# Energy balance lab report

Hasha Dar

February 4, 2020

## Contents

**1 Lab data** **3**
1.1 1 bar . . . 3
1.1.1 $T_2$ readings . . . 3
1.2 0.6 bar . . . 4
1.2.1 $T_2$ readings . . . 4
1.3 0.3 bar . . . 5
1.3.1 $T_2$ readings . . . 5

**2 Experiment 1 calculations** **6**
2.1 Volumetric flow rate . . . 6
2.2 Mass flow rate . . . 6
2.3 Energy added to air by compressor . . . 7
2.4 Power out of motor . . . 7
2.5 Heat losses in the compressor . . . 7

**3 Experiment 1 discussion** **7**
3.1 Outlet temperature against time plot . . . 7
3.2 Why does the graph have this shape? . . . 9
3.3 What happens to the system's energy input as it heats up? . . . 9
3.4 How does the energy lost as heat compare to: . . . 10
3.4.1 The work input to the compressor? . . . 10
3.4.2 The heat added to the air? . . . 10

**4 Experiment 2 calculations** **10**
4.1 Specific volume of air at atmosphere and the inlet and outlet of compressor . . . 10
4.2 Volumetric flow rate of air . . . 11
4.3 Mass flow rate of air . . . 11
4.4 Theoretical mass flow rate of air . . . 12
4.5 Pressure ratio . . . 12
4.6 Motor power . . . 13
4.7 Motor efficiency . . . 13
4.8 Energy added to the air by the compressor . . . 14
4.9 Heat loss in the apparatus . . . 14
4.10 Mechanical efficiency of the compressor . . . 14
4.11 Isentropic efficiency of the compressor . . . 15
4.12 Volumetric efficiency of the compressor . . . 15
4.13 Total efficiency of the compressor . . . 16

**5 Experiment 2 discussion** **17**
5.1 Isentropic, volumetric and total efficiency against pressure ratio plots . . . 17
5.2 Heat loss in apparatus against pressure ratio plot . . . 18
5.2.1 Why is the isentropic efficiency of the compressor smaller than 1? What can be concluded from the shape of the isentropic efficiency vs pressure ratio? . . . 18
5.2.2 What does the volumetric efficiency of the compressor represent? What are the causes that it is smaller than 1? . . . 18
5.2.3 How does the overall efficiency scale with operating condition (i.e. pressure ratio)? What does this tell us about the dominant efficiency and therefore how the design of the compressor could be improved? . . . 19
5.2.4 How does the heat loss scale with operating condition (i.e. pressure ratio)? What are the causes for this trend? 19

# 1 Lab data

## 1.1 1 bar

- $T_0 = 25$ °C
- $T_1 = 23$ °C
- $P_0 = 1$ bar
- $P_1 = 0.05$ bar
- $P_2 = 1$ bar
- $V_{in} = 285\ \mathrm{L\,min^{-1}}$
- $N = 1430\ \mathrm{rev\,s^{-1}}$
- $F = 1.5$ kg
- $\dot{W}_{el} = 1150$ W

### 1.1.1 $T_2$ readings

| Time (min) | $T_2$ (degrees C) |
|---|---|
| 0 | 95 |
| 1 | 98 |
| 2 | 101 |
| 3 | 104 |
| 4 | 106 |
| 5 | 108 |
| 6 | 110 |
| 7 | 112 |
| 8 | 114 |
| 9 | 116 |
| 10 | 118 |
| 11 | 119 |
| 12 | 121 |
| 13 | 122 |
| 14 | 124 |
| 15 | 125 |
| 16 | 127 |
| 17 | 128 |
| 18 | 130 |
| 19 | 131 |
| 20 | 131 |

Table 1: $T_2$ readings from apparatus with 1 bar compressor

## 1.2 0.6 bar

- $T_0 = 25$ °C
- $T_1 = 24$ °C
- $P_0 = 1$ bar
- $P_1 = 0.06$ bar
- $P_2 = 1$ bar
- $V_{in} = 310\ \mathrm{L\,min^{-1}}$
- $N = 1445\ \mathrm{rev\,s^{-1}}$
- $F = 1.5$ kg
- $\dot{W}_{el} = 1000$ W

