SESA2023 Propulsion

Compressible Nozzle Flow Laboratory

Objective

A small nozzle, supplied with high-pressure air at the inlet, is instrumented to permit observation of the pressure distribution along its length during operation (Figure 1).

The objectives of the experiment are to become familiar with some aspects of nozzle flow, including “choking” in compressible flows, quantifying the effect of back pressure and inlet pressure on the flow rate, and demonstrating the relationship between pressure ratio across the nozzle and the mass flow rate. The use of Mach number to characterise the flow is also introduced.

Assessment

During the lab session you will record the raw data. You will then post-process your raw data (for example using Python, Excel) to apply corrections to the measured data and generate the required plots, which you will need to save in *.png or *.pdf format.

The assessment is done in a Blackboard quiz, where you will upload the plots and answer some further questions.

Theory

The theoretical background for this lab is covered in the week 3 material of the module, Gas Dynamics. Any calculations should be done using that material and/or material from the data book found on Blackboard.

For the calculations related to the lab, we will be assuming the air to be a perfect gas. The flow through the nozzle we assume to be steady, inviscid, and one-dimensional.

We will be using the following notation in the lab:

A	Area
c	Speed of sound
γ	Ratio of specific heats
$\dot{m}$	Mass flow rate
M	Mach number
p	Pressure
ρ	Density
R	Gas constant
T	Temperature
V	Speed

Subscripts:

0	Stagnation
1..8	Tapping point
a	Ambient
r	Reference
in	Inlet
out	Outlet

Superscripts:

*	Sonic (critical) conditions

Apparatus

The equipment to be used is a Hilton Nozzle –Pressure Distribution Unit, shown schematically in Figure 1. Three nozzles are provided (Figure 2), one convergent and two convergent-divergent. Only nozzle A (convergent-divergent) will be used in these tests. The static pressure distribution along the nozzle is measured via a series of tappings attached to pressure gauges. Although ideally all instrumentation should be calibrated immediately prior to a test, experience with this apparatus has shown that the large pressure gauges (p_{in}, p_{out}) are reasonably accurate whereas the small gauges ($p_1 \dots p_8$) require correction. Pressure corrections for each rig (N1, N2, N3, N4) are listed in Table 1. Note that all the pressures used in calculations should be corrected according to Table 1 and that gauge pressures need to be converted to absolute pressures: p (absolute) = p (gauge) + p_a. A measurement of the ambient pressure p_a is therefore required.

The air mass flow rate is measured using a rotameter. A small correction factor may be required, depending on the ambient temperature and pressure, according to

$$\dot{m}_c = \dot{m}_m \times k,$$

where $\dot{m}_m$ is the measured mass flow rate, and $\dot{m}_c$ the corrected mass flow rate. The correction factor k is given by

$$k = \sqrt{\frac{p_a T_r}{p_r T_a}},$$

with the reference pressure and temperature $p_r = 1.013$ bar and $T_r = 293.15$ K.

Tasks

Task 1: Setup

Note the unit number of your rig: | N |

Record the ambient pressure in bar in Tables 2 to 5. These tables are a guide for you to record your raw data, and a suggestion of how to set up your post-processing.

Let air through the unit, and, after a few minutes, measure the inlet temperature T_{in}. Use this as an estimate of the upstream stagnation temperature T_0 and enter in Tables 2-5.

By qualitatively trying to control the flow through the nozzle at a given inlet pressure, estimate the random measurement error in the mass flow rate on the rotameter:

Determine the rotameter correction factor and enter in Tables 2 and 3.

Task 2: Effect of pressure ratio across the nozzle: choking

Close the outlet valve.

Set up a gauge pressure of 4.0 bar on the inlet pressure gauge by adjusting the regulator/filter control. **Ensure this pressure remains constant through the test**. Note that since the inlet valve (Figure 1) is kept fully open throughout this experiment, the inlet pressure p_{in} is a good estimate of the upstream stagnation pressure p_0.

Check that $\dot{m}$ = 0 with the outlet valve closed.

Slowly open the outlet valve and record p_2 (pressure at nozzle throat) and $\dot{m}$ for each of the back pressures p_{out} in Table 2.

