Design Optimization and Fabrication of Piston of Single Cylinder Nitro Engine by Direct Metal Laser Sintering

Report Submitted by

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Autumn, 2015

DECLARATION

I certify that

- The work contained in this report is original and has been done by me under the guidance of my supervisor.
- The work has not been submitted to any other Institute for any degree or diploma.
- I have followed the guidelines provided by the Institute in preparing the report.
- I have conformed to the norms and guidelines given in the Ethical Code of Conduct of the Institute.
- Whenever I have used materials (data, theoretical analysis, figures, and text) from other sources, I have given due credit to them by citing them in the text of the report and giving their details in the references. Further, I have taken permission from the copyright owners of the sources, whenever necessary.

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This is to certify that the thesis entitled "**Design Optimization and Fabrication of Piston of Single Cylinder Nitro Engine by Direct Metal Laser Sintering**" is submitted by **Hussain Bohra (12ME31004)** to the Department of Mechanical Engineering, in fulfilment for the award of the degree of Bachelor of Technology, is an authentic record of the work carried out by him under my supervision and guidance.

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Introduction

The piston acts as the vital link between the generation of power inside the combustion chamber to its transfer to the crankshaft and converting to-and-fro motion into continuous rotary motion.

A nitro engine generally refers to an engine powered with a fuel that contains some portion (usually between 10% and 40%) of nitromethane mixed with methanol. Nitromethane is a highly combustible substance that is generally only used in very specifically designed engines, and is primarily used almost entirely by itself in certain high-performance classes of automotive drag racing.

The term "nitro" has only come into use in the last few years to describe these engines, and has its origins in marketing hype in the model car market. For the fifty or so years prior to this term since the engines were first developed, they were simply referred to as "glow engines", but the term "nitro" has more impact in ad copy. These engines are actually fuelled by methanol, but the fuel is often doped with nitromethane as a performance additive. The ignition system consists of a glow plug - hence the proper term "glow" engine - which has a coil of platinum containing wire alloy, usually platinum-iridium. The glow plug is heated with electric current for starting, after which power is disconnected and the combination of residual heat and catalytic action of the platinum alloy with methanol ignites the fuel mixture.

Direct metal laser sintering (DMLS) is an additive manufacturing technique that uses a fibre laser, fired into a bed of powdered metal, aiming the laser automatically at points in space defined by a 3D model, melting or rather, welding the material together to create a solid structure.

DMLS has many benefits over traditional manufacturing techniques. The ability to quickly produce a unique part is the most obvious because no special tooling is required and parts can be built in a matter of hours. Additionally, DMLS allows for more rigorous testing of prototypes. Since DMLS can use most alloys, prototypes can now be functional hardware made out of the same material as production components.

Objective

1. Comparative study of properties of part manufactured using conventional processes and additive manufacturing process.
2. Design analysis and optimization of piston of a nitro engine for weight reduction and fuel wastage.
3. Manufacturing of piston using Direct Metal Laser Sintering and perform finishing operation for friction reduction.
4. Testing of new piston design with the nitro engine for performance improvement.

Work Plan and Methodology

1. CAD model design of nitro engine piston cylinder assembly.
2. Analysis of pistons using static stress analysis method in ansys.
3. Analysis of pistons under thermal and mechanical loads i.e. the pistons are subjected to a uniform gas pressure and non-uniform temperature distribution.
4. Optimization of piston design for fuel wastage by flow analysis.
5. Analysis of optimized model using static stress analysis.
6. Analysis of optimized piston under thermal and mechanical load.
7. 3D Printing of new piston design using DMLS Machine.
8. Post processing surface finish operation for friction reduction.
9. Testing of new piston for wear and surface roughness.
10. Comparison of effects of piston design and manufacturing method on engine performance.

Problem Definition

In designing a piston for an engine, the following points should be taken into consideration:

- It should have enormous strength to withstand the high pressure.
- It should have minimum weight to withstand the inertia forces.
- It should form effective oil sealing in the cylinder.
- It should provide sufficient bearing area to prevent undue wear.
- It should have high speed reciprocation without noise.
- It should be of sufficient rigid construction to withstand thermal and mechanical distortions.
- It should have sufficient support for the piston pin.

Estimation of the magnitude of different forces acting on the piston is important parameters while optimizing a piston design.

Selection of right process parameters is also very important while manufacturing a part using direct metal laser sintering. Mechanical and thermal properties of the final product will depend on following parameters.

- Laser Power
- Scan Speed
- Layer Thickness
- Hatching distance
- Scan strategy

Finally, the surface finish operation will play an important role in the life of the product. Since the piston is in direct contact with the sleeve, outer layer of the piston should be very smooth and hard for friction reduction and wear resistance.

Literature Survey

An Extensive literature survey was done to find the advantages of using additive manufacturing over conventional Machining Processes.

DMLS has many benefits over traditional manufacturing techniques. The ability to quickly produce a unique part is the most obvious because no special tooling is required and parts can be built in a matter of hours. Additionally, DMLS allows for more rigorous testing of prototypes. Since DMLS can use most alloys, prototypes can now be functional hardware made out of the same material as production components.

DMLS is also one of the few additive manufacturing technologies being used in production. Since the components are built layer by layer, it is possible to design internal features and passages that could not be cast or otherwise machined. Complex geometries and assemblies with multiple components can be simplified to fewer parts with a more cost effective assembly. DMLS does not require special tooling like castings, so it is convenient for short production runs.

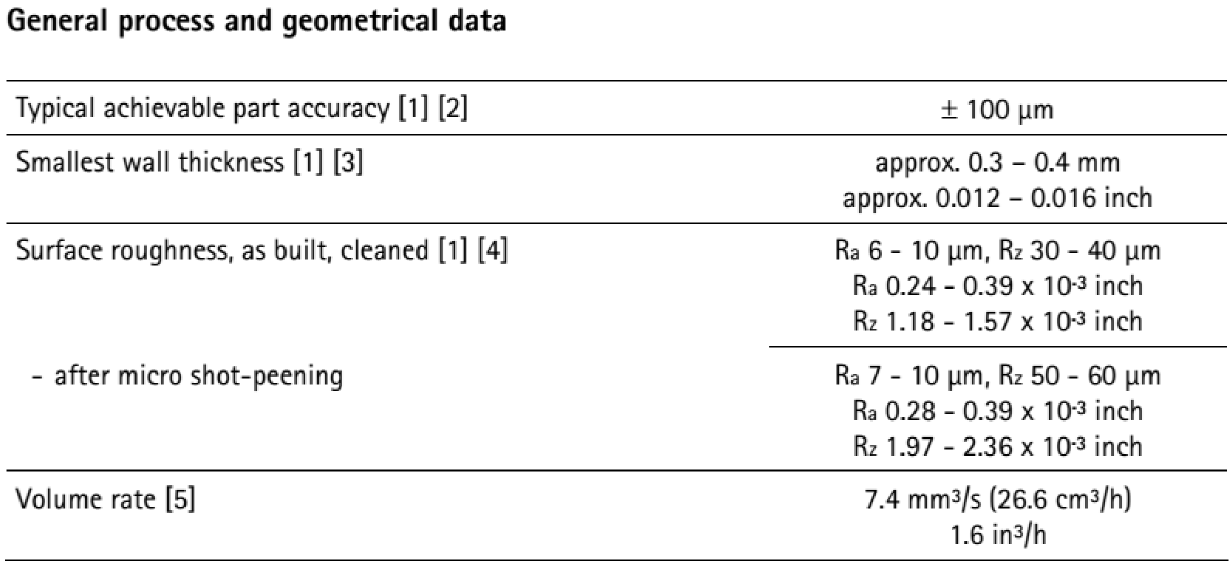
AlSi10Mg will be used for piston Manufacturing. Aluminium AlSi10Mg is a master alloy aluminium- powder. AlSi10Mg is a typical casting alloy with good casting properties and is used for cast parts with thin walls and complex geometry. The alloy combination silicon/magnesium results in a significant increase in the strength and hardness. It also features good dynamic properties and is therefore used for parts subject to high loads. Standard building parameters completely melt the powder in the entire part. Parts made of EOS Aluminium AlSi10Mg can be machined, wire eroded and electrical discharge machined, welded, micro-blasted, polished and coated.

SLM AlSi10Mg parts have mechanical properties (Hardness, UTS, elongation, impact energy) higher or at least comparable to the casted AlSi10Mg material, because of the very fine microstructure and fine distribution of the Si phase.

SLM samples show some anisotropy in elongation at break. This is because of the optimal density scanning strategy which causes Z-oriented tensile samples to form more borderline porosity. These pores make the Z-oriented tensile parts more sensitive to crack initiation, compared to XY oriented tensile samples.

Mechanical properties of the parts

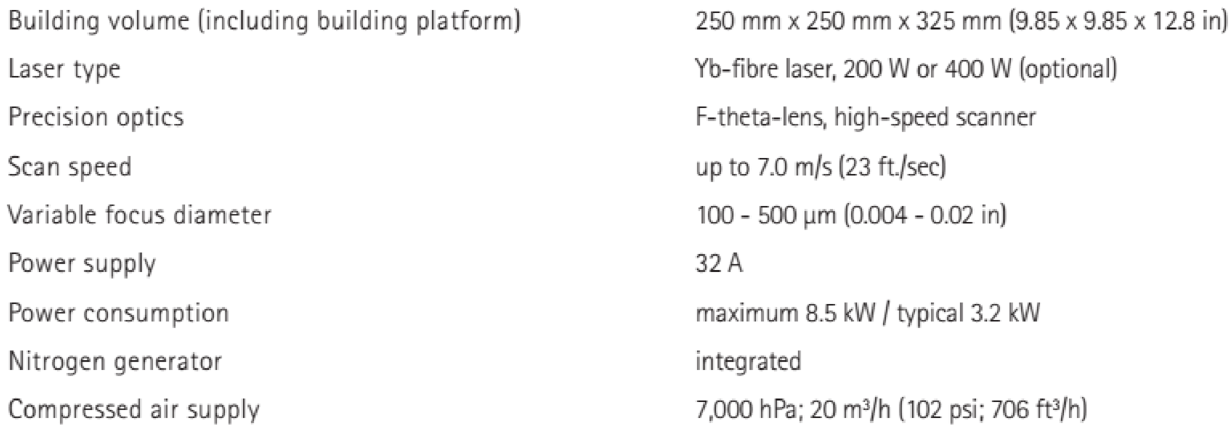
	As built	Heat treated [9]
Tensile strength [6]		
- in horizontal direction (XY)	460 ± 20 MPa 66.7 ± 2.9 ksi	345 ± 10 MPA 50.0 ± 1.5 ksi
- in vertical direction (Z)	460 ± 20 MPa 66.7 ± 2.9 ksi	350 ± 10 MPa 50.8 ± 1.5 ksi
Yield strength (Rp 0.2 %) [6]		
- in horizontal direction (XY)	270 ± 10 MPa 39.2 ± 1.5 ksi	230 ± 15 MPa 33.4 ± 2.2 ksi
- in vertical direction (Z)	240 ± 10 MPa 34.8 ± 1.5 ksi	230 ± 15 MPa 33.4 ± 2.2 ksi
Modulus of elasticity		
- in horizontal direction (XY)	75 ± 10 GPa 10.9 ± 0.7 Msi	70 ± 10 GPa 10.2 ± 0.7 Msi
- in vertical direction (Z)	70 ± 10 GPa 10.2 ± 0.7 Msi	60 ± 10 GPa 8.7 ± 0.7 Msi
Elongation at break [6]		
- in horizontal direction (XY)	(9 ± 2) %	12 ± 2%
- in vertical direction (Z)	(6 ± 2) %	11 ± 2%
Hardness [7]	approx.119 ± 5 HBW	
Fatigue strength [1] [8]		
- in vertical direction (Z)	approx. 97 ± 7 MPa approx. 14.1 ± 1.0 ksi	



General process and geometrical data

Typical achievable part accuracy [1] [2]	± 100 µm
Smallest wall thickness [1] [3]	approx. 0.3 – 0.4 mm approx. 0.012 – 0.016 inch
Surface roughness, as built, cleaned [1] [4]	R_a 6 - 10 µm, R_z 30 - 40 µm R_a 0.24 - 0.39 x 10^{-3} inch R_z 1.18 - 1.57 x 10^{-3} inch
- after micro shot-peening	R_a 7 - 10 µm, R_z 50 - 60 µm R_a 0.28 - 0.39 x 10^{-3} inch R_z 1.97 - 2.36 x 10^{-3} inch
Volume rate [5]	7.4 mm^3/s (26.6 cm^3/h) 1.6 in^3/h

Technical Data of DMLS Machine



Building volume (including building platform)	250 mm x 250 mm x 325 mm (9.85 x 9.85 x 12.8 in)
Laser type	Yb-fibre laser, 200 W or 400 W (optional)
Precision optics	F-theta-lens, high-speed scanner
Scan speed	up to 7.0 m/s (23 ft./sec)
Variable focus diameter	100 - 500 µm (0.004 - 0.02 in)
Power supply	32 A
Power consumption	maximum 8.5 kW / typical 3.2 kW
Nitrogen generator	integrated
Compressed air supply	7,000 hPa; 20 m^3/h (102 psi; 706 ft^3/h)

Finishing of DMLS Produced Parts

Parts “as built” of DMLS machines have a raw finish comparable to a fine investment cast, with a surface roughness of approximately Ra 8.75 µm, or a medium turned surface. This surface roughness can be improved all the way up to Ra 0.025 µm, qualifying as a super mirror finish. There are several processes available that can be used to achieve the desired surface roughness or finish.

