Design Considerations and Analysis of the UTSA Hypersonic Ludwieg Tube Facility

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The development of hypersonic flight systems is an emerging national priority that places unique demands on the current high-speed test and evaluation (T&E) enterprise. The University of Texas at San Antonio (UTSA), in an effort to develop a hypersonic wind tunnel testing capability, is currently designing and building a Mach 7 Ludwieg Tube facility to address this current gap in academic-scale high-speed aerodynamic research. The feasibility of building a wind tunnel capable of generating higher Mach number flows depends on a variety of factors including the mechanical limits of structural materials, desired freestream flow conditions, and available budget. This paper discusses the process and deliberations made during the design phase of UTSA's wind tunnel. An analysis of the impact of Mach number on key wind tunnel design considerations is presented, followed by a justification of the chosen design parameters for the UTSA facility. A comparison of various potential wind tunnel designs was performed, as well, and the rationale for selecting a Ludwieg tube wind tunnel discussed. A comprehensive overview of certain key components of the wind tunnel and the grounds for their selection is also provided, including reviews of the driver tube, diaphragm assembly, nozzle, test section, and vacuum tank. Based on the results of the analysis, the cost for installing wind tunnels increases exponentially after Mach 7 making building such facilities economically daunting. Finally, with currently available material, it is infeasible to build Ludwieg tube wind tunnels with speeds greater than Mach 8, that undergo external heating on the driver tube and exhausts to atmosphere due to the inability of material to sustain pressures required at needed temperatures.

Nomenclature

M	=	Mach Number
Re	=	Reynolds number
P_o	=	Stagnation Pressure
T_o	=	Stagnation Temperature
d	=	Inner Diameter of Driver Tube
P	=	Freestream Pressure
T	=	Freestream Temperature
P_{inf}	=	Exhaust Pressure
S	=	Basic Allowable Stress
E	=	Quality Factor
W	=	Weld Joint Reduction Factor
t	=	Wall thickness
Y	=	Austenitic Steel Coefficient

I. Introduction

Hypersonic flow is loosely defined as a flow regime in which objects possess velocities greater than five times the speed of sound (M >5).[1] In this flow regime shock waves closely overlay the boundary of vehicles and create enough heat to cause chemical reactions in the airflow (ionization and dissociation).[2,3] Hypersonic flight is an area of national interest as it has several applications in the aviation, defense, and aerospace industries.[45] With possible travel speeds beginning at 1500 meters per second, occurring at Mach 5 under atmospheric conditions, travel times for some cross-country and intercontinental flights could be significantly reduced. For example, a Mach 7 hypersonic flight cruising

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at an altitude of 60,000 feet, from Los Angeles to New York will take roughly half an hour as compared to the current five hours taken by conventional commercial aircraft. In the defense sector, application of hypersonic flow will help increase the response times and increase the capability of the military to project force over large distances. In the aerospace industry, knowledge of flow properties at hypersonic speeds will help in the design of space shuttles as these vessels possess similar hypersonic velocities during reentry (the orbiter space shuttle for example reentered the earth's atmosphere at Mach 28 during missions).[6]

UTSA, in its effort to develop a hypersonic ground test platform is designing and constructing an intermittent Mach 7 Ludwieg tube wind tunnel capable of achieving high Reynolds numbers. The Ludwieg tube is a cost-effective wind tunnel design adopted in ground test facilities to produce hypersonic and supersonic flows.[7,8,9,10] The main components of the facility include a driver tube, diaphragm or fast valve, a nozzle, test section, diffuser, and vacuum tank. Figure 1 presents the proposed design of UTSA's Ludwieg Tube. A test in a Ludwieg tube begins with the sudden release of high-pressure air from the driver tube through the rupture of a diaphragm or actuation of a high-speed valve. Air from the driver tube flows to the nozzle and test section and exhausts into a vacuum tank downstream of the test section after decelerating in the diffuser. There is a concurrent sound wave generated from the bursting of the diaphragm that flows upstream in the driver tube at Mach number (M_{DT}) to the end of tube and back. This expansion wave determines the duration of a test pass. Tests in the Ludwieg tube last as long as the pressure ratio between the high and low-pressure side is above the pressure ratio required for flow at the design Mach number. Test runs in the Ludwieg tube are short, on the order of hundreds of milliseconds owing to the decreased volume of the high-pressure chamber. These run times require high-speed imaging and measurement techniques to obtain test data, which can lead to increased experimental setup cost compared to facilities with longer run times. Ludwieg tubes make up for this expense through their low cost required to build, ease of operation, and ability to be operated by one or two students

