Design of a Turbocharger Combustor

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December 14, 2017

Contents

Preliminary design

0.1 Design Parameters

- Turbocharger compressor outlet diameter = 60 mm
- Turbocharger compressor outlet pressure, P_3 = 3.5 Bar or 350,000 N/m^2
- Turbocharger compressor outlet temperature, T_3 = 150 degrees C or 423 K
- Air mass flow rate, $\dot{m}_3$ = 0.3 kg/s
- Fuel mass flow rate, $\dot{m}_{fuel}$ = 0.0067 kg/s
- Temperature at the turbine inlet or combustor outlet, T_4 = 1000 degrees C or 1273 K
- The turbine inlet contains two rectangular holes of dimensions 8 x 12 mm
- The combustor used Natural gas which primarily composed of methane, CH_4 (assumed)
- The fuel injector hub diameter, D_{hub} is approx 15 mm.

0.2 Design Calculations

0.2.1 Determining cross sectional area

The diameter of the combustor is determined using the pressure loss approach as defined by Lefebvre [1] and Conrado et al. 2004 [2]:

$$A_{ref} = \left[143 \left(\frac{\dot{m}_3 \sqrt{T_3}}{P_3} \right)^2 \left(\frac{\Delta P_{3-4}}{q_{ref}} \right) \left(\frac{\Delta P_{3-4}}{P_3} \right)^{-1} \right]^{0.5} \tag{1}$$

where $\frac{\Delta P_{3-4}}{q_{ref}}$ is the ratio of the total pressure drop across the combustor and the dynamic pressure which across the maximum cross-sectional area and $\frac{\Delta P_{3-4}}{P_3}$ is the ratio of the overall pressure drop across the combustor to the inlet pressure.

Using these parameters we obtain the following values:

Table 1: Dimensionless aerodynamic factors and reference dimensions calculated

Method	Reference	$\frac{\Delta P_{3-4}}{P_3}$	$\frac{\Delta P_{3-4}}{q_{ref}}$	A_{ref}	D_{ref}
1	Lefebvra [1]	0.07	37	$4.84 \times 10^{-3}\ m^2$	0.0785 m or 78.5 mm
2	Conrado et al. 2004 [2]	0.053	40	$5.80 \times 10^{-3}\ m^2$	0.0859 m or 86 mm

0.2.2 Combustion efficiency

Using the theta parameter as defined in [1] to determine combustion efficiency

$$\theta = \frac{P_3^{1.75} A_{ref} D_{ref}^{0.75} \exp^{\frac{T_3}{300}}}{\dot{m}_3} \tag{2}$$

Plugging the value from table 1 for method 1, we obtain:

$$\theta = 4.93 \times 10^7 \tag{3}$$

which corresponds to combustion efficiency of over 90%.
Similarly, for the method 2, we obtain:

$$\theta = 6.33 \times 10^7 \tag{4}$$

which also corresponds to combustion efficiency of over 90%.

0.2.2.1 Combustion liner diameter

The larger value of reference diameter is obtained using the Conrado's parameters. Hence it would be used for following calculations.

For tubular combustor, combustor liner area A_L is 0.7 A_{ref} [1, 2, 3], hence we obtain, $A_L = 4.06 \times 10^{-3} m^2$ which gives combustor liner diameter of 0.0859 m or $\approx$ 8.60 cm.

0.2.3 Annulus area

The annulus area can be determined using the following equation:

$$A_{an} = A_{ref} - A_L \tag{5}$$

$$A_{an} = 5.80 \times 10^{-3} - 4.06 \times 10^{-3} = 1.74 \times 10^{-3} m^2 \tag{6}$$

