Performance Tests of JF-10 High-Enthalpy Shock Tunnel with a FDC Driver

Z. Jiang, J. Lin and W. Zhao
State Key Laboratory of High Temperature Gasdynamics
Institute of Mechanics, Chinese Academy of Sciences, Beijing, 100190, China

Abstract
JF-10 detonation-driven high-enthalpy shock tunnel was re-built with a forward detonation cavity (FDC) driver and the experimental data from its performance tests are summarized and reported in this paper. Test-duration of high-enthalpy flows produced with the improved JF10 is found to be extended by two times under the condition that the FDC driver is about 40% shorter than the original one. The uniform pressure area of the thus-obtained hypersonic flows in a 500 mm diameter conical nozzle is about 700 mm in length and 400 mm in diameter. Incident shock wave decay in the driven section appears to be much less by comparing with the original JF-10 shock tunnel. The performance improvement of JF-10 high-enthalpy shock tunnel was demonstrated to be very successful and high quality hypervelocity flows can be generated for aero-thermochemistry experiments.

1. INTRODUCTION

Hypersonics represents the fullest integration of both fundamentals in sciences and applications in engineering into "aerospace" systems being full of challenges [1, 2]. In order to develop hypersonic vehicles, it is important to develop hypervelocity test facilities for ground experimental researches. After more than 60 years development, high-enthalpy facilities suitable for studying aero-thermochemistry are still based on shock tunnels [3]. Three kinds of high enthalpy tunnels have been developed over the world for several decades. The first one is the heated-light-gas driven shock tunnels [4–6], the second one is the free-piston driven high-enthalpy shock tunnels [7–11], and another one is the detonation-driven high-enthalpy shock tunnels [12–14]. These hypersonic test facilities have been built over the world and valuable experimental data have been provided with the facilities for hypersonic study for years.

The heated-light-gas driven hypersonic shock tunnels [4] were developed from conventional shock tube techniques by using heated light-gas driver for tailoring interface conditions, but the problems arising from handling light gases prevents extensive use of the heated-light-gas driver. The free-piston driver was proposed first by Stalker in 1967 [7] and developed later into useful high-enthalpy test facilities [8,9]. The biggest one was built up by Itoh et al. in Kakuda, Japan in 1998 [10], and applied to both aero-thermodynamic experiments and scramjet research. For this kind of the facilities, short test duration and unstable piston motion are difficult problems to overcome. The detonation driver was first proposed by Bird in 1957 [12], and a 13.3 m long detonation driver was built later by Yu *et al*. [13, 14]. Gronig *et al*. developed TH2 in Aachen, Germany and the tunnel is operated in the backward-running detonation mode [15]. And later in 1994, the bigger one was setup in GASL, USA, and could be also operated as an expansion tube [14]. These detonation-driven shock tunnels can be operated either in the backward-running detonation mode to achieve stable test flows with long driving time at a relatively low enthalpy level, or in the forward-running detonation mode to obtain high-enthalpy flow, but with a short test duration [16, 17].

To improve performances of detonation-driven shock tunnels operated in the forward-running detonation mode to obtain high-enthalpy flows with longer test duration, a forward detonation cavity driver (short for, FDC driver) was proposed by Jiang et al.[18] based on shock reflection concept. Detonation reflection in the cavity of the FDC driver results in a strong upstream-traveling shock wave and a weak downstream-traveling one. The upstream-traveling shock wave elevated significantly the flow pressure behind detonation fronts, which decreased due to Taylor rarefaction waves. The downstream-traveling shock wave can catch up with detonation fronts, but an overdriven detonation is avoided because the shock wave is weaker. The concept of the FDC driver was successfully demonstrated both numerically and experimentally, and indicated a very promising way to improve detonation-driven hypersonic test facilities.

In order to achieve high quality test flows, JF-10 detonation-driven high enthalpy shock tunnel in Institute of Mechanics, CAS, was improved with a new FDC driver in 2003. Performance tests of the improved JF-10 shock tunnel were completed in 2006. Some experimental results from JF-10 performance tests are reported in this paper, including the improvement work on JF-10 shock tunnel, P_5 pressure variations, experimental data on nozzle flow uniformity, the incident shock decay in the driven section. These experimental data demonstrated that the improvement work on JF-10 shock tunnel is very successful and the future research work will benefit from the thus-obtained high quality hypersonic test flows.

