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Design of a supersonic wind tunnel

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DESIGN OF A SUPERSONIC WIND TUNNEL

A thesis submitted in partial fulfillment of the requirements for Honors Research in Mechanical Engineering

By

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List of Symbols

A	area
c	speed of sound
e	total stored energy per unit mass
gz	potential energy per unit mass
k	specific heat ratio
m	mass
Δm	mass differential
$\dot{m}$	mass flow rate
Ma	Mach number
$\hat{n}$	unit vector of flow
p	pressure
ρ	density
$\dot{Q}_{net_{in}}$	net rate of heat transfer
R	gas constant
T	temperature
t	time
$\check{u}$	internal energy per unit mass
V	velocity
$\dot{W}_{shaftnet_{in}}$	shaft power

Abstract

A supersonic wind tunnel was to be designed using the existing compressed air tank at the Mechanical Engineering building at the University of Arkansas. A throat area of 0.000375 m^2 was used in the design process. The properties of the air were calculated using various Mach numbers. These results are used to determine if a wind tunnel of Mach numbers between one and five can be built at the University of Arkansas and can run for a sufficient amount of time. Also, the dimensions of the supersonic wind tunnel were calculated for these various Mach numbers.

Introduction

As air travel is becoming a larger industry, the study of aerodynamics is becoming increasingly important in the understanding of the forces an object experiences as it moves through air. To aid in the understanding of the concepts of aerodynamics, wind tunnels can be used. A wind tunnel is a research device that is used to simulate drag, lift, and other forces that an object undergoes as it flows through air. They are also often used in the academic environment to help students experience the effects of air. This experience is an important aid to the theories of aerodynamics and mechanical engineering.

Francis Herbert Wenham was the first person to design and operate an enclosed wind tunnel. He did so to simulate forces on aviation objects. The simulation of forces is accomplished as air is blown or sucked through a closed test section where an object is mounted for study. To ensure accuracy of readings, the air flow must be laminar and free of turbulence. This is done by using smooth surfaces in the wind tunnel. A basic wind tunnel consists of blower units, a compressed air tank, a pressure regulator, nozzle, and a test chamber. The blower units are used to help move the air; the compressed air tank is used to store the air at a specified pressure; the pressure regulator ensures that the mass flow rate will remain constant throughout the wind tunnel; the nozzle is used to accelerate the flow of air; and the test chamber is where the aerodynamic objects are mounted for testing. But the parts of a wind tunnel can vary as result of the flow variation. For example, for wind tunnels of hypersonic speed, Mach 5 and above, a heater may be used to increase the temperature of the air before it reaches the nozzle. This is done because the temperature of the air at high speeds drops to very low temperatures as a result of the pressure drop it experiences. This pressure drop can result in liquefaction of the air. Along with the different parts of a wind tunnel, there are many types of wind tunnels. For example, a wind tunnel can be open circuit or closed circuit.

A closed circuit wind tunnel is a wind tunnel in which the air that passes through the test section is recirculated back through the test section multiple times. An advantage of this type of wind tunnel is that some energy can be recovered. There are also some disadvantages to this type of wind tunnel. These disadvantages include: a closed circuit wind tunnel is more expensive to build because of the extra return air system, and a closed circuit design is usually noisy because of the closeness of the fan. The extra noise can cause the flow in the test section to become disturbed which affects the flow in the wind tunnel.

An open circuit wind tunnel is a wind tunnel in which the air is released into the atmosphere after it goes through the test section. This type of wind tunnel also has it advantages and disadvantages. Just the opposite of a closed circuit wind tunnel, an open circuit wind tunnel is less expensive due to the lack of an extra return air system, and the flow has less turbulence. Most importantly, an open circuit wind tunnel uses less space than a closed circuit wind tunnel. A disadvantage of the open circuit wind tunnel is the flow can become cold and cause precipitation.

Another category of wind tunnels are low speed wind tunnels or high speed wind tunnels. Low speed wind tunnels are used for tests at low Mach numbers at subsonic speeds. When designing a low speed wind tunnel of Mach number less than or equal to

0.3, the air can be assumed to be an incompressible ideal gas. On the other hand, the air in a high speed wind tunnel is compressible. One can have compressible subsonic flow when the Mach is between 0.3 and 1.0 or compressible supersonic flow when the Mach number is greater than or equal 1.0. The difference between compressible and incompressible fluids is that incompressible fluids have a constant density at all points in the wind tunnel, and a velocity change in incompressible fluids has no affect on the temperature of the fluid. Incompressible fluids follow the first law of thermodynamics given by the following equation:

$$\frac{\delta}{\delta t}\int_{cv} e\rho dV + \int_{cs}\left(\check{u} + \frac{p}{\rho} + \frac{V^{2}}{2} + gz\right)\rho V * \hat{n}\, dA = \dot{Q}_{net_{in}} + \dot{W}_{shaftnet_{in}} \qquad (1)$$

Background Research

Flow in a supersonic wind tunnel is compressible because the density of air is not constant as it moves through the wind tunnel. The flow is also adiabatic, meaning there is no heat transfer, and reversible and therefore is considered isentropic. This is demonstrated when the air flows from an area to a decreased area and back to a larger area. As this process occurs the original air properties are restored. The flow through a wind tunnel is steady and mass is conserved. Therefore the conservation of mass equation can be used to model the flow of air:

$$\dot{m} = \rho AV = \text{constant} \tag{2}$$

To define the speed of the air flow in the wind tunnel a Mach number must be defined. Mach number is a dimensionless measure of compressibility and is defined as the ratio of flow velocity to the speed of sound:

$$Ma = \frac{V}{c} \tag{3}$$

where:

$$c = \sqrt{RTk} \tag{4}$$

To relate the temperature, density, and pressure for isentropic flow of an ideal gas the following gas relations can be used:

$$\left(\frac{T}{T_O}\right)^{k/(k-1)} = \left(\frac{\rho}{\rho_O}\right)^{k} = \left(\frac{p}{p_O}\right) \tag{5}$$

where the subscript O refers to the total state of air at zero flow velocity. The total state of a wind tunnel occurs at the compressed air tank.