0.2.4 Design of Diffuser

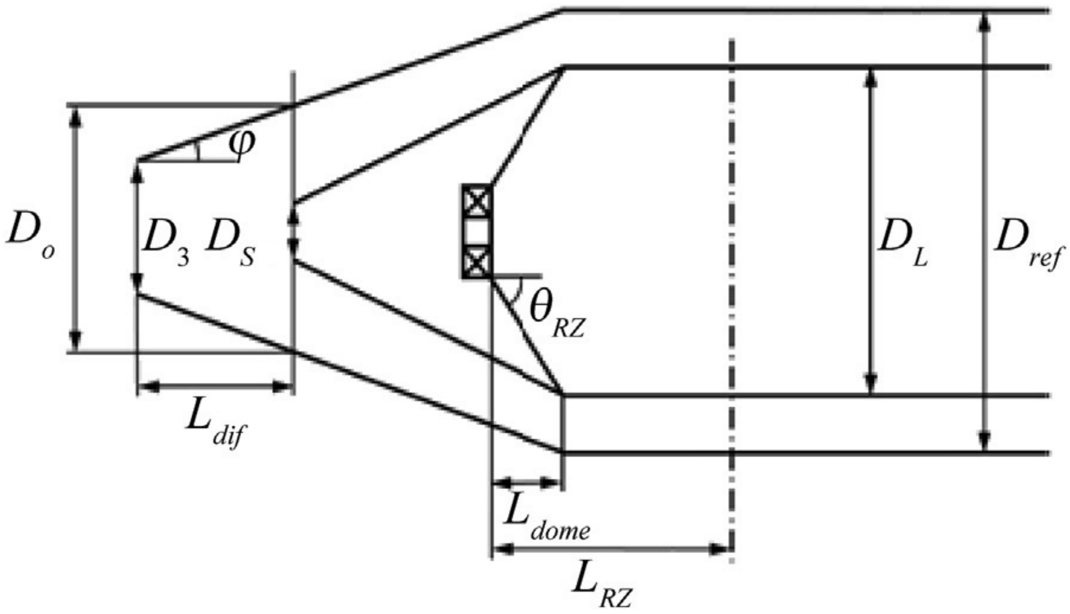


Figure 1: Diffuser geometry, Source: Mark et al. 2016 [4]

0.2.4.1 Calculating snout area

Assuming that 80% of air goes into the annulus [4, 5], we can determine the snout area using the following equation[4];

$$A_0 = \frac{\dot{m}_3}{\dot{m}_a n} A_{an} \tag{7}$$

$$= \frac{\dot{m}_3}{0.80\dot{m}_3} A_{an} = 1.25 \times A_{an} \tag{8}$$

$$= 1.25 \times 1.74 \times 10^{-3} = 2.175 \times 10^{-3} m^3 \tag{9}$$

0.2.4.2 Snout outer diameter

$$D_o = \sqrt{\frac{A_o \times 4}{\pi}} = 0.0526 \text{ m } or \text{ } 5.26 \text{ cm} \tag{10}$$

Now, the snout outer diameter, $D_o < D_3$, hence, D_{ref} needs to be larger. After many iterations in Excel, the D_{ref} calculated equal to 12 cm which gives $A_{ref} = 1.1309734 \times 10^{-3} m^2$.

Repeating the above calculations again for $D_{ref} = 12$ cm, we obtain:

0.2.4.3 Liner area

$$0.7 \times A_{ref} = 0.0079 \ m^2 \tag{11}$$

The liner diameter can be calculated using:

$$D_L = \sqrt{\frac{4 \times A_L}{\pi}} = 0.01 \text{ m } or \text{ } 10 \text{ cm} \tag{12}$$

0.2.4.4 Annulus area

$$A_{an} = A_{ref} - A_L = 0.00339292 \ m^2 \tag{13}$$

0.2.4.5 Snout outer area

Again assumming 80% of air goes into the annulus:

$$A_0 = \frac{\dot{m}_3}{\dot{m}_{an}} A_{an} \tag{14}$$

$$= \frac{\dot{m}_3}{0.80\dot{m}_3} A_{an} = 1.25 \times A_{an} \tag{15}$$

$$= 1.25 \times 1.74 \times 10^{-3} = 4.24115 \times 10^{-3} m^2 \tag{16}$$

0.2.4.6 Snout outer diameter

$$D_0 = \sqrt{\frac{A_o \times 4}{\pi}} = 0.073484692 \text{ m } or \text{ } 7.34 \text{ cm } or \text{ } 73.4 \text{ mm.} \tag{17}$$

0.2.4.7 Snout area

The snout area is calculated using the following equation [4]:

$$A_S = A_0 \frac{\dot{m}_{RZ}}{\dot{m}_3} \frac{1}{Cd_S} \tag{18}$$

where $\dot{m}_{RZ}$ is approximately 20% $\dot{m}_3$ [4, 5], Cd_S is the coefficient of discharge of snout is assumed to be 0.65 [4]. Hence, $A_S = 0.001304969\ m^2$.

The snout diameter can be determined using the following equation:

$$D_S = \sqrt{\frac{A_s \times 4}{\pi}} \tag{19}$$

which gives $D_S = 0.0407$ m m or ≈ 4.0 cm or 40 mm.

