its prescription is not possible. A special case occurs if the assumption of an adiabatic wall is made or, physically more realistic, of a radiation-adiabatic wall. For a radiation-adiabatic wall the net heat flux (the sum of the convective heat flux to the surface and the heat flux radiated from the surface) vanishes. The only cooling the wall experiences is caused by radiation. In practice this appears to be the case for large parts of the vehicle surface. Therefore, in this respect the designer has to tune the material and the construction in the first place on the radiation-adiabatic temperature. At those locations where radiation cooling is not possible, for example in the inlet and exhaust, the recovery temperature may serve as design datum which leads to a requirement for forced cooling.

These facts, together with the often very strong coupling of aerothermal effects require an appropriate technological approach using sophisticated experimental techniques capable to solve separated problems according to their occurrence in practice. We then achieve:

- an increased understanding of aerothermodynamical phenomena (attached and separated flow, interaction effects, heat loads, etc.);
- a more representative experimental data base for design purposes;
- the transfer models, in particular the computational results will provide a more realistic simulation of flow physics (transition laminar - turbulent, turbulence itself) and thermodynamics (real gas effects, catalytic wall effects).
3. Aerothermodynamic Simulation Facilities

In view of the design problems outlined above it is evident that experimental hypersonic research has to satisfy high demands. To do the aerothermodynamical job according to physical reality, a first approach should be to start with a hot modelsurface. In [3] the concept of a 'Hot Experimental Technique' is mentioned, this refers to a simulation technique made up of the following components:

- the facility itself (wind tunnel);
- the technical possibility to use hot models with the appropriate instrumentation;
- the application of transfer models (scaling methods, computational methods).

Since this memorandum is in the first place meant to assert the initiation of experimental hypersonic research and education at the University of Technology Delft, we will in the next only describe the kind of research that could be performed in a relatively inexpensive facility that could be purchased in a joint financial effort by a number of participants. This modest attitude implies that the simulation of high enthalpy flows is left out of consideration and also that tests demanding long running times of the facility ( > 0.2 or 0.3 sec.) are out of discussion, because both requirements result in extremely expensive plants.

Type of flow simulation

Because of the restrictions discussed in the last paragraph, external-flow research has to be applied to models that contain the essentials of parts of space plane configurations. These configurations are long and slender having an airbreathing RAM/SCRAM propulsion at the rear. The surface is mainly radiation cooled, only special parts have a forced cooling (around the engine, inlet, exhaust and regions with a large heat production due to stagnation conditions). The partly attached and partly separated flow regions may be simulated in radiation-adiabatic equilibrium or near equilibrium. The flow at the windside of the forebody at angles of attack for cruise conditions (6 to 8 deg.) is of particular importance, since it is the upstream flow of the inlet. The thick turbulent boundary layer may cause unstarting of the engine. In all probability this effect is intensified by the viscous interaction of the boundary layer and the inviscid external flow and the interaction of the strong inlet shock and the boundary layer.

Type of flow research

The just mentioned flow problems can be investigated very fundamentally if one thinks of transition from a laminar to turbulent boundary layer, interference between the various phenomena (shock-turbulent boundary layer, boundary layer-external flow, etc.), separation, vortices, inletflow problems (bleed).

Similarity-/flow parameters

In order to achieve a reliable prediction of the aerothermodynamical characteristics for a vehicle design, a nearly exact simulation is necessary of the parameters Mach number, Reynolds number and the total enthalpy. With regard to the economical restrictions we put ourselves, simulation is possible of vehicles having lengths of 50 to 80 meters, moving at Mach numbers up to about 8 (2.5 km/sec.) at altitudes up to 35 km [3].
Type of facility

The above mentioned requirements for the flow parameters could be met by a Ludwieg type of facility in which test periods of 0.1 to 0.3 sec. can be realized. In the low hypersonic Mach number range (M = 6 to 10) the Reynolds number will satisfy the demands for HERMES like re-entry trajectories, which is necessary because there are no boundary layer tripping techniques available for high Mach numbers [5]. The total enthalpy is somewhat more difficult, since the achievement of stagnation temperatures of more than 1000 K requires special (although not impossible) provisions for the material and the heating system.

