Cranfield University

CRANSEDS

CRANFIELD STUDENTS FOR THE EXPLORATION AND DEVELOPMENT OF SPACE

CRANSEDS - HYDRA

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UK RACE TO SPACE

HYDRA
Hybrid Engine Development for Rocketry Applications

Centre for Autonomous and Cyber-Physical Systems, Cranfield University

School of Aerospace, Transport and Manufacturing, Cranfield University

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1. Team Management

1.1 Engine Type

Hybrid Engine

- building step towards liquid bi-propellant engine
- small scaled
- non-hazardous solid fuel
- only one liquid to control (easier than 2)
- best route to start the project with

1.2 Sponsors

Centre for Autonomous and Cyber-Physical Systems, Cranfield University	Financial Support
SmallSpark	Financial Support
School of Aerospace, Transport and Manufacturing	Financial Support, Technical Support
CranSEDS	Financial Support
Cranfield University Test Facility	Technical Support

TABLE 1: Table of Sponsors

1.3 Team roster

Name	Role
Triyan Pal Arora	Project Manager; Technical Lead
Sanmukh Khadtare	Emeritus Project Manager
Yi Qiang Ji Zhang	Systems Lead
Cian McDonnell	DAQ Lead
Peter Kirman	Propulsion and Manufacturing Lead
Emeric Tenailleau	Risk and Safety Lead
Eeshaan Kamath	CFD Lead

TABLE 2: Team Member roster

2. Systems

2.1 Requirements and Compliance

Req. ID	Parameter	Requirements	Traceability	Compliance
HY-1001	Thrust	The Engine shall be designed to deliver a thrust of 300 N		**Not compliant**
HY-1002	Burn Time	The burn time shall be greater than 5 seconds	AEL-J1 Nitrous oxide test-rig ICD	**Compliant**
HY-1003	Propellants	The liquid propellants used shall be Nitrous Oxide or IPA		**Compliant**
HY-1004	Ignition system	The engine shall be ignited using an external fuse wire to create sparks in the combustion chamber	AEL-J1 Nitrous oxide test-rig ICD	**Compliant**
HY-1005	Mass flow rate	The mass flow rate of propellants shall be lower than 2.3 kg/sec (Nitrous Oxide), 0.5 kg/sec (IPA)	AEL-J1 Nitrous oxide test-rig ICD	**Compliant**
HY-1006	Feed pressure	The feed line shall be able to hold pressures up to 80 bars.		**Compliant**
HY-1007	Chamber pressure	The chamber pressure for the complete fire sequence shall be lower than 51 bars (Nitrous Oxide Vapor Pressure)		**Compliant**
HY-1008	Mounting bracket	The mounting bracket shall provide support in all 3 axes from the experienced loads		**Compliant**

TABLE 3: Table of Requirements

2. Systems

2.2 Project Budgets

Propellant	Purpose	Volume used	Required minimal storage pressure
Nitrous oxide	Liquid oxidizer	1.20 litres	44.50 bars
High density Polyethylene	Solid fuel	0.12 kg	0.98 bars
Oxygen gas	Pre-charge gas	0.60 litres	40.00 bars
Nitrogen	Purge gas	5.50 litres	50.00 bars

TABLE 4: Propellant Budget. SOURCE: Own

Sub-assemblies	Mass (kg)	Cost (£)
Test stand	10.01	143.20
Combustion chamber	13.36	2850.71
Fuel block	0.14	45.80
Data acquisition system	0.90	-
TOTAL	**24.41**	**3039.71**

TABLE 5: Mass and Cost Budget. SOURCE: Own

2. Systems

2.3 Gantt chart

WBS	TASK	PREDECESSOR	START	END	DAYS	% DONE	WORK DAYS
0	**Important Deadlines**			-			-
0.1	Project and Competition Introduction		05/12/2022	05/12/2022	0	100%	1
0.2	Project Understanding and Work Plan Setting		05/12/2022	03/01/2023	30	100%	22
0.3	Hyrdostatic (Cold Fire) Test		10/02/2023	21/03/2023	40	100%	28
0.4	Hot Test Firing		01/04/2022	10/04/2022	10	30%	6
0.5	Competition Presentation		07/07/2023	07/07/2023	0	0%	1
1	**Systems**			-			-
1.1	Review Requirements		26/01/2023	01/02/2023	7	100%	5
1.2	Gantt Chart		26/01/2023	29/01/2023	4	100%	2
1.3	Risks and COSHH Assessments		26/01/2023	29/01/2023	4	80%	2
1.4	Design Review Freeze		26/01/2023	03/02/2023	9	100%	7
1.5	Cost Budget and Purchase List		26/01/2023	12/02/2023	18	100%	12
1.6	Cost Codes Resolution		26/01/2023	15/02/2023	21	100%	15
1.7	Manufacturing & Supervision Estimates		26/01/2023	15/02/2023	21	100%	15
1.8	Monthly Mentor Meetings		13/02/2023	27/06/2023	135	100%	97
1.9	Race to Space Progress Report		13/02/2023	28/02/2023	16	100%	12
1.10	Race to Space Design Report		13/02/2023	20/03/2023	36	100%	26
1.11	Race to Space Event		02/07/2023	07/07/2023	6	0%	5
1.12	Sponsorship Lookout		26/01/2023	02/04/2023	67	100%	47
2	**Propulsion**			-			-
2.1	Verify Design & Components		26/01/2023	29/01/2023	4	100%	2
2.2	Issue Clarification		26/01/2023	03/02/2023	9	100%	7
2.3	Component List, OEM Tanks, Propellants		26/01/2023	05/02/2023	11	100%	7
2.4	Review Design Drawings		13/02/2023	15/02/2023	3	100%	
2.5	Perform Thermal Analysis and Flow Simulation		13/02/2023	28/02/2023	16	70%	
2.6	Procurement for Propellants		20/02/2023	28/02/2023	9	75%	7
3	**Structures**			-			-
3.1	Movable Test Stand Base Design		26/01/2023	05/02/2023	11	100%	7
3.2	Modification / Design of Test Stand for Westcott		26/01/2023	12/02/2023	18	100%	12
3.3	Finalize Drawings for Manufacturing		26/01/2023	12/02/2023	18	100%	12
3.4	Modification Manufacturing for Rig		01/03/2023	16/03/2023	16	100%	12
3.5	Movable Test Stand Manufacturing		01/03/2023	16/03/2023	16	30%	12
3.6	Engine Structure AIT/AIV		16/03/2023	20/03/2023	5	100%	3
3.7	Component FEA		01/02/2023	31/05/2023	120	100%	86
4	**Controls**			-			-
4.1	Controls Schematic		26/01/2023	29/01/2023	4	100%	2
4.2	Hardware List Prep		26/01/2023	03/02/2023	9	100%	7
4.3	Software Skeleton Prep		26/01/2023	28/02/2023	34	50%	
4.4	COTS Component Procurement		20/02/2023	05/03/2023	14	80%	
4.5	Hardware Assembly and Testing		26/01/2023	28/02/2023	34	70%	24
5	**Manufacturing**			-			-
5.1	Bill of Materials, P&L List		26/01/2023	05/02/2023	11	100%	7
5.2	Raw materials		26/01/2023	05/02/2023	11	100%	7
5.3	Verify 2-D Drawings		26/01/2023	05/02/2023	11	100%	7
5.4	Risk and COSHH Assessments		26/01/2023	29/01/2023	4	100%	2
5.5	Complete Assembly and Integration		01/03/2023	20/03/2023	20	80%	14
5.6	Cold Fire Testing		26/01/2023	21/03/2023	55	100%	39
5.7	Integration with Propellants		22/03/2023	03/04/2023	13	75%	9
5.8	Safety Inspections and Procedures		27/03/2023	03/04/2023	8	50%	6
5.9	Series Hot Fire Testing		03/04/2023	07/04/2023	5	0%	5

