Lab Report – Claudio Vestini

Introduction

Over the past week, I have analysed the design and operation of a Francis Turbine. This inward-flow reaction turbine combines radial and axial flow concepts and was invented by James B. Francis in the 1850s.

This report will highlight meaningful data and findings obtained in this process.

Design and Geometry

The part drawings provided allowed us to create SolidWorks models for each component and join them in a Solid Assembly. However, we noticed a problem with said assembly: since each crank was connected to the next via a rigid link through an eccentric linkage, every crank's instantaneous centre of rotation was slightly offset from the next one's, resulting in each guide vane being turned through a different radius in the mechanism.
This was clear when plotting the distance (magnitude) between adjacent vanes: the first two vanes behaved differently from the last two at every handle operational point (fig1).

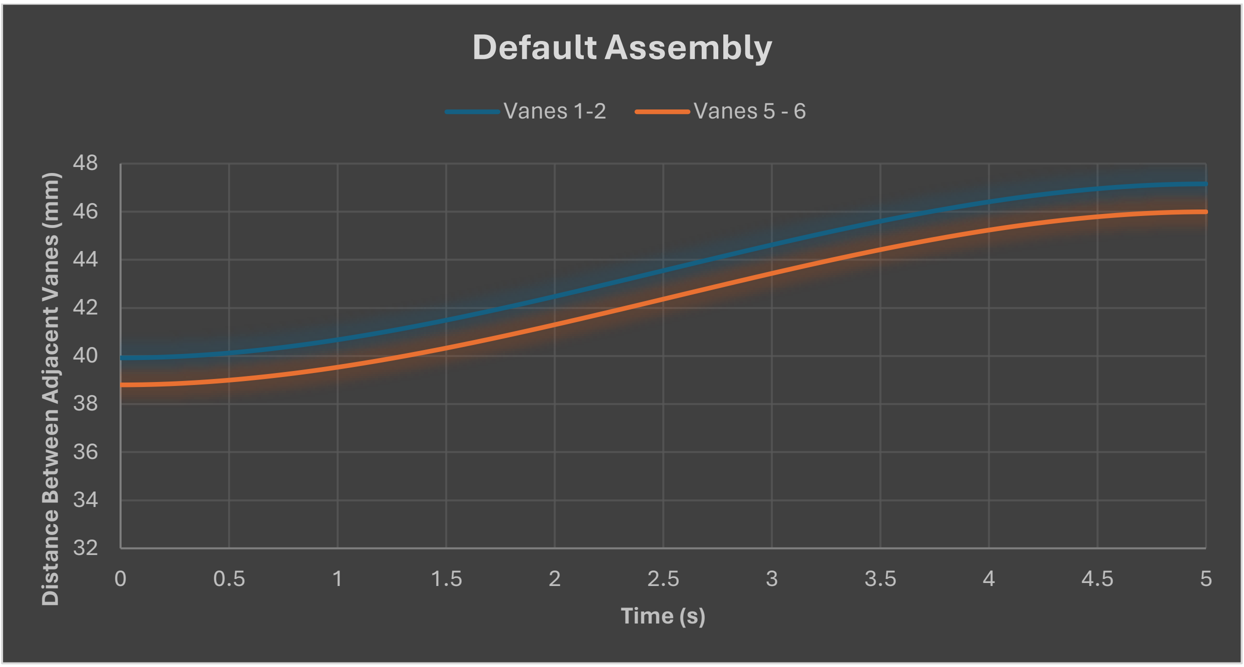


Figure 1 Default assembly vane distance plot

See the end of this document for technical drawings of all (default and not) parts [1].

Two approaches were implemented in trying to resolve this issue:

1. Create a solid large ring to guide every crank simultaneously. This approach revealed to be very energy-intensive, lengthy, and produced poor results (fig2): the vanes behaved as wanted for small handle angles, but diverged at high angles

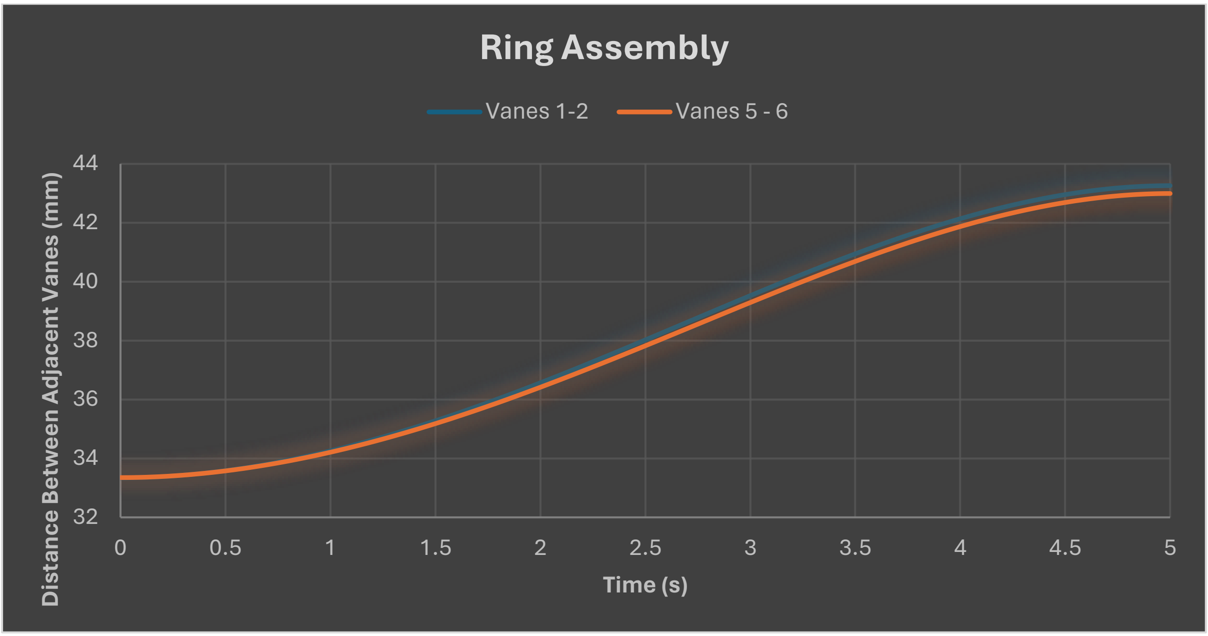


Figure 2 Ring assembly vane distance plot

2. Place each crank at its fully open position, then manually measure the distance between the adjacent connection holes (equally spaced for all cranks due to symmetry) and create a new link geometry with holes spaced apart by the same distance. This was a much simpler approach, which also resulted in its being very successful. There was no notable difference between the guide vanes' distances close to and far away from the handle (fig 3), so this new assembly was eventually selected as the final solution.