Equations relating Mach number to temperature, pressure, and density must also be defined. Because a wind tunnel can be modeled as a converging-diverging duct, the following equations can be used:

$$\frac{T}{T_o} = \frac{1}{1+[(k-1)/2]Ma^2} \tag{6}$$

and

$$\frac{p}{p_o} = \left[\frac{1}{1+[(k-1)/2]Ma^2}\right]^{k/(k-1)} \tag{7}$$

and

$$\frac{\rho}{\rho_o} = \left[\frac{1}{1+[(k-1)/2]Ma^2}\right]^{1/(k-1)} \tag{8}$$

Equation 6, equation 7, and equation 8 allow one to calculate the temperature, pressure, and density of air anywhere in a wind tunnel. These equations show that the temperature and pressure of air decrease with an increase in Mach number. Since the flow starts from rest at the compressed air tank, the maximum allowable Mach number at the throat is one. This condition is referred to as choked flow. Substituting Mach number equal to one into equation 4, equation 5, and equation 6 the critical temperature ratio, critical pressure ratio, and critical density ratio are developed:

$$\frac{T^*}{T_o} = \frac{2}{k+1} \tag{9}$$

and

$$\frac{p^*}{p_o} = \left(\frac{2}{k+1}\right)^{k/(k-1)} \tag{10}$$

and

$$\frac{\rho^*}{\rho_o} = \left(\frac{2}{k+1}\right)^{1/(k-1)} \tag{11}$$

where the superscript * refers to the critical properties at choked flow. Using equation 2, equation 3, equation 4, equation 5, equation 7, equation 9, and equation 11 the ratio of area to critical area can be derived:

$$\frac{A}{A^*} = \frac{1}{Ma}\left[\frac{1+[(k-1)/2]Ma^2}{1+[(k-1)/2]}\right]^{(k+1)/[(2(k-1)]} \tag{12}$$

This critical area is used to determine the ratio of test section area to throat area of the wind tunnel.

Because the pressure of the tank drops as air flows out of the tank, a pressure regulator is needed to keep the mass flow rate constant throughout the wind tunnel. The following equation:

$$\Delta t = \frac{\Delta m}{\dot{m}} \tag{13}$$

can be used to determine the run time of the wind tunnel using a pressure regulator. Where Δm is the mass differential of air at different pressures.

Goal and Objectives

The goal of this honors project is to determine the parameters necessary to build a supersonic wind tunnel for the existing compressed air tank in the Mechanical Engineering building at the University of Arkansas. To accomplish this goal, the above equations were used and analysis was conducted to decide what was needed to build an inexpensive and feasible supersonic wind tunnel.

Figure 1: The existing compressed air tank at the Mechanical Engineering building at the University of Arkansas

Design Process

After measuring the compressed air tank in the Mechanical Engineering building at the University of Arkansas it was determined that its area was approximately $0.6255 m^3$. This area was used in the design of the supersonic wind tunnel. By varying the pressure in the tank from 689.5 kPa (100 psi) to 1379 kPa (200 psi) and using an ambient tank temperature of 293K and a specific heat ratio of 1.4 it was determined that the density of the air varies from 8.2 kg/m^3 to 16.4 kg/m^3 . The mass of the air was then found by multiplying the volume of the tank by the density of air. This calculation found that the mass of air varied from 5.1 kg to 10.3 kg. Equation 1 was then used to determine the mass flow rate throughout the wind tunnel. It was found that the mass flow rate varied from 0.67 kg/s to 1.3 kg/s.

After conducting research, a throat area of 0.000375 m^2 was assumed to determine the remaining parameters of a supersonic wind tunnel. Assuming that the flow was choked at the throat, equation 9, equation 10, and equation 11 were used to determine the temperature, pressure, and density of air at the throat. The tables of results are shown in Figures 3-7 in Appendix A. From these results and equation 6, equation 7, and equation 8 the temperature, pressure, and density of the air the test section was found by varying the Mach number at the test section. The tables of results are shown in Figures 8-12 in Appendix A.

The next step was to find the effects of a pressure regulator. Equation 13 was used to find the effects of a pressure regulator on the run time of the supersonic wind tunnel.

By varying the pressure downstream of the regulator, the run time can be calculated. The results can be seen in Figures 13-18 of Appendix A.

The last step in the design process was to determine the test section dimensions. This was done using equation 12. An angle of 20 degrees was used in the design of the transition of the throat to test section. Also, the length and width of the throat were changed to determine the final dimensions of the test section. After analysis a throat dimension of 4 cm x 0.9375 cm (width x height) was used. The results of the dimensions of the test section are shown in Figure 19.

