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Advances in critical technologies for hypersonic and high-enthalpy wind tunnel

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Abstract Hypersonic and high-enthalpy wind tunnels and their measurement techniques are the cornerstone of the hypersonic flight era that is a dream for human beings to fly faster, higher and further. The great progress has been achieved during the recent years and their critical technologies are still in an urgent need for further development. There are at least four kinds of hypersonic and high-enthalpy wind tunnels that are widely applied over the world and can be classified according to their operation modes. These wind tunnels are named as air-directly-heated hypersonic wind tunnel, light-gas-heated shock tunnel, free-piston-driven shock tunnel and detonation-driven shock tunnel, respectively. The critical technologies for developing the wind tunnels are introduced in this paper, and their merits and weakness are discussed based on wind tunnel performance evaluation. Measurement techniques especially developed for high-enthalpy flows are a part of the hypersonic wind tunnel technology because the flow is a chemically reacting gas motion and its diagnosis needs specially designed instruments. Three kinds of the measurement techniques considered to be of primary importance are introduced here, including the heat flux sensor, the aerodynamic balance, and optical diagnosis techniques. The techniques are developed usually for conventional wind tunnels, but further improved for hypersonic and high-enthalpy tunnels. The hypersonic ground test facilities have provided us with most of valuable experimental data on high-enthalpy flows and will play a more important role in hypersonic research area in the future. Therefore, several prospects for developing hypersonic and high-enthalpy wind tunnels are presented from our point of view.

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1. Introduction

The hypersonic and high-enthalpy flow is referred to as a gas flow with high kinetic energy, in which there may exist thermal and chemical reactions behind the bow shock or within the boundary layer. The term “hypersonic” was first used by Tsien in his research article ‘Similarity laws of hypersonic flows’[1] to distinguish the flows at speeds much higher than the local speed of sound from supersonic flows where thermal and chemical reaction effects on flow motion can be ignored. By far, hypersonics, the research field of hypersonic and high-enthalpy flows, has become a leading discipline branch of gas dynamics for more than a half century, featuring the distinguishing characteristics and a promising background of engineering application.[2] Here, the critical techniques that we are going to talk about are the wind tunnel techniques to generate hypersonic and high-enthalpy test flows for the study on the aerodynamic performance of hypersonic aircraft.[3]

The primary features of a hypersonic and high-enthalpy flow are the high kinetic energy and the high stagnation temperature. The key aerodynamic phenomena and their effects on aircraft performance were first discovered during the atmospheric reentry of the space vehicles such as space capsules or space shuttles. Such vehicles encounter extremely strong nose shock waves and viscous friction along the surfaces that can heat the surrounding air to a temperature up to thousands or even ten thousand degrees. Molecule vibration excitation, gas dissociation and atom ionization may occur successively as the gas temperature increases. In such a situation, air will no longer be an ideal gaseous mixture, but a chemically reacting media varying with the flow temperature. The substantial change in the flow media results in changes to the constitutive relation of the high-enthalpy flows in which the energy transition takes place within chemically reacting gases and flow motions. This is the fundamental issue of hypersonic and high-enthalpy flows and boosts study on the chemical physics of gas dynamics.[4]

The aforementioned physicochemical processes occurring in high-enthalpy flows at micro scales may have significant effects on aerodynamic performance of hypersonic vehicles. Being different from subsonic and supersonic flows, the chemically reacting gas flows feature nonlinearity, non-equilibrium, multi-scale and multi-physics properties and impose a big gap between theoretical analysis and the high-enthalpy flows. For numerical simulations, the difficulty is still there on the way to interpret the chemical reaction processes correctly because of the fact that the flight test data have demonstrated discrepancies from both the numerical simulations and the wind tunnel experiments. Therefore, modeling the hypersonic and high-enthalpy flows with acceptable accuracy is still an open problem. Consequently, developing advanced hypersonic wind tunnel techniques to gain reliable experimental data is the primary research approach for high temperature gasdynamics.[3–5]

There are four challenging issues for us to consider for developing hypersonic and high-enthalpy wind tunnels. The first issue is how to duplicate the total temperature of hypersonic flights. The temperature is a primary requirement to reproduce the thermo-chemical reactions occurring at different flight March numbers. For instance, the total temperature should be around 2300 K to simulate the hypersonic flight at altitude of 30 km for a Mach number of 7. Oxygen molecules around the stagnation region start to dissociate at the temperature level. The total temperature of the test flow rises to 4500 K for a Mach number of 10 and nitrogen molecules begin to dissociate behind the bow-shock. In the Mach number 20 hypersonic flight, both oxygen and nitrogen atoms may ionize in the boundary layer around hypersonic vehicles. Therefore, the total temperature is the key parameter for simulating high-enthalpy flows. The second one is how to make the chemically reacting processes similar to each other at both the scaled test model and the full-size vehicle in flight tests. The binary scaling is not applicable for chemically reacting flows where recombination reactions take place since the flow temperature decreases downstream from the stagnation region. Furthermore, for the hypersonic boundary layer transition, the surface roughness and catalytic reactions are also not scalable. Therefore, large-scale test models, if applicable, are required in hypersonic and high-enthalpy flow tests to avoid the model-scaled effect associated with chemical reactions. So, both the pure air and the large test flow field are also the primary requirements for acquiring reliable experimental data from hypersonic wind tunnel tests. The third one is how to simulate the flow velocity according to flight conditions. The reasonable simulation of velocity profiles of the boundary layer along a vehicle surface is a base to obtain both the friction drag and heat flux with acceptable accuracy.

The last issue is how to simultaneously realize the hypervelocity, chemical kinetics and large-scale test models, while maintaining sufficient long test time with hypersonic and high-enthalpy wind tunnels. For instance, to simulate the real flight conditions for a Mach number of 8 at an altitude of 30 km, the required total temperature is up to 3000 K. Furthermore, if a test flow field with a diameter of 3 m is required to accommodate large-scale models, the output power of the facility is about 900 MW. The output power is even higher than the total installed power capacity of the Gezhouba hydropower station located in the Yangtze River in west China. It is not practicable to meet such an output power for conventional blow-down wind tunnels operated in a continuous mode.

After more than sixty years' research work, hypersonic ground test facilities suitable for exploring aerothermochemistry still rely on high-enthalpy shock tunnels. Many shock tunnels were built over the world, for example, the Large Energy National Shock tunnels (LENS) in USA, the High-Enthalpy Shock Tunnel (HIEST) in Japan, the High-Enthalpy Shock Tunnel (HEG) in Germany, the JF-10 high-enthalpy shock tunnel, the JF-12 hypersonic flight-duplicated shock tunnel and the JF-16 hypervelocity expansion tunnel in China.[3–6] Some examples of high-enthalpy shock tunnels running in the world and their main features are listed in Table 1. Valuable data have been produced with these shock tunnels for both hypersonic gas dynamics and hypersonic vehicle development.

Fig. 1 shows the flight trajectory of various hypersonic vehicles. The total temperature of the test flow is about 1500 K to simulate the hypersonic flight at the velocity U_∞ of 1.5 km/s with a wind tunnel while it rises to around 10000 K for the flow velocity of 10 km/s, h is the height. The challenge is obvious for developing measurement techniques to diagnose the high-enthalpy flows under such a severe thermo-environment. A series of the measurement techniques have been developed and applied to high-enthalpy flow tests during the recent decades. These techniques can be classified into three types, i.e., the

Table 1 Examples of high-enthalpy shock tunnels in operation over the world.