### 1.2.1 $T_2$ readings

| Time (min) | $T_2$ (degrees C) |
|---|---|
| 0 | 63 |
| 1 | 68 |
| 2 | 71 |
| 3 | 74 |
| 4 | 77 |
| 5 | 79 |
| 6 | 81 |
| 7 | 84 |
| 8 | 86 |
| 9 | 88 |
| 10 | 89 |
| 11 | 91 |
| 12 | 92 |
| 13 | 94 |
| 14 | 95 |
| 15 | 97 |
| 16 | 98 |
| 17 | 99 |
| 18 | 101 |
| 19 | 102 |
| 20 | 103 |

Table 2: $T_2$ readings from apparatus with 0.6 bar compressor

## 1.3 0.3 bar

- $T_0 = 25$ °C
- $T_1 = 25$ °C
- $P_0 = 1$ bar
- $P_1 = 0.08$ bar
- $P_2 = 1$ bar
- $V_{in} = 320\ \mathrm{L\,min^{-1}}$
- $N = 1459\ \mathrm{rev\,s^{-1}}$
- $F = 1.5$ kg
- $\dot{W}_{el} = 850$ W

### 1.3.1 $T_2$ readings

| Time (min) | $T_2$ (degrees C) |
|---|---|
| 0 | 52 |
| 1 | 55 |
| 2 | 58 |
| 3 | 60 |
| 4 | 62 |
| 5 | 63 |
| 6 | 65 |
| 7 | 67 |
| 8 | 68 |
| 9 | 69 |
| 10 | 70 |
| 11 | 71 |
| 12 | 72 |
| 13 | 73 |
| 14 | 74 |
| 15 | 75 |
| 16 | 76 |
| 17 | 76 |
| 18 | 77 |
| 19 | 78 |
| 20 | 78 |

Table 3: $T_2$ readings from apparatus with 0.3 bar compressor

# 2 Experiment 1 calculations

All the calculations completed below were done with data from the 1 bar experiment.

## 2.1 Volumetric flow rate

The formula for the volumetric flow rate is:

$$\dot{V} = \frac{V_{in}}{60 \times 10^3} \text{ m}^3\,\text{s}^{-1} \tag{2.1}$$

Thus, our volumetric flow rate (using equation 2.1) is:

$$\dot{V} = \frac{285}{60 \times 10^3} = \frac{19}{4000} = 4.75 \times 10^{-3} \text{ m}^3\,\text{s}^{-1} \text{ (3sf)} \tag{2.2}$$

## 2.2 Mass flow rate

The specific volume through flowmeter is given by the following equation

$$v_0 = \frac{RT_0}{P_0} \text{ m}^3\,\text{kg}^{-1} \text{ where } R = 0.287 \text{ kJ}\,\text{kg}^{-1}\,\text{K}^{-1} \tag{2.3}$$

The mass flow rate is given by the following equation:

$$\dot{m} = \frac{\dot{V}}{v_0} \text{ kg}\,\text{s}^{-1} \tag{2.4}$$

Calculating the specific volume (2.3) and inputting the volume flow rate calculated previously (2.1) our mass flow rate is:

$$v_0 = \frac{0.287 \cdot (25 + 273.15)}{100} = 0.856 \text{ kg}\,\text{s}^{-1} \text{ (3sf)} \tag{2.5}$$

$$\dot{m} = \frac{4.75 \times 10^{-3}}{0.856} = 5.55 \times 10^{-3} \text{ kg}\,\text{s}^{-1} \text{ (3sf)} \tag{2.6}$$

## 2.3 Energy added to air by compressor

The equation to calculate the energy added to air by compressor is:

$$\dot{H}_c = \dot{m} c_P (T_2 - T_1) \text{ W where } c_P \text{ is } 1005 \text{ kJ kg K}^{-1} \tag{2.7}$$

Inputting the variables into equation 2.7, we get:

$$\dot{H}_c = 5.55 \times 10^{-3} \times 1005 \times (131 - 23) = 602.296 \text{ W (3dp)} \tag{2.8}$$

## 2.4 Power out of motor

The equation for the power out of the motor is:

$$\dot{W}_m = \frac{19.62 NFL\pi}{60} \text{ W} \tag{2.9}$$

Thus, our motor power is:

$$\dot{W}_m = \frac{19.62 \times 1430 \times 1.5 \times 0.2 \times \pi}{60} = 440.712 \text{ W (3dp)} \tag{2.10}$$

## 2.5 Heat losses in the compressor

The equation for the heat emitted from the compressor is:

$$\dot{Q}_c = \dot{W}_m - \dot{H}_c \text{ W} \tag{2.11}$$

Thus, our motor heat losses are:

$$\dot{Q}_c = 440.712 - 602.296 = -161.685 \text{ W (3dp)} \tag{2.12}$$

# 3 Experiment 1 discussion

## 3.1 Outlet temperature against time plot

Importing the data into MATLAB, I plotted the data on a graph.

