International Journal of Engineering Trends and Technology
ISSN: 2231 – 5381 /doi:10.14445/22315381/IJETT-V69I10P228

Volume 69 Issue 10, 217-226, October, 2021

Original Article

Design, Modelling, and Thermal Analysis of Hot Piston of IC Engine using Ansys Workbench 2021 R2

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Abstract - *A Novel idea was thought to improve the efficiency of a single-cylinder diesel engine twofold. In this design, a hot piston is mounted over the conventional piston, and firing is shifted over the hot piston. The hot piston is planned to be fabricated out of SS304 grade stainless steel material. No lubricant oil is made available between the hot piston and hot cylinder, and a very close gap is maintained between them. The hot piston is fabricated, and its design is unique. The parametric 3D model is created in AUTODESK Inventor Professional 2019 Version Software. Temperature distribution and heat dissipation were analyzed using ANSYS Workbench 2021 R2 Software and compared. The relevant study information is dealt with here.*

Keywords - *Hot Piston, SS304 Stainless Steel, Temperature distribution, Heat dissipation, Transient thermal*

I. INTRODUCTION

In an IC Engine, diesel burnt increases the temperature and pressure of the gases produced, and the gas expands to forcibly displace the piston, and linear motion of the same is converted into rotary movement of the crankshaft [1]. The piston is exposed to the gas at a temperature of about 2500 K for an instant and room temperature air at the very next instant itself. Thus the piston is exposed to high-temperature gas and room temperature air alternatively at a very high frequency [2].

In a conventional engine, the piston transmits heat to the cylinder walls and through the bottom of the surface of the piston[3].

In our research work, the conventional Al piston is surmounted by an SS304 Stainless steel piston through an SS304 grade Stainless steel pipe, which is named as piston rod, hoping that this idea will improve the fuel efficiency largely.

We have named the surmounted piston the hot piston because the firing is shifted over the hot SS304 grade stainless steel piston. The engine is thus modified. In the modified engine, we have avoided lubricant oil available between the hot piston and the hot cylinder, and an extremely close gap only will be maintained. Cares were taken to see that the gas leakage between the hot piston and the hot cylinder is almost avoided.

After the modification, the loss due to cooling in the conventional cylinder portion is totally avoided and surrounding the hot cylinder, and it is insulated tightly. Hence the hot piston does not transmit any heat through the hot cylinder, and the only feasible heat loss is through the bottom surface of the hot piston.

Vinay V.Kuppast et al. [4] This paper analyzes the temperature of the burnt gases. The high temperature of the gases developed during the power stroke increases piston material temperature very high, resulting in high thermal expansion of the piston. This reduces the gap between the piston and cylinder. Hongyuan Zhang et al. [5] In this paper, the piston is analyzed based on the corresponding thermal analysis. Transient temperature and the transient heat transfer coefficient to find the heat losses involved were found after developing the model using AVL boost software. Preeti Kumari et al. [6] This paper deals with thermal analysis of temperature distribution in the piston, and based on this, the piston material is selected. The crown of the piston is designed to withstand the thermal load and stresses produced. Because of thermo-mechanical overload by insufficient inter cooling and over-fueling, the piston may get damaged. K.S. Mahajan et al. [7] In this paper, ways of effective utilization of heat energy by avoiding cooling losses in an IC engine are discussed. The cylinder is insulated in this IC engine, and hence temperature reaches very high; and a conventional engine material cannot withstand such high temperatures, and it is concluded to use a ceramic-coated piston, and if the coating thickness is increased, the piston crown may attain maximum temperature. I.V.Syeswanth et al. [8] The paper investigates that by reducing piston weight and by using composite material instead of aluminum material, the fuel consumption can be reduced. The piston capability is analyzed by structural and transient thermal analysis.

About 35 - 40% of fuel supplied is simply wasted by radiator cooling. The radiator is used to see that the engine material temperature is kept below 140ºC so that the lubricant does not get charred and sticky and the piston and cylinder does not seize.

Thus in our work, theoretical analysis is made using ANSYS workbench 2021 R2 software and heat losses through the bottom face of the hot piston and temperature distribution for three conditions, presuming the top face of the hot piston can be at a temperature of a) 700ºcelcius b) 600ºcelcius c)500ºcelcius

II. MATERIALS & METHODS

The Hot piston is selected to withstand the expected temperature of over 600º Celcius and also should satisfy the following requirements of Lightweight, Better Wear Resistance, Better Thermal conductivity, High strength to weight proportion, Rust free, Easy to cast, Easy to machine, Non-Attractive and Non Harmful.

Austenitic Cr-Ni stainless steel (SS 304 grade) is preferred for its corrosion resistance, high ductility, superb drawing, shaping, and turning properties. Low carbon content means less carbide precipitation in the heat-influenced zone during welding and has lower weakness due to intergranular corrosion. SS304 grade has very good resistance to oxidation in continuous support of 870°celcius and irregular support of 925°celcius. Also, SS 304 stainless steel is used for various household and industrial hardware such as food processing equipment parts of the screw, utensils, and in-car headers. It is normally used for vaporizer coil material. The elemental weight composition (by weight percentage) of SS 304 grade stainless steel material is listed in table 1. The mechanical and physical properties (values) of SS 304 grade stainless steel material are listed in table 2.