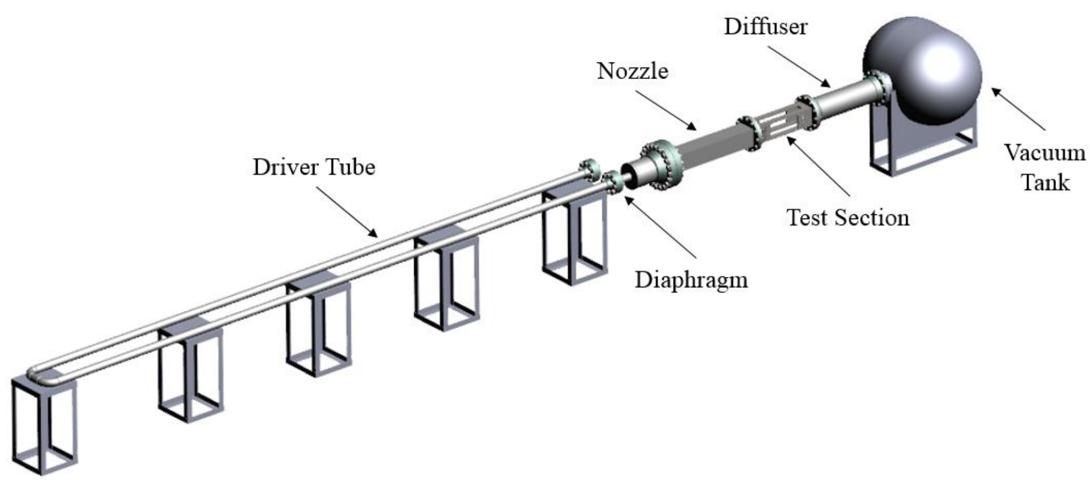

Figure. 1: UTSA's proposed Ludwieg tube wind tunnel.

II. Analytical Considerations for Wind Tunnel Design

Anderson, in his textbook on compressible flow provides a comprehensive coverage of the equations needed to calculate properties experienced in wind tunnel facilities.[2] These properties are key in part sizing and the design of wind tunnels. These equations were applied to UTSA's facility with a known Mach number of 7, a test section size of 8 in × 8 in, while assuming isentropic flow.[2] The results from the numeric analysis are displayed in the table below.

Table 1: UTSA Wind Tunnel Parameters

Parameter	Value	Unit
Mach number (M)	7	-
Test Section Size	0.2 x 0.2	meters
Vacuum Tank Size	6	m^3
Stagnation Pressure (P_o)	13.8	MPa
Stagnation Temperature (T_o)	702	K
Freestream Pressure (P_{inf})	3.18	KPa
Freestream Temperature (T_{inf})	66	K
Mass Flux	8.34	kg/s
Reynolds number (Re)	4.3×10^7	m^{-1}
Velocity	1135.8	m/s
Enthalpy	713.6	KJ/kg.K
Length of Test Pass	0.075	s
Number of Tests Passes	4	

III. Design Considerations for Wind Tunnel

A. Material Selection

The replication of Reynolds numbers on the order of 1×10^7 to 1×10^8, produce turbulent flows that are complex, and demanding when solved through numerical simulation. A more accurate environment can be created for investigating phenomena associated with aerothermodynamics if these high-pressure conditions are attained. One of the first steps to building a facility capable of mimicking such conditions capable of producing these Reynolds numbers is the selection of materials capable of handling the high-pressure requirements of these high Reynolds and high Mach number facilities.

In wind tunnel facilities, stagnation pressure has a direct correlation to the attainable Reynolds number observed during freestream flow. As such, to generate turbulent flows at high Mach numbers (M>5), materials being selected for the driver tube should have the capability of withstanding the pressure requirement needed to yield such an effect.

Air accelerated through nozzles to high Mach numbers undergoes an expansion process, which causes a significant drop in temperature across the nozzle. If unchecked, this cooling could lead to freezing of air downstream of the nozzle which give unrealistic flows, create icing on the instruments and impedes measurements. For this reason the stagnation temperature in the high-pressure section of high Mach number wind tunnels is increased through heating to compensate for the temperature loss. The sharp fluid temperature gradient across the nozzle requires initial heating to prevent freezing and gives a sizable restriction on material that can be used for construction. The lower freestream temperature limit in UTSA's tunnel is about 60K. To maintain this, the stagnant air in the driver tube has to be heated to 700K.

Materials used in the construction of high Mach number and high Reynolds number facilities should have the capability of withstanding elevated pressures which yield the desired high Mach and Reynolds numbers while withstanding high temperatures to prevent condensation of test fluids which is a prevalent issue at high Mach numbers.

As the desired Mach number increases (M>6), this pressure-temperature combination severely limits the types of material that could work for this application. The graph below provides a visualization of how these requirements for high pressure and temperature scale for high Reynolds number facilities at some hypersonic speeds. The calculations for this representation are based on a Ludwieg tube design, undergoing initial heating, discharging to an open pipe atmospheric diffuser with 45% efficiency.