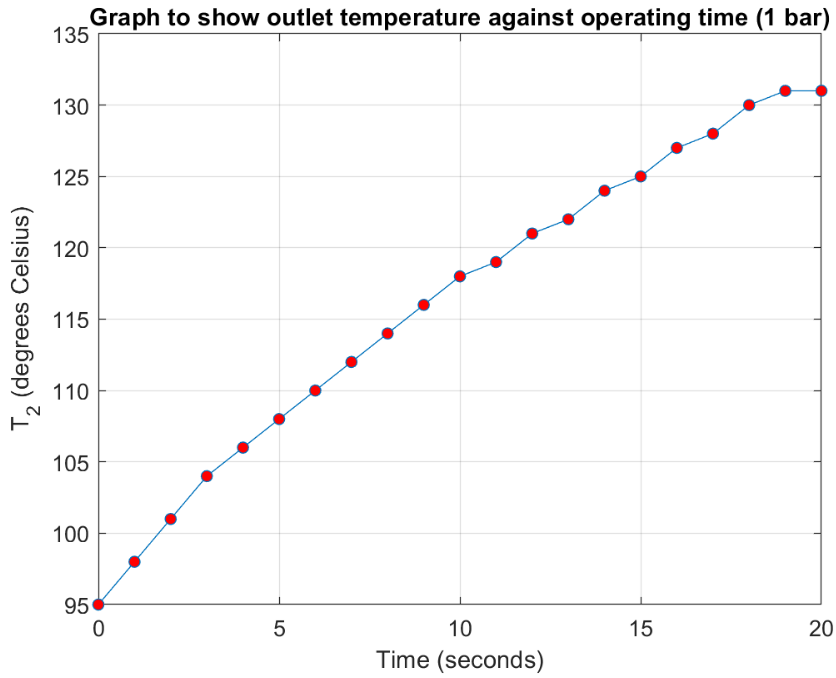


Figure 1: Plot of $T_2$ against the operating time of the apparatus (1 bar)

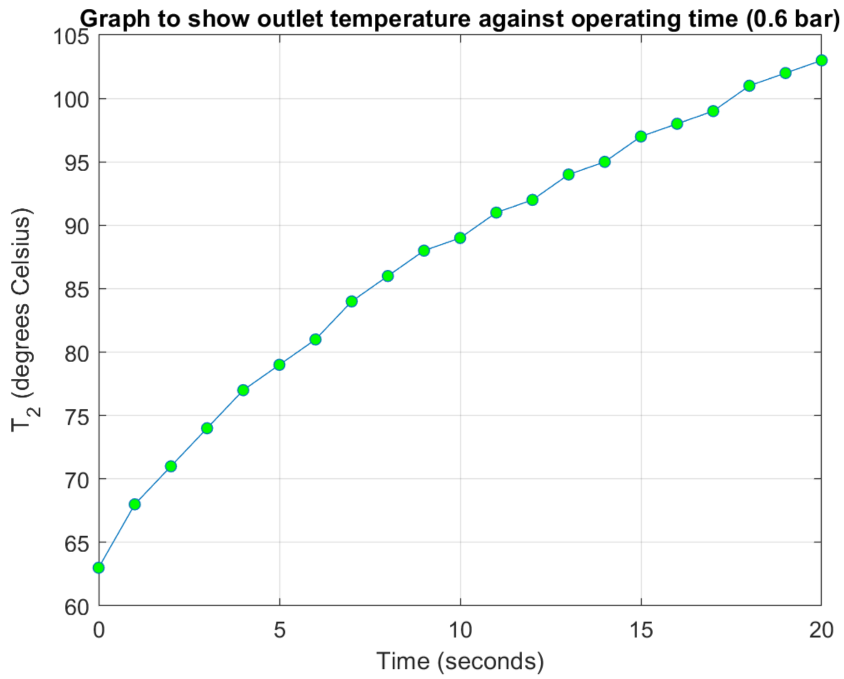


Figure 2: Plot of $T_2$ against the operating time of the apparatus (0.6 bar)

