ISSN 2176-5480

22nd International Congress of Mechanical Engineering (COBEM 2013)
November 3-7, 2013, Ribeirão Preto, SP, Brazil

PERFORMANCE AND CAPABILITY OF THE UFABC DIAPHRAGMLESS HYPERSONIC WIND TUNNEL

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Abstract. *Laboratory study of hypervelocity vehicles such as rockets, reentry capsules, missiles and future hypersonic aerospace liners and engines demands experimental facilities capable of simulating flights at Mach numbers in excess of 5 with high stagnation temperatures. This paper shows the performance curves of a diaphragmless hypersonic wind tunnel which has recently been designed for experimentation on hypervelocity flight at Universidade Federal do ABC (UFABC). Operational curves for reservoir conditions as function of the pressure ratio across the diaphragmless structure were obtained via ideal shock-tube theory which assumes instantaneous diaphragm removal. We developed algorithms to solve the ideal shock-tube theory applied to our hypersonic facility. Also, various aspects of how to enhance the reservoir conditions such as gas combination and heating are discussed.*

Keywords: *Shock waves; Shock tubes; Performance Curves; Hypervelocity; Aerospace Engineering*

1. INTRODUCTION

1.1 Hypersonic Flow

For Mach numbers greater than 5, the flow is conventionally defined as hypersonic. However, hypersonic is best defined as the flow where certain physical phenomena become progressively more important as its Mach number increases in a manner that it is physically different from supersonic flows. Briefly, these physical phenomena are: Thin shock layers, entropy layer, viscous interaction and chemically reacting boundary layer (Anderson, 2006). Also, hypersonic flow is important because it is the flow that will dictate many of the new civilian and military aerospacecraft and air-breathing engine designs for the 21st century (Anderson, 2003).

1.2 Impulse Hypersonic Wind Tunnel

Hypersonic wind tunnels are the often the most rapid, economical, and accurate means for conducting research, development and innovation on high-speed vehicles and engines (Lu and Marren, 2002). Conceptually, a pulsed hypersonic wind tunnel is a shock tunnel equipped with a convergent-divergent nozzle, a test section and a dump tank, as shown in Fig. 1. The shock tunnel is a very long pipe in which a strong shock wave is generated inside the tube and propagates along the tube producing a high-temperature, high-pressure gas behind it. The shock runs into an end wall and reflects back, producing an even higher temperature and pressure gas behind the reflected shock wave. This reservoir of very high temperature and pressure gas then expands through the convergent-divergent nozzle, creating a hypersonic flow in the test section, where a test model is placed for experimentation. This flow is subsequently exhausted into the dump tank.

