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CFD on Parametric Analysis of Compression Ignition Engine by using Star CCM+

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Abstract

Stringent emission from the conventional vehicles draws attention of automobile researches to develop engine either high fuel efficiency and low emission of NOx, CO and unburnt hydrocarbons. Hence, there by Homogeneous charge compression ignition came to the effect. Homogeneous charge compression ignition engine is the type of engine the well organised mixture of air and fuel ratio enters into the combustion chamber, and it is compressed up to auto-ignited temperature and there by combustion takes place. HCCI combines the characteristics of both SI and CI engine. In the current study, we will discuss about the performance parameters of the HCCI engine like Pressure, Temperature, Turbulent kinetic viscosity and swirl inside the cylinder at three different speed 1000, 2000, 3000 rpms through CFD analysis. The modelling of each part like cylinder, piston, Intake manifold and exhaust manifold in CATIA v5 and Computational fluid dynamics analysis was performed on STAR CCM+ by using large eddy simulational (LES) model. As we discussed about the combustion parameters pressure, temperature, Turbulent kinetic viscosity, swirl and identified behaviour of those parameters at suction, compression, expansion and exhaust in four stroke single cylinder diesel engine at 1000rpm,2000rpm and 3000rpm.The graphs are drawn between parameters with respect to crank angle as pressure vs crank angle, temperature vs crank angle, turbulent kinetic viscosity vs crank angle, swirl vs crank angle. The maximum a pressure obtained at 2000 rpm which is 57 bar, Maximum temperature obtained at 3000 rpm which is 1399.3 k, maximum turbulent kinetic viscosity at the speed of 3000 rpm in the exhaust process is 8424.3 j/kg. The maximum swirl obtained at 3000 rpm.

Keywords: Homogeneous charge compression ignition engine, CFD, LES model, StarCCM+, pressure, Temperature, Turbulent kinetic viscosity, Swirl.

INTRODUCTION

Conventional engine like Spark ignition (SI) and compression ignition has their own benefits and drawbacks. In SI engine emits less pollutants to the atmosphere with the lower efficiency, Whereas the CI engine has higher efficiency but emits high toxic emission when compared to the SI engine. Homogeneous charge compression ignition engine combines the parameters of both the SI and CI engine that gives the high performance and reduces the emissions. During this process, the ratio of air fuel mixture is mixed spontaneously and compressed up to auto-ignition temperature. The fuel and air mixture process done prior to the combustion by the port fuel injection (PFI) that homogeneously mixes the air fuel and enters into the combustion chamber and some fuel is introduced through fuel injector at the end of the compression stroke so then entire process leads to give the better performance with lower emission. However, HCCI engine have some advantages and limitations. The advantages are like better fuel efficiency and lean mixture combustion possible by

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using the HCCI engine. There are certain limitations like achieving the cold start capability, control the ignition timing over wide range of speeds, not appreciated to have the large loads, increases the HC emissions [1-5].

CFD ANALYSIS

The design and manufacture of internal combustion engine are under significant pressure for improvement. The generation of engine require being light, reliable, robust, flexible and powerful. Innovative engine design will be required for satisfying the requirements. The ability to accurately the performance of multiple engine design is too much critical and crucial, because IC engine consists of complex fluid dynamics interactions between airflow, fuel injection, moving parts and combustion. Using CFD results, the flow phenomenon can be visualized on a 3D geometry and analysed numerically, providing insight into the complex interactions that occur inside the engine. CFD simulations is used as the part of the design process in automative engineering, especially with the rise of modern technology. In this current study, we are going to discuss the combustion parameters of HCCI engine inside the cylinder like cylindrical pressure, Temperature, Turbulent kinematic viscosity and swirl at three different speeds 1000 rpm, 2000 rpm and 3000 rpm [6-9].

The modelling and assembly of the engine parts, intake manifold, exhaust manifold, cylindrical head and piston done by using CATIA V5. The analysis part performed on the STAR CCM+ tool. STAR-CCM+ is Computational fluid dynamics-based software developed by the Siemens digital industries.

LARGE EDDY SIMULATION (LES) MODEL

LES stands for the large eddy simulation. LES is closely related to the DNS (direct numerical simulation) model. But suppose somebody wants to perform a DNS but the grid that would be required exceeds the capacity of the available computer so a coarser grid is used . The coarser grid is used to resolve the larger eddies in the flow bit not the ones smaller than one or two cells. LES model does not adopt conventional time or ensemble-averaging RANS approach with additional modelled transport equation being solved to obtain the so-called Reynolds stresses resulting from the average process. In LES the large-scale motions of turbulent flow are computed directly, and only small-scale motion are modelled, resulting in a significant reduction in computational cost compared to DNS. LES is more accurate than RANS approach since the large eddies contain most of the turbulent energy and are responsible for the most of the momentum transfer and turbulent mixing ,and LES captures these eddies in a full detailed directly whereas modelled in the RANS approach. Furthermore, the small scales tend to be more isotropic and homogeneous than the large ones, and thus modelling the SGS motions should be easier than modelling all scales within a single model as in the RANS approach. Therefore, currently LES is the most viable numerical tool for simulating realistic turbulent flows. This method requires greatest computational resources than RANS method and K-epsilon method, but it is far cheaper than DNS approach [10-13].

MATERIALS AND METHODOLOGY

The materials used in process is Four-stroke compression ignition engine (HCCI-mode) and methods performed are the Modelling is done by CATIA V5 and CFD analysis is on STAR CCM+ tool using LES model.

Design Specification

The Design part is done by using the CATIA V5 and modelled parts Cylinder Head, Cylinder, Piston, Intake manifold, Exhaust manifold in required dimensions as shown in Figure 1 (a-d).

Assembly

After the completion of all the parts we assembled all the parts using CATIA V5 as shown in Figure 2.

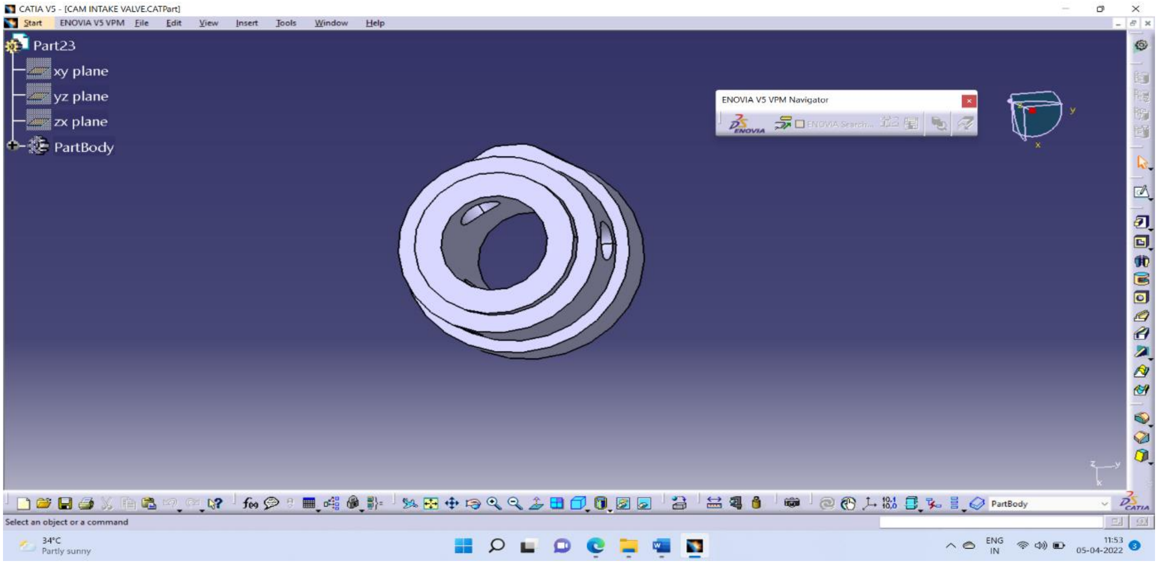

Figure 1. (a) Cam intake valve.

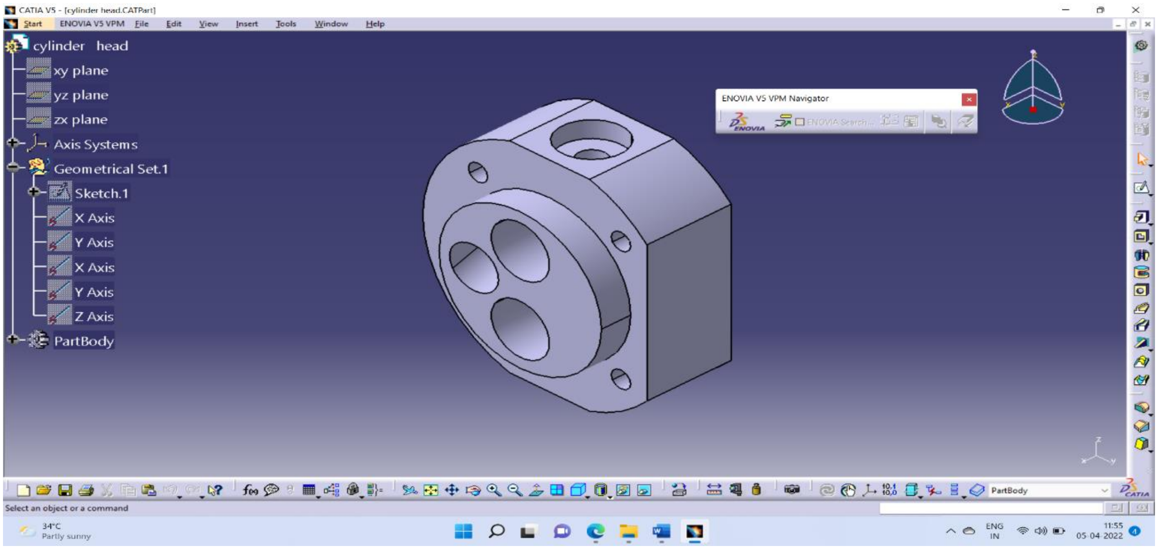

Figure 1. (b) Cylindrical Head.

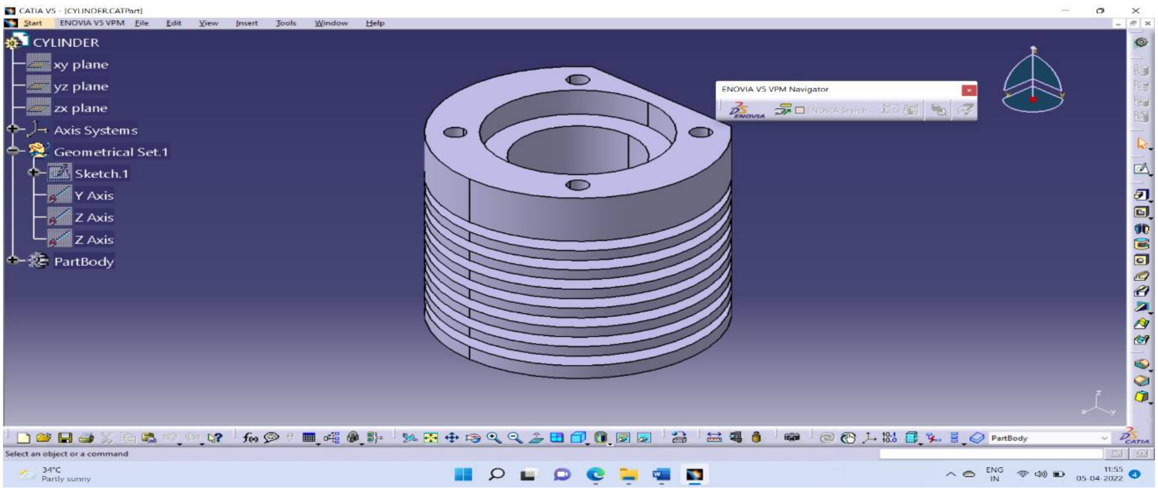

Figure 1. (c) cylinder.

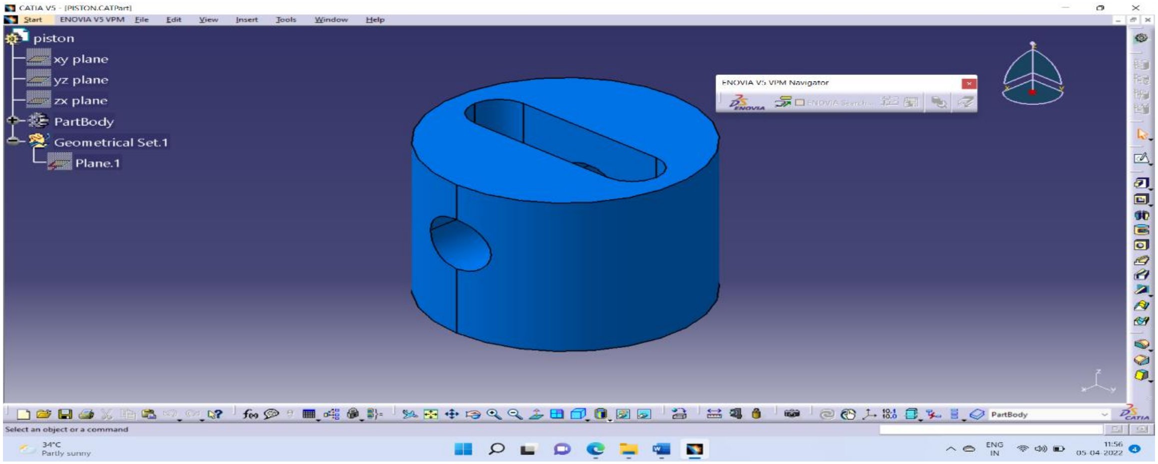

Figure 1. (d) piston.

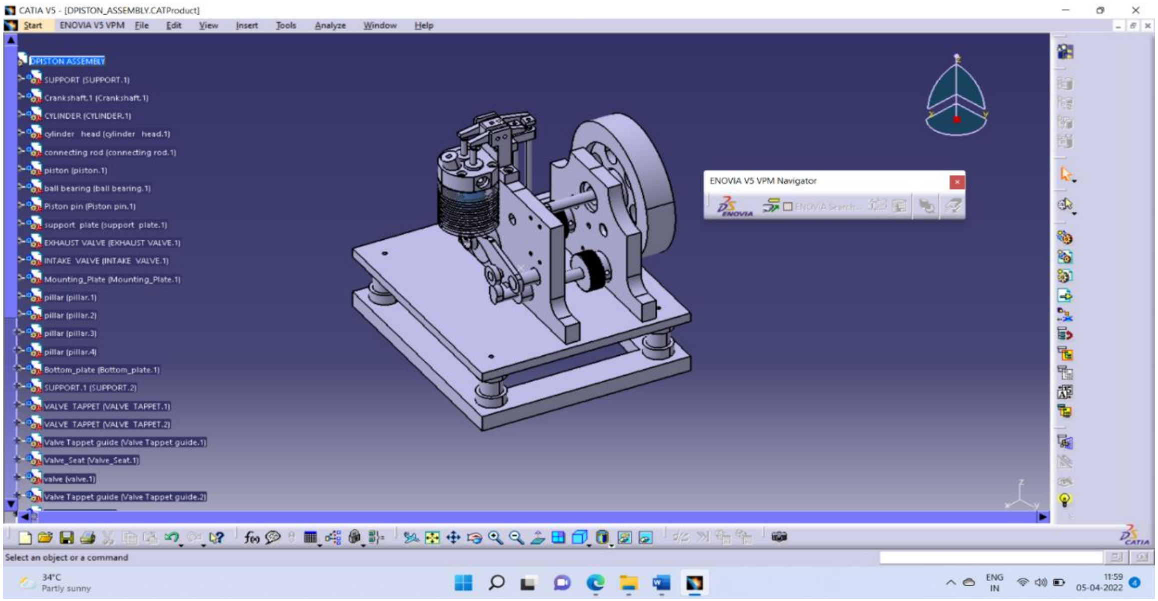

Figure 2. Engine assembly.

Meshing

The meshing of the model done after the assembly of parts. Meshing type is a course mesh.

(a) Mesh is generated on inside and outside of the engine at different stages

The specification engine in the process of combustion the several things are taken into the considerations during the rotation of the crankshaft angles are taken into consideration. Figure 3 (a-e) shows the mesh is generated on inside and outside of the engine at different stages.

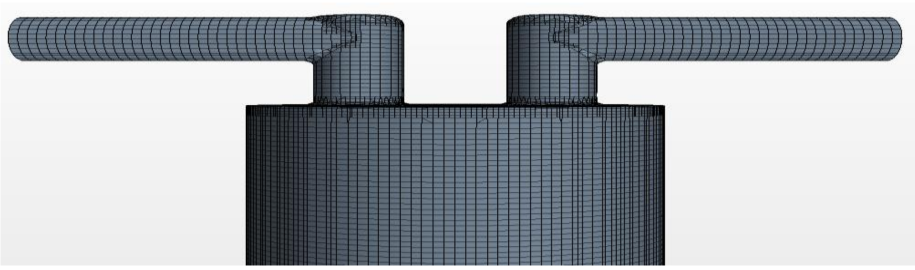

Figure 3. (a) Mesh is generated on the engine outside.

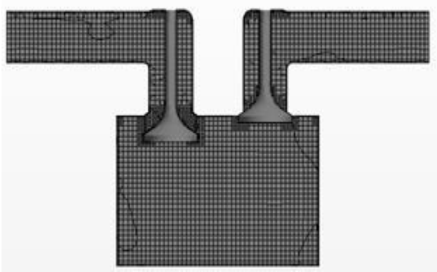

Figure 3. (b) Mesh is generated during suction process when the inlet valve opens.

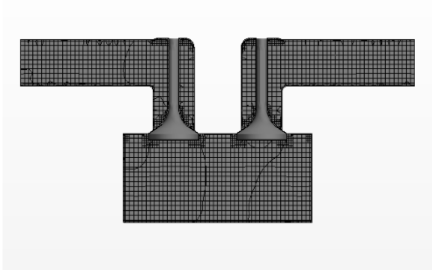

Figure 3. (c) Mesh is generated during compression process when both the valves are closed.

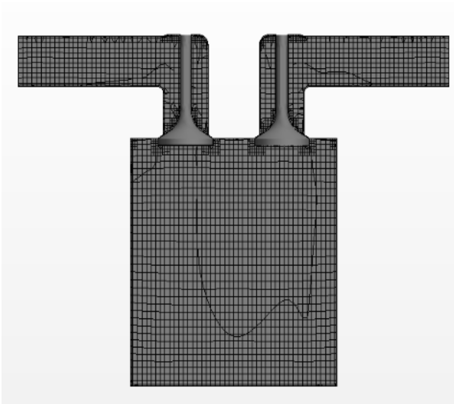

Figure 3. (d) Mesh is generated during expansion process when both the valves are closed.

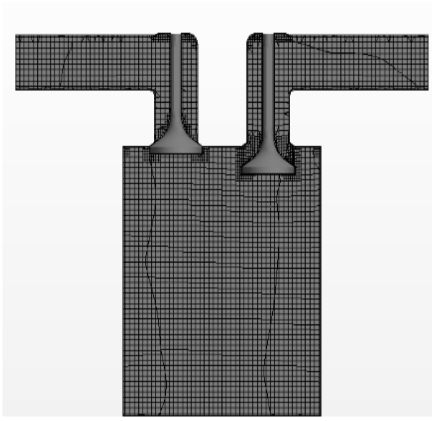

Figure 3. (e) Mesh is generated during exhaust process when the exhaust valve opens.

Valve Timings Aand Valuve Lift Curves

The valve timing & valve lift curves shows in the Table 1.

Table 1. Valve Timing and Valve Lift curves.

Inlet valve open	After TDC 6.5 deg. in suction
Inlet valve close	AfterB.D.C110 deg. in compression
Exhaust valve open	BeforeB.D.C285 deg. in expansion
Exhaust valve close	BeforeT.D.C348 degrees exhaust process
Compression start	AfterB.D.C 89
Compression end	BeforeT.D.C 185
Power stroke start	AfterT.D.C 190
Power stroke end	AfterB.D.C 285
Fuel injector opens	Before T.D.C 185.5
Fuel injector close	After T.D.C 205.5
Port Injection opens	Before T.D.C 185.5
Port Injection closes	After T.D.C 205.5

RESULTS AND DISCUSSIONS

Simulations are carried on the HCCI mode at three different speeds 1000 rpm, 2000 rpm, 3000 rpm. Identified the parameters Average static pressure, temperature, Turbulent Kinetic viscosity, swirl numbers and plotted graphs with respect to the crank angle and speeds. The fuel used for the entire process is ISO-BUTANE.

Computated pressure counters of four stroke diesel engine with HCCI mode

The Pressure counters are analysed at each and every stage of the engine process and identified the maximum and minimum pressure at different speeds.

