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Development and Performance Validation of Konkuk University Ludwieg Tube(KULT)

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Abstract

Ground-based test facilities are widely used to study different aspects of hypersonic flows. Ludwieg tube can produce hypersonic flow with high Reynolds number and the run time is longer than that of a shock tunnel. Konkuk University has developed a Ludwieg tube with a fast acting valve, named as Konkuk University Ludwieg Tube(KULT). To verify the performance of KULT, shock wave angle and pressure measurement were performed. The performance of KULT validated through the comparison between the experimental results and the theoretical calculation values.

Keywords : *Ludwieg tube, Wind tunnel, Hypersonic, Real gas effects*

1. Introduction

Hypersonic flow is an extremely complex regime where numerous aerothermodynamic phenomena arise: shock waves, separation bubbles, recombining shock waves and high-temperature effects that acting on the surface of a vehicle when a vehicle flies at hypersonic velocity. The investigation of the flow field for a vehicle cruising at hypersonic velocity is essential to development of any hypersonic vehicles including thermal protection system(TPS).

Computational fluid dynamics(CFD), ground testing, and flight testing are mutually complementary each other and are mainly used for hypersonics research development testing and evaluation(RDT&E). Ground testing is used for the early stage of hypersonic vehicle development mainly to predict the aerothermodynamic phenomena, e.g., force and moment, distribution of pressure and heat, etc. Various ground test facilities are used on ground testing because there is no single facility capable of duplicating the hypersonic environment [1]. There are five types of facilities that duplicating the hypersonic flow: conventional wind tunnel, shock-heated wind tunnel, shock tube, arc-heated test facility, ballistic ranges [2]. These facilities have disadvantages such as flow quality, short run times, expensive operating costs, etc.

In 1955, Hubert Ludwieg developed a new type of facility to improve the disadvantage of shock tunnels [3]. Among various hypersonic flow ground testing facilities, a Ludwieg tube shows its strength in test time duration, which is orders of magnitude longer than a typical shock tunnel. This later became named as the Ludwieg tube wind tunnel. The Ludwieg tube wind tunnel is largely composed of five parts: a storage tube, a fast-acting valve or diaphragm, a nozzle, a test section, and a vacuum tank. The type of Ludwieg tube with fast acting valve can be operated with lower operating costs than Ludwieg tube with diaphragms.

Based on the above advantages, a team of Konkuk university developed a Ludwieg tube with a fast acting valve, named it as Konkuk University Ludwieg Tube(KULT).

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2. Operating principle of Ludwieg tube

Fig. 1 outlines the operating principle of the Ludwieg tube with x-t diagram. When the piston of the fast acting valve opens the nozzle throat, the test gas in the storage tube is accelerated through the nozzle and becomes a steady flow in test section during the run time. The run time is determined by the length of the storage tube and the speed of the expansion wave. The expansion wave propagates toward upstream direction from fast acting valve and is reflected at the end of the tube which then propagates back again to fast acting valve. The run time is basically time of expansion wave from and to fast acting valve.