ISSN 2176-5480

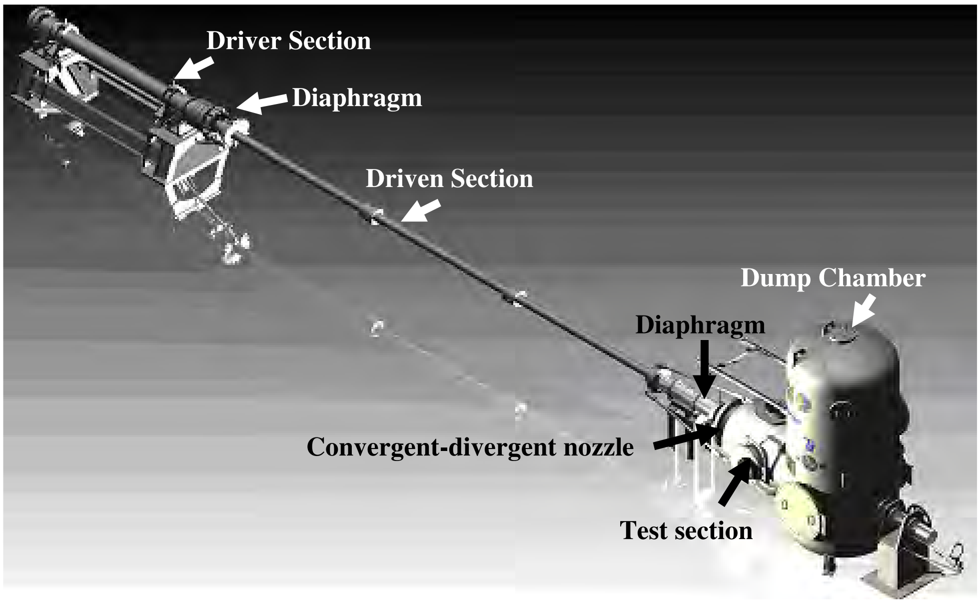

Figure 1. Scheme of the IEAv Hypersonic Wind Tunnel - T3 (Adapted from Toro, 2005).

A new type of hypersonic facility is being designed by UFABC in collaboration with IEAv (Benetti, 2012). This paper presents the analytical performance of the diaphragmless hypersonic wind tunnel which will be built in the near future at UFABC. Figure 2 shows the capability of some types of hypersonic wind tunnels, including the operation envelope of both IEAv and UFABC hypersonic wind tunnels. Note that impulse shock tunnels can produce very high velocity and in turn, very high total enthalpy, but can do so only for a very short duration.

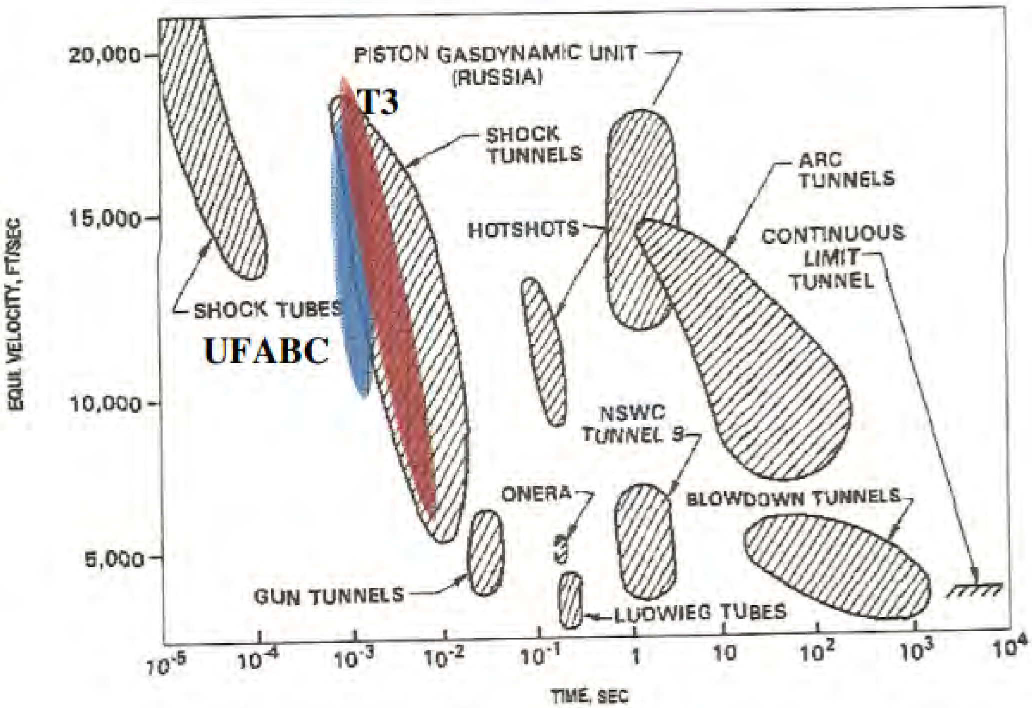

Figure 2. Hypersonic facility capability including IEAv and UFABC operation envelopes (Benetti, 2012).