Tunnel	Driver mode	Total length (m)	Exit nozzle diameter (m)	Test time (ms)	Mach number simulated
JF-12	Detonation driver	~275	1.5 or 2.5	100–130	5–9
LENS-II	Heated H_2 or He	~65	1.07, 1.52 or 1.83	20–100	7–15
HEG	Free piston driver	~62	0.88	3–6	6–10

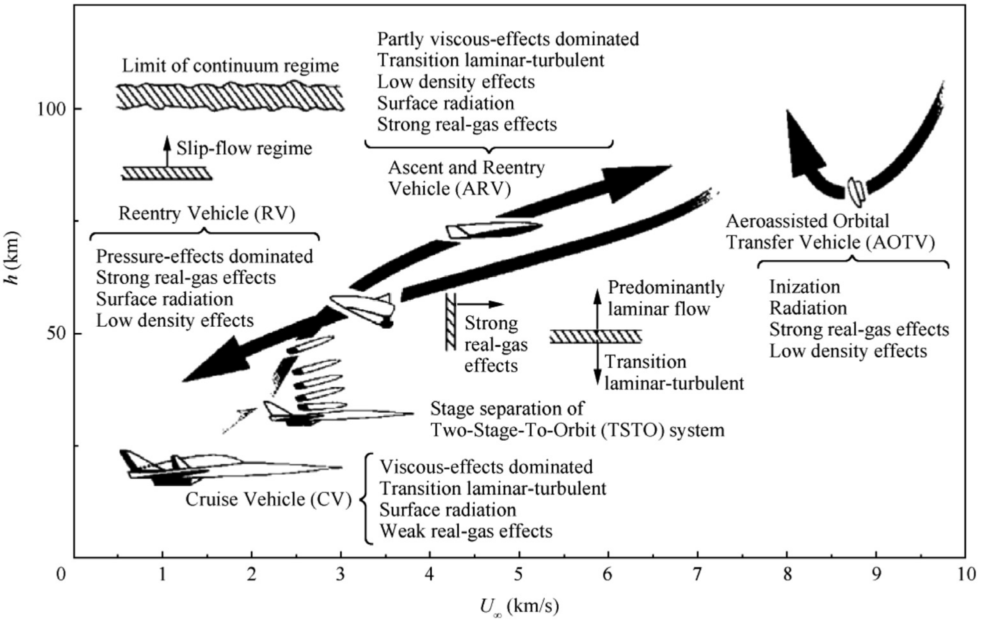


Fig. 1 Typical flight trajectories of various hypersonic vehicles (altitude vs velocity).[5]

balance for measuring aerodynamic forces and moments, thermal sensors for aerodynamic heating, and optical techniques for flow diagnosis. When developing these techniques, one of the critical issues is the trade-off between measurement accuracy and device survivability under the chemically reacting environment of high-enthalpy flows. The test duration is the second issue that is subject to the extremely high thermal loads upon high-enthalpy test facilities. Consequently, the short test time of high-enthalpy wind tunnels reduces the accuracy of the balance and brings forth severe constraints to the technical development of aerodynamic balances. The third issue is the high-temperature flow environment which can induce the surface erosion, washout, oxidization and charged ions to thermal sensors, which affect their lifetime and experimental data accuracy. Therefore, the key technique for aerodynamic heat transfer measurement is how to develop the high-accuracy thermal-sensors. Optical techniques for flow visualization and diagnosis work in a non-intrusive mode, and can keep high-enthalpy flow phenomena free from disturbances. One can obtain shock and flow structures, flow temperature, gas species, and flow velocity using special optical techniques. Image quantification and data accuracy are the key issues for improving optical measurement techniques.

During the recent decades, hypersonic ground test facilities have provided us with most of valuable data on high-enthalpy flows and played an important role in the hypersonic research area. However, the critical technologies as mentioned above have their own limitations on high-enthalpy flow generation and measurement techniques. It is the limitations that result in experimental data uncertainties that make the hypersonic wind tunnel tests have difficulties to meet the requirements from continuously growing aerospace engineering projects. Hypersonic technology has become the top priority of the aerospace and aviation industries since the beginning of the 21st century. Its development has significant effects on modern society. Therefore, hypersonic and high-enthalpy tunnels and their measurement techniques are the critical technologies for hypersonic research, and their importance can hardly be overemphasized.

2. Progress in high-enthalpy tunnels

During the recent decades, several types of high-enthalpy tunnels have been investigated and built up over the world.[3] The primary difference among these wind tunnels is their operation mode that is how to heat the compressed test gas and accelerate it to a required flow velocity. By far, there are two methods broadly used to gain high-enthalpy flows, i.e., the air-directly-heated blow-down type hypersonic wind tunnels and the shock-heated high-enthalpy tunnels. The latter can be further divided into three classes according to the driving mode, i.e., the light-gas-heated driver, the free-piston driver and the detonation driver. These three kinds of shock tunnels are widely used for high-enthalpy flow tests over the world and they have provided us with massive experimental data. The critical technologies for developing these wind tunnels are introduced in this section, and their merits and weakness are discussed based on wind tunnel performance evaluation. The problems encountered in their development are also described and the techniques for solving the problems are the potential challenges to the research and development of advanced high-enthalpy tunnels in future.

2.1. Air-heated hypersonic wind tunnel

Following the operation mode of conventional supersonic wind tunnels, heating the test gas directly is one way to generate hypersonic flows. This kind of hypersonic wind tunnel is referred to as the air-directly-heated hypersonic wind tunnel. Several kinds of the heating systems can be used to heat air at high pressure conditions to a required temperature, and then the same process is carried out for all the wind tunnels, that is, the high-pressure and high-temperature gas is expanded through a convergent-divergent nozzle and accelerated to a hypersonic state in the test section. Because the air-heating process usually takes long time, the high heat-resistant capability is required for both the air-directly-heated system and the test gas reservoir. As the crucial technology of the air-directly-heated hypersonic wind tunnel, four types of air heaters are accepted widely, i.e., (A) Nickel-Chromium electric resistance heater which can endure a high temperature up to 1000 K; (B) Ferrum-Chromium-Aluminum electric resistance heater which can endure the maximum temperature up to 1450 K; (C) Nitrogen-Tungsten electric resistance heater which can endure a temperature of 2200 K; (D) Graphite electric resistance heater which can endure a maximum temperature of 2800 K. These heaters are usually used to heat a device with special structure, named as accumulator made of high-heat-resistance materials for heat accumulation. The test gas will be heated to a required temperature when it moves by passing through accumulators. The total temperature of the test flows depends on the accumulator's configuration, test flow speed and heat transfer rate between the accumulator materials. The heat transfer rate between the test gases and accumulators is the critical issue for the air-heating system to obtain a constant temperature of the test gas. The aluminum-oxide/gravel heat accumulator can be operated at a high temperature of 1670 K. The zirconium-oxide/gravel heat accumulator works for the maximum temperature of 2500 K. The test time of the conventional air-directly-heated hypersonic wind tunnels is of a magnitude from seconds to minutes,[3] and the maximum Mach number simulated by the hypersonic wind tunnels is less than 7. Actually, the arc-heated wind tunnel is also operated in the air-directly-heated mode, but it is not discussed here because its usage is focused mainly on materials erosion tests.

Another approach was tried in the NASA Glenn Research Center, where nitrogen is heated first with the electric arc, and then mixed later with oxygen to produce the high-enthalpy air flow. The Hypersonic Tunnel Facility (HTF)[7] setup in Glenn RC is a typical air-directly-heated hypersonic wind tunnel. The HTF was built up in 1966 for testing atomic rocket engines and reconstructed to be a hypersonic wind tunnel in 1969 for testing air-breathing hypersonic engines. The original gravel heat accumulator was replaced with a graphite heat accumulator to enhance the HTF performance. In each operation, the nitrogen is heated first in the HTF, and then mixed with oxygen subsequently. In this way, the surface oxidation occurring in the air-heated mode can be weakened and the working environment of the heater and accumulator can be improved. The HTF can be used to simulate hypersonic and high-enthalpy flows of Mach number 5–7 at altitude 20–30 km. The total temperature is about 1200–2200 K. The experimental research on Hypersonic Research Engine (HRE) was conducted with HTF. A full-scale, water-cooled, hydrogen-oxygen fueled scramjet model was tested and its experimental results were reported.