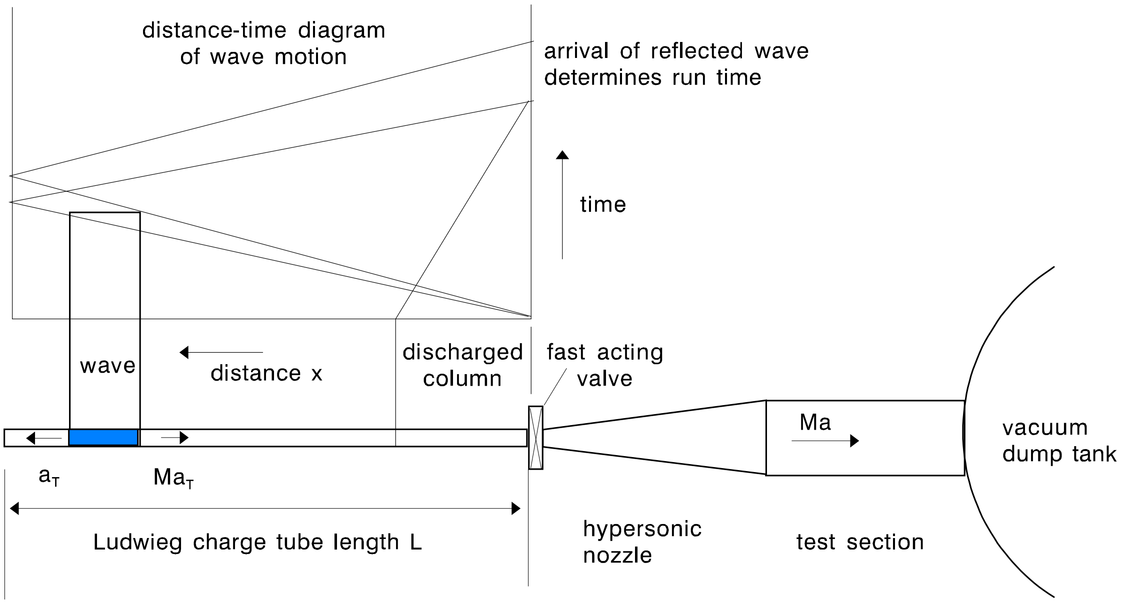

Fig 1. The operating principle of Ludwieg tube [4]

3. Conceptual design of KULT

Upon its conceptual design, related formulations were summarized and integrated into program, LTDT. Conceptual design was verified by using a CFD solver (called KFLOW): an in-house code of CFD laboratory of Konkuk University. The initial conditions for both LTDT and CFD were set to 20.0 bar and 900 K in high pressure section, while 0.02 bar and 288 K were given in low pressure section. Table 1 shows the conceptual design parameters.

Table 1. Conceptual design parameter [5]

	Values
Storage tube diameter	57.3 mm
Storage tube length	21 m
Storage tube pressure	15 ~ 100 bar
Storage tube temperature	Up to 900 K
Nozzle exit diameter (contoured)	100 mm (M=4, 5)
	300 mm (M =6 ~ 10)
Test section diameter	600 mm
Vacuum tank volume	0.53 m^3

Fig. 2 shows the performance envelop of the KULT. KULT can simulate a Mach 4 flow with enthalpies and Reynolds numbers corresponding to the altitudes from 10 km to 23 km. The run time predict from in LTDT is 66.02ms and CFD result is 65.57ms. The comparison results show that the present conceptual design can be successfully applied to the development of KULT.

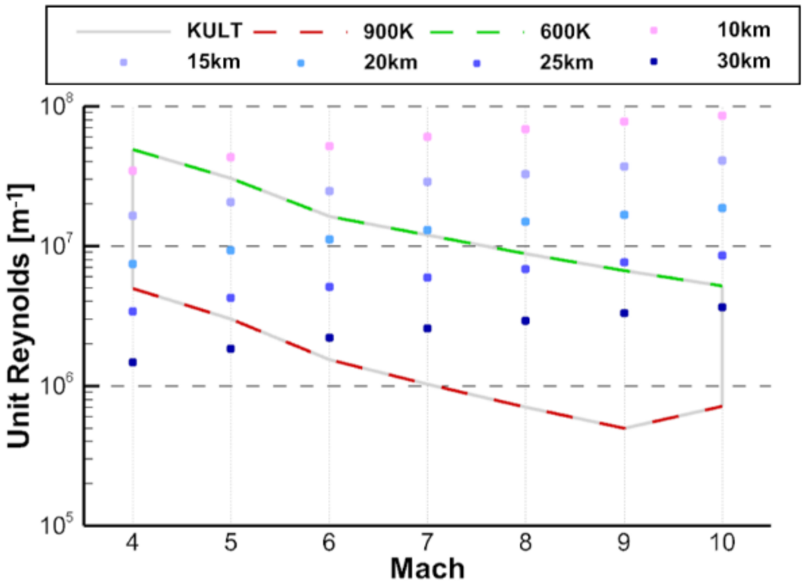

Fig 2. Performance envelop of KULT [5]

4. Detailed design and installation of KULT

Fig. 3 displays the detailed design and completed installation without heating system. KULT consists of a vacuum tank, a test section, a nozzle, a fast acting valve, a storage tube, heater, 6 stands, and supporters. Installation of heating system will be done in the second half of 2018.