1.3 Principle of the double-piston actuated driver and Sizing

The great advantage of using diaphragms in shock tubes is the fact that the aperture time is very short (a fraction of milliseconds), resulting in shock waves with higher Mach numbers. However, operationally, shock tube with diaphragm shows various disadvantages such as the long replacement time of the ruptured diaphragm, requiring two or more

ISSN 2176-5480

experimentalists working hard to do so. Also, eventual diaphragm fragments can be carried by the hypersonic flow and eventually hit a measure instrument or even the test model, compromising the experiment.

The operation of the UFABC hypersonic facility will be based on the pneumatic double-piston mechanism (Rêgo, 2007). A main sliding piston with dynamic sealing will replace the use of any diaphragm for separating the driver (high pressure) and driven (low pressure) sections. An auxiliary sliding piston with dynamic sealing is used to start the fast sliding motion of the main piston. When the main piston slides back actuated by the auxiliary one, the high-pressure gas in the driver section is massively discharged to the driven section, resulting in compression waves in the driven section (low pressure). The most important parts of the non-diaphragm driver are showed in the Fig. 3.

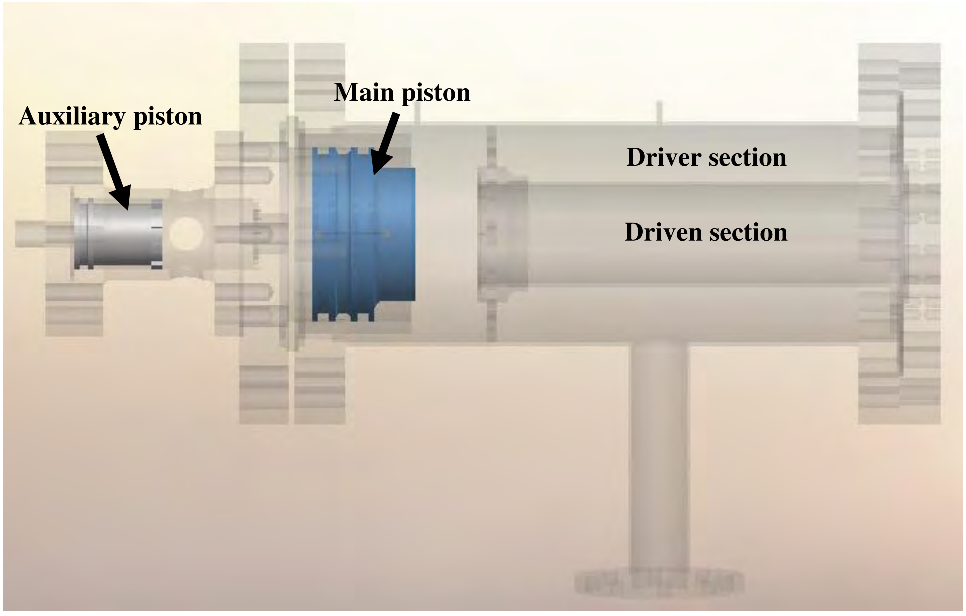

Figure 3. Design of the double-piston actuated driver.

The running shock wave into the driven section is generated as follows: First, right behind the auxiliary piston is injected an auxiliary gas. Due to a low-conductance pinhole on the base of the auxiliary piston, both the main and auxiliary pistons slide forward to seal the auxiliary chamber and the passage between the driver and driven section, respectively (see Fig. 4a). Second, a light gas is introduced in the driver section until the pressure therein (P_4) reaches slightly below of the pressure behind the main piston in a manner to keep it in position. After sealing the passage with the main piston, the driven section is filled with the test gas (for aerodynamic and propulsion studies, dry air is employed). Usually, the pressure in the driven section (P_1) is far below P_4. To start the sliding motion of both pistons, gas is exhausted from behind the auxiliary piston by means of a solenoid valve (shown in Fig. 4b). In consequence, an abrupt misbalance of pressure is established through the auxiliary piston forcing it to slide back. At the same time, the gas behind the main piston is purged outside from high-conductance orifices, creating again a misbalance of pressure through the main piston which quickly slides back, then opening the passage for the gas in the driver section discharges massively into the driven section (Figure 4c) thereby, generating compression waves. As the compression waves travel along the driven section, they superimposed on each other, resulting in a running shock wave that will form the reservoir of very high temperature, pressure and enthalpy at the tunnel end.