(a) Pressure contours of four processes (suction, compression, combustion, expansion & exhaust) for four stroke diesel engine with HCCI mode at 1000rpm

Figure 4 (a-d) shows the pressure contours of four process (suction, compression, combustion, expansion & exhaust).

(b) Pressure contours of four processes (suction, compression, expansion & exhaust) for four stroke diesel engine with HCCI mode at 2000rpm

Figure 5 (a-d) shows the Pressure contours of four processes (suction, compression, expansion & exhaust).

(c) Pressure contours of four processes (suction, compression, expansion & exhaust) for four stroke diesel engine with HCCI mode at 3000rpm

Figure 6 (a-d) shows the Pressure contours of four processes (suction, compression, expansion & exhaust) for four stroke diesel engine with HCCI mode at 3000rpm.

Computated Temperature fields of four stroke diesel engine with HCCI mode

The distribution of the temperature inside the cylinder was identified at different stages observed the maximum and minimum temperature at different speeds.

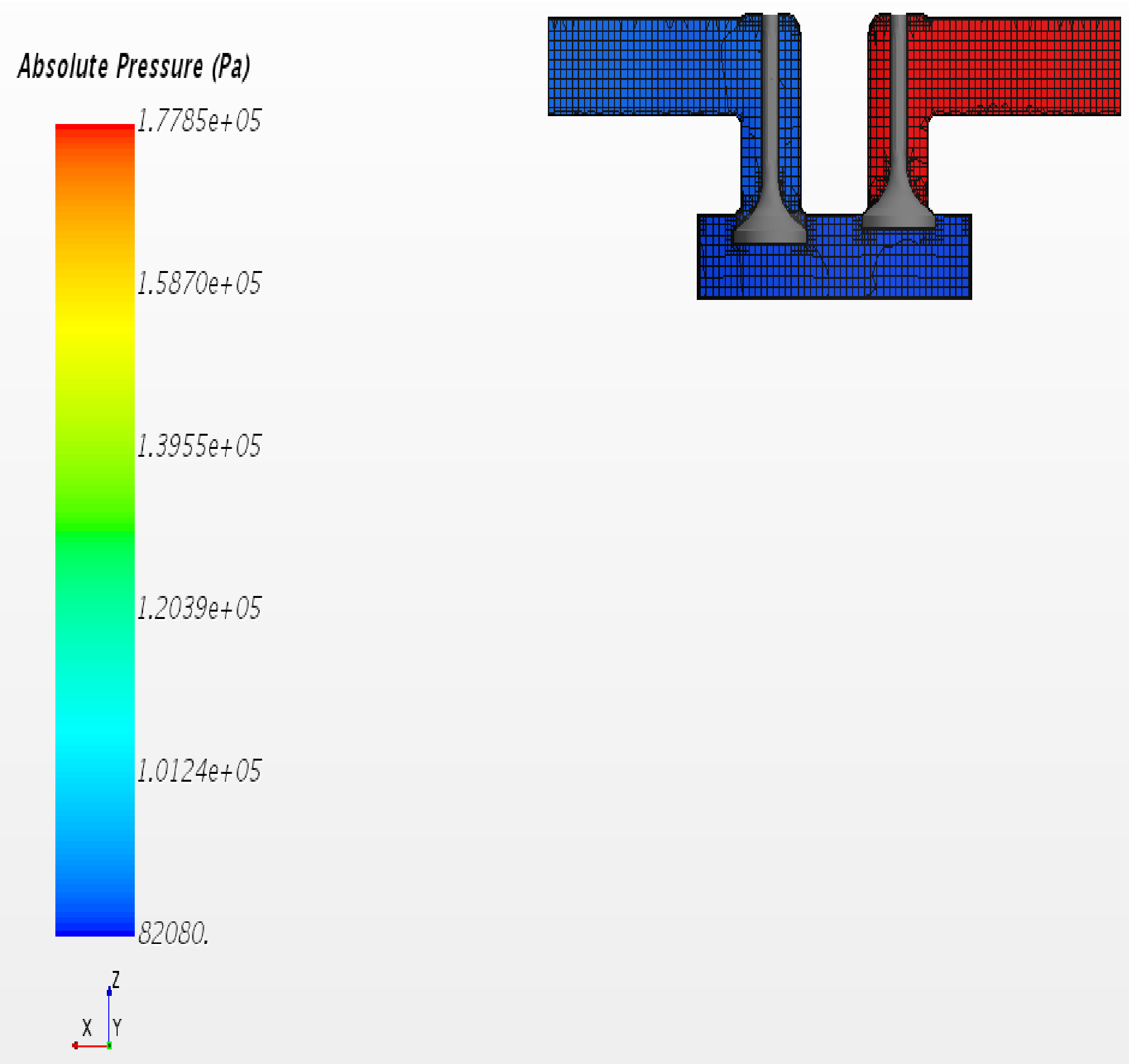

Figure 4. (a) Suction process.

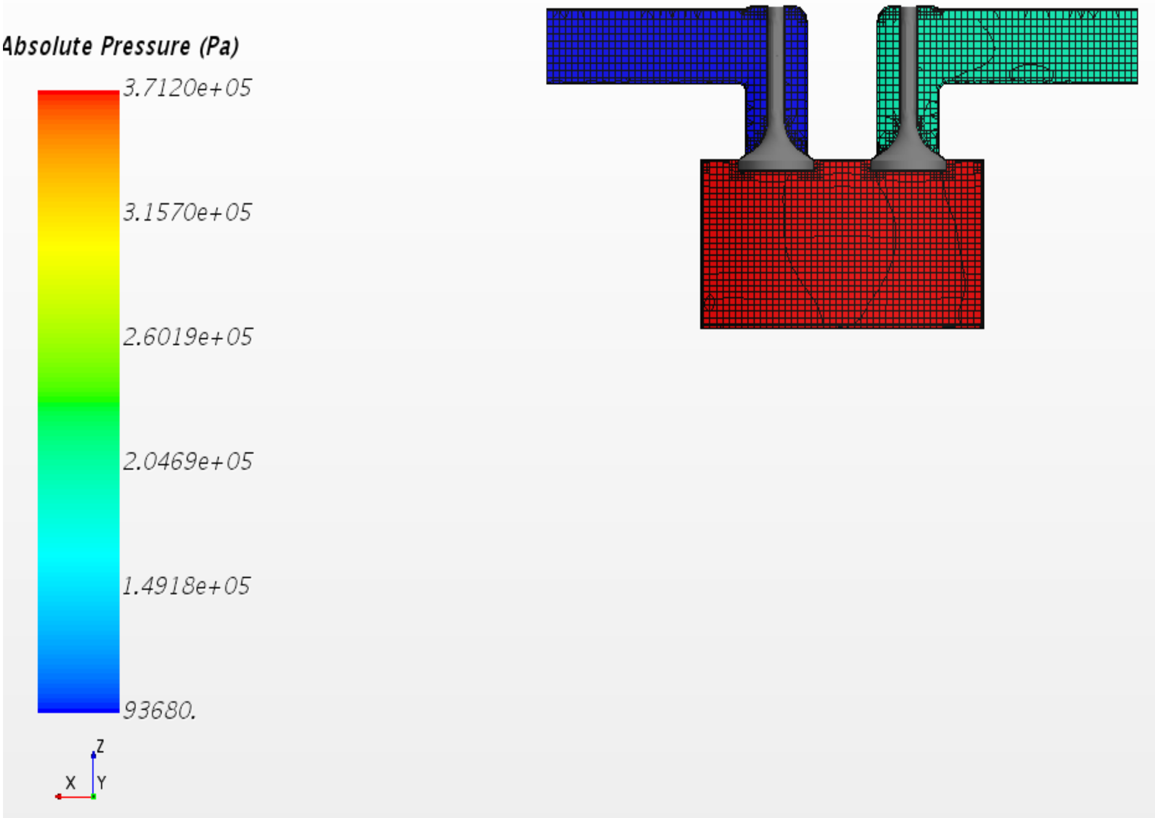

Figure 4. (b) Compression process.

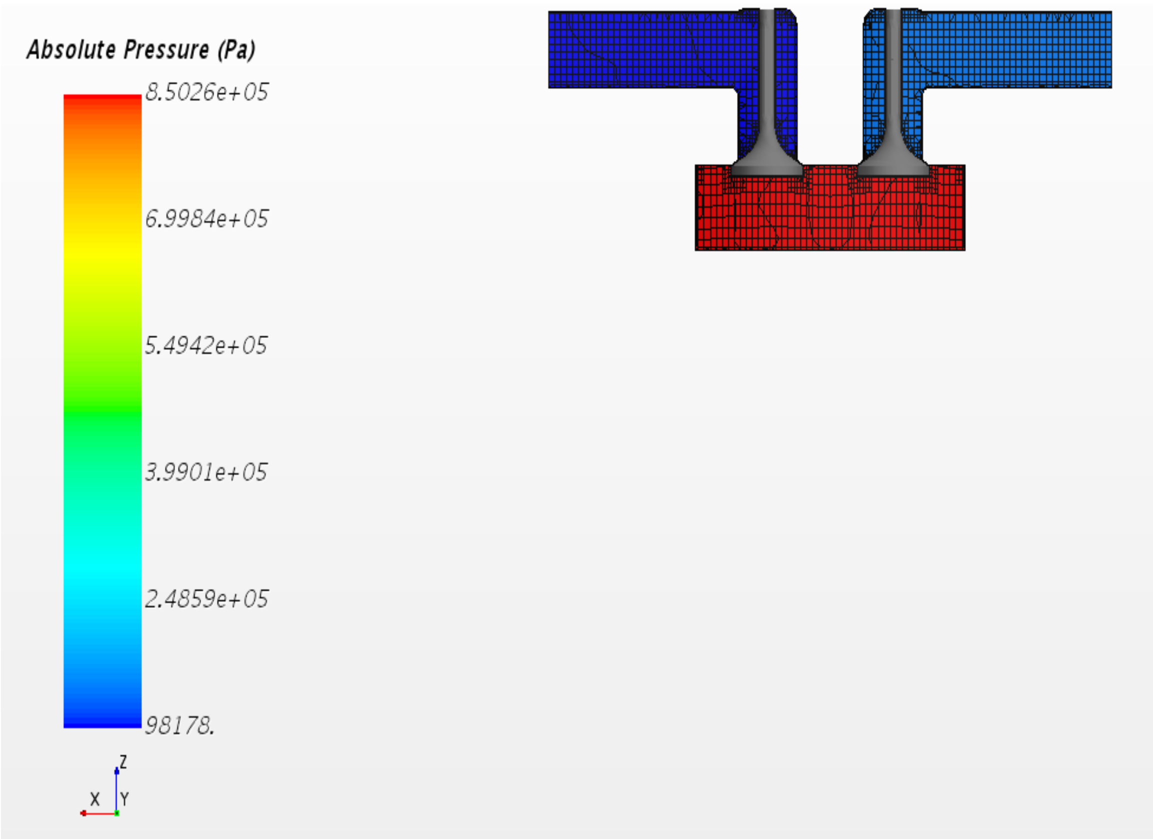

Figure 4. (c) Expansion process.

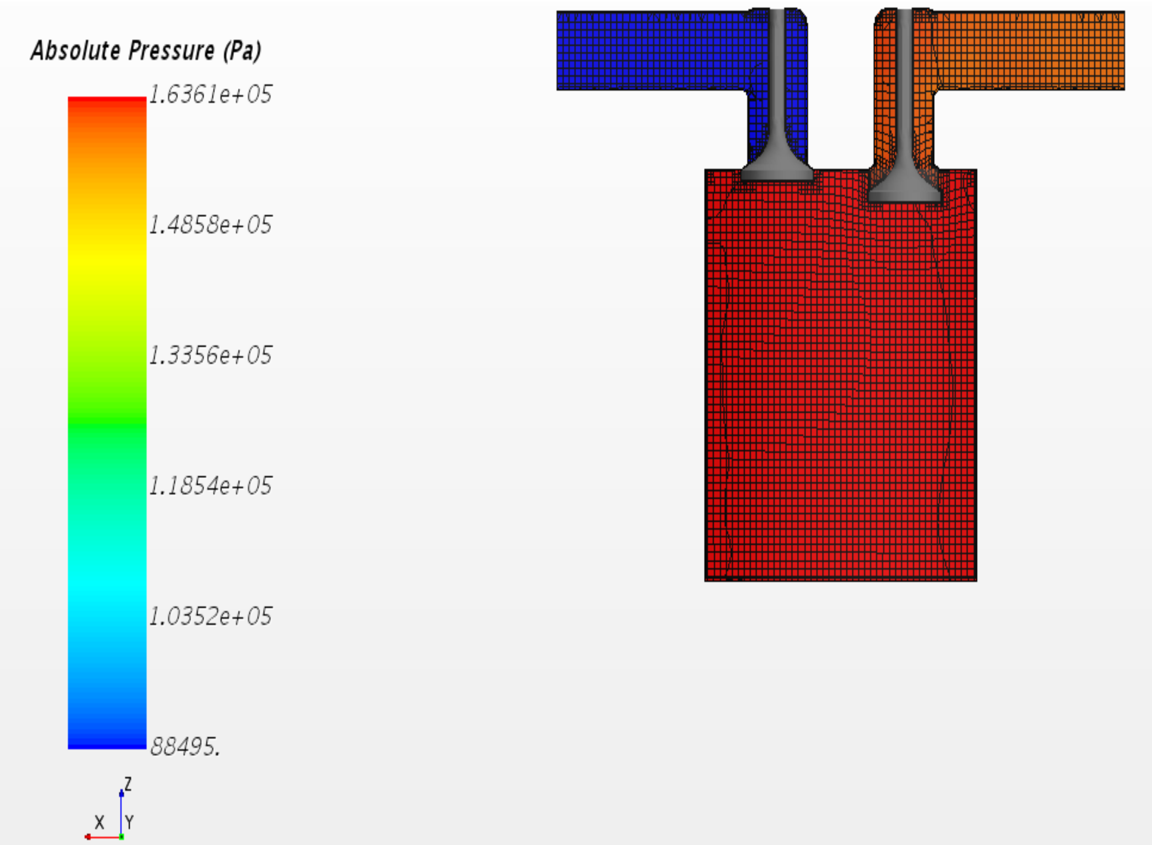

Figure 4. (d) Exhaust process.

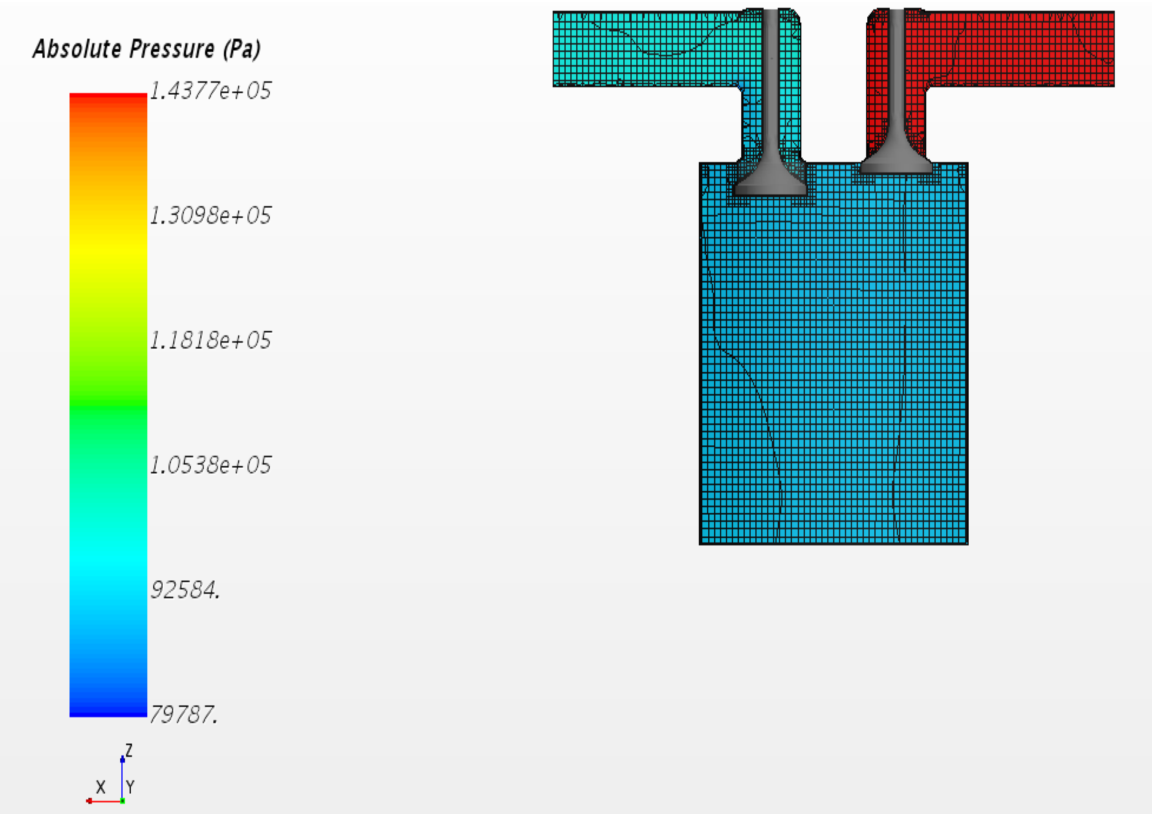

Figure 5. (a) Suction process.

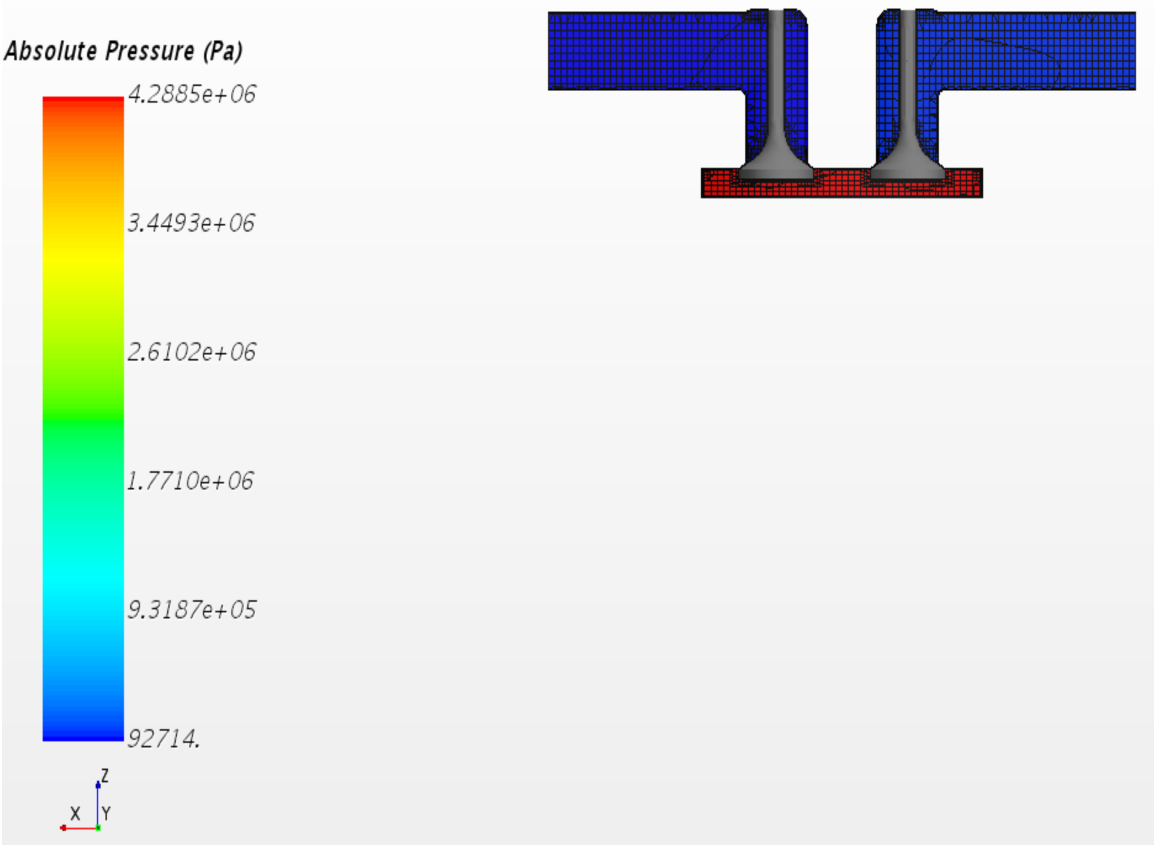

Figure 5. (b) End of compression.