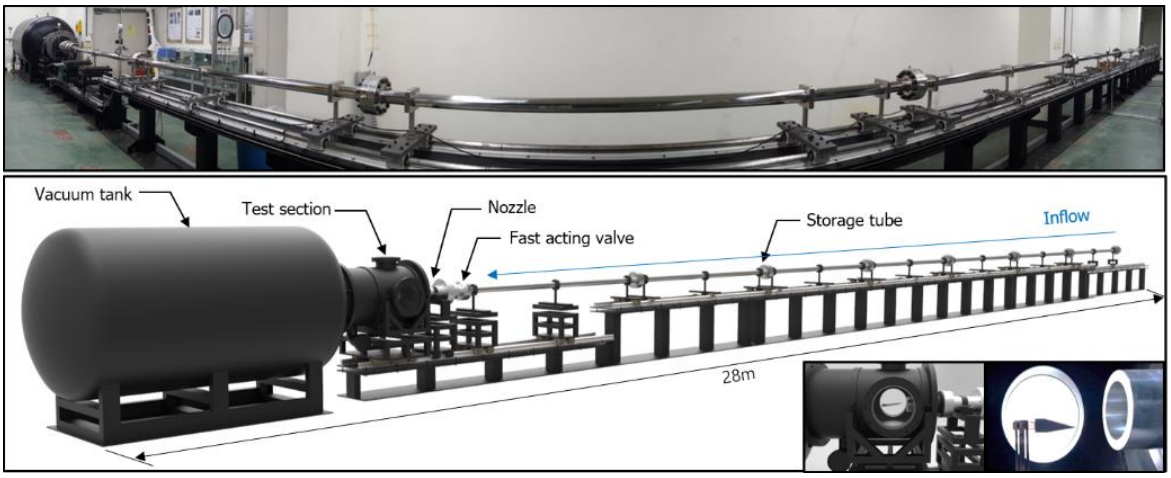

Fig 3. KULT and 3D rendering image

Based on the conceptual design, the detailed design was carried out considering the various constraints. The total length of KULT is about 28 m. The length of the vacuum tank is 3 m, the length of the storage tube is 21.2 m, and it is designed to withstand a maximum pressure of 100 bar and a temperature of 900 K. All of the control for the operating can be done in the control panel.

4.1. Storage tube

In order to satisfy the conceptual design, the pressure of the storage tube must be 100 bar and the temperature must be up to 900 K at the same time. It was made with 7 pieces of 3 m length each. The flange is designed to be coupled in a concave and convex manner so that the copper gasket is compressed and designed to maintain airtightness.