ISSN 2176-5480

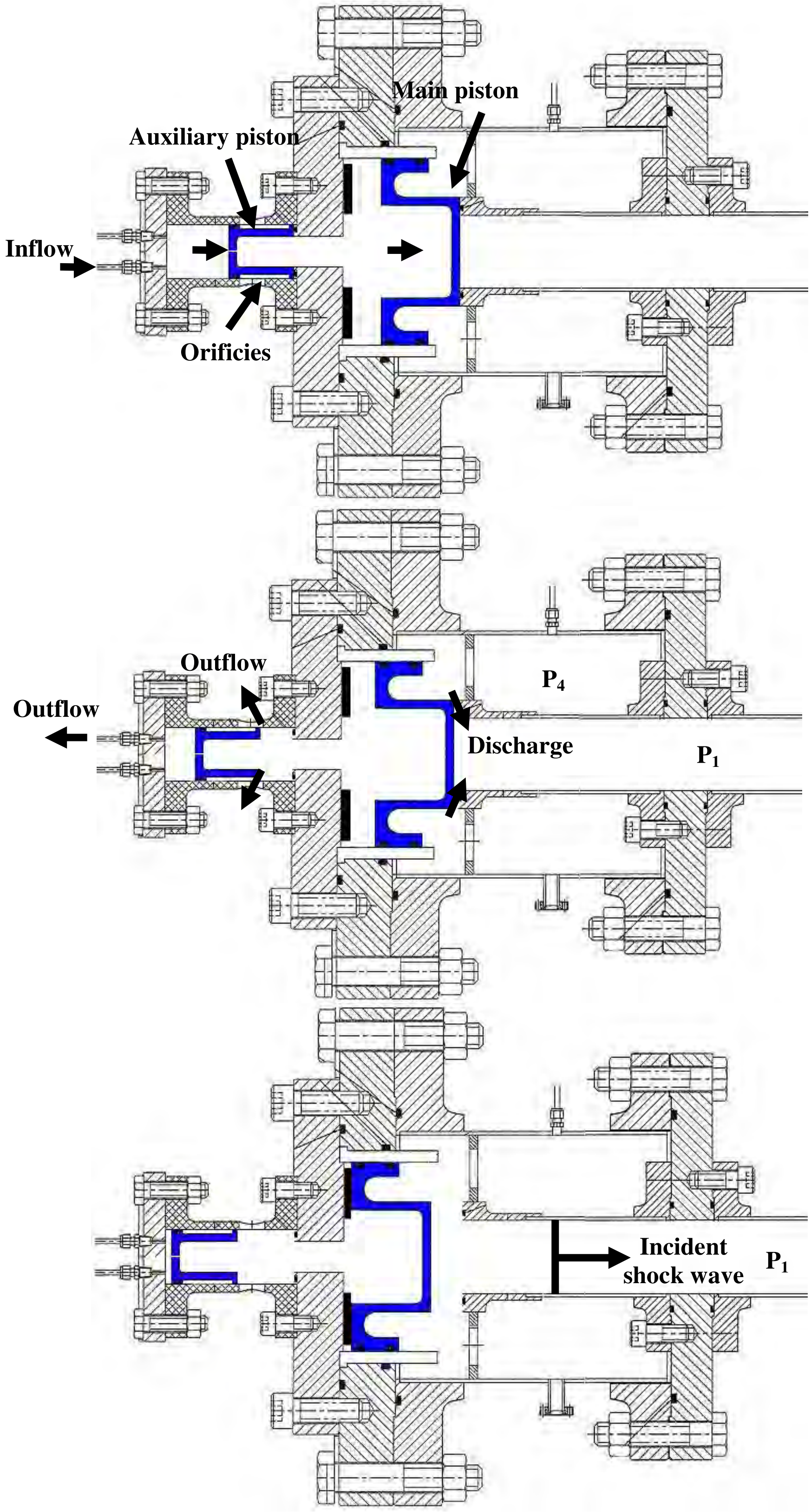

Figure 4. Non-diaphragm driver operation scheme: Inflow (top), outflow (center) and wave compression (bottom) (Adapted from Rêgo, 2007).