- Abrasive Blast (Grit & Ceramic)
- Shot Peen
- Polishing
- CNC Finishing/Machining
- Abrasive Flow Machining (Extrude Hone) Polishing
- Electrochemical Polishing

Nitro Engine

2-Stroke engines only have one cycle to produce power and no cams. This single cycle can be divided into two strokes. Asuuming the start with the air/fuel mixture in the combustion chamber with the piston just past TDC (top dead center) the highest point of travel of the piston **(1)**. The air fuel mixture explodes (combustion) and we initialize the power stroke. The exhaust gases are rapidly expanding and this increase in pressure forces the piston down (pressure X area = Force). As the piston moves down it uncovers the exhaust port on the side of the sleeve **(2)**. This opening is also present on the engine block so that exhaust gases can escape to the atmosphere or through the manifold. As the piston travels down the sleeve, it pressurizes the crankcase (that is bathed in an air/fuel mixture) The pressurized crankcase is given a relief port that is opened when the piston almost reaches the bottom of the stroke. These relief ports are also called sleeve intake ports. The ports direct the fuel to the top of the piston. Shortly thereafter, the piston reaches BDC (bottom dead center); this is the lowest point that the piston can travel **(3)**. This is where the second stroke begins. The piston now starts to move up into the sleeve. This upward movement seals the intake ports and then blocks the exhaust port. The combustion chamber now starts to become pressurized as the piston travels higher into the sleeve **(4)**. As the piston approaches TDC the mixture's ignition point begins to be lowered until the heat from the glow plug initiates the combustion process. This explosion initiates the power stroke once again **(5)**.

Two common types of glow plug engine; ringed and ABC.

The primary difference is in the method of the compression seal; a traditional ringed engine uses an iron ring inserted around the aluminium piston that presses against the steel cylinder wall to keep the fuel/air mixture inside the compression chamber and oil out of it, whereas a more modern ABC engine does not have a ring but instead features a tapered sleeve inside the cylinder.

The letters **ABC** refer to the materials used; the **piston** is **aluminium**, the cylinder is **brass** and the inside of the **cylinder** (**sleeve**) is **chrome plated**.

The sleeve is tapered inwards towards the top of the compression chamber and expands outwards as the engine heats up. The tolerances between sleeve and piston are such that a perfect seal is created when the engine is at running temperature.

