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Design and characterization of a 6-in high-enthalpy impulse test facility

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Abstract

A 6-inch high-enthalpy impulse test facility is constructed at Korea University. Impulse facilities, including an expansion tube, are capable of reproducing a wide range of high-enthalpy gas flows. While impulse facilities are renowned for their mechanical simplicity and cost-effectiveness, they have shorter test times. The primary objective of the expansion tube is to delve into the combustion characteristics of the scramjet combustor. In order to maximize test time, each section's dimensions were meticulously optimized based on analytical solution. Subsequently, numerical simulations were carried out to verify the calculated test durations and conditions and assess the expansion tube's performance. The facility was then constructed in accordance with the design specifications.

Keywords: *Test facility, Shock Tube, Supersonic Flow, Shock Wave*

Nomenclature

1 – Initial state of driven section
2 – State 1 being compressed by shock wave
3 – State 4 being expanded by expansion wave
4 – Initial state of driver section
5 – Initial state of expansion section
6 – State 5 being compressed by shock wave
7 – State 2 being expanded by expansion wave

1. Introduction

Creating hypervelocity flight conditions demands a substantial energy investment, and impulse facilities offer economic benefits when compared to continuous test facilities like supersonic wind tunnels. The genesis of impulse facilities can be traced back to the concept of a shock tube. Following Vieille's initial proposal of the shock tube in 1899 [1], the pursuit of harnessing the shock tube's potential led to the development of various updated iterations of impulse facilities, including the reflected shock tunnel and expansion tube.

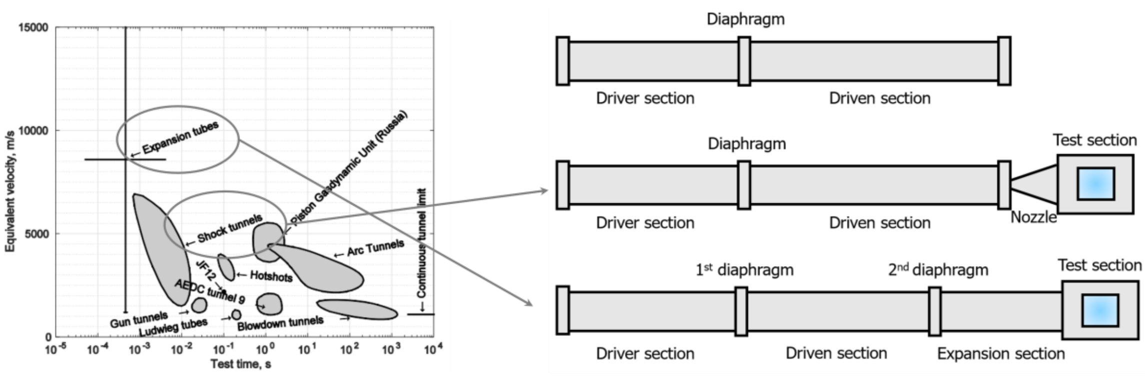

Fig 1. Ground test facilities categories

Unlike many other impulse facilities, such as the shock tunnel, which necessitate nozzle replacements to adapt to different test conditions, an expansion tube offers a distinct advantage. In a shock tunnel,

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the nozzle often experiences issues like chemical and vibrational freezing. In contrast, the expansion tube allows for a broad spectrum of test flows with reduced chemical dissociation and ionization by simply adjusting the initial fill pressure [2]. Nonetheless, it's worth noting that expansion tube tends to yield shorter test durations as shown in Fig.1 and exhibit more prominent boundary layer effects. Moreover, it requires additional considerations regarding secondary diaphragms, which may result in the occurrence of substantial test flow disturbances [3].

2. Gas dynamic processes in the expansion tube

The operation of an expansion tube begins by the pressurization of the driver section until the diaphragm bursts. This leads to the creation of compression waves moving towards the driven section and expansion waves traveling in the direction of the driver section due to a significant pressure differential across the diaphragm, as noted in [4]. As these waves progress, the expansion waves gradually spread out, forming a continuous expansion region, while the compression waves are compacted into a distinct shock wave. The utilization of a secondary diaphragm further expands the flow that was initially compressed by the first incident shock, resulting in the generation of a high-Mach number test flow. The entire process is depicted in Fig.1, which is a space-time diagram illustrating the wave phenomena occurring during the operation of an expansion tube