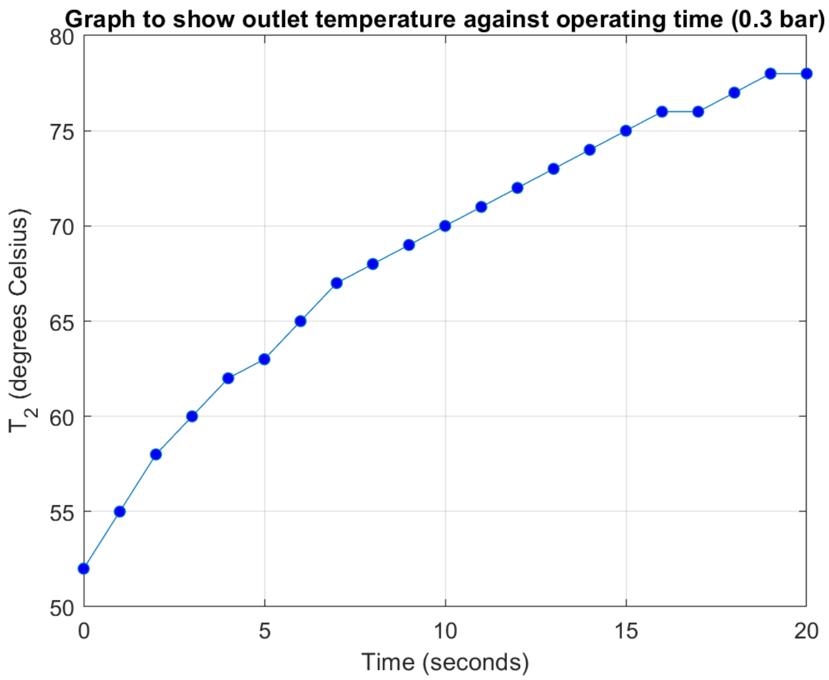


Figure 3: Plot of $T_2$ against the operating time of the apparatus (0.3 bar)

## 3.2 Why does the graph have this shape?

The graph has this shape, due to the fact that the compressor is initially cold. As the compressor runs, the apparatus becomes warmer and hence is able to transfer more heat energy to the air. The graph appears to level off towards the end due to the system reaching a finite temperature limit. When this happens, no extra heat can be transferred to the air. The gradient of the graph shows that the change in temperature of the apparatus is larger initially and smaller 20 minutes later.

## 3.3 What happens to the system's energy input as it heats up?

The systems electrical input does not change during the 20 minutes. However, more heat would be transferred to the air later in the cycle.

### 3.4 How does the energy lost as heat compare to:

#### 3.4.1 The work input to the compressor?

The work input to the compressor is almost 1000W. Comparatively, our motor power is only 600W. Hence, we are losing 40% of our electrical power to heat.

#### 3.4.2 The heat added to the air?

This is quite large as both the compressor and the apparatus are adding heat to the air.

# 4 Experiment 2 calculations

### 4.1 Specific volume of air at atmosphere and the inlet and outlet of compressor

We can calculate the specific volumes at atmosphere, before and after the compressor using equation 2.3, which is shown below.

$$v_0 = \frac{RT_0}{P_0} \ (\mathrm{m^3\,kg^{-1}}) \text{ where } R = 0.287 \ \mathrm{kJ\,kg^{-1}\,K^{-1}} \tag{2.3}$$

Thus, at atmosphere, our specific volume of air is:

$$v_0 = \frac{0.287 \times (25 + 273.15)}{100} = 0.856 \ \mathrm{m^3\,kg^{-1}} \text{ (3sf)} \tag{4.1}$$

The temperature is constant before the compressor and $T_2$ approaches a constant value after some time, hence we can use a formula for specific volume where T is constant:

$$v_1 = v_0 \times \left( \frac{P_0}{P_0 - P_1} \right) \ \mathrm{m^3\,kg^{-1}} \tag{4.2}$$

Using equation 4.2, the specific volume before the compressor is:

$$v_1 = 0.856 \times \left(\frac{100}{100-5}\right) = \frac{428}{475} = 0.901 \text{ m}^3\,\text{kg}^{-1} \text{ (3sf) (1 bar)} \tag{4.3}$$

$$v_1 = 0.856 \times \left(\frac{100}{100-6}\right) = \frac{214}{235} = 0.911 \text{ m}^3\,\text{kg}^{-1} \text{ (3sf) (0.6 bar)} \tag{4.4}$$

$$v_1 = 0.856 \times \left(\frac{100}{100-8}\right) = \frac{107}{115} = 0.930 \text{ m}^3\,\text{kg}^{-1} \text{ (3sf) (0.3 bar)} \tag{4.5}$$