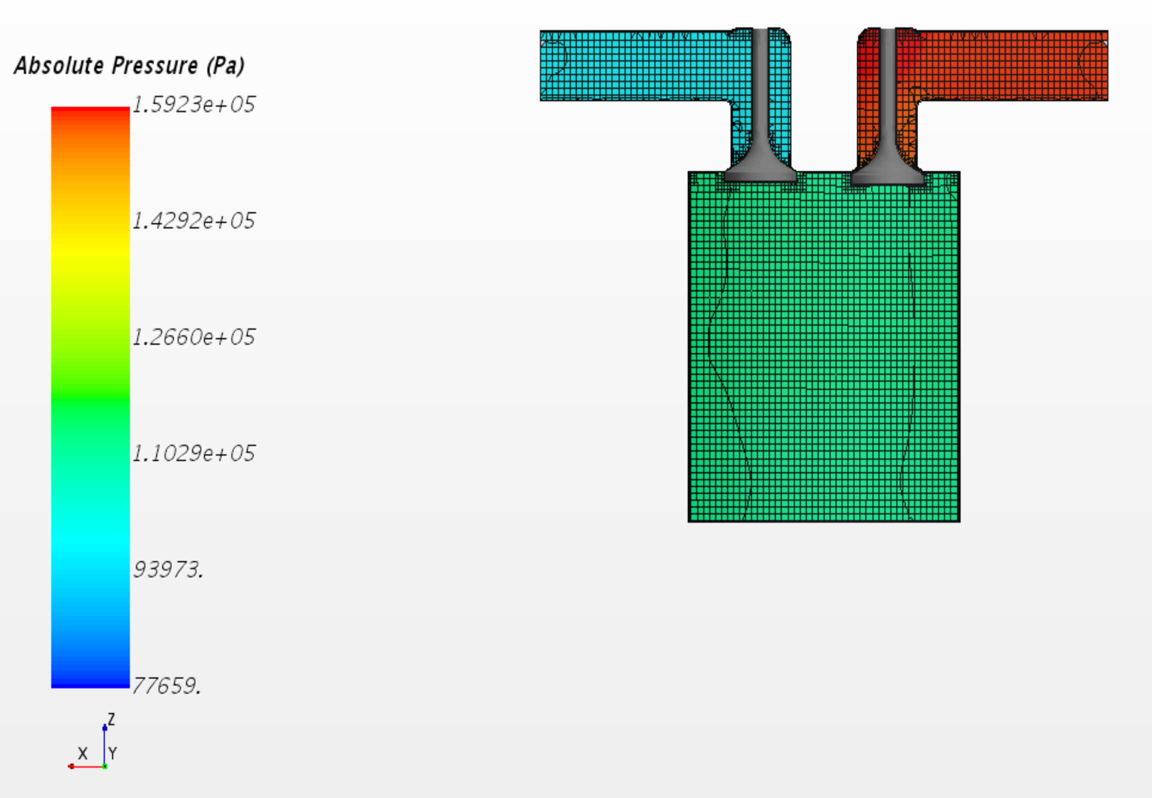

Figure 5. (c) Expansion process.

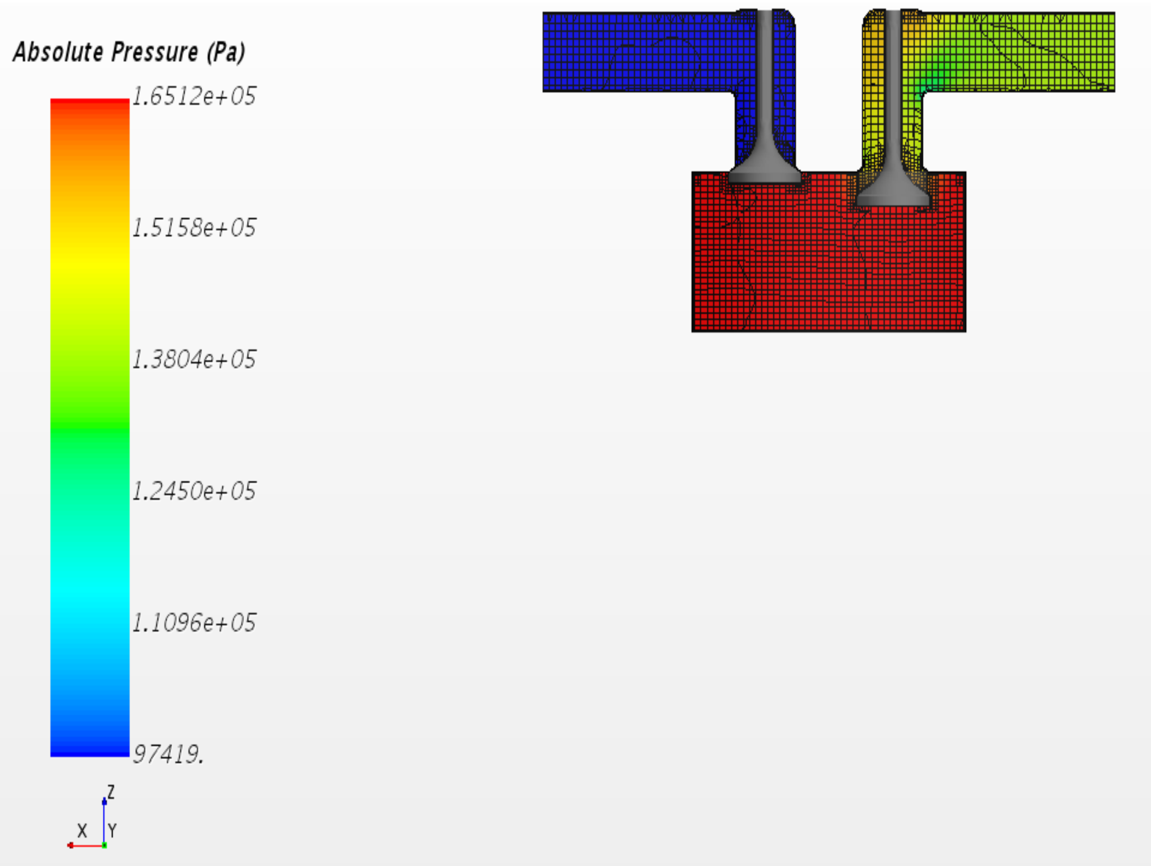

Figure 5. (d) Exhaust process.

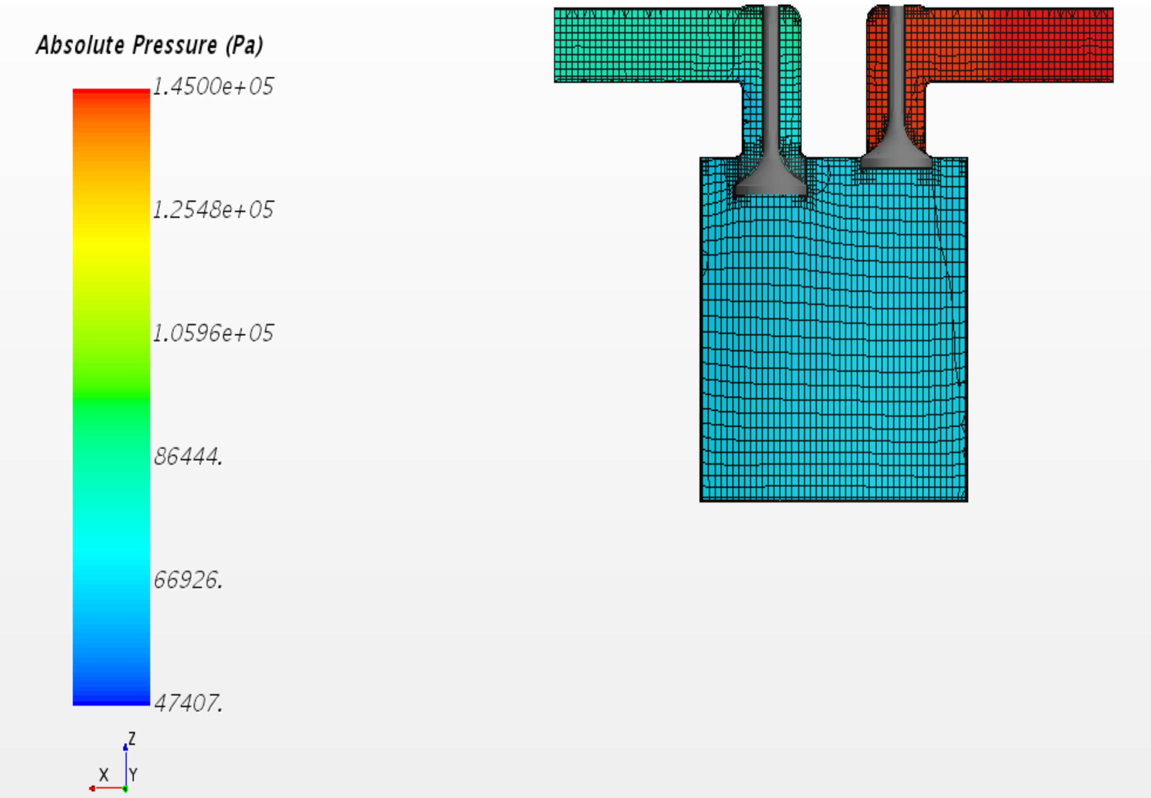

Figure 6. (a) Suction process.

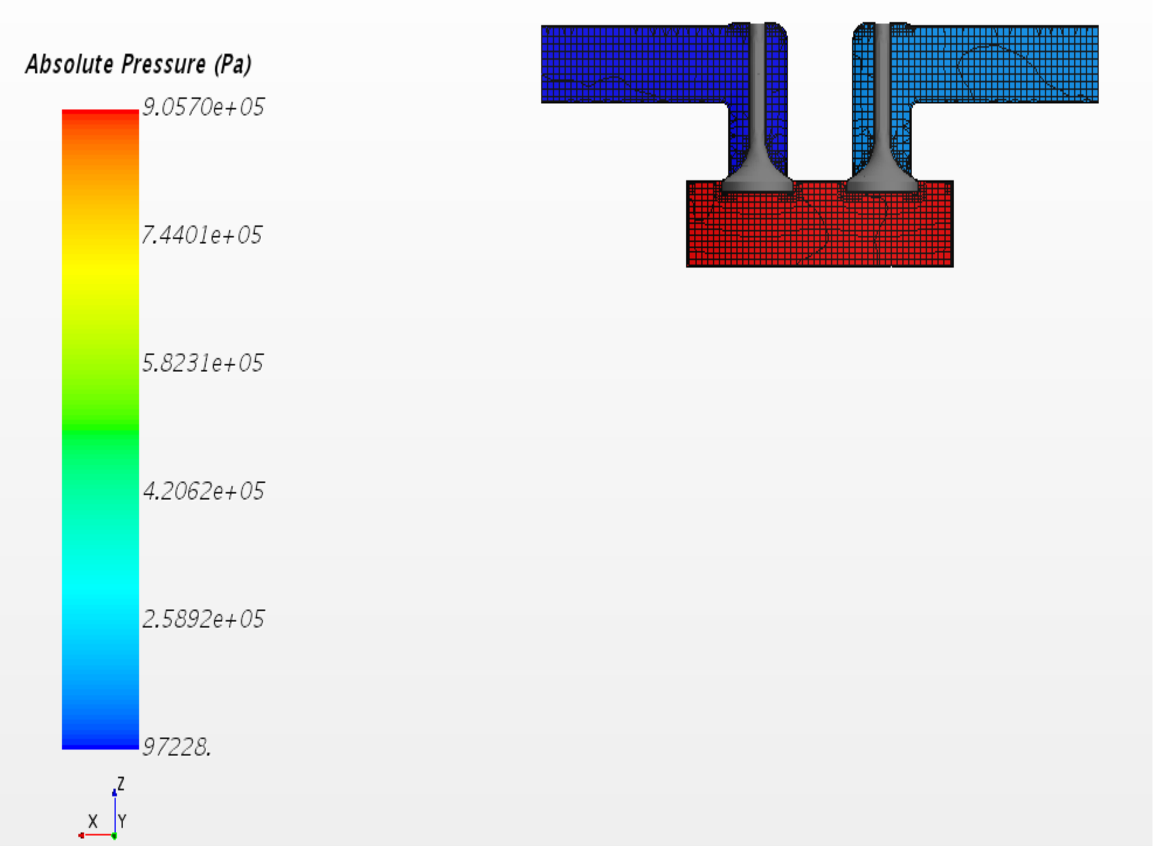

Figure 6. (b) Compression Process.

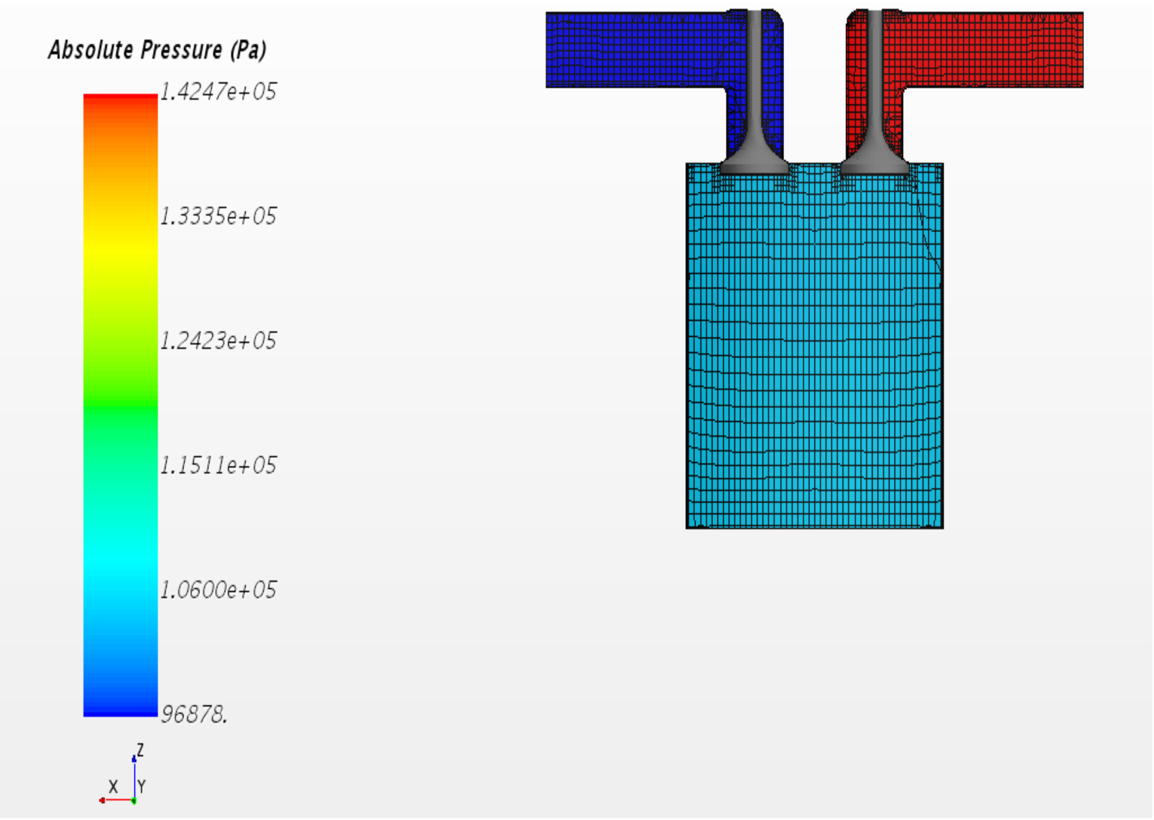

Figure 6. (c) Expansion Process.

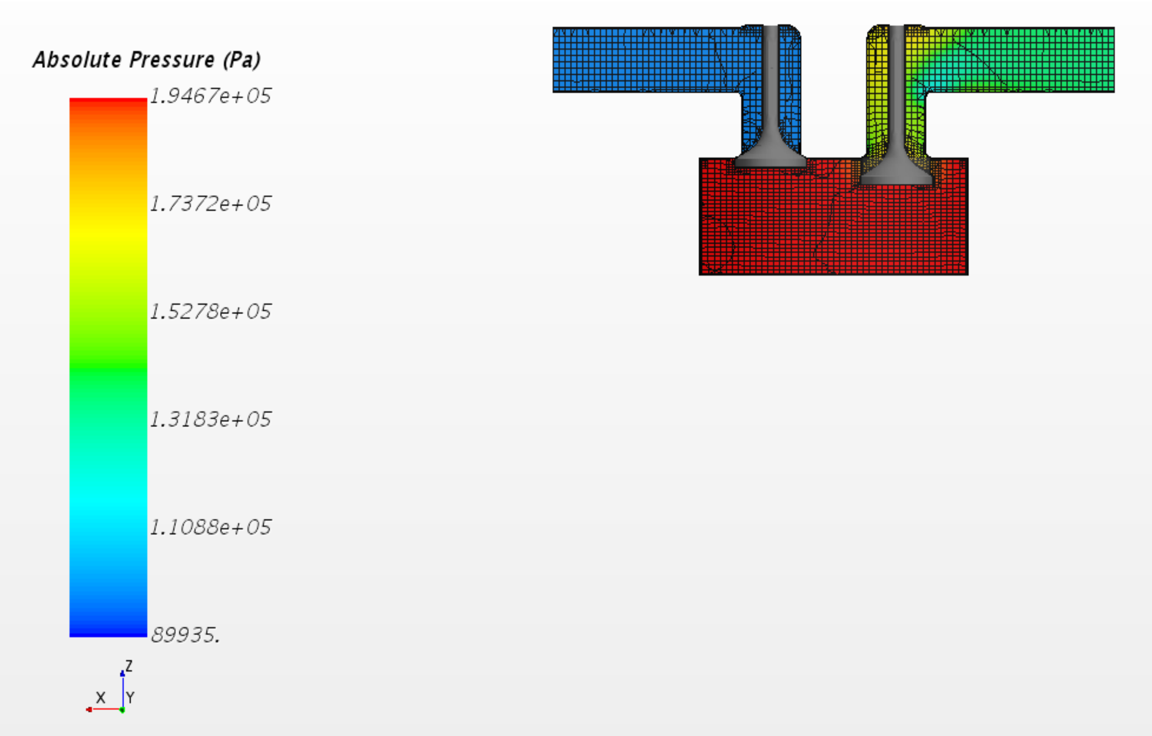

Figure 6. (d) Exhaust process.

(a) Computed temperature fields four processes (suction, compression, combustion, expansion & exhaust) for four stroke diesel engine with HCCI mode at 1000 rpm

Figure 7 (a-e) shows the Computed temperature fields four processes (suction, compression, combustion, expansion & exhaust) for four stroke diesel engine.

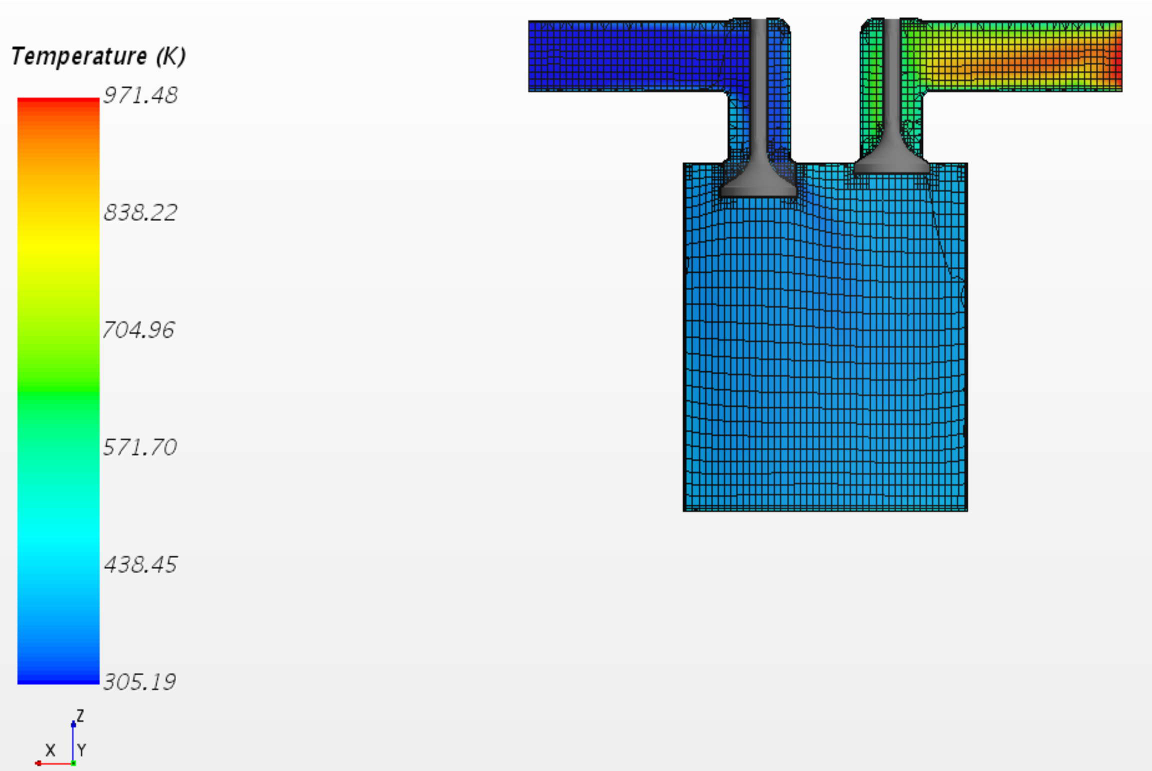

Figure 7. (a) End of the suction.