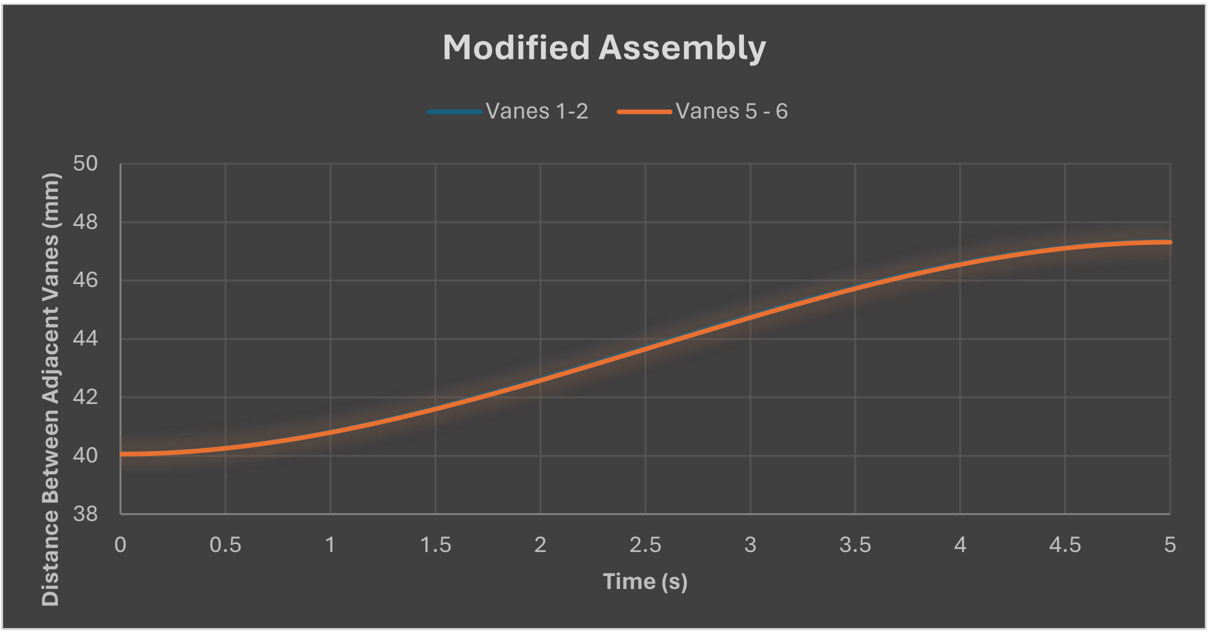


Figure 3 Finalised assembly vane distance plot

Figure 4 Modified link design

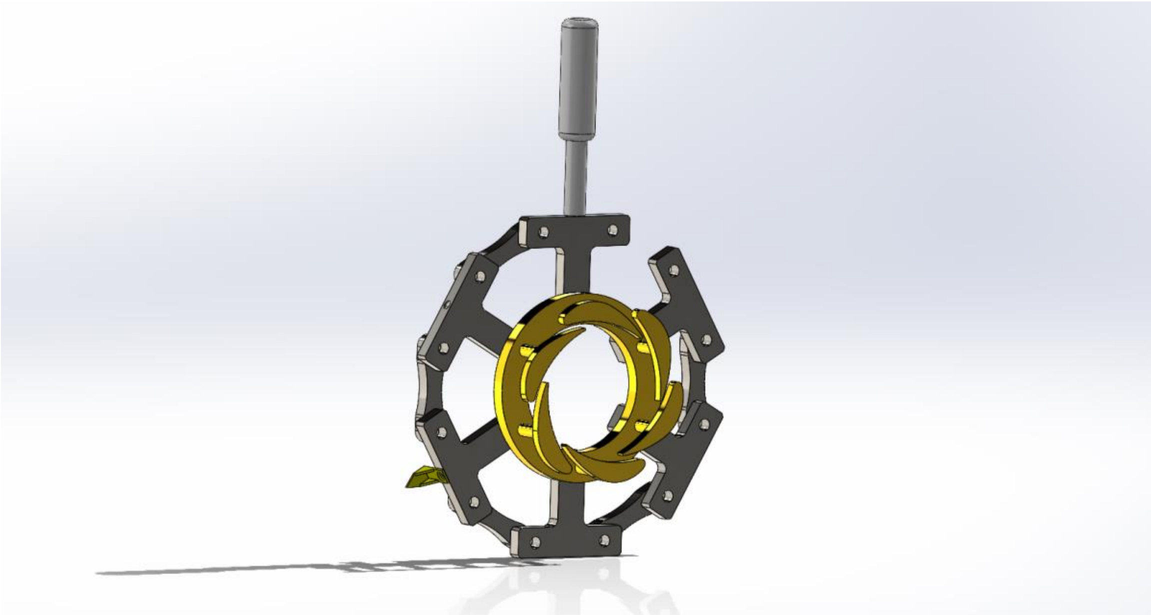


Figure 5 Final design for the guide vane assembly

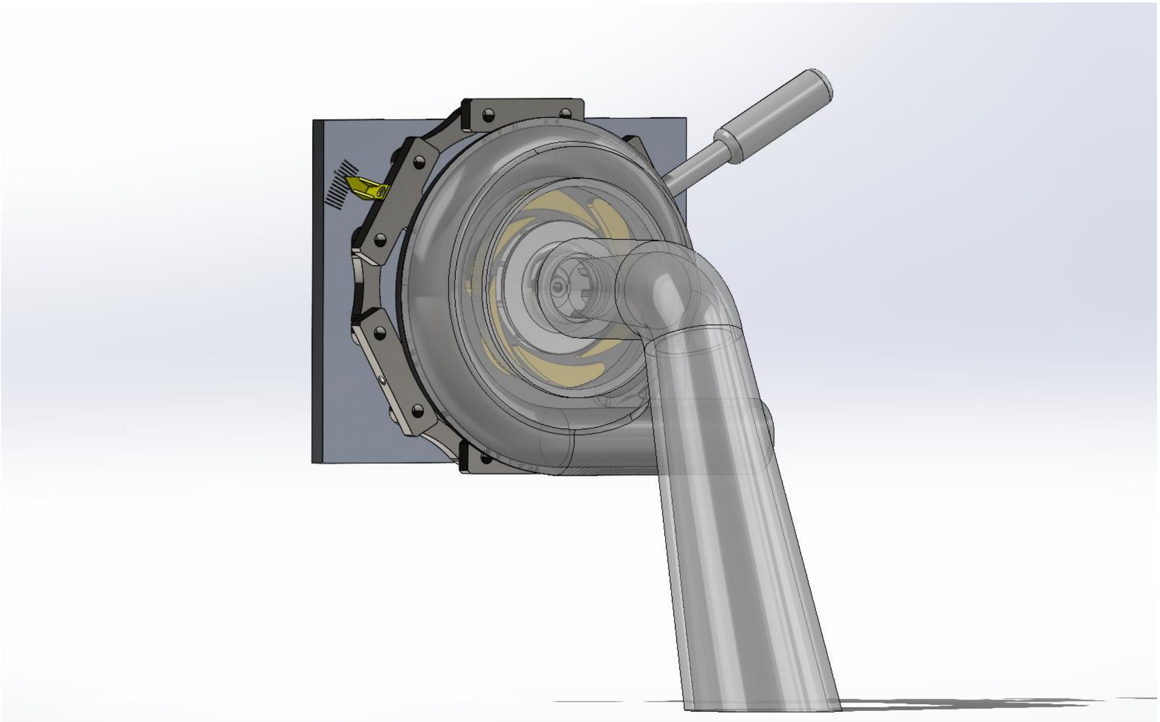
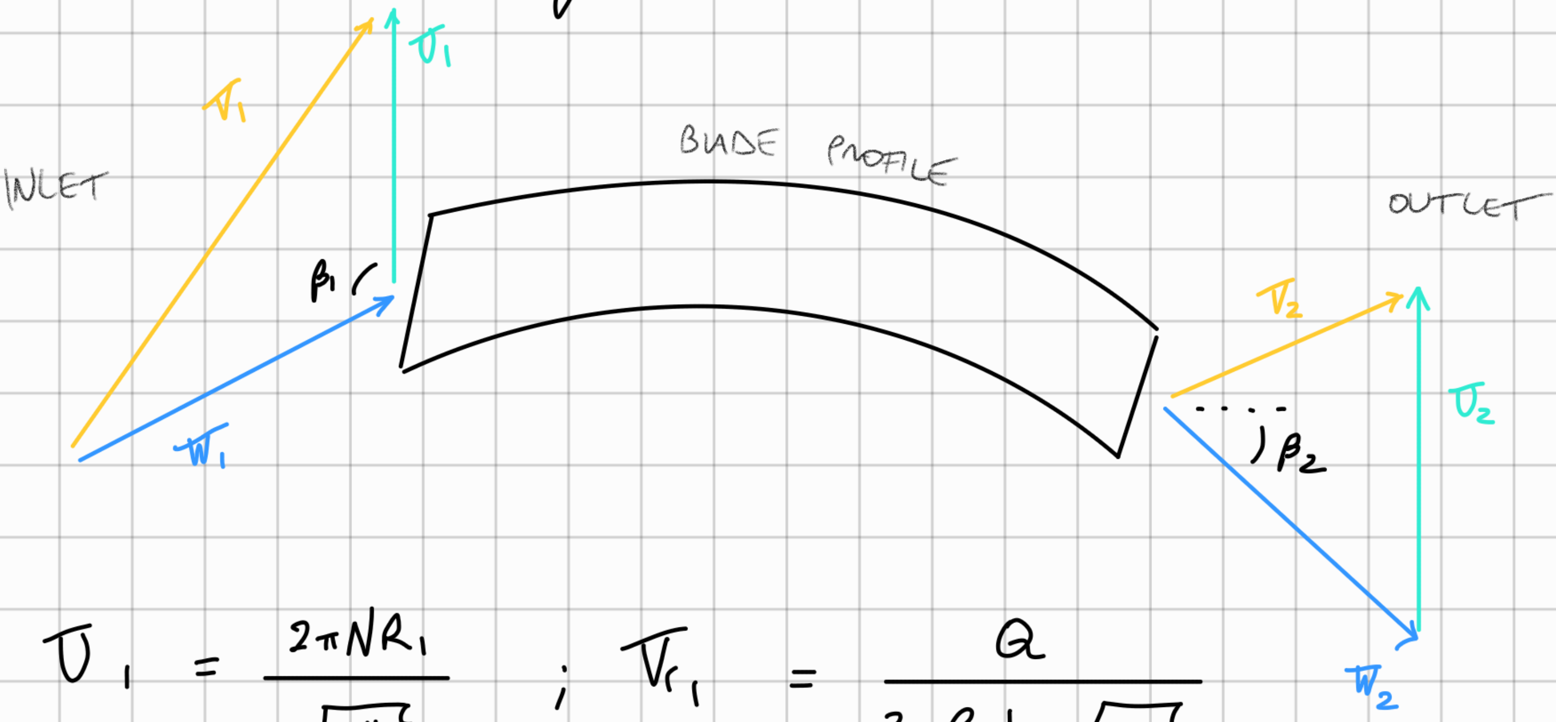


Figure 6 Finalised global assembly

ANGLES CALCULATIONS

- OBJECTIVE : FIND β_1 AND β_2

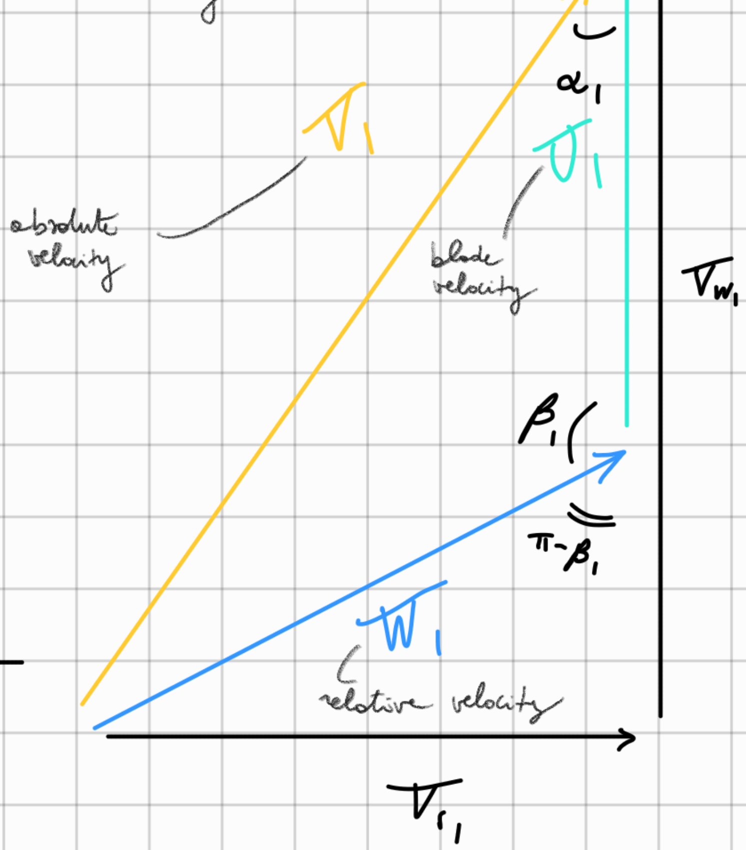
GEOMETRY OF RUNNER :



$$U_1 = \frac{2\pi N R_1}{\sqrt{gH}} \quad ; \quad V_{r_1} = \frac{Q}{2\pi R_1 h_1 \sqrt{gH}}$$

INLET :

VELOCITY TRIANGLE



$$W_1 \sin(\pi-\beta_1) = V_{r_1}$$

$$W_1 = \frac{Q}{2\pi R_1 h_1 \sqrt{gH} \sin\beta_1}$$

$$V_{w_1} = -W_1 \cos(\beta_1) + U_1 =$$

$$= -\frac{Q}{2\pi R_1 h_1 \sqrt{gH} \tan\beta_1} + \frac{2\pi N R_1}{\sqrt{gH}}$$

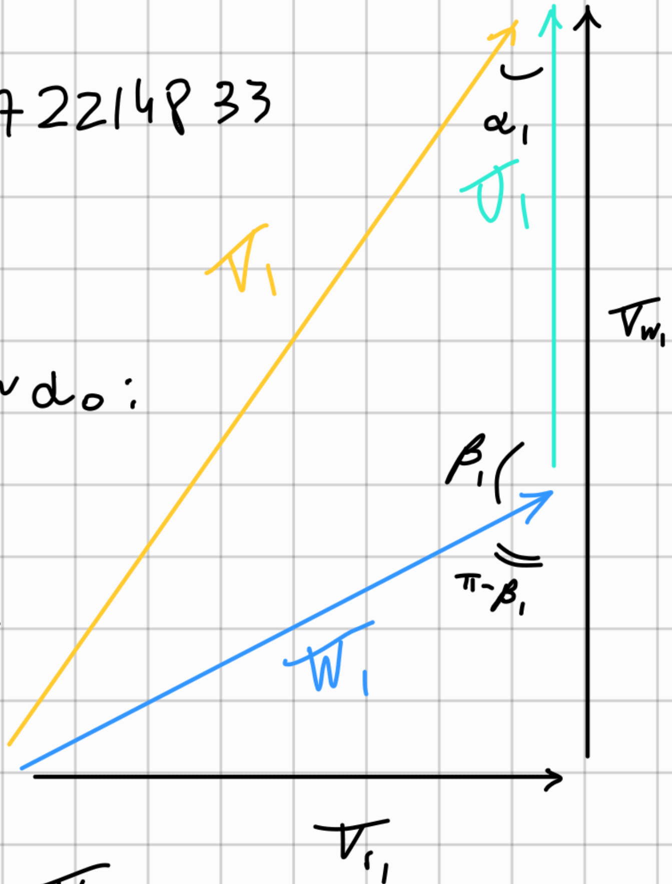
SUBSTITUTE NUMERICAL VALUES:

AT AN OPERATING POINT OF $\theta \sim 63\%$ (GUIDE VANE INDICATOR ANGLE):

$H = 0.7e5$ Pa ; $Q = 2e\text{-}3\ m^3s^{-1}$; $N = 1300 \cdot \frac{2\pi}{60}$ rad s^{-1} ; $\alpha_0 = 9.8°$

$R_1 = 39.8e\text{-}3$ m ; $R_2 = 21.3e\text{-}3$ m ; $h_1 = 7e\text{-}3$ m ; $h_2 = 10e\text{-}3$ m

INLET:



$$U_1 = \frac{2\pi N R_1}{\sqrt{gH}} = 0.641418004 7$$

$$V_{r_1} = \frac{Q}{2\pi R_1 h_1 \sqrt{gH}} = 0.1172214833$$

$$W_1 = \frac{V_r}{\sin\beta_1}$$; ASSUME $\alpha_1 \sim \alpha_0$:

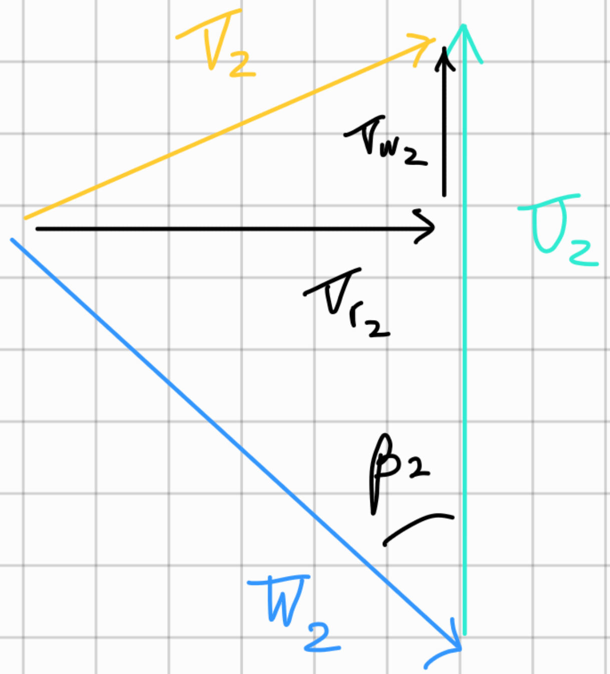
$$V_1 = \frac{V_r}{\sin\alpha_1} = 0.688689432$$

$$V_{w_1} = -W_1\cos\beta_1 + U_1 = V_1\cos\alpha_1 =$$

$$= -\frac{V_r}{\tan\beta_1} + U_1$$

$$\beta_1 = \tan^{-1}\left\{\frac{V_r}{U_1 - V_1\cos\alpha}\right\} = 107.6164°$$

OUTLET :



$$U_2 = \frac{\frac{2\pi}{60} N R_2}{\sqrt{gH}} =$$

$$= 0.3432714447$$

$$V_{r_2} = \frac{Q}{2\pi R_2 h_2 \sqrt{gH}} = 0.1533234988$$

$$W_2 = U_2 \quad (\text{ASSUMPTION})$$

$$W_2 \sin \beta_2 = V_{r_2}$$

$$\beta_2 = \arcsin\left(\frac{V_{r_2}}{W_2}\right) = 26.53^\circ$$

$$\beta_1 + \beta_2 = 134.1464$$

Experimental Results

After performing a hands-on experiment with the physical rig, we were able to graph the performance characteristics of the Francis turbine. The results showed that the peak efficiency is obtained at a flow rate of about 2 l/s at 70% opening (with a maximum efficiency of 23%).