Using equation 4.2, the specific volume after the compressor is:

$$v_2 = 0.856 \times \left(\frac{100}{100+100}\right) = \frac{107}{115} = 0.428 \text{ m}^3\,\text{kg}^{-1} \text{ (3sf) (1, 0.6, 0.3 bar)} \tag{4.6}$$

## 4.2 Volumetric flow rate of air

Using equation 2.1 we can calculate the volumetric flow rate of air.

$$\dot{V} = \frac{V_{in}}{60 \times 10^3} \text{ m}^3\,\text{s}^{-1} \tag{2.1}$$

$$\dot{V} = \frac{285}{60 \times 10^3} = \frac{19}{4000} = 4.75 \times 10^{-3} \text{ m}^3\,\text{s}^{-1} \text{ (3sf) (1 bar)} \tag{4.7}$$

$$\dot{V} = \frac{310}{60 \times 10^3} = \frac{31}{6000} = 5.17 \times 10^{-3} \text{ m}^3\,\text{s}^{-1} \text{ (3sf) (0.6 bar)} \tag{4.8}$$

$$\dot{V} = \frac{320}{60 \times 10^3} = \frac{2}{375} = 5.33 \times 10^{-3} \text{ m}^3\,\text{s}^{-1} \text{ (3sf) (0.3 bar)} \tag{4.9}$$

## 4.3 Mass flow rate of air

The mass flow rate of air can be calculated using equation 2.4.

$$\dot{m} = \frac{\dot{V}}{v_0} \text{ kg}\,\text{s}^{-1} \tag{2.4}$$

Calculating the specific volume (2.3) and inputting the volume flow rate (2.1) our mass flow rate is:

$$v_0 = \frac{0.287 \cdot (25 + 273.15)}{100} = 0.856 \text{ kg s}^{-1} \text{ (3sf)} \tag{4.10}$$

$$\dot{m} = \frac{4.75 \times 10^{-3}}{0.856} = 5.55 \times 10^{-3} \text{ kg s}^{-1} \text{ (3sf) (1 bar)} \tag{4.11}$$

$$\dot{m} = \frac{5.17 \times 10^{-3}}{0.856} = 6.04 \times 10^{-3} \text{ kg s}^{-1} \text{ (3sf) (0.6 bar)} \tag{4.12}$$

$$\dot{m} = \frac{5.33 \times 10^{-3}}{0.856} = 6.23 \times 10^{-3} \text{ kg s}^{-1} \text{ (3sf) (0.3 bar)} \tag{4.13}$$

## 4.4 Theoretical mass flow rate of air

The compressors swept volume is $V_{comp} = 2.67 \times 10^{-4}$, hence we can calculate the theoretical mass flow rate using equation 2.4.

$$\dot{m} = \frac{\dot{V}_{comp} \times N}{60 \times v_0} \text{ kg s}^{-1} \tag{2.4}$$

$$\dot{m} = \frac{2.67 \times 10^{-4} \times 1430}{60 \times 0.856} = 7.43 \times 10^{-3} \text{ kg s}^{-1} \text{ (3sf) (1 bar)} \tag{4.14}$$

$$\dot{m} = \frac{2.67 \times 10^{-4} \times 1445}{60 \times 0.856} = 7.51 \times 10^{-3} \text{ kg s}^{-1} \text{ (3sf) (0.6 bar)} \tag{4.15}$$

$$\dot{m} = \frac{2.67 \times 10^{-4} \times 1459}{60 \times 0.856} = 7.58 \times 10^{-3} \text{ kg s}^{-1} \text{ (3sf) (0.3 bar)} \tag{4.16}$$

## 4.5 Pressure ratio

The pressure ratio is given by the following equation:

$$r_P = \frac{\text{Pressure out}}{\text{Pressure in}} = \frac{P_0 + P_2}{P_0 - P_1} \tag{4.17}$$

Thus, our pressure ratios are:

$$r_P = \frac{100000 + 100000}{100000 - 5000} = \frac{40}{19} = 2.11 \text{ (3sf) (1 bar)} \tag{4.18}$$

$$r_P = \frac{100000 + 100000}{100000 - 6000} = \frac{100}{47} = 2.13 \text{ (3sf) (0.6 bar)} \tag{4.19}$$

$$r_P = \frac{100000 + 100000}{100000 - 8000} = \frac{50}{23} = 2.17 \text{ (3sf) (0.3 bar)} \tag{4.20}$$

## 4.6 Motor power

The equation for motor power is already given in equation 2.9.