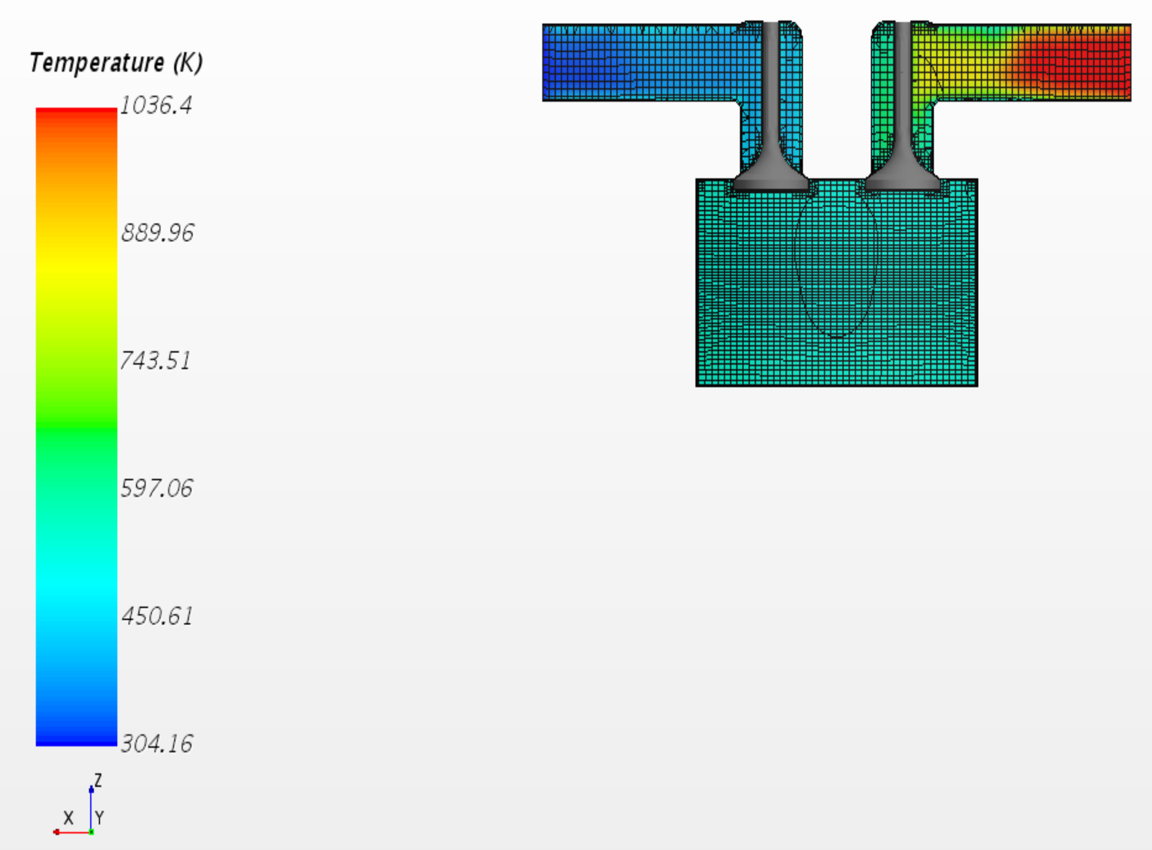

Figure 7. (b) compression.

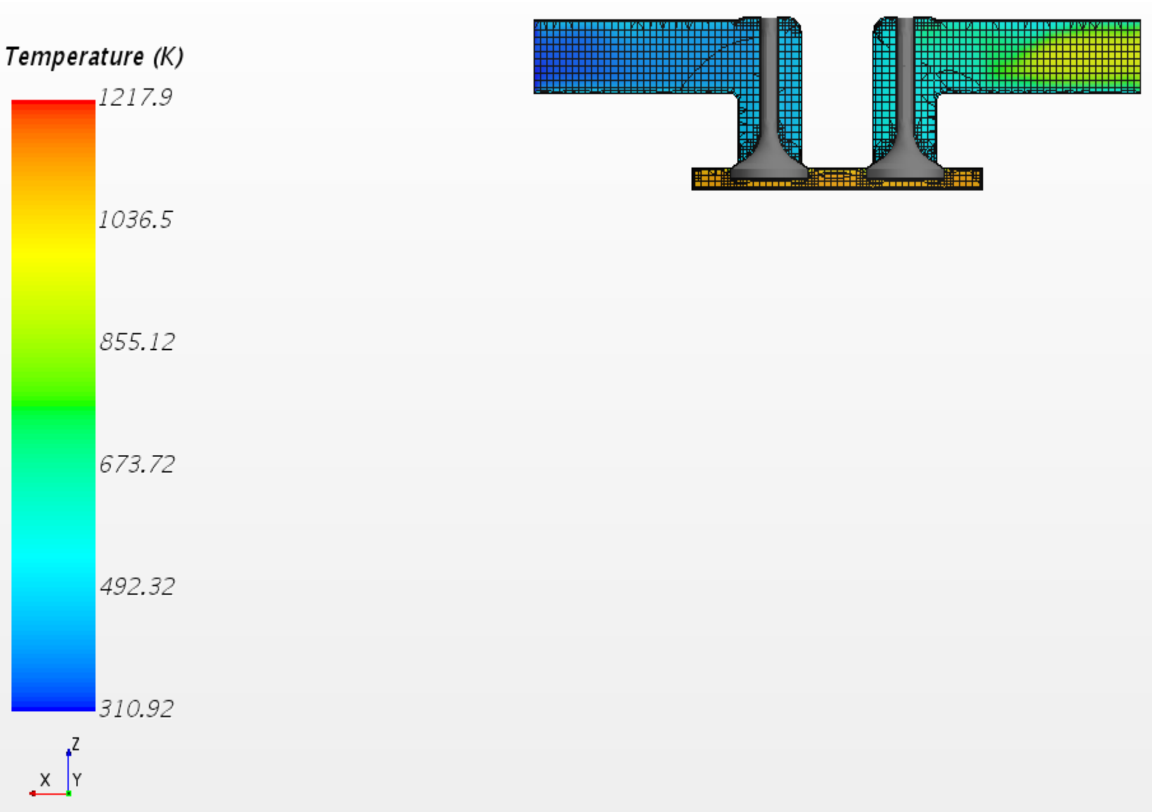

Figure 7. (c) Combustion.

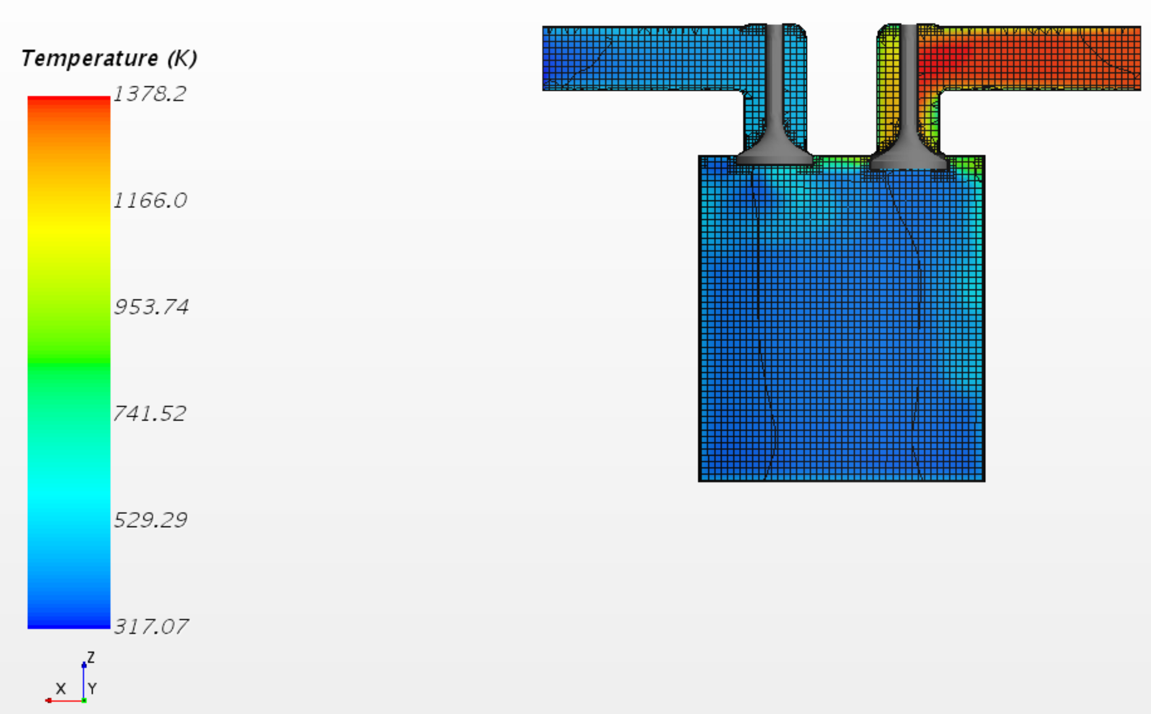

Figure 7. (d) During expansion.

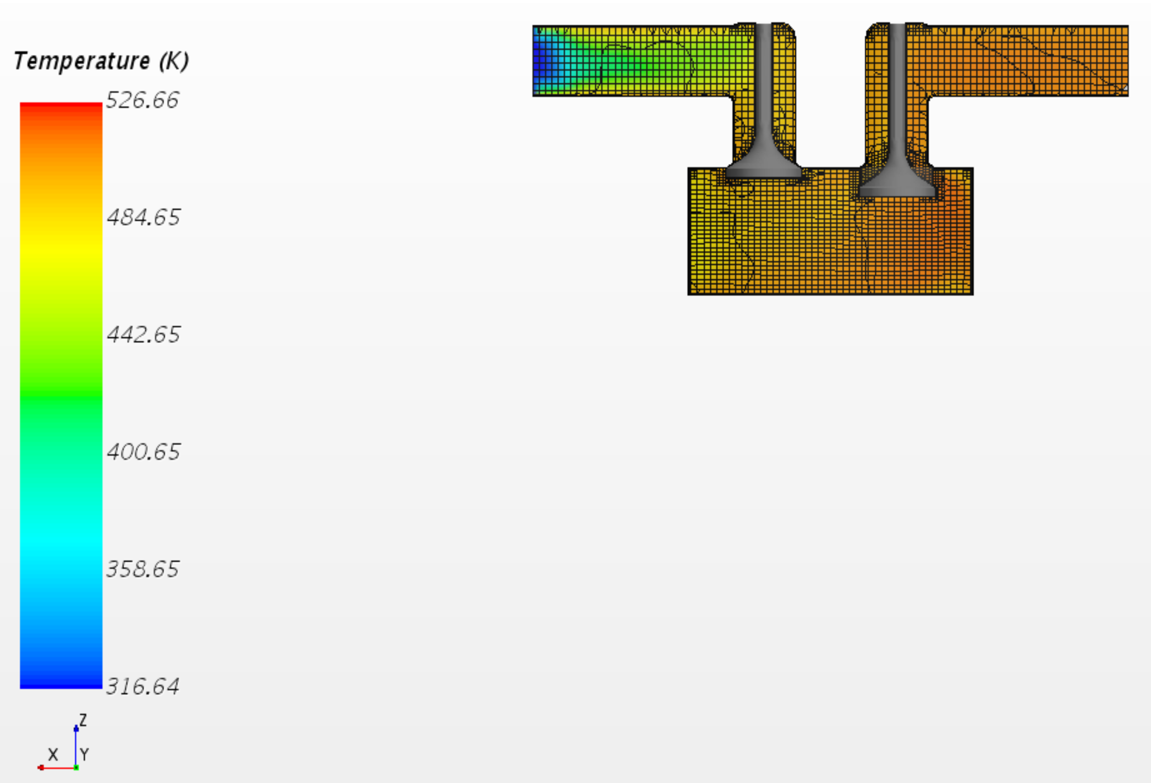

Figure 7. (e) Exhaust.

(b) Computed temperature contours of four processes (suction, compression, combustion, expansion & exhaust) for four stroke diesel engine with HCCI mode at 2000 rpm

Figure 8 (a-e) shows the Computed temperature contours of four processes (suction, compression, combustion, expansion & exhaust) for four stroke diesel engine.

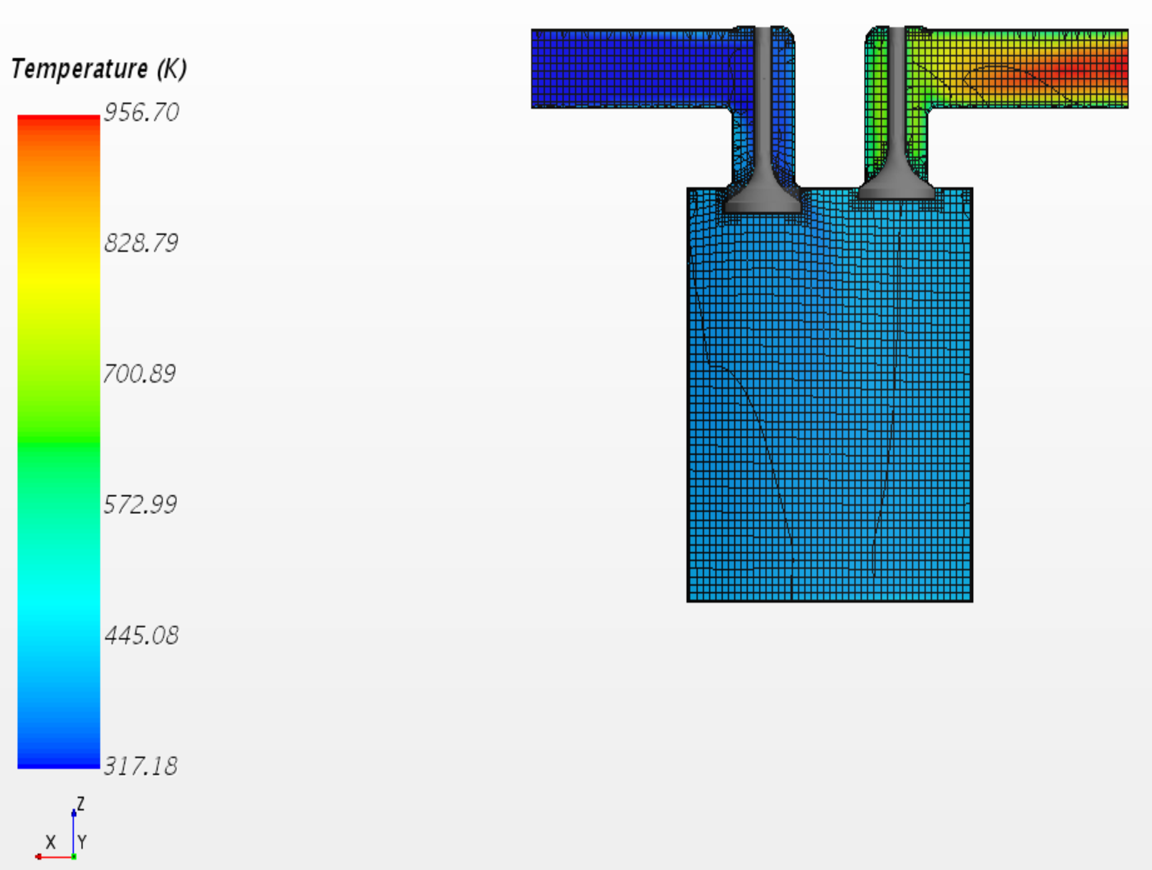

Figure 8. (a) During suction.

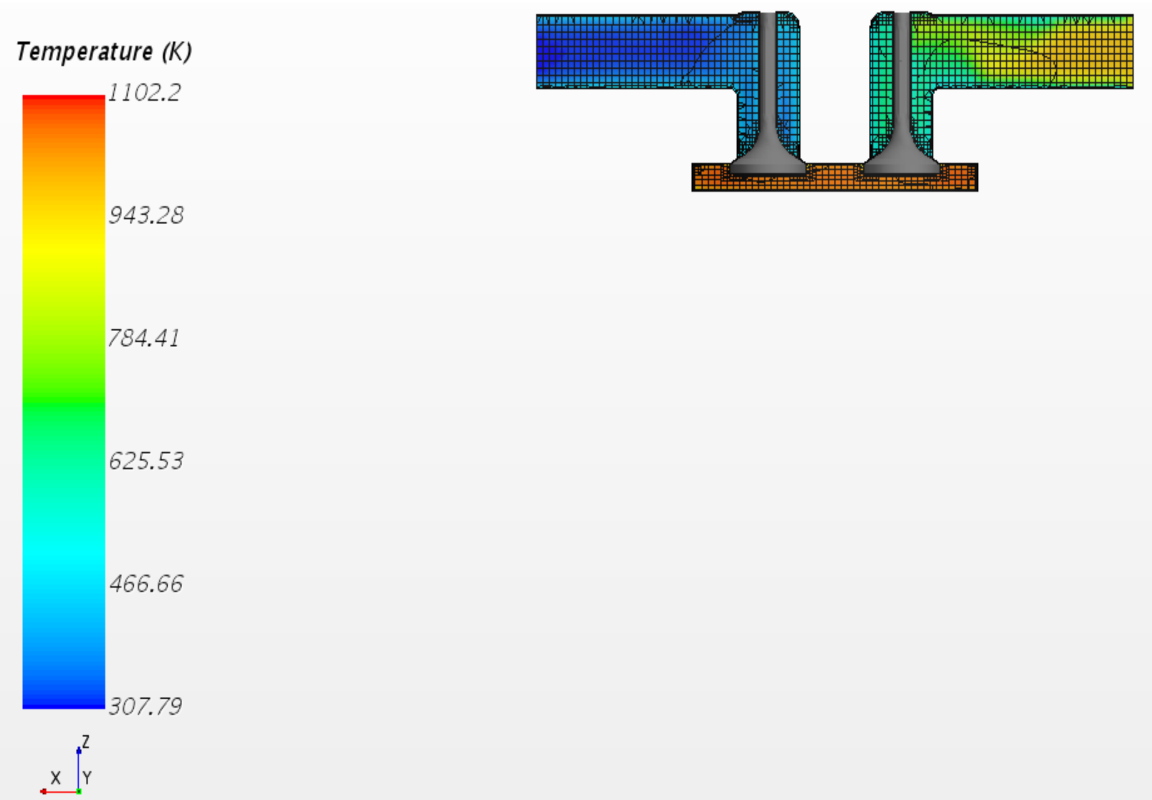

Figure 8. (b) End of compression.

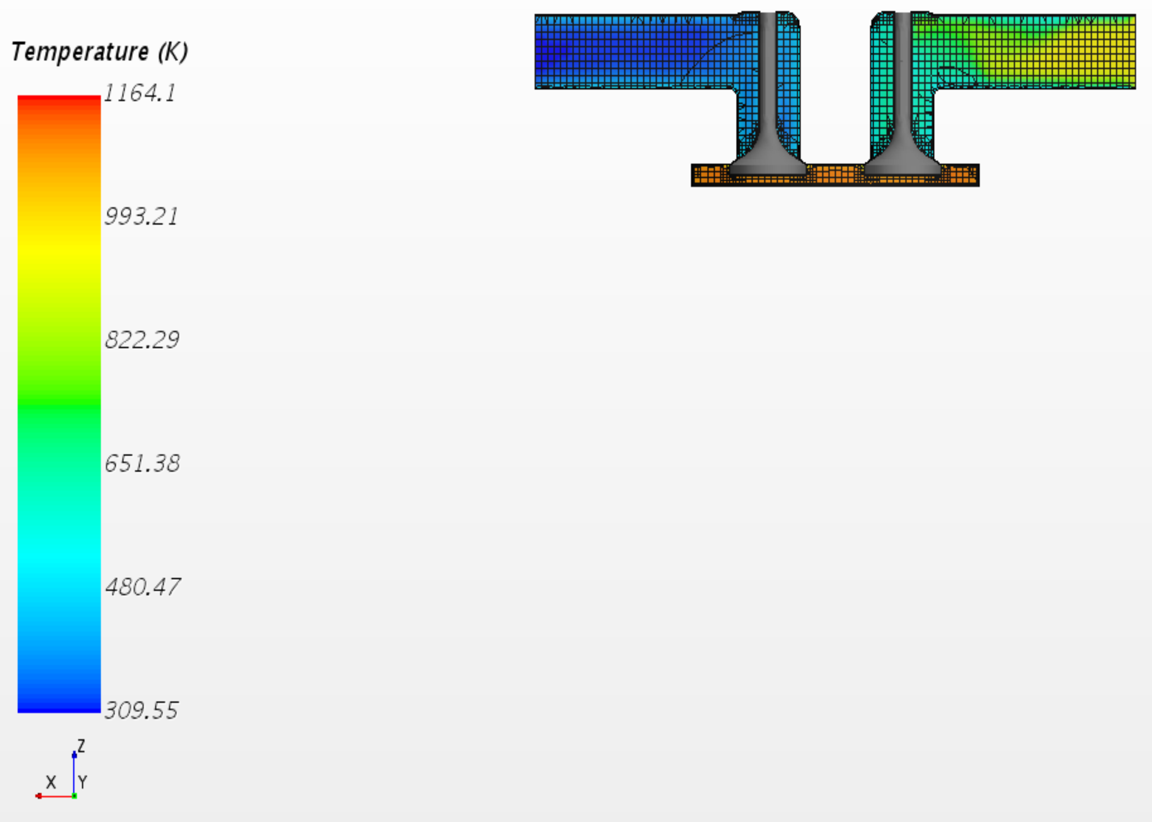

Figure 8. (c) Combustion.