2. IDEAL SHOCK TUBE THEORY

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The ideal shock tube theory assumes ideal gas, no friction and instantaneous gas discharge, that is, very short opening times or instantaneous pressure decay. These hypotheses and simplifications lead to the relation between the pressure ratio P_4/P_1 across the main piston and the Mach number M_s of the running shock wave in the driven tube (Anderson, 2003):

$$\frac{P_4}{P_1} = \frac{2\gamma_1 M_s^2 - (\gamma_1 - 1)}{\gamma_1 + 1}\left[1 - \frac{\gamma_4 - 1}{\gamma_1 + 1}\frac{a_1}{a_4}\left(M_s - \frac{1}{M_s}\right)\right]^{-\frac{2\gamma_4}{\gamma_4 - 1}}, \qquad (1)$$

where γ is the ratio of specific heats of the gas, a is the sound velocity of the gas (in m/s) and the indexes 1 and 4 mean driven and driver, respectively.

The temperature and pressure in the reservoir before the rapid expansion through a convergent-divergent nozzle are referred as stagnation conditions and abbreviated by T_5 and P_5, respectively. The reservoir conditions are given immediately after the reflection of the incident shock wave starting from the end wall of the shock tube. The stagnation conditions are calculated through the Rankine-Hugoniot relations of temperature and pressure (Anderson, 2003):

$$\frac{T_5}{T_1} = \frac{\left[2(\gamma_1 - 1)M_s^2 + (3 - \gamma_1)\right]\left[(3\gamma_1 - 1)M_s^2 - 2(\gamma_1 - 1)\right]}{(\gamma_1 - 1)M_s^2} \quad \text{and} \qquad (2)$$

$$\frac{P_5}{P_1} = \left[\frac{2\gamma_1 M_s^2 - (\gamma_1 - 1)}{\gamma_1 + 1}\right]\left[\frac{(3\gamma_1 - 1)M_s^2 - 2(\gamma_1 - 1)}{(\gamma_1 - 1)M_s^2 + 2}\right] \text{, respectively.} \qquad (3)$$

To solve Eqs. 1 to 3, input numerical data, execute commands and display the output numerical data we utilized the MATLAB language.

3. RESULTS AND DISCUSSION

3.1 M_s VERSUS P_4/P_1

Since the UFABC hypersonic wind tunnel will be dedicated to aerothermodynamics and propulsion research, air is the gas in the driven gas, while several other gases are used in the driver section to verify the gas composition effects on the facility performance. The air temperature and pressure of the air in the driven tube is fixed at 300 K and 10^5 Pa, respectively. The driver gases are: Helium, nitrogen, argon and air itself. The importante properties of them are listed in Tab. 1. Table 2 shows the sound velocity ratio a_4/a_1.

Table 1. Properties of driver gases at T_4 = 300K.

Driver gas	γ	R [J/Kg.K]	a_4 [m/s]
Helium	1.660	2077.00	933.99
Nitrogen	1.404	296.80	353.07
Argon	1.670	208.00	295.57
Air	1.400	287.04	347.21

Table 2. Ratio a_4/a_1 for driver and driven gases.