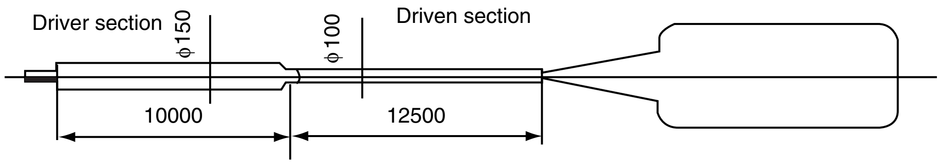
2. JF-10 HIGH-ENTHALPY SHOCK TUNNELS

The improved and the original JF-10 detonation-driven high-enthalpy shock tunnels are schematically shown in Fig. 1. The improved JF-10 shock tunnel, as shown in Fig. 1b, consists of three main parts. The first part is a FDC driver being about 6.225 m in length and 150 mm in diameter, the second one is a driven section being 12.5 m in length and 100 mm in diameter, and the last is a conical nozzle having a 500 mm diameter exit. For the original JF-10 shock tunnel, its driver section is 10 m in length, and is about 4 m longer than the FDC driver. Other parts are the same with the improved JF-10 shock tunnel. The cavity of the FDC drive is 300 mm in diameter and 2 m in length. The detailed research work on the FDC driver was reported by Jiang *et al* in 2002 [18]. For high-enthalpy shock tunnels, the shorter driver section is very effective in reduction of experimental costs and nozzle throat ablation.

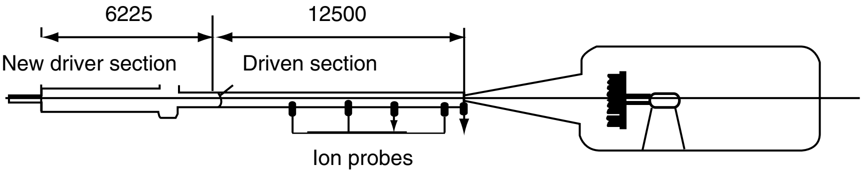
3. PRESSURE VARIATIONS AT THE END OF DRIVEN SECTION

For shock tunnels, P_5 pressure variation at the end of the driven section is a key parameter that indicates the test flow quality and stands for one of the most important performance parameters of shock tunnels. To obtain P_5, the experiment was carried out in the condition of P_{4i} = 3.0 MPa and P_1 = 11 KPa in the FDC driver. The incident shock Mach number is found to be 11.8 and P_5 pressure variation is plotted in Fig. 2.

Figure 2 shows the pressure variation measured at the end of the driven section. This pressure profile acts as a measure of the reservoir pressure during nozzle working duration. The more stable the reservoir pressure is, the more uniform the nozzle flows. From this figure, it is observable that the pressure level maintains approximately constant for more than 6 ms. By comparing it with the 2 ms test time achieved with HEIST, this pressure variation is very promising and demonstrated well the performance of the improved JF-10 shock tunnel.



(a) Original JF10 shock tunnel



(b) Improved JF10 shock tunnel

Figure 1. Schematic of the improved and the original JF-10 high-enthalpy shock tunnels.