Initially, a literature survey was conducted from various journal resources, and then AUTODESK Inventor Professional 2019 software was used to model the pistons. After that, the modeled piston was analyzed by ANSYS Workbench 2021 R2 software, and the simulations on transient temperature distribution and total heat flux dispersal were obtained. The methodology adopted to complete piston analysis is shown in Fig.1

Table 1. Chemical composition of SS 304 grade stainless steel

Component	Weight Percentage
C	Max 0.08
Cr	18 - 20
Fe	66.345 - 74
Mn	Max 2
Ni	8 - 10.5
P	Max 0.045
S	Max 0.03
Si	Max 1

Table 2. Physical and mechanical properties of SS 304 grade stainless steel

Properties	Value
Poisson ratio	0.265 - 0.275
Density	8.00 g/cm3
Melting Point	1450 °C
Youngs Modulus	193 GPa
Electrical Resistivity	0.72 x 10^{-6} Ω.m
Thermal Conductivity	16.2 W.m -1.K-1
Thermal Expansion	17.2 x 10^{-6} m/mK
Tensile Strength min	515 MPa
Yield Strength 0.2% Proof min	205 MPa
Elongation (% in 50 mm) min	40

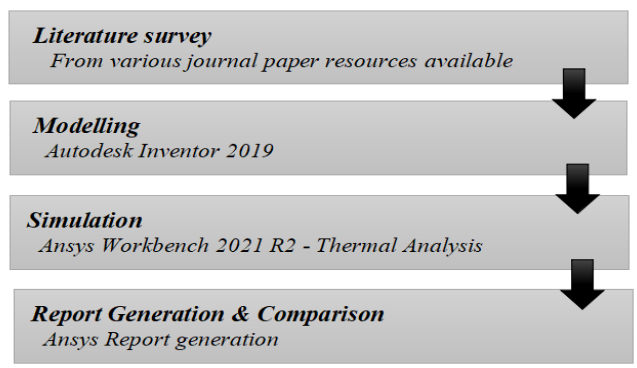

Fig 1. Flow diagram of the methodology adopted

III. DESIGN CONSIDERATION

The piston is required to have enormous strength and heat-resistant properties to withstand high pressure and rigorous condition. The piston should be made rigid enough to withstand thermal and Mechanical Loading and also to maintain a temperature within limits. The dimensions shall be as compact as possible to keep the weight of the Hot piston is minimum.

A. Engine Specifications

Kirloskar's four-stroke diesel engine is selected as a test engine because it cannot be challenging to carry out the necessary modifications. In this paper, the focus is on the hot

Piston; The geometry and requirements depend exclusively on the engine configuration. Engine specification is given in table 3.

Table 3. Summary of Engine specifications

Engine	Air-Cooled
Stroke	Four Stroke
Fuel Type	Diesel Engine
Model	VA320-2
No. of Cylinders	1
Bore x Stroke (mm)	74 X 74
Cubic Capacity (Ltr)	0.318
Compression Ratio	22:01
Rated Output kW(hp)	2.94(4)
Rated Speed rpm	1800
Fuel Tank Capacity (Ltr)	4.5
Flywheel rotates	Clockwise
Starting	Hand Start
Combustion System	Indirect Combustion
Overloading capacity of the engine	10% of the rated output

B. Piston design

The Hot Piston was designed for the above specified Four-stroke diesel engine using the Design data book by PSG College of Technology, Coimbatore. Hot piston consists of Top cover, Bottom cover, Connecting Pin, and Hot piston wall pipe. The detailed 2D CAD drawings are portrayed in Fig.2,3,4,5, and 6. The overall dimensions and weight of the parts used in the hot piston are entered in Table 4.