0.2.5 Swirler flow area

The swirler flow area is calculated using the following equation [2, 4]:

$$A_{SW} = \sqrt{\frac{A_{ref}^2}{\left[\frac{\frac{\Delta p}{q_{ref}}}{K_{SW}} \left(\frac{\dot{m}_3}{\dot{m}_{SW}}\right)^2 + \left(\frac{A_{ref}}{A_L}\right)^2\right] cos^2 \beta_{SW}}} \tag{20}$$

where K_{SW} is the swirling constant, it is 1.3 for flat vanes and 1.15 for curved vanes [1].
β_{SW} is assumed to be 45 ° for preliminary design
and $\frac{\Delta p}{q_{ref}}$ is 3.33% [2], hence, we obtain:

$$A_{SW} = 0.008185034\ m^2 \tag{21}$$

0.2.5.1 Swirler diameter

The swirler diameter is computed using the following equation [4]:

$$D_{SW} = \sqrt{\left[\frac{A_{SW}}{nB} + \left(\frac{\pi}{4} D_{hub}^2\right)\right] \frac{4}{\pi}} \tag{22}$$

where, $n_B = 10$, $D_{hub} = 15$ mm (assumed).
Hence, we obtain, $D_{SW} = 0.0323$ m.

0.2.5.2 Recirculation zone length

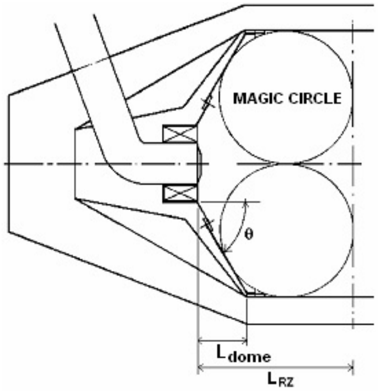


Figure 2: Front end geometry of the combustor, Source: Conrado et al. 2004 [2]

The length of recirculation zone is determined using the following equation [4]:

$$L_{RZ} = 2 \times D_{SW} \tag{23}$$

L_{RZ} = 0.0645 m or 6.45 cm.

0.2.5.3 Recirculation zone angle

The recirculation zone angle is computed using the following equation [2, 4]:

$$\theta_{RZ} = cos^{-1}\left[\frac{-D_L(D_L - 2D_{SW}) - (D_L - 4L_{RZ})\sqrt{D_L^2 - 4D_L D_{SW} + 4D_{SW}^2 - 8D_L L_{RZ} + 16L_{RZ}^2}}{2D_L^2 - 4D_L D_{SW} + 4D_{SW}^2 - 8D_L L_{RZ} + 16L_{RZ}^2}\right] \tag{24}$$

which gives recirculation zone angle $\theta_{RZ} = 68°$.

0.2.5.4 Dome length

The dome length is again computed using [2, 4]:

$$L_{dome} = \frac{D_L - D_{SW}}{2tan\theta_{RZ}} \tag{25}$$

which gives $L_{dome} = 0.017163166m$.

0.2.6 Length of a combustion zones

0.2.6.1 Length of primary zone

Length of Primary zone = 0.75 $\times D_L$ [1] or 0.75 × 0.10 m = 0.075 m or ≈ 7.5 cm

0.2.6.2 Length of secondary zone

Length of Primary zone = 0.5 $\times D_L$ [1] or 0.5 × 0.10 m = 0.05 m or ≈ 5.00 cm

0.2.6.3 Length of Dilution zone

Lengh of dilution zone as specified in Lefebrva [1] is approx 1.5 to 1.8 $\times D_L$, in the present case, to minimise the form factor, lengh of dilution zone is considered 1.5 $\times D_L$ = 0.15 m or 15 cm.

0.2.7 Distribution for the Airflow:

0.2.7.1 Cooling

The percentage of total air that shall be reserved for cooling through the liner using is computed using the following equation [2, 3]:

$$\frac{\dot{m}_{cool}}{\dot{m}_3} = 0.10T_3 - 30 \tag{26}$$

Since, $T_3 = 423K$, hence, $\frac{\dot{m}_{cool}}{\dot{m}_3} = 13\%$

The air in other zones is calculated using the overall equivalence ratio which is computed using following equations, assuming fuel is natural gas and is primarily comprised of methane, CH_4

$$\phi_{overall} = \frac{AFR_{stoic}}{AFR} = \frac{\frac{4.71a}{1}\frac{MW_{air}}{MW_{fuel}}}{\frac{\dot{m}_3}{\dot{m}_{fuel}}} \tag{27}$$

$MW_{air} = 28.85$, $MW_{fuel} = 16.04$, a is 2 for CH_4 hence, we obtain $\phi = 0.38$.

0.2.7.2 Primary zone, PZ

According to Silva [3], the maximum temperature should be around 1773K to prevent NO_x and other pollutants formation due to thermal due to thermal decomposition which corresponds to an equivalence ratio of 0.6.