Conclusion

After using the previously mentioned equations to find the properties of air and the assumptions previously stated, it was concluded that a wind tunnel of Mach number between one and five would run a sufficient amount of time. While they all may run long enough, it was calculated that wind tunnels of Mach number greater than or equal to four would need a pre-heat system in the form of a heater or dryer. The presence of a pre-heat system would increase the cost to build a supersonic wind tunnel a significant amount. For engineering purposes at the University of Arkansas, a pre-heat system for a supersonic wind tunnel is not necessary, and therefore wind tunnels of Mach number less than four would be best.

Discussion

The following is a list of some of the necessary materials needed for the design of the aforementioned supersonic wind tunnel:

- Adjustable pressure regulator for pressures between 50 psi and 100 psi and valve area greater than 0.000375 m^2.
- Tubing that gradually transforms from a circular area to a rectangular area.
- Throat with dimensions of 4 cm x 0.09375 cm.
- Test section with dimensions of: 4 cm x 0.0938 cm (Mach 1)
  4 cm x 1.103 cm (Mach 1.5)
  4 cm x 1.582 cm (Mach 2)
  4 cm x 2.472 cm (Mach 2.5)
  4 cm x 3.970 cm (Mach 3)
  4 cm x 6.365 cm (Mach 3.5)
  4 cm x 10.049 cm (Mach 4)
  4 cm x 15.527 cm (Mach 4.5)
  4 cm x 23.438 cm (Mach 5)

Some further considerations:

- Reynolds number calculations
- Simulation of flow for various nozzle contours

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Appendix A: Data Tables

tank pressure (psi)	tank pressure (Pa)	gas constant (J/kg*K)	tank temperature (K)	tank density (kg/m^3)	specific heat ratio	c (m/s)	throat velocity (m/s)
100	689500	287	293	8.199451	1.4	343.1143	343.1142667
125	861875	287	293	10.24931	1.4	343.1143	343.1142667
150	1034250	287	293	12.29918	1.4	343.1143	343.1142667
175	1206625	287	293	14.34904	1.4	343.1143	343.1142667
200	1379000	287	293	16.3989	1.4	343.1143	343.1142667

throat area (m^2)	volume of tank (m^3)	mass of air (kg)	mass flow rate (kg/s)
0.000375	0.62549998	5.128756187	0.668808344
0.000375	0.62549998	6.410945234	0.836010429
0.000375	0.62549998	7.693134281	1.003212515
0.000375	0.62549998	8.975323328	1.170414601
0.000375	0.62549998	10.25751237	1.337616687

Figure 2: Table showing the assumed parameters and calculations of tank density, throat velocity, mass of air, and mass flow rate.

at throat (100psi)					
Mach Number	throat temperature (K)	throat pressure (Pa)	throat pressure (kPa)	throat density (kg/m^3)	mass flow rate (kg/s)
1	244.1666667	364250.3	364.250293	5.197945	0.668808344

Figure 3: Table showing the conditions of air at the throat with a tank pressure of 100 psi

at throat (125 psi)					
Mach Number	throat temperature (K)	throat pressure (Pa)	throat pressure (kPa)	throat density (kg/m^3)	mass flow rate (kg/s)
1	244.1666667	455312.9	455.312866	6.497431	0.836010429

Figure 4: Table showing the conditions of air at the throat with a tank pressure of 125 psi

at throat (150 psi)					
Mach Number	throat temperature (K)	throat pressure (Pa)	throat pressure (kPa)	throat density (kg/m^3)	mass flow rate (kg/s)
1	244.1666667	546375.4	546.375439	7.796917	1.003212515

Figure 5: Table showing the conditions of air at the throat with a tank pressure of 150 psi

at throat (175 psi)					
Mach Number	throat temperature (K)	throat pressure (Pa)	throat pressure (kPa)	throat density (kg/m^3)	mass flow rate (kg/s)
1	244.1666667	637438	637.438012	9.096403	1.170414601

Figure 6: Table showing the conditions of air at the throat with a tank pressure of 175 psi

at throat (200 psi)					
Mach Number	throat temperature (K)	throat pressure (Pa)	throat pressure (kPa)	throat density (kg/m^3)	mass flow rate (kg/s)
1	244.1666667	728500.6	728.500585	10.39589	1.337616687

Figure 7: Table showing the conditions of air at the throat with a tank pressure of 200 psi

at test section (100 psi)							
Mach Number	test section temperature (K)	test section pressure (Pa)	test section pressure (kPa)	test section density (kg/m^3)	test section area (m^2)	test section area (mm^2)	Instantaneous mass flow rate (kg/s)
1	244.166667	364250.2926	364.2502926	8.637895915	0.000375	375	1.111419496
1.25	223.238095	266186.8998	266.1868998	8.86191161	0.000392532	392.5323486	1.19355282
1.5	202.068966	187821.9143	187.8219143	9.117796541	0.000441063	441.0626447	1.379840699
1.75	181.705426	129504.6132	129.5046132	9.398756294	0.000519935	519.934518	1.676709465
2	162.777778	88121.22031	88.12122031	9.698839106	0.000632813	632.8125	2.105879808
2.25	145.590062	59629.15553	59.62915553	10.01305118	0.000786163	786.1631417	2.700958373
2.5	130.222222	40354.82396	40.35482396	10.3373288	0.00098877	988.7695313	3.507051809
2.75	116.616915	27426.03488	27.42603488	10.66843643	0.001251622	1251.621593	4.581551756
3	104.642857	18770.72991	18.77072991	11.00383807	0.001587963	1587.962963	5.995471408
3.25	94.1365462	12961.38796	12.96138796	11.34156907	0.00201341	2013.410128	7.835093208
3.5	84.9275362	9039.979336	9.039979336	11.68012127	0.002546108	2546.107701	10.20382258
3.75	76.852459	6372.352435	6.372352435	12.01834623	0.003206903	3206.902963	13.22419689
4	69.7619048	4541.107199	4.541107199	12.35537636	0.004019531	4019.53125	17.04002255
4.25	63.5230352	3271.575472	3.271575472	12.69056219	0.005010808	5010.807711	21.81862485
4.5	58.019802	2382.39872	2.38239872	13.02342302	0.006210823	6210.822965	27.75320053
4.75	53.1519274	1753.130163	1.753130163	13.35360851	0.007653141	7653.141223	35.06526647
5	48.8333333	1303.181464	1.303181464	13.68086893	0.009375	9375	44.00719978