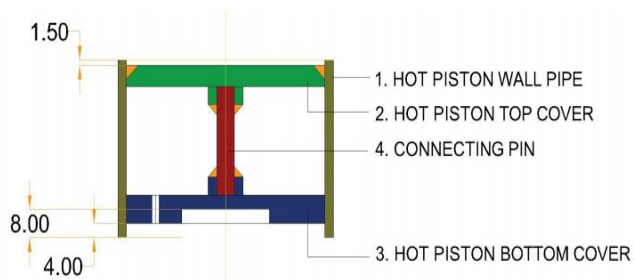

Fig 2. Sub-Assembly drawing for Hot Piston

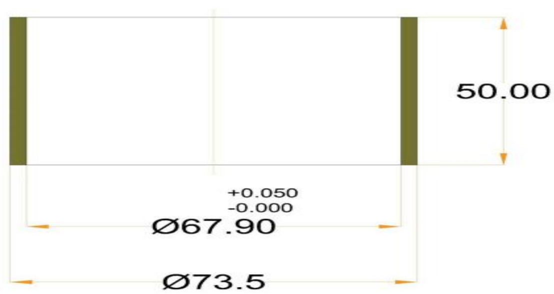

Fig 3. Part drawing for Hot piston wall pipe

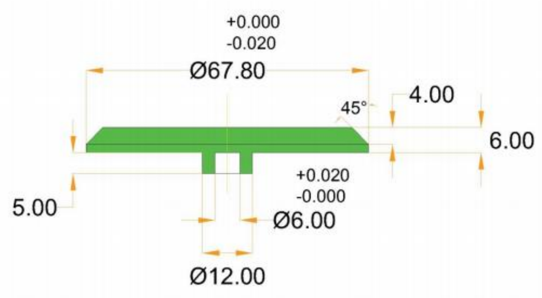

Fig 4. Part drawing for Hot piston Top cover

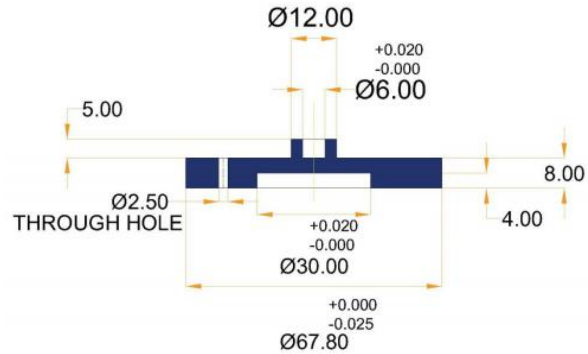

Fig 5. Part drawing for Hot piston Bottom cover

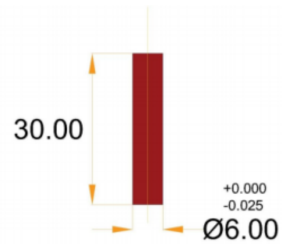

Fig 6. Part drawing for Connecting Pin

Table 4. Dimensions& Weight of the parts used in Hot Piston

Part No.	Descriptio n	Overall Dimension (mm x mm x mm)	Weight as per drawing (kg)
1.	Top cover	Ø67.8 x 11 mmthick	0.2440
2.	Bottom cover	Ø67.8 x 13 mm thick	0.1732
3.	Connecting Pin	Ø6 mm x 30 mm long	0.2299
4.	Hot piston wall pipe	Ø73.5 mm x 50mm long	0.0066
Overall weight as per drawing			**0.6537**

C. Modeling of Piston

By using AUTODESK Inventor 2019 software, the 3D piston model was done. The piston model is portrayed in Fig.7,8 & 9. Then the 3D model is converted to IGES format, and the file is imported in ANSYS workbench 2021 R2, and meshing is done.

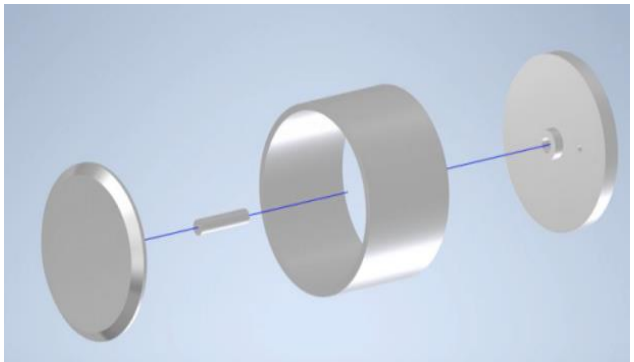

Fig 7. 3D model of Hot piston

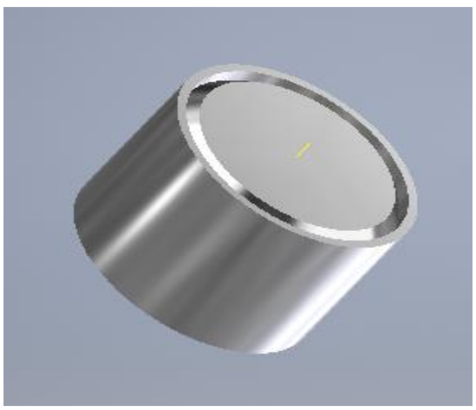

Fig 8. Geometric model of the Hot Piston Isometric view - 1

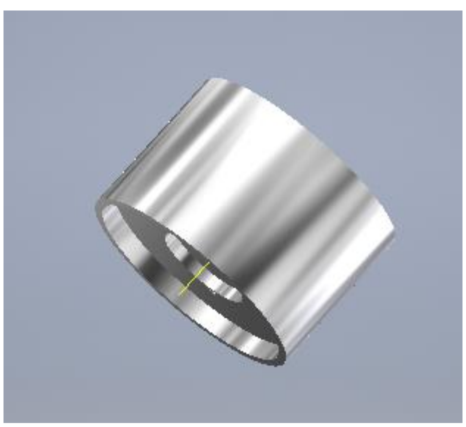

Fig 9. Geometric model of the Hot Piston Isometric view - 2

IV. ANALYSIS OF PISTON

A. Meshing of Piston

Triangular mesh is adopted for the piston model. The model was initially checked for free edges, and geometry clean-up was done. The piston is fabricated out of stainless steel SS304 grade material. The details of the meshing are given in Table 5. Tetra mesh was adopted for the piston sidewall, as shown in Fig.10.The connectivity is to be made among the elements of all the materials for proper results.

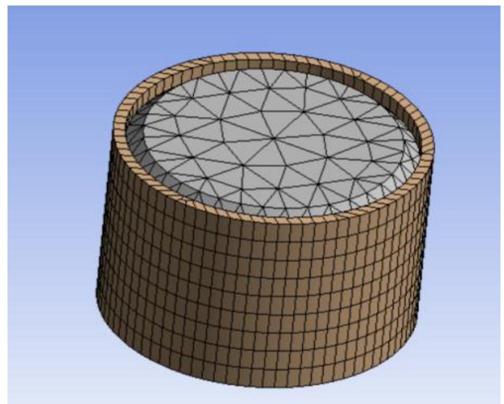

Fig 10. Meshed model of Hot Piston

Table 5. Meshed model of Hot piston

Element size	0
No of elements	24870
No of nodes	8210
Type of element	tetra4

B. Preprocessing

a) The explanation for Transient heat transfer

Transient heat transfer is the case of unsteady-state heat transfer and is experienced initially for a short period of time. During transient heat transfer, the heat energy transferred through the medium is not stable. Heat transfer begins as transient and then reaches a steady-state on reaching thermal equilibrium.

b) The explanation for Steady-State heat transfer

After some time has passed, the transient heat transfer becomes stable and attains a steady state. Steady-state heat transfer can be conduction, convection, or radiation process. In a steady-state heat transfer, the heat-flow rate remains stable at any point in time. After reaching steady-state heat transfer, the temperature distribution becomes fixed.

