Increasing the Actively Controlled Expansion Wind Tunnel's Mach and Reynolds number operating ranges

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One of the major issues currently faced by the Actively Controlled Expansion (ACE) high speed wind tunnel is liquefaction of the air in the tunnel test section during certain testing conditions. A ubiquitous problem in high speed wind tunnel testing, liquefaction refers to the condensation of oxygen out of air at certain thermodynamic gas states determined by flow conditions. The formation of this condensate can lead to error in pressure fluctuation readings, hence rendering the flow data unreliable. One way to combat this issue is to strategically increase the thermal capacity of the tunnel infrastructure. As can be proven by the basic isentropic flow relations, increasing the temperature of the air which reaches the test section increases the testing envelope of Reynolds and Mach numbers, thus opening the door for a plethora of novel high speed flow experiments. In addition, greater thermal capacity of the tunnel will reduce preheat running times which will save valuable compressed air needed to run the tunnels. Using commercially available heaters in conjunction with several PID controllers, a setup was designed and installed which successfully heated key ACE tunnel sections.

Nomenclature

Λ	=	ratio of settling chamber pressure to diffuser pressure
M	=	Mach Number (ratio of air velocity to the local speed of sound)
Re	=	Reynolds Number (ratio of inertial to viscous forces in the flow)
T_t	=	Settling Chamber Static Temperature
P_t	=	Settling Chamber Static Pressure

I. Introduction

THE Actively Controlled Expansion tunnel, currently located at the National Aerothermochemistry Laboratory at Easterwood Airport, is a high speed wind tunnel used to perform fundamental hypersonic aerodynamics research. As a typical blowdown high speed wind tunnel, compressed air at 2400 drives the air through the tunnel's test section. The tunnel produces test flows with speeds of Mach 5 – 7+ (depending on the configuration of the inlet nozzle) and a Reynolds numbers typically on the order of $1x10^6$. A side view of the tunnel can be seen in figure 1.

Fig. 1: Side view of ACE tunnel settling chamber, nozzle, expansion chamber, and diffuser

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The tunnel has the capability of producing speeds of Mach 8 and higher Reynolds numbers in the test section, but it is at these conditions that liquefaction begins. The motivation behind eliminating the liquefaction in the test section lies in the negative effects of the condensate. Frequently, data taken during the high speed tests is of the pressure gradients in the boundary layers. As can be seen in figure 2, the fluctuations in pitot pressure readings in the test section increase by an order of magnitude in the presence of liquefaction, thus rendering any recorded data useless.

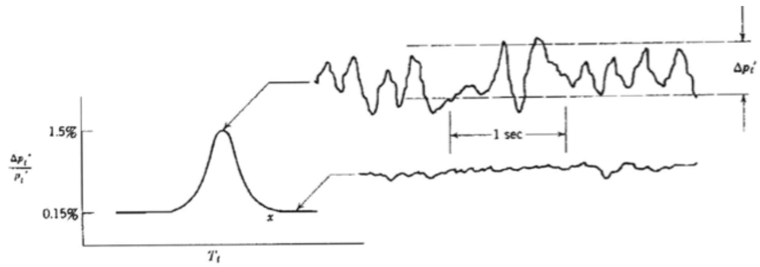

Fig. 2: Fluctuations in Pitot pressure readings in the presence of liquefaction[1]

In addition, these pressure fluctuations cause a fluctuation in Mach number producing unsteady testing conditions.

Through a combination of experiments and calculations assuming isentropic flow in the test section, an operational curve for the ACE tunnel was produced. Figure 3 below shows the operational limits of the ACE tunnel.