FIGURE 1: Project Gantt Chart. SOURCE: Own

3. Propulsion

3.1 Propellants

Oxidiser: Liquid Nitrous Oxide

Requirement ID	Statement
Number	Description
Weighting Rubric	
1	Low priority
2	Medium priority
3	High priority
Scoring Rubric	
1	<20 % of the desired value
2	20-40 % of desired value
3	40-60 % of desired value
4	60-80 % of desired value
5	80-100 % of desired value

TABLE 6: Rubrics for Trade study. SOURCE: Own

Alternative	Availability	Simplicity	Reactivity	Oxidising potential	Stability	Compatibility with the fuel	Vapour Pressure	Temperature sensitivity	Safety	Feasibilty	Total (110)
Weights	2	1	3	2	2	3	3	1	3	2	
N_2O	4	4	4	5	3	5	5	2	5	4	**95**
LOx	3	5	5	4	2	5	2	1	2	3	**72**
IPA	5	4	2	3	5	5	3	5	4	5	**87**

TABLE 7: Trade study for oxidiser alternatives. SOURCE: Own

Fuel: Solid High-Density PolyEthylene

Figure 1: HDPE block. SOURCE: Own

3. Propulsion

3.2 Engine Design

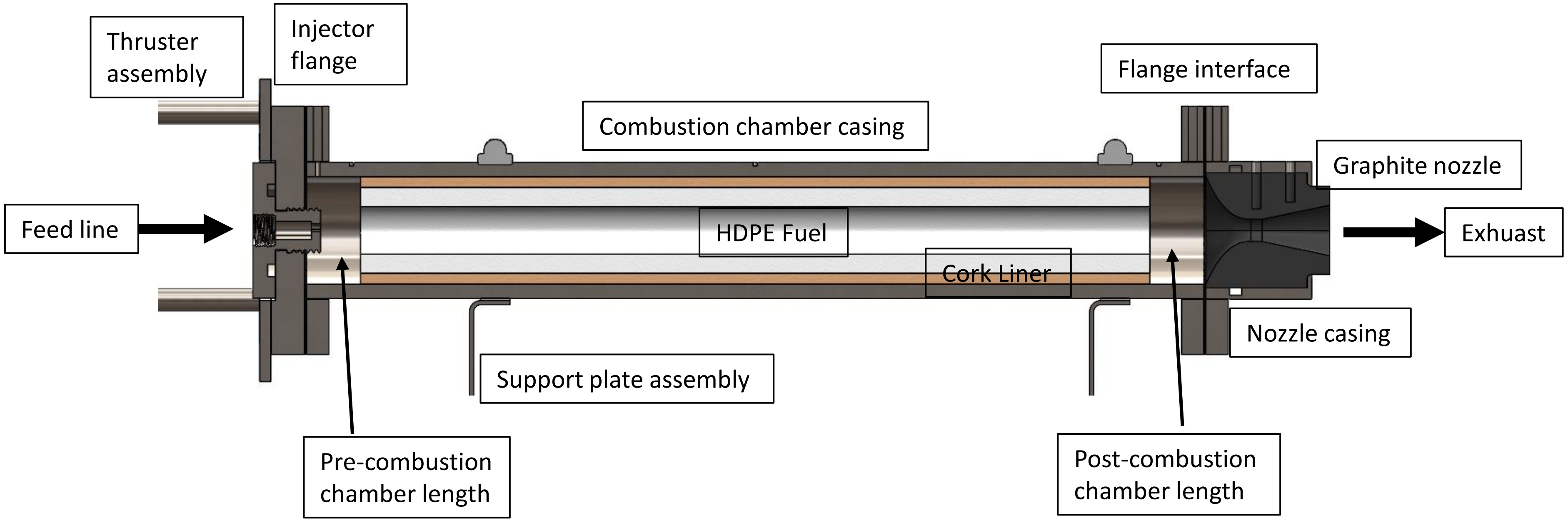


Figure 2: Engine Design overview. SOURCE: Own

The initialisation inputs given to the software were:

- Temperature of ingredient of 298 K (ambient condition)
- Chamber pressure of 3.35 MPa
- Exhaust pressure of 0.1013 MPa (1 bar: ambient condition)
- The mass of propellant used – Nitrous Oxide: 905.3 grams, and HDPE: 119.1 grams.

3. Propulsion

3.3 Propulsion Simulation

ProPEP3

Isp*	206.3573
C*	5329.005
Density	0.0626778
Molecular Wt.	26.58859
Chamber CP/CV	1.238274
Chamber Temp.	3553.142

Figure 11.14: Simulation Outputs. Source: Own.

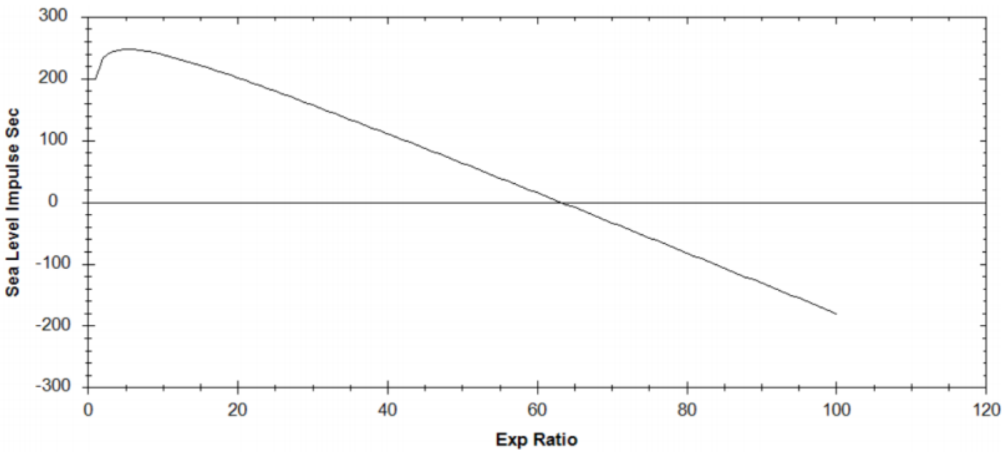


Figure 3: ProPEP simulation results. SOURCE: Own

Initial Conditions	Value	Units
Burn time	6.26	s
Oxidiser to fuel ratio	7.6	
Thrust	300	N
Chamber pressure	3.35	MPa
Exit pressure	0.1013	MPa
Specific impulse	203.49	$m\ s^{-1}$
Thrust coefficient	1.185	
Total mass flow rate	0.164	$kg\ s^{-1}$
Fuel density	935	$kg\ s^{-1}$
Regression rate	$1.84 \cdot 10^{-3}$	$m\ s^{-1}$
Initial steps for the sizing		
Throat area	$7.55 \cdot 10^{-5}$	m^2
Throat diameter	$9.81 \cdot 10^{-3}$	m
Exit Mach number	3.92	
Expansion ratio	5.18	
Exit area	$3.91 \cdot 10^{-4}$	m^2
Exit diameter	$2.23 \cdot 10^{-2}$	m
Mass Data		
Fuel mass flow rate	0.019	$kg\ s^{-1}$
Oxidiser mass flow rate	0.144	$kg\ s^{-1}$
Fuel mass	0.119	kg
Total mass flux	306.713	$kg\ s^{-1} m^{-2}$
Sizing		
Initial Port Area	$2.10 \cdot 10^{-2}$	m^2
Port diameter	$2.56 \cdot 10^{-2}$	m
Fuel grain length	0.35	m
Final Port diameter Chamber	$3.03 \cdot 10^{-2}$	m
Post-Comb. Chamber length	$2.4 \cdot 10^{-2}$	m
Pre-Comb. Chamber length	$2.4 \cdot 10^{-2}$	m
From Simulations		
Characteristic velocity, C^*	5343.622	$m\ s^{-1}$
Chamber Cp/Cv	1.245	
Stabilized chamber temperature	3337.053	K