Driver/driven	a_4/a_1
Helium/air	2.69
Nitrogen/air	1.02
Argon/air	0.85
Air/air	1.00

Figure 5 shows the calculated incident Mach number M_s against P_4/P_1 for He, N_2, Ar and air in the driver section. They are initially at 300K. The ratio P_4/P_1 increases keeping P_1 constant as P_4 varies from 0 to around 2 MPa, that is, 20 times P_1. The achievable P_4 relies on acceptable mechanical loading on the main piston. For the case of Nylon plastic piston, it is around 2 MPa (Rêgo, 2007). It is clear that as the driver gas becomes lighter, higher incident Mach numbers can be reached. This occurs mainly because the increase in ratio a_4/a_1. This is the gas composition effect. Helium shows the best performance while argon the worst one. However, argon is cheaper than helium and then, may represent an alternative in term of operation cost. Nitrogen and air shows almost the same performance. Unfortunately, M_s shows an asymptotic tendency with increasing P_4/P_1 so that beyond a given P_4/P_1 there is little gain in M_s whatever the driver gas.

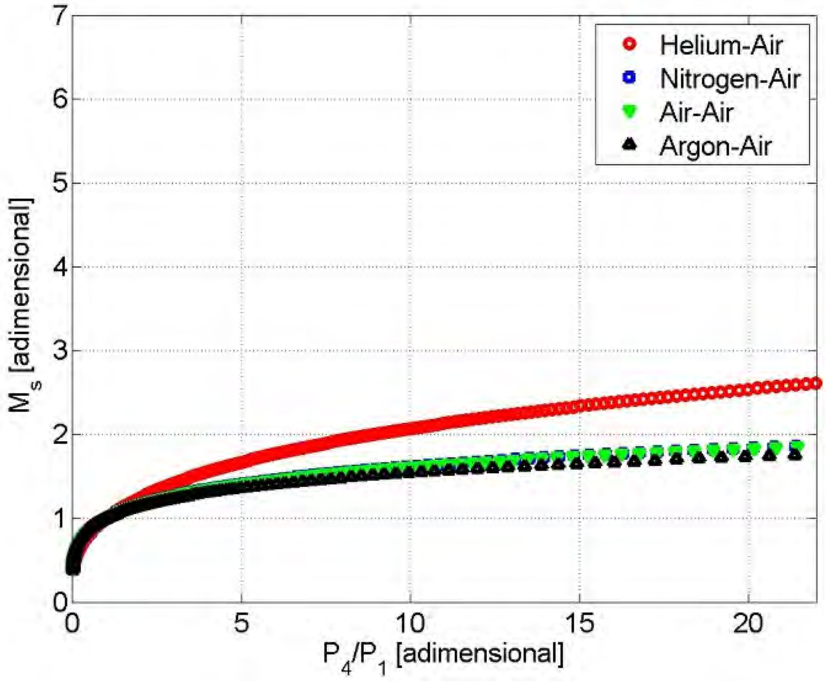

Figure 5. M_s versus P_4/P_1 for He, N_2, Ar and air in the driver section.

An alternative way of producing stronger shock waves is to added heat to the driver gas before the run. By increasing T_4 the ratio a_4/a_1 increases (see Tab. 2), resulting in faster incident shock waves. Figure 6 shows clearly the positive effect of heating the driver gas, where M_s increases a bit with increasing T_4 and thereby, enhancing the shock tube performance. Obviously, helium at 500 K leads to higher incident Mach numbers.