Figure 8: Table showing the conditions of air with a tank temperature of 100 psi

at test section (125 psi)							
Mach Number	test section temperature (K)	test section pressure (Pa)	test section pressure (kPa)	test section density (kg/m^3)	test section area (m^2)	test section area (mm^2)	instantaneous mass flow rate (kg/s)
1	244.166667	455312.8658	455.3128658	10.79736989	0.000375	375	1.38927437
1.25	223.238095	332733.6248	332.7336248	11.07738951	0.000392532	392.5323486	1.491941025
1.5	202.068966	234777.3929	234.7773929	11.39724568	0.000441063	441.0626447	1.724800874
1.75	181.705426	161880.7664	161.8807664	11.74844537	0.000519935	519.934518	2.095886831
2	162.777778	110151.5254	110.1515254	12.12354888	0.000632813	632.8125	2.63234976
2.25	145.590062	74536.44441	74.53644441	12.51631398	0.000786163	786.1631417	3.376197967
2.5	130.222222	50443.52995	50.44352995	12.921661	0.00098877	988.7695313	4.383814761
2.75	116.616915	34282.5436	34.2825436	13.33554553	0.001251622	1251.621593	5.726939695
3	104.642857	23463.41239	23.46341239	13.75479759	0.001587963	1587.962963	7.49433926
3.25	94.1365462	16201.73495	16.20173495	14.17696134	0.00201341	2013.410128	9.793866511
3.5	84.9275362	11299.97417	11.29997417	14.60015159	0.002546108	2546.107701	12.75477823
3.75	76.852459	7965.440544	7.965440544	15.02293279	0.003206903	3206.902963	16.53024611
4	69.7619048	5676.383999	5.676383999	15.44422046	0.004019531	4019.53125	21.30002818
4.25	63.5230352	4089.469339	4.089469339	15.86320274	0.005010808	5010.807711	27.27328107
4.5	58.019802	2977.9984	2.9779984	16.27927877	0.006210823	6210.822965	34.69150067
4.75	53.1519274	2191.412703	2.191412703	16.69201064	0.007653141	7653.141223	43.83158309
5	48.8333333	1628.97683	1.62897683	17.10108616	0.009375	9375	55.00899973

Figure 9: Table showing the conditions of air with a tank temperature of 125 psi

at test section (150 psi)							
Mach Number	test section temperature (K)	test section pressure (Pa)	test section pressure (kPa)	test section density (kg/m^3)	test section area (m^2)	test section area (mm^2)	instantaneous mass flow rate (kg/s)
1	244.166667	546375.4389	546.3754389	12.95684387	0.000375	375	1.667129244
1.25	223.238095	399280.3498	399.2803498	13.29286742	0.000392532	392.5323486	1.79032923
1.5	202.068966	281732.8715	281.7328715	13.67669481	0.000441063	441.0626447	2.069761049
1.75	181.705426	194256.9197	194.2569197	14.09813444	0.000519935	519.934518	2.515064197
2	162.777778	132181.8305	132.1818305	14.54825866	0.000632813	632.8125	3.158819713
2.25	145.590062	89443.73329	89.44373329	15.01957677	0.000786163	786.1631417	4.05143756
2.5	130.222222	60532.23594	60.53223594	15.5059932	0.00098877	988.7695313	5.260577713
2.75	116.616915	41139.05232	41.13905232	16.00265464	0.001251622	1251.621593	6.872327634
3	104.642857	28156.09487	28.15609487	16.50575711	0.001587963	1587.962963	8.993207113
3.25	94.1365462	19442.08194	19.44208194	17.01235361	0.00201341	2013.410128	11.75263981
3.5	84.9275362	13559.969	13.559969	17.52018191	0.002546108	2546.107701	15.30573388
3.75	76.852459	9558.528652	9.558528652	18.02751935	0.003206903	3206.902963	19.83629533
4	69.7619048	6811.660798	6.811660798	18.53306455	0.004019531	4019.53125	25.56003382
4.25	63.5230352	4907.363207	4.907363207	19.03584329	0.005010808	5010.807711	32.72793728
4.5	58.019802	3573.59808	3.57359808	19.53513452	0.006210823	6210.822965	41.6298008
4.75	53.1519274	2629.695244	2.629695244	20.03041277	0.007653141	7653.141223	52.59789971
5	48.8333333	1954.772196	1.954772196	20.52130339	0.009375	9375	66.01079967