TABLE 8: ProPEP simulation results. SOURCE: Own

3. Propulsion

3.3 Propulsion simulation

RPA

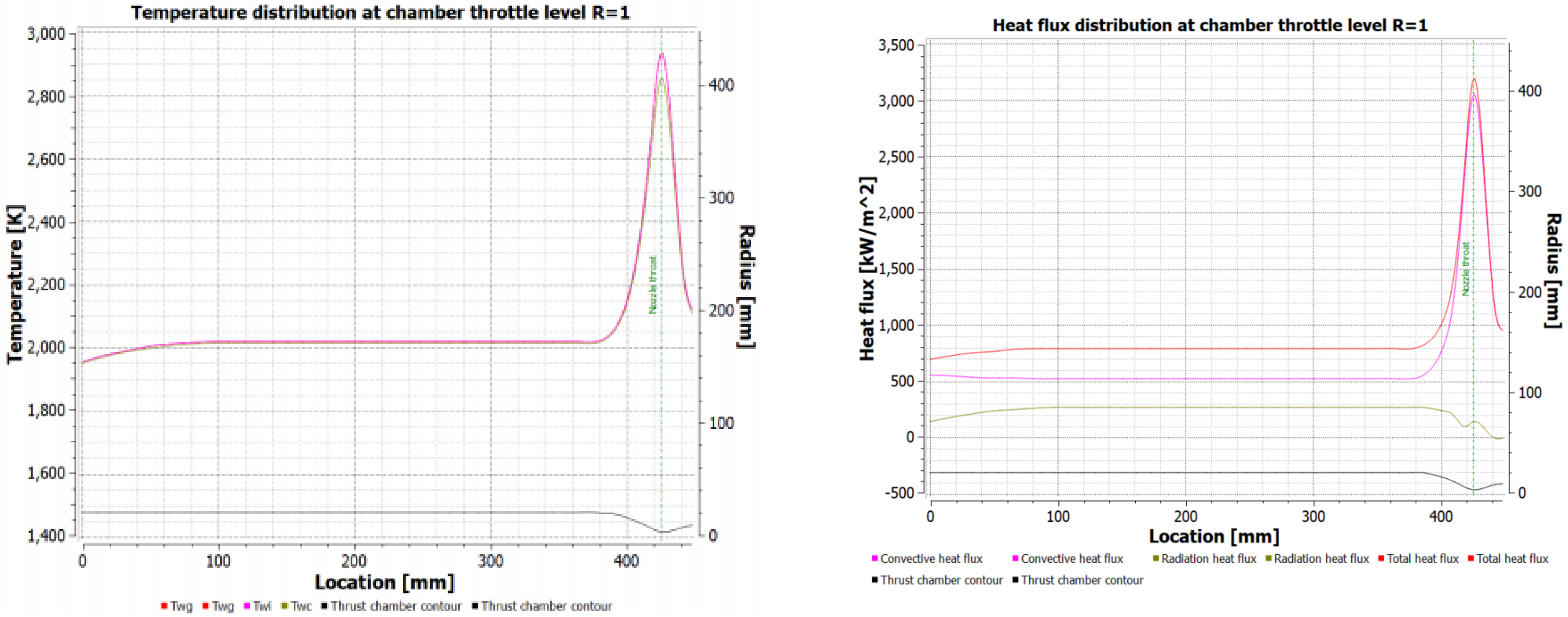


Figure 4: RPA simulation results. SOURCE: Own

4. Computational Fluid Dynamics (CFD)

- Density based transient solver with a Steady state asymmetric flow
- Energy model and standard k-ε viscous model
- Propellent used is N_2O without species transport due to 2-D model of nozzle
- Pressure inlet = 335 kPa at 3375 K temperature, Pressure outlet = 101.325 kPa at 300K temperature and symmetry is considered as wall for boundary conditions.
- Coupled solution methods is used and the solution is initialized at the inlet.
- Solution is run for over 5000 iterations and the pressure, velocity, density and temperature contour plotted.

- The Computational value of thrust varies from 327.3 N which is around 9.1% of the predicted value (300N)
- The mass flow rate is equal to 0.1765 kg/s which is around 7.88% of the predicted value (0.1636 N)
- The thrust is constant and then there is a sudden drop as we move along the length of the nozzle.

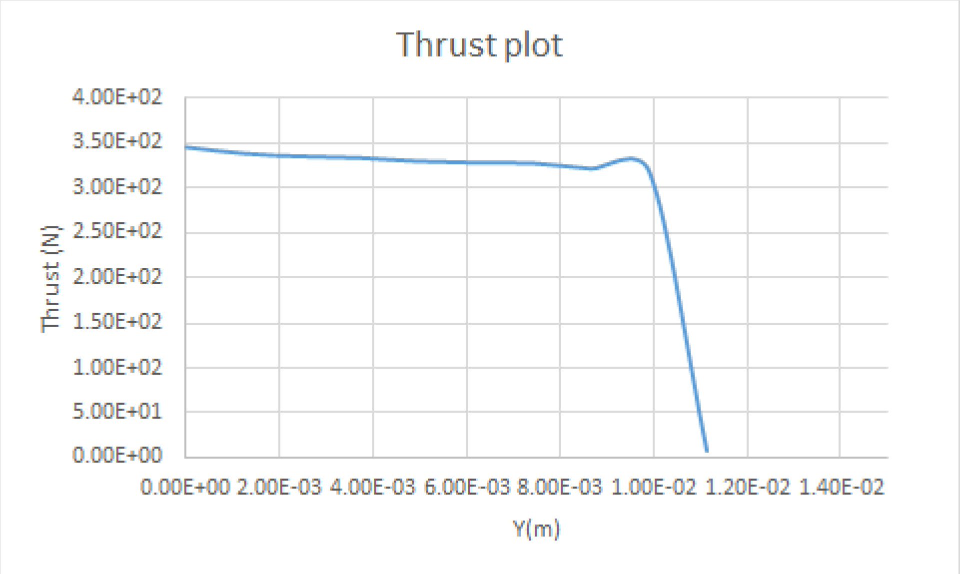
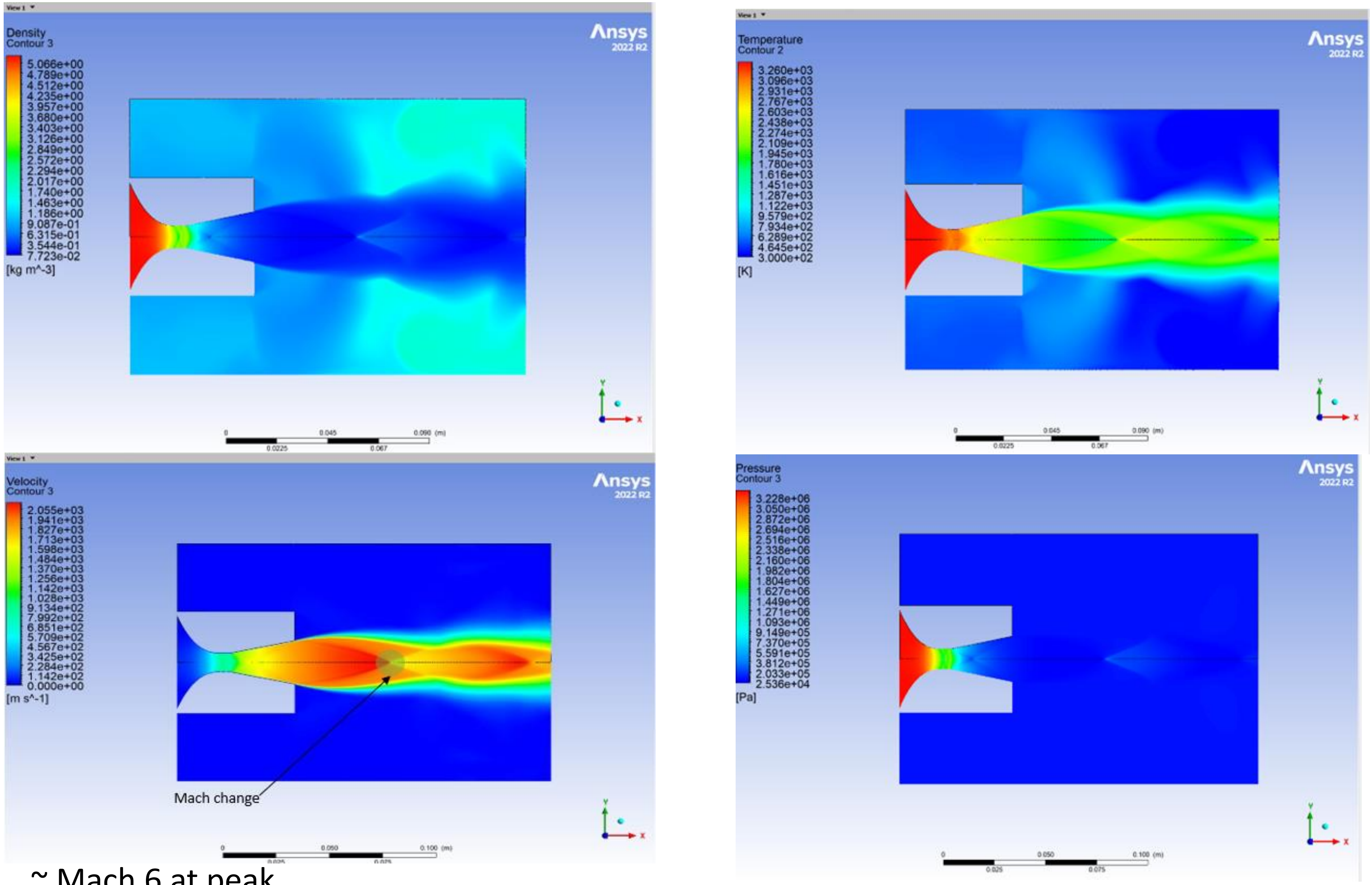