Engine Specification

ASP S25AII

Bore: 22.40mm

Stroke: 21.5mm

Displacement: 8.47cc

Output: 1.5kw/12000rpm

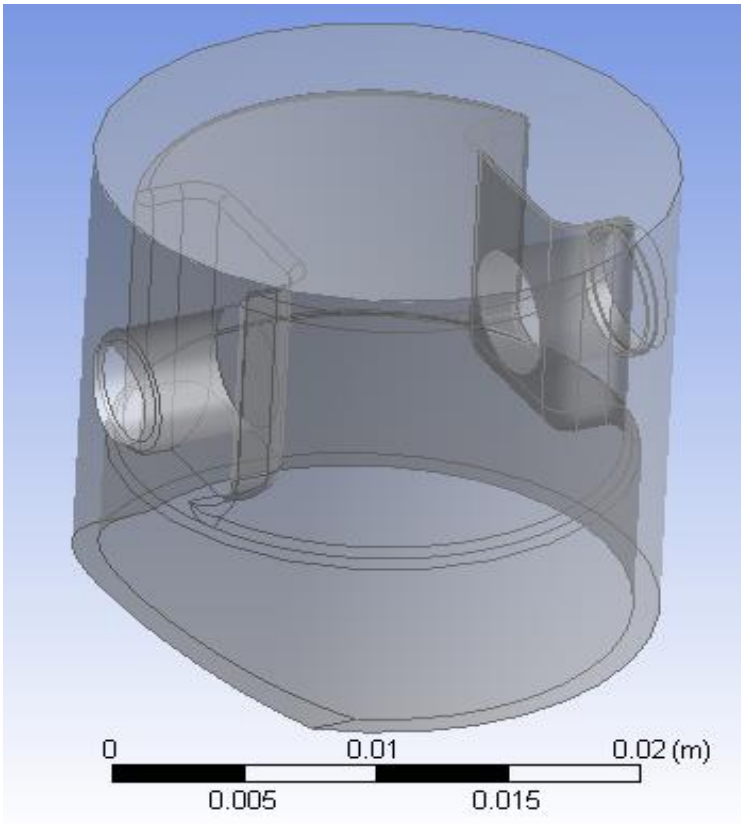
Practical rpm: 2,000-18,000rpm

Weight: 484g

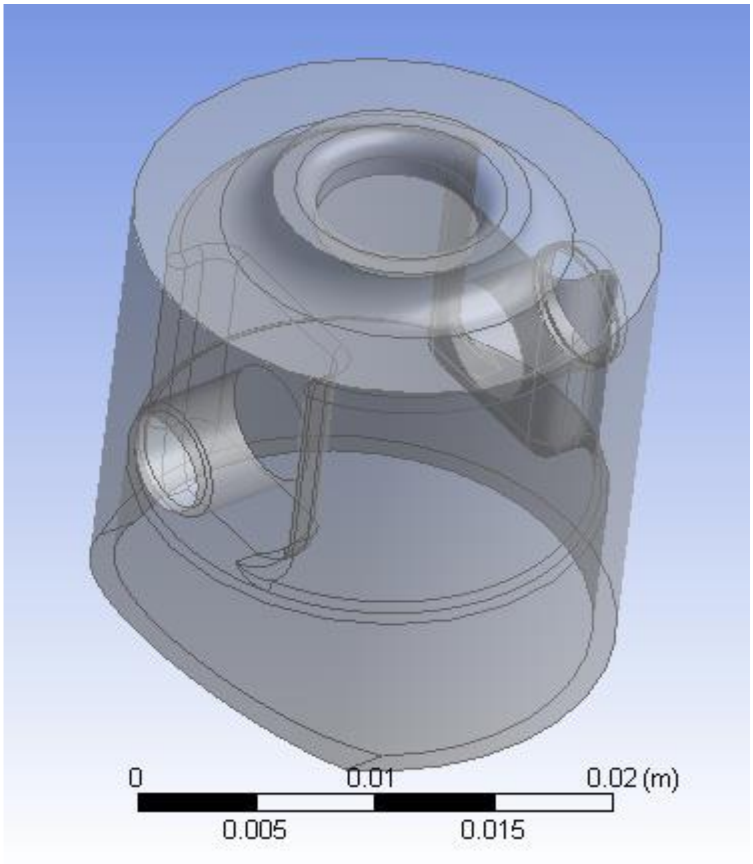
Static Stress Analysis of Piston

Starting the analysis with the stock piston provided with engine,

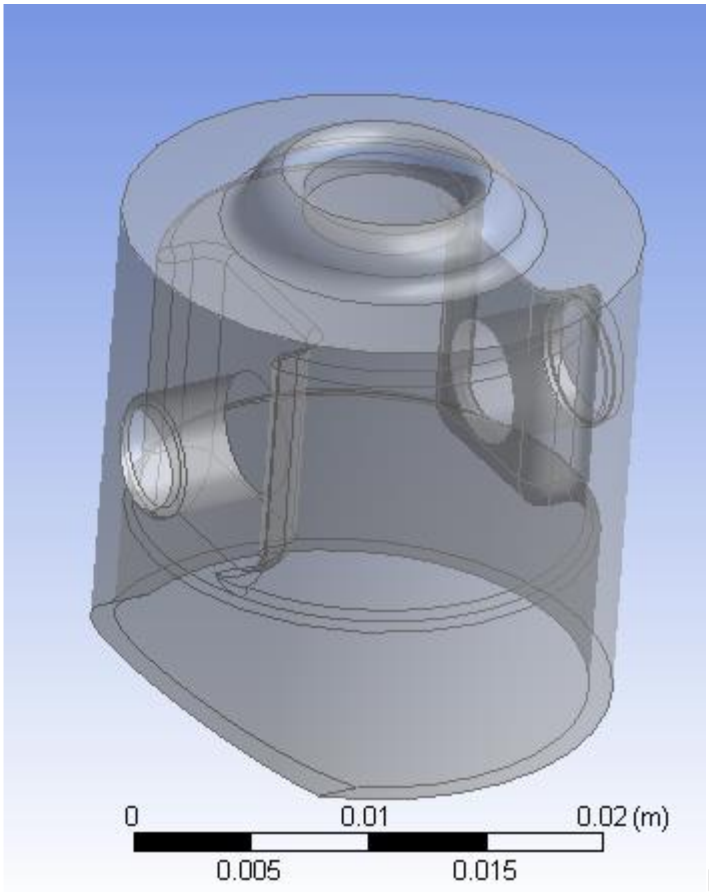
- 3D CAD Model is created



Design 1

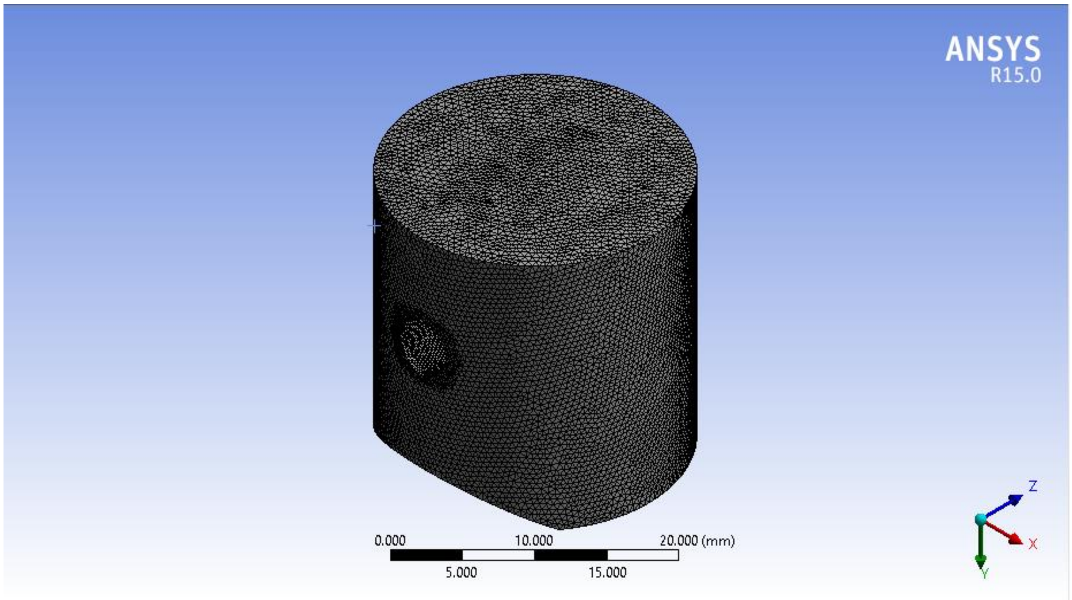


Design 2

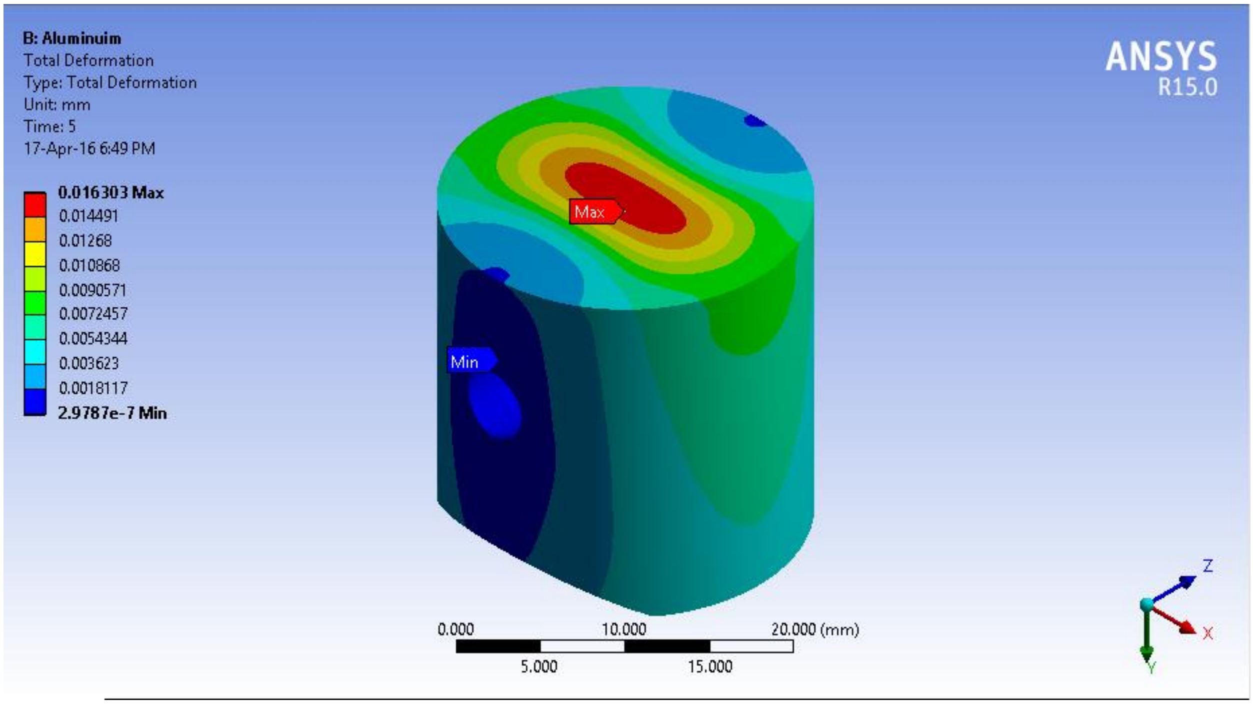


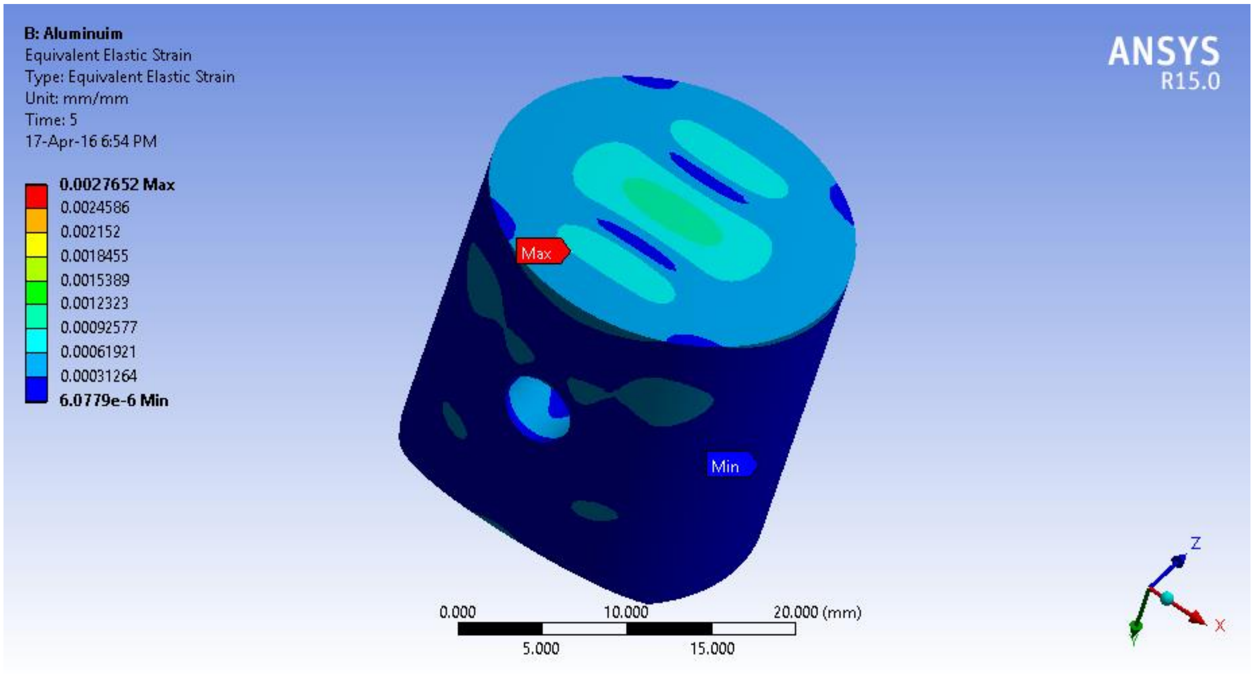
Design 3

- Frictionless support at pin bore areas and cylindrical face.
- Downward pressure (9 MPa) due to gas load acting on piston head.
- Mesh Is Created

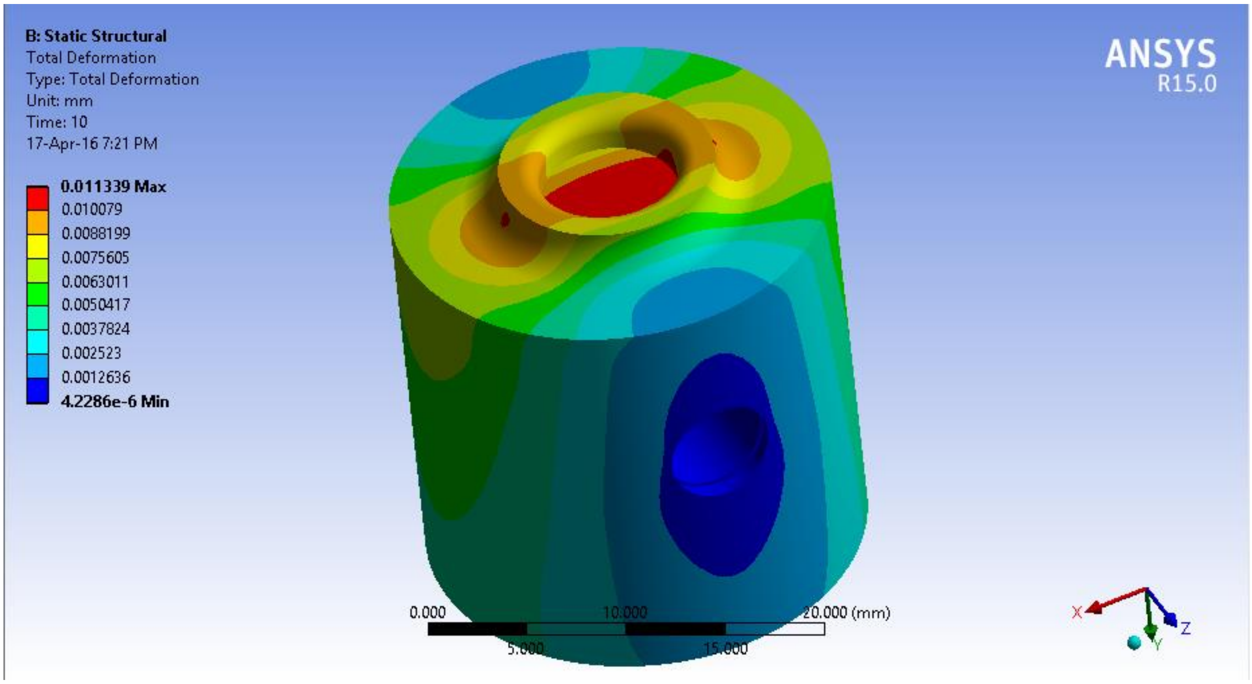


Design 1(Stock Piston Design)





Design 2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Total Deformation
Type: Total Deformation
Unit: mm
Time: 10
17-Apr-16 7:21 PM
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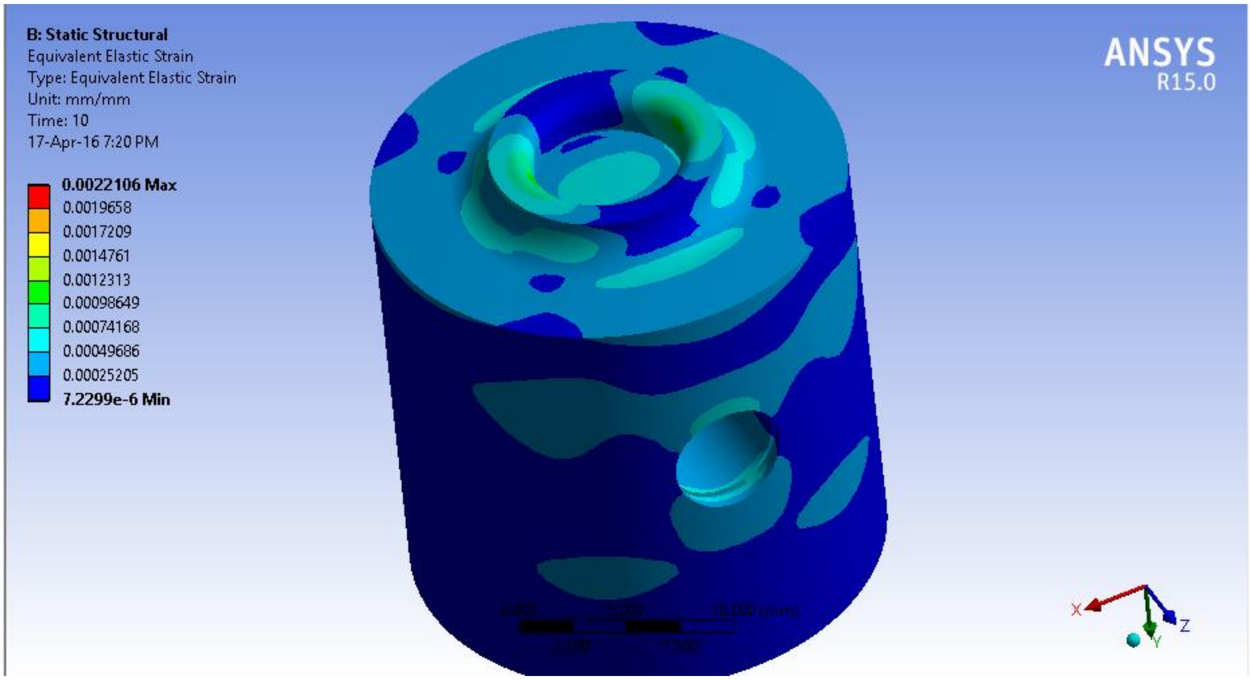
0.010079
0.0088199
0.0075605
0.0063011
0.0050417
0.0037824
0.002523
0.0012636
4.2286e-6 Min
ANSYS
R15.0
0.000
10.000
20.000 (mm)
5.000
15.000
X
Y
Z


B: Static Structural
Equivalent Elastic Strain
Type: Equivalent Elastic Strain
Unit: mm/mm
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17-Apr-16 7:20 PM
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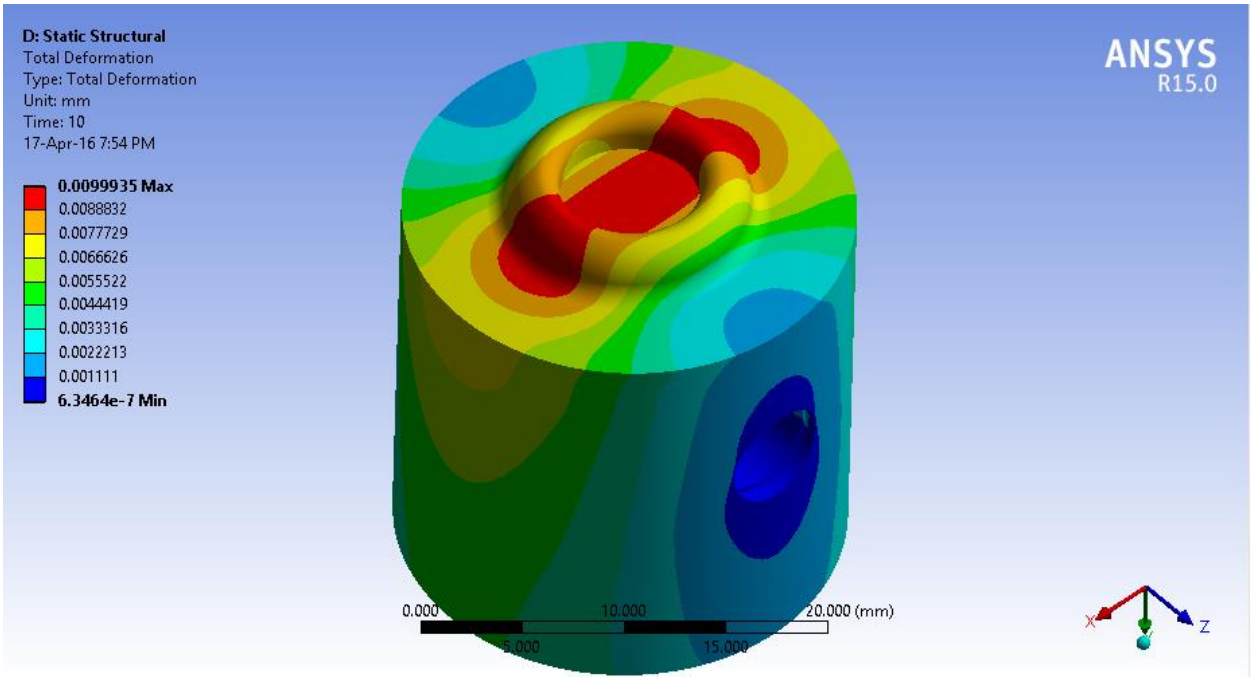
0.0019658
0.0017209
0.0014761
0.0012313
0.00098649
0.00074168
0.00049686
0.00025205
7.2299e-6 Min
ANSYS
R15.0
0.000
5.000
10.000 (mm)
2.500
7.500
X
Y
Z