Model technique

As has been discussed earlier in section 2 real flight may contain radiation-adiabatic wall conditions. Thus, in the running period of the Ludwieg tube the surface of the model should reach the equilibrium temperature of a radiation-adiabatic wall. Therefore, the model must be pre-heated, either externally or internally by surface-sheet heating. A further point of importance is that the model surface should have the correct emissivity coefficient.

Measuring techniques

The application of hot models will impose large heat loads on the measuring instruments in the model (pressure- and temperature transducers, force balances, etc.). Yet, under these circumstances, a correct distribution of the radiation-adiabatic wall temperature is asked for. Since such a reliability appears difficult with instruments built in in the model, the obvious method seems to be nonintrusive measuring using opto-electronic techniques suitable for the very short test periods. Of these techniques infrared photography and digital holographic interferometry may be considered as promising candidates. The former is a well known measuring method for surface temperatures, whereas the latter measures density distributions in the external flow field. At the Faculty of Aerospace Engineering of the Delft University both (expensive) techniques are being used. The holographic interferometer is developed and applied successfully in the investigation of high supersonic flows past generic re-entry models.

Transfer models

In [3] has been shown that the radiation-adiabatic wall temperature is scale dependent; this implies that the transformation of the wind tunnel results to real flight conditions necessitates upscaling of these results. Also other measuring results will need the use of scaling laws or validated computational methods, both procedures are transfer models. The fundamental results obtained with the Ludwieg tube will improve the physical flow modelling by computational methods in the sense that boundary layer transition criteria will be improved, an increased understanding of interaction phenomena will be obtained, while the existing, but often insufficient, turbulence models enhanced. Proceeding in the way just indicated will result in adequate transfer models.
4. Experimental hypersonic research and education at the Delft University of Technology.

State of the art

The aerodynamics group of the Faculty of Aerospace Engineering considers the actual participation in hypersonic aerodynamics of major importance for the aerospace efforts of the Netherlands. Although education and research in high speed aerodynamics has been part of the curriculum of the Faculty, until recently this only concerned the supersonic speedregime. In 1989 the hypersonics study was taken up; the activities are restricted to theoretical work (analytical, computational) mostly performed by way of student's projects and/or Ph.D theses. However, a strong need is felt to complete the theoretical studies with experiments in a hypersonic facility located at the Faculty. Of course, such a facility should be considered in view of what has been discussed in the preceding three sections: it has to simulate as close as possible features of real hypersonic flight and yet has to be an affordable apparatus. Fortunately, the aerodynamics group's wishes went along with the important fact of a growing interest in re-entry aerodynamics at ESTEC. This is due to the increased need of verification of computational results coming from their own work or from studies issued outside.

The Aerothermodynamics group of ESTEC has examined the possibility to do fundamental experimental hypersonic research on a modest scale at acceptable cost. Since the nature of the intended work would fit very well into that at a university laboratory where a continuous flow of students, stagiaires and Ph.D. students will guarantee the academic build up of a high level expertise and also because the High Speed Laboratory of the Faculty of Aerospace Engineering is very well equipped with facilities for high speed aerodynamics, ESTEC is biased to stimulate the establishment of such an experimental hypersonic facility at the Delft University of Technology. In mutual consultation between the Aerothermodynamics group of ESTEC and the High Speed Laboratory of the Aerospace Faculty Delft plans have been worked out to purchase a relatively simple facility: a Ludwieg tube. In the next subsection a Ludwieg tube will be described in a particular version very well suited for university purposes.