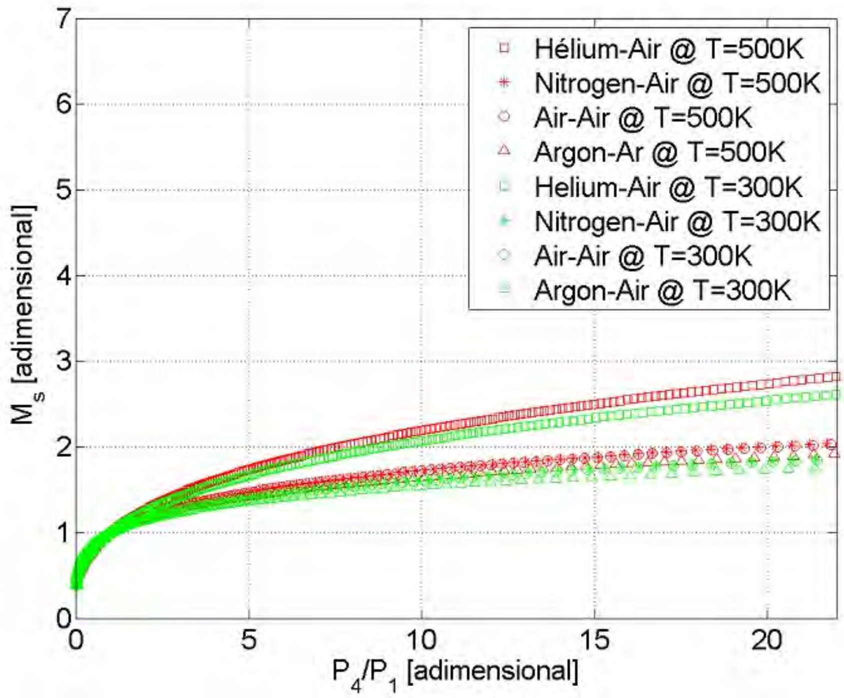

Figure 6. M_s versus P_4/P_1 for T_4 for He, N_2, Ar and air at 300 K and 500 K in the driver section.

ISSN 2176-5480

3.2 STAGNATION CONDITIONS T_5 AND P_5

Figures 7 and 8 show the dependence of the reservoir conditions on the incident Mach number. Note that the both stagnation temperature and pressure increases with M_s. Thus, ways of increasing M_s are vital to enhance the reservoir conditions. The rate of increase in stagnation pressure is more pronounced for helium gas at 500 Kelvin. The gas composition acts only on the maximum T_5 achievable not its shape.

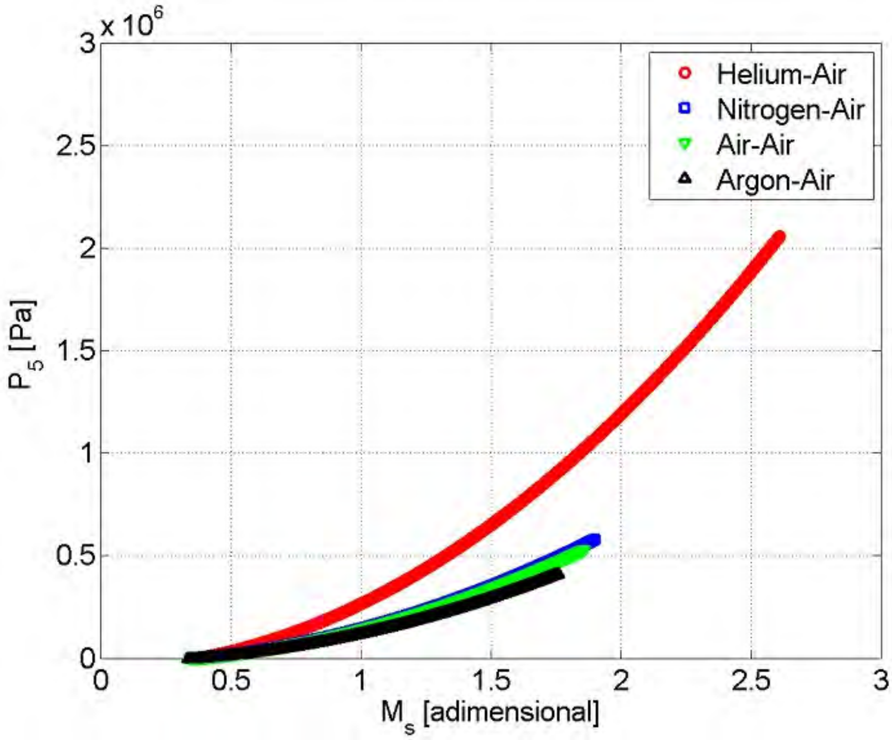

Figure 7. M_s versus P_5 for heated driver gases and $P_1 = 10^5$ Pa.