Figure 10: Table showing the conditions of air with a tank temperature of 150 psi

at test section (175 psi)							
Mach Number	test section temperature (K)	test section pressure (Pa)	test section pressure (kPa)	test section density (kg/m^3)	test section area (m^2)	test section area (mm^2)	instantaneous mass flow rate (kg/s)
1	244.166667	637438.0121	637.4380121	15.11631785	0.000375	375	1.944984118
1.25	223.238095	465827.0747	465.8270747	15.50834532	0.000392532	392.5323486	2.088717435
1.5	202.068966	328688.3501	328.6883501	15.95614395	0.000441063	441.0626447	2.414721223
1.75	181.705426	226633.073	226.633073	16.44782351	0.000519935	519.934518	2.934241563
2	162.777778	154212.1355	154.2121355	16.97296844	0.000632813	632.8125	3.685289665
2.25	145.590062	104351.0222	104.3510222	17.52283957	0.000786163	786.1631417	4.726677153
2.5	130.222222	70620.94193	70.62094193	18.0903254	0.00098877	988.7695313	6.137340665
2.75	116.616915	47995.56104	47.99556104	18.66976374	0.001251622	1251.621593	8.017715573
3	104.642857	32848.77735	32.84877735	19.25671663	0.001587963	1587.962963	10.49207496
3.25	94.1365462	22682.42893	22.68242893	19.84774587	0.00201341	2013.410128	13.71141311
3.5	84.9275362	15819.96384	15.81996384	20.44021223	0.002546108	2546.107701	17.85668952
3.75	76.852459	11151.61676	11.15161676	21.0321059	0.003206903	3206.902963	23.14234455
4	69.7619048	7946.937598	7.946937598	21.62190864	0.004019531	4019.53125	29.82003946
4.25	63.5230352	5725.257075	5.725257075	22.20848384	0.005010808	5010.807711	38.1825935
4.5	58.019802	4169.19776	4.16919776	22.79099028	0.006210823	6210.822965	48.56810093
4.75	53.1519274	3067.977785	3.067977785	23.36881489	0.007653141	7653.141223	61.36421633
5	48.8333333	2280.567562	2.280567562	23.94152063	0.009375	9375	77.01259962

Figure 11: Table showing the conditions of air with a tank temperature of 175 psi

at test section (200 psi)							
Mach Number	test section temperature (K)	test section pressure (Pa)	test section pressure (kPa)	test section density (kg/m^3)	test section area (m^2)	test section area (mm^2)	instantaneous mass flow rate (kg/s)
1	244.166667	728500.5853	728.5005853	17.27579183	0.000375	375	2.222838992
1.25	223.238095	532373.7997	532.3737997	17.72382322	0.000392532	392.5323486	2.38710564
1.5	202.068966	375643.8287	375.6438287	18.23559308	0.000441063	441.0626447	2.759681398
1.75	181.705426	259009.2263	259.0092263	18.79751259	0.000519935	519.934518	3.353418929
2	162.777778	176242.4406	176.2424406	19.39767821	0.000632813	632.8125	4.211759617
2.25	145.590062	119258.3111	119.2583111	20.02610236	0.000786163	786.1631417	5.401916747
2.5	130.222222	80709.64792	80.70964792	20.6746576	0.00098877	988.7695313	7.014103618
2.75	116.616915	54852.06976	54.85206976	21.33687285	0.001251622	1251.621593	9.163103512
3	104.642857	37541.45983	37.54145983	22.00767615	0.001587963	1587.962963	11.99094282
3.25	94.1365462	25922.77592	25.92277592	22.68313814	0.00201341	2013.410128	15.67018642
3.5	84.9275362	18079.95867	18.07995867	23.36024255	0.002546108	2546.107701	20.40764517
3.75	76.852459	12744.70487	12.74470487	24.03669246	0.003206903	3206.902963	26.44839377
4	69.7619048	9082.214398	9.082214398	24.71075273	0.004019531	4019.53125	34.08004509
4.25	63.5230352	6543.150943	6.543150943	25.38112438	0.005010808	5010.807711	43.63724971
4.5	58.019802	4764.79744	4.76479744	26.04684603	0.006210823	6210.822965	55.50640107
4.75	53.1519274	3506.260325	3.506260325	26.70721702	0.007653141	7653.141223	70.13053295
5	48.8333333	2606.362928	2.606362928	27.36173786	0.009375	9375	88.01439956

Figure 12: Table showing the conditions of air with a tank temperature of 200 psi

pressure differential (psi)	del m (kg)	m dot (kg/s)	del t (s)
70-50	1.025751237	0.334404172	3.067399644
80-50	1.538626856	0.334404172	4.601099466
90-50	2.051502475	0.334404172	6.134799288
100-50	2.564378094	0.334404172	7.66849911
110-50	3.077253712	0.334404172	9.202198932
120-50	3.590129331	0.334404172	10.73589875
130-50	4.10300495	0.334404172	12.26959858
140-50	4.615880569	0.334404172	13.8032984
150-50	5.128756187	0.334404172	15.33699822
160-50	5.641631806	0.334404172	16.87069804
170-50	6.154507425	0.334404172	18.40439786
180-50	6.667383044	0.334404172	19.93809769
190-50	7.180258662	0.334404172	21.47179751
200-50	7.693134281	0.334404172	23.00549733

Figure 13: Table showing the calculation of run time with a pressure regulator with reference to 50 psi

pressure differential (psi)	del m (kg)	m dot (kg/s)	del t (s)
80-60	1.025751237	0.401285006	2.55616637
90-60	1.538626856	0.401285006	3.834249555
100-60	2.051502475	0.401285006	5.11233274
110-60	2.564378094	0.401285006	6.390415925
120-60	3.077253712	0.401285006	7.66849911
130-60	3.590129331	0.401285006	8.946582295
140-60	4.10300495	0.401285006	10.22466548
150-60	4.615880569	0.401285006	11.50274866
160-60	5.128756187	0.401285006	12.78083185
170-60	5.641631806	0.401285006	14.05891503
180-60	6.154507425	0.401285006	15.33699822
190-60	6.667383044	0.401285006	16.6150814
200-60	7.180258662	0.401285006	17.89316459