Figure 5: CFD simulation thrust plot results. SOURCE: Own

4. Computational Fluid Dynamics (CFD)



~ Mach 6 at peak

Figure 6 - 9: ANSYS FLUENT simulations of Density, Velocity, Temperature & Pressure (respectively). SOURCE: Own

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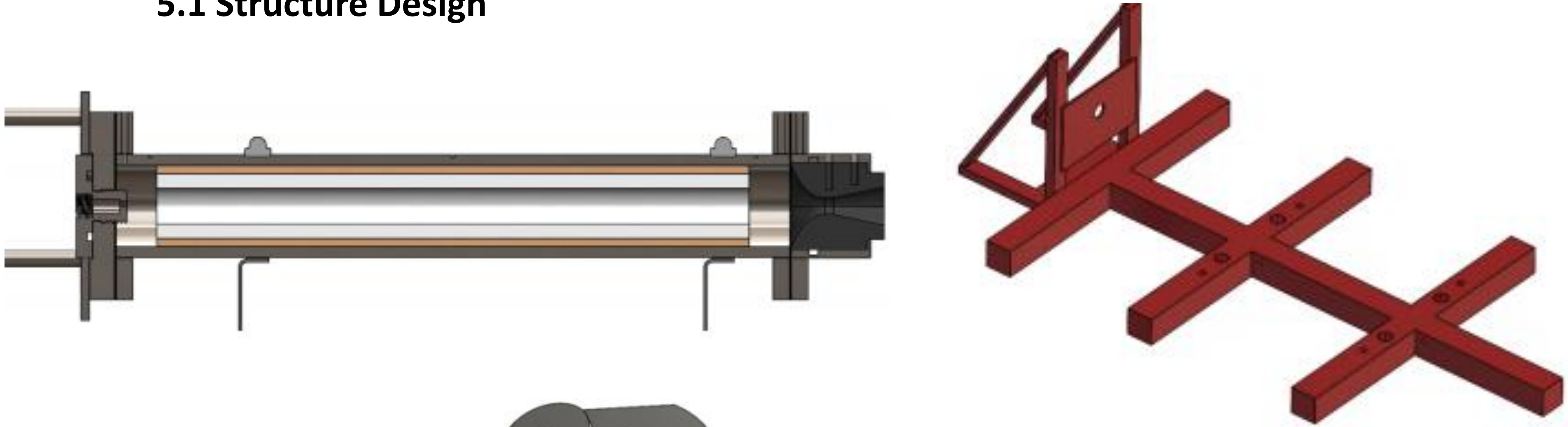
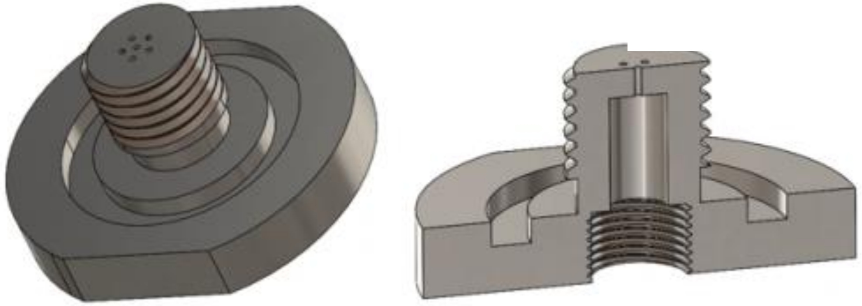
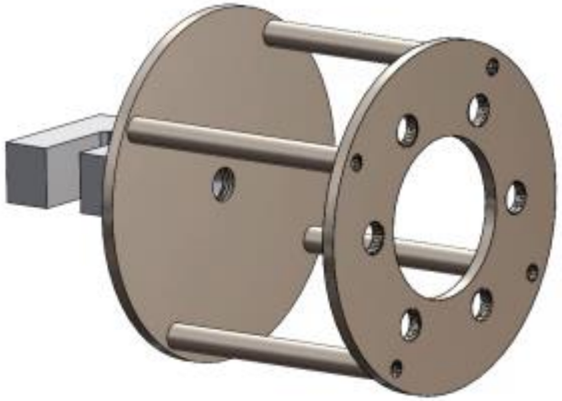
5. Structures