C. Post-Processing

All the modeled piston dimensional details were imported into the ANSYS workbench tool. Then, different boundary phenomena were employed to carry out virtual simulations to plot the temperature distribution and heat flux. The post-processing results are established and reported in following Figures 11-28.

V. RESULT AND DISCUSSIONS

Boundary conditions are applied to the hot piston. The temperature is applied at the top surface of the piston. The hot piston wall pipe is perfectly insulated.

A. Condition 1:

The boundary conditions used to analyze the Modified Hot Piston are maximum and minimum temperatures of 700ºCand 500ºC. The ambient temperature is assumed to be 30ºC. The convection coefficient is taken as 5 W/m^{2}K, and the Thermal conductivity of SS304 grade material is 16.2 W/mK.

The conditions are shown in Figure 11.

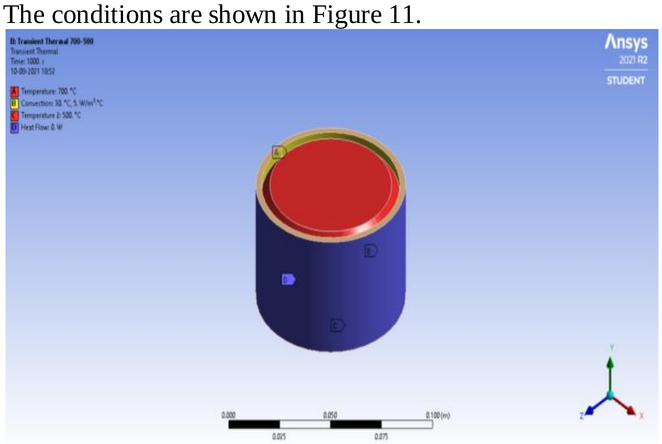

Fig 11. Boundary conditions of Hot piston of SS 304 grade Stainless steel at 700^{o}C

a) Transient Temperature Distribution

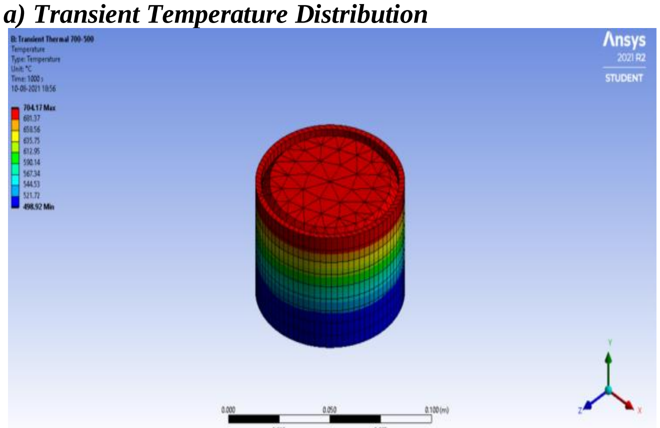

Fig 12. Transient temperature distribution of Hot piston ofSS 304-grade Stainless steel at 700ºC for 1000 seconds

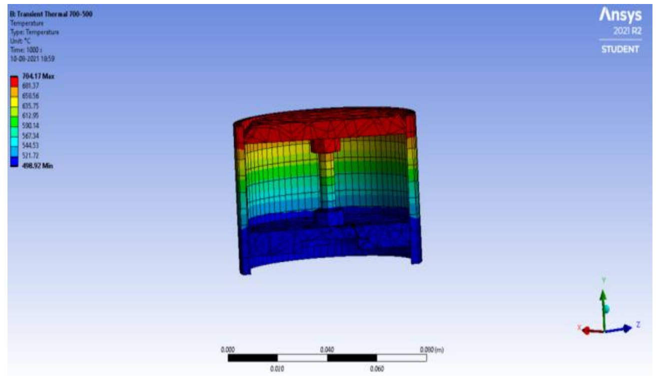

Fig 13. Sectional View - Transient temperature distribution of Hot piston of SS 304 grade Stainless steel at 700ºC for 1000 seconds

Table 6. Tabular Data for Transient temperature distribution of Hot piston of SS 304 grade Stainless steel at 700ºC for 1000 seconds

S.No	Time(s)	Minimum [ºC]	Maximum [ºC]	Average [ºC]
1.	100	412.92	700	519.99
2.	200	497.62	700.85	573.22
3.	233.33	499.29	700.71	579.13
4.	266.67	499.55	700.63	581.25
5.	300	499.48	700.59	582.05
6.	333.33	499.45	700.58	582.37
7.	366.67	499.44	700.57	582.49
8.	400	499.43	700.57	582.54
9.	433.33	499.43	700.57	582.57
10.	466.67	499.43	700.56	582.58
11.	500	499.43	700.56	582.58
12	533.33	499.43	700.56	582.58
13	600	499.43	700.56	582.58
14	733.33	499.43	700.56	582.58
15	1000	499.43	700.56	582.58

From table 6, it is inferred that the transient temperature attains steady-state condition after 300 seconds.