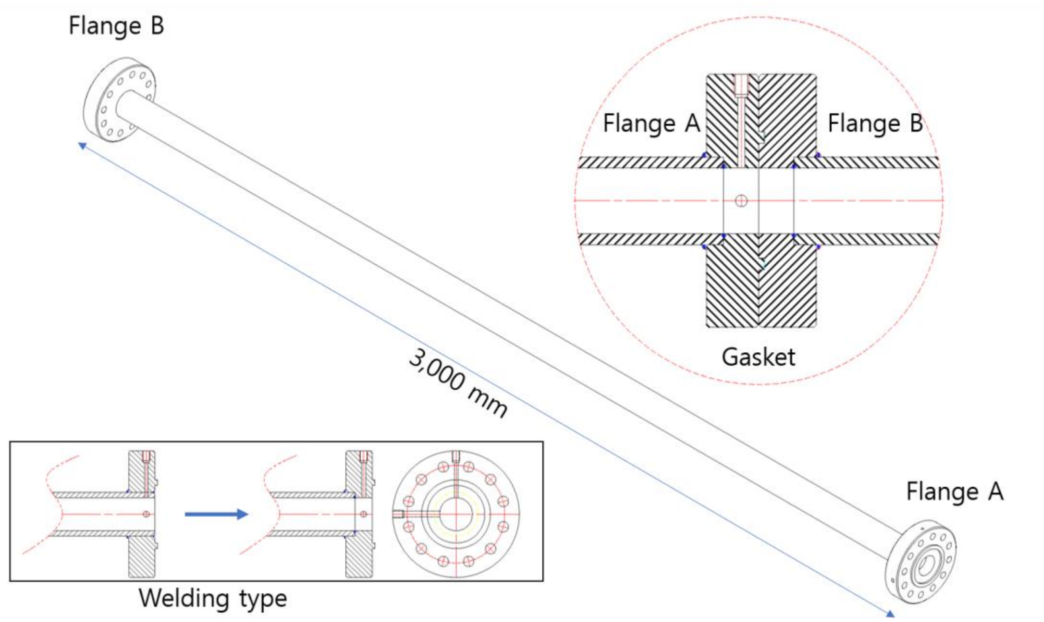

Fig 4. Detailed design of storage tube

4.2. Fast acting valve

The fast acting valve consists of three components: a body, a housing, and a piston. The total mass and the area of the pressure acting on the driving speed of the piston are important design factors. The area indicated by the red arrow in Figure 5 is the area where the pressure charged in the storage tube acts on the piston and the area indicated by the blue arrow is the area where the pressure charged in the cylinder of piston acts on the piston. the blue area is bigger than the red area. Due to the difference in size of these areas, the fast acting valve is operated.

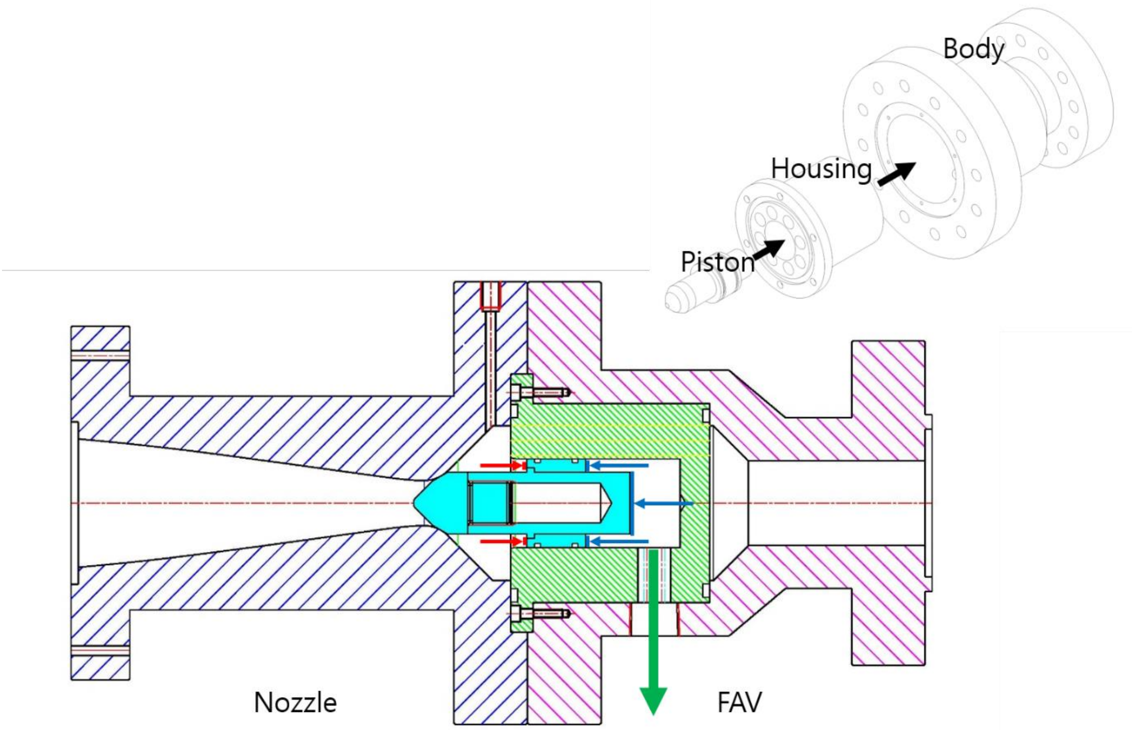

Fig 5. Detailed design of fast acting valve

4.3. Test section

The test section of the KULT was designed by open jet type for the common use of Mach 4 and 5 (nozzle outlet 100 mm) and Mach 6 to 10 (nozzle outlet 300 mm) nozzles. It is also designed to use flow visualization and measurement techniques available in this laboratory.