Column1	Column2	Column3	Column4	Column5	Column6	Column7	Column8	Column9	Column10
Measure									
Δp1 (bar)	0.27	0.23	0.19	0.12	0.09	0.14	0.22	0.26	0.27
p2 (bar)	0.71	0.81	0.93	1.15	1.25	1.06	0.84	0.74	0.72
T (Nm)	0.56	0.57	0.57	0.45	0.35	0.51	0.57	0.55	0.55
N (RPM)	1479	1506	1503	1506	1509	1495	1504	1498	1505
W_ts (W)	87	89	89	70	54	79	89	87	86
GV %	100	80	60	40	30	50	70	90	100
Q_v(m^3/s)	0.00238677	0.002203	0.002002	0.001591	0.001378	0.001719	0.002154	0.002342	0.0023868
W_th (W)	411.300194	401.6418	389.0758	344.2121	311.8764	356.3235	399.2768	410.6381	413.68696
n_t	21.1524335	22.15905	22.87472	20.3363	17.31455	22.17087	22.2903	21.18654	20.788666

Figure 7 Excel experimental data

Where the LHS column represents:

- Δp1 = pressure difference across the venturi, used to calculate flow rate
- p2 = gauge pressure at the inlet of the turbine, used to calculate W_th
- T = torque produced by rotating runner
- N = runner speed in units of revolutions per minute
- W_ts = power generated by the turbine
- GV% = percentage of opening of the guide vane angle
- Q_v = volumetric water flow rate
- W_th = head of water available at the turbine entry (in units of power)
- n_t = turbine efficiency

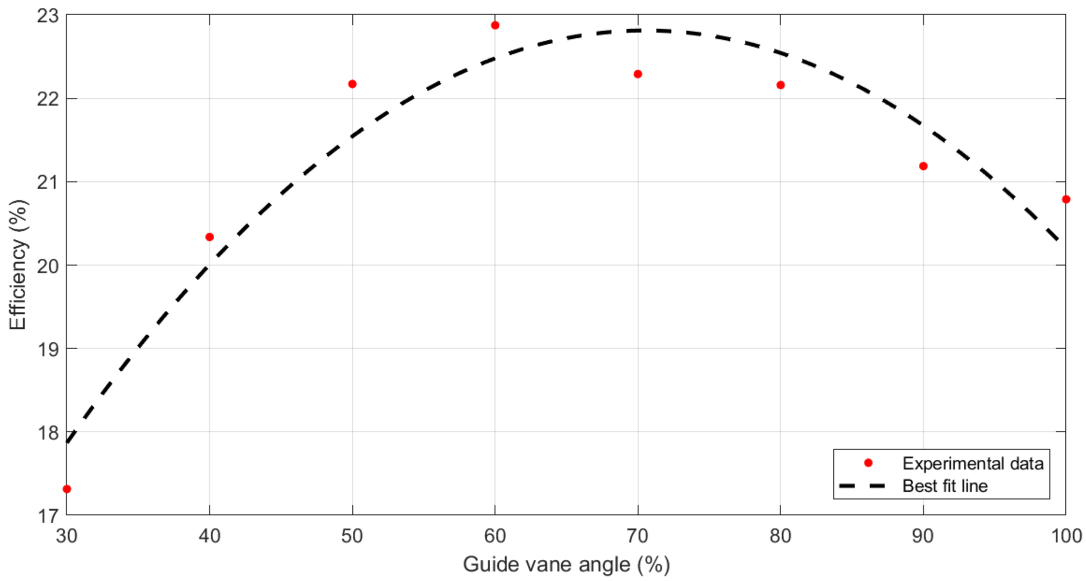


Figure 8 Efficiency vs Vane angle plot

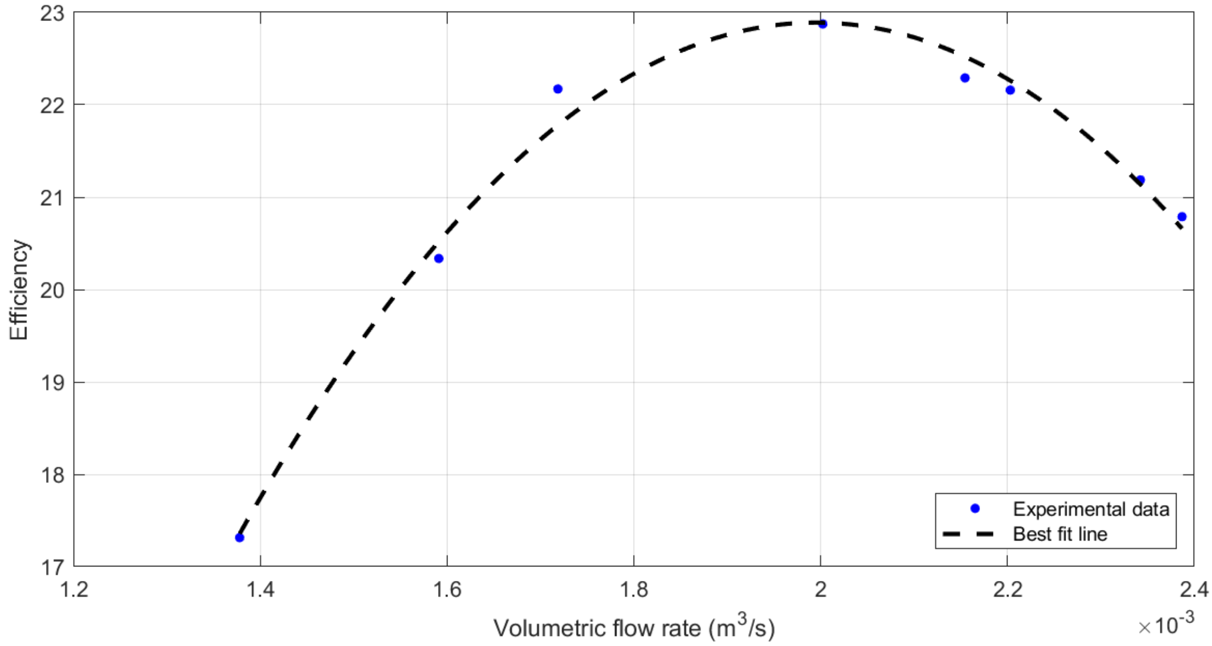
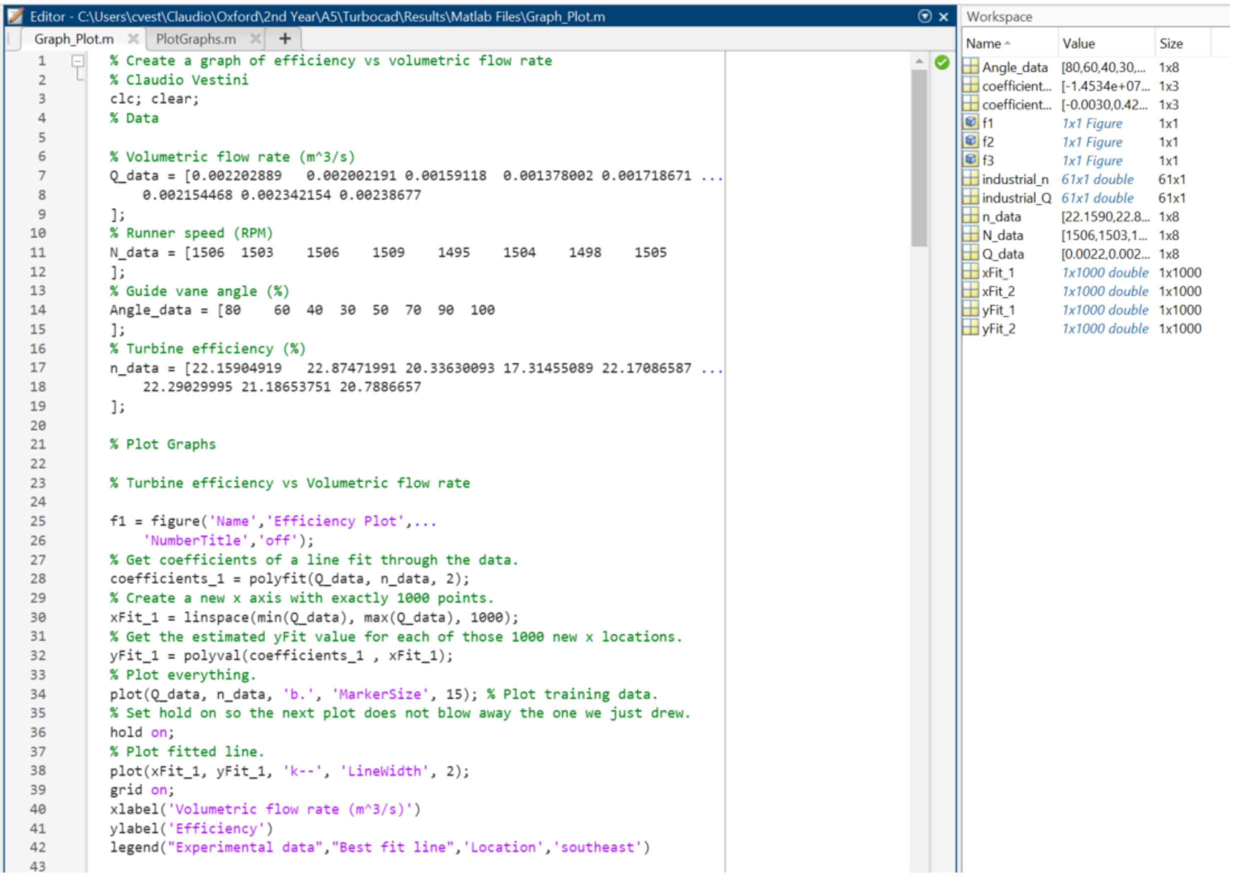


Figure 9 Efficiency vs flow rate plot




```
% Create a graph of efficiency vs volumetric flow rate
% Claudio Vestini
clc; clear;
% Data

% Volumetric flow rate (m^3/s)
Q_data = [0.002202889   0.002002191 0.00159118  0.001378002 0.001718671 ...
    0.002154468 0.002342154 0.00238677
];
% Runner speed (RPM)
N_data = [1506  1503    1506    1509    1495    1504    1498    1505
];
% Guide vane angle (%)
Angle_data = [80    60  40  30  50  70  90  100
];
% Turbine efficiency (%)
n_data = [22.15904919   22.87471991 20.33630093 17.31455089 22.17086587 ...
    22.29029995 21.18653751 20.7886657
];

% Plot Graphs

% Turbine efficiency vs Volumetric flow rate

f1 = figure('Name','Efficiency Plot',...
    'NumberTitle','off');
% Get coefficients of a line fit through the data.
coefficients_1 = polyfit(Q_data, n_data, 2);
% Create a new x axis with exactly 1000 points.
xFit_1 = linspace(min(Q_data), max(Q_data), 1000);
% Get the estimated yFit value for each of those 1000 new x locations.
yFit_1 = polyval(coefficients_1 , xFit_1);
% Plot everything.
plot(Q_data, n_data, 'b.', 'MarkerSize', 15); % Plot training data.
% Set hold on so the next plot does not blow away the one we just drew.
hold on;
% Plot fitted line.
plot(xFit_1, yFit_1, 'k--', 'LineWidth', 2);
grid on;
xlabel('Volumetric flow rate (m^3/s)')
ylabel('Efficiency')
legend("Experimental data","Best fit line",'Location','southeast')
```

Workspace

Name	Value	Size
Angle_data	[80,60,40,30,...	1x8
coefficient...	[-1.4534e+07...	1x3
coefficient...	[-0.0030,0.42...	1x3
f1	1x1 Figure	1x1
f2	1x1 Figure	1x1
f3	1x1 Figure	1x1
industrial_n	61x1 double	61x1
industrial_Q	61x1 double	61x1
n_data	[22.1590,22.8...	1x8
N_data	[1506,1503,1...	1x8
Q_data	[0.0022,0.002...	1x8
xFit_1	1x1000 double	1x1000
xFit_2	1x1000 double	1x1000
yFit_1	1x1000 double	1x1000
yFit_2	1x1000 double	1x1000

Figure 10 MATLAB script

Turbomachinery CAD CWM PART 3A

RADIAL FLOW WATER TURBINE

Exercise 2 - Design, Manufacture and Testing of a Runner for Given Operating Point Conditions

Runner Performance

This part of the exercise is concerned with the testing of the runner over a range of flow rates through the turbine. Here, a series of measurements will be taken for varied settings of applied load at a target head and guide vane opening. The performance will be assessed in terms of power efficiency η versus flow rate Q. If a successful design has been achieved, the resulting curve should peak at the design operating point condition Q. Note that 1 bar = 10kPa.