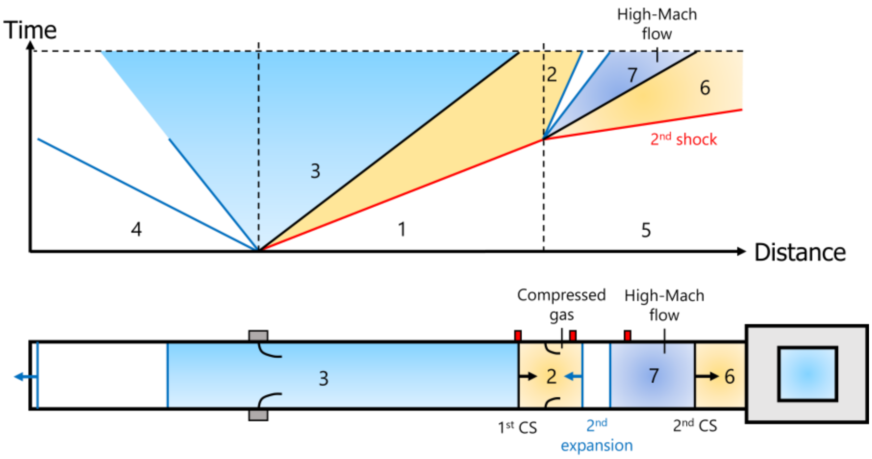

Fig 2. Space-time diagram of an expansion tube

3. Facility characterization

Assuming a perfect gas with inviscid and one-dimensional flow, it is possible to derive the analytical solution for every states as well as the propagation speeds of shock discontinuities, contact discontinuities, and rarefaction waves for a specified initial condition [4].

3.1. Target flow conditions

The target conditions are selected so that the test flow match the entry conditions of scramjet combustor, as summarized in Table 1.

Table 1. Selected target flow conditions

Target	Mach number	Temperature	Pressure
1	3.0	1400 K	25 kPa
2	2.2	650 K	95 kPa

3.2. Fill pressure of each section

Given specific initial conditions (state 4, 1, and 5), it is possible to calculate the test flow condition (state 7) using analytical solutions. Conversely, when aiming for a particular test flow (state 7), one can compute the initial conditions (state 4, 1, and 5). By employing Helium for both the driver section and expansion section fill gas, and air for the driven section fill gas, and assuming an initial temperature equal to room temperature, the required fill pressures for each target condition are shown in Fig.3.

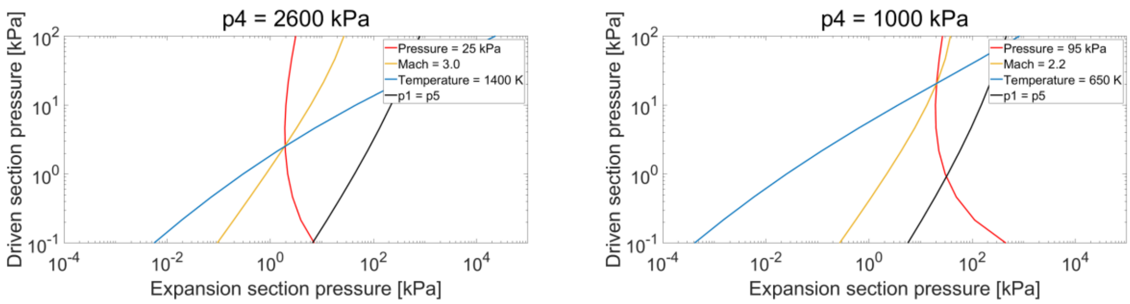

Fig 3. Fill pressures for each target flow condition

3.3. Length of each section

The test duration of an expansion tube can be determined using analytical solutions. In cases where the driver section is sufficiently extended, the termination of the test time due to the reflected wave from the driver section can be disregarded. Consequently, the end of test time in an expansion tube is determined either by the arrival of the second expansion head or the second expansion tail. The longest achievable test time occurs when both second expansion head and expansion tail arrive simultaneously.

There is a direct positive relationship between the maximum achievable test duration and the total length of the expansion tube. If the total length is fixed, and the influence of the reflected wave from the driver section is excluded, the test duration of the expansion tube hinges solely on the placement of the second diaphragm. Consequently, selecting the second diaphragm's position is critical to optimizing the expansion tube for the longest possible test duration. The ideal position for the second diaphragm, where the maximum test duration can be achieved, is computed for each target condition, as shown in Fig.4, and the midpoint between these two positions is chosen as the final location.

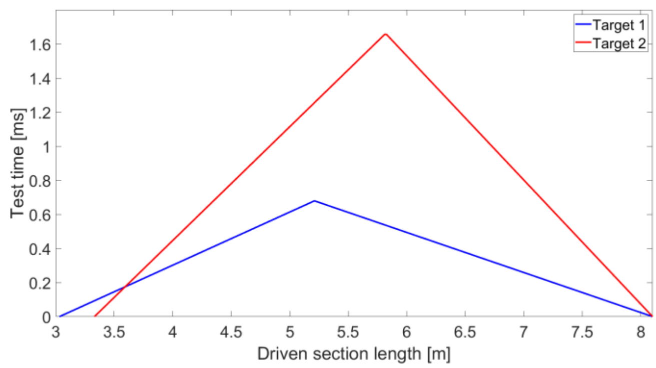

Fig 4. Length of driven section for total length of 8.1 m

4. Numerical simulations

To assess the deviation of test flow properties and test duration from the ideal solution, numerical simulations are conducted. RANS Standard k-epsilon model is used for the turbulence model and the computational domain is discretized by 15,909,621 cells. The generated mesh is shown in Fig.5.