The air-directly-heated hypersonic wind tunnels can be operated in a continuous mode for long test time and are broadly used in aerodynamic tests for hypersonic vehicles. However, the construction cost of the wind tunnel is massive due to its complicated air-heating system. The heat accumulator is subject to heavy thermal loads, surface erosion and oxidation, and washout of high-speed flows. Test gas contamination is also a problem and can result in some uncertainties of experimental data. In addition, a test gas flow with a total temperature higher than 2000 K can hardly be generated by such wind tunnels due to the capability limitation on the heater and the accumulator. Nevertheless, the air-directly-heated hypersonic wind tunnel plays an essential role in hypersonic flow tests, especially for measuring aerodynamic forces and moments. However, there are still some technical problems to be solved for improving wind tunnel operation and one of them is about the total temperature. To reduce the huge thermal load on heating systems, test gases are heated to the temperature that is required not by flight conditions but by no air condensation after its expansion. In the case, the test flow has low static temperature but high March number. Therefore, for hypersonic wind tunnel tests, the hypersonic flow may not be equal to the hypervelocity flow even if the flow Mach number is the same, and this may lead to confusion.

2.2. Light-gas-heated high-enthalpy shock tunnel

For shock tunnels, the shock theory indicates that the incident shock Mach number increases with the increase of the pressure and the sound speed of the driver gas, and the total temperature of the test gas depends on the incident shock Mach number. For the light-gas-heated shock tunnel, the light gas with a high sound speed is accepted as the driver gas, and heating the light gas can further increase its sound speed. The U-12 shock tunnel developed by Russian TSNIIMASH Center is driven by a light-gas-heated driver and a hydrogen-oxygen combustion driver. Typical light-gas-heated shock tunnels are the Large Energy National Shock tunnels (LENS) facilities located in Calspan University of Buffalo Research Center (CUBRC) in Northeast of America. The LENS I uses electric-heated hydrogen or helium as the driver gas and the LENS II uses a helium-nitrogen mixture.[6,8–12]

The research and development of the LENS can be traced back to 1986 with a goal of providing with high-enthalpy test flows and long test time for the study on turbulent flows at high Reynolds numbers and high Mach numbers. The design indexes at that time are as follows: total pressure of 180 MPa, total enthalpy of 35 MJ/kg, and total temperature of 12,000 K.[9] To fulfill the design index, the hydrogen heated to a very high temperature was used as the driver gas, and unfortunately, a severe accident occurred during the tunnel calibration due to the facility erosion caused by the high-temperature hydrogen. Then, the research plan of the LENS was modified by reducing the total flow enthalpy down to 12.5 MJ/kg.[10] Later, CUBRC further upgraded the shock tunnels for simulating hypersonic flights at Mach number 6–15 to match with requirements from the NASP program for scramjet research. The recent upgrading work of the LENS is to improve its capability to simulate flight conditions at different altitudes so that it can be used to study the aero-optic problem induced by flow field variation in the vicinity of mounted transducers. At present, the LENS I can be used to simulate hypersonic flows of Mach number 7–14, and the LENS II can do the flow of Mach number 3–7. The LENS XX is an expansion shock tunnel that can simulate high-enthalpy flows above Mach number 12. The dual diaphragm technique applied in LENS guarantees their repetitiveness of test flows.

Symmetrical experiments have been conducted with the LENS at CUBRC, such as the shock/boundary layer interaction, heat flux over double-cone models, surface catalysis effect, and aero-optical problem.[11,12] Moreover, the experiments covering most of the American hypersonic projects have also been conducted, including the full-scale X-51A, HTV-2 and X-43A. The LENS is a successful example in the hypersonic research area. These facilities at CUBRC become one of the few hypersonic facilities in the world, which can duplicate hypersonic flight conditions. However, because the heated light gas is used for the LENS facilities, the operation cost is extremely high due to the massive consumption of light gas for each shot. In addition, the security problem is also a critical issue that may occur during the storage, transportation, heating and exhausting processes of the driver gas. Nevertheless, there is a limitation on the LENS output power since a mechanical compression approach is accepted to increase the driver gas pressure. All the aforementioned factors are technical challenges to the light-gas-heated shock tunnels for the future scale-up and the output power enhancement.

The U-12 shock tunnel at the TSNIIMASH Research Center is a large-scale hypersonic test facility. The high pressure section has an inner diameter of 500 mm and is 120 m in length. The low pressure section has an inner diameter of 402 mm and is 190 m in length. The filling pressure of the high pressure section can be up to 20 MPa while the initial pressure of the low pressure section is from 1 Pa to 5 MPa. Both a contoured nozzle and a conical nozzle can be used for the U-12 shock tunnel. Available papers reported its experimental results on flow visualization and aerodynamic force measurement. However, there is a lack of the relevant literatures presenting the later progress on tunnel techniques and experimental studies. From the given configuration parameters, it can be identified that the length-to-diameter ratio of the low pressure section is too large, which can result in not only the severe attenuation of the incident shock wave but also the excessive development of the boundary layer. Such problems should be avoided in design of high-enthalpy shock tunnels.

2.3. Free-piston driven high-enthalpy shock tunnel

In a free-piston driven high-enthalpy shock tunnel, the high pressure driver gas is generated by a rapidly-moving piston. During shock tunnel operation, a heavy piston is first accelerated to a high speed in a shock tube, and then compresses the driver gas in front of its nose. When the driver gas pressure reaches a required value, the primary diaphragm between the driver section and the driven section ruptures. Subsequently, an incident shock wave is generated in the driven section and compresses test gases at the end of the driven section. The concept of a free-piston driver is first proposed by Stalker from Australia, and the shock tunnel development was reported in his later publication.[13] At present, the free-piston driving technique is applied broadly over the world,[13–24] and many free-piston driven shock tunnels have been built up and put in operation, including T3 at National University of Australia, T4, X2 and X3 at Queensland University,[14–16] T5 at California Institute of Technology,[17,18] HEG at DLR in Germany,[19] and HEK and HIEST at JAXA of Japan.[20,21] These free-piston driven shock tunnels have provided valuable experimental data of high-enthalpy flows. For example, Eitelberg (1994) studied the heat flux over the thin model with the HEG shock tunnel. The experimental data indicated that the longitudinal decay rate of the heat flux is different from computation results.[19] Hornung et al. investigated the high-temperature effect caused by a relatively large jet impinging spot where the heat flux could be severely enhanced when they studied shock/shock interaction in the T5 shock tunnel.[22] The results highlight significant importance of studies on high-enthalpy flows.

Among free-piston driven shock tunnels over the world, the HIEST located at JAXA, Japan is a typical one for its large scale, long test time and technical maturity. The compression tube of the HIEST is 42 m long with an inner diameter of 600 mm, and its shock tube is 17 m long with an inner diameter of 180 mm. The weight of free pistons in use can be 220, 290, 580, and 780 kg, respectively. The exit diameter of the conical nozzle is 1.2 m while its throat diameter can be 24–50 mm. The exit diameter of the contoured nozzle is 0.8 m with a throat of 50 mm. The key parameters are listed as follows: the maximum stagnation pressure is 150 MPa, the maximum total enthalpy is 25 MJ/kg, and the effective test time is about 2–5 ms. The test time can be longer under test conditions of low total flow enthalpies. The test flow generated is characterized with the parameters as follows: the flow velocity ranges from 3 to 7 km/s, the Mach number covers 8–16, and the dynamic pressure is 50–100 kPa. During the HIEST calibration, Itoh proposed a tuned operation method for realizing soft landing of a heavy piston to avoid facility damages from the piston impact. Both numerical and experimental studies demonstrated that the method is successful for safe operation of free-piston driven shock tunnels.[21] A series of high-enthalpy flow tests have been conducted by JAXA with HIEST so far, such as the high-temperature effect on the pitching moment of Hope-X, the surface catalysis in high-enthalpy flows, scramjet engine tests at Mach number 8, etc.[23] A large-scale free-piston driven shock tunnel has been set up and put in operation in China in recent years with its techniques and performance reported.[24]

There is no doubt that the technical development of free-piston drivers is successful and free-piston driven shock tunnels became a hypersonic test facility widely accepted for the study on high-enthalpy flows over the world. However, from its operation experience, it is recognized that the flow quality is not high and the test time is short. The problems arise from the free piston motion without any constant speed period, which results in a continuously varying pressure of the test gas state. Although the overall size of the HIEST facility is almost 100 m in length, its test time for the typical hypervelocity condition is only about 2–5 ms. For free-piston driven shock tunnels, the pressure in front of the moving piston will fall rapidly once the diaphragm ruptures. Such a phenomenon results in a rapid decay of the incident shock wave. The tuned operation mode can be applied to improve the incident shock decay and the test duration of the free-piston driven shock tunnels could be extended, but it is still measured in millisecond. Another problem is due to the moving part of free piston drivers. A heavy piston of 1000 kg, moving at high speeds, will lead to technical difficulties in operation for piston launching and stopping. The heavier the piston is, the more difficult the shock tunnel operation is.