MEASURED QUANTITIES

H	FLUID ENERGY HEAD	(bar)
Q	FLUID FLOW RATE	(litres/sec)
N	RUNNER SPEED	(revs/min)
T	ALTERNATOR TORQUE	(Nm)

Power Out

$$P_o = T \times \omega = T \times N/60 \times 2\pi = 0.10472 \times T \times N \ (W)$$

Power In

$$P_i = \rho g Q H = 1000 \times 9.81 \times Q \times 10^{-3} \times H \times 10.19$$

$$= 100 \times Q \times H \ (W)$$

Efficiency $\eta = P_o/P_i$

NAME:	COLLEGE:	DATE:
Claudio Vestini	Keble	04/06/2024
DESIGN ANGLES:	β_1 = 107.616	β_2 = 26.53

OPERATING POINT:			
H = 0.7 bar	**Q = 2.0 l/s**	**N = 1300 rpm**	**α_o = 9.8°**

Θ^o = Guide Vane Indicator Angle ≈ 63%

Use Matlab to Plot efficiency η against volumetric flow Q for the points recorded, along with a best fit curve. Note the value of Q for maximum η. Include a title, a grid, and axes labels and units.
Include the graph and suitable comments in your report.

$(Q)_{\eta \max}$ = 2 l/s $(\eta)_{\max}$ = 23%

Comparison to industrial equipment

To complete the analysis, I compared the Thom building experimental results to some of the industry standard-level Francis turbines.

The results of this comparison showed how poor our maximum efficiency (23%) was in comparison to that achievable by some of the world-leading plants (which can get upwards of 95%). For the graph (fig) I used this resource: [Francis Turbine Design on Malabar Mini Hydropower Plant, *R.P. Dewi, ResearchGate, 2018.*]

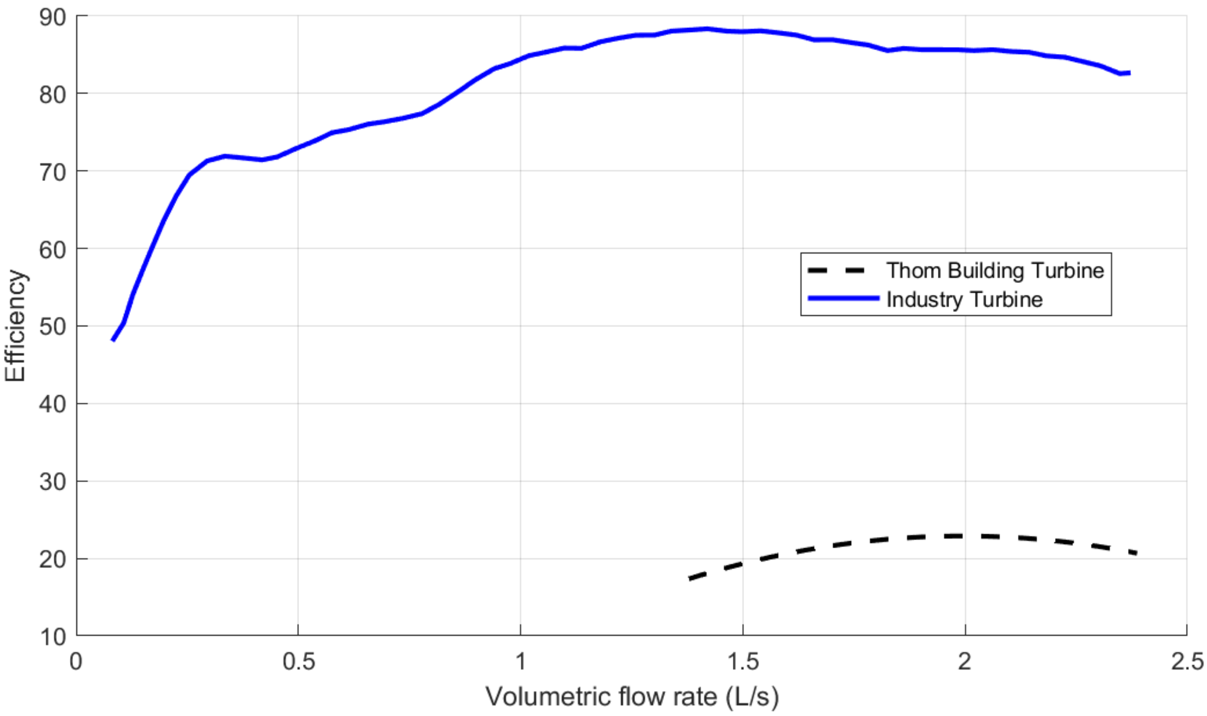


Figure 11 Comparison of efficiency plots to industry standard

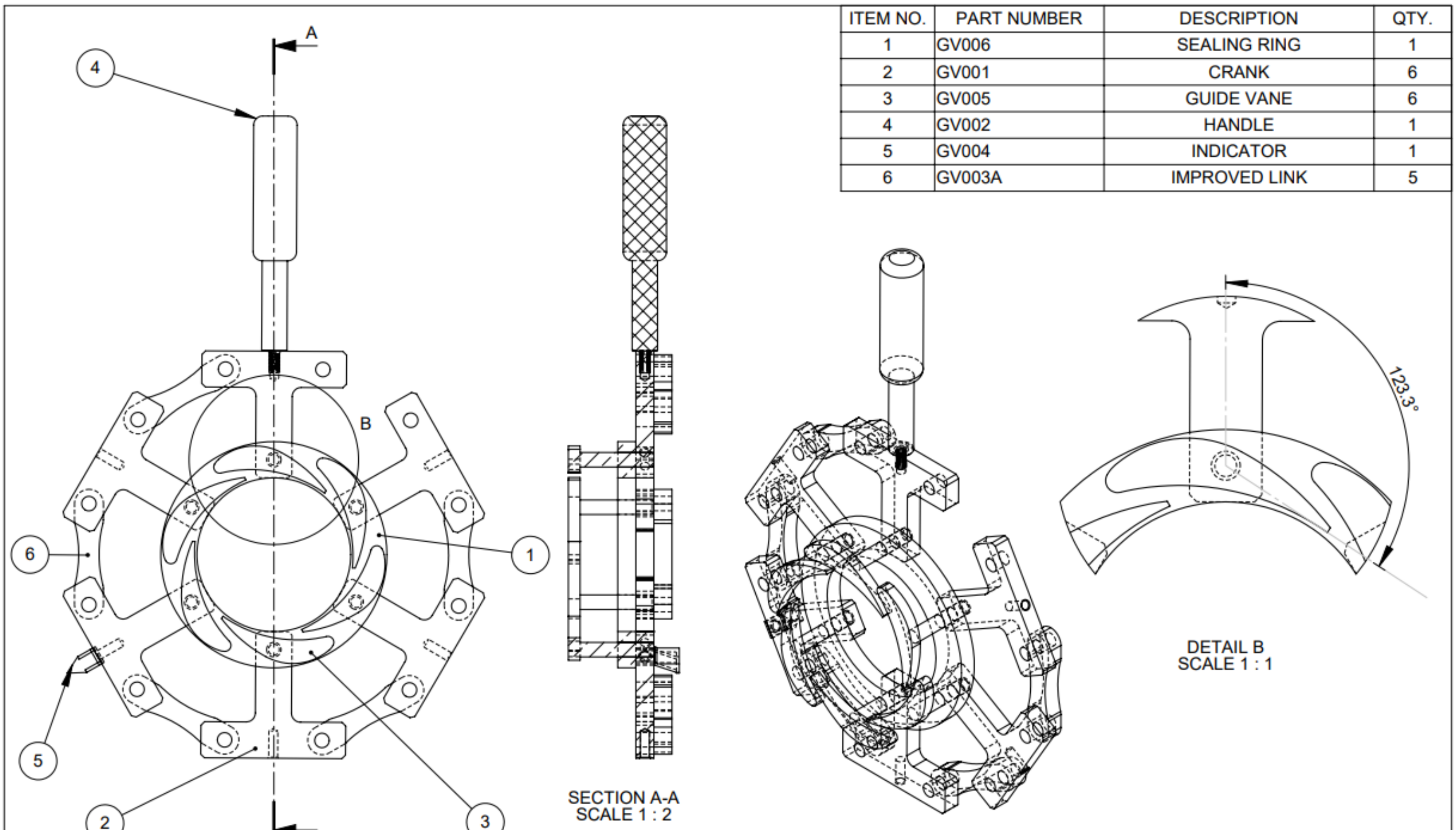
Some possible reasons behind this large gap in performance include:

- Leakage: there was constant spillage in the Thom building rig, which resulted in head loss across the system
- Size and scale: the Thom building turbine is very small in size. This means that boundary layers and viscous friction have much larger effects on the system efficiency. The best industrial turbines are much larger, which also permits them to turn the water flow by a larger angle in the axial direction. They generate more impulse as well as lift forces, which is why their efficiencies can be so high
- Pump-induced vorticity: we used a centrifugal pump as a “virtual reservoir”. This, however, is not entirely the same as having a physical reservoir to draw water from, as it introduces vorticity in the flow, and possibly makes flow cavitate as well

Technical Drawings

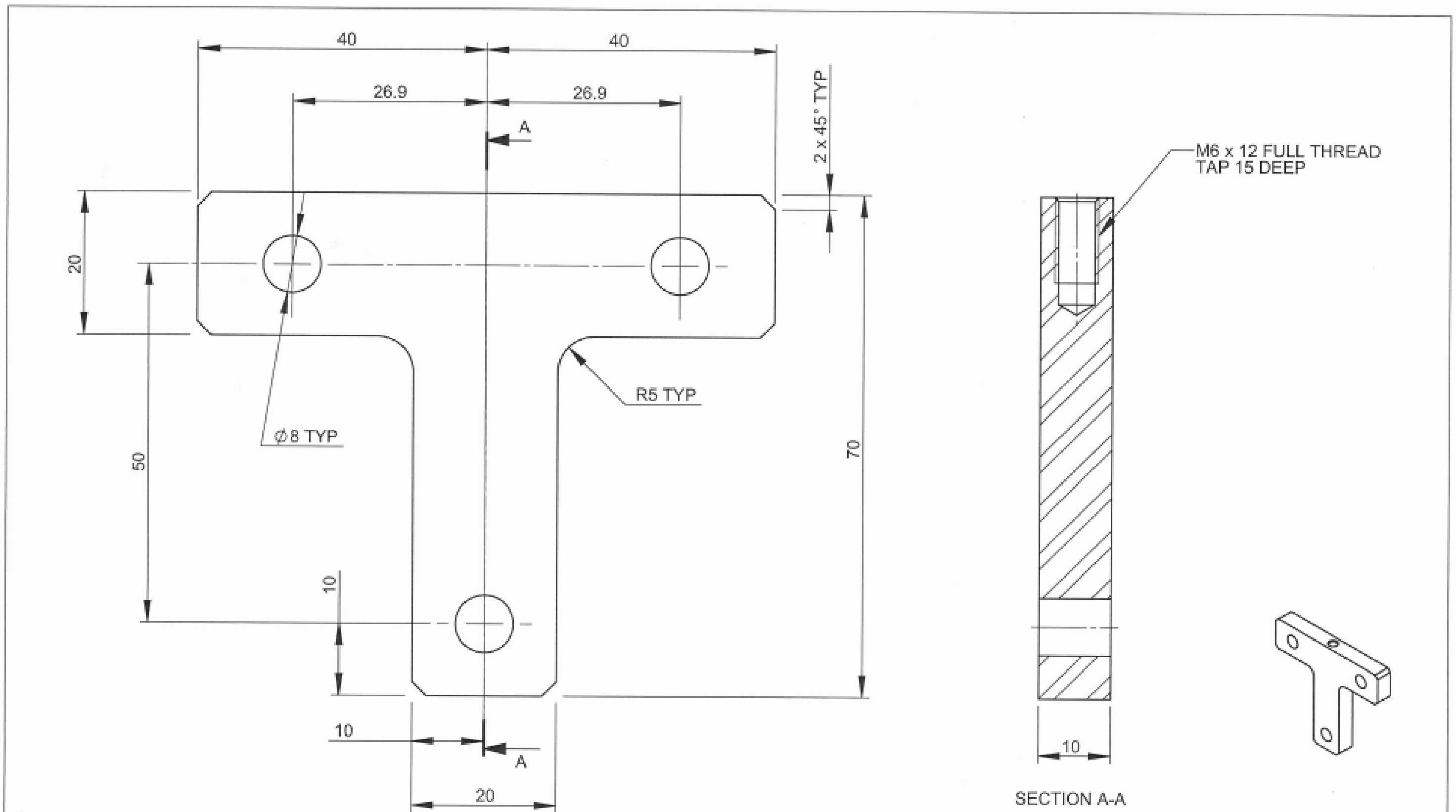
Drg No	**Title**
GV000	Guide Vane Mechanism Assembly - *Modified*
GV001	Guide Vane Crank
GV002	Handle
GV003A	Guide Vane Link - *Modified*
GV004	Indicator
GV005	Guide Vane
GV006	Guide Vane Sealing Ring
TC000	Turbine Assembly - *Modified*
DT002	Draft Tube Reducer
RU001	Runner
VC001	Volute Casing Front
VC002	Volute Casing Rear
MP001	Mounting Plate
SP001	Sealing Plate
DS001	Drive Shaft