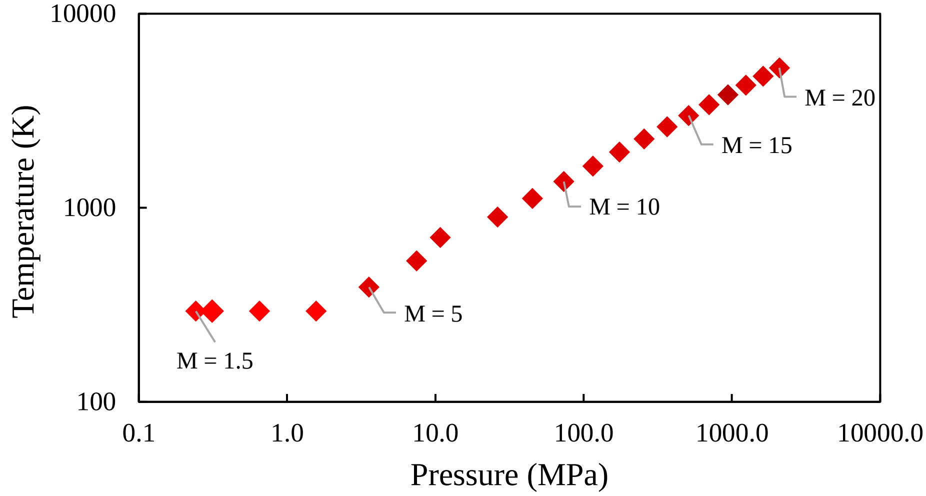

Figure. 2 : Stagnation pressure and temperature requirements for Ludwieg tube wind tunnels possessing Mach numbers between 1.5 and 20, discharging to atmosphere with a 45% efficient diffuser.

From the above graph, it is seen that for Mach numbers less than 5, temperature stays constant while pressure increase but for Mach numbers greater than 5, pressure and temperature scale linearly. Although there are several materials currently capable of handling high pressures, these materials quickly lose their ability to withstand these pressures at the elevated temperatures. Aluminum, steel, and its usual variants such as stainless steel are commonly used materials for building wind tunnels. The graph below represents the basic allowable stresses for some variants of aluminum, stainless steel and carbon steel at various temperatures.

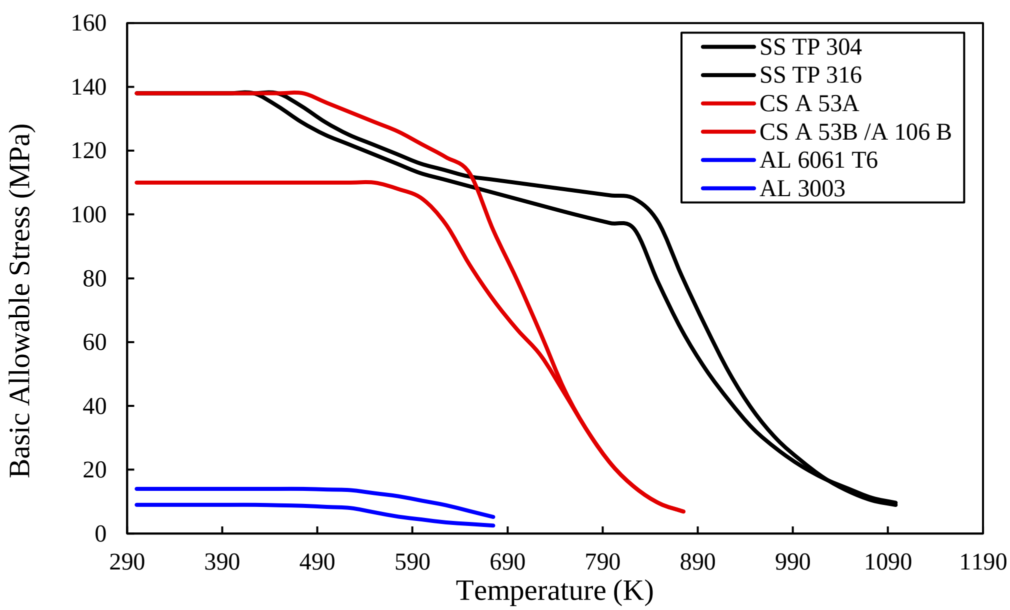

Figure 3 Allowable stresses for various grades of stainless steel (SS), carbon steel (CS), and aluminum (AL) at various temperatures.