After the lab

Determine the *theoretical* critical pressure ratio p^*/p_0 using the estimated stagnation temperature.

From your data plot $\dot{m}$ in g/s (y-axis) versus p_{out}/p_0 (x-axis). On the same axes, plot $\dot{m}$ as a function of p_2/p_0 and the theoretical prediction of $\dot{m}$ as a function of p_2/p_0. Add an appropriate legend indicating the theory and experimental data.

Task 3: Effect of upstream conditions

Close the regulator so that p_0 (gauge) = 0 bar, and fully open the outlet valve.

Increase p_0 over the range of values suggested in Table 3 whilst recording $\dot{m}$.

> **After the lab**
>
> From your data plot $\dot{m}$ in g/s (y-axis) versus p_0 in bar (x-axis). Verify that if the nozzle is choked, the results satisfy a relationship of the form $\dot{m} = constant \times p_0$. Add a linear fit to the plot, by fitting to the range of data where this relation holds (this might not be very clear, so you need to estimate the range). Note that the relationship dictates that the fit passes through the origin. Indicate the slope of this fit in the plot, i.e., the experimental value of the constant in the relation.
>
> Determine the *theoretical* value of this constant (or slope of the linear fit) with the units g s^{-1} bar^{-1}. *Hint: use the isentropic relation for choked flow in your Data Book.*

Task 4: Mach number distribution

Fully open the outlet valve and set up an inlet pressure of 4.0 bar (gauge). Record, in Table 4, values of p_1 to p_8.

For rigs N1, N2, N4, reduce the mass flowrate to 3.2 g s^{-1} by closing the outlet value but *maintain* p_0 = 4.0 bar (gauge). For rig N3, reduce the mass flowrate to 2.2 g s^{-1}.

Repeat the above procedure, recording your results in Table 5.

> **After the lab**
>
> Determine M_1 to M_8 and plot M (y axis) versus x in mm (x axis) for both cases on the same axes. Add a legend to the figure to indicate the high mass flow rate (Table 4) and the low mass flow rate (Table 5).