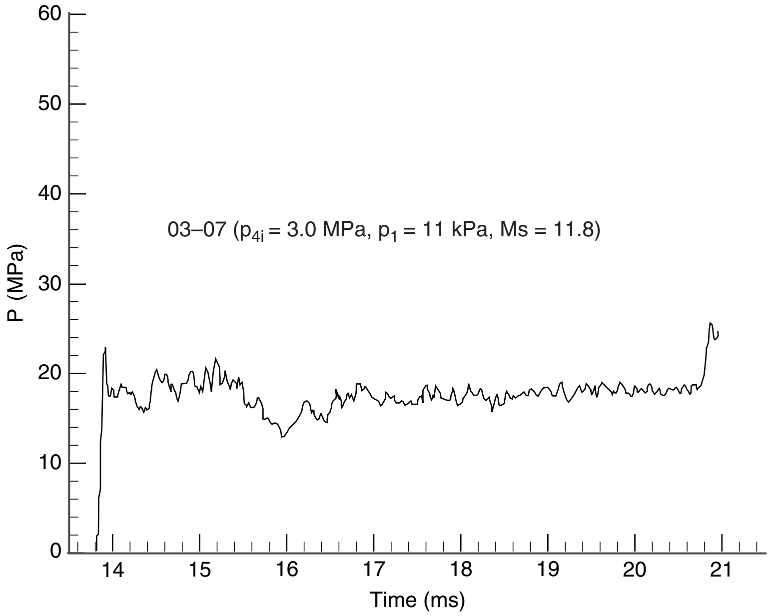


Figure 2. Pressure variations measured at the end of the driven section in the improved JF-10 shock tunnel.

Figure 3 show Pitot pressure variations measured in nozzle flows at the same experiment. The pressure profile looks similar to the reservoir pressure variation as shown in Fig. 2. Agreement between these two pressure profiles indicates not only experimental certification, but also effective test time possibly available from the improved JF-10 shock tunnel. This time duration is not only long enough both for flow pressure and heat transfer measurements, but also for aerodynamic force tests with available measurement instrumentations. So far as it is well known, force balance techniques are very

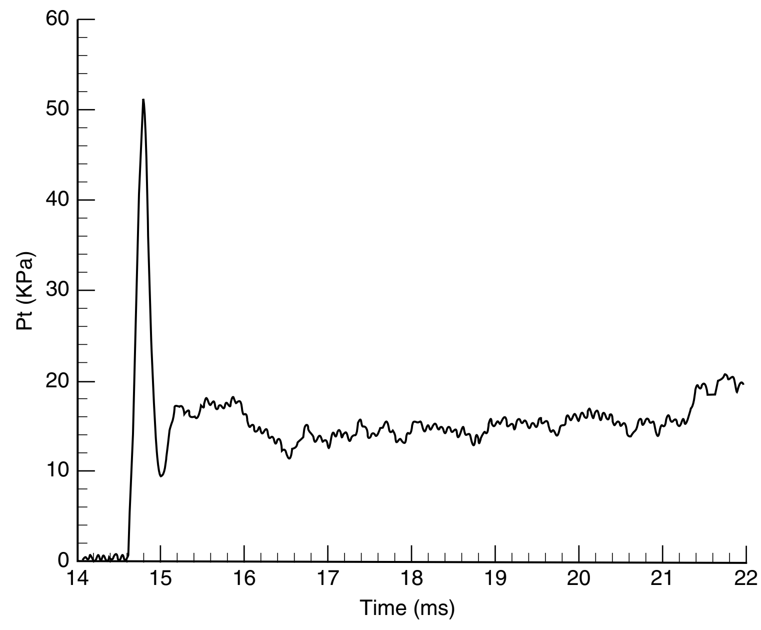


Figure 3. Pitot pressure variations measured in the nozzle flow.

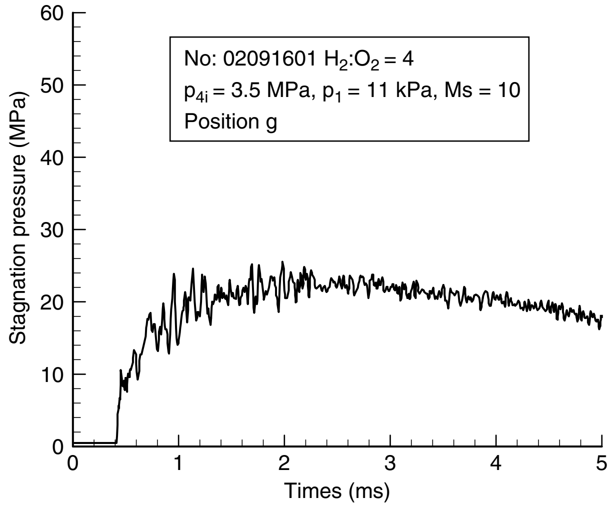


Figure 4. Pressure variations measured at the end of driven section in the original JF-10 shock tunnel.

difficult for shock tunnel tests because of short test duration. Aerodynamic force measurement will be more reliable if more than 3 ms test duration could be provided with shock tunnels. Therefore, 6 ms test duration is useful for high-enthalpy flow experiments.