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	GV006	SEALING RING	1
2	GV001	CRANK	6
3	GV005	GUIDE VANE	6
4	GV002	HANDLE	1
5	GV004	INDICATOR	1
6	GV003A	IMPROVED LINK	5



DO NOT SCALE. ALL DIMENSIONS IN MM

MATERIAL	THIRD ANGLE PROJECTION	SCALE 1:2	DRAWN DATE 03/06/2024	DEPARTMENT OF ENGINEERING SCIENCE OXFORD UNIVERSITY
FINISH DEBURR; CLEAN	TOLERANCE (UNLESS STATED) +/- 0.1	APPROVED BY	DATE	DRAWN BY C. VESTINI
		PROJECT	COLLEGE KEBLE	TITLE GUIDE VANE MECHANISM
				DRAWING NO. GV000 Final



DO NOT SCALE. ALL DIMENSIONS IN MM

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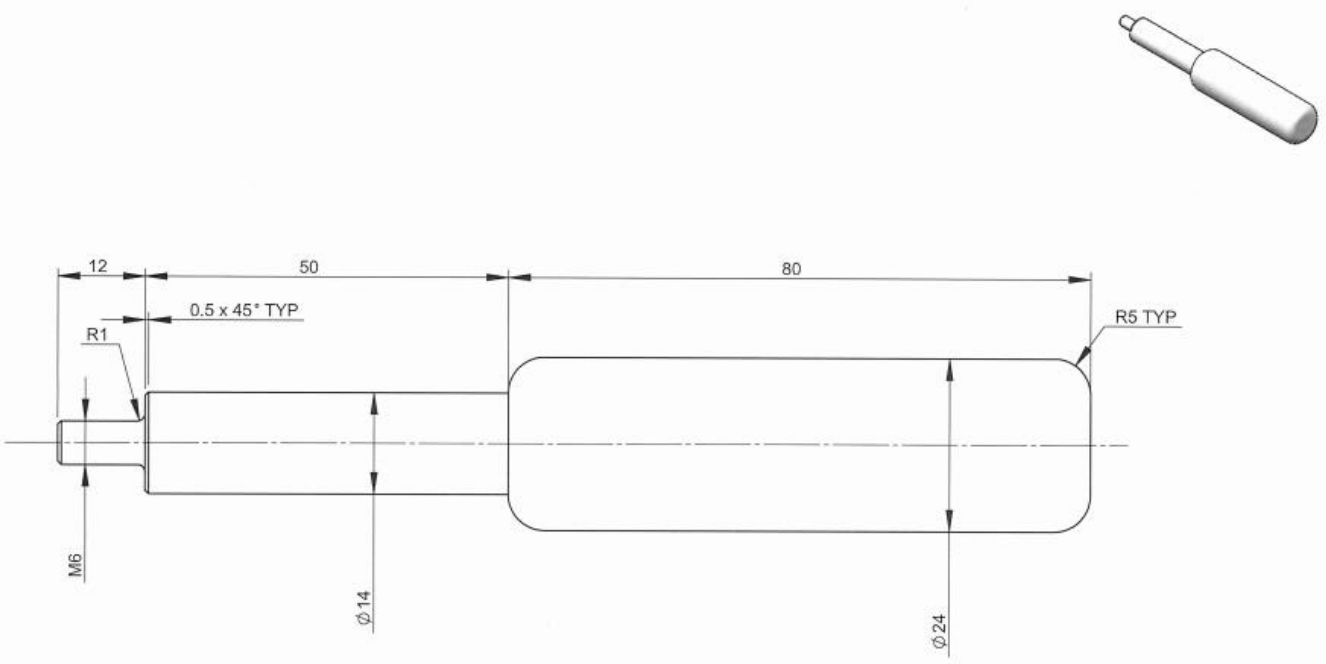
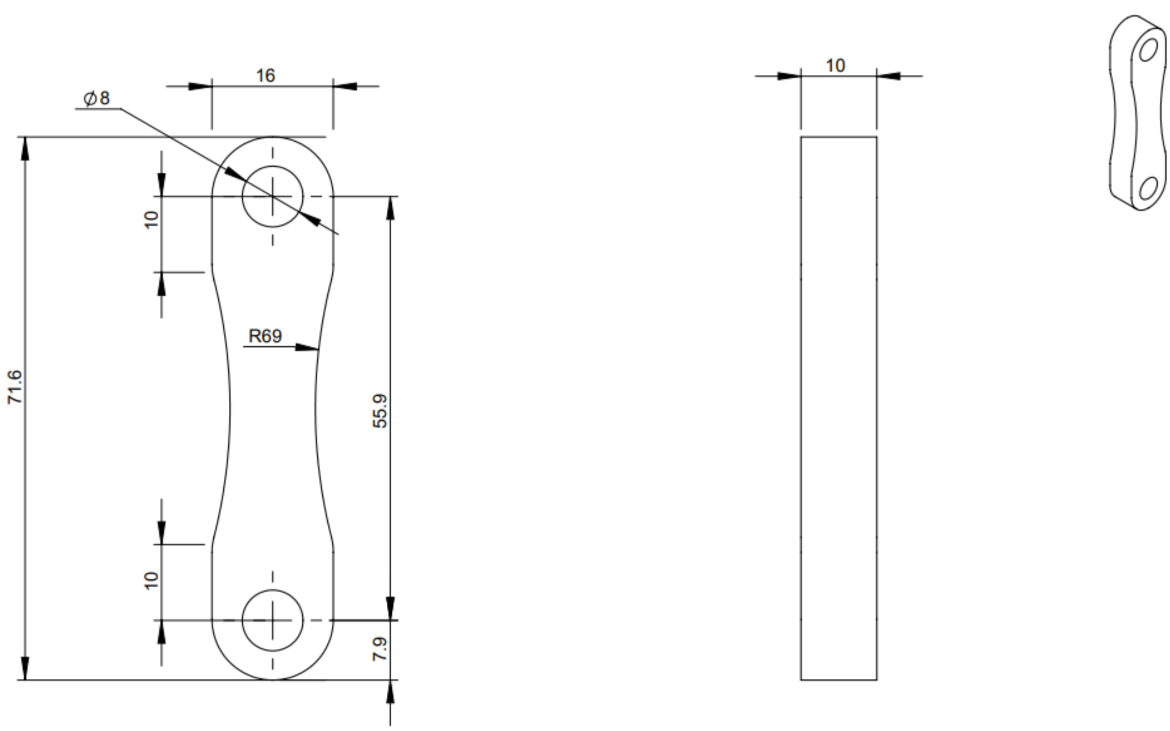
FINISH DEBURR; CLEAN	TOLERANCE (UNLESS STATED) +/- 0.1	APPROVED BY	DATE	DRAWN BY BHS
		PROJECT	COLLEGE DES	TITLE GUIDE VANE CRANK
				DRAWING NO. GV001



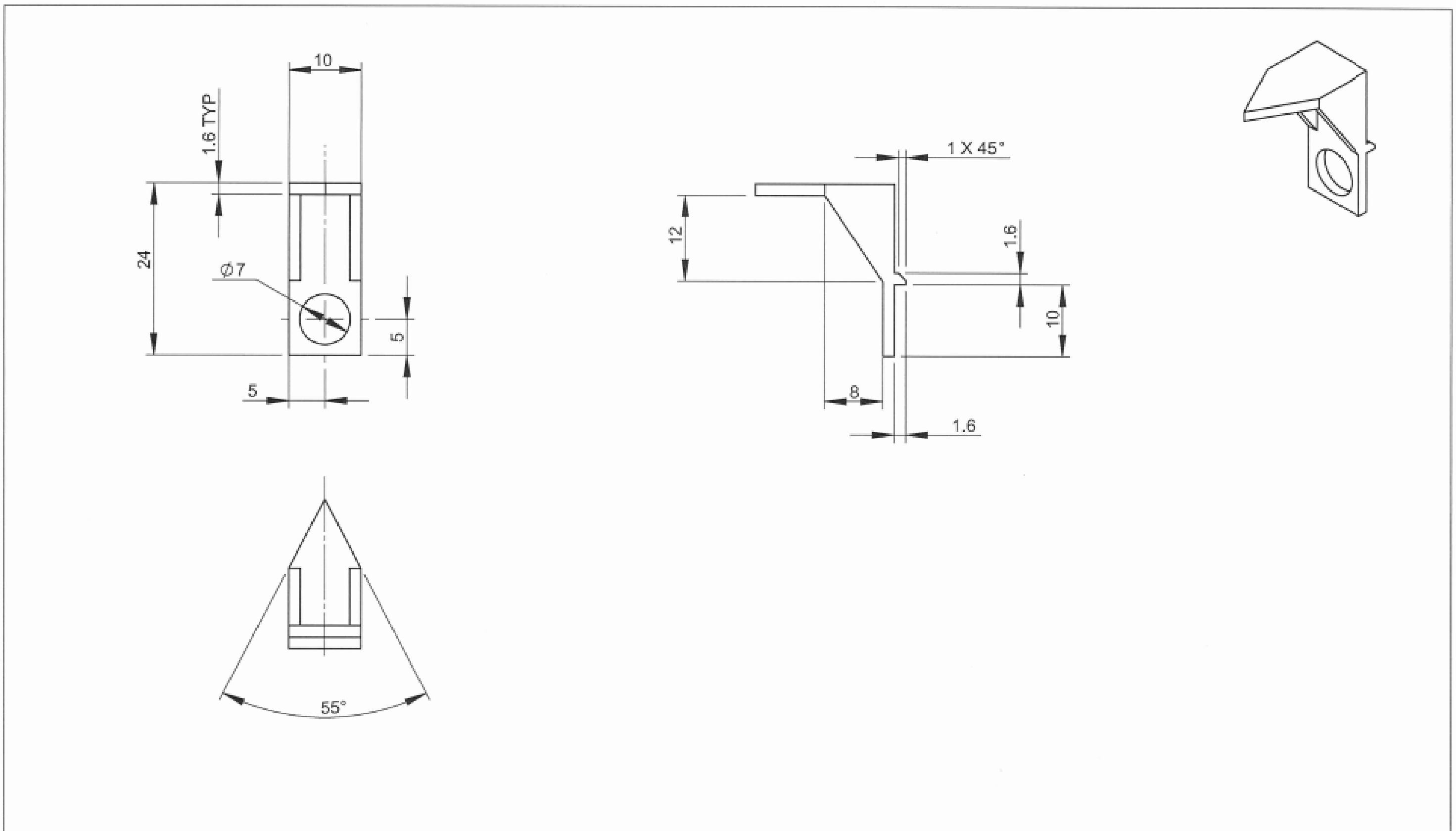
DO NOT SCALE. ALL DIMENSIONS IN MM

MATERIAL: PVC Rigid	THIRD ANGLE PROJECTION	SCALE: 2:1	DRAWN DATE: 23MAR23	DEPARTMENT OF ENGINEERING SCIENCE OXFORD UNIVERSITY	
FINISH: DEBURR; CLEAN	TOLERANCE (UNLESS STATED) +/- 0.1	APPROVED BY	DATE	DRAWN BY: BHS	TITLE: **HANDLE**
		PROJECT		COLLEGE: DES	DRAWING NO. **GV002**