$$\dot{W}_m = \frac{19.62NFL\pi}{60} \text{ W} \tag{2.9}$$

Thus, our motor powers are:

$$\dot{W}_m = \frac{19.62(1430)(1.5)(0.2)\pi}{60} = 440.712 \text{ W (3dp) (1 bar)} \tag{4.21}$$

$$\dot{W}_m = \frac{19.62(1445)(1.5)(0.2)\pi}{60} = 445.335 \text{ W (3dp) (0.6 bar)} \tag{4.22}$$

$$\dot{W}_m = \frac{19.62(1459)(1.5)(0.2)\pi}{60} = 449.650 \text{ W (3dp) (0.3 bar)} \tag{4.23}$$

## 4.7 Motor efficiency

The efficiency of the motor is given by the following equation.

$$\eta_m = \frac{\dot{W}_m}{\dot{W}_{el}} \tag{4.24}$$

Thus, our motor efficiencies are:

$$\eta_m = \frac{440.712}{1150} = 0.383 \text{ (3sf) (1 bar)} \tag{4.25}$$

$$\eta_m = \frac{445.335}{1000} = 0.445 \text{ (3sf) (0.6 bar)} \tag{4.26}$$

$$\eta_m = \frac{449.650}{850} = 0.529 \text{ (3sf) (0.3 bar)} \tag{4.27}$$

$$\tag{4.28}$$

## 4.8 Energy added to the air by the compressor

The equation for the energy added to the air by the compressor is already given by equation 2.7.

$$\dot{H}_c = \dot{m}c_P(T_2 - T_1) \text{ W where } c_P \text{ is } 1005 \text{ kJ kg K}^{-1} \tag{2.7}$$

Thus, the energy added to the air (for each pressure) by the compressor is:

$$\dot{H}_c = (5.55 \times 10^{-3})(1005)(131 - 23) = 602.397 \text{ W (3dp) (1 bar)} \tag{4.29}$$

$$\dot{H}_c = (6.04 \times 10^{-3})(1005)(103 - 24) = 479.546 \text{ W (3dp) (0.6 bar)} \tag{4.30}$$

$$\dot{H}_c = (6.23 \times 10^{-3})(1005)(78 - 25) = 331.841 \text{ W (3dp) (0.3 bar)} \tag{4.31}$$

## 4.9 Heat loss in the apparatus

The equation for the heat loss in the apparatus is given by the following equation.

$$\dot{Q}_c = \dot{W}_{el} - \dot{H}_c \text{ W} \tag{4.32}$$

Thus, the heat loss in the apparatus is:

$$\dot{Q}_c = 1150 - 602.397 = 547.603 \text{ W (3dp) (1 bar)} \tag{4.33}$$

$$\dot{Q}_c = 1000 - 479.546 = 520.454 \text{ W (3dp) (0.6 bar)} \tag{4.34}$$

$$\dot{Q}_c = 850 - 331.841 = 518.159 \text{ W (3dp) (0.3 bar)} \tag{4.35}$$

## 4.10 Mechanical efficiency of the compressor

The mechanical efficiency of the compressor is given by the following equation.

$$\eta_c = \frac{\dot{H}_c}{\dot{W}_m} \tag{4.36}$$

Thus, our mechanical efficiences are:

$$\eta_c = \frac{602.397}{440.712} = 1.367 \text{ (3sf) (1 bar)} \tag{4.37}$$

$$\eta_c = \frac{479.546}{445.335} = 1.077 \text{ (3sf) (0.6 bar)} \tag{4.38}$$

$$\eta_c = \frac{331.841}{449.650} = 0.738 \text{ (3sf) (0.3 bar)} \tag{4.39}$$

## 4.11 Isentropic efficiency of the compressor

The isentropic efficiency of the compressor is given by the following equations.

$$\eta_s = \frac{h_1 - h_{2s}}{h_1 - h_{2a}} \tag{4.40}$$

$$\eta_s = \frac{T_1 - T_{2s}}{T_1 - T_{2a}} \tag{4.41}$$

$$\text{where } T_{2s} = T_1 \times r_P^{\left(\frac{\gamma-1}{\gamma}\right)} \tag{4.42}$$