The air distribution in the primary zone is computed using the following relationship [2, 3]:

$$\frac{\dot{m}_{PZ}}{\dot{m}_3} = \frac{\phi_{overall}}{\phi_{PZ}} \tag{28}$$

$\phi_{PZ} = 0.6$ (assumed for design) and $\phi_{overall}$ is 0.38, hence, air distribution in primary zone would be approximately 63.7%.

0.2.7.3 Secondary zone, SZ

The total air in the primary and secondary zone is defined by considering the richest operating condition [2]:

$$\frac{\dot{m}_{PZ} + \dot{m}_{SZ}}{\dot{m}_3} = \frac{\phi_{overall,rich}}{0.8} \tag{29}$$

where $\phi_{overall,rich} = 0.6$, hence we obtain air distribution in secondary zone approx 11.6%.

0.2.7.4 Dilution zone, DZ

The distribution of air in dilution zone is calculated using:

$$\dot{m}_3 - \dot{m}_{PZ} - \dot{m}_{SZ} - \dot{m}_{cooling} \tag{30}$$

which shows that air distribution in dilution zone is approximately 11.7%.

0.2.8 Estimating the size of holes

The effective hole area in each zone is calculated using the following method as recommended in [2, 3, 6]

At first total effective hole area in each zone is calculated using equation [2, 3, 6]:

$$A_h = \sqrt{\frac{143.5 m_h^2 T_3}{Cd_h^2 P_3^2 \frac{\Delta p_h}{P3}}} \tag{31}$$

where $\frac{\Delta p_h}{P3} = 0.06$ [2]

Once a value of A_h has been calculated, the area ratio α, and bleed ratio β can be calculated, along with the ratio, mu ratio between the bleed ratio and the area ratio.

$$\alpha = \frac{A_h}{A_{an}} \tag{32}$$

$$\beta = \frac{m_h}{m_{An}} \tag{33}$$

$$\mu = \frac{\beta}{\alpha} \tag{34}$$

The next step is to calculate the hole pressure loss factor k using the following relationship [1, 2, 3, 6];

$$k = 1 + 0.64 + \delta^2 \left[2\mu^2 + (4\mu^4 + (\mu^2/\delta^2)(4\beta - \beta^2))^{0.5}\right] \tag{35}$$

where, δ is a momentum loss factor and lies between 0.75 and 0.9 [2, 3]. The value used for plain holes is 0.8 [3].

The values obtained of effective hole area using these equations are presented in tables below.

0.2.8.1 Primary zone

Table 2: Predicted parameters for primary zone holes

Parameter	Values
Cd	≈0.61
A_h	0.000617626 m^2
k	38.87
$\dot{m}_{PZ}$	0.1311 kg/s
α	0.182033657
β	0.54625
μ	3.000818695
Diameter of hole	≈ 3.5 mm
Number of holes	10

0.2.8.2 Secondary zone

Table 3: Predicted parameters for secondary zone holes

Parameter	Values
Cd	≈0.61
A_h	0.000166679 m^2
k	37.37
$\dot{m}_{PZ}$	0.0348 kg/s
α	0.048320147
β	0.145
μ	3.000818695
Diameter of hole	≈ 1.5 mm
Number of holes	10

0.2.8.3 Dilution zone

Table 4: Predicted parameters for dilution zone holes

Parameter	Values
Cd	≈0.61
A_h	0.000162693 m^2
k	38.5537052
$\dot{m}_{DZ}$	0.0351 kg/s
α	0.0487367
β	0.14625
μ	3.000818695
Diameter of hole	≈ 1.5 mm
Number of holes	20

0.2.8.4 Cooling

Table 5: Predicted parameters for cooling zone holes

Parameter	Values
Cd	≈0.61
A_h	0.000183733 m^2
k	37.47461337
$\dot{m}_{cool}$	0.039 kg/s
α	0.054151889
β	0.1625
μ	3.000818695
Diameter of hole	≈ 1 mm
Number of holes	16

0.2.8.5 Dome

Table 6: Predicted parameters for dome holes

Parameter	Values
Cd	≈0.61
A_h	0.000141333 m^2
k	37.24965045
$\dot{m}_{PZ}$	0.03 kg/s
α	0.041655299
β	0.125
μ	3.000818695
Diameter of hole	≈ 1.5 mm
Number of holes	10