5.1 Structure Design







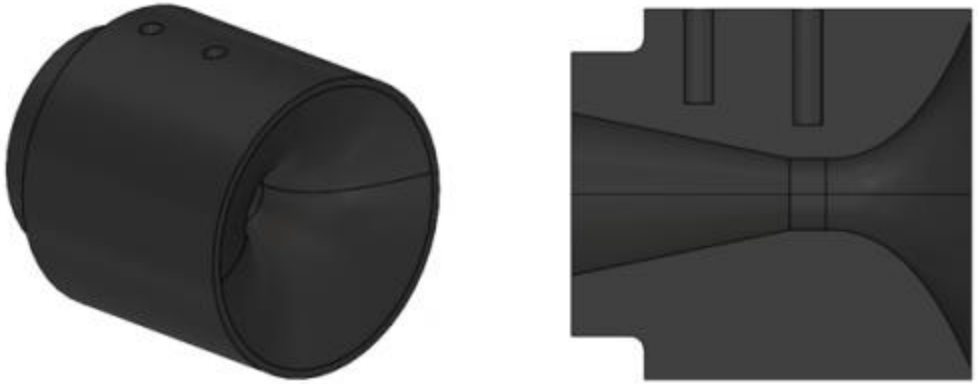


Figure 10: CAD Assembly parts SOURCE: Own

5. Structures

5.1 Finite Element Analyses

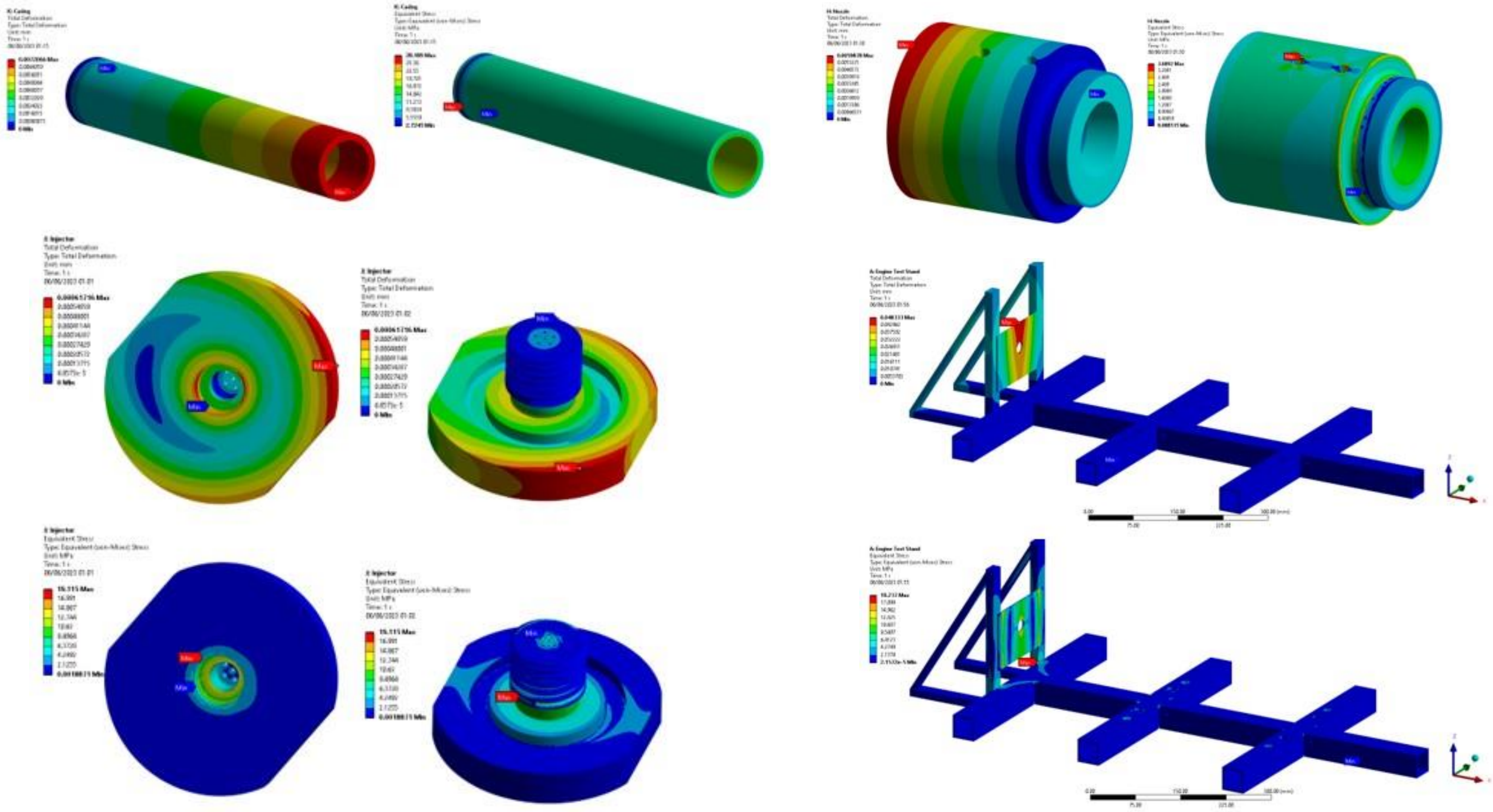


Figure 11: CAD Stress Test simulation using FEA SOURCE: Own

6. Data acquisition system (DAQ)

6.1 Thrust: Load cell

Figure 12: Load Cell

Tedea Huntleigh model 615 Load cell

Capacity: 50 kg - 1000 kg
Rated output: 2 mV/V
Zero balance: 0.02 mV/V
Material: Electroless nickel plated alloy steel
Function: To measure engine thrust

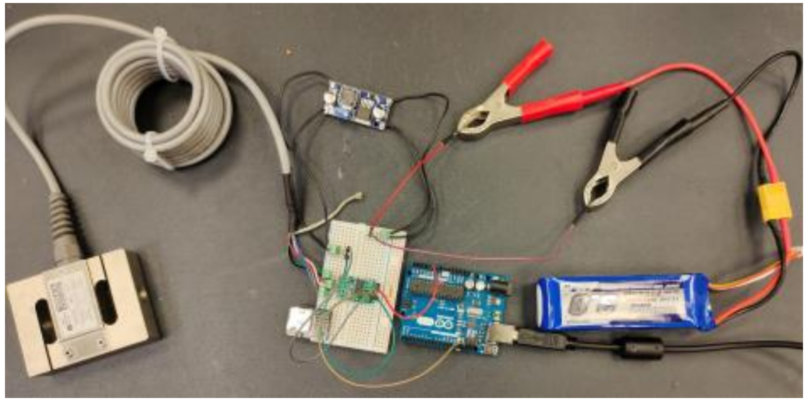


Figure 13: Load Cell Power & control Set up
SOURCE: Own

6.2 Temperature: Thermocouple

Figure 14: Load Cell Power & control Set up. SOURCE: Own

RS Pro K type thermocouple

Measurement range: 1100 deg C
Type: K
Probe diameter: 1.5 mm
Probe material: Stainless stell 310
Function: To measure temperature conducted to the steel casing at various points of the combustion chamber

6. Data acquisition system (DAQ)

6.3 Chamber pressure: Pressure transducer

Figure 15: Pressure Transducer. SOURCE: Own

Omega PX-119 1.5 kgi Pressure transducer

Capacity: 1 – 345 bars
Output: 4 – 20 mA
Accuracy: 0.50 % BFSL
Operating temperature: -40 – 135 deg C
Material: 304 SS
Function: To measure the internal chamber pressure of the combustion chamber