2.4. Detonation-driven high-enthalpy shock tunnel

A detonation driver is established based on high pressure and temperature detonated products from which the required incident shock wave is generated. Because of the fact that the gas detonation pressure is much higher than the filling pressure of detonable gas mixtures and detonated products have high sound speeds, the detonation driver is a convenient, powerful and efficient technique for high-enthalpy shock tunnels. The concept of detonation drivers was proposed first by Bird and the performance of a detonation driven shock tube was investigated when the detonable mixture was ignited at each end of the deriver section, respectively.[25]

To explain the working principle of detonation drivers, we take a circular steel tube with one end closed as a detonation section. When a detonable gas mixture is ignited at its closed end, a detonation wave generated propagates towards the other end. Due to the stationary boundary condition at its closed end, an expansion wave system is developed behind the detonation front through which the gas flow velocity gradually decreases to a stationary state. The column length of the detonated-gas at rest, which still has very high temperature and pressure, is about half of the propagation distance of the detonation front. The operation mode is called the forward detonation driving if the driven section is located at the open end of the detonation section and there is no steady flow region behind the incident shock wave due to rarefaction waves. The operation mode is called the backward-detonation driving if the ignition point is located at the primary diaphragm between the detonation section and the driven section and there is the column length of the detonated-gas that is ready for driver gases.[26]

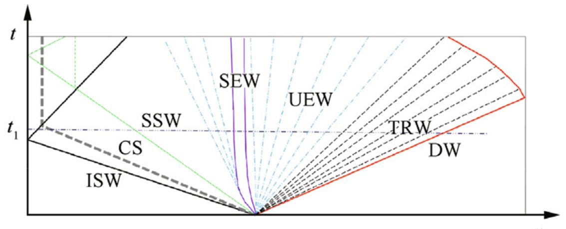
However, in a backward-detonation driven shock tunnel, the detonation front propagates along the detonation section and is reflected from the end of the driver section. This physical phenomenon results in extremely high pressure loads on the facility and can impose a severe safe problem in shock tunnel operation. Yu proposed a concept by appending a damping section to the open end of a detonation tube for accommodating the gases with huge energy carried by the detonation front to ensure shock tunnel operation safety.[27] With Yu's damping concept, the backward detonation driver became applicable in engineering. A detonation-driven high-enthalpy shock tunnel (laboratory series number JF-10) was set up in 1998 in the Institute of Mechanics (IMECH), Chinese Academy of Sciences.[27–32] The high-enthalpy shock tunnel (TH2-D) located in Aachen Industry University (AIU) in Germany is another detonation-driven shock tunnels which was developed through cooperation between IMECH and AIU.[33,34] The HYPULSE shock tunnel built up at NASA Langley Research Center (LaRC) can work in dual operation modes: the detonation driven mode and the heated-light-gas driven mode.[35,36] These shock tunnels have been applied to study aerodynamic forces and heat fluxes of hypersonic flows, and the experimental data of the high-temperature effect, aero-physics, supersonic combustion and scramjet engine tests are also reported.

For development of the critical techniques for detonation driven shock tunnels, the research work completed in IMECH is systematic and innovative. Yu et al. has initialized the study on detonation drivers since 1960s, and a series of concepts and technique validation were carried out with the JF-8 shock tunnel.[37] The BBF100 detonation tube and the JF-10 detonation-driven high-enthalpy shock tunnel were successively developed and operated for high-enthalpy flow tests.[38] The JF-10 shock tunnel has a driver section of 10 m in length with an inner diameter of 150 mm. Its driven section is 12.5 m long with an inner diameter of 100 mm. A conical nozzle is used in the JF-10 shock tunnel and its exit diameter is 500 mm. The main performance parameters of the JF-10 shock tunnel are listed as follows: the total temperature up to 8000 K, nozzle flow velocity up to 6 km/s and the test duration about 3–6 ms. The successful development of the JF-10 shock tunnel is a turning point since which the detonation-driven high-enthalpy shock tunnel has become a practical test facility from a concept.

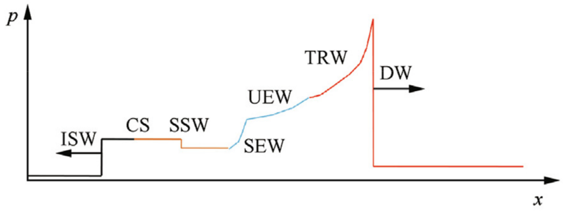
The backward-detonation driver utilizes only detonation products at rest behind the detonation front as the driver gas. The pressure of the products is about half of the C-J pressure. Theoretically speaking, the driving power of the forward detonation driver is about five times higher than that of the backward detonation driver under the same initial conditions by measuring with the C-J detonation parameters. However, the Taylor expansion waves lead to a gradual attenuation of the incident shock wave, and result in the fact that the forward detonation driver is not acceptable for practical applications to shock tunnels. To solve the aforementioned problem, Jiang et al. proposed the Forward Detonation Cavity (FDC) driver based on the multi-shock reflection concept.[14] The FDC driver consists of three parts, i.e., the detonation section, the reflecting cavity and the auxiliary detonation section. When a detonation wave passes through the reflecting cavity, its middle part propagates directly into the auxiliary detonation section while the circumferential part of the detonation front is reflected back from the end wall of the cavity and forms a reflected shock wave that is travelling upstream. The coming gas flow passes through the upstream-travelling shock wave, and the shock interaction results in the pressure and temperature increase of the coming flows. Considering the shock system developed in the FDC driver, it is understood that the stronger upstream-travelling shock wave and the weaker downstream-travelling shock wave from shock interaction are favorable for enhancing the FDC driver performance. This is also the principle for configuration optimization of the FDC driver. The JF-10 shock tunnel was further improved by introducing a FDC driver to achieve the test time of 6 ms and the critical techniques were well validated.[39]

Under the support of Chinese National Project of Scientific Instrumentation research and development, Jiang and Yu et al. developed the Long-test-duration Hypervelocity Detonation-driven Shock Tunnel (LHDST) based on the backward detonation driver with several innovative techniques by the end of May in 2012.[32,40,41] The laboratory series number of the shock tunnel is JF-12 and its operation principle is depicted in Fig. 2 by the wave diaphragm and transient wave structure. Fig. 3 shows schematically the JF12 shock tunnel with a photo showing the entire nozzle, the test section and vacuum system.[32] From its left to right, the first part is the vacuum system for damping wave reflection during the nozzle starting process, and the vacuum tank with a volume of 600 m^3 is 3.5 m in diameter. The second part is the test section being 15 m in length and 3.5 m in diameter. The contoured nozzle is 15 m in length and 2.5 m in its exit diameter. The second nozzle is smaller, having a nozzle exit of 1.5 m in diameter for Mach number of 5–7. Next to the nozzle, there is the driven section being 89 m in length and 720 mm in diameter. The detonation driver is 99 m in length and 400 mm in diameter. The driver operates in the backward detonation mode. The driver and the driven section are connected with the transient part by which the tube diameter is gradually reduced from 720 mm to 400 mm. Between the driver section and the transient part, there is the diaphragm rig that is used to produce the incident shock wave in the shock tunnel after the direct detonation initiation. The damping section is located at the far right end of the facility, and is 19 m in length and 400 mm in diameter.