Such the performance test was also carried out with the original JF-10 shock tunnel before and P_5 pressure variations measured at the end of driven section was presented in Fig. 4. From the figure, it is observable that the test duration is about 3 ms before the pressure level decreases significantly. Considering that 6 ms test duration was achieved in the improved JF-10 shock tunnel with the shorter FDC driver, one could understand the meaning of the progress achieved in detonation driven high-enthalpy shock tunnel techniques by using the FDC driver.

4. UNIFORMITY TEST OF NOZZLE FLOWS

To find out nozzle flow uniformity, five measurement positions in JF-10 nozzle flows are determined along the nozzle centerline and the standard position locates at the nozzle exit. These positions are denoted with (a) Z = −50 mm; (b) Z = 100 mm; (c) Z = 265 mm; (d) Z = 400 mm and (e) Z = 600 mm, respectively. Experimental setup of Pitot pressure measurements is shown in Fig. 5. Measurements were carried out at each measurement position both in the vertical and the horizontal directions. The measurement data was plotted together to demonstrate the nozzle flow uniformity.

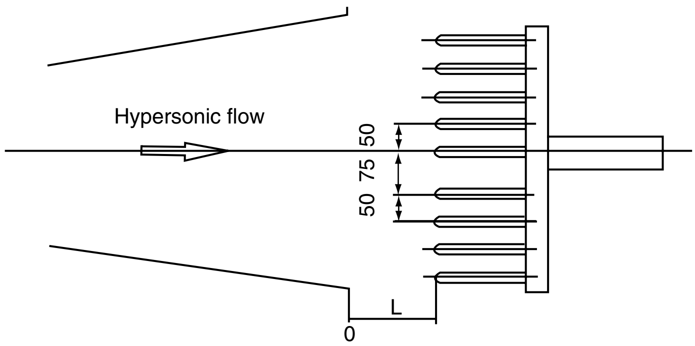


Figure 5. Experimental setup of Pitot pressure measurement in the improved JF-10 nozzle flow.

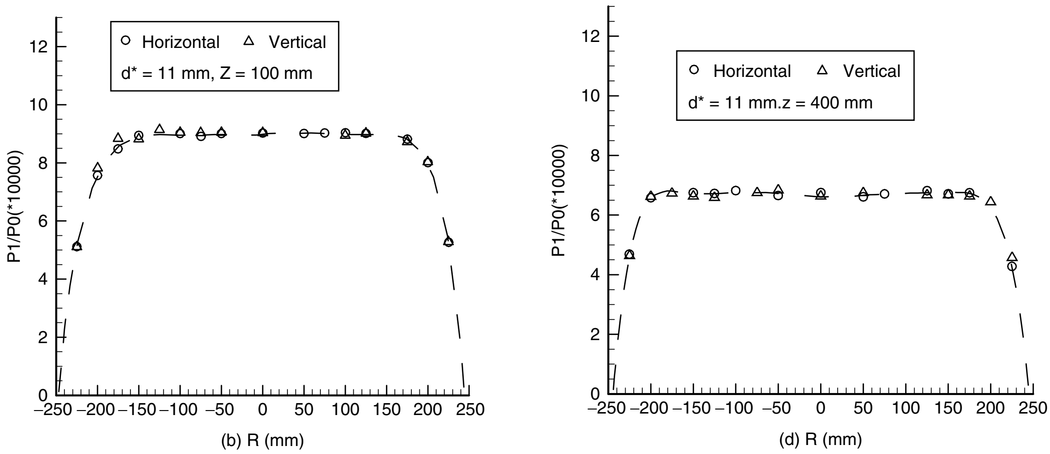


Figure 6. Pitot pressure distributions in nozzle flows at two measurement positions in two directions.

Figure 6 shows Pitot pressure distributions in nozzle flows at both positions (b) and (d). It is observable that hypersonic flows in the nozzle central area appear quite uniform if evaluated from a view point of Pitot pressure distribution. This uniform flow area is found to be approximate 700 mm in length and 400 mm in diameter. Although the Piot pressure uniformity does not fully confirm hypersonic flow uniformity, but these results are quite promising and very encouraging for showing nozzle flow quality. We are now working more actively to figure out the test flow quality from the aero-thermodynamic viewpoint.