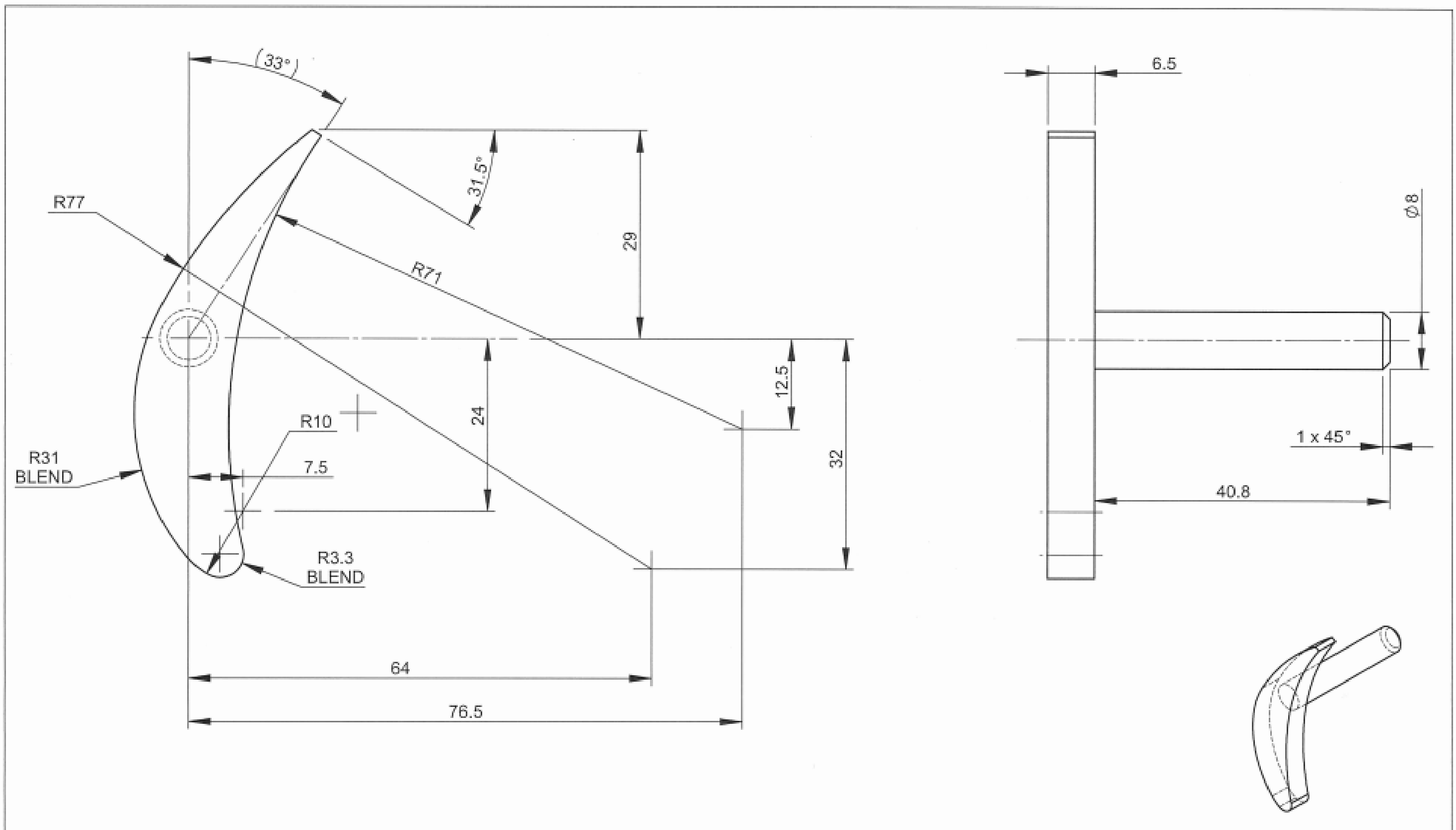
DO NOT SCALE. ALL DIMENSIONS IN MM

MATERIAL: AISI 304	THIRD ANGLE PROJECTION	SCALE: 2:1	DRAWN DATE	DEPARTMENT OF ENGINEERING SCIENCE OXFORD UNIVERSITY	
FINISH: DEBURR; CLEAN	TOLERANCE (UNLESS STATED) +/- 0.1	APPROVED BY	DATE	DRAWN BY: C. VESTINI	TITLE: **GUIDE VANE LINK**
		PROJECT		COLLEGE: KEBLE	DRAWING NO. **GV003A**



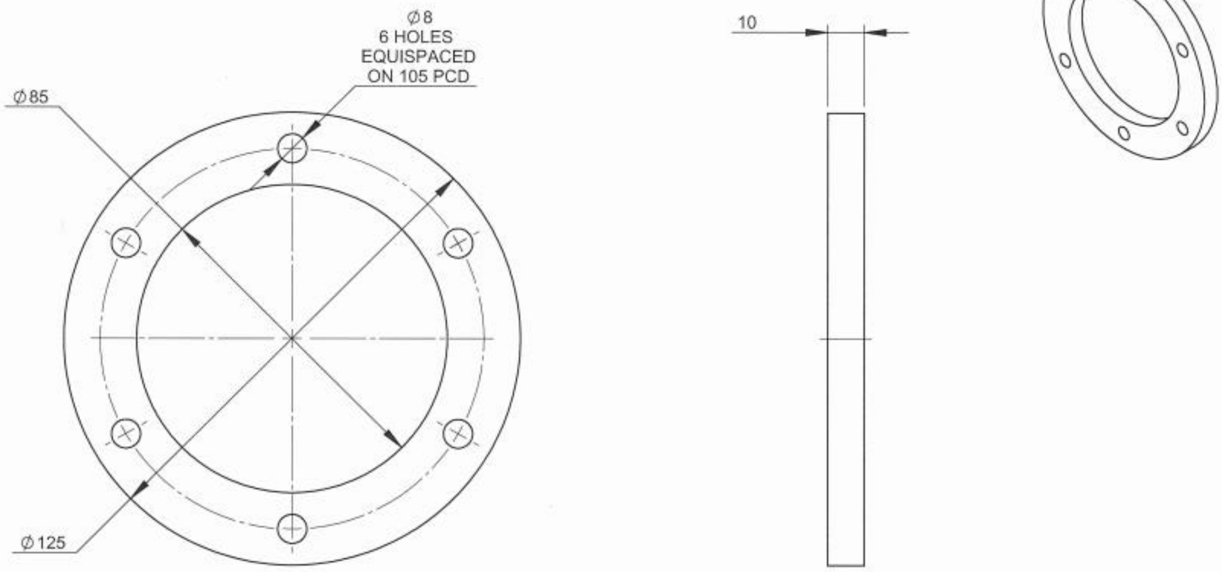
DO NOT SCALE. ALL DIMENSIONS IN MM

MATERIAL ABS - YELLOW	THIRD ANGLE PROJECTION	SCALE 2:1	DRAWN DATE 23MAR23	DEPARTMENT OF ENGINEERING SCIENCE OXFORD UNIVERSITY	
FINISH DEBURR; CLEAN	TOLERANCE (UNLESS STATED) +/- 0.1	APPROVED BY	DATE	DRAWN BY BHS	TITLE **INDICATOR**
		PROJECT		COLLEGE DES	DRAWING NO. **GV004**



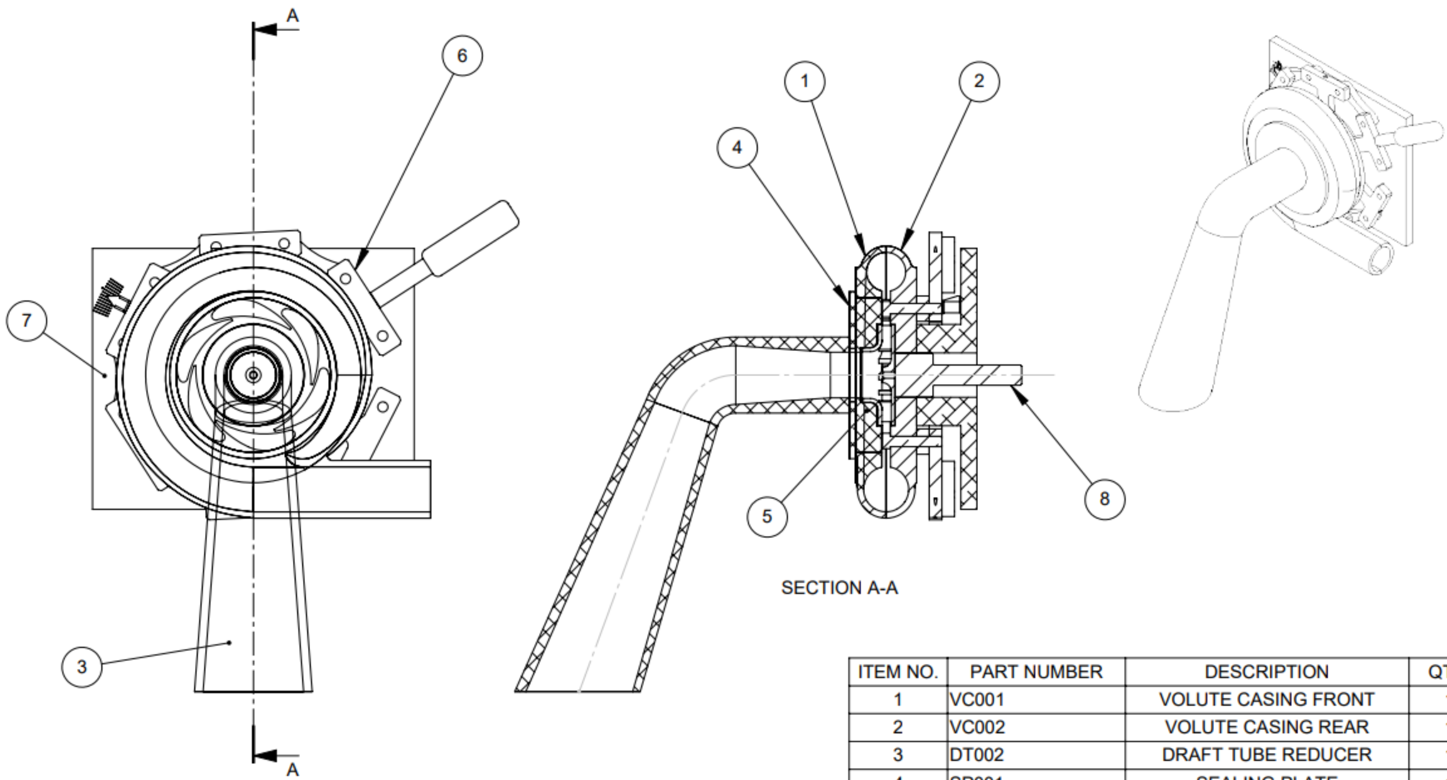
DO NOT SCALE. ALL DIMENSIONS IN MM

MATERIAL BRASS	THIRD ANGLE PROJECTION	SCALE 2:1	DRAWN DATE 23MAR23	DEPARTMENT OF ENGINEERING SCIENCE OXFORD UNIVERSITY	
FINISH DEBURR; CLEAN	TOLERANCE (UNLESS STATED) +/- 0.1	APPROVED BY	DATE	DRAWN BY BHS	TITLE **GUIDE VANE**
		PROJECT		COLLEGE DES	DRAWING NO. **GV005**



DO NOT SCALE. ALL DIMENSIONS IN MM

MATERIAL: AISI 304 SS	THIRD ANGLE PROJECTION	SCALE: 1:1	DRAWN DATE: 23MAR23	DEPARTMENT OF ENGINEERING SCIENCE OXFORD UNIVERSITY	
FINISH: DEBURR; CLEAN	TOLERANCE (UNLESS STATED) +/- 0.1	APPROVED BY	DATE	DRAWN BY: BHS	TITLE: GV SEALING RING
		PROJECT		COLLEGE: DES	DRAWING NO. GV006



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	VC001	VOLUTE CASING FRONT	1
2	VC002	VOLUTE CASING REAR	1
3	DT002	DRAFT TUBE REDUCER	1
4	SP001	SEALING PLATE	1
5	RU001	RUNNER	1
6	GV000 Final	GV MECHANISM ASSEMBLY	1
7	MP001	MOUNTING PLATE	1
8	DS001	DRIVE SHAFT	1