Figure 14: Table showing the calculation of run time with a pressure regulator with reference to 60 psi

pressure differential (psi)	del m (kg)	m dot (kg/s)	del t (s)
90-70	1.025751237	0.468165841	2.190999746
100-70	1.538626856	0.468165841	3.286499618
110-70	2.051502475	0.468165841	4.381999491
120-70	2.564378094	0.468165841	5.477499364
130-70	3.077253712	0.468165841	6.572999237
140-70	3.590129331	0.468165841	7.66849911
150-70	4.10300495	0.468165841	8.763998983
160-70	4.615880569	0.468165841	9.859498855
170-70	5.128756187	0.468165841	10.95499873
180-70	5.641631806	0.468165841	12.0504986
190-70	6.154507425	0.468165841	13.14599847
200-70	6.667383044	0.468165841	14.24149835

Figure 15: Table showing the calculation of run time with a pressure regulator with reference to 70 psi

pressure differential (psi)	del m (kg)	m dot (kg/s)	del t (s)
100-80	1.025751237	0.535046675	1.917124777
110-80	1.538626856	0.535046675	2.875687166
120-80	2.051502475	0.535046675	3.834249555
130-80	2.564378094	0.535046675	4.792811944
140-80	3.077253712	0.535046675	5.751374332
150-80	3.590129331	0.535046675	6.709936721
160-80	4.10300495	0.535046675	7.66849911
170-80	4.615880569	0.535046675	8.627061499
180-80	5.128756187	0.535046675	9.585623887
190-80	5.641631806	0.535046675	10.54418628
200-80	6.154507425	0.535046675	11.50274866

Figure 16: Table showing the calculation of run time with a pressure regulator with reference to 80 psi

pressure differential (psi)	del m (kg)	m dot (kg/s)	del t (s)
110-90	1.025751237	0.601927509	1.704110913
120-90	1.538626856	0.601927509	2.55616637
130-90	2.051502475	0.601927509	3.408221827
140-90	2.564378094	0.601927509	4.260277283
150-90	3.077253712	0.601927509	5.11233274
160-90	3.590129331	0.601927509	5.964388197
170-90	4.10300495	0.601927509	6.816443653
180-90	4.615880569	0.601927509	7.66849911
190-90	5.128756187	0.601927509	8.520554566
200-90	5.641631806	0.601927509	9.372610023

Figure 17: Table showing the calculation of run time with a pressure regulator with reference to 90 psi

pressure differential (psi)	del m (kg)	m dot (kg/s)	del t (s)
120-100	1.025751237	0.668808344	1.533699822
130-100	1.538626856	0.668808344	2.300549733
140-100	2.051502475	0.668808344	3.067399644
150-100	2.564378094	0.668808344	3.834249555
160-100	3.077253712	0.668808344	4.601099466
170-100	3.590129331	0.668808344	5.367949377
180-100	4.10300495	0.668808344	6.134799288
190-100	4.615880569	0.668808344	6.901649199
200-100	5.128756187	0.668808344	7.66849911

Figure 18: Table showing the calculation of run time with a pressure regulator with reference to 100 psi

Throat Width (m)	Throat Height (m)	Throat Area (m^2)	Mach Number	A/A*	Area (m^2)
0.04	0.009375	0.000375	1	1	0.000375
0.04	0.009375	0.000375	1.5	1.176167052	0.000441063
0.04	0.009375	0.000375	2	1.6875	0.000632813
0.04	0.009375	0.000375	2.5	2.63671875	0.00098877
0.04	0.009375	0.000375	3	4.234567901	0.001587963
0.04	0.009375	0.000375	3.5	6.789620536	0.002546108
0.04	0.009375	0.000375	4	10.71875	0.004019531
0.04	0.009375	0.000375	4.5	16.56219457	0.006210823
0.04	0.009375	0.000375	5	25	0.009375

Height (m)	Height (cm)	Height (mm)	Angle (deg)	Angle (rad)	Length (m)	Length (mm)
0.009375	0.9375	9.375	20	0.34906585	0	0
0.011026566	1.10265661	11.02656612	20	0.34906585	0.004537641	4.537640613
0.015820313	1.58203125	15.8203125	20	0.34906585	0.017708351	17.70835056
0.024719238	2.47192383	24.71923828	20	0.34906585	0.042157948	42.1579482
0.039699074	3.96990741	39.69907407	20	0.34906585	0.083314709	83.31470878
0.063652693	6.36526925	63.65269252	20	0.34906585	0.149126735	149.1267346
0.100488281	10.0488281	100.4882813	20	0.34906585	0.250331683	250.3316828
0.155270574	15.5270574	155.2705741	20	0.34906585	0.400844795	400.8447955
0.234375	23.4375	234.375	20	0.34906585	0.618182419	618.1824194

Figure 19: Table showing the dimensions of the wind tunnel based on a throat area of 0.04 m x 0.009375 m