Thus, our isentropic efficiences are:

$$\eta_s = \frac{23 - \left(23 \times \frac{40}{19}^{\left(\frac{1.4-1}{1.4}\right)}\right)}{23 - 131} = 0.050 \text{ (3sf) (1 bar)} \tag{4.43}$$

$$\eta_s = \frac{24 - \left(24 \times \frac{100}{47}^{\left(\frac{1.4-1}{1.4}\right)}\right)}{24 - 103} = 0.073 \text{ (3sf) (0.6 bar)} \tag{4.44}$$

$$\eta_s = \frac{25 - \left(25 \times \frac{50}{23}^{\left(\frac{1.4-1}{1.4}\right)}\right)}{25 - 78} = 0.117 \text{ (3sf) (0.3 bar)} \tag{4.45}$$

## 4.12 Volumetric efficiency of the compressor

The volumetric efficiency of the compressor is given by the following equation.

$$\eta_{vol} = \frac{\dot{m} \times v_1 \times 60}{N \times V_{comp}} \tag{4.46}$$

$$\eta_{vol} = \frac{\dot{m} \times v_1 \times 60}{N \times 267 \times 10^{-6}} \tag{4.47}$$

Thus, our volumetric efficiencies are:

$$\eta_{vol} = \frac{7.46 \times 10^{-3} \times 0.901 \times 60}{1430 \times 267 \times 10^{-6}} = 1.056 \text{ (3dp) (1 bar)} \tag{4.48}$$

$$\eta_{vol} = \frac{7.51 \times 10^{-3} \times 0.911 \times 60}{1445 \times 267 \times 10^{-6}} = 1.064 \text{ (3dp) (0.6 bar)} \tag{4.49}$$

$$\eta_{vol} = \frac{7.58 \times 10^{-3} \times 0.930 \times 60}{1459 \times 267 \times 10^{-6}} = 1.093 \text{ (3dp) (0.3 bar)} \tag{4.50}$$

## 4.13 Total efficiency of the compressor

The total efficiency of the compressor is given by the following equation.

$$\eta = \eta_m \times \eta_c \times \eta_s \tag{4.51}$$

Thus, our total efficiences are:

$$\eta = 0.050 \times 1.367 \times 0.383 = 0.026 \text{ (3dp) (1 bar)} \tag{4.52}$$

$$\eta = 0.073 \times 1.077 \times 0.445 = 0.035 \text{ (3dp) (0.6 bar)} \tag{4.53}$$

$$\eta = 0.117 \times 0.738 \times 0.529 = 0.046 \text{ (3dp) (0.3 bar)} \tag{4.54}$$

# 5 Experiment 2 discussion

## 5.1 Isentropic, volumetric and total efficiency against pressure ratio plots

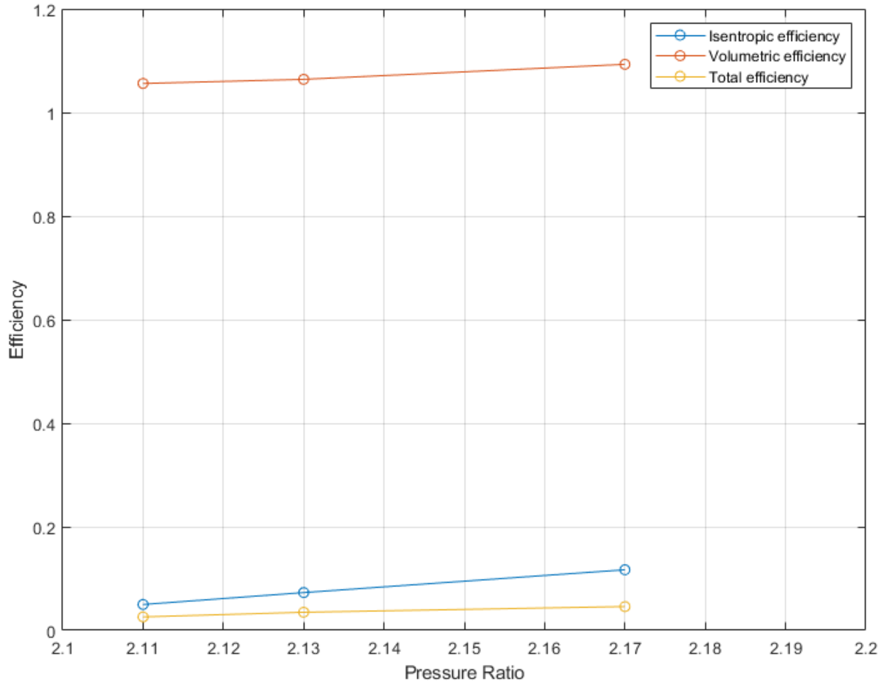


Figure 4: Plot to show isentropic, volumetric and total efficiency of compressor against pressure ratio