Design 3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Total Deformation
Type: Total Deformation
Unit: mm
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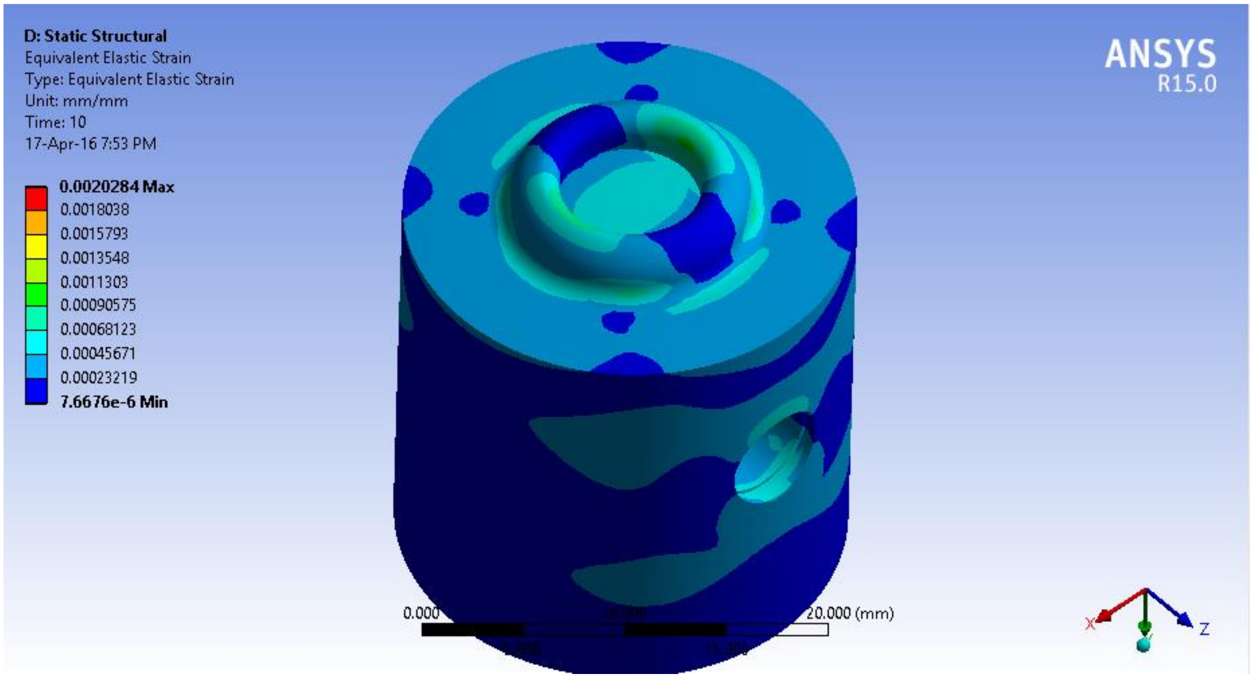
0.0077729
0.0066626
0.0055522
0.0044419
0.0033316
0.0022213
0.001111
6.3464e-7 Min
ANSYS
R15.0
0.000
10.000
20.000 (mm)
5.000
15.000
X
Y
Z


D: Static Structural
Equivalent Elastic Strain
Type: Equivalent Elastic Strain
Unit: mm/mm
Time: 10
17-Apr-16 7:53 PM
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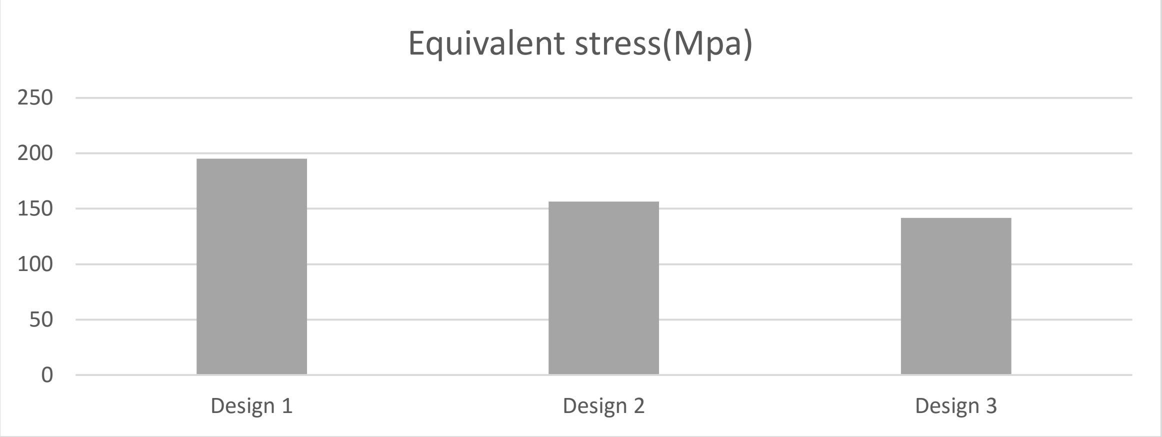
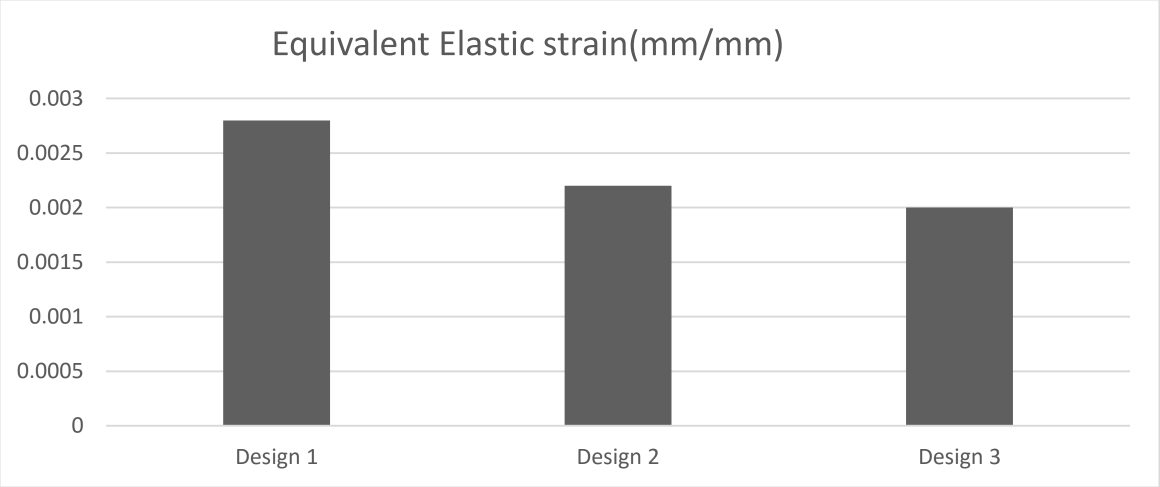
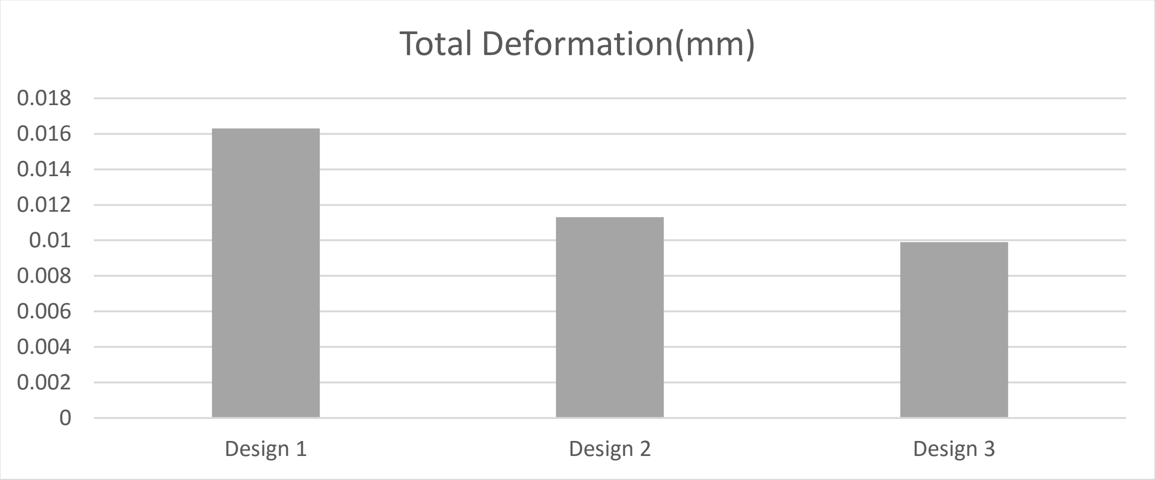
0.0018038
0.0015793
0.0013548
0.0011303
0.00090575
0.00068123
0.00045671
0.00023219
7.6676e-6 Min
ANSYS
R15.0
0.000
20.000 (mm)
X
Y
Z

Comparison of the design

	Design 1	Design 2	Design 3
Equivalent stress(MPa)	195.22	156.39	141.69
Equivalent Elastic strain(mm/mm)	0.0028	0.0022	0.002
Total Deformation(mm)	0.0163	0.0113	0.0099





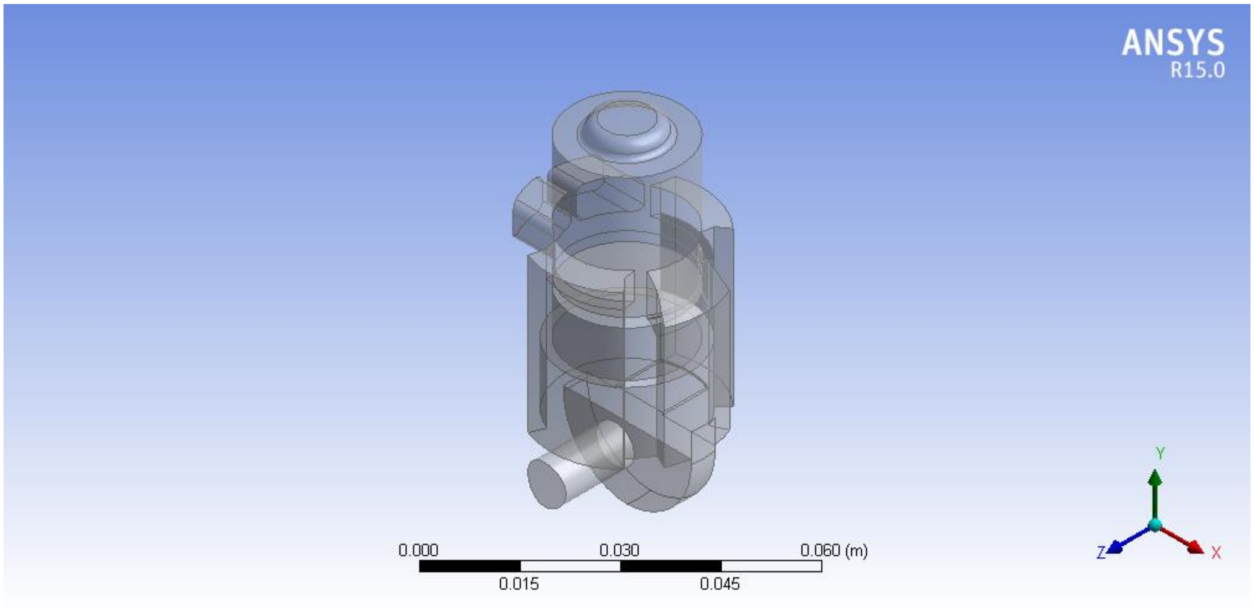


Conclusion

It can be concluded that the design 2 & 3 is better in terms of stress produced and the deformation, the difference in both of them is negligible and the flow analysis will determine the better design

Flow Analysis

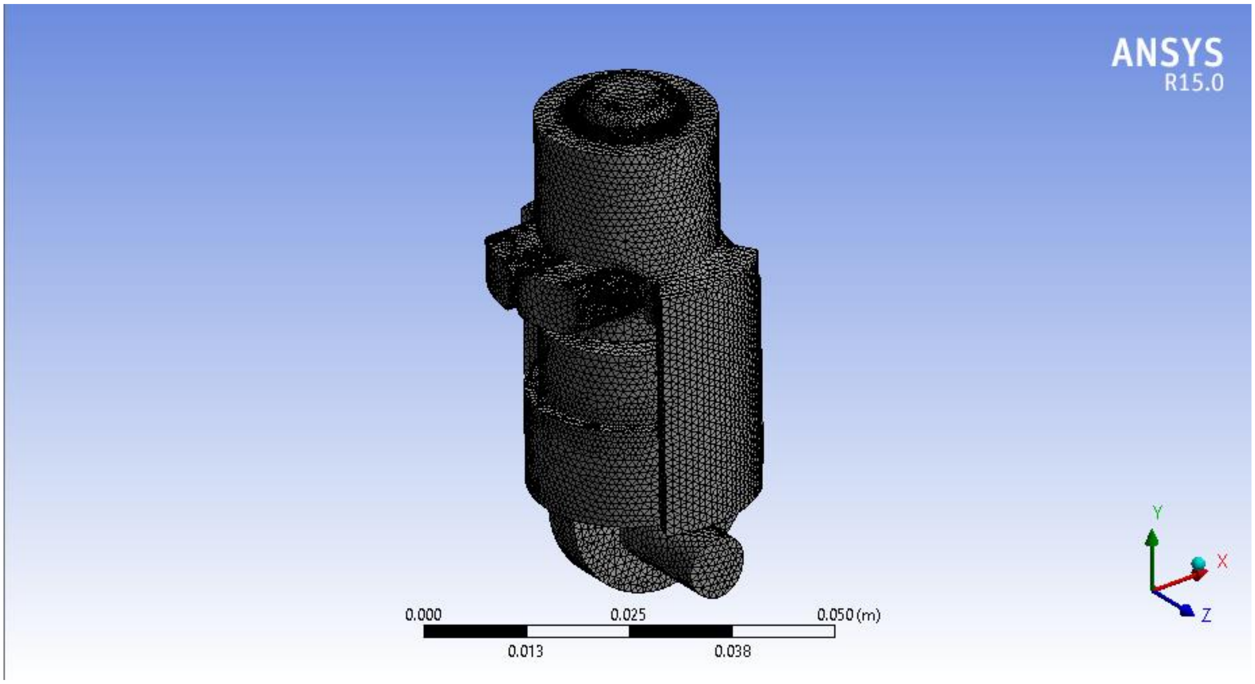
The model of the engine was created to understand the flow of air fuel mixture inside the engine.