Due to the huge pressure and temperature requirements, which prove infeasible in some cases and fiscally out of, reach in others, changes to the pressure at which the wind tunnels exhaust to (backpressure) can be made to cut down on pressure requirements. The graph below shows the pressure and temperature requirements for Ludwieg tubes running at various Mach numbers exhausting to 0.01, 0.1, 0.25, 0.5, and 1 atm pressures. From the figure, the effects of reduced backpressure can be seen. For example, at Mach 20, the last point on the curve, at a backpressure of 1 atm, a stagnation pressure of 2088 MPa is required. However, when the backpressure is reduced to 0.5 and 0.25 atm, the stagnation pressure required reduces to 1044.12 and 522.06 MPa respectively. The reduced pressure requirements at a constant temperature can make some of the high Mach number facilities attainable with current material with a downside of lowered maximum attainable Reynolds number.

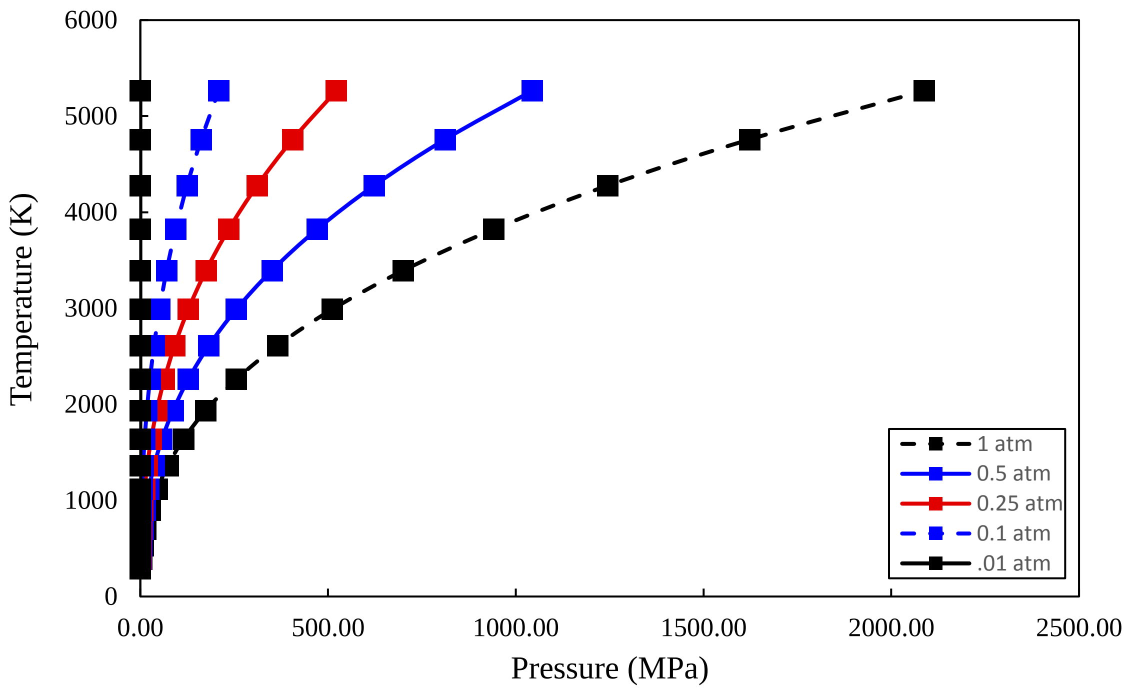

Figure 4: Pressure and temperature requirements for Ludwieg tube running at various Mach numbers exhausting to 0.01, 0.1, 0.25, 0.5, and 1 atm.

The list of suitable materials considered during the design process of UTSA's wind tunnel, was centered on variants of stainless steel. Stainless steel provides a corrosion resistant product that maintains several of the strength capabilities found in carbon steel. Aluminum as an optional product does not meet the necessary pressure and temperature requirements as seen in figure 3 and hence, was not considered.

B. Cost Based Analysis

To better comprehend the fiscal requirements of building a Ludwieg tube facility, a cost-based analysis was performed to quantify overall costs associated with the installation of a tunnel. This analysis covered main components of the tunnel including the drive tube, nozzle, test section, diffuser, and vacuum tank. The major mechanical elements such as the compressor and vacuum pump were also accounted for. The range of Mach numbers analyzed was 1.5 to 20.

In the first analysis, some general assumptions were made to restrict the number of free design variables present. It was assumed the facility being priced followed the Ludwieg tube convention of using pipe as a driver tube, maintained a constant flow Mach number of 0.04 in the driver tube section during testing, and exhausted to atmosphere in the dump tank. Next, the tunnels being priced were to have an 8 in × 8 in test section size, and be capable of producing test runs made up of 4 test passes at 75ms per pass with a diffuser that was assumed to be 45% efficient. 304 stainless steel was used as the material of choice and commercially available piping components following ASME B16.5, B16.47, B31.3 and boiler pressure and vessel codes were used where applicable.[11,12,13]

The driver tube analysis was performed by calculating the thickness of pipe capable of withstanding the internal pressures present at the given temperatures for the calculated diameters. The ASME equation for calculating minimum thickness for a straight pipe under Internal Pressure (eq. 1) was used to perform thickness calculations.[13]

$$t = \frac{P_o d}{2[SEW - P_o(1 - Y)} \quad (1)$$

Based on the calculated wall thickness, the amount of mass per meter was obtained and this was converted to cost, based on the going rates of stainless steel per kilogram obtained from local vendors. The allowable pressures used in the ASME formula were obtained from ASME B31.3 basic allowable stress tables for the various temperatures. For Mach numbers greater than 8, a relation equating the amount of mass needed to handle the temperature-pressure combination was used to predict the mass needed and associated costs as current ASME codes (ASME Boiler and pressure vessel code division I & II, ASME B31.1, B31.3) do not cover material and vessels at these elevated temperatures and pressures.

