# MAE 352 - Experimental Aerodynamics II
# Lab 5 – Converging-Diverging 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-diverging nozzle.
- Plot and study the pressure and temperature variations across the converging-diverging nozzle from no-flow to supersonic-isentropic flow condition.

Theory: Ramjets, scramjets, and rockets all use nozzles to accelerate hot exhaust to produce thrust as described by Newton's third law of motion. The amount of thrust produced by the engine depends on the mass flow rate through the engine, the exit velocity of the flow, and the pressure at the exit of the engine. The value of these three flow variables are all determined by the nozzle design. A nozzle is a relatively simple device, just a specially shaped tube through which hot gases flow. Ramjets and rockets typically use a fixed convergent section followed by a fixed divergent section for the design of the nozzle. This nozzle configuration is called a convergent-divergent, or CD, nozzle. In a CD nozzle, the hot exhaust leaves the combustion chamber and converges down to the minimum area, or throat, of the nozzle. The throat size is chosen to choke the flow and set the mass flow rate through the system. The flow in the throat is sonic which means the Mach number is equal to one in the throat. Downstream of the throat, the geometry diverges and the flow is isentropically expanded to a supersonic Mach number that depends on the area ratio of the exit to the throat. The expansion of a supersonic flow causes the static pressure and temperature to decrease from the throat to the exit, so the amount of the expansion also determines the exit pressure and temperature. The exit temperature determines the exit speed of sound, which determines the exit velocity. The exit velocity, pressure, and mass flow through the nozzle determines the amount of thrust produced by the nozzle [1].

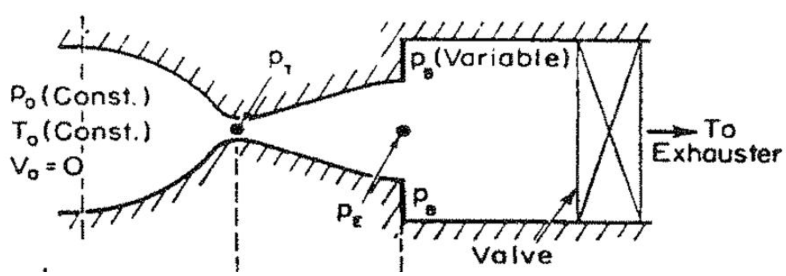


Figure 1: Schematic of a converging-diverging nozzle.

As observed in the converging nozzle experiments, once the flow becomes choked, the velocity can no longer increase beyond the choked flow value. Based upon the equation,

$$\frac{du}{u} = -\frac{dA}{A}\left(\frac{1}{1-M^2}\right)$$

where u is the velocity, A is the nozzle area, and M is the Mach number:

a) At M = 0, static flow
b) At 0 < M < 1, as the area decreases, a proportional increase in the velocity of the flow will be observed
c) At M > 1, any increase in area will produce a proportional increase in speed

Once the flow becomes choked, there are three possible flow conditions that can occur, subsonic isentropic flow (the flow decelerates after the choked condition), supersonic non-isentropic flow (where the flow accelerates supersonically, forms a normal shock, and decelerates subsonically after the shock), and supersonic isentropic flow (where the flow accelerates supersonically after the choked condition). Figure 2 shows the following seven profiles in the position versus pressure ratio plot:

1) Subsonic flow (never reaches choked condition).
2) Subsonic flow reaching choked condition, never reaching supersonic velocities (considered isentropic).

3) Subsonic flow reaching choked condition, the resulting supersonic flow results in a normal shock, then subsonic deceleration.
4) Subsonic flow reaching choked condition, the resulting supersonic flow results in a normal shock, after the nozzle (considered isentropic in the nozzle).
5) Over-expanded flow.
6) The flow after the choked condition is supersonic through the nozzle, and no shock is formed.
7) Under-expanded flow.