Appendix B: Graphs

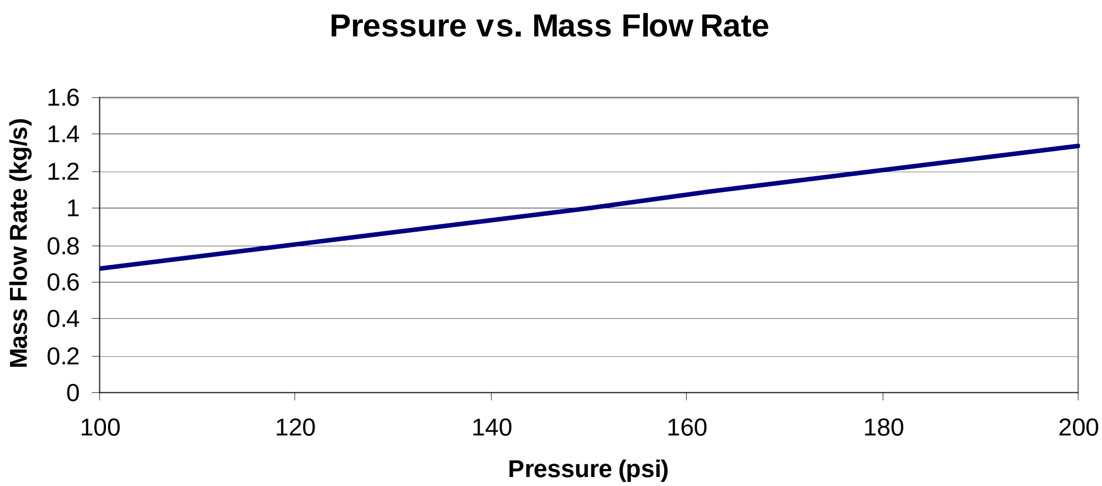

Figure 20: Graph showing the relationship between tank pressure and mass flow rate

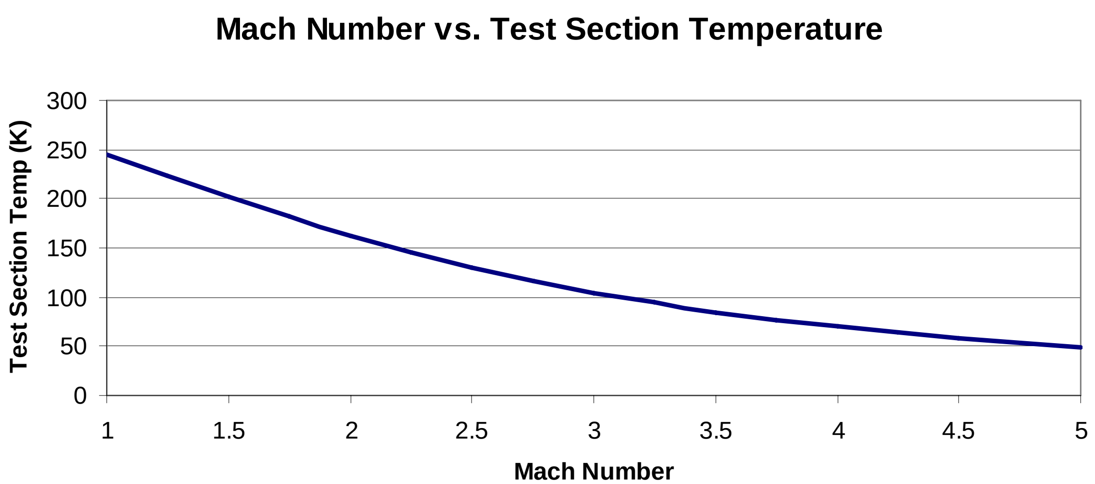

Figure 21: Graph showing Mach number versus test section temperature

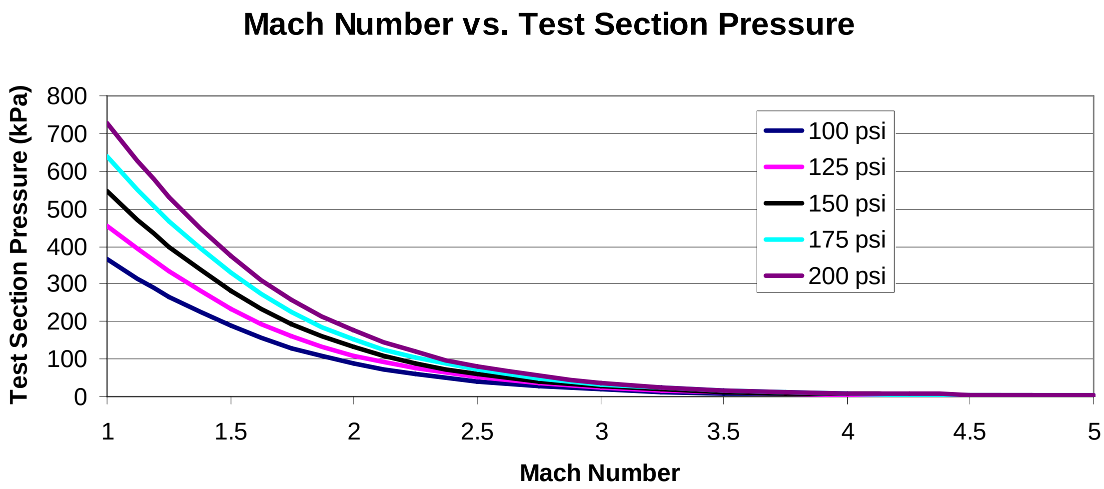

Figure 22: Graph showing Mach number versus test section pressure for various pressures