DO NOT SCALE. ALL DIMENSIONS IN MM

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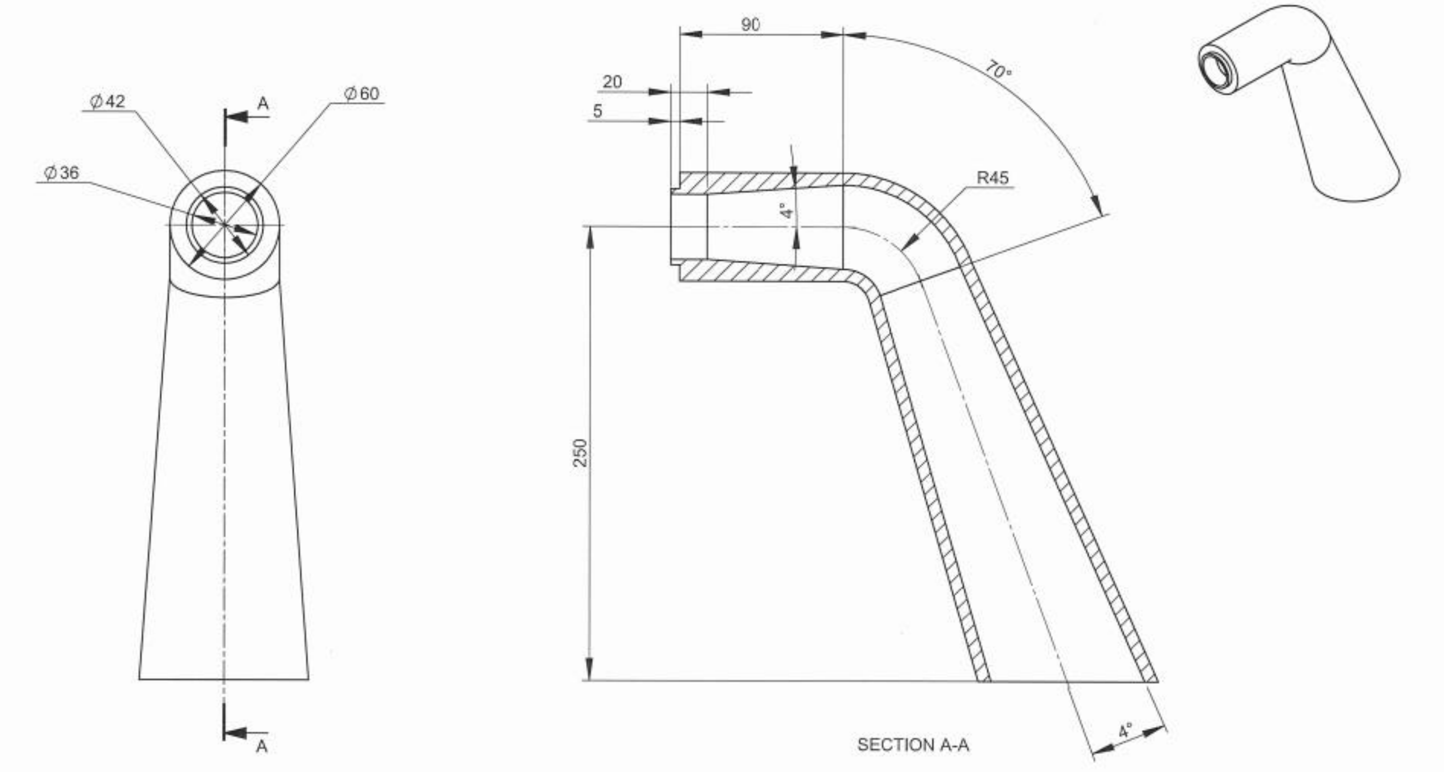
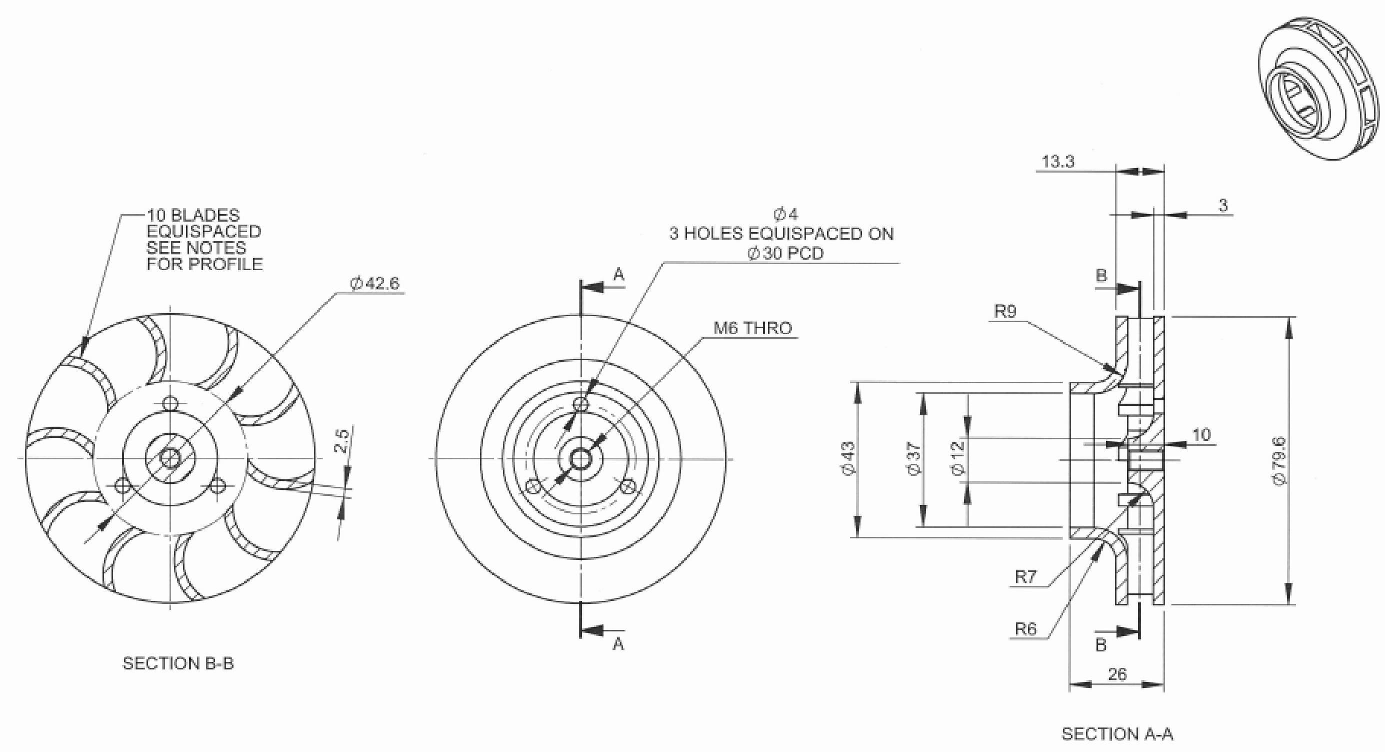
		PROJECT		COLLEGE: KEBLE	DRAWING NO. Turbine Assembly



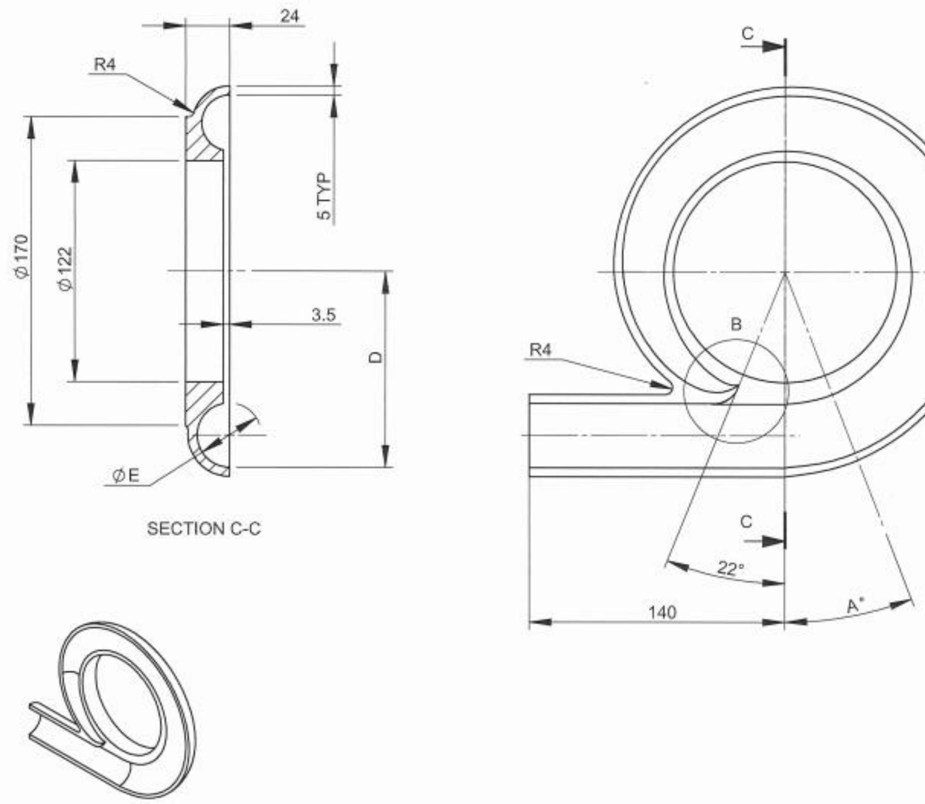
DO NOT SCALE. ALL DIMENSIONS IN MM

MATERIAL Perspex (TM) GS Acrylic Cast Sheet	THIRD ANGLE PROJECTION	SCALE 1:2	DRAWN DATE 31MAR23	DEPARTMENT OF ENGINEERING SCIENCE OXFORD UNIVERSITY	
FINISH DEBURR; CLEAN	TOLERANCE (UNLESS STATED) +/- 0.1	APPROVED BY	DATE	DRAWN BY BHS	TITLE **DRAFT TUBE REDUCER**
		PROJECT		COLLEGE DES	DRAWING NO. **DT002**

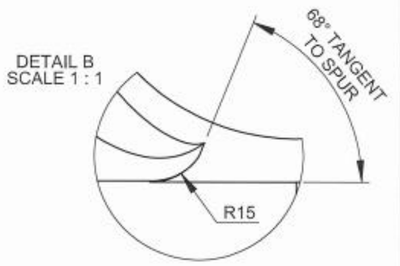


DO NOT SCALE. ALL DIMENSIONS IN MM

MATERIAL PP COPOLYMER	THIRD ANGLE PROJECTION	SCALE 1:1	DRAWN DATE 30MAR23	DEPARTMENT OF ENGINEERING SCIENCE OXFORD UNIVERSITY	
FINISH DEBURR; CLEAN	TOLERANCE (UNLESS STATED) +/- 0.1	APPROVED BY	DATE	DRAWN BY BHS	TITLE **RUNNER**
		PROJECT		COLLEGE DES	DRAWING NO. **RU001**

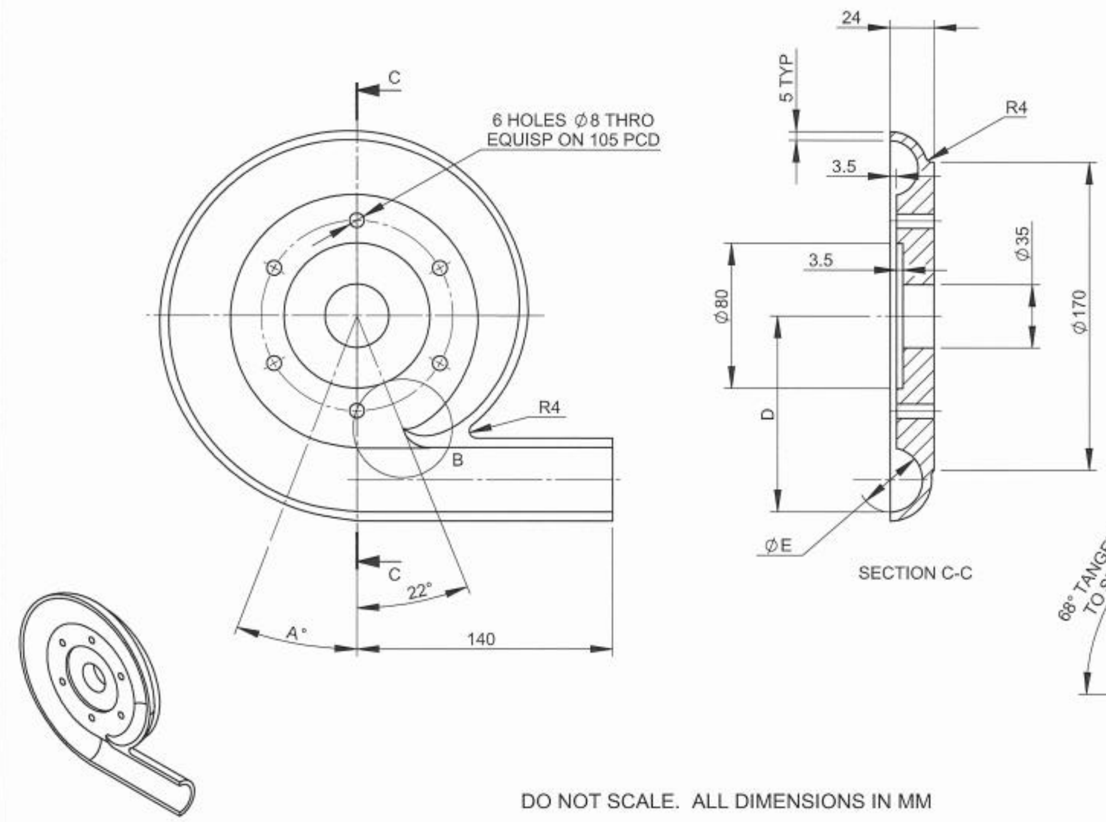


A°	ØE	D
0	**35.4**	**108**
15	35.2	107.3
30	35.0	106.5
45	34.9	105.6
60	34.7	104.8
75	34.3	103.9
90	**34.0**	**103**
105	33.6	102.1
120	33.1	101.1
135	32.6	100.2
150	32.0	99.1
165	31.4	98.1
180	**30.6**	**96.9**
195	29.8	95.8
210	28.8	94.6
225	27.7	93.2
240	26.4	91.8
255	24.9	90.3
270	**23.1**	**88.7**
285	**20.9**	**86.8**
300	**18.1**	**84.7**
315	**14.4**	**82.1**
330	**8.8**	**76.6**
338	**-**	**67.0**

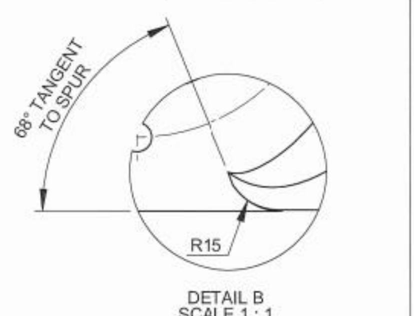


DO NOT SCALE. ALL DIMENSIONS IN MM

MATERIAL Perspex (TM) GS Acrylic Cast Sheet	THIRD ANGLE PROJECTION	SCALE 1:2	DRAWN DATE 28MAR23	DEPARTMENT OF ENGINEERING SCIENCE OXFORD UNIVERSITY
FINISH DEBURR; CLEAN	TOLERANCE (UNLESS STATED) +/- 0.1	APPROVED BY	DATE	DRAWN BY BHS
		PROJECT		COLLEGE DES
				TITLE **VOLUTE FRONT**
				DRAWING NO. **VC001**