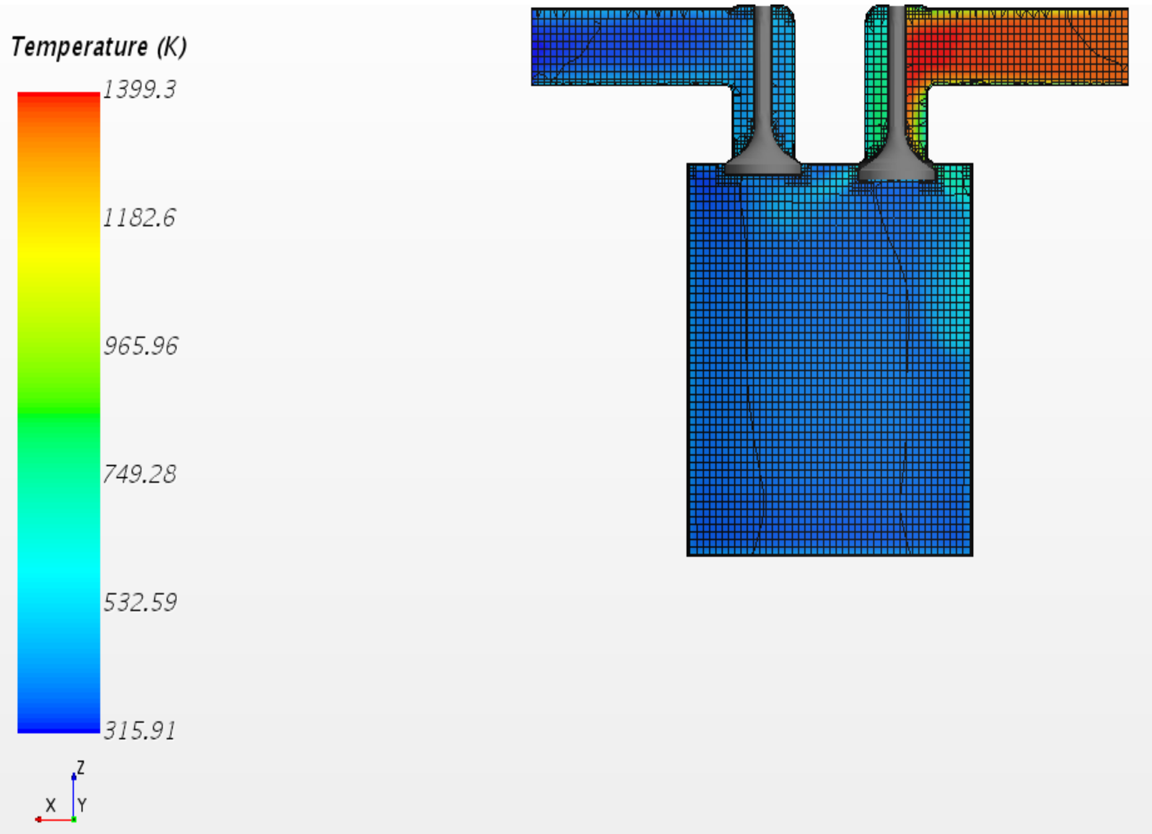

Figure 8. (d) Expansion.

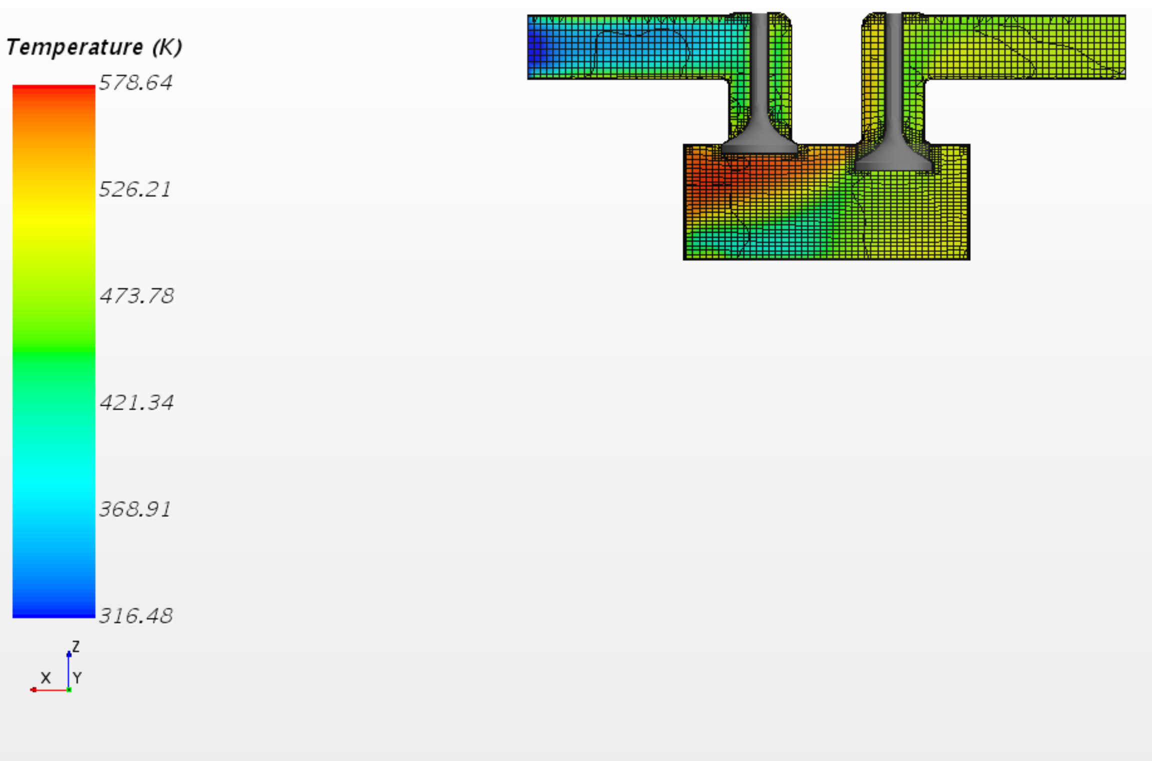

Figure 8. (e) Exhaust.

(c) Computed temperature contours of four processes (suction, compression, combustion, expansion & exhaust) for four stroke diesel engine with HCCI mode at 3000 rpm

Figure 9 (a-e) shows the Computed temperature contours of four processes (suction, compression, combustion, expansion & exhaust) for four stroke diesel engine.

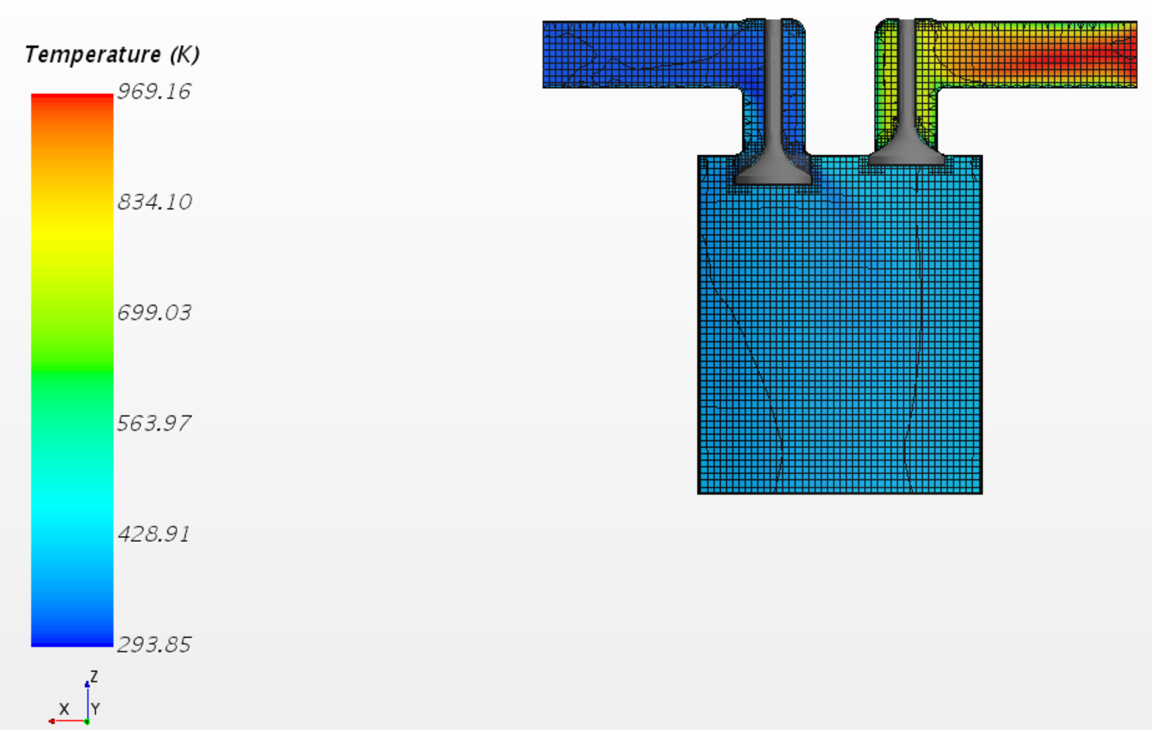

Figure 9. (a) Suction.

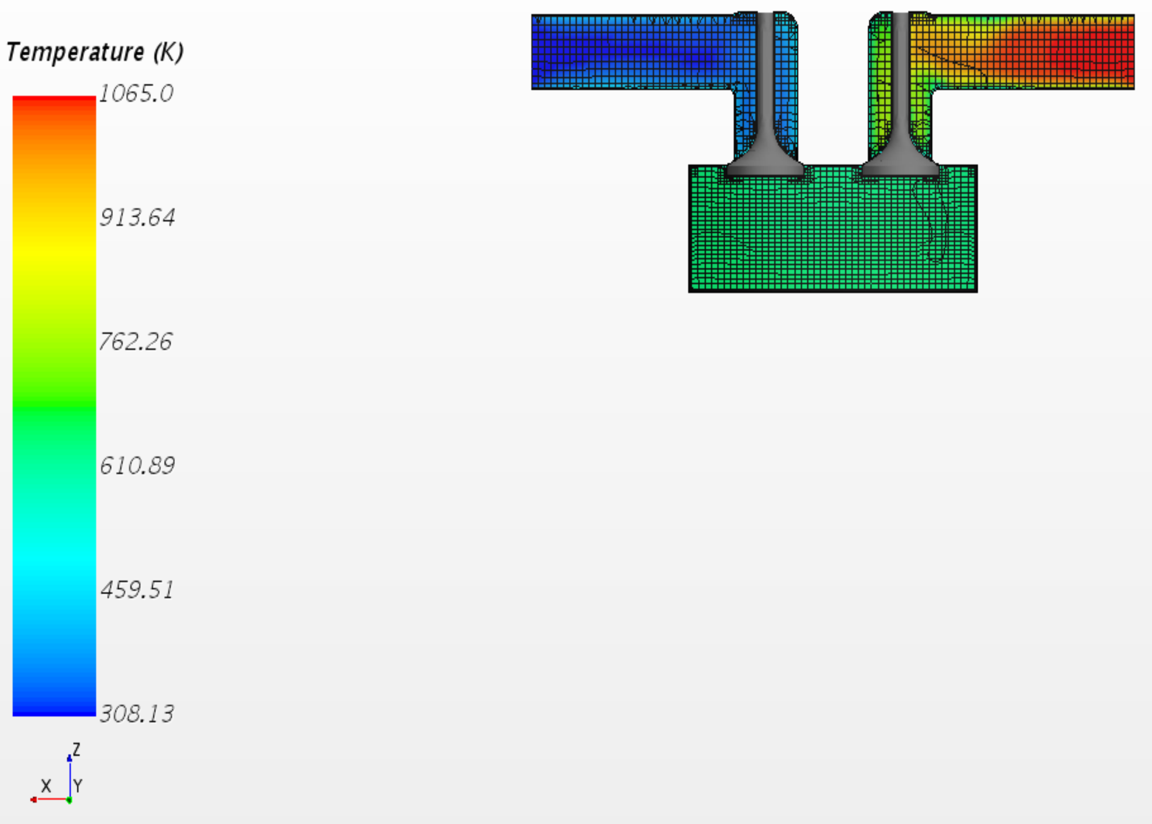

Figure 9. (b) End of compression.

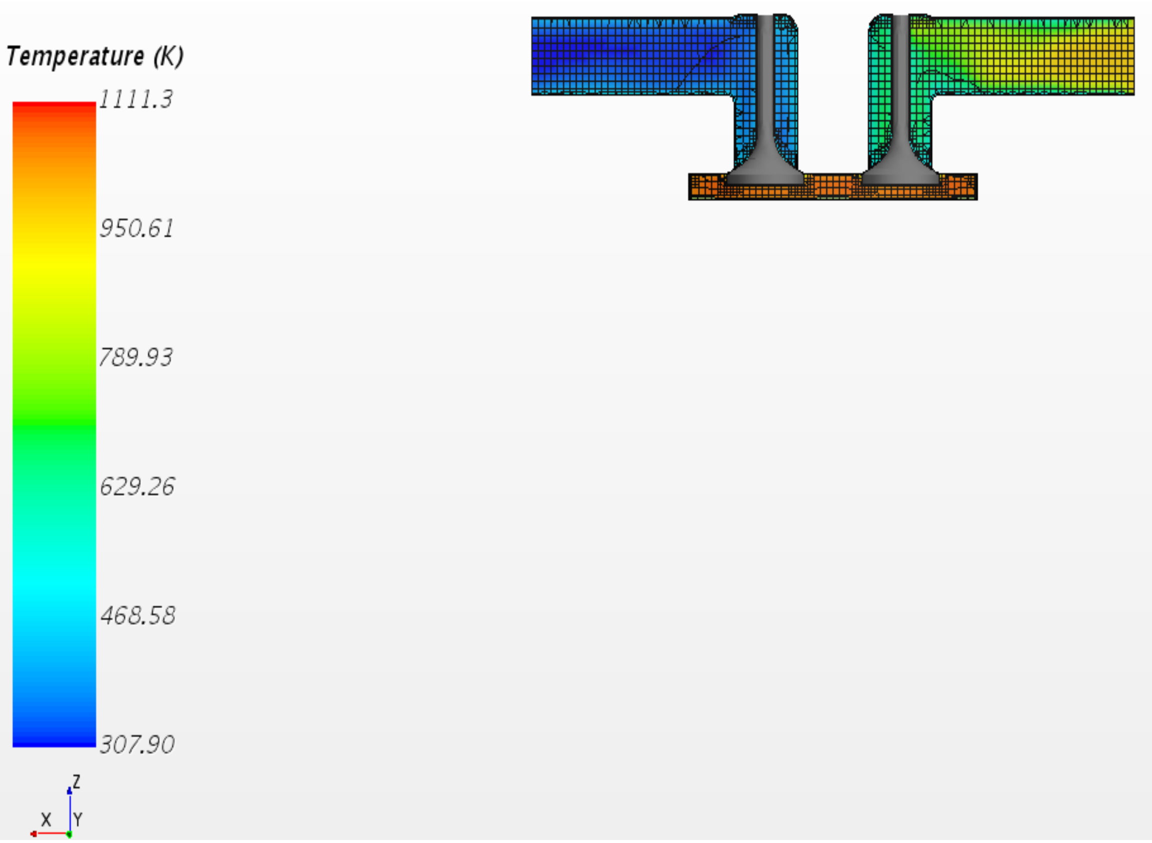

Figure 9. (c) Combustion.

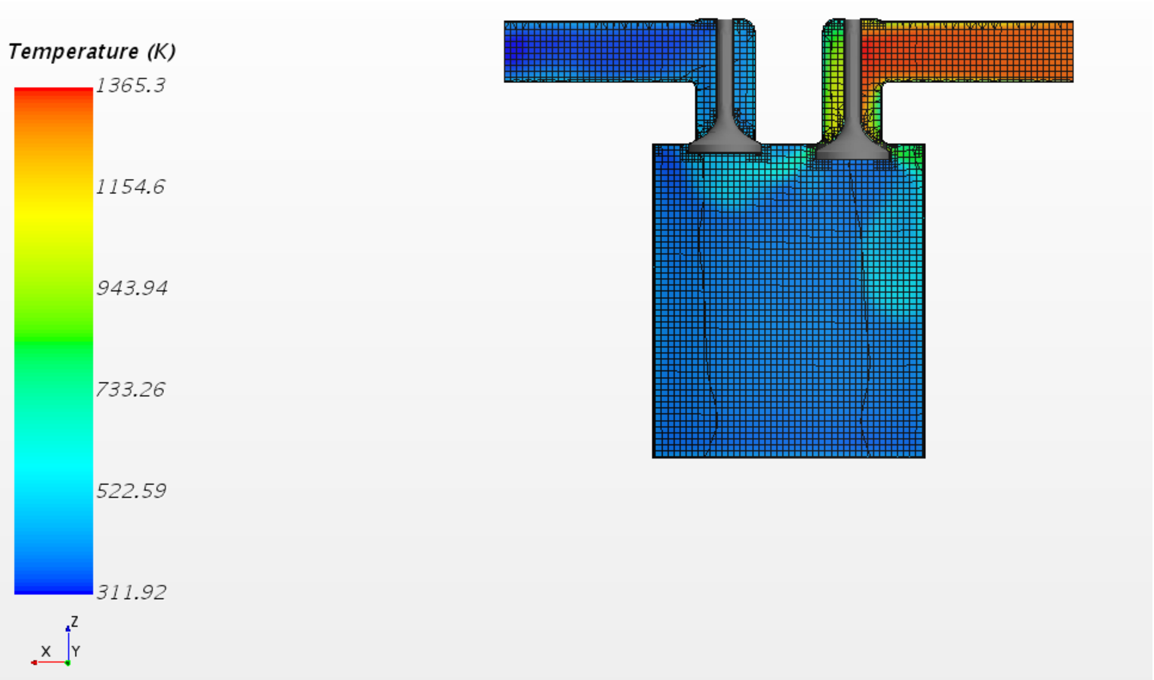

Figure 9. (d) Expansion.

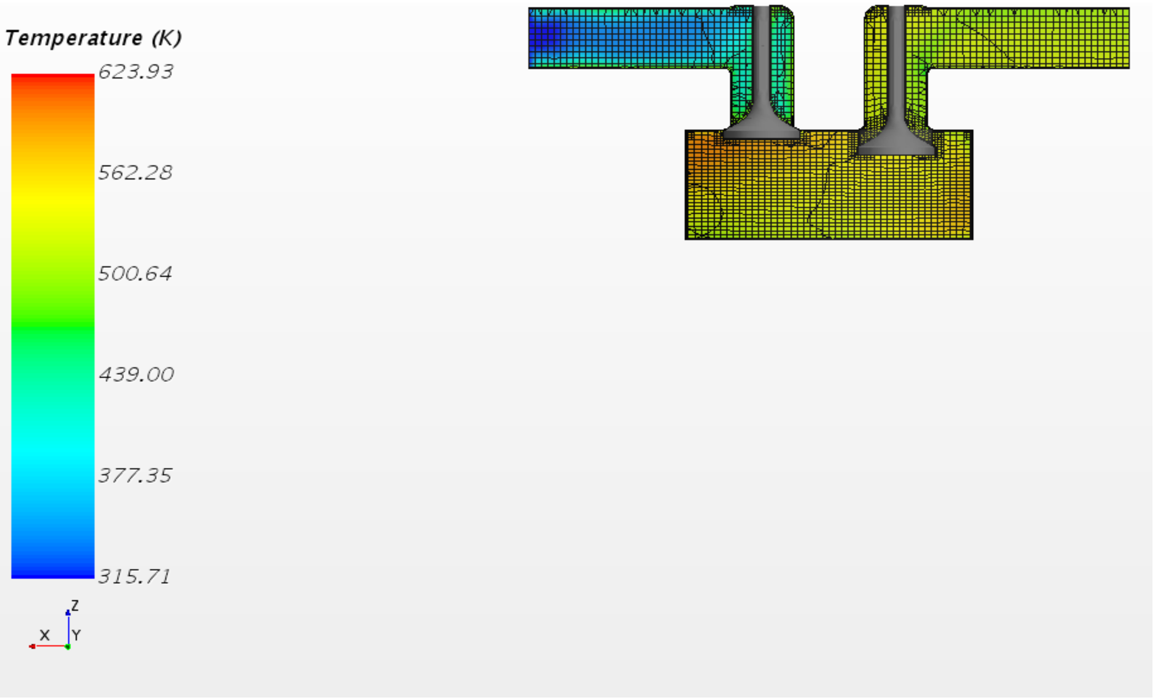

Figure 9. (e) Exhaust.