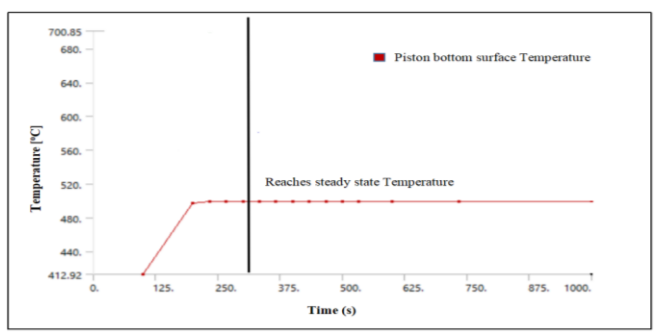

Fig 14. Graph plotted for Transient temperature distribution of Hot piston of SS 304 grade Stainless steel 700ºC for 1000 seconds

a) Heat Flux

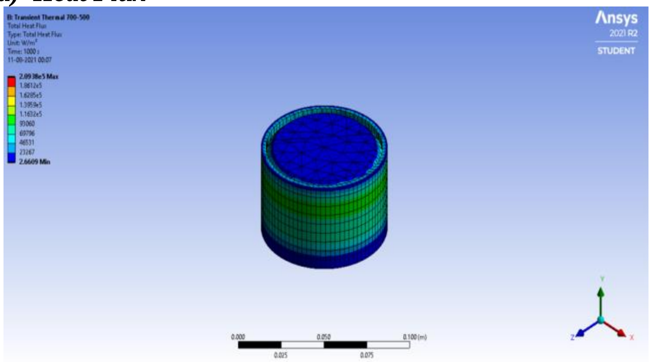

Fig 15. Transient heat flow analysis of Hot piston of SS 304 grade Stainless steel at 700°C for 1000 seconds

Table 7. Tabular Data for Transient heat flow analysis of Hot piston of SS 304 grade Stainless steel at 700°C for 1000 seconds

S.No	Time(s)	Minimum [W/m²]	Maximum [W/m²]	Average [W/m²]
1	100	105.23	9.70e+05	1.05E+05
2	200	3.5425	3.15e+05	59295
3	233.33	0.99888	2.55e+05	59209
4	266.67	2.0346	2.30e+05	59390
5	300	2.393	2.19e+05	59458
6	333.33	2.5419	2.14e+05	59486
7	366.67	2.6075	2.11e+05	59498
8	400	2.6368	2.10e+05	59503
9	433.33	2.6501	2.10e+05	59505
10	466.67	2.656	2.10e+05	59506
11	500	2.6587	2.09e+05	59507
12	533.33	2.6599	2.09e+05	59507
13	600	2.6607	2.09e+05	59507
14	733.33	2.6609	2.09e+05	59507
15	1000	2.6609	2.09e+05	59507

From table 7, it is inferred that the average heat loss is almost maintained steady after 200 seconds.

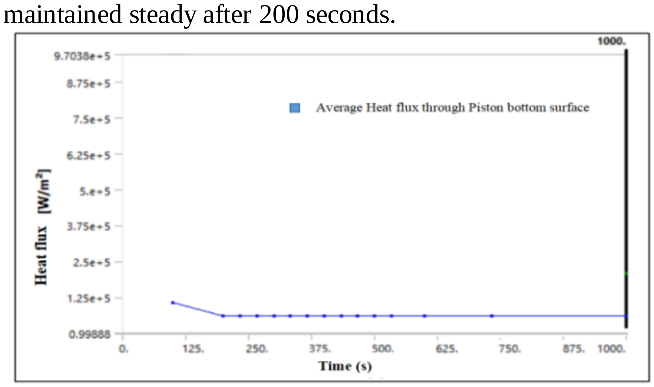

Fig 16. Graph plotted for Total Heat flow Transient thermal analysis of Hot piston of SS 304 grade Stainless steel at 700°C for 1000 seconds

c) Heat loss calculation

Heat flow through piston

Piston heat flow area = $\pi/4 \times 0.073^2$

= 4.185×10^{-3} m^2

Heat flux = 59507 W/m^2

∴ Heat loss through piston downwards

Q_{LP} = $59507 \times 4.185 \times 10^{-3}$

= 249.03 W

B. Condition 2:

The boundary conditions used to analyze the modified hot piston are maximum and minimum temperatures of 600°C and 500°C. The Ambient temperature is assumed to be 30°C. The convection coefficient is taken as 5 W/m^2K, and the Thermal conductivity of SS304 grade material is 16.2 W/mK.

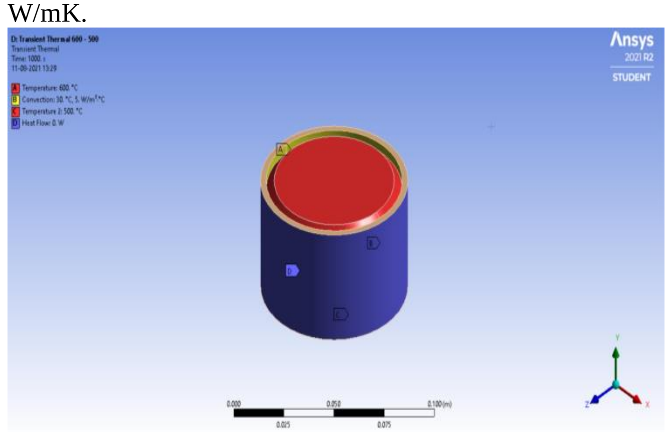

Fig 17. Boundary conditions of Hot piston of SS 304 grade Stainless steel at 600°C

a) Transient Temperature Distribution

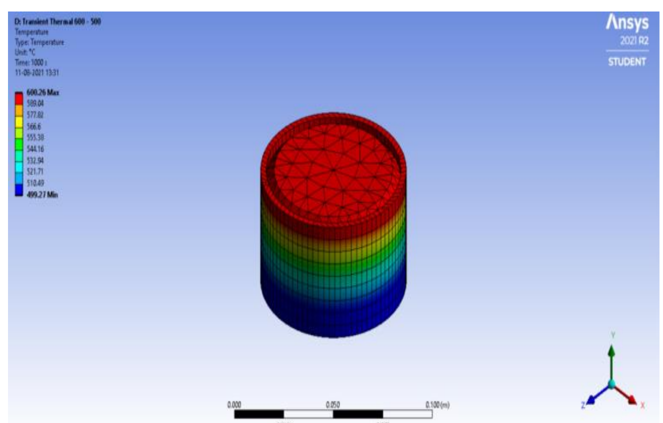

Fig 18. Transient temperature distribution of Hot piston of SS 304 grade Stainless steel at 600°C for 1000 seconds