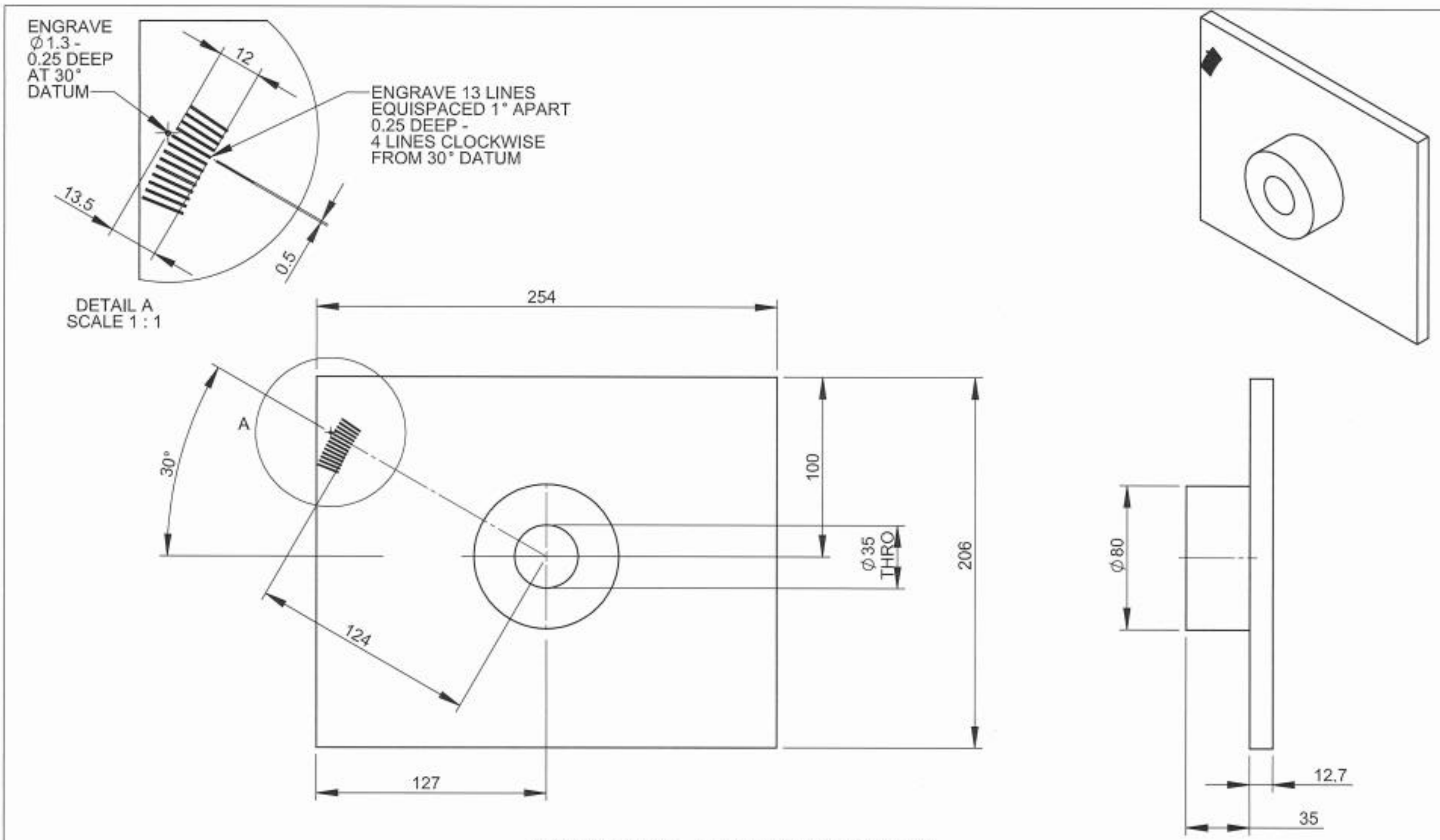


A°	ØE	D
0	**35.4**	**108**
15	35.2	107.3
30	35.0	106.5
45	34.9	105.6
60	34.7	104.8
75	34.3	103.9
90	**34.0**	**103**
105	33.6	102.1
120	33.1	101.1
135	32.6	100.2
150	32.0	99.1
165	31.4	98.1
180	**30.6**	**96.9**
195	29.8	95.8
210	28.8	94.6
225	27.7	93.2
240	26.4	91.8
255	24.9	90.3
270	**23.1**	**88.7**
285	**20.9**	**86.8**
300	**18.1**	**84.7**
315	**14.4**	**82.1**
330	**8.8**	**78.6**
338	**-**	**67.0**



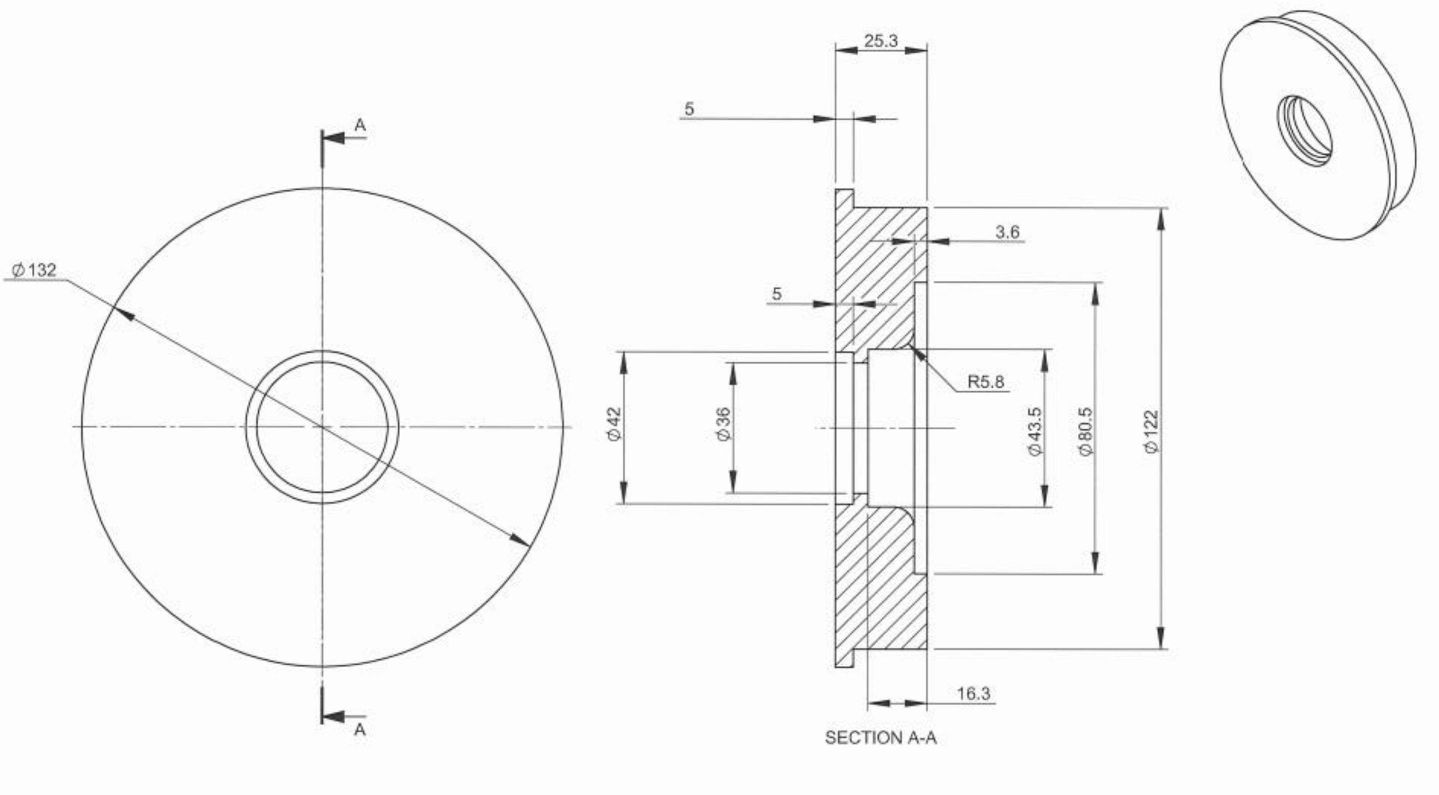
DO NOT SCALE. ALL DIMENSIONS IN MM

MATERIAL Malleable Cast Iron	THIRD ANGLE PROJECTION	SCALE 1:2	DRAWN DATE 30MAR23	DEPARTMENT OF ENGINEERING SCIENCE OXFORD UNIVERSITY
FINISH DEBURR; CLEAN	TOLERANCE (UNLESS STATED) +/- 0.1	APPROVED BY	DATE	DRAWN BY BHS
		PROJECT		COLLEGE DES
				TITLE **VOLUTE REAR**
				DRAWING NO. **VC002**



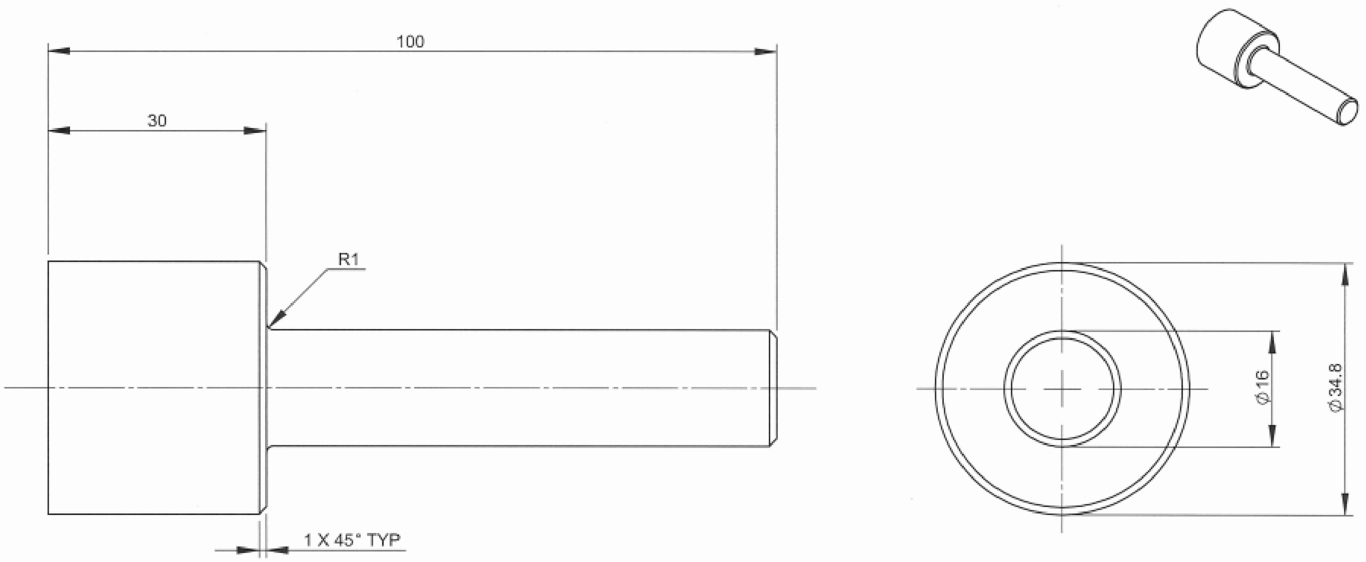
DO NOT SCALE. ALL DIMENSIONS IN MM

MATERIAL 6063-T6	THIRD ANGLE PROJECTION	SCALE 1:2	DRAWN DATE 30MAR23	DEPARTMENT OF ENGINEERING SCIENCE OXFORD UNIVERSITY	
FINISH DEBURR; CLEAN	TOLERANCE (UNLESS STATED) +/- 0.1	APPROVED BY	DATE	DRAWN BY BHS	TITLE **MOUNTING PLATE**
		PROJECT		COLLEGE DES	DRAWING NO. **MP001**



DO NOT SCALE. ALL DIMENSIONS IN MM

MATERIAL PERSPEX	THIRD ANGLE PROJECTION	SCALE 1:1	DRAWN DATE 30MAR23	DEPARTMENT OF ENGINEERING SCIENCE OXFORD UNIVERSITY	
FINISH DEBURR; CLEAN	TOLERANCE (UNLESS STATED) +/- 0.1	APPROVED BY	DATE	DRAWN BY BHS	TITLE **SEALING PLATE**
		PROJECT		COLLEGE DES	DRAWING NO. **SP001**



DO NOT SCALE. ALL DIMENSIONS IN MM

MATERIAL AISI 304	THIRD ANGLE PROJECTION	SCALE 2:1	DRAWN DATE 30MAR23	DEPARTMENT OF ENGINEERING SCIENCE OXFORD UNIVERSITY	
FINISH DEBURR; CLEAN	TOLERANCE (UNLESS STATED) +/- 0.1	APPROVED BY	DATE	DRAWN BY BHS	TITLE **DRIVE SHAFT**
		PROJECT		COLLEGE DES	DRAWING NO. **DS001**