Computed turbulent kinetic energy fields of four stroke diesel engine with HCCI mode

The turbulent kinetic energy was identified at different stages of the engine and found out the maximum and minimum kinetic energy at different speeds.

(a) Computed turbulent kinetic energy contours of four processes (suction, compression, combustion, expansion & exhaust) for four stroke diesel engine with HCCI mode at 1000 rpm

Figure 10 (a-d) shows the Computed turbulent kinetic energy contours of four processes (suction, compression, combustion, expansion & exhaust) for four stroke diesel engine.

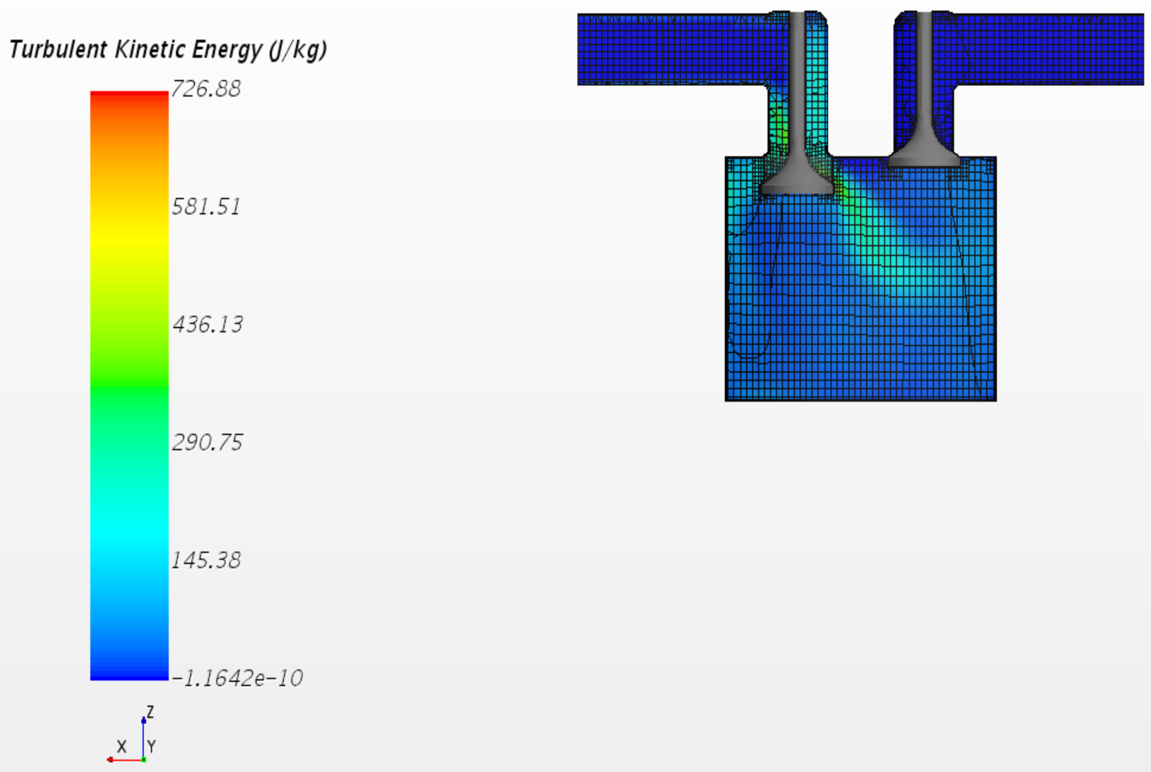

Figure 10. (a) Suction process.

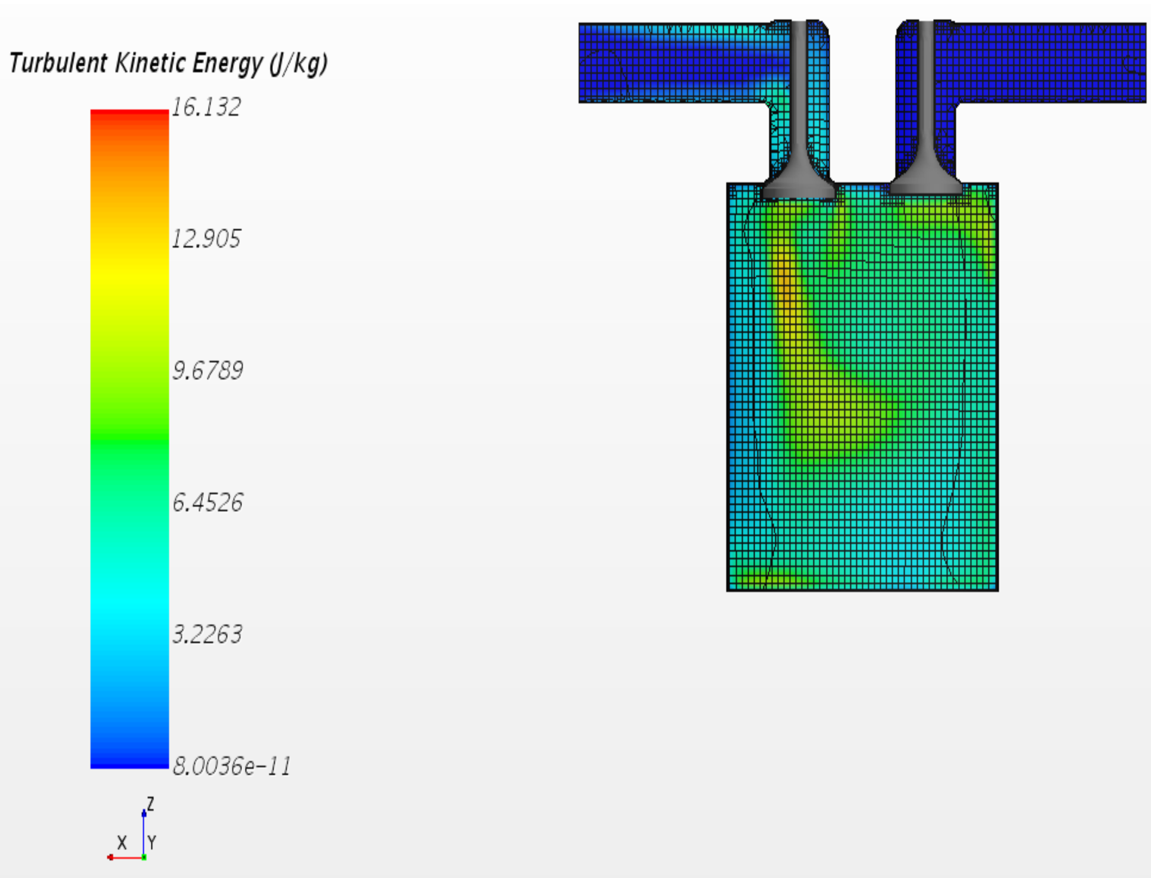

Figure 10. (b) Compression process.

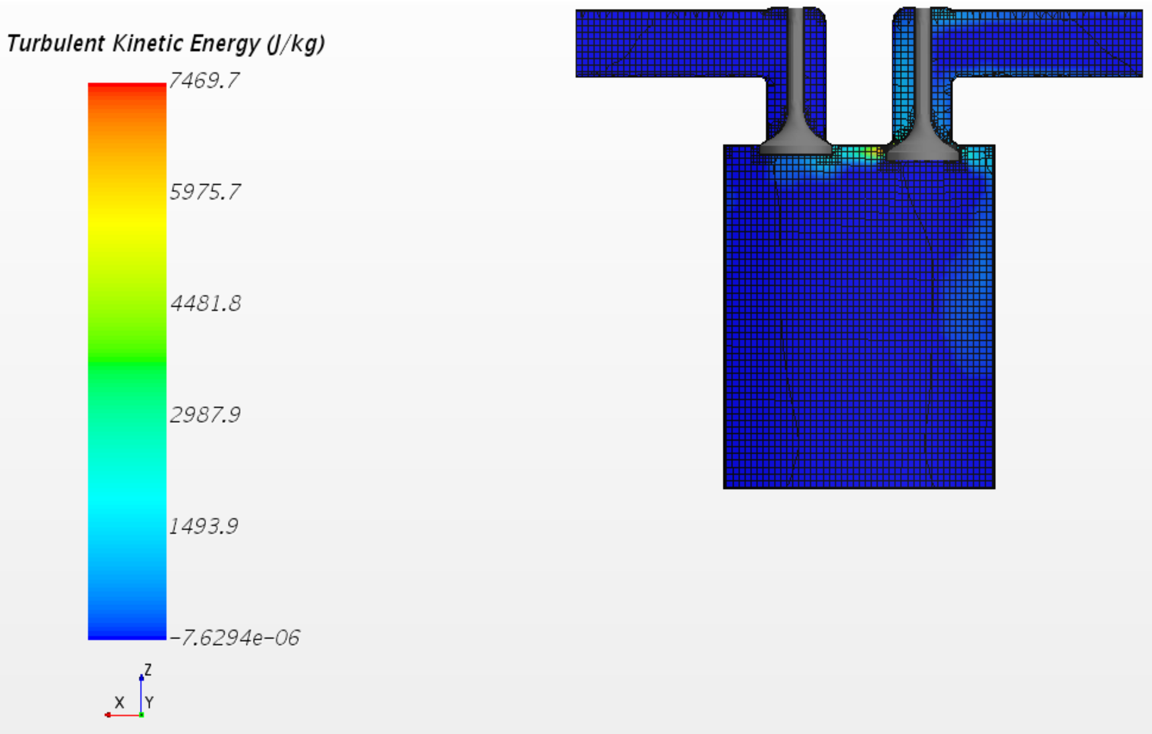

Figure 10. (c) Expansion Process.

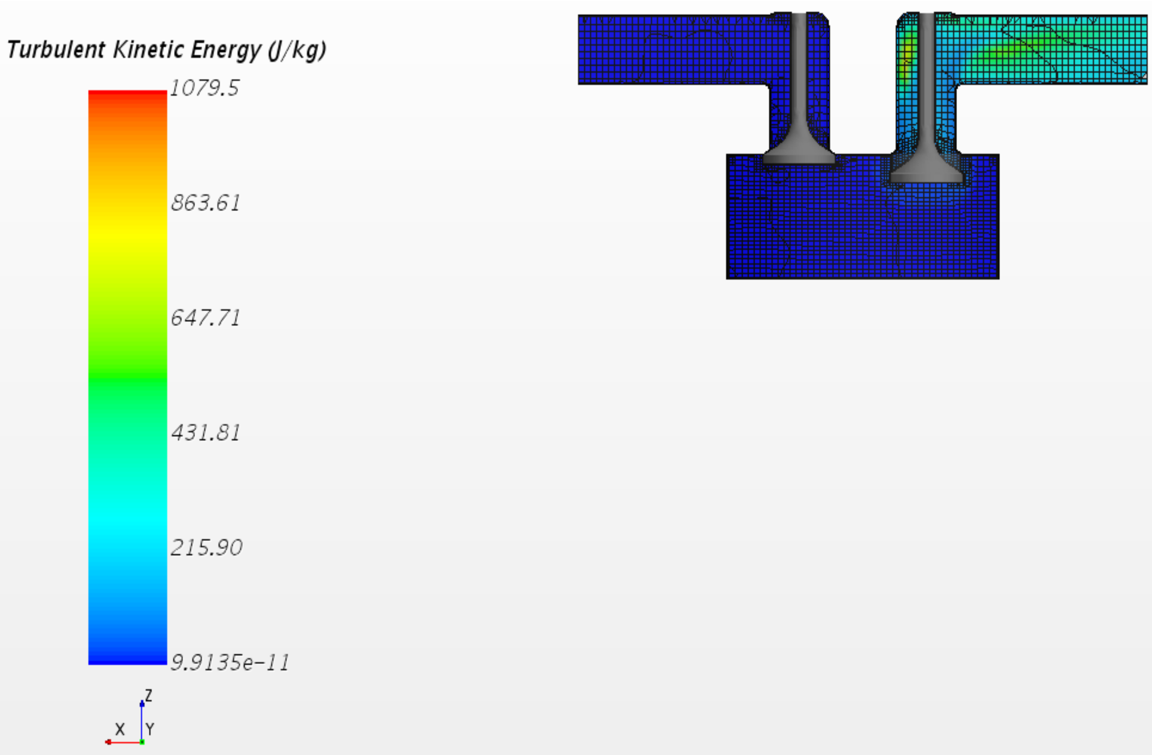

Figure 10. (d) Exhaust Process.

(b) Computed turbulent kinetic energy contours of four processes (suction, compression, combustion, expansion & exhaust) for four stroke diesel engine with HCCI mode at 2000 rpm

Figure 11 (a-d) shows the Computed turbulent kinetic energy contours of four processes (suction, compression, combustion, expansion & exhaust) for four stroke diesel engine.

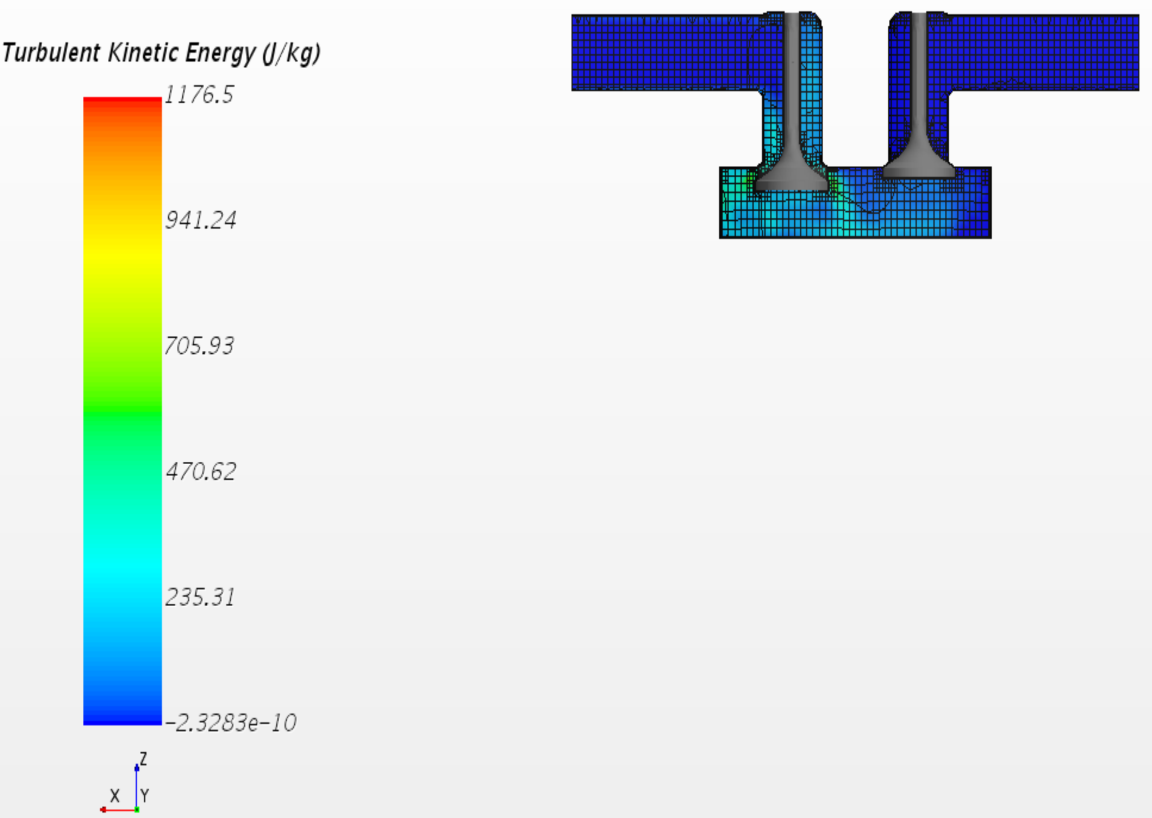

Figure 11 (a) Suction Process.

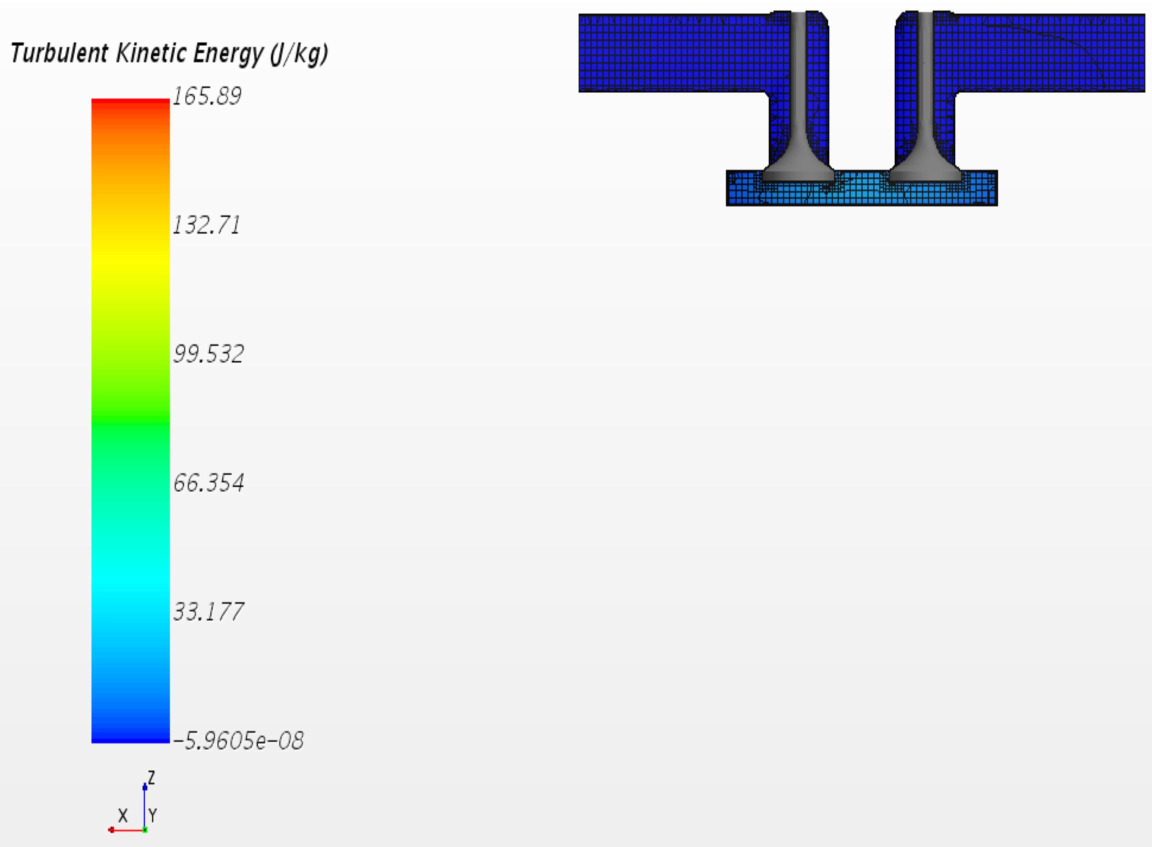

Figure 11. (b) Compression Process.