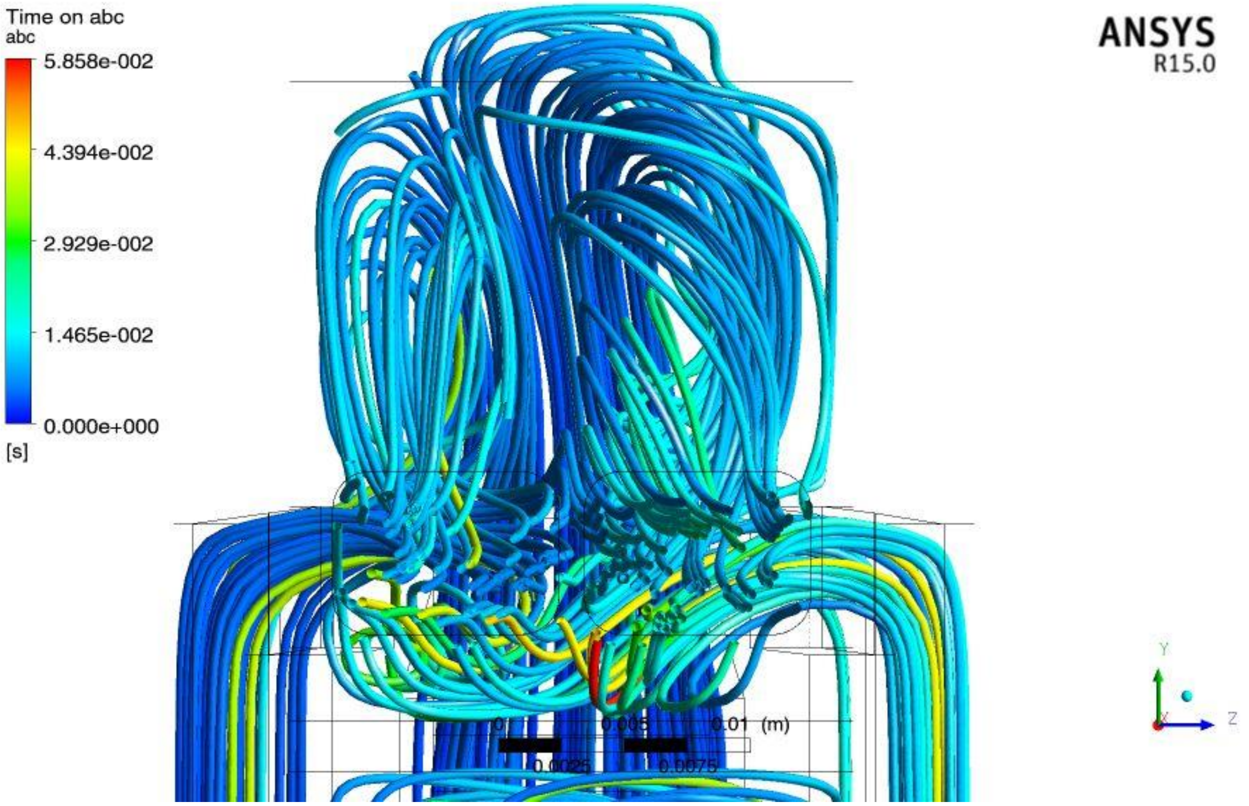
ANSYS CFX Module was used for creating the flow lines. The Boundary condition used are as follows

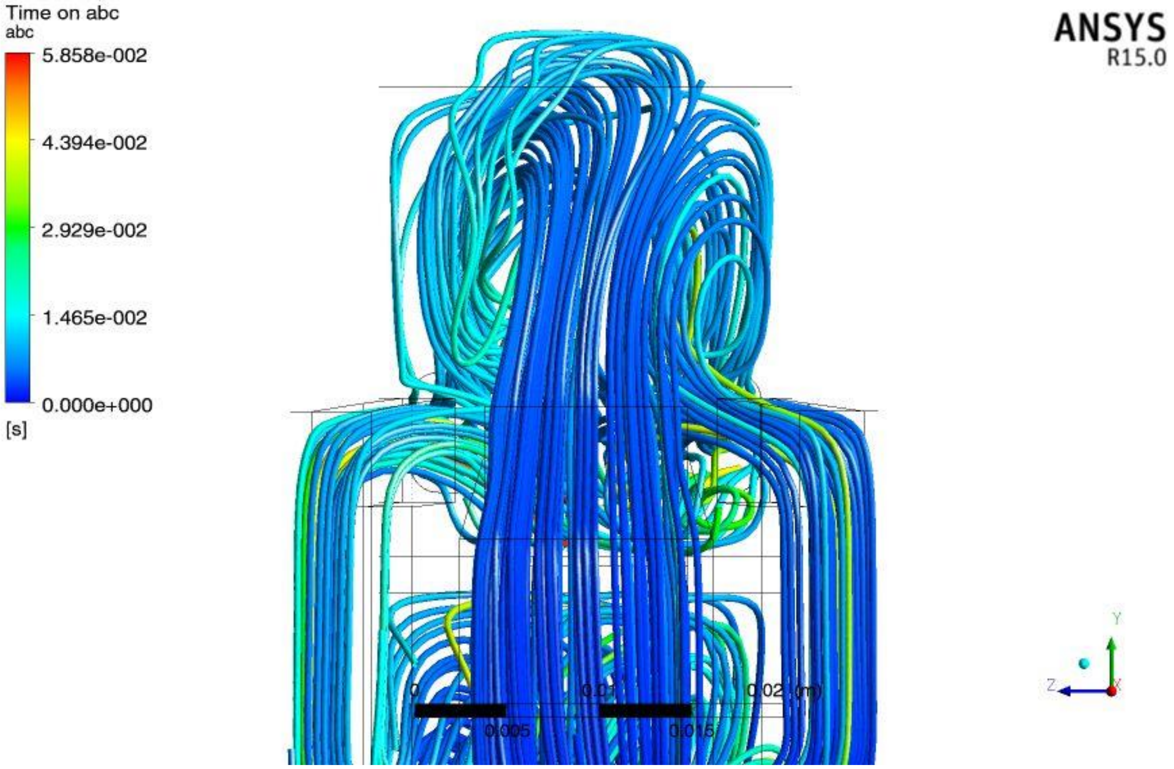
- Mass flow rate of 2 g/s from the inlet (Calculated by engine capacity and rpm)
- Atmospheric pressure at the outlets or exhaust.

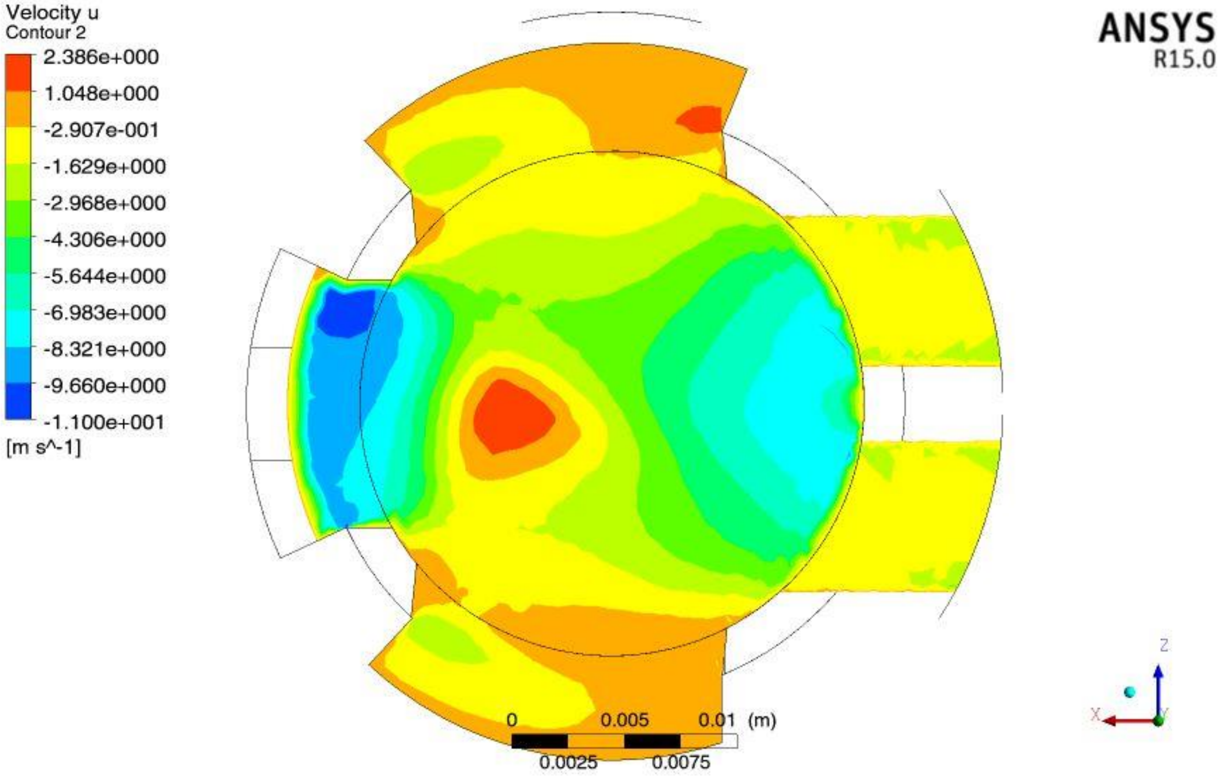
The mesh used is shown below

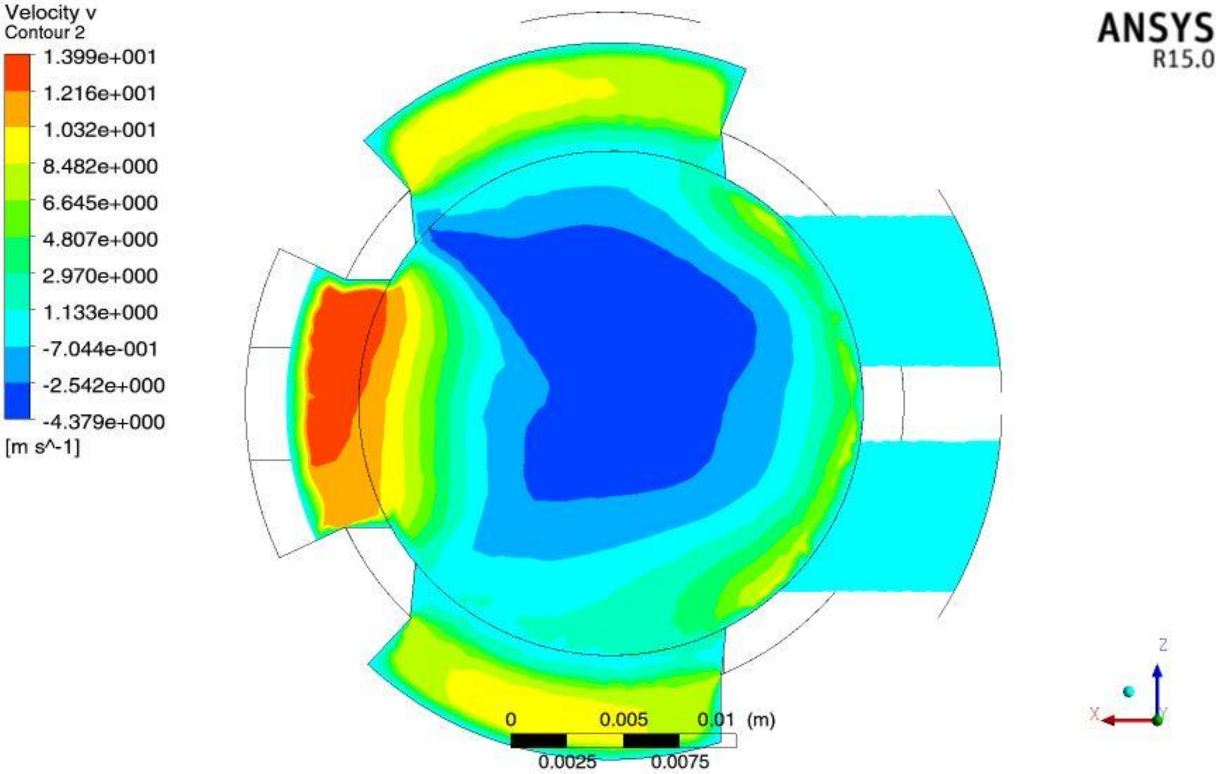


The flow pattern is shown below




Time on abc
abc
5.858e-002
4.394e-002
2.929e-002
1.465e-002
0.000e+000
[s]
ANSYS
R15.0
0
0.01
0.02 (m)
0.005
0.015
Y
Z
X


Velocity u
Contour 2
2.386e+000
1.048e+000
-2.907e-001
-1.629e+000
-2.968e+000
-4.306e+000
-5.644e+000
-6.983e+000
-8.321e+000
-9.660e+000
-1.100e+001
[m s^-1]
ANSYS
R15.0
0
0.005
0.01 (m)
0.0025
0.0075
Z
X
Y



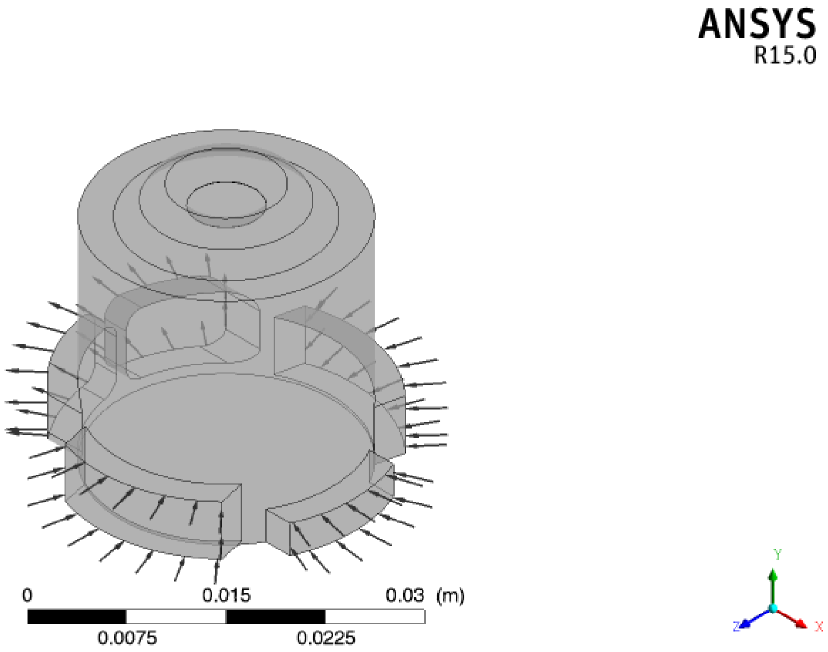
Observation

Looking at the streamlines and the velocity following things can be concluded

- Flow from the inlet 1 is almost twice compared to the flow rate from inlet 2 and 3.
- The contribution of the inlet 2 and 3 is more than the inlet 1 in the fuel which is escaping directly without combustion, this is due to the design of the inlet path. The path in inlet 2 is directed upwards and 2 & 3 it is almost at 90 degrees.