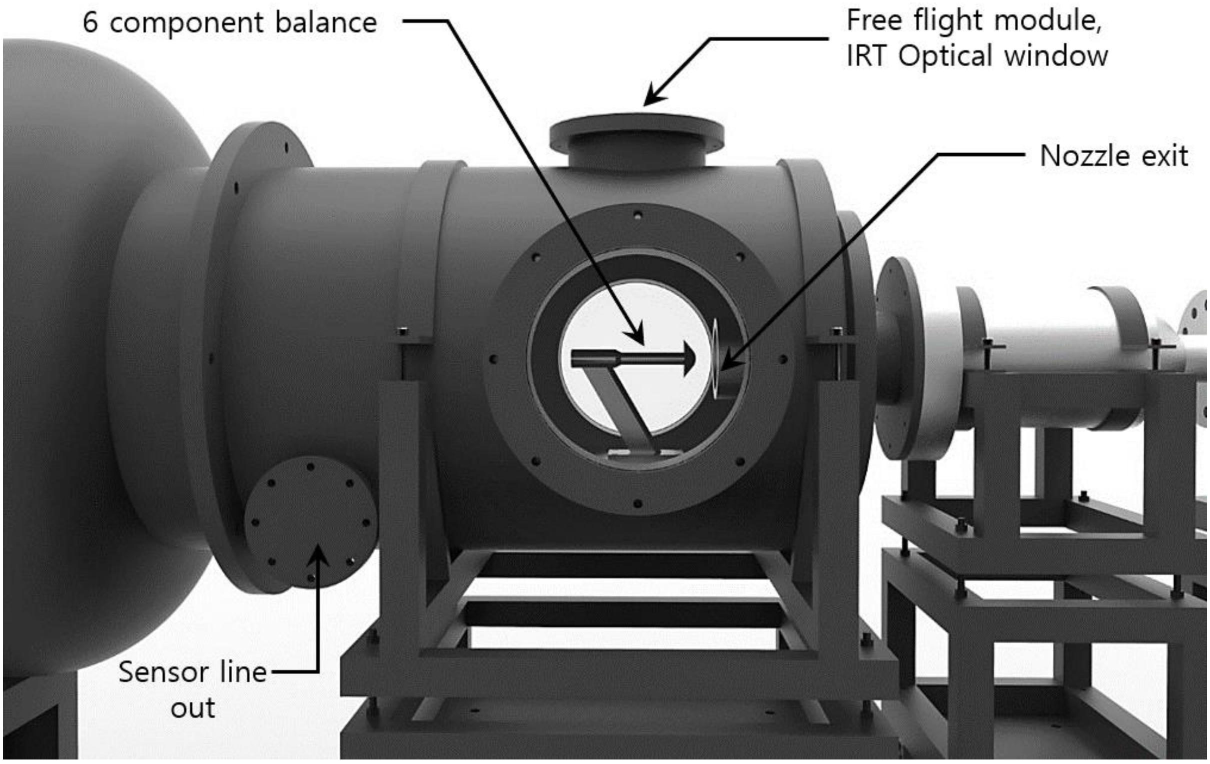

Fig 6. Detailed design of test section

5. Performance validation

5.1. Shock angle measurement on a wedge model

To validate the performance of KULT, two of experiments was carried out. Fig. 7 shows the set up for the first experiment. A z-type shadowgraph system was set up near the test section. A wedge model is installed in the test section. Shadowgraph system depicted the flow establishment, measured the steady test time of nozzle exit flow and the shock wave angle of the test model. Initial operating conditions were storage tube pressure 20 bar, vacuum tank pressure 0.12 bar, and temperature 292.8K.