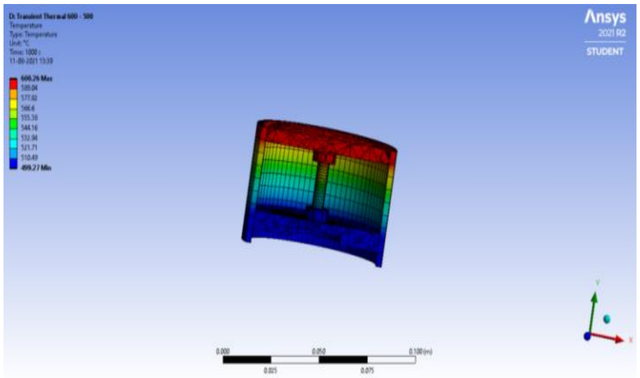

Fig 19. Sectional View - Transient temperature distribution of Hot piston of SS 304 grade Stainless steel at 600°C for 1000 seconds

b) Heat Flux

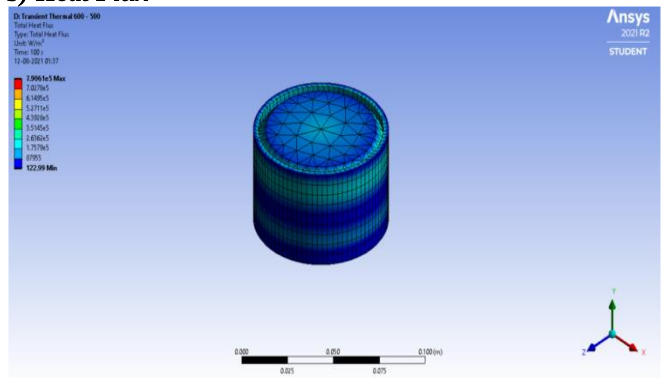

Fig 21. Transient heat flow analysis of Hot piston of SS 304 grade Stainless steel at 700°C for 1000 seconds

Table 8. Tabular Data for Transient temperature distribution of Hot piston of SS 304 grade Stainless steel at 600°C for 1000 seconds

S.No	Time(s)	Minimum [°C]	Maximum [°C]	Average [°C]
1	100	388.64	600	483.54
2	200	492.62	600.53	532.27
3	233.33	498.59	600.4	537.67
4	266.67	499.04	600.33	539.61
5	300	499.17	600.29	540.34
6	333.33	499.23	600.28	540.63
7	366.67	499.25	600.27	540.74
8	400	499.26	600.27	540.79
9	433.33	499.27	600.26	540.81
10	466.67	499.27	600.26	540.82
11	500	499.27	600.26	540.82
12	533.33	499.27	600.26	540.82
13	600	499.27	600.26	540.82
14	733.33	499.27	600.26	540.82
15	1000	499.27	600.26	540.82

From table 8, it is inferred that the transient temperature attains steady-state condition after 266.67 seconds.

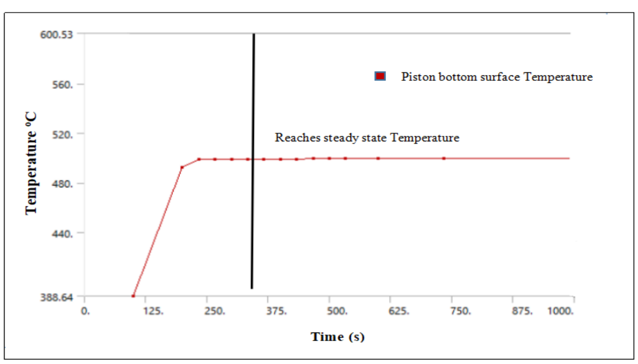

Fig 20. Graph plotted for Transient temperature distribution of Hot piston of SS 304 grade Stainless steel at 600°C for 1000 seconds

Table 9. Tabular Data for Transient heat flow analysis of Hot piston of SS 304 grade Stainless steel at 600°C for 1000 seconds

S.No	Time(s)	Minimum [W/m²]	Maximum [W/m²]	Average [W/m²]
1	100	122.99	7.91e+05	90005
2	200	4.9806	2.16e+05	31587
3	233.33	0.51716	1.62e+05	29661
4	266.67	0.46062	1.39e+05	29654
5	300	0.79526	1.28e+05	29699
6	333.33	0.93302	1.24e+05	29720
7	366.67	0.99349	1.22e+05	29729
8	400	1.0205	1.2e+05	29733
9	433.33	1.0327	1.20e+05	29735
10	466.67	1.0382	1.20e+05	29736
11	500	1.0407	1.20e+05	29736
12	533.33	1.0418	1.20e+05	29736
13	600	1.0425	1.20e+05	29736
14	733.33	1.0427	1.20e+05	29736
15	1000	1.0428	1.20e+05	29736

From table 9, it is inferred that the average heat loss is almost maintained steady after 233.33 seconds.