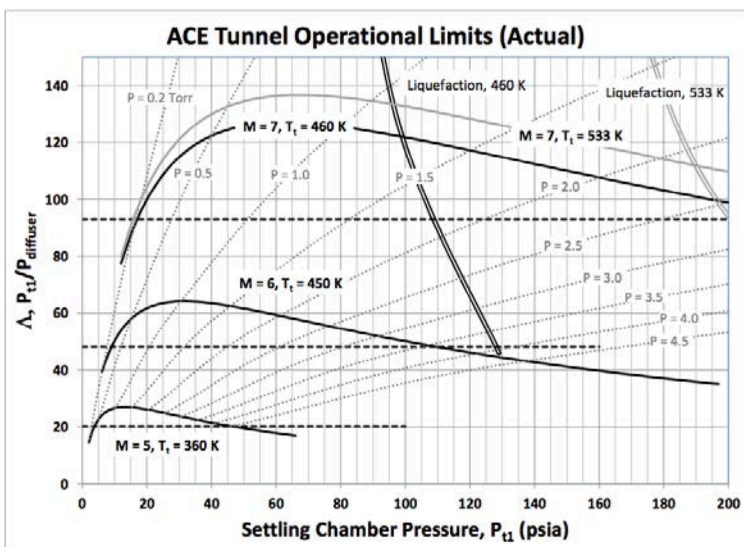

Fig. 3: ACE operational limits [2]

In figure 3, the horizontal dotted lines correspond to the necessary Λ ratio that will keep the tunnel from "unstarting" (flow in the tunnel test section becoming subsonic from supersonic) for a diffuser with 75% efficiency [2]. The dark lines indicate the relationship between the settling chamber pressure and the Λ ratio based on the indicated Mach number and settling chamber temperature. The tunnel can operate at supersonic speeds in the region bounded by the dark lines and the dotted line. Also included on the graph are liquefaction lines. Liquefaction will occur in the tunnel testing section anywhere to the right of the liquefaction lines. The conditions in which liquefaction occurs is a combination of air speed, pressure, and temperature, all of which can be related through the isentropic flow equations. Pressure and temperature in the settling chamber are measured using a piezoelectric transducer and a quick response thermocouple probe respectively [2]. A static pressure port in the nozzle and a pitot probe in the test section are used to monitor Mach number. Analyzing the contraction area to nozzle area ratio allows the Mach number to be set (as the nozzle area in ACE is adjustable). Once the Mach number is set, with the settling chamber pressure known a test section pressure can be calculated. By relating this value with the mass flow, pressure ratios in front of and behind the shock wave, and the pressure on the vacuum side of the tunnel, a pressure in the diffuser can be found. With this information we have a Λ ratio and can graph P_{t1} vs Λ. The double liquefaction line creation was started with picking a Mach number and settling chamber temperature. With these values a test section temperature could be calculated using isentropic flow equations. Then through the use of a static saturation graph for air, the pressure at which the air will condensate can be found. Finally, this value can be used to calculate the static pressure in the test section and the Λ ratio where liquefaction will occur.

In figure 3, two operational curves are indicated for flows of Mach 7. The first curve (dark) is the current operational limits with the static temperature of the air in the settling chamber at 460 K. The lighter (gray) curve is the operational curve of the tunnel if the static temperature of the air in the settling chamber is 533 K. At Mach 7 with air temperatures of 460 K tests can be run at pressures of approximately 97 psi before liquefaction occurs, whereas with air temperatures of 533 K tests can be run at pressures of approximately 190 psi before liquefaction occurs. This increase in pressure testing envelope directly correlates to an increase in Reynolds number testing envelope. Figure 4 examines this relationship.

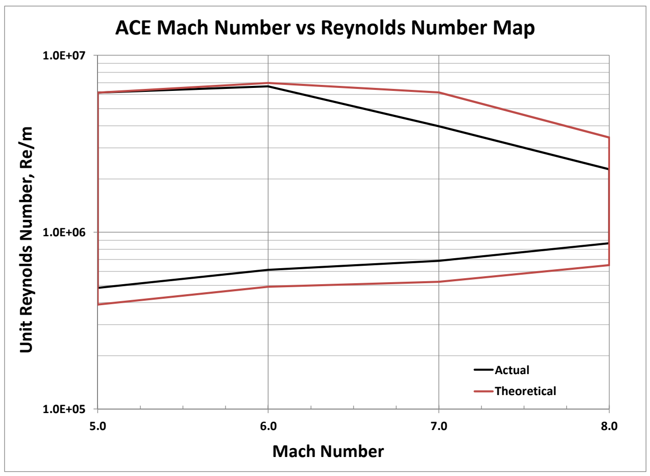

Fig. 4: Mach Number vs Reynolds number. The black line indicates the current operational limits while the red line is the theoretical limit if the air in the settling chamber was 533 K [2]

In addition to the effect on Reynolds number, figure 3 could be expanded to show that increasing air temperatures in the settling chamber allows tests to be run at higher Mach numbers without liquefaction occurring (granted the temperatures are sufficiently high).