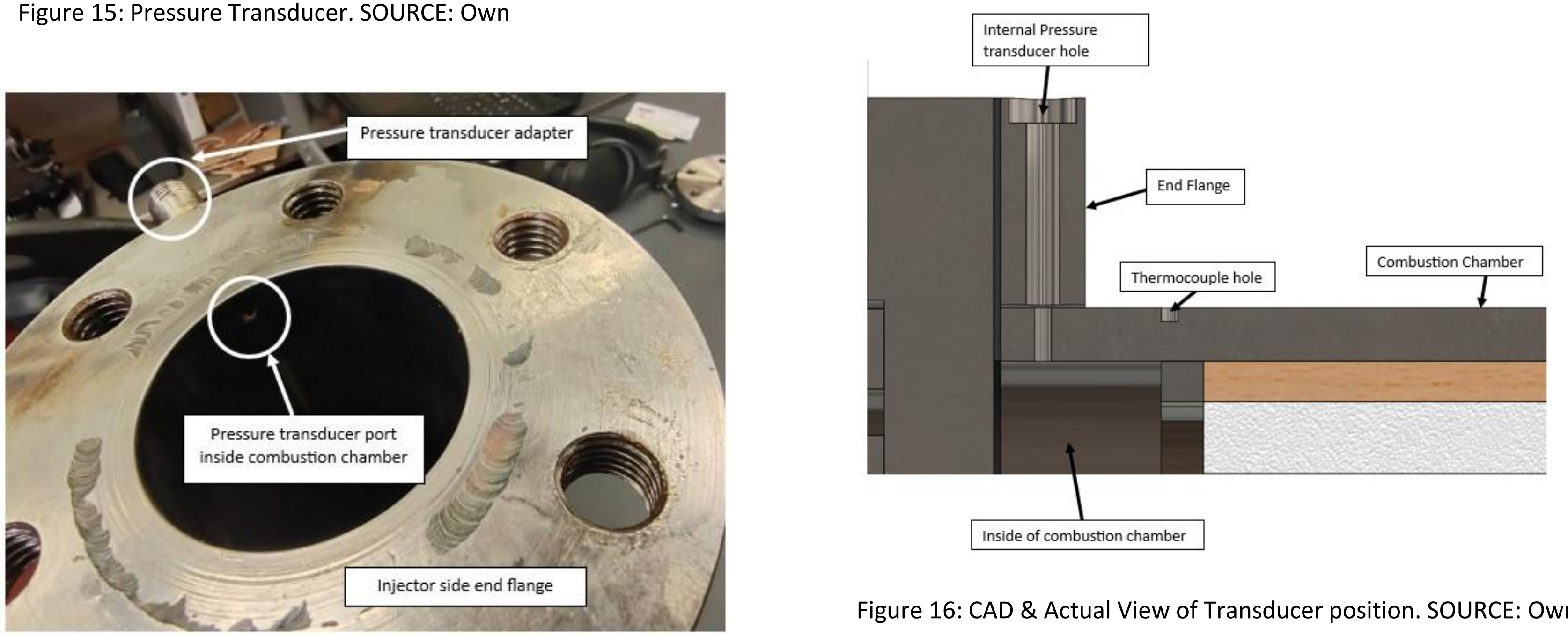


Figure 16: CAD & Actual View of Transducer position. SOURCE: Own

7. Manufacturing

7.1 Combustion chamber

Figure 17: Chamber casing assembly   SOURCE: Own

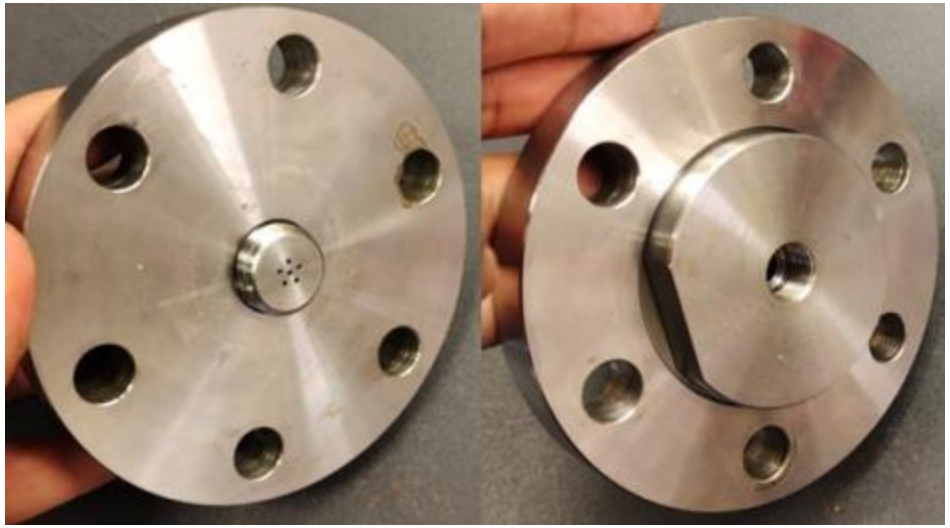


FIGURE 19: Injector sub-assembly   SOURCE: Own

Figure 18: Thruster assembly   SOURCE: Own

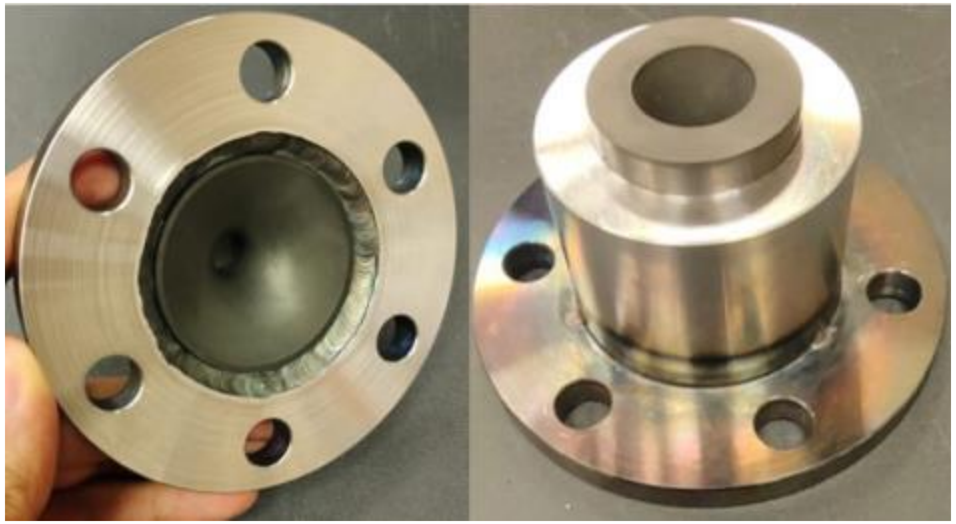


Figure 20. Nozzle sub- assembly   SOURCE: Own

7. Manufacturing

7.2 Test stand

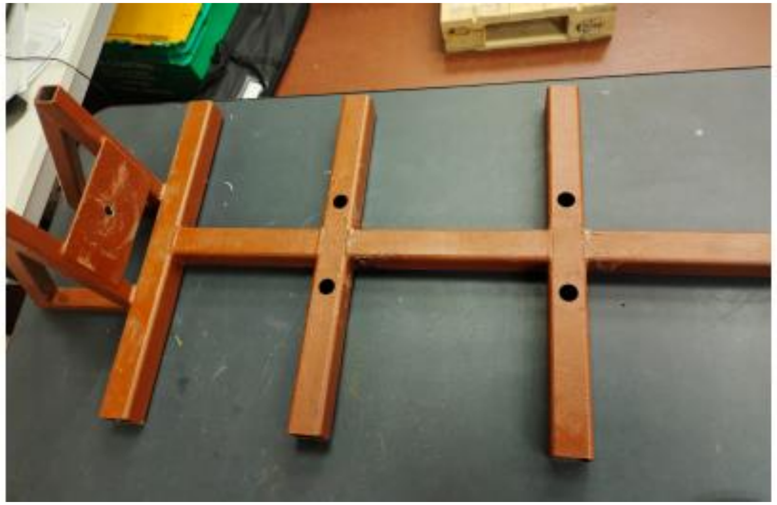


Figure 21: Stainless steel welded Test stand. SOURCE: Own

7.3 Fuel block

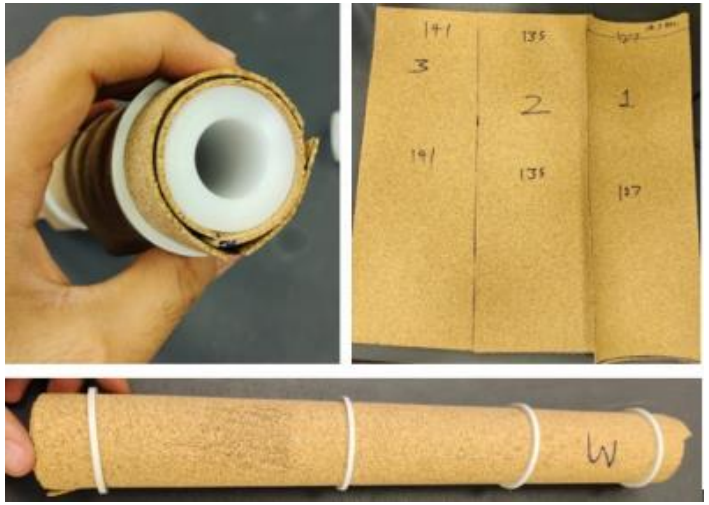


Figure 22: Fuel block side and front view SOURCE: Own

Figure 23: Preparing the fuel block. SOURCE: Own

8. Testing

8.1 Pressure testing

Figure 24: Pressure test Setup   SOURCE: Own

8.2 Cold flow testing

This test aims to test the feed line system and the flow of the oxidiser through the injector plate into the combustion chamber. For this, the whole feed line system is set up, and the thruster assembly and the injector plate are connected to the test stand.
This setup tests and checks the oxidizer flow through the injector plate. This test aids in observing the showerhead flow, properties and the force exerted by the flow itself (if any).