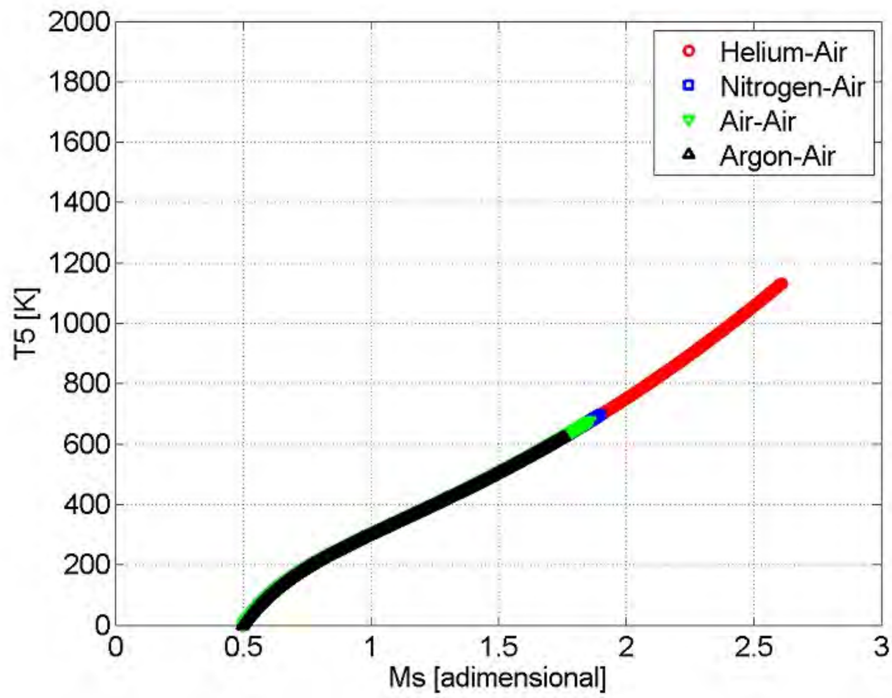

Figure 8. M_s versus T_5 for heated driver gases and $T_1 = 300$ K.

It should be noted that the M_s, P_5 and T_5 data shown in Figs. 5 to 8 are overestimated because of the ideal shock tube theory. Deviations from the ideal shock tube theory will certainly occur because of the following: Real gas effects will play a rule as M_s increases, friction effects will not be neglected because of the long length of the driven tube and the relatively small i.d. of it, and the opening time of the main piston is in fact not instantaneous. Table 3 summarizes the theoretical data on M_s, P_5 and T_5 for helium at 500 K (best performance) taking into account a reduction of 10 %.

Table 3. Reduction of 10 % in M_s, P_5 and T_5 data (He at 500 K).

Driver/Driven gas	**P_4 [MPa]**	**P_1 [MPa]**	**P_4/P_1**	**M_s**	**P_5 [MPa]**	**T_5 [K]**
He at 500 K/Air	2	0,1	20	2,25	2,7	990

4. CONCLUSIONS

Hypersonic wind tunnels are vital to the study and development of high-speed vehicles and propulsion systems. A hypersonic wind tunnel based on an innovative no-diaphragm driver is being designed by UFABC in collaboration with IEAv. It was shown that theoretically the operation of the diaphragmless shock tube is improved with the use of lighter driver due to the increase of the Mach number of the incident shock waves into the tube. Also, heating up the driver gases is beneficial to enhance the stagnation conditions prior expansion. Helium at 500 K may lead to stagnation temperatures around of 990 K and stagnation pressures up to 27 atm into the reservoir region. Subsequently, we will draw x-t diagrams for localizing the incident shock waves in the shock tube and scaling the tube length and analyze the performance of a convergent-divergent nozzle for the rapid expansion of the stagnant driven gas.

5. ACKNOWLEDGEMENTS

The first author thanks the Universidade Federal do ABC for the PIC/PIBIC research fellowship.

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