The nozzle's analysis was broken into a material and machining pricing analysis. The material cost for the nozzle was based on the mass, obtained from a volume of steel from which the nozzle was to be manufactured. This volume, had a height corresponding to the depth of steel at the throat plus a machining allowance factor. Pricing of steel came from multiplying the mass obtained at each Mach number by local vendors' costs per mass. The cost of machining the nozzle was obtained from a linearly scaled cost based on pricing for machining a Mach 7 nozzle.

The test section pricing was obtained from costs derived from the design and build of a similar sized test section for UTSA's facility. Finally, with the test system discharging to atmosphere, the cost of the vacuum tank and pump were disregarded.

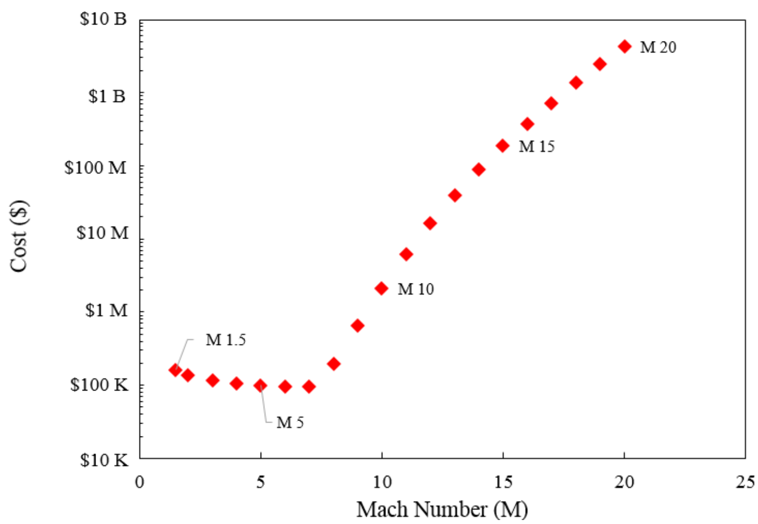

Figure. 5 : Cost analysis for various Ludwieg tube wind tunnels designed with an 8 in x 8 in test section size, a 45% efficient diffuser exhausting to atmosphere, and undergoing external heating where required.

From the graph above, the cost of building a facility decreases from Mach 1.5 to Mach 3, stays constant until Mach 6 and then rises exponentially to extremely high costs at Mach 20. The cost at Mach 2 is about the same as a Mach 7 tunnel due to the huge driver tube diameter needed to hold the flow Mach number at 0.04 and produce high Reynolds numbers. As the Mach number increases to Mach 3, the diameter reduces and hence decreases costs. Stagnation temperature remains constant at ambient conditions for Mach numbers less than 4. From Mach 3 to 6 the cost and temperature requirements remain fairly constant with the diameter decreasing but driver tube pipe thickness increasing.

Above Mach 8, the cost to construct a Ludwieg tube wind tunnel exponentially increases with Mach number. This is caused by a variety of variables, which include the increased thickness of pipe necessary to withstand high pressures at elevated temperatures, costly equipment required to deliver higher pressure, and longer supersonic nozzles.

Another critical point in this graph that is well represented below is the transition in price escalation when moving from a Mach 7 to a Mach 8 Ludwieg tube wind tunnel. For Mach number 7 and below, there is a gradual change is cost. The price keeps decreasing due to the fact that the diameter of the driver tube drops faster than the increasing thickness of steel needed to maintain facility pressures and temperatures. At Mach 8, the limit of 304 stainless steel is reached causing a reversal in the trend. The thickness of the pipe begins to grow exponentially to compensate for the sharply decreased basic allowable stress which is represented in figure 3. This transition point was taken into account during the design phase of UTSA's facility.