A series of the innovative techniques are integrated into the JF-12 shock tunnel, such as the tailored interface condition for detonation-driven shock tunnels, the precursor shock attenuation in damping tank, and the shock/boundary layer interaction control at the end of the driven section. Its performance tests demonstrated that the facility is capable of reproducing the pure airflow for Mach numbers from 5 – 9 at altitude of 25–50 km with 100 ms test duration, so the JF-12 shock tunnel will be a useful tool for testing engine/frame-integrated hypersonic vehicles and investigating into fundamental physical issues in hypersonic and high-temperature gas dynamics. 2016 AIAA Ground Testing Award was presented to Jiang and AIAA commented that Jiang's work had advanced the state of the art in large-scale hypersonic test facility. The JF-12 shock tunnel has a series of advantages, such as long test time, low operation cost, good repeatability and large-scale test flow field. These made it become the first hypersonic ground test facility over the world, which can duplicate the real flight conditions both in flow parameters and test model size. On the other hand, the challenges still exist in design and operation of such high-enthalpy tunnels, such as safe and robust detonation initiation,[42] material limitation on the total temperature and pressure, the tunnel inner surface erosion caused by the high-temperature gas flows, hydrogen brittleness, facility cleaning after each shot, etc.



(a) Wave diaphragm



(b) Transient wave structure

Fig. 2 Wave diaphragm and transient wave structure of JF-12 shock tunnel (DW-detonation wave, TRW-Taylor rarefaction wave, UEW-unsteady expansion wave, SEW-steady expansion wave, SSW-secondary shock wave, CS-contact surface, ISW-incident shock wave).

3. Measurement and diagnostic technology

Hypersonic vehicles encounter an aero-thermodynamic environment characterized by strong shocks, high temperatures and chemical reactions, and the surrounding air flow in hypersonic regime behaves quite differently from supersonic flows. The kinetic energy associated with hypersonic flight is converted into the internal energy which increases the air flow temperature and induces endothermic reactions, such as molecule vibration excitation, dissociation and ionization of the air flow near the vehicle surface. Thus, the air flow becomes a chemically-reacting gas media. Aerodynamic heating where the heat transfer from the surrounding high-temperature gases to the vehicle surface is the critical issue for hypersonic technology and makes the hypersonic vehicle design different from supersonic ones. The heat transfer rate depends on many factors, such as the free-stream flow velocity, the vehicle surface curvature, the temperature difference between the gases and wall surfaces and surface catalysis. Therefore, for the chemically reacting flow, it is a challenge to develop flow diagnostic technologies with high precision for high-enthalpy wind tunnel tests. From requirements from hypersonic vehicle development, there are three types of measurement technologies widely used in exploring hypersonic and high-enthalpy flows, including the heat-transfer measurement, the aerodynamic balance and optical diagnostic techniques. These technologies based on different physical principles have gotten great progress during the recent decades and contributed a lot to wind tunnel dada acquisition.

3.1. Heat-transfer measurement

Aerodynamic heating is a unique physical phenomenon for hypersonic vehicles where the heat is transferred from the flow to vehicle surfaces. This is a severe problem for long-flight hypersonic crafts and results in a special need for a Thermal Protection System (TPS). Accurately measuring heat-flux distribution over the aircraft surface is a primary basis for designing the TPS structure and selecting heat-resistant materials.

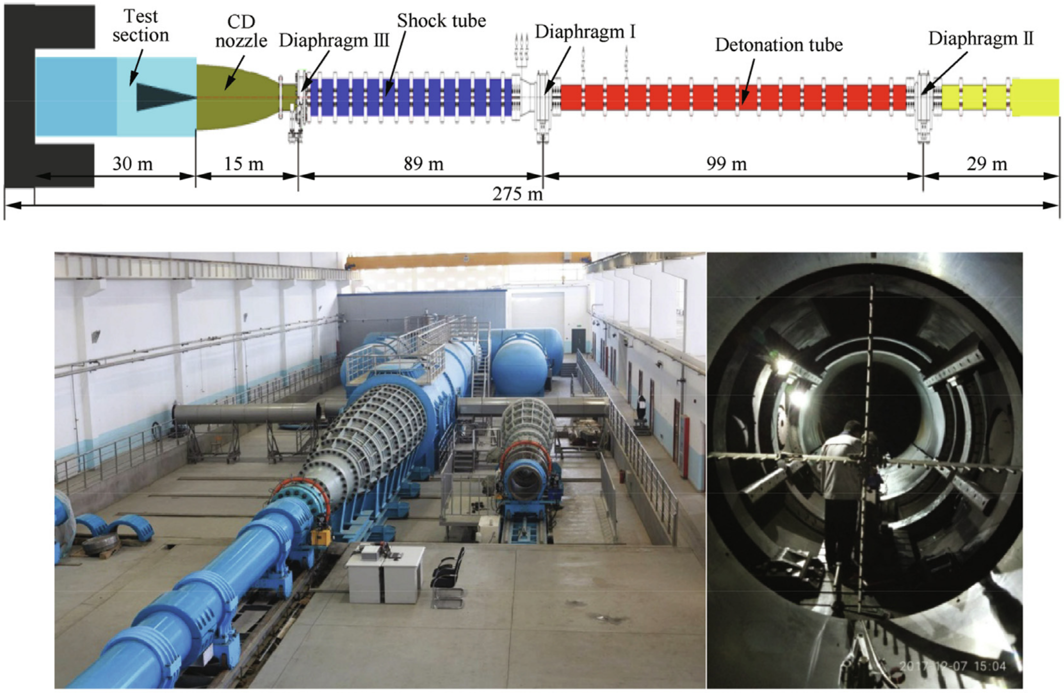


Fig. 3 JF-12 shock tunnel.[32]

For development of high-enthalpy shock tunnels, one of the important objectives is to identify the aero-thermal-environment of hypersonic vehicles.[43] Due to short test time, high temperature and chemical reactions of the high-enthalpy flows, the development of heat-flux sensors with high sensitivity, short response time and low thermal load is a challenge.

According to the working principles, the heat-flux sensor that can meet the above requirements can be divided into two categories, i.e., the surface thermometer and the calorimeter.[44] The surface thermometer detects the temperature variation on the sensor surface during testing, and then the heat transfer rate is calculated with the heat conduction theory. The thin-film resistance thermometer and the coaxial thermocouple are two types of the commonly used surface thermometers, and each has its own advantages and limitation. The thin-film resistance thermometer is of high sensitivity, but has poor anti-erosion capability. Therefore, it is suitable for the test flow of a low total temperature with short test duration. In contrast, the coaxial thermocouple is of relatively low sensitivity, but has the strong anti-erosion capability. Therefore, it is suitable for the test flow of the high total temperature with long test duration. The plug-type copper foil calorimeter is a representative of the calorimeter sensors and has good stability and strong anti-erosion capability. However, its thermal response feature is significantly affected by its machining process, and its miniaturization is also difficult to achieve for improving spatial accuracy.

Although a variety of heat-transfer sensors are available for high-enthalpy flow tests, there are still some technical problems to overcome, such as large dispersion and low accuracy of experimental data, flow-scouring effect, and short lifetime.[45] At present, the data accuracy of the advanced heat-flux sensors is generally about 10% error band, and will be much lower in the region of shock/boundary-layer interaction. Moreover, the repeatability of the heat-transfer experiment is not good due to high-temperature-induced oxidation on the sensor surface and the conductivity of high-enthalpy flows. Therefore, further development should be focused on improving the measurement accuracy and increasing sensor's service life.