0.3 Temperature profile

The combustor has four zones: recirculation zone, primary zone, secondary zone and dilution zone. For each region, the local temperature will be assumed to vary linearly between the zone inlet temperature (T_{in}) and zone outlet temperature (T_{out}). For every zone, the outlet temperature is calculated by the following equation [2]:

$$T_{out} = T_3 + \eta \Delta T \tag{36}$$

0.3.0.1 Recirculation zone

T_{in} is assumed to equal to T_3. ΔT is the temperature rise from T3 to adiabatic flame temperature for equivalence ratio equals one which is calculated approximately equal to 2236K (considering fuel is a natural gas and is primarily comprised of methane and pressure is constant), and η is the combustion efficiency in the recirculation zone and is calculated using:

$$\eta_{RZ} = 0.56 + 0.44 tanh[1.5475 \times 10^{-3} \times (T_3 + 108 log P_3 - 1863)] \tag{37}$$

The combustion efficiency in RZ is calculated approximately 52% and $T_{out,RZ}$ is computed approx 1364K.

0.3.0.2 Primary zone minus recirculation zone

The combustion efficiency in the PZ is obtained using:

$$\eta_{PZ} = 0.71 + 0.29tanh[1.5475 \times 10^{-3} \times (T_3 + 108logP_3 - 1863)] \tag{38}$$

Using (38), the combustion efficiency of PZ obtained approx 68%, and temperature at the PZ outlet is computed, $T_{out,PZ} = 1546$K.

0.3.0.3 Secondary zone

For the lean mixture as for the present case, the combustion efficiency is computed using the following equation [2]:

$$log(log\frac{1}{\eta}) = 0.911log\psi_{T_3} + 8.02\psi_{T_3} - 1.097 + D^* \tag{39}$$

where D^* is an emprical constant and is computed using

$$D^* = 0.736 - 0.0173\left(\frac{P_{3-4}}{P3}\right)^{-1} \tag{40}$$

which gives $D^* = 0.4095$.

ψ_{T_3} is the kinetic fuel loading and for $T_3 = 300$k, it is defined using the equation:

$$\psi_{T_3=300} = \frac{\dot{m}_{fuel}}{V_{PZ}P_3^n} \tag{41}$$

where V_{PZ}, primary zone volume which is computed equal to 4.67 $\times 10^{-3}$ m^3, n is reaction order, n which is 1 for $\phi_{SZ} \leq 0.5$ which is for the present case. Hence, we obtain, $\psi_{T_3=300} = 4.10 \times 10^{-6}$.

Since, T_3 is different than 300k, hence, we use the following equation to compute ψ_{T_3} [2]:

$$\frac{\psi_{T_3}}{\psi_{T_3=300}} = \left(10^{-3.54y^{-1.205}}\right)\left(T^{1.2327y^{-1.205}}\right) \tag{42}$$

which is computed equal to 2.64.

Hence, $\psi_{T_3} = 1.085 \times 10^{-5}$.

Putting all the values in the equation (41), we obtain $\eta_{SZ} = 0.99$.

Hence, we obtain $T_{out,SZ} = 1459$K.

0.3.0.4 Dilution zone

Similarly temperature at the exit of the dilution zone is calculated $T_{out} = 1224\text{k} \approx 951^\circ$

0.4 Calculation Summary

From the above calculations, the following dimensions are obtained (Please go to next page, see Table 7):