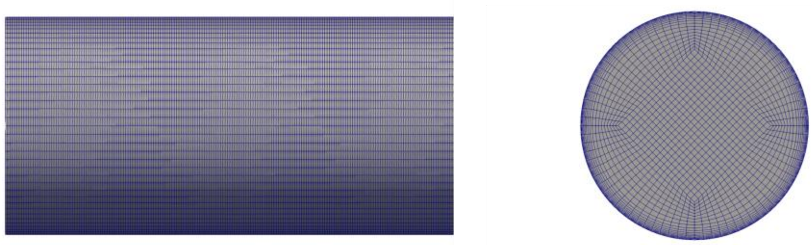

Fig 5. Discretization of the computational domain

While the simulation results indicated a minor elevation in pressure, temperature, and Mach number, these increments are not substantial. However, due to the shock wave attenuation caused by viscous effects and the resulting acceleration of the contact surface, the test duration significantly deviates from the ideal solution as shown in Fig.6.

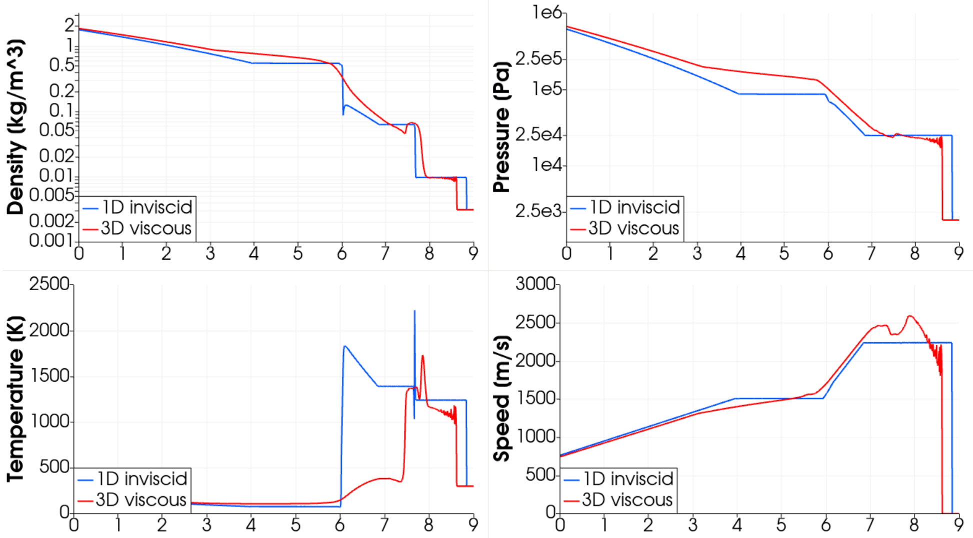

Fig 6. Density, pressure, temperature, and speed vs axial distance of the expansion tube

5. Facility construction

The facility is composed of a 11 m long stainless steel pipe, comprised of a driver, buffer, driven, and expansion section. Image of the fully assembled facility is presented in Fig.7. The whole tube is supported by rollers, enabling convenient shifting of the pipe for diaphragm replacement and interchange of subsections.

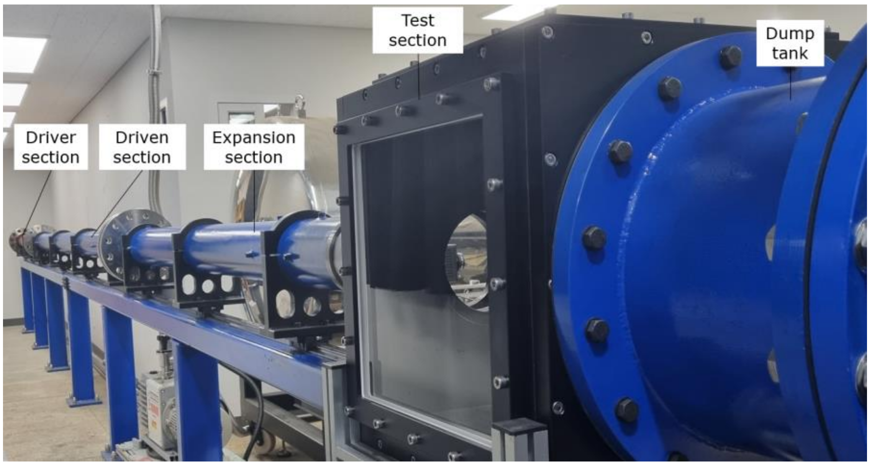

Fig 7. View of the facility looking upstream from the dump tank

References

1. Hertzberg, A.: Shock Tubes: Proceedings of the Seventh International Shock Tube Symposium held at University of Toronto, Toronto, Canada 23-25 June 1969. Paul Vieille Lecture: Shock Tube Research, Past, Present and Future: A Critical Survey. G. Irving Israel, University of Toronto Press: 3-5.

2. Miller, C. G., III and J. L. Shinn: Experimental perfect-gas study of expansion-tube flow characteristics. United States, NASA Center for Aerospace Information. (1978)

3. Paull, A. and R. Stalker: Theoretical and experimental test times available in an expansion tube. 10th Australasian Fluid Mechanics Conference, Volume 2. (1989)

4. Liepmann, H. W. and A. Roshko: Elements of gasdynamics. Courier Corporation. (2001)