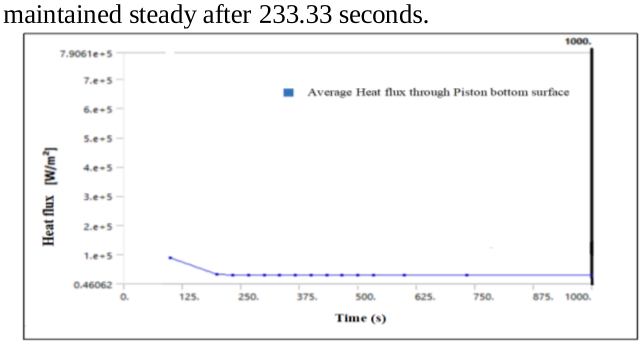

Fig 22. Graph plotted for Transient heat flow analysis of Hot piston of SS 304 grade Stainless steel at 600°C for 1000 seconds

c) Heat loss calculation

Heat flow through piston

Piston heat flow area $= \pi/4 \times 0.073^2$

$= 4.185 \times 10^{-3}\,m^2$

Total Heat flux $= 29736\ W/m^2$

∴ Heat loss through piston downwards

$Q_{LP} = 59507 \times 4.185 \times 10^{-3}$

$= 124.445\ W$

C. Condition 3:

The boundary conditions used to analyze the modified hot piston are maximum and minimum temperatures of 500°C and 400°C. The Ambient temperature is assumed to be 30°C. The convection coefficient is taken as 5 W/m²K, and the Thermal conductivity of SS304 grade material is 16.2 W/mK

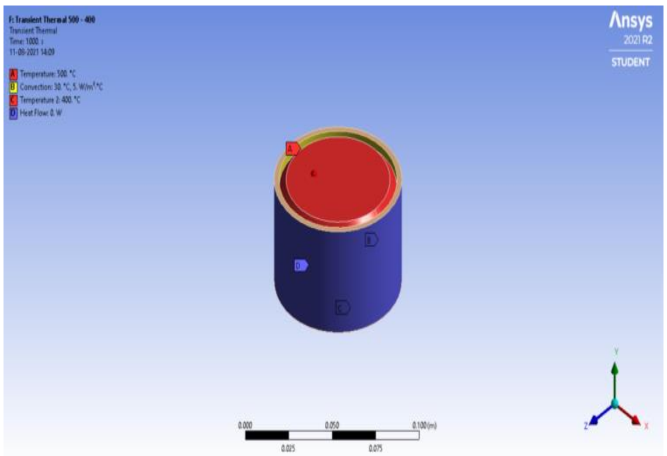

Fig 23. Boundary conditions of Hot piston of SS 304 grade Stainless steel at 500°C

a) Transient Temperature Analysis

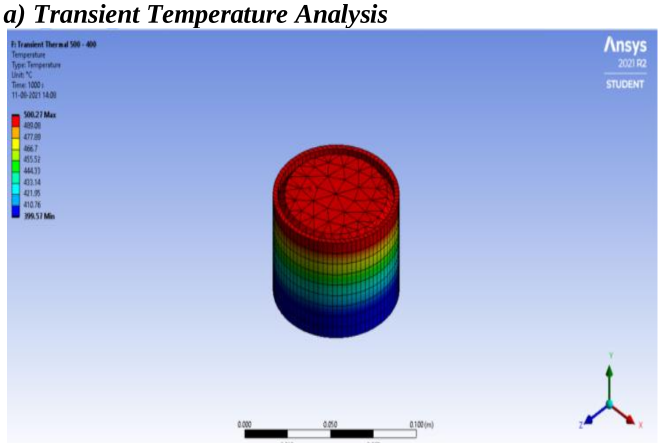

Fig 24. Transient temperature distribution of Hot piston of SS 304 grade Stainless steel at 500°C

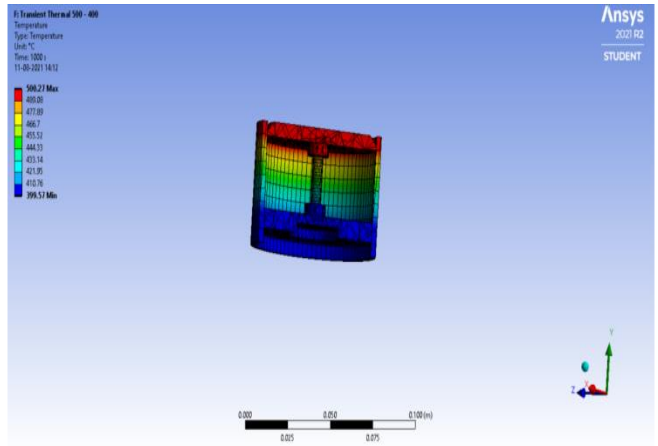

Fig 25. Sectional View - Transient temperature distribution of Hot piston of SS 304 grade Stainless steel at 500°C

Table 10. Tabular Data for Transient temperature distribution of Hot piston of SS 304 grade Stainless steel at 500°C for 1000 seconds

S.No	Time(s)	Minimum [°C]	Maximum [°C]	Average [°C]
1	100	317.96	500	394.61
2	200	397.12	500.49	434.09
3	233.33	399.06	500.38	438.46
4	266.67	399.38	500.32	440.04
5	300	399.49	500.29	440.63
6	333.33	399.53	500.28	440.86
7	366.67	399.55	500.28	440.96
8	400	399.56	500.27	440.99
9	433.33	399.57	500.27	441.01
10	466.67	399.57	500.27	441.02
11	500	399.57	500.27	441.02
12	533.33	399.57	500.27	441.02
13	600	399.57	500.27	441.02
14	733.33	399.57	500.27	441.02
15	1000	399.57	500.27	441.02

From table 10, It is inferred that the transient temperature attains steady-state condition after 300 seconds.