For further analysis, the design is simplified, the portion inside the piston cylinder is only considered in the next step with modified boundary conditions to take care of the modified design.

The new geometry is shown below

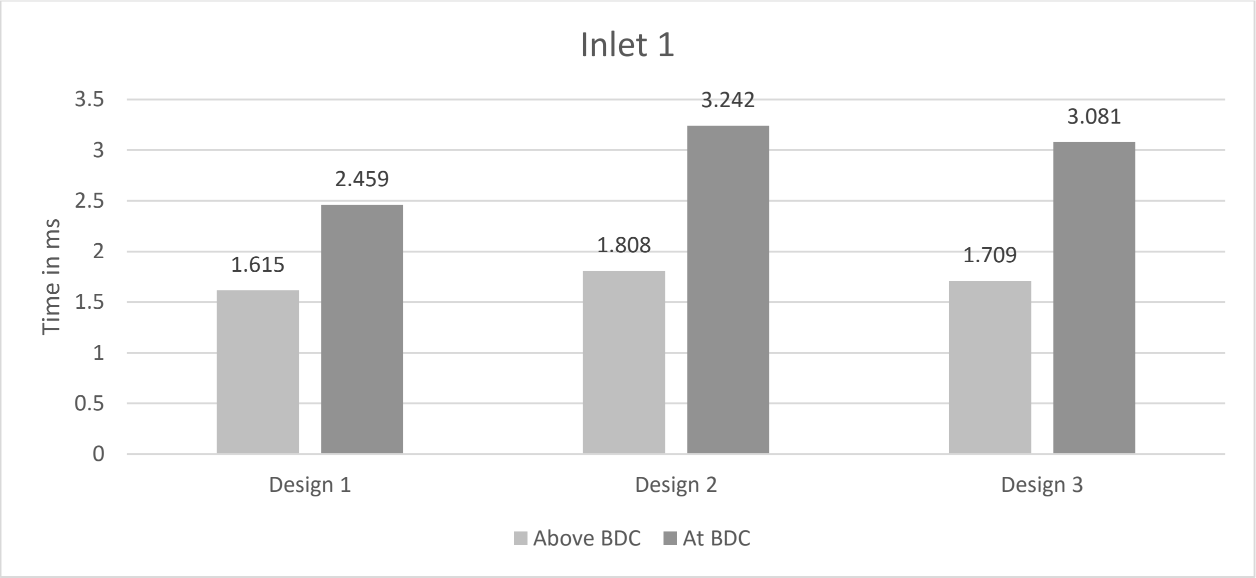


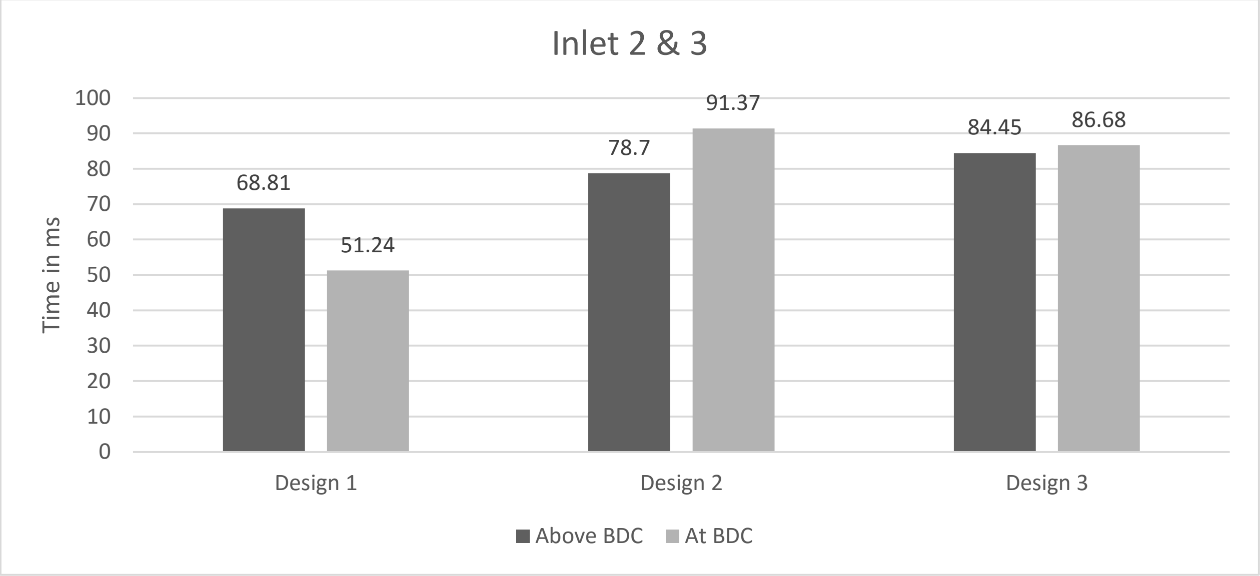
Flow pattern at two position of the piston head is analysed, 1st at the BDC and the 2nd one at a height of 2.5 mm from BDC.

Time on streamline is measured to estimate if the path of the air is directed

Above BDC	Design 1	Design 2	Design 3
Inlet 1 (ms)	1.615	1.808	1.709
Inlet 2 & 3 (ms)	68.81	78.7	84.45

At BDC	Design 1	Design 2	Design 3
Inlet 1 (ms)	2.459	3.242	3.081
Inlet 2 & 3 (ms)	51.24	91.37	86.68



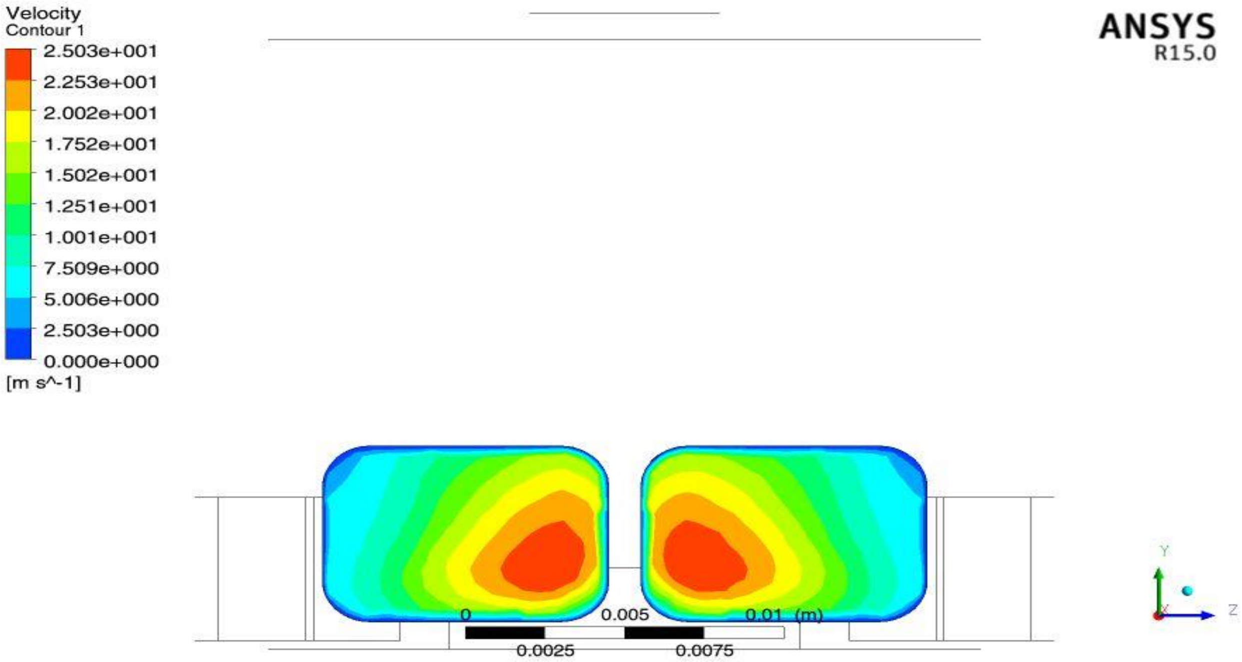


Increased time in case design 2 & 3 are prove that the flow has directed and fever particles are passing through the outlet before combustion.

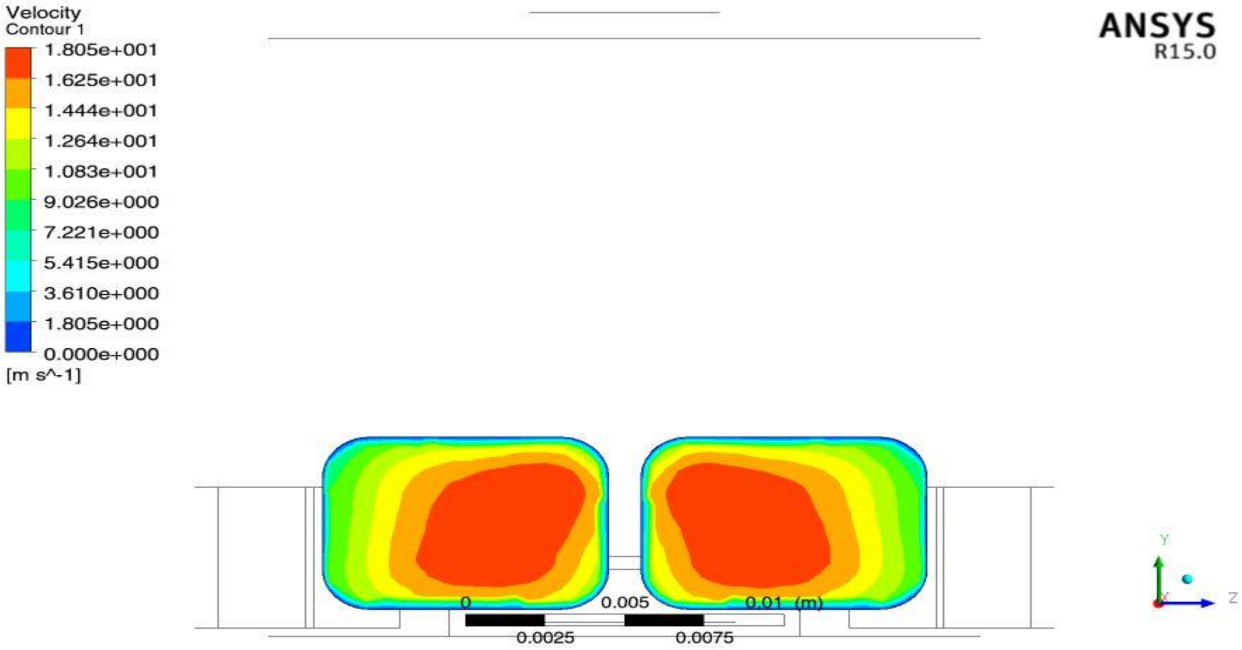
Below is the velocity profile at the outlet port for both this position and the design