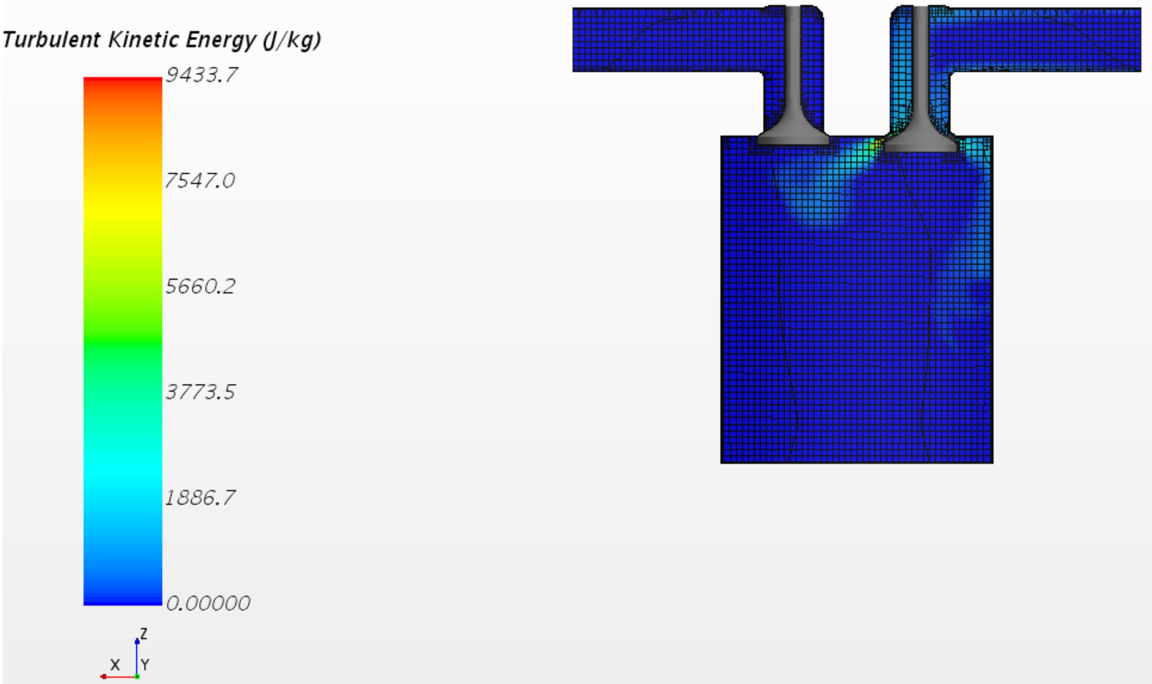

Figure 11. (c) Expansion Process.

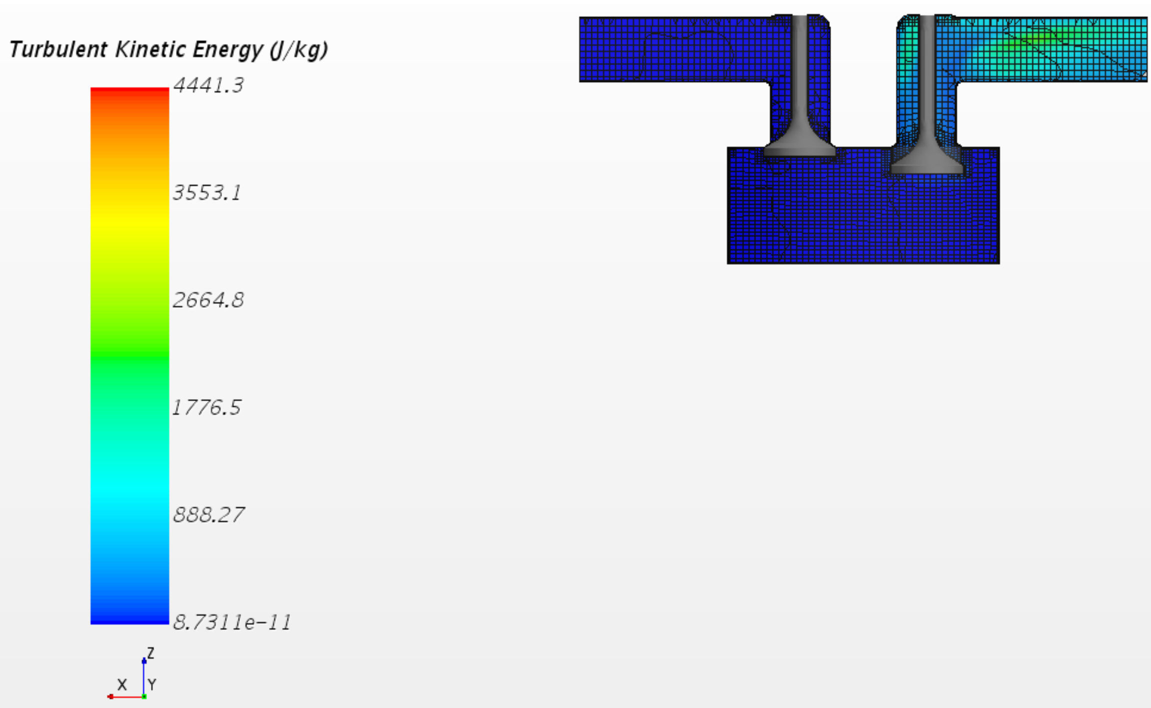

Figure 11. (d) Exhaust Process.

(c) Computed turbulent kinetic energy contours of four processes (suction, compression, combustion, expansion & exhaust) for four stroke diesel engine with HCCI mode at 3000 rpm

Figure 12 (a-d) shows the Computed turbulent kinetic energy contours of four processes (suction, compression, combustion, expansion & exhaust) for four stroke diesel engine.

Computed compound velocity counters of four stroke diesel engine with HCCI mode

The compound velocity counters were identified at different stages of the engine at different speeds.

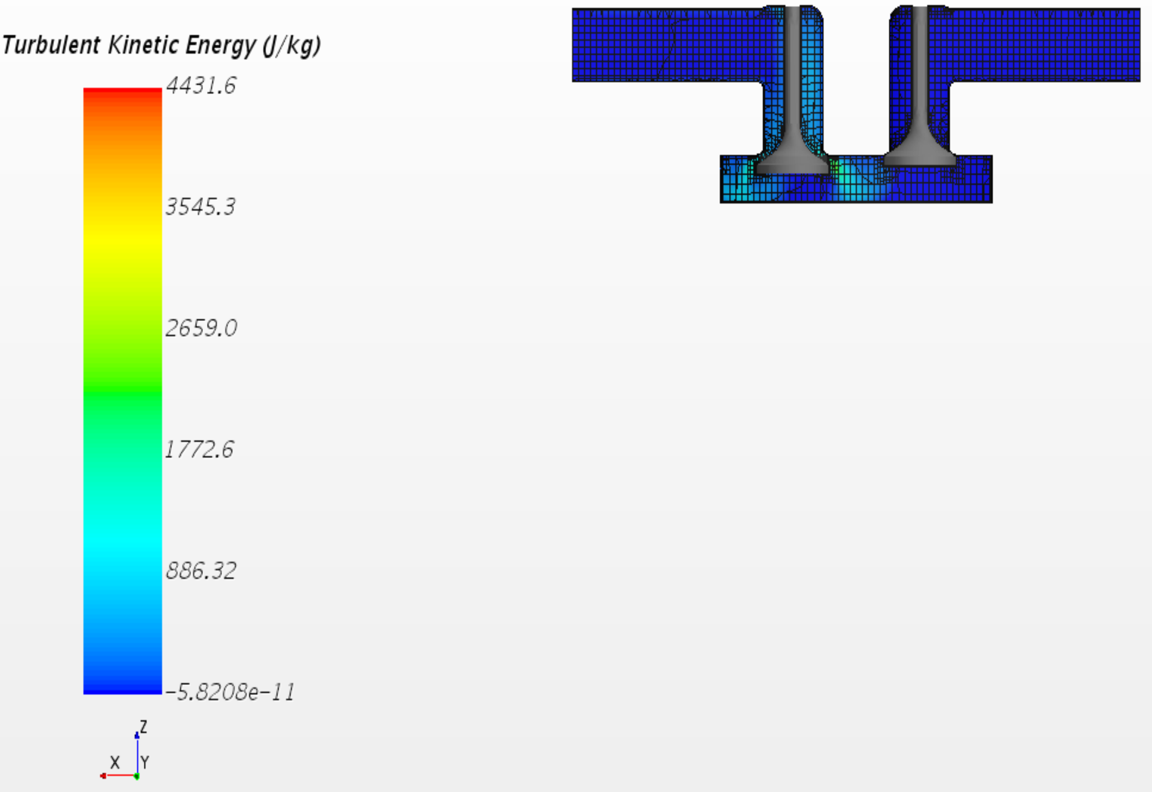

Figure 12. (a) Suction Process.

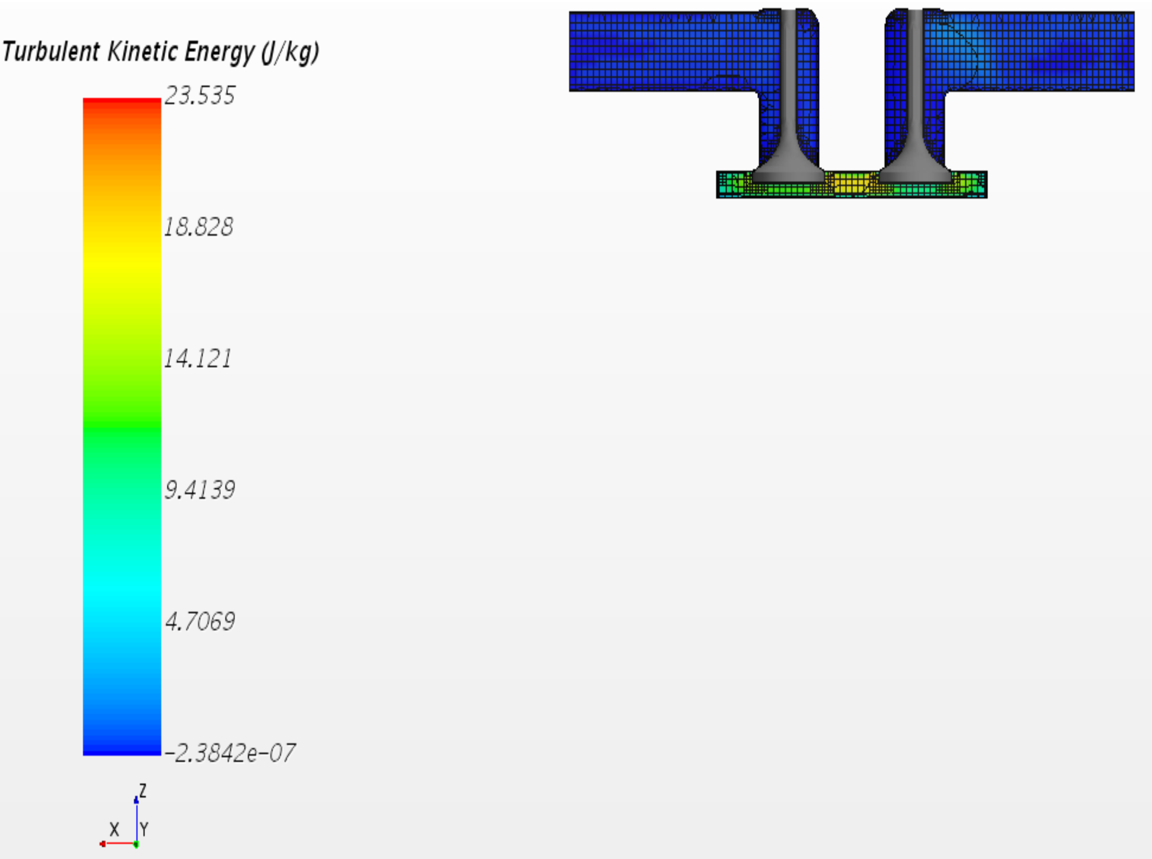

Figure 12. (b) compression Process.

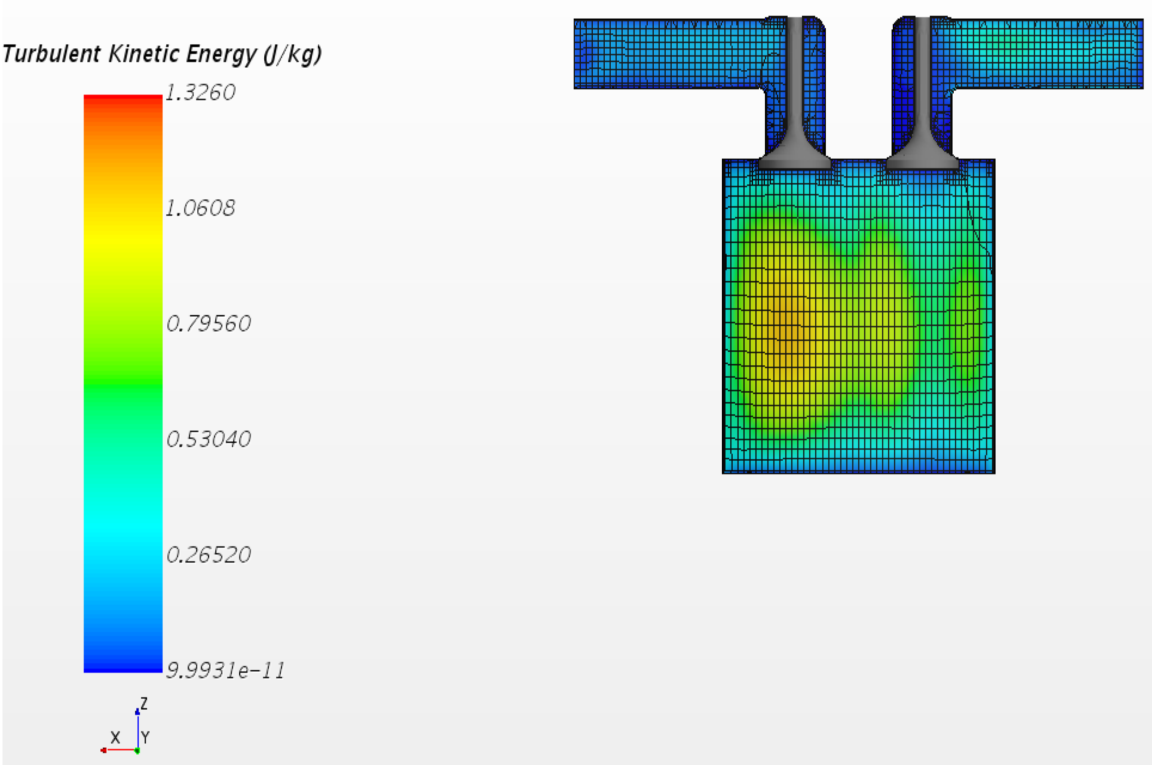

Figure 12. (c) Expansion Process.

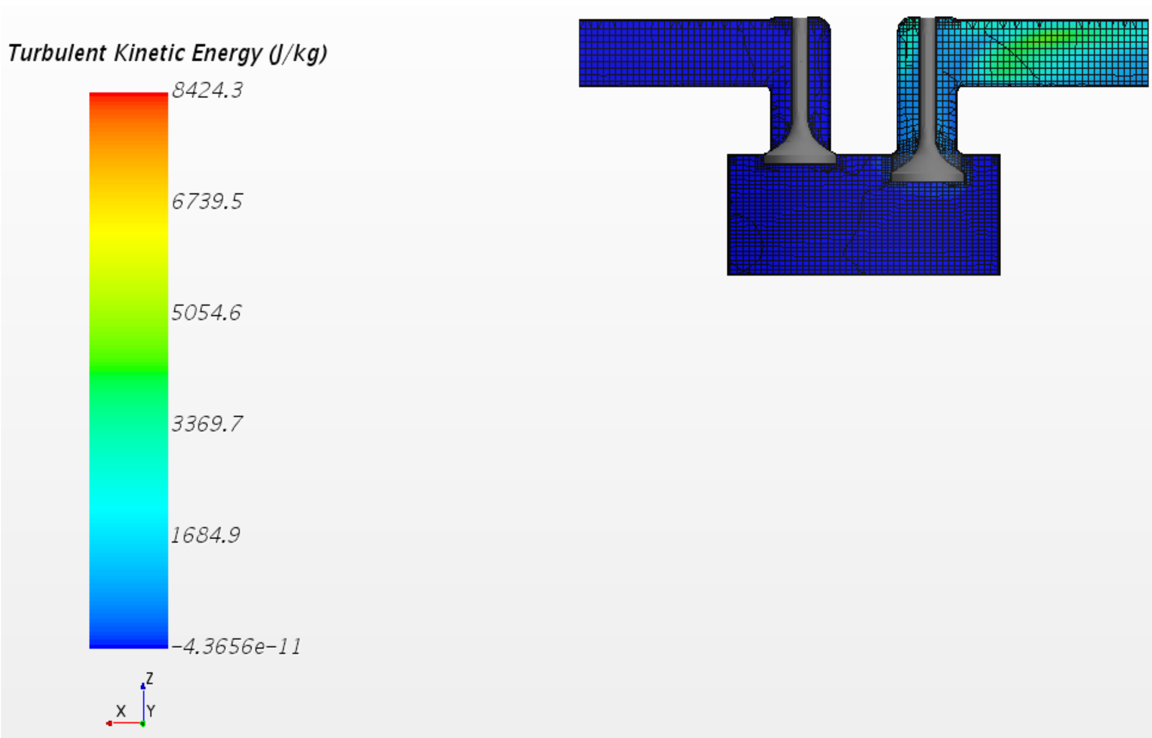

Figure 12. (d) Exhaust Process.

(a) Computed velocity contours of four processes (suction, compression, combustion, expansion & exhaust) for four stroke diesel engine with HCCI mode at 1000 rpm

Figure 13 (a-d) shows the Computed velocity contours of four processes (suction, compression, combustion, expansion & exhaust) for four stroke diesel engine.

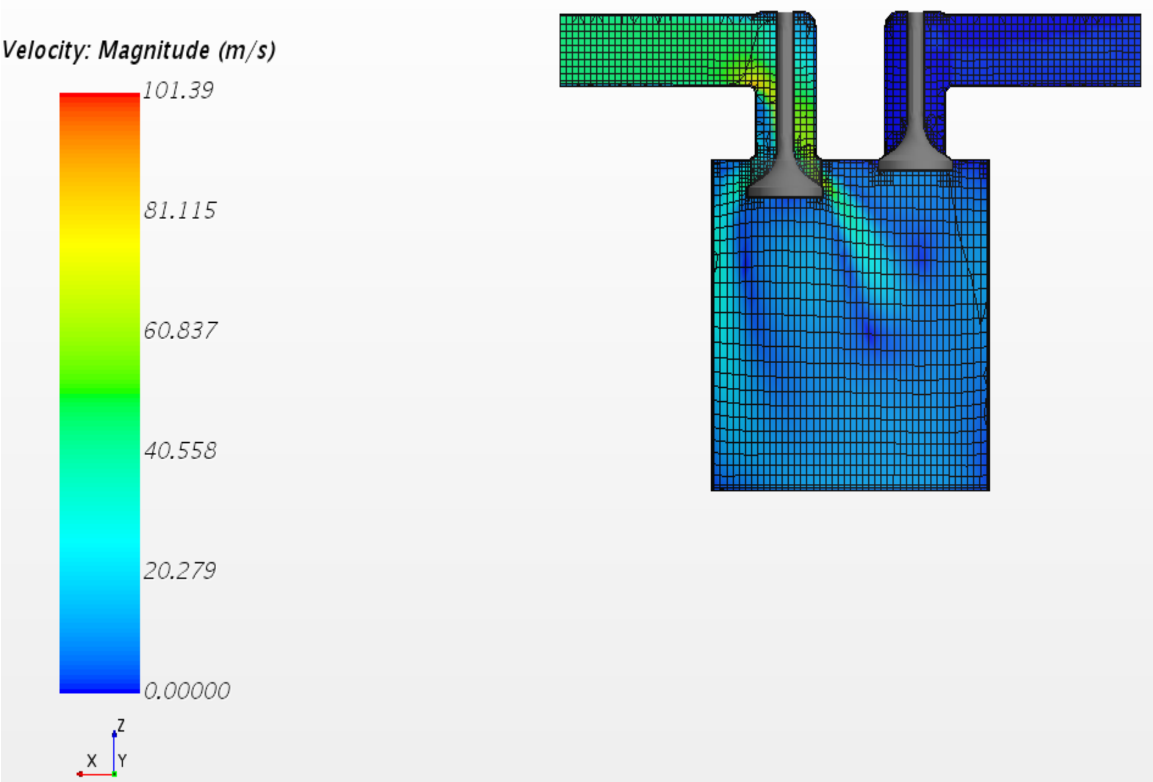

Figure 13. (a) Suction process.