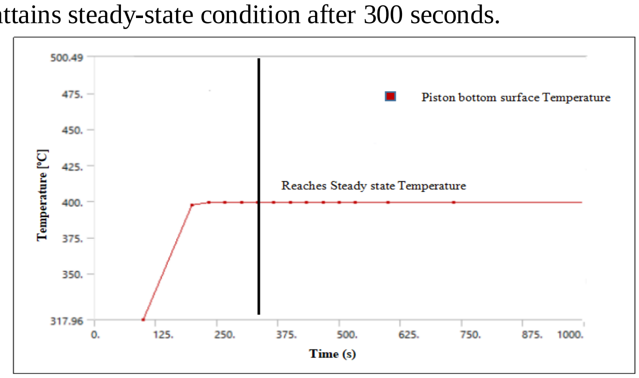

Fig 26. Graph plotted for Transient Transient temperature distribution of Hot piston of SS 304 grade Stainless steel at 500°C for 1000 seconds

b) Heat Flux

Table 11. Tabular Data for Transient heat flow analysis of Hot piston of SS 304 grade Stainless steel at 500°C for 1000 seconds

S.No	Time(s)	Minimum [W/m²]	Maximum [W/m²]	Average [W/m²]
1.	100	97.059	6.6273e+005	73936
2.	200	3.6359	1.915e+005	30485
3.	233.33	8.6556e-002	1.4718e+005	29569
4.	266.67	0.69553	1.2859e+005	29661
5.	300	0.96518	1.2026e+005	29706
6.	333.33	1.0765	1.1649e+005	29724
7.	366.67	1.1253	1.1478e+005	29732
8.	400	1.1472	1.1401e+005	29736
9.	433.33	1.1571	1.1366e+005	29737
10.	466.67	1.1615	1.135e+005	29738
11.	500	1.1635	1.1343e+005	29738
12.	533.33	1.1644	1.134e+005	29738
13.	600	1.165	1.1338e+005	29739
14.	733.33	1.1652	1.1337e+005	29739
15.	1000	1.1652	1.1337e+005	29739

From table 11, it is inferred that the average heat loss is almost maintained steady after 266.67 seconds.

3) Heat loss calculation

Heat flow through piston

Piston heat flow area = $\pi/4 \times 0.073^2$

= $4.185 \times 10^{-3}\,m^2$

Total Heat flux = $29739\ W/m^2$

∴ Heat loss through piston downwards

Q_{LP} = $29739 \times 4.185 \times 10^{-3}$

= 124.45 W

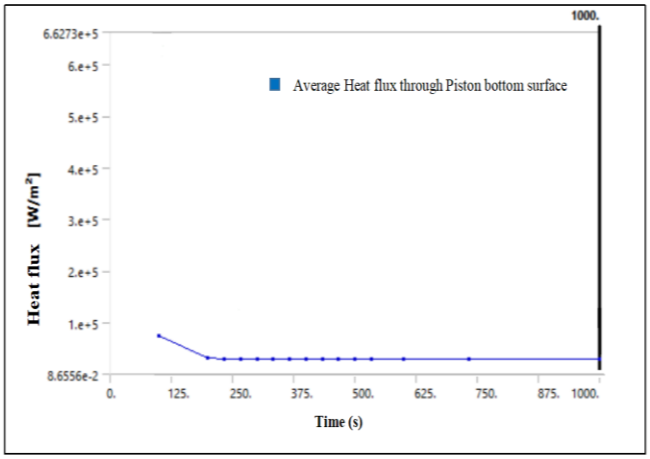

Fig 27. Graph plotted for Transient heat flow analysis of Hot piston of SS 304 grade Stainless steel at 500°C for 1000 seconds

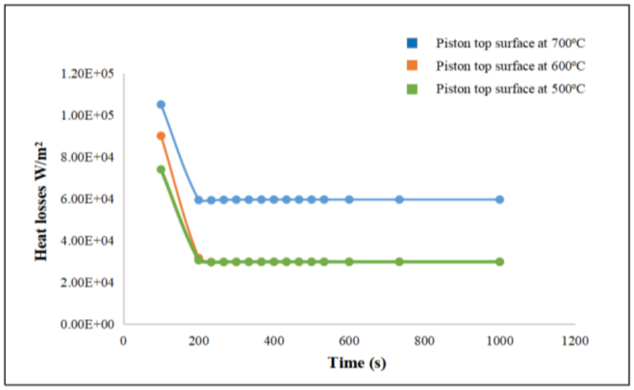

Fig 28. Graph plotted for heat losses reaching steady-state with piston top surface temperature for three conditions

(i) Heat losses in reaching steady-state with piston top surface temp on 700°C = 250 W.
(ii) Heat losses in reaching steady-state with piston top surface temp on 600°C = 124.445 W.
(iii) Heat losses in reaching steady-state with piston top surface temp on 500°C = 124.45 W.

VI. CONCLUSION

Through the analysis, it is explicit that the maximum temperature occurs at the top surface of the piston as it is exposed to the hot gases in the combustion chamber, while the bottom surface of the piston has the lowest temperature as it is exposed to the ambient air. Heat losses on reaching steady-state with piston top surface temperatures on 700°celcius, 600°celcius& 500°celciusare 250 W, 124.45 W & 124.45 W. These heat losses from the bottom surface of the hot piston are maintained at the above values by cooling the bottom surface with a cooling fan suitably.

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