1. **Above BDC**

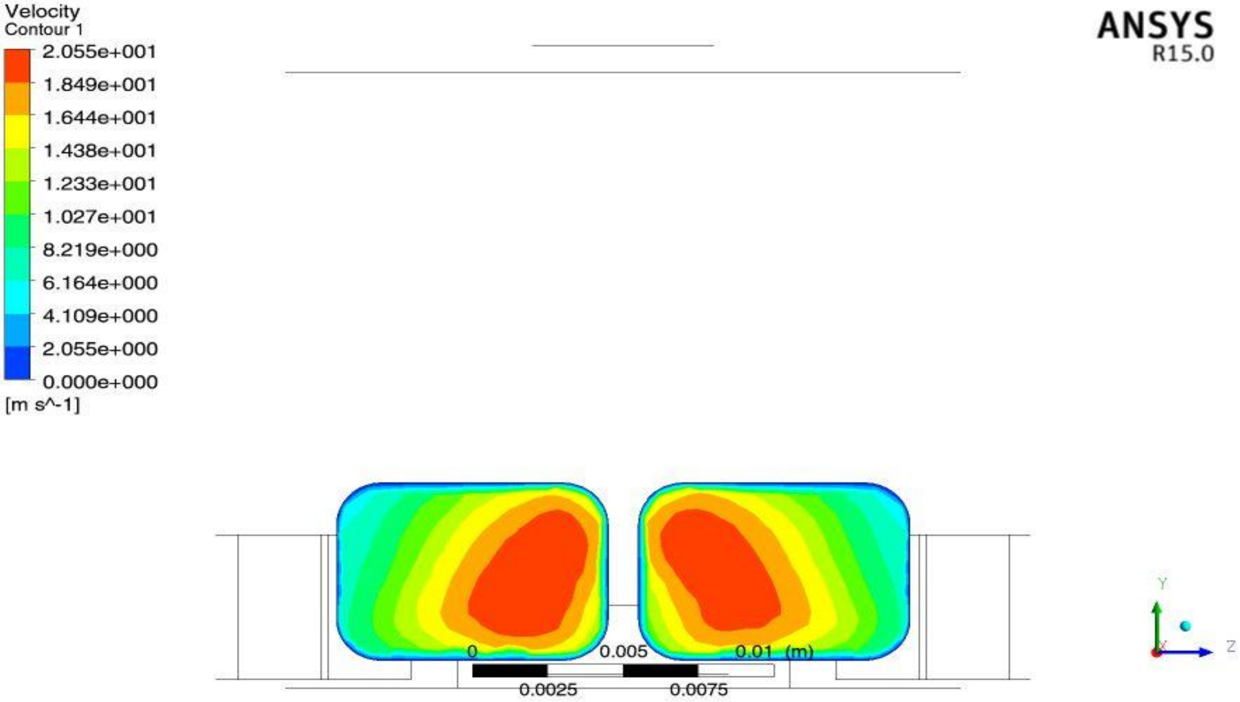
Design 1



Design 2

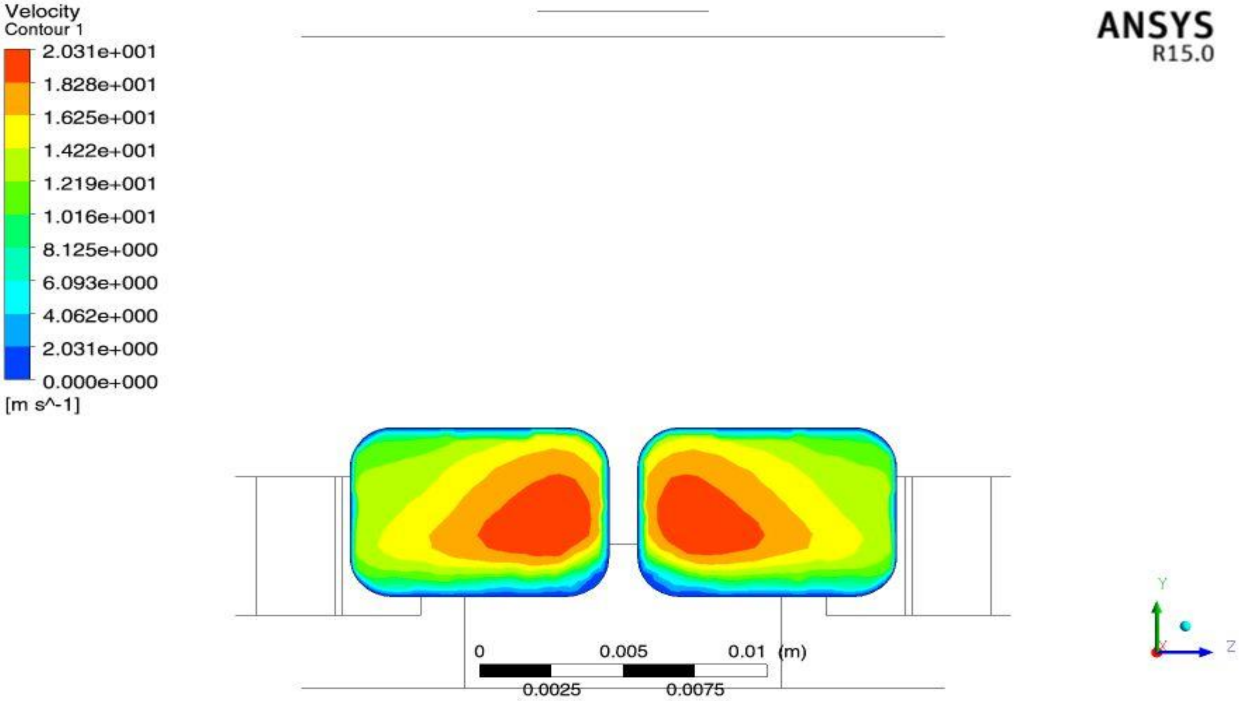


Design 3

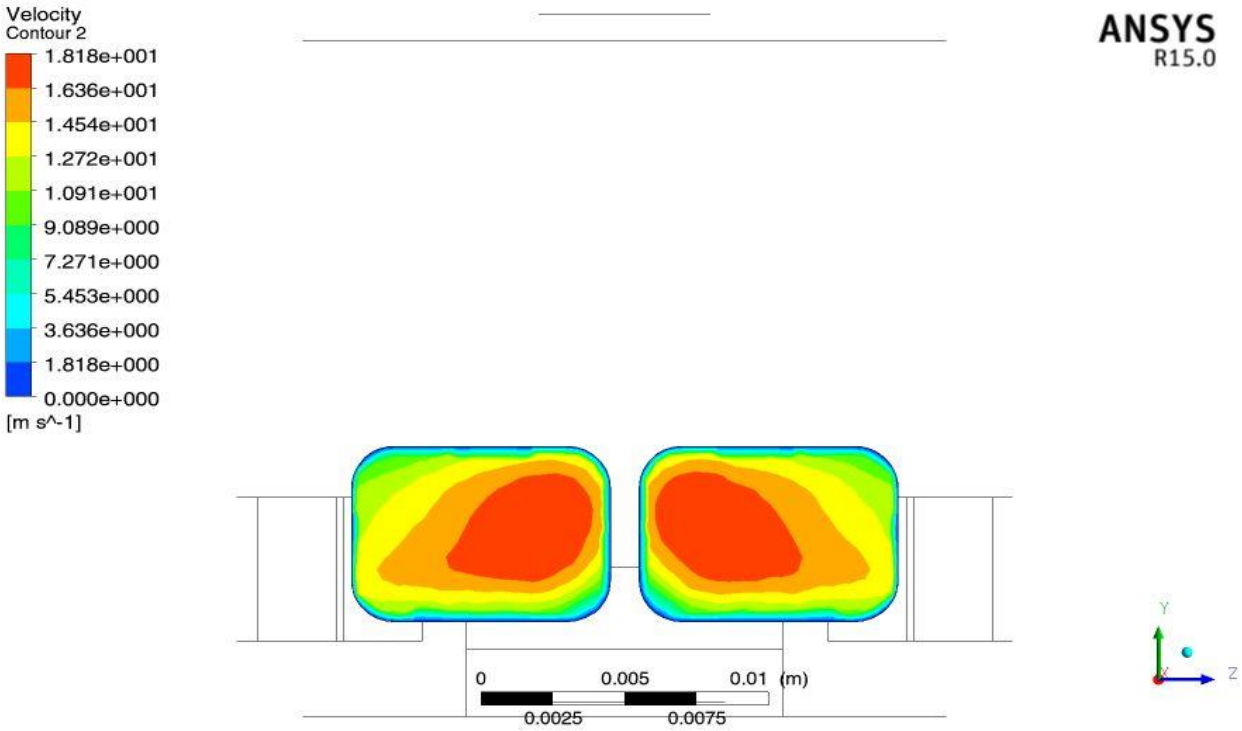


2. At BDC

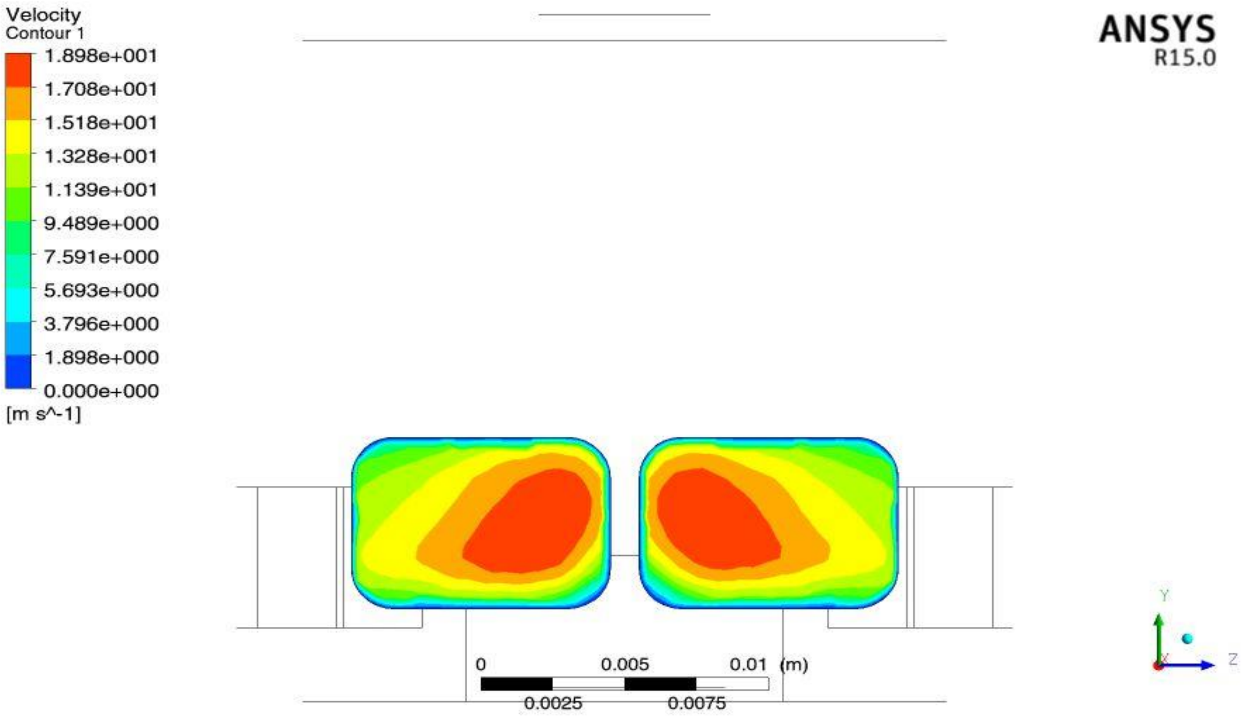
Design 1



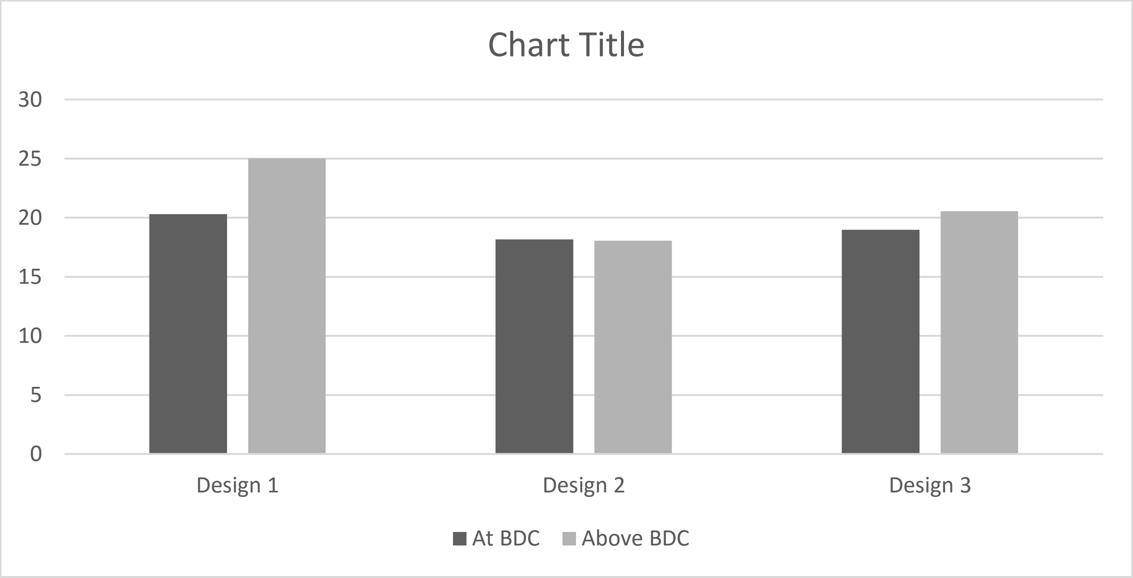
Design 2



Design 3



Velocity	Design 1	Design 2	Design 3
At BDC(m/s)	20.31	18.18	18.98
Above BDC(m/s)	25.03	18.05	20.55