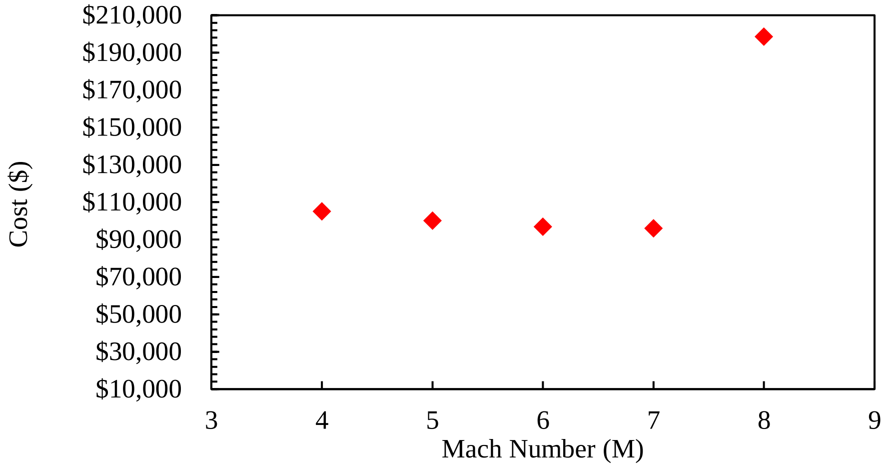

Figure 6: Price analysis for various Ludwieg tube wind tunnels designed with an 8 in x 8 in test section size, a 45% efficient diffuser exhausting to atmosphere, and undergoing external heating where required.

In an alternate attempt, a cost analysis looking at similar setups but this time exhausting to various sub atmospheric pressures was considered. For conditions exhausting to pressures lower than 1 atm, a vacuum tank and pump were included in the price analysis as these will be essential. A graph and a comparison table of the results are presented below. From the results, for Mach numbers less than 8, the wind tunnels exhausting to sub atmospheric levels proved to be more expensive due to the added costs from the vacuum pump and tank. At Mach 8, this trend reversed as the driving factor of cost became the thickness of driver tube needed to maintain costs.

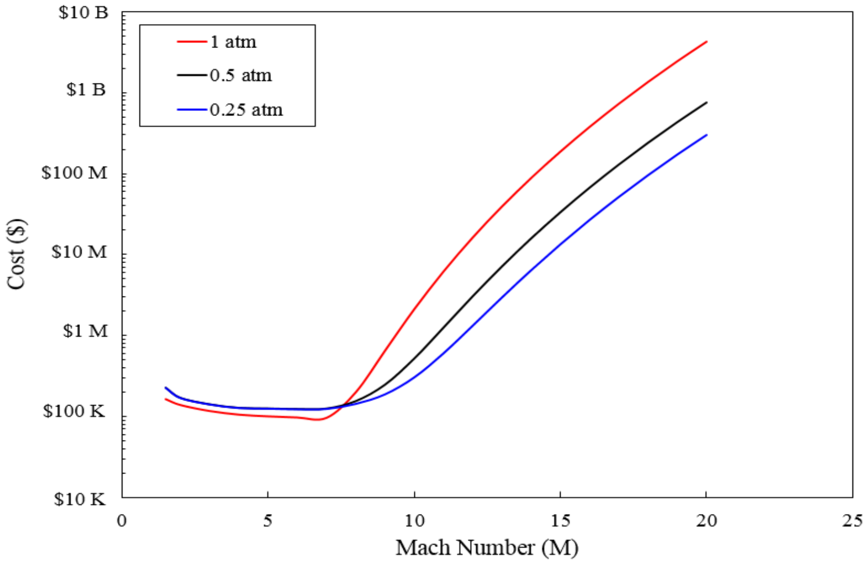

Figure 7 : Price analysis for various Mach number Ludwieg tubes design for an 8 in x 8 in test section, undergoing initial heating, equipped with a 45% efficient diffuser and exhausting to 0.25, 0.5, and 1 atm.

Table 2 : Tabular Values for results presented in Figures 6 and 7

M	1 atm	0.5 atm	.25 atm
1.5	$163,151	$225,524	$224,511
3	$116,606	$140,692	$140,040
5	$100,062	$124,958	$124,219
6	$96,901	$123,129	$122,087
7	$96,004	$124,775	$123,295
8	$198,504	$154,208	$142,333
9	$645,887	$246,017	$186,829
10	$2,105,356	$517,237	$302,363
14	$87,917,099	$15,785,193	$6,394,978
16	$376,785,735	$67,044,851	$26,774,369
18	$1,354,550,524	$240,516,224	$95,739,105
20	$4,257,563,080	$755,504,709	$300,476,047

The analysis performed above was centered on the main components of the Ludwieg tube and do not reflect costs of auxiliary piping, valves, support stands, or instrumentation.

One more analysis was performed to cover the financial effects of varying test section size at various Mach numbers. The results are presented below. From the data it can be inferred that the cost of wind tunnel facilities are directly proportional to test section size. Based on the cost analysis performed, an intermittent Mach 7 Ludwieg tube wind tunnel capable of achieving high Reynolds numbers made from 304 stainless steel fell within the fiscal capabilities and hence was chosen.