8. Testing

8.3 Hot fire testing

Figure 25: Hot Test Fire 1 SOURCE: Own

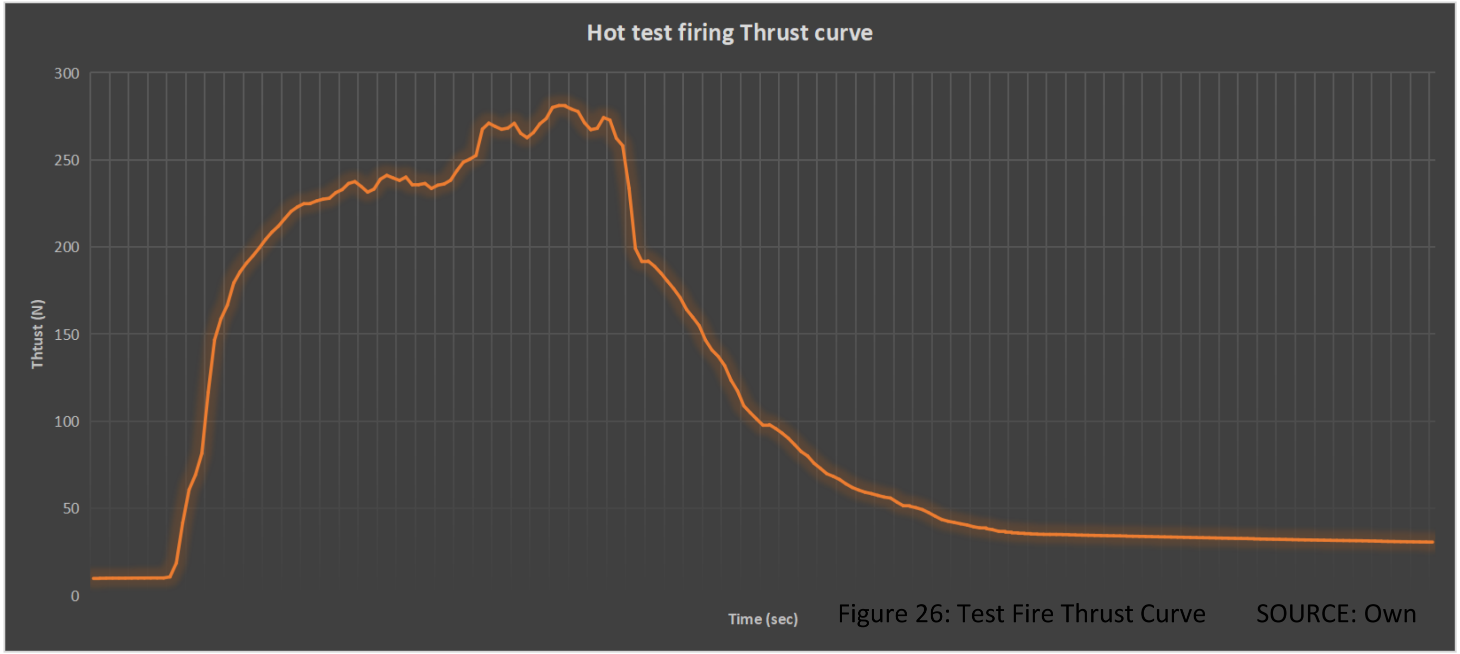


Figure 26: Test Fire Thrust Curve SOURCE: Own

9. Conclusions

9.1 Lessons learnt

1. Tolerance in designing
2. Self powered data acquisition system
3. Pressure and cold flow testing
4. Thermocouples holding positions
5. Keeping ‘ready to go’ spares
6. Ignition failure in 2nd attempt: Blocked injector holes
7. Applied paint on the chamber evaporated
8. Not enough space for feed line adapter connection to the injector plate
9. Bolts not long enough on injector flange side
10. Not to do last minute work
11. Shall not use vibration based etching tool. Rather to use Dremel engraver
12. Understand complex, yet clear feed system assembly of Protolaunch, and use as an inspiration for setting up own feed system at the university’s test facility

Further lessons learnt points are being brainstormed by the team. Will be completely and orderly documented in the Event report.

9. Conclusions

9.2 Knowledge transfer plan

1. Provided with all the official documents, team meeting minutes, progress reports, essential emails, post-event reports, videos, and literature with important sections marked that will be directly beneficial for them during designing and manufacturing.

2. At the start of the team induction, a 2-day workshop for the new team members to provide them with an overview of the work done last year and the information that may be essential for them to start working.

3. The team cannot summarize everything in just 2 days, especially if the team will manufacture after 5-6 months. For this, the team members have individually decided to assist the new team by making themselves available for monthly or bimonthly progress and doubt clearance sessions.

4. A separate hand over document will be created by the current team in as such detail as possible, to help the new team, in any aspect possible.

5. Through our initiative of keeping contact with the new team, we act purely as team mentors and aid them through inevitable problems they will face throughout the year, including designing, manufacturing, testing, procurement, sponsorships, dealing with administration, and in general managing their coursework with the team.

9. Conclusions

9.2 Future works

1. Increasing the thrust from 300 N to higher than 1000 N values
2. Reiterating experimentation with same feed and structure configuration, but changing the cross-section geometry of the slid fuel block
3. Reiterating experimentation with varying pre combustion chamber length, and post combustion chamber length
4. Setting up feed system at Cranfield university's test facility to allow for safe and sound hot fire testing in campus facility
5. Varying the oxidizer and solid fuel with different propellants available, and comparing the results for same configuration and experiment
6. 13th EASN International Conference, Salerno, Italy, September 2023: Abstract submitted

fin.

10. Appendices

Index

3. Propulsion

3.1 Pressure drop calculation

Injector Pressure Drop

Mass flow rate, $m^{\cdot} = 0.1636 kgs^{-2}$
The general value of the Coefficient of Discharge for Nitrous Oxide, $C_d = 0.8$
(Historical Data) Diameter of Injector, $d_{inj} = 1mm$
Area of Injetor, $A_{inj} = 7.854 \cdot 10^{-7} m^2$
Density of Nitrous Oxide, $\rho_{ox} = 822.2 kgm^{-3}$
Number of Injector holes, n = 6.
Using the modified Bernoulli's equation for a single-phase incompressible fluid, we have [9] [10]

$$m^{\cdot} = Q \cdot \rho = C_d \cdot A_{inj} \cdot \sqrt{\frac{2 \cdot dP_{inj} \cdot \rho_{ox}}{1 - (\frac{A_{inj}}{A_1})^2}} \tag{6.37}$$

where A_1 is the upstream cross-sectional area, i.e., the area of the inlet side of the injector, which is $A_1 = 5.026 \cdot 10^{-5}$. Also, $A << A_1$. Rearranging the equation above and substituting the values, we get the value of pressure drop for total n = 6 holes as

$$0.1636 = 0.8 \cdot 6 \cdot 7.854 \cdot 10^{-7} \cdot \sqrt{\frac{2 \cdot dP_{inj} \cdot 822.2}{1 - (\frac{7.854 \cdot 10^{-7}}{5.026 \cdot 10^{-5}})^2}} \tag{6.38}$$