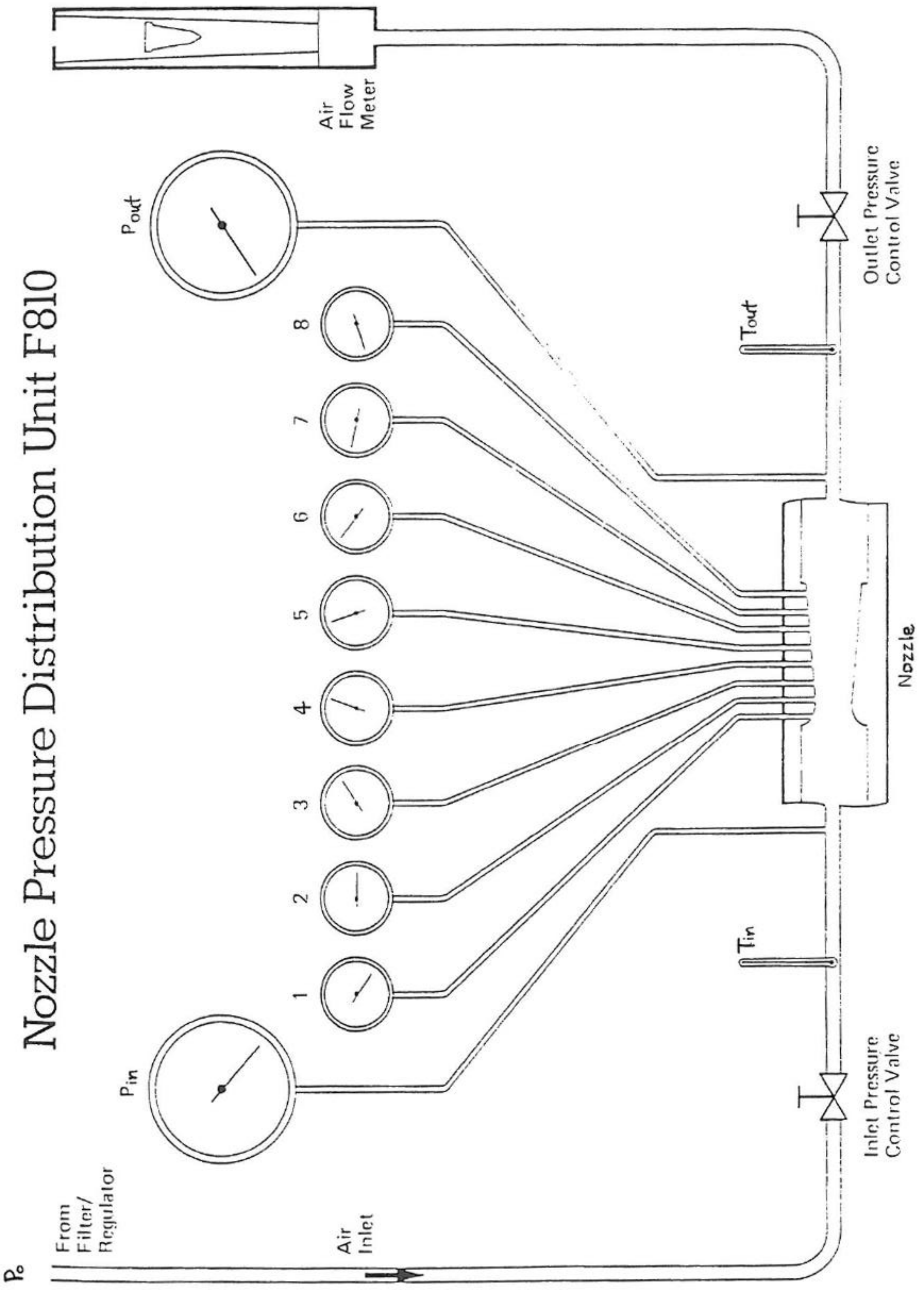
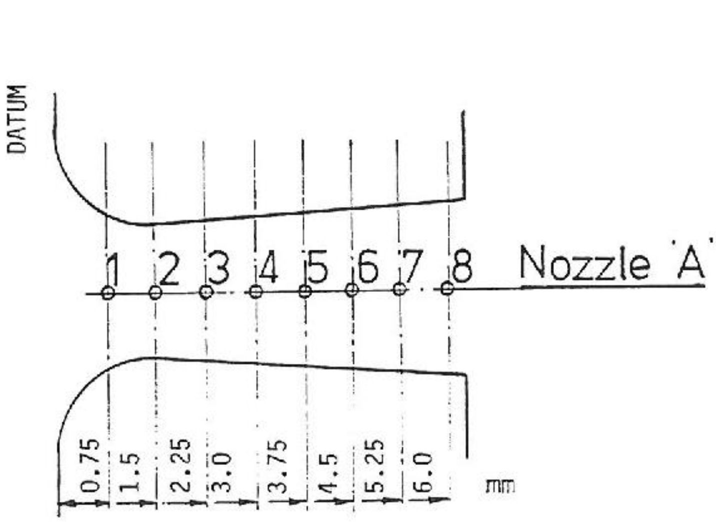
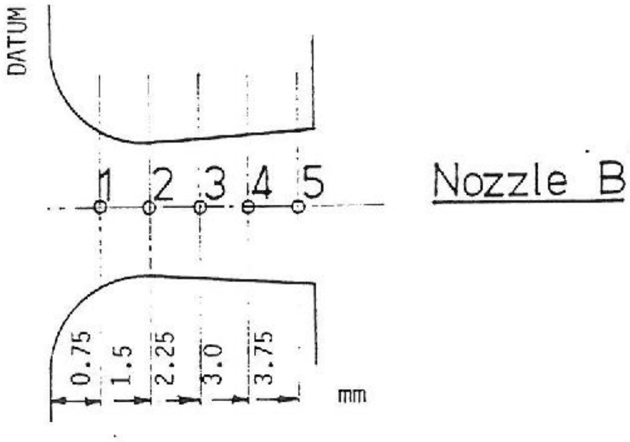