Table 7: In this table, the calculations are summarised

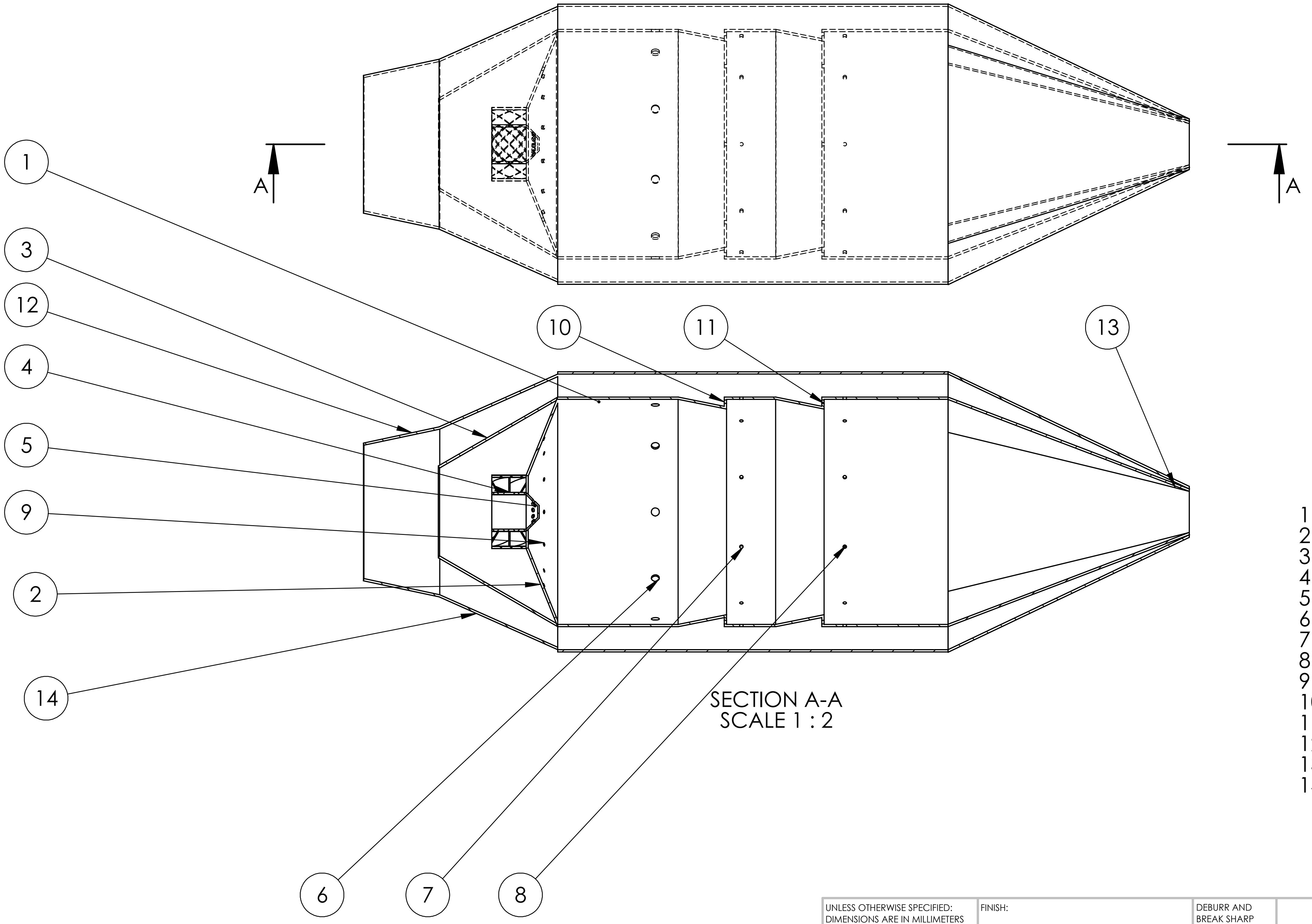
Parameter	**Symbol**	**Dimension**
Reference Area	A_{ref}	1.1309734 $\times 10^{-3} m^2$
Reference Diameter (Outer diameter)	D_{ref}	0.012m or 120 mm
Liner Area	A_L	0.00339292 m^2
Liner Diameter	D_L	0.010 m or 100 mm
Annulus area	A_{an}	0.00339292 m^2
Snout outer area	A_0	0.24115 $\times 10^{-3} m^3$
Snout outer diameter	D_0	0.0328 m or 32 mm
Snout area	A_S	0.001304969 m^2
Snout diameter	D_S	0.004 m or 40 mm
Swirler flow area	A_{SW}	0.008185034 m^2
Swirler diameter	D_{SW}	0.0323 m or ≈ 33 mm.
Recirculation zone length	L_{RZ}	0.0645 m or 64.5 mm
Recirculation zone angle	θ_{RZ}	68°
Dome Length	L_{dome}	0.0171 m or ≈17 mm.
Length of Primary zone	l_{PZ}	0.075 m or 75 mm
Diameter of primary holes	D_{PH}	0.0035 m or 3.5 mm
Number of primary holes		10
Length of Secondary zone	L_{SZ}	0.050 m or 50 mm
Diameter of secondary holes	D_{SH}	0.0015 m or 1.5 mm
Number of secondary holes		10
Length of Dilution zone	L_{DZ}	0.015 m or 150 mm
Diameter of Dilution holes	D_{DZ}	0.0015 m or 1.5 mm
Number of Dilution holes		10
Dome holes diameter	$D_{h,dome}$	0.0015 m or 1.5 mm
Number of Dome holes		10

The design realised after the above calculations are presented on subsequent pages. The snout angle is around 35 degrees since there is no guideline to calculate it in reference, a parametric CFD study was performed to check flow field in snout at different angles from 25 to 35 degrees. The solution obtained using 35-degree angle showed a good compromise between the occurrence of recirculation region in a snout and momentum loss due to an increase in length with a decrease in snout angle.