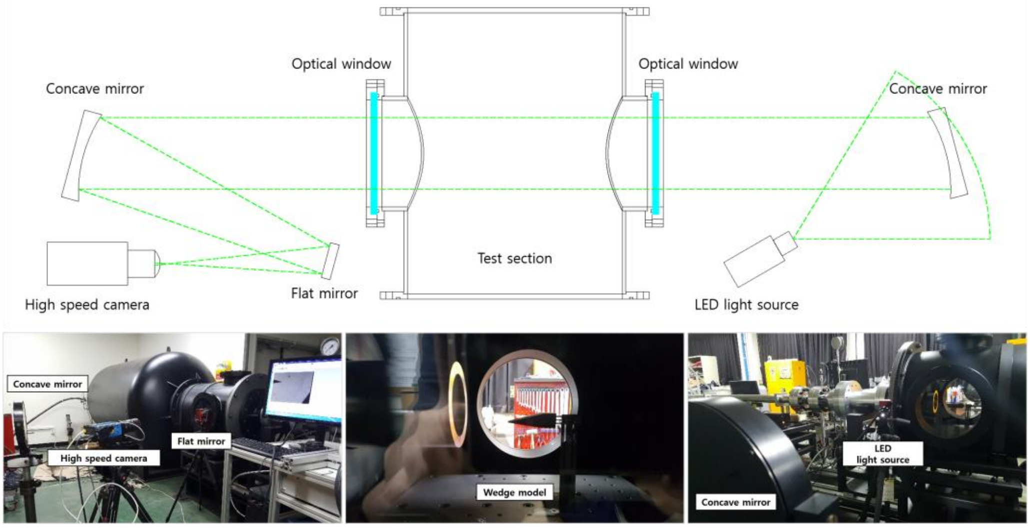

Fig 7. Experimental set up for shadowgraph

Fig. 8 shows the experiment result. Shadowgraph system gets the images of shock angle on wedge model which is installed test section. The Mach number of nozzle exit is calculated by the theta(θ)-beta(β)-M relation equation. the wedge angle(θ) is 15 degrees and shock angle(β) is 27 degrees. According to θ-β-M relation, the Mach number is estimated as 4. The test time of KULT in test section was indirectly measured from shadowgraph images. Steady flow was formed after 9ms (flow establishment: 9ms). Steady flow and test rhombus constructed during the 9 to 116ms (steady flow: 107ms). after 117ms, flow became unsteady. It means that the test time of KULT is 107ms for the present case.