Figure 1 – Apparatus

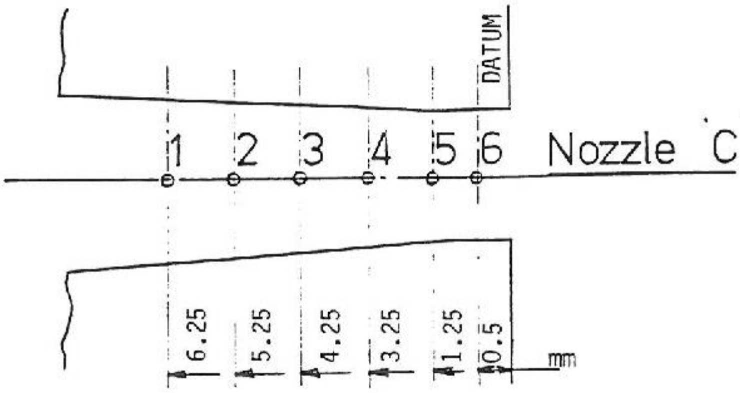
NOZZLE PROFILES



Tapping Point	Nominal Diameter mm	$\frac{\text{Area}}{\text{Throat Area}}$
1	2.4	1.44
2	2.0	1.0
3	2.13	1.13
4	2.26	1.28
5	2.39	1.42
6	2.52	1.59
7	2.66	1.77
8	2.79	1.94



1	2.4	1.44
2	2.0	1.0
3	2.13	1.13
4	2.26	1.28
5	2.39	1.42



1	2.86	2.05
2	2.65	1.75
3	2.43	1.48
4	2.21	1.2
5	2.03	1.03
6	2.0	1.0

Figure 2 – Nozzle profiles

TABLE 1: Correction for small pressure gauges.

p is pressure registered by gauges 1-8

Δp is the correction to be applied i.e. $p_{actual} = p + \Delta p$

Table 1a: Experiment N1

p bar (gauge)	Δp bar							
	1	2	3	4	5	6	7	8
0	0	0	-0.10	0	-0.10	-0.20	-0.20	0
0.50	+0.10	+0.10	+0.05	+0.10	0	0	-0.05	0
1.00	+0.20	+0.20	+0.10	+0.20	0	0	-0.05	+0.05
1.50	+0.20	+0.20	+0.10	+0.15	0	0	-0.05	+0.10
2.00	+0.20	+0.20	+0.10	+0.15	0	0	0	+0.10
2.50	+0.20	+0.20	+0.15	+0.15	0	0	0	+0.15
3.00	+0.20	+0.20	+0.15	+0.15	0	0	0	+0.10
3.50	+0.25	+0.20	+0.20	+0.20	0	+0.05	0	+0.15
4.00	+0.20	+0.20	+0.20	+0.20	0	+0.05	0	+0.20
4.50	+0.20	+0.20	+0.20	+0.20	0	0	0	+0.15
5.00	+0.20	+0.15	+0.15	+0.15	-0.05	0	-0.05	+0.10

Table 1b: Experiment N2

p bar (gauge)	Δp bar							
	1	2	3	4	5	6	7	8
0	0	0	0	0	0	0	0	0
0.50	+0.10	+0.10	0	0	0	-0.10	+0.10	0
1.00	0	0	0	0	0	-0.20	0	0
1.50	+0.05	+0.10	+0.10	+0.05	+0.05	-0.10	+0.10	0
2.00	0	0	0	0	0	-0.05	0	-0.05
2.50	0	0	+0.05	0	+0.05	-0.05	+0.10	0
3.00	0	0	0	0	0	-0.10	0	-0.10
3.50	-0.10	-0.10	-0.05	-0.10	0	-0.10	0	-0.10
4.00	-0.10	-0.10	-0.05	-0.10	0	-0.10	0	-0.15
4.50	-0.10	-0.10	0	-0.10	0	-0.10	0	-0.15
5.00	-0.15	-0.15	-0.15	-0.15	-0.05	-0.15	-0.10	-0.15