And so, the Overall Injector Pressure Drop, $dP_{overallinj} = 1.1097 MPa = 10.952\ bars$

From the above 2 sections, we get the overall pressure drop as,

$$dP_{overall} = dP_{overallinj} + dP_{feed} = 10.952\ bars \tag{6.39}$$

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3. Propulsion

3.2 Propulsion thermochemistry

$$2\ (C_2H_4)_n\ +\ 2\ (N_2O)\ \rightleftharpoons\ 2\ CO_2\ +\ n\ H_2O\ +\ N_2\ +\ \Delta$$

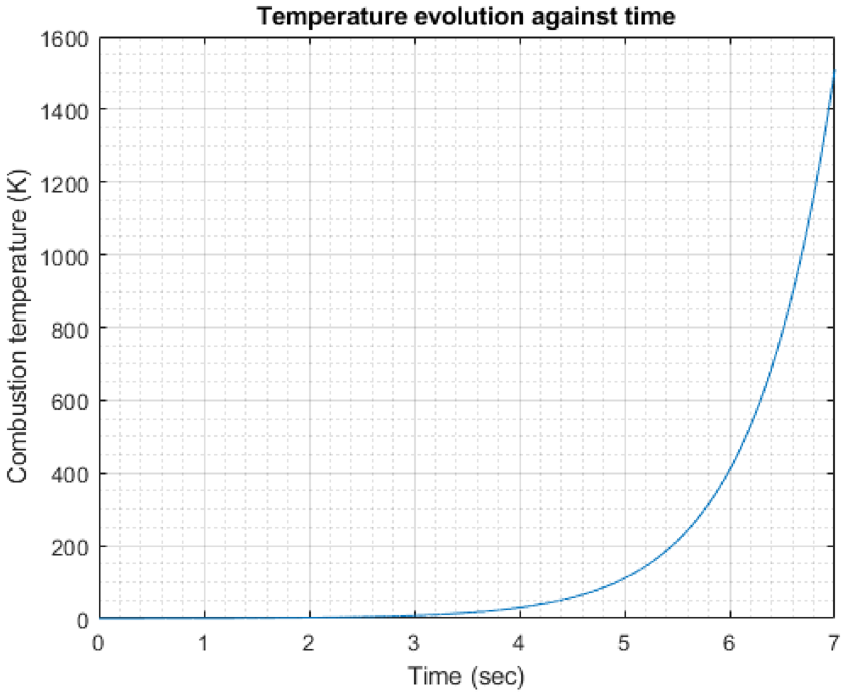
- Carbon dioxide: 20.58 mol
- Water vapour: 8.50 mol
- Nitrogen: 10.29 mol

$$\Delta H_{reaction} = 2\ \Delta H_f(CO_2)\ +\ n\ \Delta H_f(H_2O)\ +\ \Delta H_f(N_2)\ -\ 2\ \Delta H_{comb}(HDPE)\ -\ 2\ \Delta H_{red}(N_2O)$$

$Q_{reaction} = \Delta H_{reaction} \cdot N_{HDPE}$ and $Q_{reaction} = n \cdot C_{p,eq.} \cdot dT$

$$T_{f_{reaction}} = dT_{reaction}\ +\ T_{ambient} = 1059.19K$$

$$T_{CC} = T_A \cdot e^{B \cdot t}$$



5. Structures

5.1 Stress calculation

Circumferential stress, $$\sigma_c = \frac{P.d}{2.t} = 13.4\ MPa$$

Hoop stress, $$\sigma_h = \frac{P.d}{4.t} = 6.7\ MPa$$

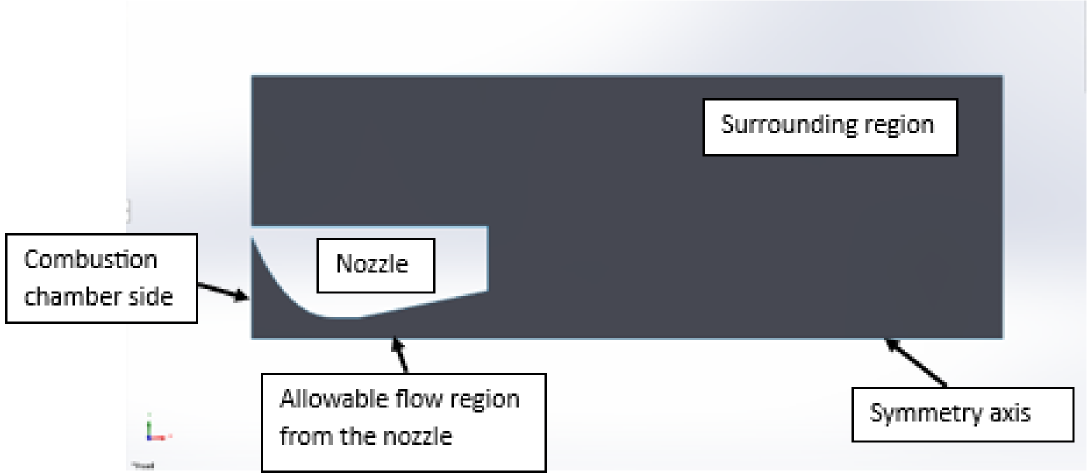
Shear stress, $$\sigma_s = \frac{P.d}{8.t} = 3.35\ MPa$$

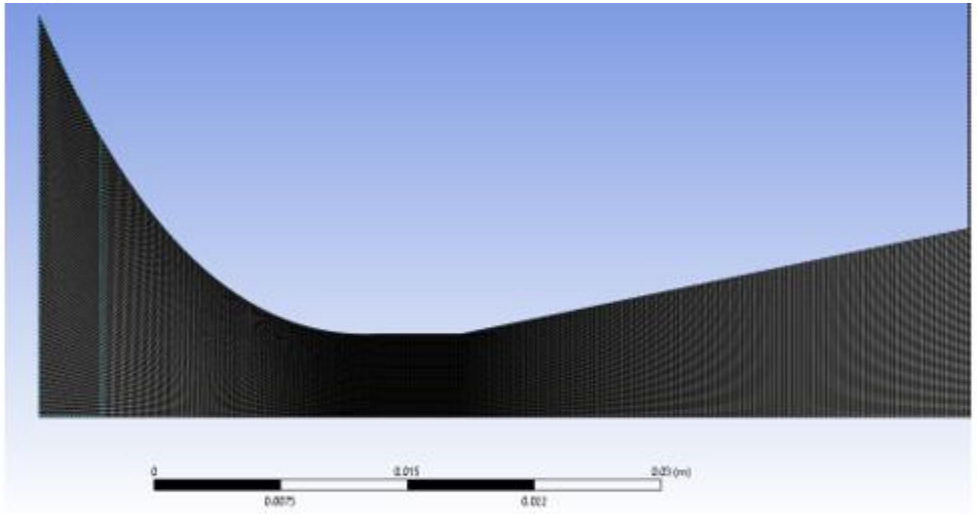
Max. possible stress, $$\sigma_T = 15.71 MPa$$

Yield stress for Mild Steel, $$\sigma_Y = 250\ MPa$$

Factor of Safety, $$\mathrm{FOS} = \frac{\sigma_Y}{\sigma_T} = 15.9$$

4. Computational Fluid Dynamics (CFD)





- The model was finely meshed. The obtain a perfect structured mesh the nozzle was split using face split in design modeler and was divide into the sections and the face meshing was applied to it.
- The orthogonal quality was near to 0.98 and the skewness was maintained to the value of 0.05786

Statistics	
Nodes	89567
Elements	88778