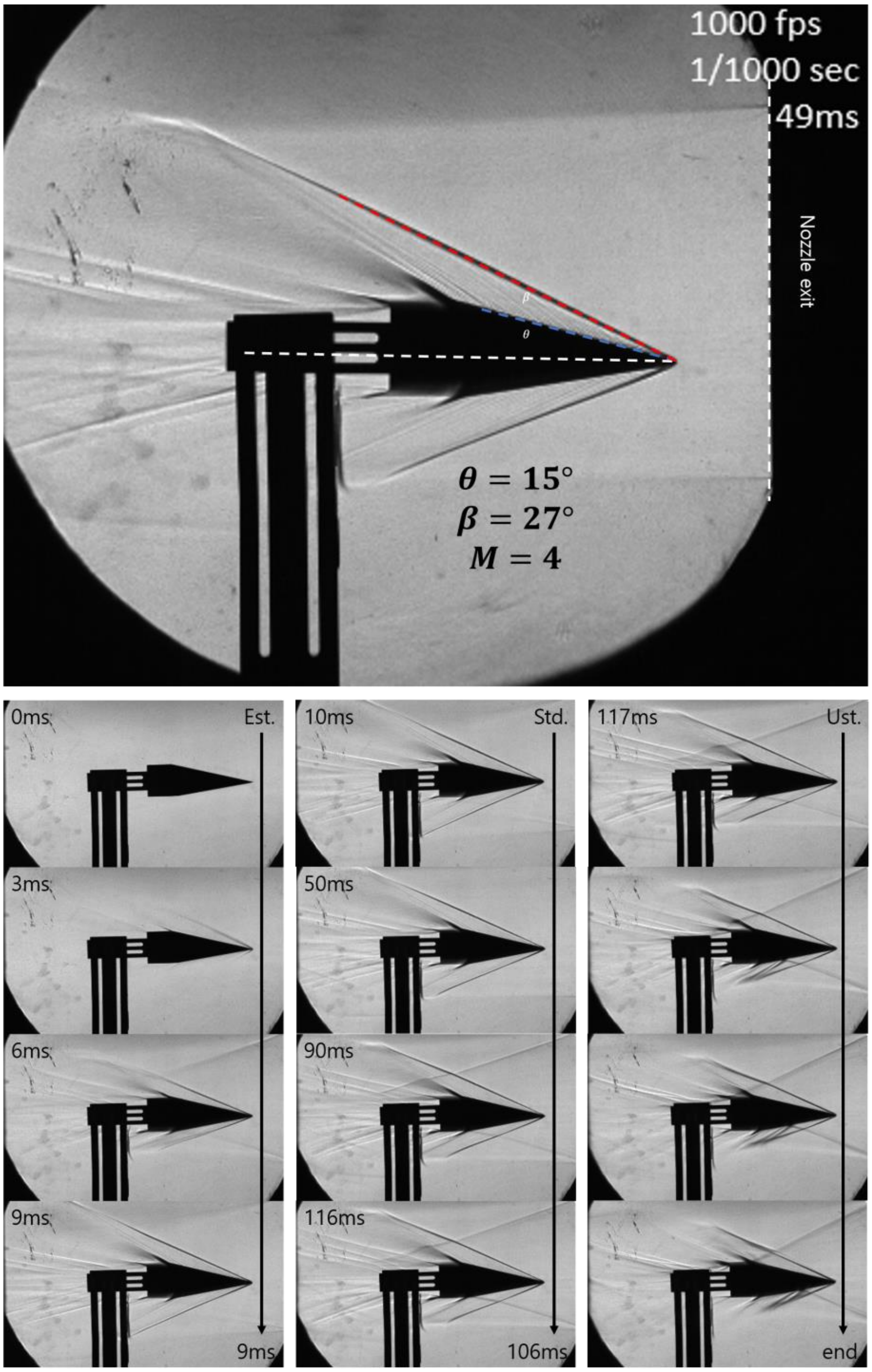

Fig 8. Shock angle measurement on a wedge model

5.2. Pressure measurements

Fig. 9 shows the set up for the experiment. Pitot rake is located at the nozzle exit and two pressure sensors are located at the storage tube and piston tube each. Both pressure sensors are measured storage tube pressure and piston cylinder pressure. Initial operating conditions were storage tube pressure 30 bar, vacuum tank pressure 0.13 bar, and temperature 303.45K.

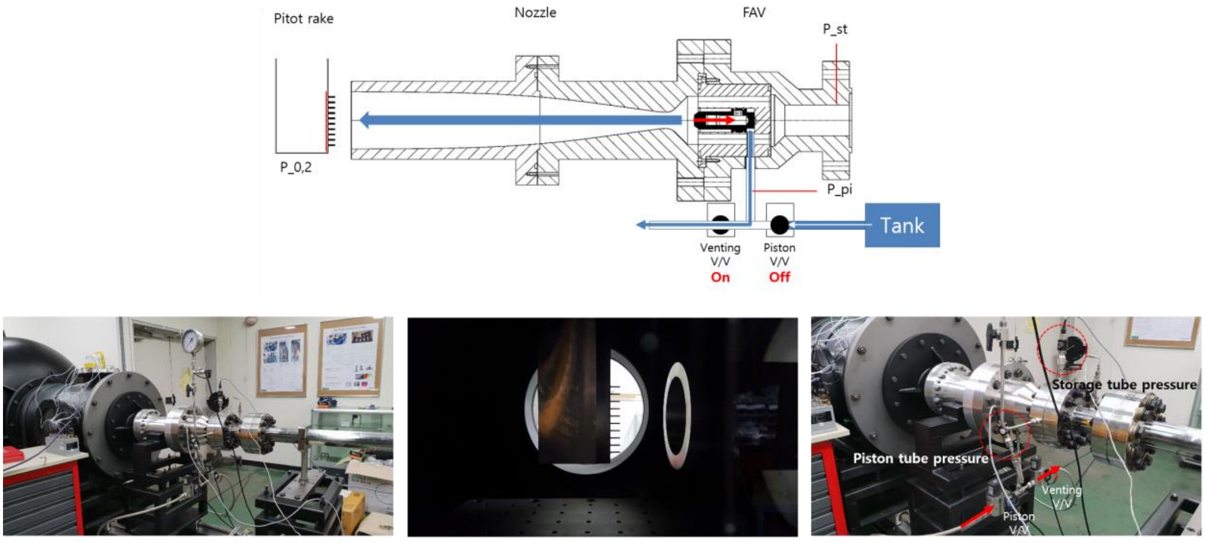

Fig 9. Experimental set up for pressure measurements

Storage tube pressure shift down once when the expansion wave travels via the pressure sensor to the end of the tube. Expansion wave which reflected at the end of the tube arrivals at the pressure sensor was shifted down again. The time between the first and second shift down is the run time. Calculated result of run time in LTDT is 114.88 ms and calculate result of storage tube pressure after expansion waves is 23.84 bar. Both results look very compatible with the result of the experiment.