Conclusion

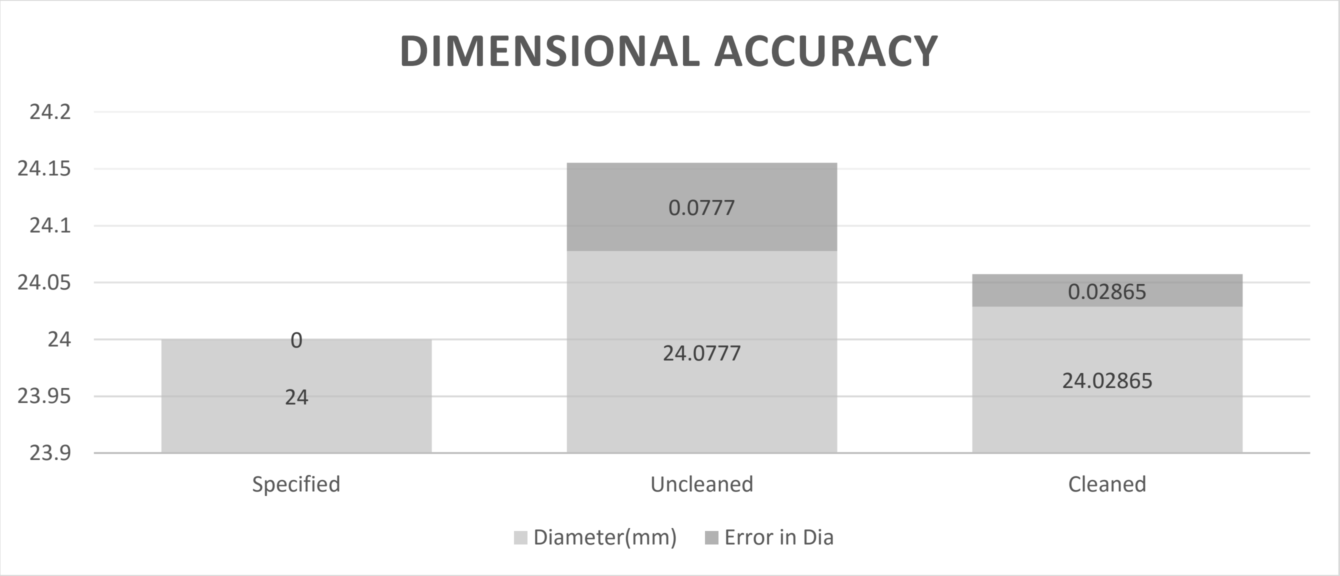
The main disadvantage of 2 stroke engine is the fuel wastage. In this study it I tried to reduce that by modifying the piston head which was successfully done. There was a significant reduction the fuel wastage. Design 3 is the best suited has the maximum benefit. The additional advantage is the increase in compression ratio which results in higher power generation.

Comparison of Piston Manufactured by Conventional and 3D Printing

1. Dimensional Accuracy of Machine

The dimension produced by the laser sintering machine are compared with dimension of provided in the CAD model for Manufacturing. Roundness or circularity of the produced part is also measured using the coordinate measuring machine.

	Specified	Uncleaned	Cleaned
Diameter(mm)	24	24.0777	24.02865
Error in Dia	0	0.0777	0.02865
Percentage Error	0	.32%	.12%



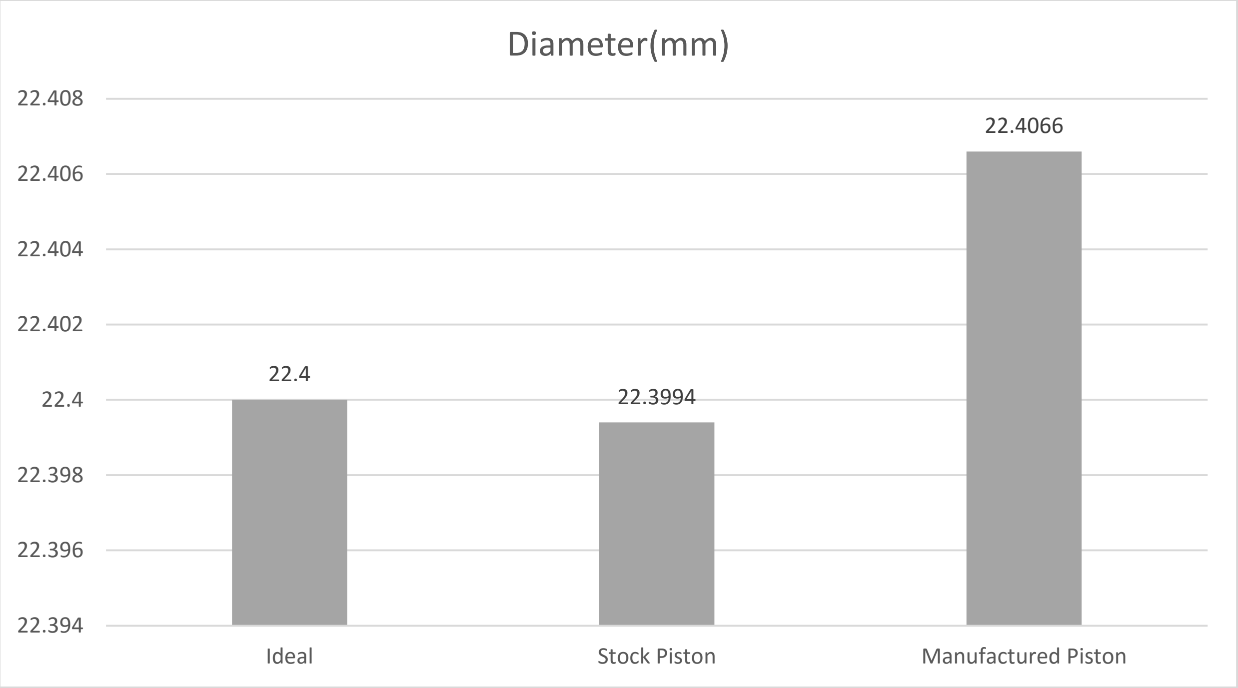
It was observed that the dimension of the part is more than what is specified by the user. The error is less than .3% and can be easily taken care of cleaning the part with sand paper.

2. **Dimensional Accuracy of final part**

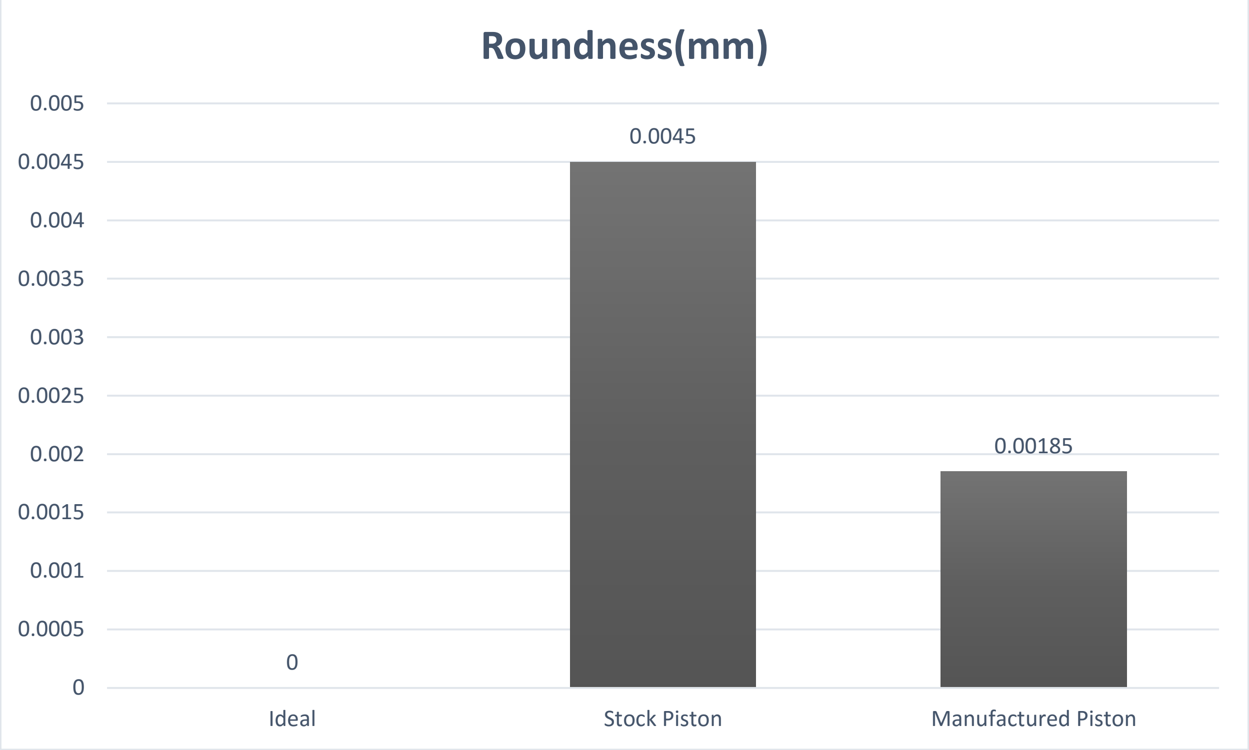
Dimension of part after machining are compared with the dimension of original part and the ideal part dimension. The error in dimension is less than .03% and the part is accurately manufactured with dimension accurate till 2 decimal places. The tolerance of the part is ±.001 mm

	Ideal	Stock Piston	Manufactured Piston
Diameter(mm)	22.4	22.3994	22.4066
Error in Dia	0	-0.0006	0.0066
Percentage Error	0	0.003%	0.0294
Roundness(mm)	0	0.0045	0.00185

The produced part is made of stainless steel and the original piston is aluminium alloy which has a higher thermal expansion coefficient than steel. So the larger dimension of steel will give better seal. The smaller dimension of aluminium can be justified because of its higher thermal expansion.



	Stock Piston (Aluminium)	3D Printed (Stainless Steel)	Casted Stainless Steel
Hardness (Vickers)	140.2	439.8	
Depth(µm)	3.6975	2.07	



1. Hardness (Life of piston)

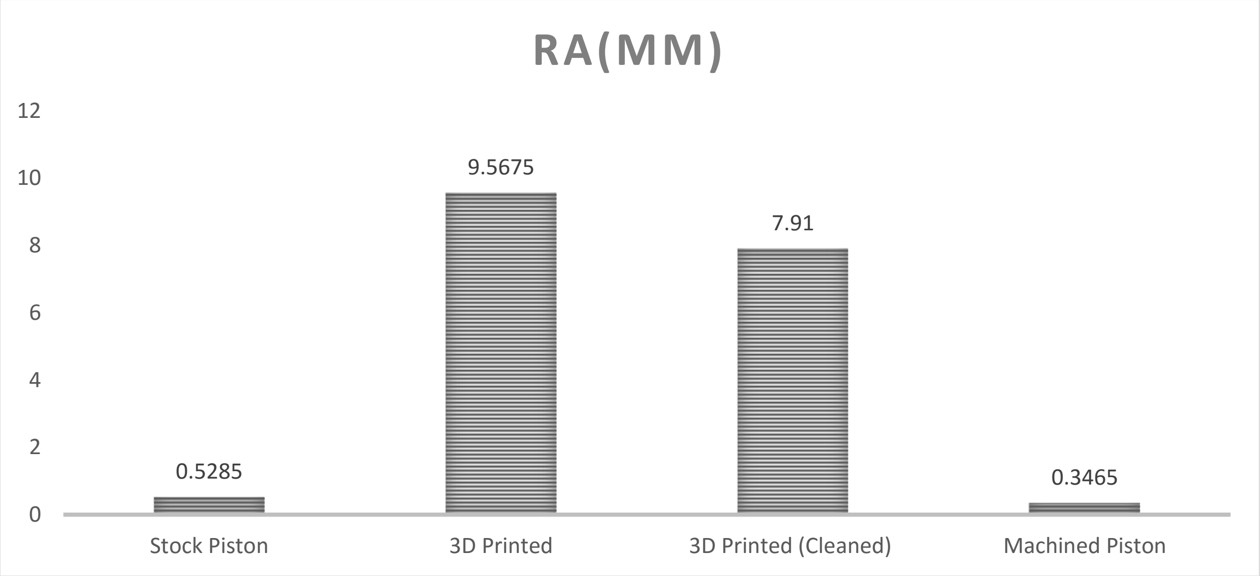
The Hardness of the original piston is very low compared to the 3D Printed one because of the material. Hardness of printed material is compared to the casted steel and it is found to be comparable.

2. Surface Roughness

Surface roughness is directly related to the friction coefficient of the part and and ultimately the life of the piston and cylinder.

The part manufactured directly by 3D printing is very rough, it can be improved by cleaning with sand paper but still the final finish is no appropriate for being used in engine. Post processing in the form of lathe machining is done to reduce the surface roughness.

	Stock Piston	3D Printed	3D Printed (Cleaned)	Machined Piston
Ra(µm)	0.5285	9.5675	7.91	0.3465
Rz(µm)	3.12	51.8	40.2	2.93
Rmax(µm)	17.88	65.9	46.3	4.31



Surface Finish can be drastically improved by using machining the part with controlled parameters. The feed was kept low during the final finishing cut. The resulting surface finish is better than the original piston.

Conclusion

Looking at the quality of the part produced in the direct metal laser sintering it can be said that additive manufacturing can be used to make working parts other than prototyping. Some post processing is required, but is also the case with conventional manufacturing. The clear advantage is the customization that can be done using 3D printing which has an edge over conventional which cannot be used to manufacture complex geometry. The cost involved may be slightly higher but it will come down as more research is done in the area.

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