3.2. Aerodynamic balance technique

Aerodynamic forces and moments acting on aircraft are the most important experimental dada for wind tunnel tests, and the aerodynamic balance is a necessary device for wind tunnel technique. The aerodynamic balance can be divided into two classes: the multi-component balance and the single-component balance. The six-component balance is widely used in wind tunnel tests and the single-component balance is accepted mainly for engine tests. Based on their working principles, the aerodynamic balance can be classified further into three types: the mechanical balance, the strain gauge balance and the piezoelectric balance. For the mechanical balance, the force is decomposed and transmitted through mechanical components on the balance, and then measured by mechanically measuring elements or load cells. The strain gauge balance is designed based on the strain acting on the elastic element, and strain gauge making up a Wheatstone-bridge is used to measure the aerodynamic force acting on the test model. For the piezoelectric balance, the aerodynamic force is measured with piezoelectric elements.[46] Usually, the mechanical balance was used in the low-speed wind tunnel tests and the strain balance was used for the high-speed wind tunnels. Since the 1970s, the strain gauge balance has been commonly used in low-speed wind tunnels due to the development of resistance strain gauges, automated measurement and control technology. The piezoelectric balance has also begun to be used for high-speed aircraft tests in some hypersonic wind tunnels since then.

For high-enthalpy flow experiments, the impulse-typed strain gauge balance is often used to cope with short test duration of shock tunnels because the aerodynamic balance must have fast response (high-frequency above 1000 Hz) to match with short test time. The stagnation pressure is very high in hypersonic and high-enthalpy flows, so that the balance must be able to withstand a large starting impulse load. In addition, the dynamic pressure variation of high-enthalpy shock tunnels is also very large and a wide measurement range is required for the balance. Compared with traditional strain gauge balances, the measured signals of the impulse-type strain gauge balance usually contain inertial force signals generated from vibrations of the test model and force measurement system, and test flow perturbations. Therefore, the inertia compensation and wave-filtering measures are needed in balance design.[47]

When the low natural vibration period of the force measurement system is close to the test duration of shock tunnels, the inertial force will affect seriously the balance output signal and the force measurement accuracy. The inertia compensation becomes one of the key issues that must be solved in the development of the impulse-type balance. In particular, the hypersonic wind tunnel test requires to use large-scale aircraft test models, and thus, the aerodynamic balance for high-enthalpy shock tunnel has always been a critical technology attracting much attention for decades.

There are some structure interferences whether the tail- or back-type model support is employed, and the interferences become particularly serious in testing the hypersonic aircraft/engine-integrated model. The model support can interfere not only with the flow field around the aircraft tail, but also with the engine nozzle operation. In addition, when testing aircraft at a high attack angle, the unsteady aerodynamic force acting on the test model will also cause low-frequency vibrations of the model support system, which will ruin the experimental data accuracy and can cause damage to balances. To solve the problems, a concept of the tension-supported balance was proposed. Being different from the conventional balance support, the test model is connected to a strain gauge balance which is suspended by several steel wires from the wind tunnel test section. Because the suspension support has low interferences with test flowfield, the model support effect on aerodynamic forces and moments becomes smaller than both the tail- and back-supports. To further reduce support interferences, a magnetic suspension support was developed and the test model is suspended with the magnetic constraint. Aerodynamic forces and moments are obtained by continuously measuring model acceleration and displacement.

The technique development of the aerodynamic balances indicates that to obtain the high-accuracy data of the forces and moments acting on test models, it is important not only to develop the new conceptual balance and improve the support structure from interferences, but also to consider the overall-designing strategy of whole measurement system including wind tunnels, test models, balances, and support for balance development.[48] In such a balance-integrated design concept, the balance design must be based on the following factors: the wind tunnel test duration, the starting process of nozzle flows, the natural frequencies of model support system, and the low frequency of each component of the balance.[49] In addition, the temperature effect on strain gauges and the flow-field perturbation at the model tail, arising from the support system, also have significant impacts on measurement data reliability and accuracy.

3.3. Optical diagnostic techniques

There are more parameters, defining high-enthalpy flows where gases are chemically reacting, than those that can be measured with the above mentioned techniques. These parameters include gas components, reacting rates and constants, heat transfer coefficient, diffusion property, relaxation time, etc., which are of significant importance for highlighting the chemical-physical phenomena in high-enthalpy flows. Optical diagnostic techniques possess special advantages to diagnose chemically reacting flows, such as the non-intrusive measurement, multi-parameter detection feature (temperature, components, concentration, velocity), high time resolution, overall review of flow structures and so on. Therefore, these techniques have received more and more attention during the recent decades. Spectacular progress has been made in the development of new, nonintrusive, optical methods for probing supersonic and hypersonic flows in ground-testing facilities.[50]

Schlieren, shadows and interference fringe optical systems are widely used to visualize shock structures, density variation, shear layer insatiability and vortex evaluation. These mature techniques have provided us with a large amount of flow field information to understand gas physics, but quantitative measurements are still in need. The absorption spectrum technique and the planar laser-induced fluorescence were developed successfully. The high-enthalpy flow with different total temperatures has different constitution with different spectral characteristics. The absorption spectrum for each gas component is closely related to its temperature and density, so the absorption spectrum technique can perform an identification of each gas species and their temperature. The application of the absorption spectroscopy to the high-enthalpy flow measurement is successful, but the three-dimensional integration effect results in some uncertainness on experimental data of complex flows. The Planar Laser Induced Fluorescence (PLIF) is a promising diagnostic method for three-dimensional high-enthalpy flows. Based on the measured gas species, the PLIF technique can excite electronic transitions among energy levels for a selected species in high-enthalpy flows by using a specially-modulated pulsed planar laser. After the planar laser disappears, the electronic transition of the selected species within the excited flow field jumps back to the original energy levels to produce fluorescence with different intensities, and the intensity distribution is related to the concentration distribution of the selected gas species. By using the enhanced photography technique, the fluorescence distribution can be obtained and contains both the quantitative and qualitative information of the selected species in flow field. The Pressure- and Temperature-Sensitive Paint (PSP and TSP) techniques also belong to optical diagnostic methods. With PSP and TSP techniques, the overall view of temperature and pressure distributions on test models can be obtained at the same time. This kind of the experimental information is useful not only for aerodynamic heating and forces analysis, but also for diagnosing boundary layer development and transition process.[51,52]

So far, we can see that the optical diagnostic technique plays more and more important role in hypersonic and high-enthalpy wind tunnel tests, but how to improve the accuracy of quantitative measurements is a critical issue in future. Moreover, the identification of three-dimensional chemically-reacting flows is a promising research topic. It could be concluded that, with advanced aerospace aircraft development, the optical diagnostic technique may initiate a revolutionary process on the critical technologies of ground-based hypersonic test facilities.

4. Concluding remarks and future challenges

With the development of hypersonic aerospace vehicles, the critical technologies of hypersonic and high-enthalpy flow have been continuously improved by aiming to duplicate hypersonic flight conditions for decades. However, there are still some limitations to meet engineering requirements that include the flight Mach number, freestream Reynolds number, flow velocity, static pressure at flight altitude, total enthalpy, density ratio cross shocks, test gas composition, air chemistry and reaction process, and these parameters affect experimental data accuracy and reliability in different ways. To promote hypersonic technology development, the following research topics should be paid more attention in the future.