5. INCIDENT SHOCK WAVE DECAY

Incident shock decay in driven sections is a very important parameter for hypersonic test facilities and the test flow quality is affected significantly. For this investigation, three test cases were selected for comparison and the relevant test conditions are listed in Table 1. Cases A and B were carried out, respectively in the improved JF-10 shock tunnel, and Case C was done in the original one. Experimental data from Cases A and B are used to examine the incident shock decay at different initial conditions in detonation drivers, and Case C is used for the comparison between two different detonation drivers. The total flow enthalpy is kept to be the almost same for three cases.

The incident shock speed is measured with several ion probes distributed along driven section with equal intervals. The result of qualified tests for these ion probes is given in Fig. 7. The sign jumps occur sharply and indicate the arrival of shock waves. Therefore, the incident shock speed could be calculated with high accuracy.

Figure 8 shows incident shock decay rates along the driven section and the decay rates are determined by calculating Mach number drop per tube diameter, that is, the diameter of the driven section. By examining case A and C, it could be seen that the stronger incident shock wave could be driven out with the FDC driver and Mach number could be 10% higher at the similar operation condition. The incident shock decay in the improved JF-10 shock tunnel is 30% less than that in the original one, and actually the decay rate is 3.04% in case A and 3.94% in case C. The experimental

Table 1. Test conditions for investigating the incident shock decay in the driven section

Test Conditions	P_{4i} (Mpa)	P_1 (Kpa)	P_{50} (Mpa)	T_{50} (K)
A	1.5	4.5	8.0	7480
B	3.0	11	19.4	7920
C	1.5	4.7	8.3	7200

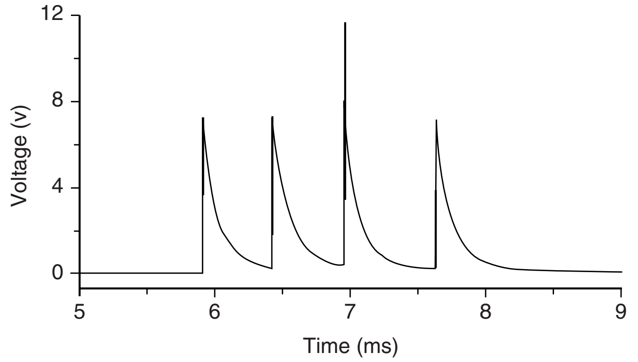


Figure 7. Ion probe signs for incident shock speed measurement.

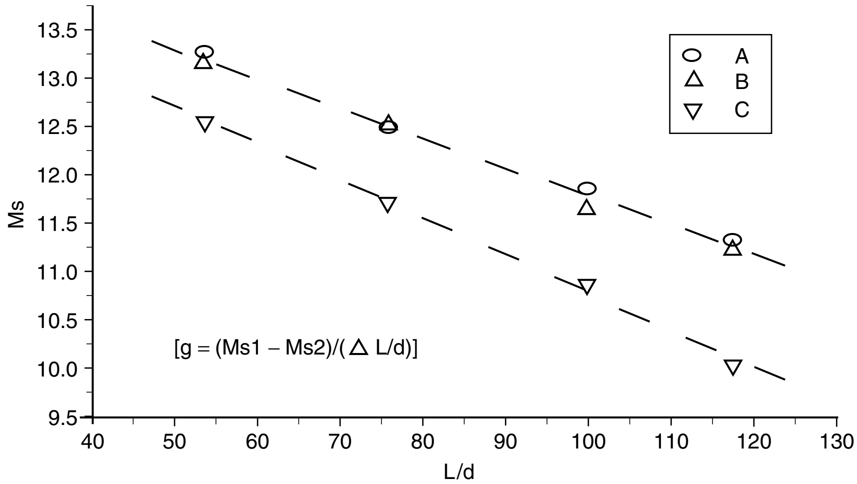


Figure 8. Incident shock wave decay for three test cases.

data of cases A and B are almost the same and this indicates that the initial pressure ratio in the driver and driven section has no significant effects on incident shock decay if the total flow enthalpy is the same. The shock wave decay is weaker in Case A than one in Case C and this indicates that the FDC driver is of better performance.