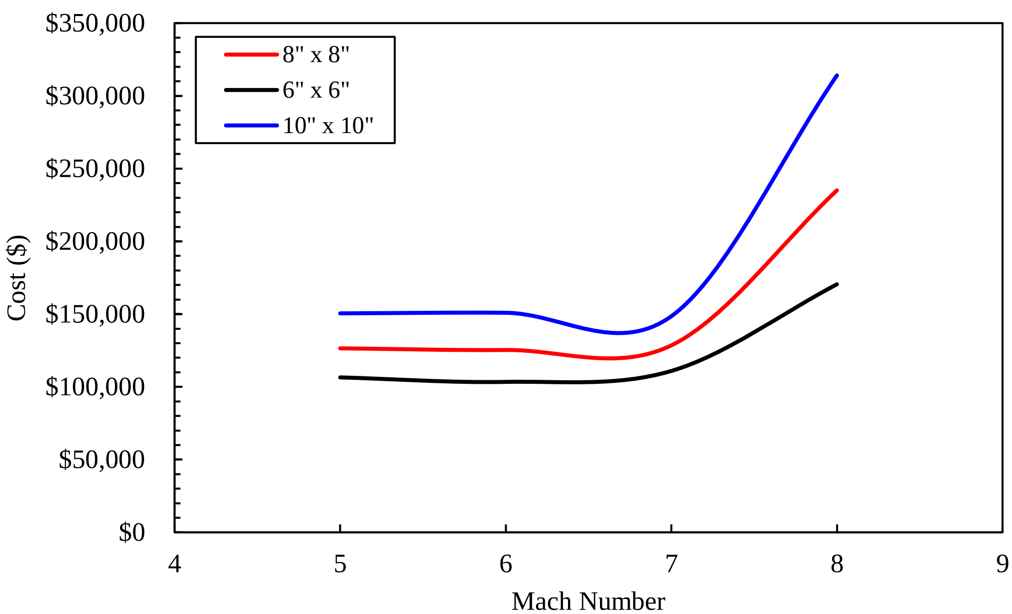

Figure 8 : Effects of test section sizing on wind tunnel cost.

IV. Major Components for UTSA's Mach 7 tunnel

A. Driver Tube

The driver tube serves as the high-pressure chamber and provides the driving force for operating the wind tunnel. Naturally, due to the role it plays, it sees the highest pressure and temperatures experienced in the facility and must be designed to handle these conditions. The driver tube designed for the UTSA tunnel represented in figure 7 is to be constructed with 60-feet of 4-inch schedule 160, 304 stainless steel pipe. Due to space constraints, there will be a U-bend installed midway to cut the length down to two equal 30-foot runs. Similar facilities under space constraints have adopted the use of the u-bend and have reported no impact on flow quality.[14] There will be two 4 inch, 1500-lb, 304 stainless steel flanges, welded on both ends of the driver tube per the design. One of the flanges will have a blind flange to seal the pipe run and the other will provide a connection point for the diaphragm. The driver tube is to be pressurized with the aid of a Max-Air 35 Electric air compressor through a connection point in the blind flange. The air compressor will be equipped with Hand-Off-Auto (H-O-A) controls allowing it to be operated remotely. Based on the mass flowrate through the system and the volume of the driver tube, it was deduced that only air from the first 20-feet of the driver tube would be used during test. As such, 13 Omega FGH102-100 high temperature heat tapes have been selected to provide external heating to raise the stagnation temperature in the driver tube to the required temperature of 700 kelvin.

B. Diaphragm

Diaphragms serve as low cost triggering devices used for setting off tests in wind tunnels. They are rivaled in use by fast acting valves.[15,16,17] The adoption of either in a wind tunnel is based on the test facility's requirements. The main two variants of diaphragms adopted for use in Ludwieg tubes are the single and double diaphragm setups. Diaphragms are designed to fail at a predetermined pressure and in a fashion that releases all the stored energy contained in a pressurized chamber. Based on the application, they can be made out of several types of material ranging from Mylar to different grades of steel. Various gauges and grades of stainless steel or aluminum are used as diaphragms in high-pressure applications and are scored or pre-tensioned to better predict the mode and pressure point of rupture.

In single diaphragm setups, a rupture disk is installed securely in a disk mount or between flanges, to prevent loss by suction to high velocity air and pressure differentials. Once in place, the pressure on the driver side of the diaphragm is increased to the test pressure at which the diaphragm fails and releases the elevated pressure. The double diaphragm setup utilizes two discs mounted in a holder that has space between both discs. When in place, the region between both discs is pressurized to a level below the rupture point of the discs and then the driver tube is brought up to test pressure. The pressurization of the region between both discs prevents the initiation of a test due to the reduced pressure gradient across the diaphragms. When ready, the chamber between the discs can be evacuated to begin the test. Of the two, the double diaphragm setup produces a more predictable and controllable rupture time. The single diaphragm setup has been adopted by UTSA for use in its facility due to ease of use and its ability to be easily modified to a double diaphragm setup.