4.1. Hypersonic and high-enthalpy wind tunnels

The development of hypersonic technology requires more advanced high-enthalpy test facilities to highlight high-temperature gas dynamic phenomena. These facilities should be capable of duplicating hypersonic flight conditions for various Mach numbers at different altitudes so that high-enthalpy flows can be reproduced correctly for reliable ground testing. To achieve this goal, the following parameters are of primary importance: (A) the flow velocity should be the same to the flight speed so that the prediction of aerodynamic forces and heat transfer rates could be more reliable; (B) the pure air is better to use as the test gas so that the chemistry can be correctly simulated to approach reasonable energy transitions; (C) the static pressure and temperature are important for the performance prediction of hypersonic propulsion systems since the chemical reaction processes can be guaranteed for a required hypersonic flow; (D) the large test flow field appears more and more important for high-enthalpy flow tests because there is not any properly scaling law for simulating chemically-reacting flows. Therefore, the large test model could minimize the model-scaled effect on experimental data.

In addition, the test duration is also a key performance parameter for hypersonic and high-enthalpy shock tunnels and usually measured in milliseconds. It takes time for the flow field around test models to reach a steady state and the short test time also imposes a challenge to measurement techniques. Generally speaking, the test duration is longer, and the experiment will be easier. However, the long test duration not only can increase significantly experimental cost, but also will cause severe damages to test facility structures due to the heavy heat load from hypersonic and high-temperature flows. Usually, it takes 5–30 ms for heat transfer measurements to obtain reliable experimental data and the long test duration may result in surface erosion of heat flux sensors. For aerodynamic forces and moments tests, it takes longer time than the heat transfer measurement. The test time needed can be determined according to test model sizes and balance stiffness. The requirement is that the test time should be three times longer than the period of the first-order modal vibration of the balance system. The inertial compensation technique is a nice method to obtain accurate experimental data from shock tunnel tests. Long test time is in need for scramjet engine tests since many physical processes have to complete to obtain stable combustion. The 100 ms test time could be long enough to investigate supersonic combustion phenomenon.[53] Another issue necessary to emphasize is that for development of the high-enthalpy wind tunnel technology, it should focus not only on high Mach number simulations, but also on hypervelocity flow duplication. Sometimes, the hypersonic flow is not equal to the hypervelocity flow at the same Mach number if the static temperature of the test flows is different. Therefore, there may be a discrepancy between hypersonic wind tunnels and hypervelocity wind tunnels since the hypersonic flow is measured with the local sound speed while the hypervelocity flow is in meters per second.

4.2. Measurement techniques for high-enthalpy flows

To complete hypersonic and high-enthalpy flow tests, the measurement techniques are required to have some special features: (A) the sensor should have an anti-erosion capability due to the high flow velocity; (B) the response of the measurement systems must be fast enough because of the short test duration of shock tunnels; (C) the disturbances on the local flow field where sensors are installed should be small because of the fact that shock-induced flow structures can change significantly thermal-dynamic states, Therefore, the non-intrusive measurement technique is promising; (D) the sensor should have a heat-resistant capability because of the severe harsh thermo-environment of high-enthalpy flows. Most of sensor damages could be taken to be induced by huge thermo-loads imposed on the sensor surface exposed to high-enthalpy flows. There is another critical issue that was not considered seriously before. This is the effect of the charged particles in the chemically reacting gases, which will interfere with sensor signals and result in uncertainness in experimental results. The interference is also varying with local flow states and there is still no feasible correction method. The measurement techniques of hypersonic and high-enthalpy flows are the challenging problems and belong to the critical technologies of hypersonic and high-enthalpy wind tunnels. From our experience, the miniaturized heat-flux sensor has a promising future because of its small exposed surface and spatial measurement accuracy. However, its heat- and erosion-resistant capabilities need to be further improved. The aerodynamic balance for large-scale test models in pulse hypersonic test facilities like shock tunnels is worth more attention since it is of great significance for improving test data accuracy and minimizing the model-scaled effect.

For chemically reacting flows, optical diagnostic techniques are quite promising, because these techniques do not interfere with the test flow field and also can diagnose more parameters than conventional measurement techniques. Schlieren, shadows and interference fringe optical systems are widely used for flow visualization. The absorption spectroscopy, the emission spectroscopy, and the planar laser induced fluorescence are also used to diagnose the chemically reacting flows and are of significant importance for investigating chemical-physical flow phenomena of hypersonic and high-enthalpy flows. The optical diagnostic techniques have been improved for high-enthalpy flows in various aspects, but improving their quantitative measurement capability and data accuracy is the future research direction.

4.3. Modeling high-enthalpy flows for computing

The development of the critical technologies of hypersonic and high-enthalpy wind tunnels is an extremely difficult topic, but a fundamental research realm. Its limitation is imposed not only by a large amount of manpower and cost, but also by material strength and structure regulation. However, as the rapidly increasing need for hypersonic aerospace vehicles, a large amount of wind tunnel test data is in urgent need for understanding hypersonic and high-enthalpy gas flows that are of non-linear, multi-physical and non-equilibrium characteristics. Facing such a huge challenge, it is absolutely necessary to develop different research methods for exploring the high-enthalpy flows, and the most important one is how to model the high-enthalpy flow for reliable numerical computations.

There are a lot of complaints about big discrepancies between fight tests and computational results. This indicates that the present models of high-enthalpy flows are lack of accuracy and reliability. There are four aspects being important for modeling high-enthalpy flows to build a computing platform that can meet the need from aerospace engineering projects. First, the chemical shock tube should be further developed to gain the detailed information on the chemically reacting gas kinetic properties. Such information is important for tuning simplified reaction models of high-enthalpy flows. It is also understood that the chemically reacting flow is dominated by the static flow temperature, but the local pressure also plays an important role in reaction processes. The chemical shock tube is a valuable facility available at present. Secondly, a series of experiments of typical hypersonic vehicle models under different flight conditions are necessary to carry out with hypersonic and high-enthalpy wind tunnels, so that the reliable validation and verification of physical models and computing techniques can be completed. Thirdly, it is necessary to develop special algorithms for solving the multi-species governing equations aimed at resolving chemical-reaction stiffness, hypersonic boundary-layer transition, reasonable discretization of complex boundaries, and computing dissipation and dispersion. In this way, the high-performance computing can work as numerical wind tunnels providing comprehensive data of high-enthalpy flows for the hypersonic vehicle development.

In addition, considering limitations on hypersonic and high-enthalpy wind tunnel techniques and computational methods, the ground-to-flight correlation of aerodynamic force and heat transfer experimental data from hypersonic and high-enthalpy wind tunnels appears to be a critical issue. Because of lack of similarity simulation criteria for experimental gas dynamics, some hypersonic flow phenomena cannot be accurately predicted. Therefore, the ground-to-flight correlation theory can bridge over the gap, make the best use of experimental data and support directly hypersonic technology development.

These comments are remarked from a point of view of gaseous dynamics and indicate an urgent need for technological innovation and theoretical discovery. The hypersonic technology is obviously different from the aviation and aerospace technologies that we have had for decades, and their upgrading may not be enough to support such a new generation of high technology.

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References

1. Tsien HS. Similarity laws of hypersonic flows. *J Math Phys* 1946;**25**:247–51.
2. Bertin JJ, Cummings RM. Fifty years of hypersonics: where we've been, where we're going. *Prog Aerosp Sci* 2003;**39**:511–36.
3. Lu FK, Marren DE. *Advanced hypersonic test facilities*. Reston: AIAA Inc.; 2002. p. 17–27.
4. Anderson JD. *Hypersonic and high temperature gas dynamics*. New York: McGraw-Hill Book Company; 1989.
5. Bertin JJ, Cummings RM. Critical hypersonic aerothermodynamic phenomena. *Annu Rev Fluid Mech* 2006;**38**:129–57.
6. Dufrene A, Maclean M, Parker R, et al. Characterization of the LENS expansion tunnel facility. Reston: AIAA; 2010. Report No.: AIAA-2010-1564.
7. Thomas SR, Trefny CJ, Pack WD. Operating capability and current status of the reactivated NASA Lewis Research Center Hypersonic Tunnel Facility. Reston: AIAA; 1995. Report No.: AIAA-1995-6146.
8. Dufrene A, Maclean M, Parker R, et al. Experimental characterization of the LENS expansion tunnel facility including blunt body surface heating. Reston: AIAA; 2011. Report No.: AIAA-2011-626.
9. Dumm MG, Moller JC, Steele RC. Development of a new high-enthalpy shock tunnel. Reston: AIAA; 1988. Report No.: AIAA-1988-2782.
10. Holden MS. Recent advances in hypersonic test facilities and experimental research. Reston: AIAA; 1993. Report No.: AIAA-1993-5005.
11. Holden MS, Wadhamst P, Candler GV. A review of experimental studies in the LENS shock tunnel and expansion tunnel to examine real-gas effects in hypervelocity flows. Reston: AIAA; 2004. Report No.: AIAA-2004-0916.
12. Holden MS, Chadwick KM, Kolly JM. Hypersonic studies in the LENS facilities. Reston: AIAA; 1995. Report No.: AIAA-1995-6040.
13. Stalker RJ. A study of the free-piston shock tunnel. *AIAA J* 1967;**5**(12):2160–5.
14. Stalker RJ, Morrson WRD. New generation of free piston shock tunnel facilities. Proceeding of 17th international symposium on shock tube and waves. 1989.