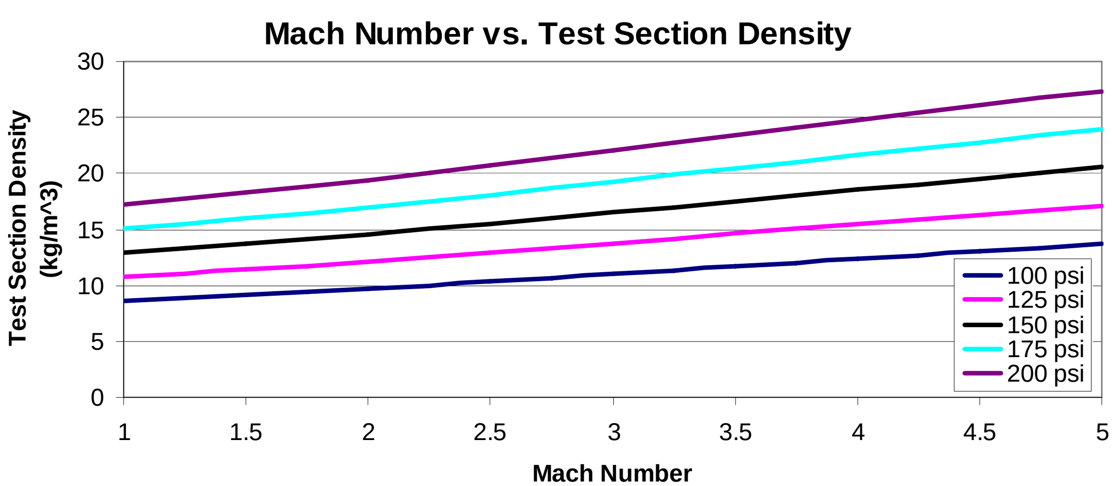

Figure 23: Graph showing Mach number versus test section density for various pressures

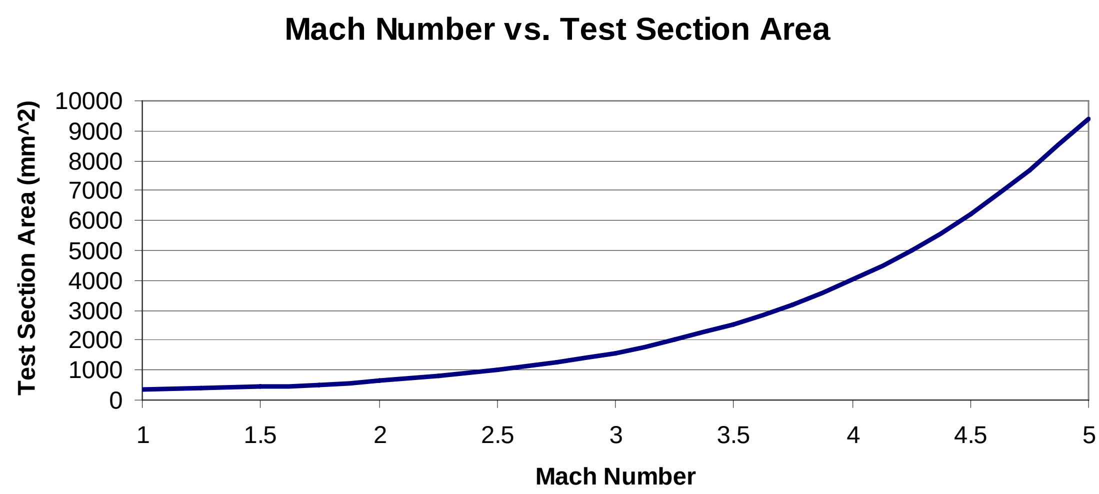

Figure 24: Graph showing Mach number versus test section area

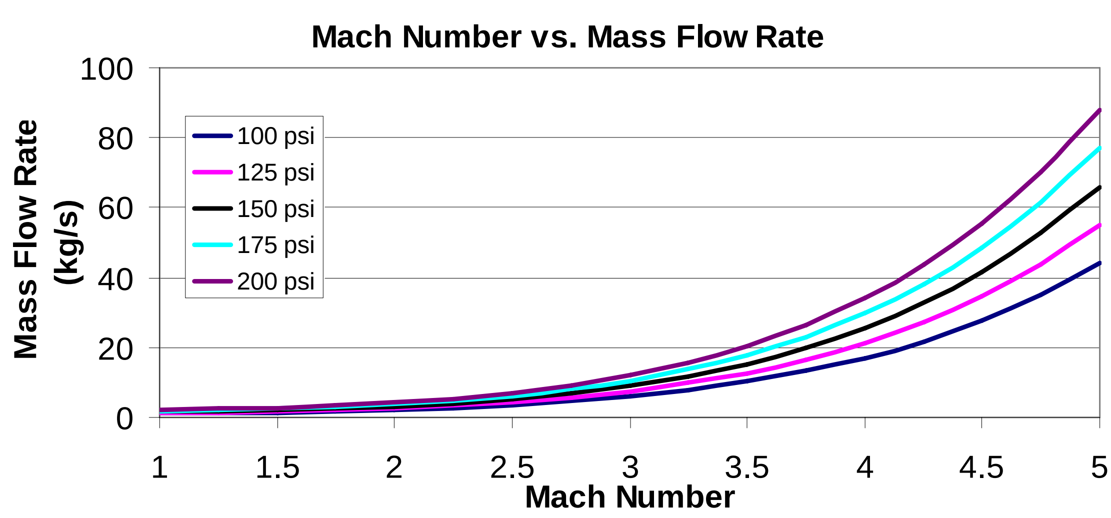

Figure 25: Graph showing Mach number versus mass flow rate for various pressures