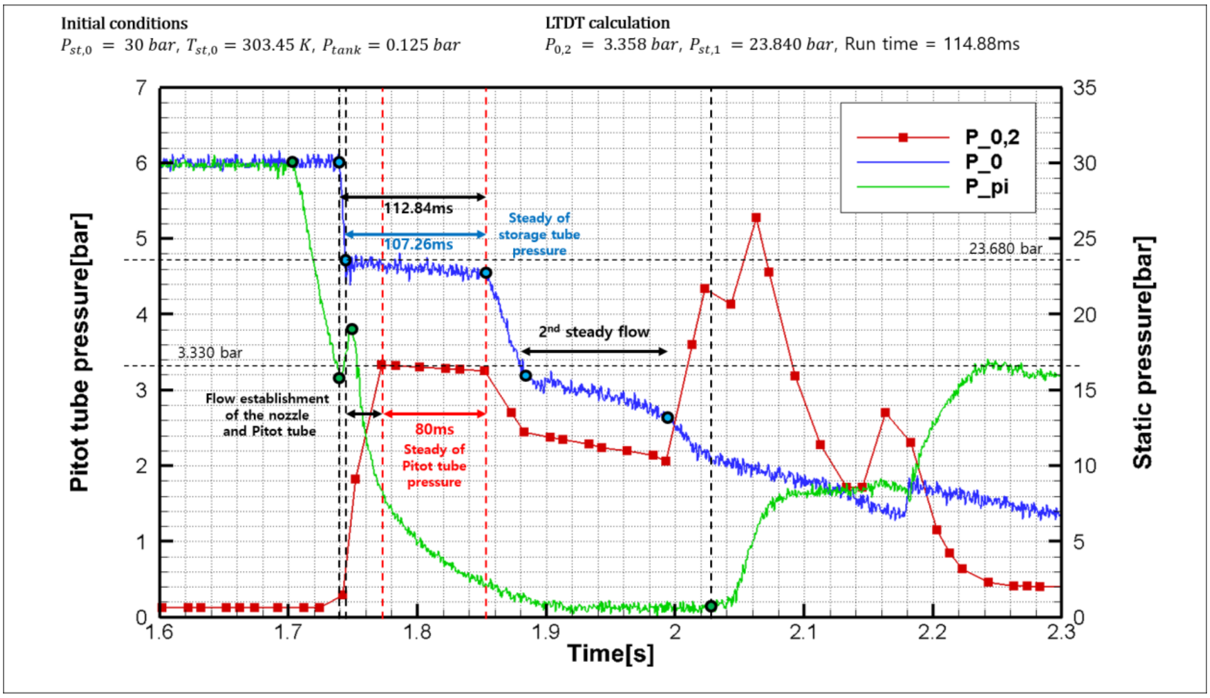

Fig 10. Result of pressure measurements

The Pitot tube pressure using LTDT is 3.358 bar and the actual experiment result is 3.33 bar. It is converted to the Mach number using the Rayleigh pitot tube formula and is about M 3.98. Through this experiment, the time of flow establishment is measured about 32 ms and the time of steady flow is measured about 80 ms. It is expected that the steady flow time will be longer when using the sensor with faster response time. Enough steady flow time is obtained to various experiment such as measurement force/moment on the model in the test section.

6. Conclusions

To verify the performance of KULT, shock wave angle and pressure measurement were performed. As a result of analyzing the performance of the equipment through the comparison between the experimental results and the theoretical calculation values, it is considered that the reliability is high. The force / moment measurement experiment using the free-flight technique will be carried out in KULT. it is a state in which the first construction except the current heater is completed. A heater designed to simulate supersonic flow will be built and installed. This paper describes the detailed design, construction process, and the performance validation process. This equipment is expected to be used for the development of hypersonic vehicles in the future.

7. Acknowledgments

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