Table 1c: Experiment N3

p bar (gauge)	Δp bar							
	1	2	3	4	5	6	7	8
0	0	0	0	0	0	0	0	0
0.50	0	0	0	0	+ 0.10	0	0	0
1.00	- 0.10	- 0.10	- 0.10	- 0.10	0	- 0.20	- 0.20	- 0.10
1.50	- 0.10	- 0.10	- 0.10	- 0.10	+ 0.10	- 0.20	- 0.20	- 0.20
2.00	0	0	0	0	+ 0.10	- 0.10	- 0.10	0
2.50	+ 0.10	0	+ 0.20	+ 0.10	+ 0.25	0	0	+ 0.20
3.00	+ 0.10	0	+ 0.10	0	+ 0.10	- 0.10	0	+ 0.10
3.50	+ 0.10	0	+ 0.10	0	+ 0.25	0	0	+ 0.10
4.00	+ 0.20	+ 0.10	+ 0.10	0	+ 0.20	0	0	+ 0.10
4.50	+ 0.20	+ 0.10	+ 0.10	0	+ 0.25	- 0.10	0	+ 0.10
5.00	+ 0.10	0	+ 0.10	0	+ 0.20	- 0.10	0	+ 0.10

Table 1d: Experiment N4

p bar (gauge)	Δp bar							
	1	2	3	4	5	6	7	8
0	- 0.10	0	0	0	0	0	0	0
0.50	0	+ 0.10	0	0	0	+ 0.10	0	0
1.00	0	+ 0.10	0	0	0	+ 0.10	+ 0.10	0
1.50	0	+ 0.10	+ 0.10	0	0	+ 0.10	+ 0.10	+ 0.10
2.00	0	+ 0.10	0	0	0	+ 0.10	0	0
2.50	0	+ 0.10	+ 0.10	0	0	+ 0.10	+ 0.10	0
3.00	0	+ 0.10	+ 0.10	0	0	+ 0.10	0	0
3.50	0	+ 0.10	+ 0.10	0	0	+ 0.10	+ 0.10	0
4.00	0	+ 0.10	+ 0.10	0	0	+ 0.10	0	+ 0.10
4.50	0	+ 0.10	+ 0.10	0	0	+ 0.10	0	+ 0.10
5.00	0	+ 0.10	0	0	0	0	0	0

TABLE 2: Effect of pressure ratio

$p_a =$ $T_0 =$

$p_0 = 4.0$ bar (gauge) Rotameter correction factor: $k =$

$p_0 =$ bar (absolute)

p_{out}(bar) gauge	p_{out}(bar) absolute	**p_2(bar) gauge**	p_2(bar) abs, corrected	**$\dot{m}$ (g/s)**	$\dot{m}$ (g/s) corrected	(p_{out}/p_0) absolute	(p_2/p_0) absolute
4.00							
3.75							
3.50							
3.25							
3.00							
2.50							
2.00							
1.00							

TABLE 3: Effect of inlet pressure

$p_a =$ $T_0 =$

Rotameter correction factor: $k =$

p_0(bar) gauge	p_0(bar) absolute	**$\dot{m}$ (g/s)**	$\dot{m}$ (g/s) corrected
0.0			
1.0			
1.5			
2.0			
2.5			
3.0			
3.5			
4.0			
4.5			
5.0			

TABLE 4: Mach number distribution

$p_a =$ $T_0 =$

$p_0 = 4.0$ bar (gauge) $\dot{m} =$ g/s

$p_0 =$ bar (absolute) $\dot{m} =$ g/s (corrected)

Tapping point	1	2	3	4	5	6	7	8
x (mm)	0.75	1.5	2.25	3.0	3.75	4.5	5.25	6.0
***p* (bar) gauge**								
p (bar) corr, abs								
(p_0/p) abs								
Mach no.								
A/A^*	1.4	1.0	1.13	1.28	1.42	1.59	1.77	1.94

TABLE 5: Mach number distribution continued

$p_a =$ $T_0 =$

$p_0 = 4.0$ bar (gauge) $\dot{m} = 3.2$ g/s (or 2.2 g/s for rig N3)

$p_0 =$ bar (absolute) $\dot{m} =$ g/s (corrected)

Tapping point	1	2	3	4	5	6	7	8
x (mm)	0.75	1.5	2.25	3.0	3.75	4.5	5.25	6.0
***p* (bar) gauge**								
p (bar) corr, abs								
(p_0/p) abs								
Mach no.								
A/A^*	1.4	1.0	1.13	1.28	1.42	1.59	1.77	1.94