MAE 352 - Experimental Aerodynamics II
Lab 4 – Converging Nozzle Analysis
Final report due date: 04/01/2019

Objective: Using the nozzle test rig in NCSU's supersonic wind tunnel facility:

- Observe the different regimes of flow in a converging nozzle.
- Plot and study the pressure variations across the converging nozzle from no-flow to chocked flow condition.

Theory: A nozzle is a tube of varying cross-sectional area (usually axisymmetric) aiming at increasing the speed of an outflow and controlling its direction and shape. Nozzle flow always generates forces associated to the change in flow momentum. In the simplest case of a rocket nozzle, relative motion is created by ejecting mass from a chamber backwards through the nozzle, with the reaction forces acting mainly on the opposite chamber wall, with a small contribution from nozzle walls. In jet propulsion, it is in the nozzle that thermal energy (or any other kind of high-pressure energy source) transforms into kinetic energy of the exhaust, and its associated linear momentum producing thrust. The isentropic model all along the nozzle is sufficient for a first-order analysis as the flow in a nozzle is very rapid (and thus adiabatic to a first approximation) with very little frictional loses (because the flow is nearly one-dimensional with a favorable pressure gradient, except if shock waves form and nozzles are relatively short). The nozzle is said to begin where the chamber diameter begins to decrease [1].

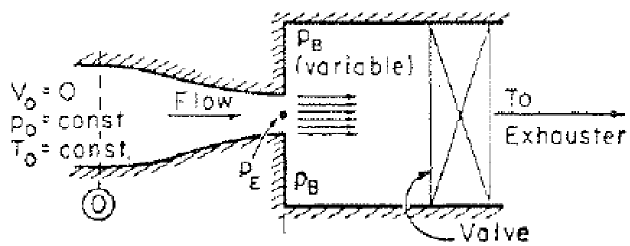

Figure 1: Schematic of a converging nozzle.

Converging nozzles, as shown in Fig. 1, are used to accelerate the fluid in subsonic gas. A converging nozzle can only become supersonic at the exit stage; the speed increases monotonically along the nozzle. If a converging nozzle is fed from a constant pressure and constant temperature chamber, the flow rate grows as the discharge pressure is being reduced, until the flow becomes sonic (choked) and the flow rate no longer changes with further decreasing in discharge-pressure (a set of expansion waves adjust the exit pressure to this lower discharge pressure). Except for old-time turbojets and military fighter aircraft, all commercial jet engines (after Concorde was retired) use converging nozzles discharging at subsonic speed (both, the hot core stream and the colder fan stream). The back pressure (p_B)/ temperature (T_B) is the driving factor that determines the flow condition in the nozzle. When $p_O = p_B$, there is no flow through the nozzle. As p_B is reduced, the Mach number at the exit (p_E) keeps rising until the flow is chocked ($M_E = 1$). The condition at which chocked flow occurs can be calculated using the isentropic relations, and for a $\gamma = 1.4$ when,

$$\frac{p_B}{p_O} = 0.5283$$

or,

$$\frac{T_B}{T_O} = 0.8333$$

the flow is said to be chocked, i.e., the Mach number no longer increases and caps off at $M = 1$. The above conditions define the boundary between the non-chocked and chocked flow regimes, as shown in Fig. 2.

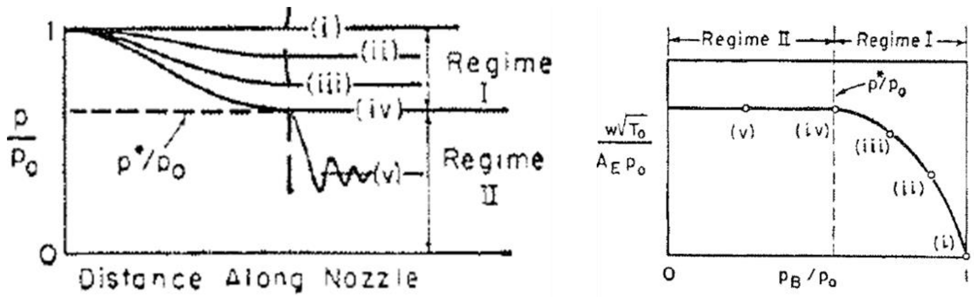

Figure 2: Flow conditions and regimes in a converging nozzle.