6. CONCLUSIONS

From experimental results and the above discussions, research progresses on detonation-driven high-enthalpy shock tunnels are summarized as follows:

The improvement on JF-10 high-enthalpy shock tunnel with a new FDC driver was demonstrated to be very successful and the stronger incident shock could be generated with a lower decay rate at the similar initial conditions by comparing with the original JF-10 shock tunnel. The test duration of the improved JF-10 shock tunnel was extended by two times even the new FDC driver is 40% shorter than the original forward-running detonation driver. The 6 ms test duration makes aerodynamic force measurements become easier. The uniform core flow of the nozzle region is about 700 mm in length and 400 mm in diameter.

REFERENCES

[1] John J. Bertin, Russell M. Cummings: Fifty years of hypersonics: where we've been, where we're going. Department of Aeronautics, Progress in Aerospace Sciences 39 (2003) 511–53.

[2] Bertin JJ and Cummings RM: Critical hypersonic aerothermodynamic phenomena. Annu. Rev. Fluid Mech. 2006. 38:129–157.

[3] Herbert Olivier, Zonglin Jiang, Hongyu Ru and Frank K. Lu: Detonation-driven shock tubes and tunnels, Advanced Hypersonic Test Facilities, published by AIAA, 135–203.

[4] Holden MS: Design, development and calibration of the LENS facility, AFOSR-TR. 1994, 94–0161.

[5] Holden MS, Wadhams TP, Candler GV: A review of experimental studies in the LENS shock tunnel and expansion tunnel to examine real-gas effects in hypervelocity flows, AIAA Paper 2004–0916, 42th AIAA Aerospace Sciences Meeting & Exhibit Reno, NV: January 5–8, 2004.

[6] Holden MS, Chadwick KM, Kolly JM: Hypersonic studies in the LENS facilities, AIAA 95-6040, 6th International Aerospace Planes and Hypersonic Technologies Conferences, Chattanooga, Tennessee, April 3–7, 1995.

[7] Stalker RJ: A study of the free-piston shock tunnel, AIAA J 5: 2160–2165, 1967.

[8] Stalker RT and Morrson WRD.: New generation of free piston shock tunnel facilities, Proceeding of 17th International Symposium on Shock Tube and Waves, Bethem, 1989.

[9] Hornung HG: The piston motion in a free-piston driver for shock tubes and tunnels. GALCIT Rep. FM88-1, 1988.

[10] Itoh K, Ueda S et al.: Improvement of a free piston driver for a high-enthalpy shock tunnel, Shock Waves (1998) 8: 215–233

[11] Itoh K, Ueda S, Tanno H, Komuro T, Sato K: Hypersonic aerothermodynamic and scramjet research using high enthalpy shock tunnel, Shock Waves (2002) 12: 93–98.

[12] Bird GA: A note on combustion driven tubes, Royal Aircraft Establishment, AGARD Rep. P. 146 , May 1957.

[13] Yu HR, Esser B, Lenartz M, Gronig H: Gaseous detonation driver for a shock tunnel, Shock Waves, 1992, Vol. 2, 245–254.

[14] Zhao W, Jiang ZL, Saito T., Lin JM, Yu HR and Takayama K: Performance of a detonation driven shock tunnel, Shock waves, (2005) Volume 14, Numbers 1–2, 53 – 59.

[15] Habermann M, Olivier H and Grong H: Operation of a high performance detonation driver in upstream propagation mode for a hypersonic shock tunnel, Proceedings of the 22nd International Symposium on Shock Waves, Vol. 1, 1999, pp. 447–452.

[16] Bakos RJ, Erdos JI: Options for enhancement of the performance of shock-expansion tubes and tunnels. AIAA 95-0799, 1995.

[17] G.J. Wilson, M.A. Sussman, D.W. Bogdanoff: A study of combustion and detonation drivers for high enthalpy expansion tubes and shock tubes, NASA CDTP-20000. 1995.

[18] Zonglin .Jiang, Wei Zhao, C.Wang: Forward-running detonation drivers for high-enthalpy shock tunnels, AIAA Journal, 40(10), 2002.