In the UTSA application, the diaphragm will be fabricated with a bolt hole pattern and will be compressed between two 4 inch weld neck flanges. Since the diaphragm is connected directly to the driver tube, it is expected that the diaphragm will experience some elevated temperatures. This condition limits the types of material that can be used for diaphragms. Currently 304 stainless steel is being evaluated for its feasibility across the spectrum of working pressures. Alternate material such as other grades of stainless steel, aluminum and tin will be assessed for feasibility.

To have a sustainable facility, UTSA is planning on manufacturing diaphragms in house using similar techniques to those employed by Harberden.[18] Once a material has been selected, several diaphragms will be laser cut and then scored with the aid of a calibrated press. The diaphragms will be used for testing to obtain the best manufacturing process possible and to develop a relationship between scoring and bursting pressures. Scoring of diaphragms helps to provide guided failure of diaphragms and helps to prevent metal shards created during the rupture from flying downstream to damage vital components.

C. Nozzle and Test Section

The nozzle in this facility was designed using code from Dr. Rodney Bowersox (TAMU),which is based on the method of characteristics model created by Liepmann and Roshko (1957).[19] This contour is being refined through various CFD simulations to obtain the best geometry, which leads to a steady, shock free acceleration of air.[20] The nozzle on UTSA's facility is to be a modular unit built from 304 stainless steel. All the pieces of the nozzle should bolt together once machined to form a coherent assembly. The nozzle will be sealed with the aid of o-rings. It will have flanged end connections made from blind flanges milled to match the assembly of the nozzle. Locating pins will be used to perfectly align the flanged end connections between the nozzle and the test section.

The test section, similar to the nozzle, will be a modular unit made out of 304 stainless steel and will be sealed with the aid of o-rings. It is designed with observation windows on the ceiling, floor, and both sidewalls and has flanged connections for integration with the adjacent wind tunnel components. These windows can be plugged when needed. The test chamber has nominal dimensions of 8 in × 8 in and is 38.5 in long from the face of the inlet flange to face of the exit flange. The door of the test section is designed to either open horizontally using hinges or vertically with the aid of gas struts. The dual access design is to help provide greater access to the test section.

D. Diffuser

The main focus of UTSA's wind tunnel facility is to build an intermittent Mach 7 Ludwieg tube capable of attaining high Reynolds numbers. In doing so, flow quality in the test section is prioritized over the overall efficiency of the system. It was decided to go with a straight pipe model for the diffuser section. Although this route provides a rather low efficiency of 45%, it turned out to be the most cost efficient option congruent with the vision for the wind tunnel. The current diffuser will be a 12-inch piece of schedule 40, 304 stainless steel piping that has 150-lb weldneck flanges on both ends. This will connect the outlet of the test section to the vacuum tank where the test gas is to be captured before being released to the atmosphere. The current vacuum tank is sized for 6 m^3 and will be connected to a vacuum pump, which is capable of creating a backpressure as low as 2 torr.

V. Conclusion

As the desired Mach number in a test facility increases, the stagnation temperature and pressure requirements also increase. The temperature increases mainly to help prevent freezing of test medium downstream of the nozzle due to the temperature loss in the expansion process through the nozzle. Stagnation pressure also increases the Reynolds number achievable in the facility. With current mainstream material available, such as carbon steel, stainless steel, and aluminum, it is impossible to build high Mach number facilities ($M > 8$), using the method of external heating (heating strips) employed in this analysis due to unobtainable pressure and temperature combinations. One way to go around this is to reduce the back pressure at which the facility exhausts to. This technique will lower the stagnation pressure requirements at a given temperature making some Mach numbers attainable.

Based on the cost analysis conducted to predict fiscal requirements of producing a wind tunnel capable of handling elevated pressures and temperatures, it was noticed that it is not feasible to build a Ludwieg tube wind tunnel running Mach numbers greater than 8 with currently available materials. Moving from Mach 7 to 8, the cost of production severely increases making this design challenging. Also, from the approximations, it will cost exponentially more to build facilities greater than Mach 8 with every single point increment in Mach number. One reprieve to cost at Mach numbers greater than 8 as shown in the figured is exhausting to sub atmospheric pressure.

The future of wind tunnel testing relies strongly in part to the material capabilities available at the time. As seen in the analysis performed earlier on, current readily available materials tend to fail in application for high hypersonic Mach number wind tunnels. The creation of newer cost-effective materials capable of withstanding high pressures at elevated temperatures will further open the way for affordable hypersonic testing. Also, alternative techniques for heating stagnant air coherent heating of the driver tube itself could provide more opportunity for test facility advancement.

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