Based on Fig. 2, the following are the flow conditions that can be observed in a converging nozzle,

i. No flow condition, where the back pressure is equal to the total pressure.
ii. Subsonic flow, where the flow accelerates as area decreases and the pressure drops.
iii. Subsonic flow, significantly higher acceleration and pressure drops.
iv. Choked flow, where any pressure drop does not accelerate the flow.
v. Choked flow, where the flow expands after the nozzle exit (considered non-isentropic).

Experiment: Using the nozzle test rig in NCSU's supersonic wind tunnel facility, we will create a pressure driven flow using a compressed air source. The back pressure and mass flow rate will be controlled using a valve, and the pressure along the nozzle will be measured using pressure transducers. The stagnation pressure (p_O) and temperature (T_O) will be measured using a Kiel probe, and the mass flow rate will be measured using a rotameter. Record the following data at the locations shown in Fig. 3 for multiple back pressure settings:

Table 1: Data collected for the converging nozzle experiment.

Tap Number	Tap Axial Positon (inches)	Nozzle Area Ratio (A/A_i)	P_{static} (psi)	P_O (psi)	Mass Flow Rate (slugs/second)	P_{atm} (psi)
from Fig. 3	from Fig. 3	from Fig. 3	gauge pressure from Scanivalve	gauge pressure from Scanivalve	from rotameter	gauge pressure from Scanivalve

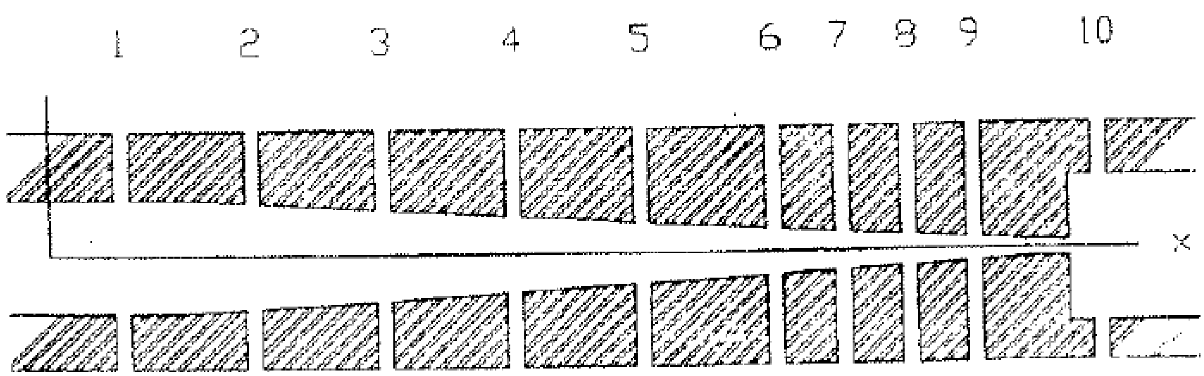

Figure 3: Geometry of converging nozzle.

The following constants can be used to help with your analysis:

1. Specific heat of dry air, γ: 1.4
2. Reference nozzle area, A_i = 3.17e-5 m^2
3. Stagnation temperature, T_O = 22ºC

In the final report,

- Plot the following data (calculated at the tap locations) with respect to the normalized nozzle distance for all runs:
    - p/p_O
    - Mach Number
- Plot the mass flow parameter (*MFP*) with respect to the back pressure ratio (p_B/p_O). The *MFP* is given by the equation,

$$MFP = \frac{\dot{m}\sqrt{T_O}}{A_E p_O}$$

- Identify the flow regimes and flow conditions in the above plots (analogous to Fig. 2).
- Pressure readings from tap 10 can be considered as the back pressure (p_B) conditions.
- Pressure readings from tap 9 can be assumed to be the exit pressure (p_E) conditions.
- *EXTRA CREDIT:* We know that, in a converging nozzle, at p_B/p_O = 0.5283 and T_B/T_O = 0.8333, Mach number at the nozzle exit should be 1 (M_E = 1). Based on the above plots, find out if the above condition holds true for the current experiment. If the above condition does not agree with theory, explain why?
- All results must be presented in SI units.
- Present your code in the Appendix.

References: [1] Martinez, I., 'Nozzles', 1995 (http://webserver.dmt.upm.es/~isidoro/bk3/c17/Nozzles.pdf).