The hole size obtained in calculations appears small and needs to be further investigated using CFD or other technique.

Calculations are not performed yet for fuel injector; the fuel injector cone is assumed to at around 45 degrees inwards to ensure fuel reaches recirculation region and mixes uniformly with air.

The thickness of combustor liner and the outer casing is assumed to be around 1 mm, similar to those used in tubular combustor made from aluminium and nickel alloys [1].



SECTION A-A
SCALE 1 : 2

1) LINER
2) DOME
3) SNOUT
4) SWIRLER
5) FUEL INJECTOR
6) PRIMARY HOLES
7) SECONDARY HOLES
8) DILUTION HOLES
9) DOME HOLES
10) COOLING SLOT ROW 1
11) COOLING SLOT ROW 2
12) DIFFUSER
13) NOZZLE (TURBINE INLET)
14) OUTER LINER

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

DWG NO.

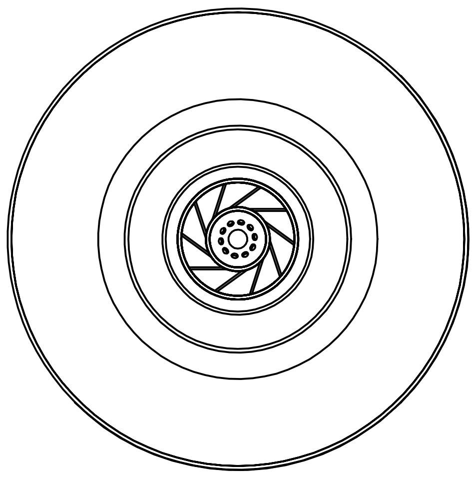
Liner-Assembly-nomenclature

A3

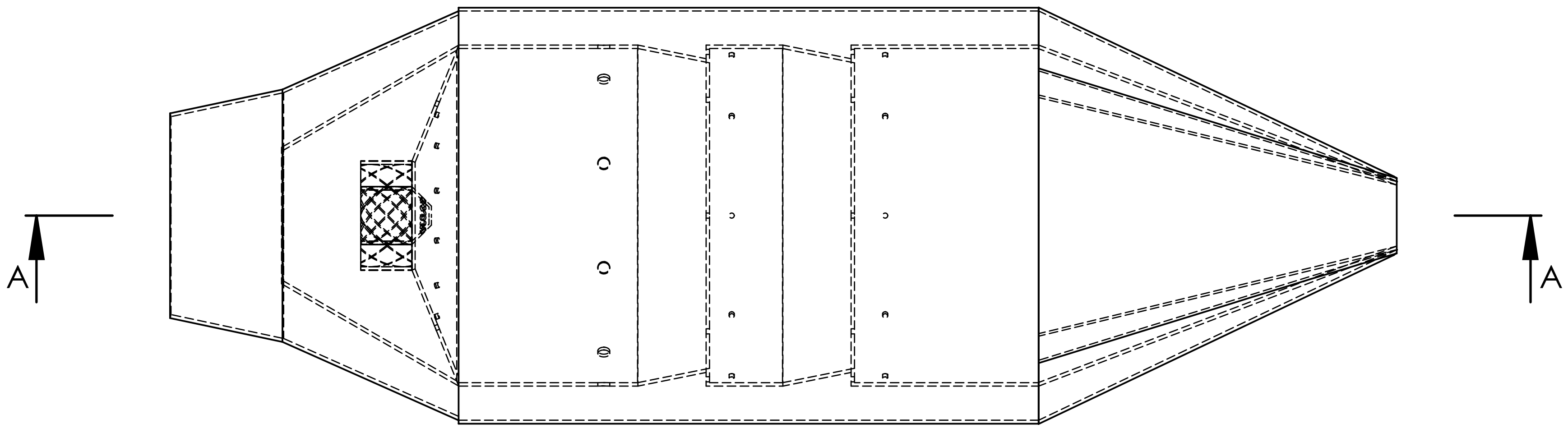
WEIGHT:

SCALE:1:5

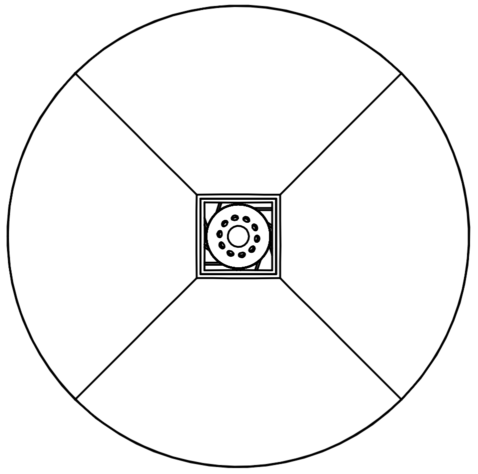
SHEET 1 OF 1



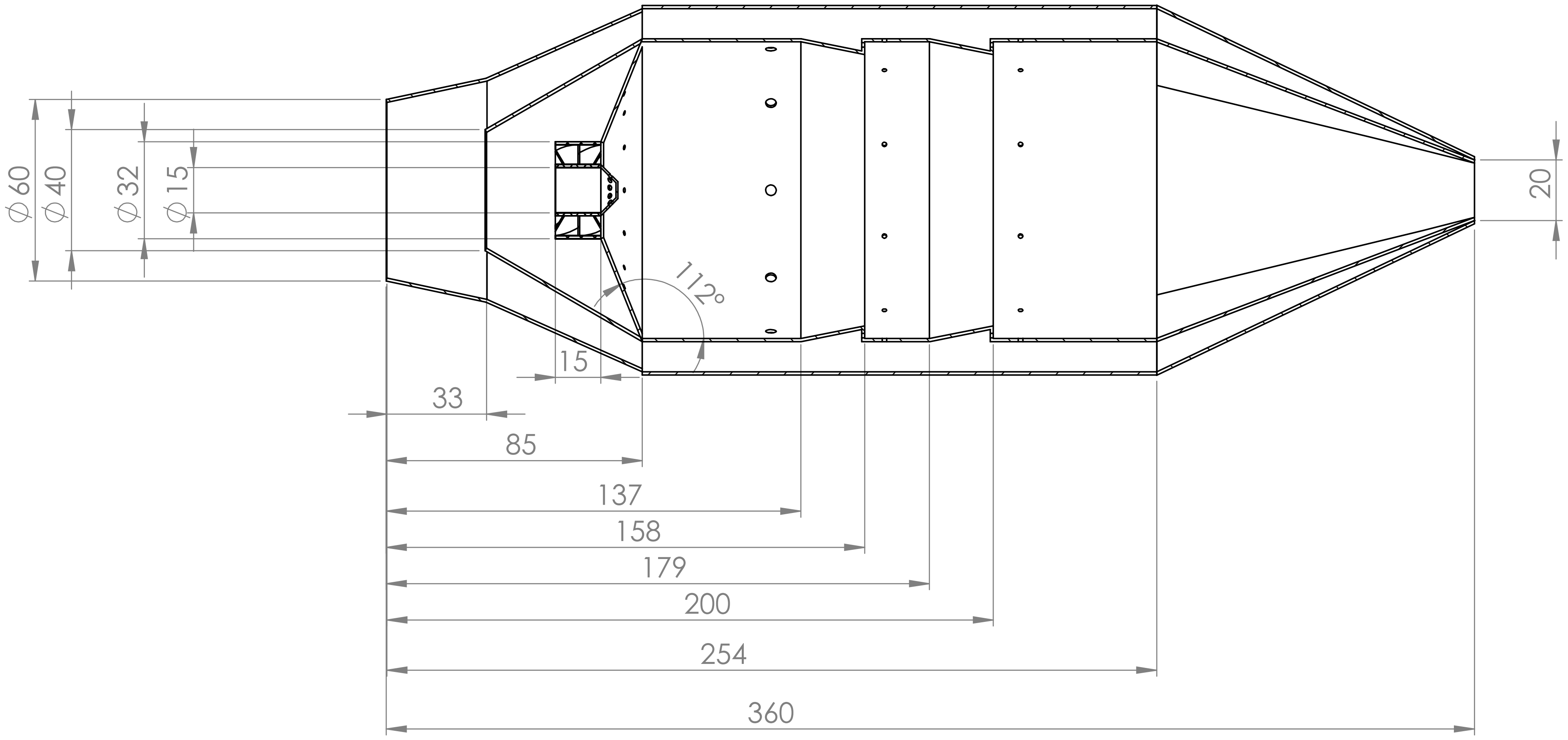
FRONT VIEW



SIDE VIEW



BACK VIEW



SECTION A-A
SCALE 1 : 2

All the dimensions are in mm

UNLESS OTHERWISE SPECIFIED:
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SURFACE FINISH:
TOLERANCES:
LINEAR:
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MFG			
Q.A			

TITLE:

MATERIAL:

DWG NO.
Liner-Assembly

A3

WEIGHT:

SCALE:1:5

SHEET 1 OF 1

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