Description of Ludwieg Tube

The facility that will be considered here is a development of the research institute Hyperschall Technologie Göttingen (HTG) in Germany. This institute is headed by Dr. George Koppenwallner, a leading scientist in experimental hypersonics in particular low density flows. The schemes, data and performances are taken from reports and brochures of the institute. In Fig.1 a sketch of the facility is shown and Table 1 gives the dimensions and performances, together with the Reynolds number of HERMES (based on the length of the vehicle) as a function of the Mach number.

The operation of the facility is as follows: The supply tube (consisting of parts I and II) is pressurized, part I just upstream of a fast operating valve is pre-heated and the vacuumtank evacuated. After opening of the valve an expansion wave runs into the supply tube; in the period necessary for the wave to run up and down the supply tube (parts I and II) a steady flow is created in the nozzle and the test section located downstream of the valve. After the test section the gas passes the diffusor and runs eventually into the vacuumtank. The valve is closed at the moment that the returning expansion wave in the supply tube again reaches the valve. This procedure makes it
possible that the rest of the gas supply in the tube (about 80% of the total) is preserved and also that the next test needs only a short refilling of the tube. The diffusor offers two important advantages: 1) it prevents upstream influence of the increasing pressure in the vacuumtank during the run and therefore it obstructs tunnel blockage; 2) for a fixed running time the volume of the vacuumtank can be smaller than in the case of no diffusor.

**Applicability of the Ludwieg Tube to education and research**

In economic respect the facility is eminently suitable for university use (the facility is recommended by HTG as Hochschul Hyperschall Kanal). The investment costs are relatively low, because the designer has been aiming at a facility that could be constructed from parts which are available off the shelf (standard piping, pumps, heating elements, pressure bottles, etc). Only the typical provisions for the windtunnel part (quick acting valve, nozzle, diffusor, etc.) are specific for this project. The operating costs are not high either: the electric power required is low (15kW), the application of the quick acting valve results in a very economical way of using the gas supply, in principle the facility may be operated by one or two people (not necessarily specialist or technicians, it may be students).

It is the intention to utilize the Ludwieg tube in the activities of research and education mentioned in the next.

**Research (‘own’ research by staffmembers and students as well as contract work)**

- Shock-boundary layer interaction (compression ramp flow);
- inlet flows;
- external flow past fundamental (generic) aerodynamic shapes;
- boundary layer transition studies;
- turbulence modelling;
- mixing, jet interaction;
- micro aerodynamics (cavities, holes, plots, gaps, steps).

**Education**

- Instruction of experimental hypersonic aerodynamics;
- projects for undergraduate students;
- research projects at masters and Ph.D level.
In principle the subjects of projects mentioned in the last two items will be obtained from the research themes.
Measuring techniques

The techniques that may be utilized for and that have proven their applicability in the measurement of flow past (cold and hot) models in a Ludwieg tube are:

- flow visualization
  * optical (schlieren, shadowgraph, interferometry)
  * surface flow (oil film, liquid crystal)
- force measurements
- heat transfer measurements
  * hot film
  * liquid crystal
- pressure distributions (transducers with a high frequency response)
- flow field explorations using digital holographic interferometry (this technique has been developed at the High Speed Laboratory of the Aerospace Faculty for high speeds in general and proves to be very successful)
- pressure sensitive paint research
- unsteady measurements.

5. Cost estimation and project financing.

To have the facility installed directly by HTG (the designer/manufacturer) i.e. it will be completely built up in the laboratory and connected to the laboratory systems, will amount to kfl. 800,-. It means that data acquisition system and other measuring capabilities (on-line computers, optical flow visualization system, measuring instruments, etc.) are excluded from the price.

As has been mentioned before, the facility has been constructed such that most of its parts (material of the structure on which the facility is mounted, supply tubes, heating elements, vacuum tank, compressor, vacuum pump, etc.) are readily available commercially; it is not necessary to make specific designs.