15. Jacobs PA. Quasi-one-dimensional modeling of free-piston shock tunnel. *AIAA J* 1994;**32**(1):137–45.
16. Gildfind DE, Jacobs PA, Morgan RG. Vibration isolation in a free-piston driven expansion tune facility. *Shock Waves* 2013;**23**:431–8.
17. Hornung HG. The piston motion in a free-piston driver for shock tubes and tunnels. 1988. Report No.: GALCIT FM88-1.
18. Hornung HG. Performance data of the new free-piston shock tunnel at GALCIT. Reston: AIAA; 1992. Report No.: AIAA-1992-3943.
19. Eitelberg G. First results of calibration and use of the HEG. Reston: AIAA; 1994. Report No.: AIAA-1994-2525.
20. Miyajima H. Design concept of the NAL/NASDA high-enthalpy shock tunnel. 4th international workshop on shock tube technologies.
21. Itoh K. Improvement of a free piston driver for a high-enthalpy shock tunnel. *Shock Waves* 1998;**8**(4):215–33.
22. Hornung HG, Cummings EB. Recent results from hypervelocity research in T5. Reston: AIAA; 1994. Report No.: AIAA-1994-2523.
23. Itoh K, Ueda S. Hypersonic aerothermodynamics and scramjet research using high-enthalpy shock tunnel. *Shock Waves* 2002;**12**:93–8.
24. Shen JM, Ma HD, Li C, et al. Initial testing of a 2m Mach-10 free-piston shock tunnel. 31st international symposium on shock waves. 2017.
25. Bird GA. A note on combustion driven tubes. Royal aircraft establishment. Paris: AGARD; 1957. Report No.: AGARD Report 146.
26. Coates PB, Gaydon AG. A simple shock tube with detonating driver gas. *Proc Roy Soc* 1965;**A283**:18–32.
27. Yu H, Zhao W. Performance of shock tunnel with H2- O2 detonation driver. Aerody Exp Meas Control 1993; 7(3):38-42 [Chinese].
28. Zhao W, Yu H. The double over-critical nozzles device for filing and mixing mixture gases. Acta Aerody Sinica 1999; 17(3):279-84 [Chinese].
29. Zhao W, Jiang ZL. Performance of a detonation driven shock tunnel. *Shock Waves* 2005;**14**:53–9.
30. Yu HR, Chen H, Zhao W. Advances in detonation driving techniques for a shock tube/tunnel. *Shock Waves* 2006;**15**(6):399–405.
31. Li JP, Feng H, Jiang ZL, et al. Numerical computation on the tailored shock Mach numbers for a hydro-gen/oxygen detonation shock tube. Acta Aerodyna Sinica 2008; 26:291-6 [Chinese].
32. Jiang ZL. Experiments and development of Long-test-duration Hypervelocity Detonation-driven shock tunnel (LHDst). Reston: AIAA; 2014. Report No.: AIAA-2014-1012.
33. Yu HR, Esser B, Lenartz M, et al. Gaseous detonation driver for a shock tunnel. *Shock Waves* 1992;**2**:245–54.
34. Habermann M, Olivier H, Grong H. Operation of a high performance detonation driver in upstream propagation mode for a hypersonic shock tunnel. In: Bal, Hilier and Roberts, editors. Proceedings of the 22nd international symposium on shock waves. 1999.
35. Erdos JI. Calleja J, Tamagno J. Increases in the hypervelocity test envelope of the HYPULSE shock-expansion tube. Reston: AIAA; 1994. Report No.: AIAA-1994-2524.
36. Bakos RJ, Erdos JI. Options for enhancement of the performance of shock-expansion tubes and tunnels. Reston: AIAA; 1995. Report No.: AIAA-1995-0799.
37. Jiang ZL, Yu HR, Takayama K. Investigation into converging gaseous detonation drivers. In: Bal, Hilier and Roberts, editors. Proceedings of the 22nd international symposium on shock waves. 1999.
38. Jiang ZL, Zhao W, Wang C. Forward-running detonation drivers for high-enthalpy shock tunnels. *AIAA J* 2002;**40**:2009–16.
39. Jiang ZL, Lin J, Zhao W. Performance tests of JF-10 high-enthalpy shock tunnel with a FDC driver. *Int J Hyper* 2011;**2**:29–35.
40. Jiang Z, Yu H. Theories and technologies for duplicating hypersonic flight conditions for ground testing. *Nat Sci Rev* 2017;**4**(3):290–6.
41. Jiang Z, Li J, Zhao W, et al. Investigation into techniques for extending the test-duration of detonation-driven shock tunnels. Chi J Theo App Mech 2012; 44(5):824-31 [Chinese].
42. Wang Q, Luo K, Li JW, et al. Investigation of dual ignition for a detonation-driven shock tunnel in forward driving mode. *Chin J Aeronaut* 2020;**33**:1468–75. https://doi.org/10.1016/j.cja.2020.01.013.
43. Schultz DL, Jones TV. Heat-transfer measurements in short-duration hypersonic facilities. Paris: AGARD; 1973. Report No.: AGARD AG-163.
44. Yu H, Li ZF, Li J, et al. Plug copper foil calorimeter for heat transfer measurement in shock tube wind tunnel. Ad Mech 1976; 6 (4):117-26 [Chinese].
45. Buttsworth DR. Assessment of effective thermal product of surface junction thermocouples on millisecond and microsecond time scales. *Exp Therm Fluid Sci* 2001;**25**:409–20.
46. He DX. *Wind tunnel balance*. Beijing: National Defense Industry Press; 2001.
47. Bernstein L. Force measurement in short-duration hypersonic facilities. Paris: AGARD; 1975. Report No.: AGARD AG-214.
48. Wang YP, Jiang ZL. Design of a pulse-type strain gauge balance for a long-test-duration hypersonic shock tunnel. *Shock Waves* 2016;**26**(6):835–44.
49. Liu YF, Wang YP, Yuan CK, et al. Aerodynamic force and moment measurement of 10° half-angel cone in JF12 shock tunnel. *Chin J Aeronaut* 2017;**30**(3):983–7.
50. Bonnet JP, Gresilon D, Taran JP. Nonintrusive measurements for high-speed, supersonic, and hypersonic flows. *Annu Rev Fluid Mech* 1998;**30**:231–73.
51. Li RY, Gao LM, Zheng TL, et al. Experimental investigation on static/dynamic characteristics of a fast-response pressure sensitive paint. *Chin J Aeronaut* 2018;**31**(6):1198–205.
52. Niu HB, Yi SH, Liu XL, et al. Experimental investigation of boundary layer transition over a delta wing at Mach number 6. *Chin J Aeronaut* 2020;**33**:1889–902. https://doi.org/10.1016/j.cja.2020.02.017.
53. Tsien HS. My knowledge on modern mechanics. Mech Eng 1995; 17(4):1 [Chinese].