II. Experimental Design

Currently, before a high speed test can be performed a preheating run is required where heated compressed air is passed through the tunnel at subsonic speeds. This air serves to heat the lines to operational temperature. Unfortunately this process uses valuable compressed air necessary to power the tunnel and is insufficient in heating the air to the desired temperatures. Therefore, in order to further increase the temperature of the air we sought to found the locations along tunnel length where the largest heat loss was taking place. We determined that the filter (which eliminates particulates in the air before it enters the settling chamber) and the settling chamber compromised the two largest heat loss zones. Both items are rated to 490^{o} Farenheit (527 K) but currently do not have any external heating devices on them.

A. Filter

With the aid of Solidworks models and simple heat transfer equations we calculated the amount of power required to heat each respective element in approximately one hour. For the filter this was found to be approximately 1250 W. Due to the cylindrical shape of the filter, two 1256W/240V Omega series STH102-080* rope heaters were chosen. An Omega CN790000 PID relay box in conjunction with a glass insulated high temperature type K thermocouple (Omega series SA1XL-K) was installed and programmed to provide power to the heaters so long as the temperature read in by the thermocouple did not exceed 490^{o} F. This experimental setup can be seen in figure 5.

Fig. 5: Filter with insulation on lower half removed and heating rope installed

Once the heating rope was successfully installed the bottom half of the custom insulation was put back in place to help the filter retain the heat.

B. Settling Chamber

Due to the box shape of the ACE settling chamber, strip heaters were chosen as the heat source. One 750W Omega model HCS-121-240V and two 250W Omega HCS-080-240V heaters were installed on the top and sides of the settling chamber respectively. Again, an Omega model CN79000 relay box in conjunction with an Omega glass insulated high temperature thermocouple were installed to automatically control power to the heaters. Two brackets were custom fabricated to hold the 250W heaters in place on the sides of the settling chamber while high temperature tape was used to secure the 750W heater in place on the top of the settling chamber.

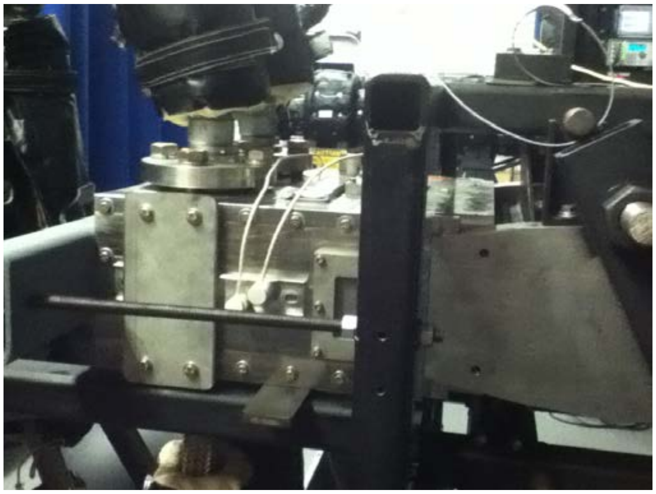

Fig. 6: Settling chamber with strip heaters installed and wired

In addition, custom fabricated insulation has been ordered which will cover the entire settling chamber.

III. Experimental Results/Conclusion

After being installed and programmed both the filter and settling chamber were successfully heated to 200^o F (366 K) and 300^o F (422 K), respectively. The heating elements successfully provided enough thermal mass to dramatically reduce the amount of air (from 300 to 150 PSI) needed to preheat the tunnel to operating temperatures. Shorter preheat times ultimately lead to longer run times providing an opportunity to collect additional data. After additional modifications to the settling chamber design are made to increase thermal limits, the upper temperature limit of the facility will be increased to the required 533K.

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