## 5.2 Heat loss in apparatus against pressure ratio plot

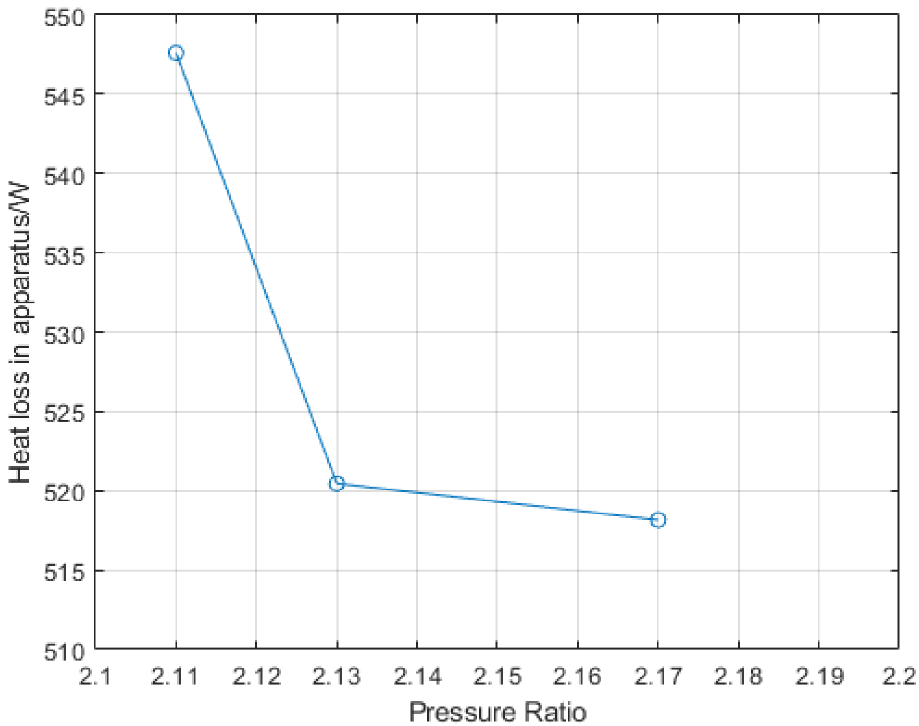


Figure 5: Plot to show heat loss in apparatus against pressure ratio

### 5.2.1 Why is the isentropic efficiency of the compressor smaller than 1? What can be concluded from the shape of the isentropic efficiency vs pressure ratio?

It is smaller than 1 due to the fact that this process is irreversible. Having an efficiency of more than 1 would imply that energy is being created. When the pressure ratio increases, the isentropic efficiency also increases. Thus, larger pressure ratios will yield higher isentropic efficiencies.

### 5.2.2 What does the volumetric efficiency of the compressor represent? What are the causes that it is smaller than 1?

The volumetric efficiency of the compressor represents how much fluid is actually displaced by the compressor in one revolution versus its swept volume.

If the compressor is pulling in air which is not at atmospheric pressures, than the air coming into the compressor will not fill the compressor to 100% of its capacity, hence reducing the volumetric efficiency.

### 5.2.3 How does the overall efficiency scale with operating condition (i.e. pressure ratio)? What does this tell us about the dominant efficiency and therefore how the design of the compressor could be improved?

The overall efficiency improves with pressure ratio, we see greater gains in isentropic efficiency, when pressure ratio is increased. The dominant efficiency is the volumetric efficiency and to improve the efficiency of the system, volumetric efficiency could be improved further, by using forced induction of air perhaps.

### 5.2.4 How does the heat loss scale with operating condition (i.e. pressure ratio)? What are the causes for this trend?

The heat loss lessens as the pressure ratio increases. The causes for this are due to the fact that at higher pressure ratios the temperature of the outlet air is relatively smaller to the room temperature, hence there is a slower energy loss to the surroundings. Hotter objects (i.e. compressor at low pressure ratio) lose more heat to the environment.

## List of Figures


1 Plot of $T_2$ against the operating time of the apparatus (1 bar) 8
2 Plot of $T_2$ against the operating time of the apparatus (0.6 bar) 8
3 Plot of $T_2$ against the operating time of the apparatus (0.3 bar) 9
4 Plot to show isentropic, volumetric and total efficiency of compressor against pressure ratio . . . . . . . . . . . . . . . . . . . 17
5 Plot to show heat loss in apparatus against pressure ratio . . . 18