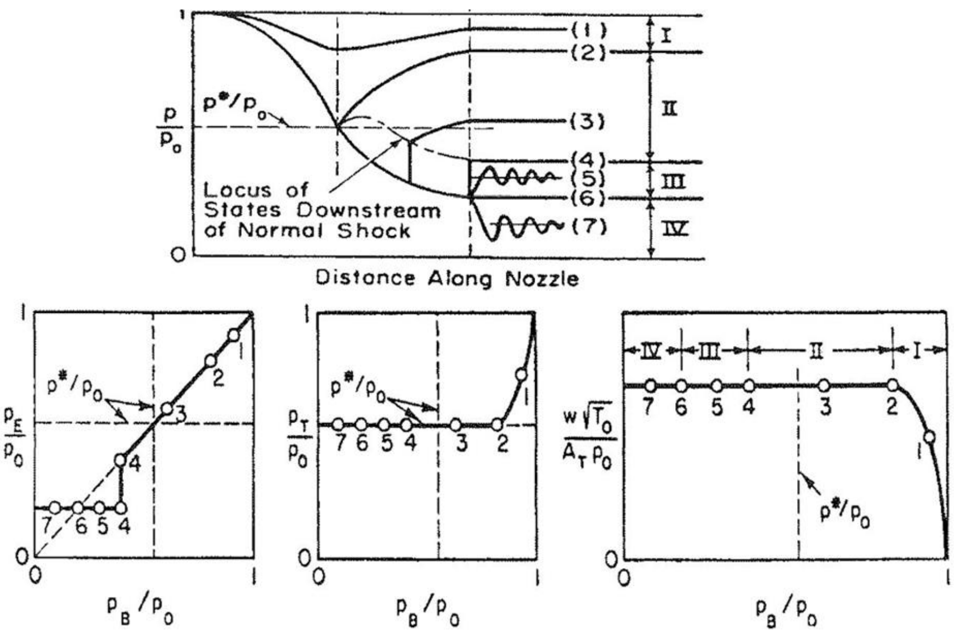

Figure 2: Flow conditions and regimes in a converging-diverging nozzle.

<u>Experiment:</u> 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 ($p_O$) 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-diverging 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 |

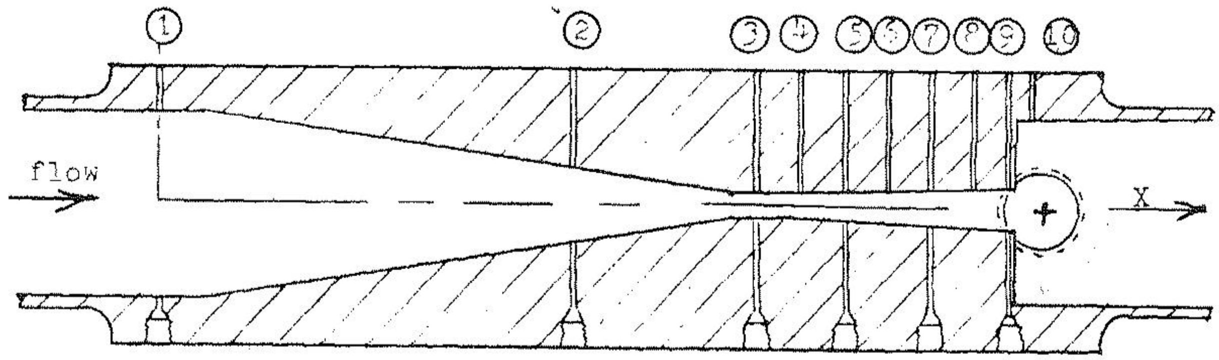


Figure 3: Geometry of converging-diverging nozzle.

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

1. Specific heat of dry air, $\gamma$: 1.4
2. Reference nozzle area, $A_i$ = 3.17e-5 m$^2$
3. Stagnation temperature, $T_O$ = 22$^o$C

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
- Identify the flow regimes and flow conditions in the above plots (analogous to Fig. 2).
- Plot the mass flow parameter (*MFP*) with respect to the back pressure ratio ($p_B/p_O$). The *MFP* for a CD-nozzle is given by the equation,

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

- Plot the pressure ratios at the throat and exit with respect to the back pressure ratio and identify the flow regimes and conditions (analogous to Fig. 2):
    - $p_E/p_O$ vs. $p_B/p_O$
    - $p_T/p_O$ vs. $p_B/p_O$
- 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.
- Pressure readings from tap 3 can be assumed to be the throat pressure ($p_T$) conditions.
- All results must be presented in SI units.
- Present your code in the Appendix.


References: [1] NASA, ‘Nozzle Design’ (https://www.grc.nasa.gov/www/k-12/airplane/nozzled.html).