The expenses for these parts are identical for supplier and buyer in case the latter would order them himself. The manufacturing of the facility in the workshop of the Delft University will probably be less expensive than it would be if put to contract externally. However, self-manufacturing will require the purchase of the construction drawings, the price of which amounts to some kfl. 160,-. The costs of the actual manufacturing of the facility in the university workshop may add up to some kfl. 450,-.

The apparatus needed to operate the facility (control instruments, I-O devices, measuring tools, etc.) are estimated at kfl. 350,- to kfl. 450,-. In this respect it must be noted that the High Speed Laboratory of the Faculty has the disposal of an adequate instrumentation for flow visualization (optical and opto-electronical) and for ‘slow’ measuring, i.e. no fast response capabilities. The first tests and the tests where cold models are used may be performed with the available instruments of the laboratory. In order to achieve a real contribution to the issue of computercode validation the estimated amount of money for instrumentation is certainly not exaggerated.

Presently, the High Speed Laboratory of the Faculty of Aerospace Engineering is able to finance the project up to kfl. 215,- from its contract research budget. The remaining amount of 40 to 50% of the facility investment money has to come from other sources, preferably in the Netherlands. A joint venture of for example the Ministry of Economic Affairs, the
Netherlands Agency for Aerospace Programs and the aerospace industry would render a very
good service to the experimental hypersonic flow research in the Netherlands if a substantial
contribution could be made to the project, at the present moment this research is nonexisting.
Having a hypersonic facility at the Faculty of Aerospace Engineering of the Delft University
will provide an extension of the Dutch aerospace discipline and, not the least, it will meet a
wish of ESTEC, the European aerospace research institute in the Netherlands, for cooperation
in this discipline.

References

2283, 1983.

Orbiter Aerodynamics". Journal of Spacecraft and Rockets, Vol. 21, No. 2, 1984, pp
136-141.

Paper 91-5031.


Cone at Mach 5". AGARD-CP-224, 1977, pp 26-1 to 26-12.
Dimensions

Diameter of test section \( D = 0.25 \text{ m} \)

Length of supply tube (part I and II) \( L_t = 24 \text{ m} \)

Internal diameter of supply tube

part I \( d_n = 30 \text{ mm} \)

part II \( d_n = 35 \text{ mm} \)

Flow data

<table>
<thead>
<tr>
<th>Mach numbers</th>
<th>M 6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stagnation pressure (bar)</td>
<td>min. 2.6</td>
<td>5</td>
<td>10</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>max. 13</td>
<td>26</td>
<td>50</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

| Stagnation temperature (K) | min. 600 | 600 | 600 | 600 | 600 | 600 |
| max. 900 | 900 | 900 | 900 | 900 | 900 |

| Reynolds number based on D (Re/10⁹) | min. 0.24 | 0.31 | 0.44 | 0.63 | 0.47 | 0.35 |
| max. 2.2 | 2.9 | 4.0 | 5.8 | 4.3 | 3.3 |

| Reynolds number of HERMES (Re/10⁹) | 7.1 | 4.6 | 3.3 | 2.5 | 2.1 | 1.7 |

Running time : \( t \) (sec) \(0.07-0.13\)

Number of tests per hour \( 20 \)

Testgases \( \text{Air, N}_2, \text{He} \)

Gas consumption per test (kg): \( \approx 0.1 \)

Other provisions

Vacuumtank volume \( 1.5 \text{ m}^3 \)

Vacuumpump delivery \( 160 \text{ m}^3/\text{h} \)

Gassupply \( 0.1 \text{ m}^3 \text{ at } 200 \text{ bar} \)

Compressor mass flowrate \( 6 \text{ kg/h at } 250 \text{ bar} \)

Total electric power \( 15 \text{ kW} \)

Table 1  Facility operation data.
Fig. 1: Scheme of hypersonic facility.
Fig. 2: Planned location of Hypersonic Test Facility in tunnelhall 4 of the High Speed Laboratory