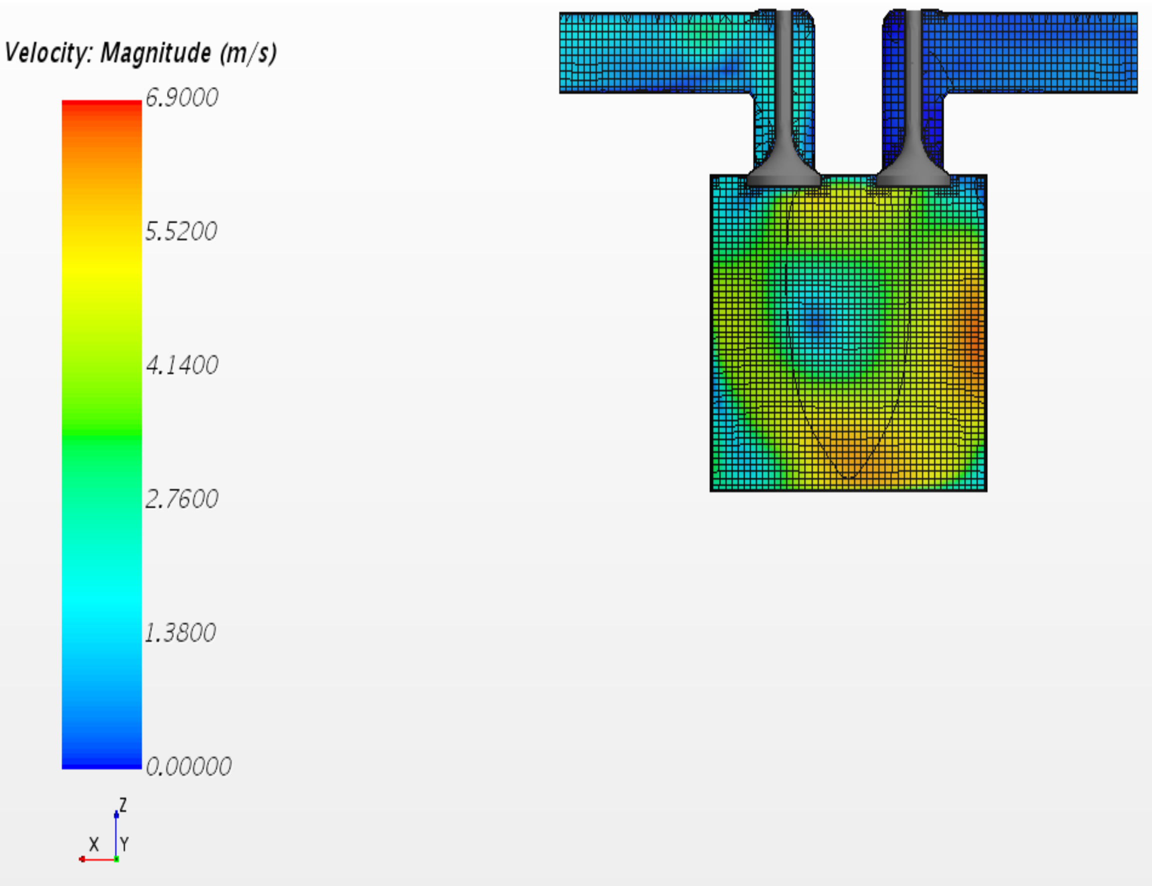

Figure 13. (b) Compression process.

International Journal of I.C. Engines and Gas Turbines
Volume 7, Issue 2
ISSN: 2582-290X

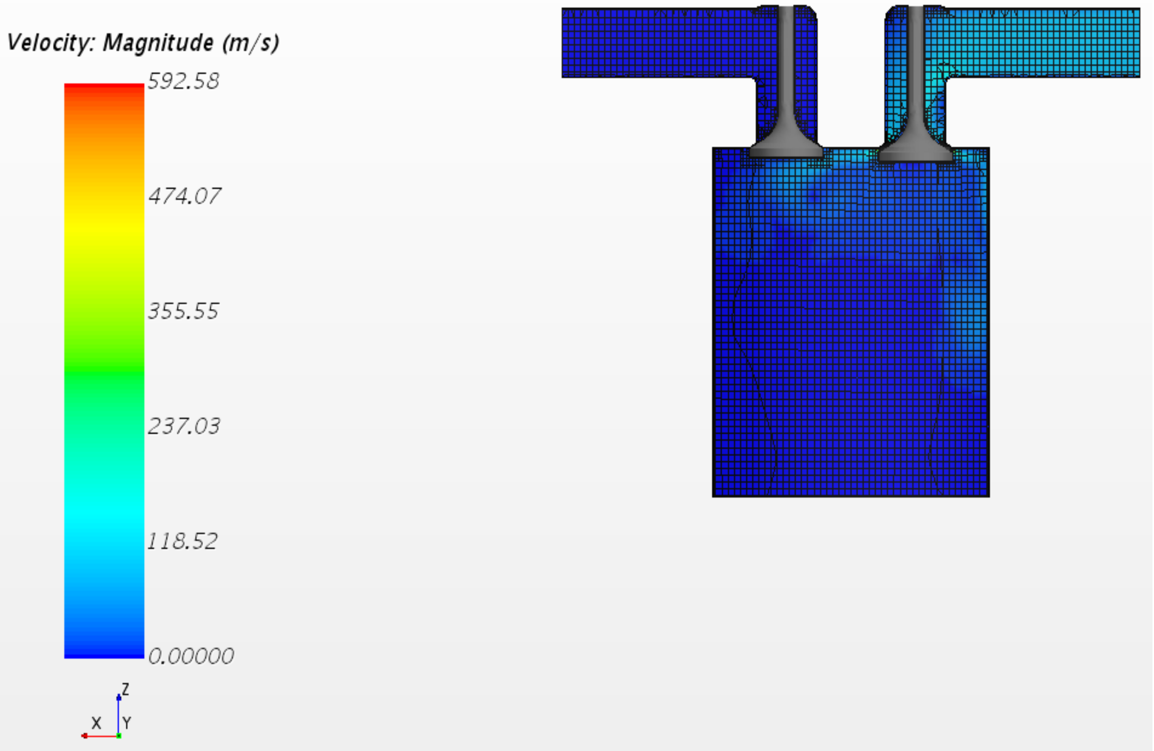

Figure 13. (c) Expansion process.

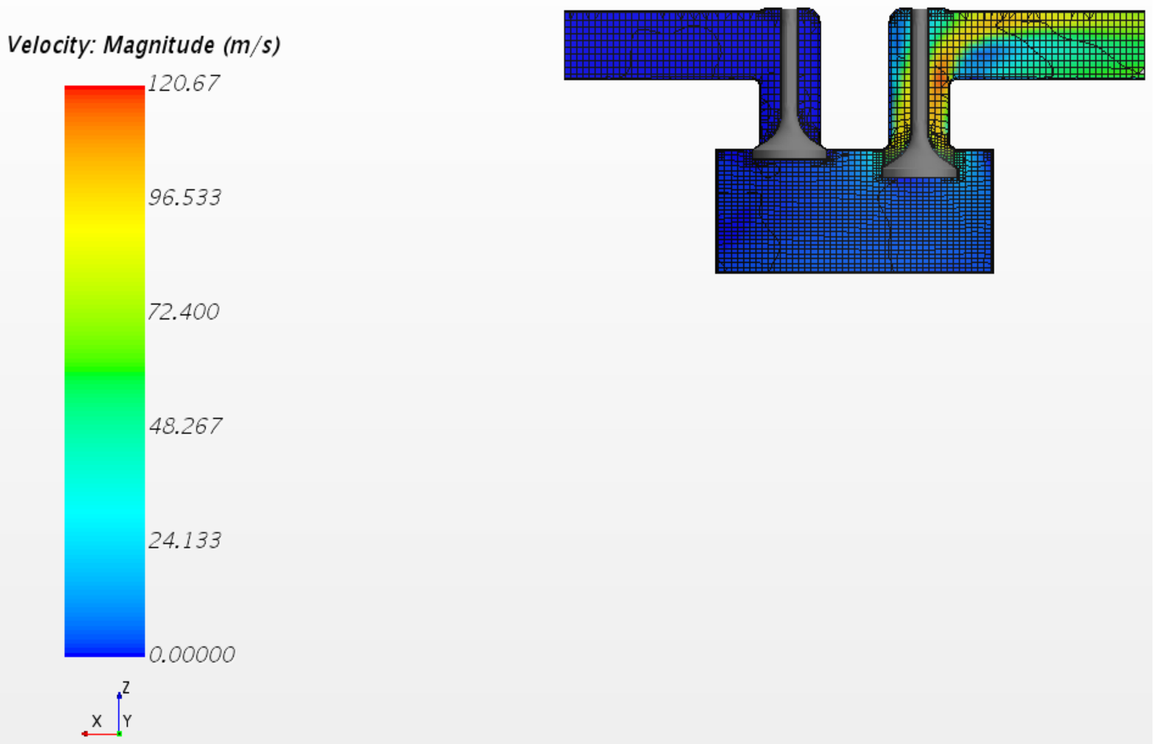

Figure 13. (d) Exhaust process.

(b) Computed velocity contours of four processes (suction, compression, combustion, expansion & exhaust) for four stroke diesel engine with HCCI mode at 2000 rpm

Figure 14 (a-d) shows the Computed velocity contours of four processes (suction, compression, combustion, expansion & exhaust) for four stroke diesel engine.

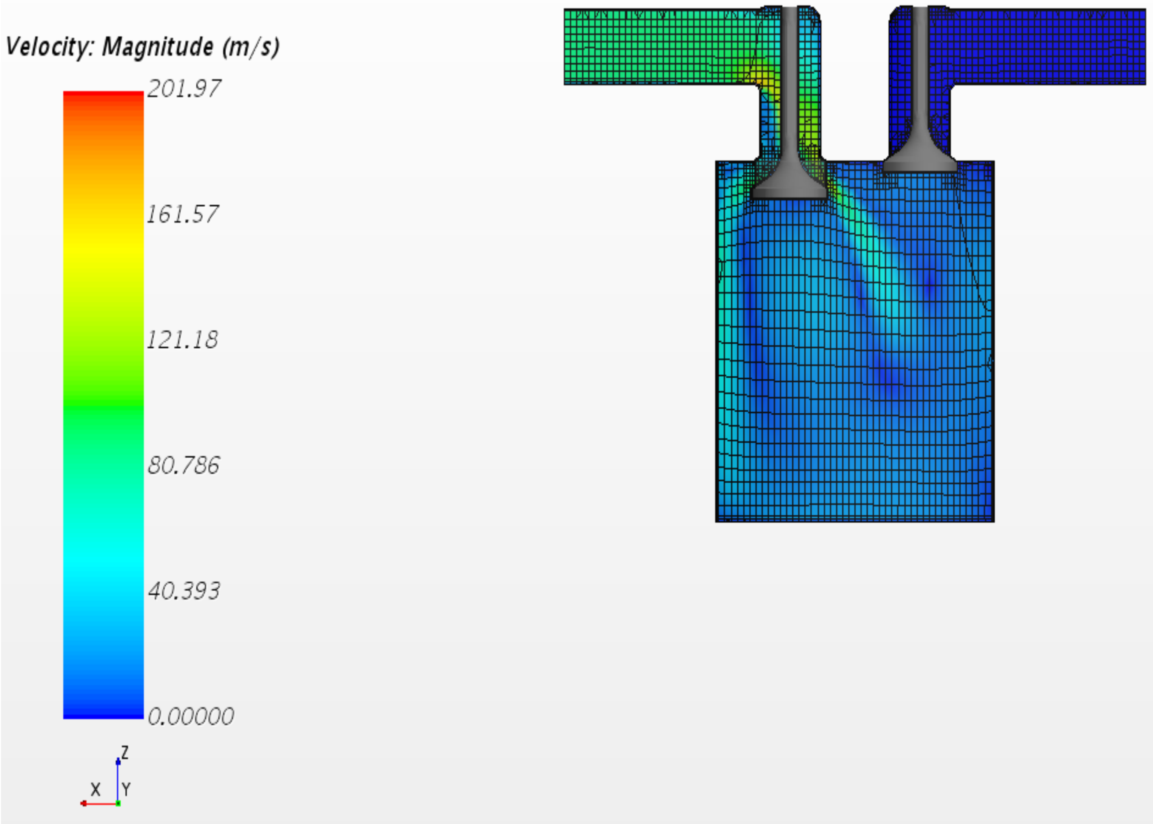

Figure 14. (a) Suction process.

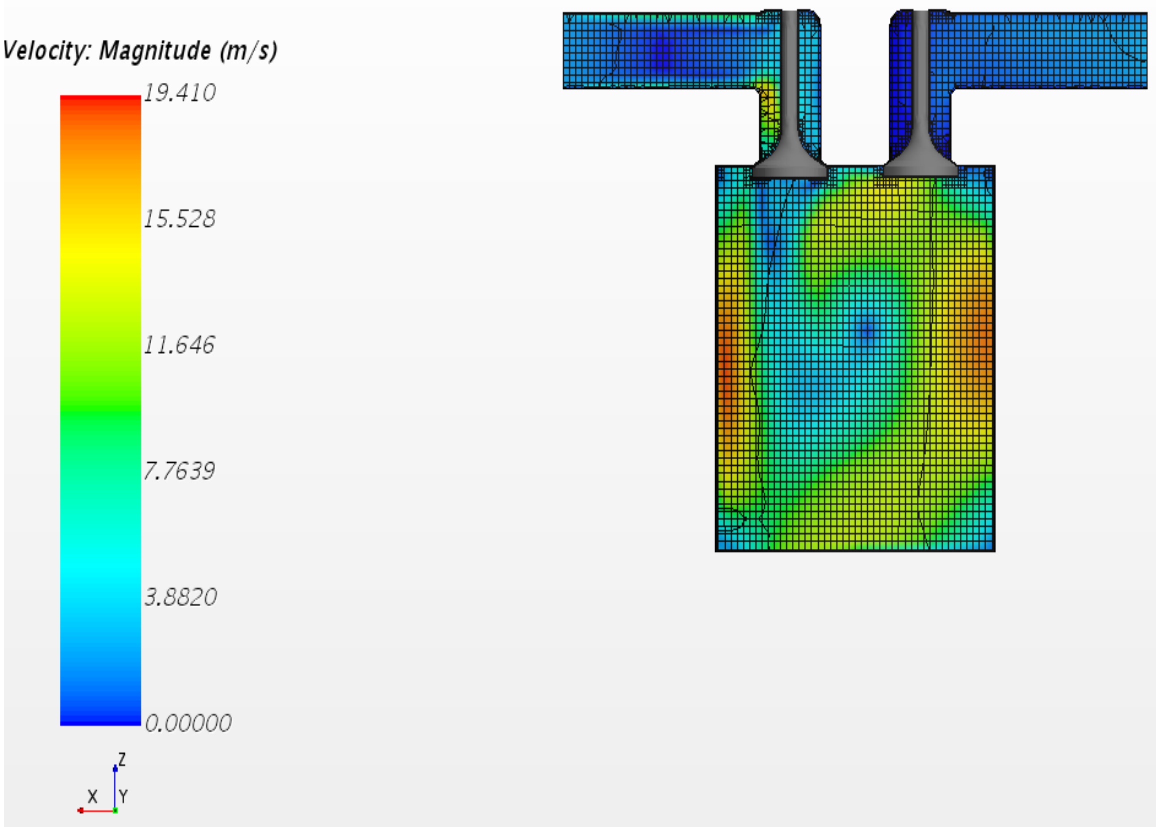

Figure 14. (b) Compression process.

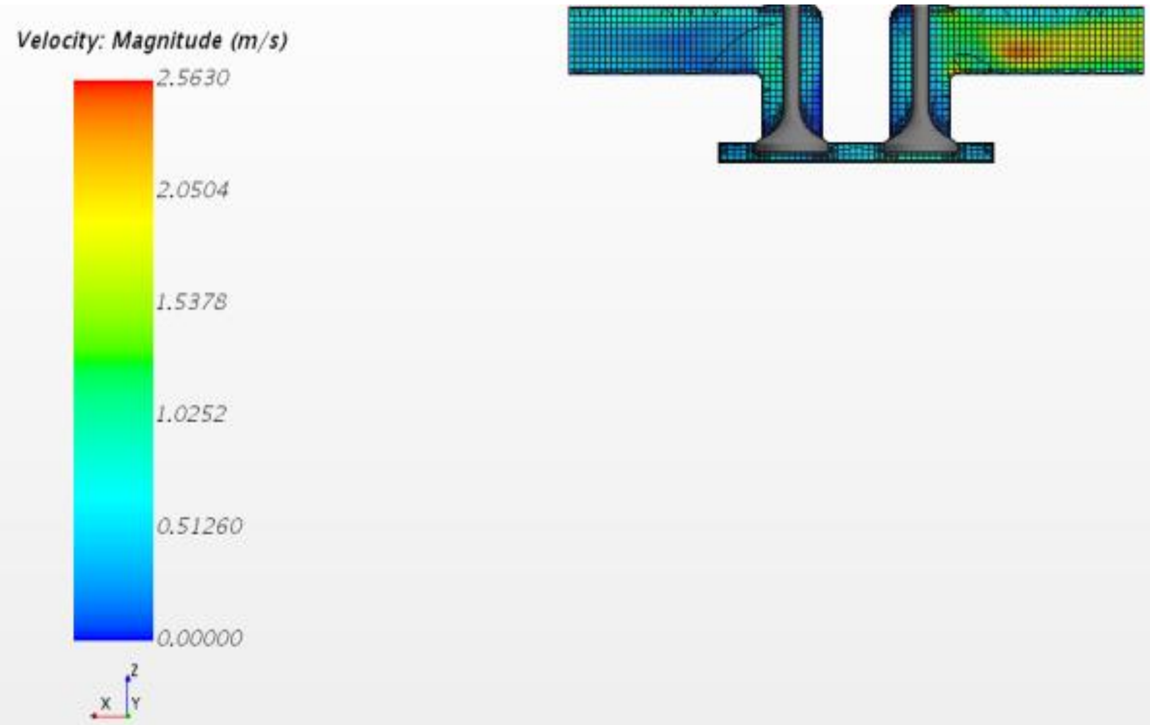

Figure 14. (c) Combustion process.

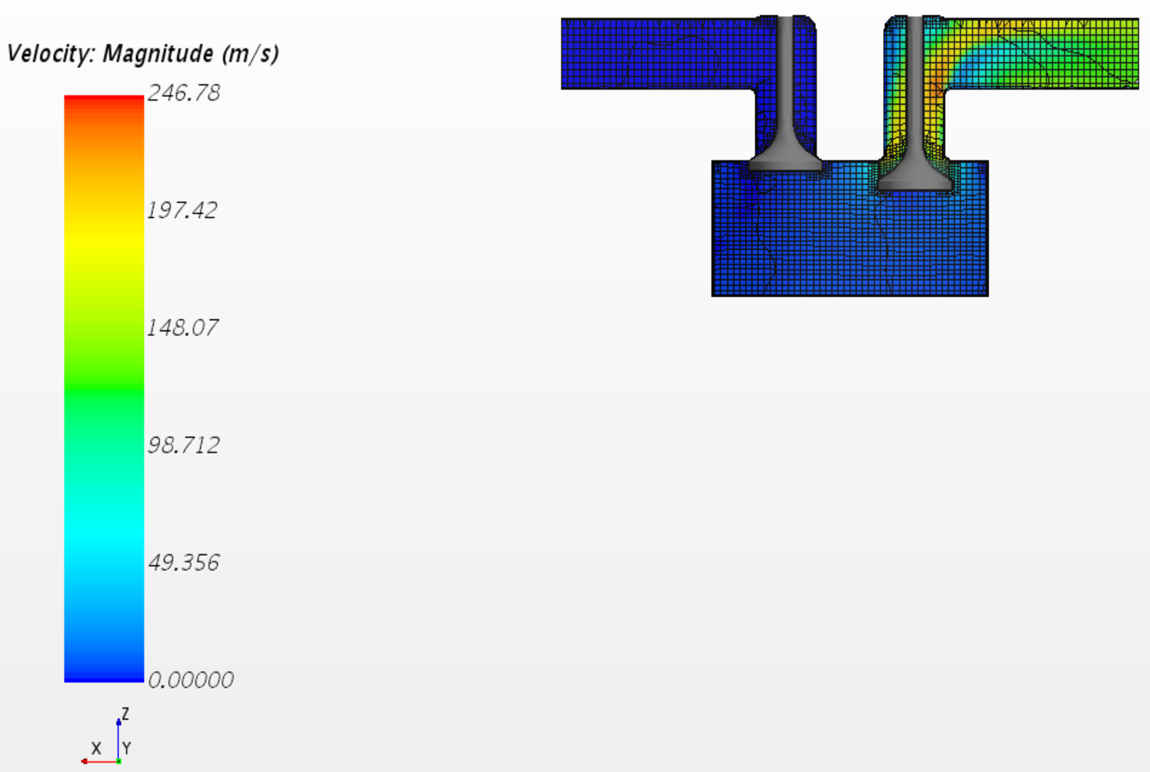

Figure 14. (d) Exhaust process.

(c) Computed velocity contours of four processes (suction, compression, combustion, expansion & exhaust) for four stroke diesel engine with HCCI mode at 3000 rpm

Figure 15 (a-d) shows the Computed velocity contours of four processes (suction, compression, combustion, expansion & exhaust) for four stroke diesel engine.

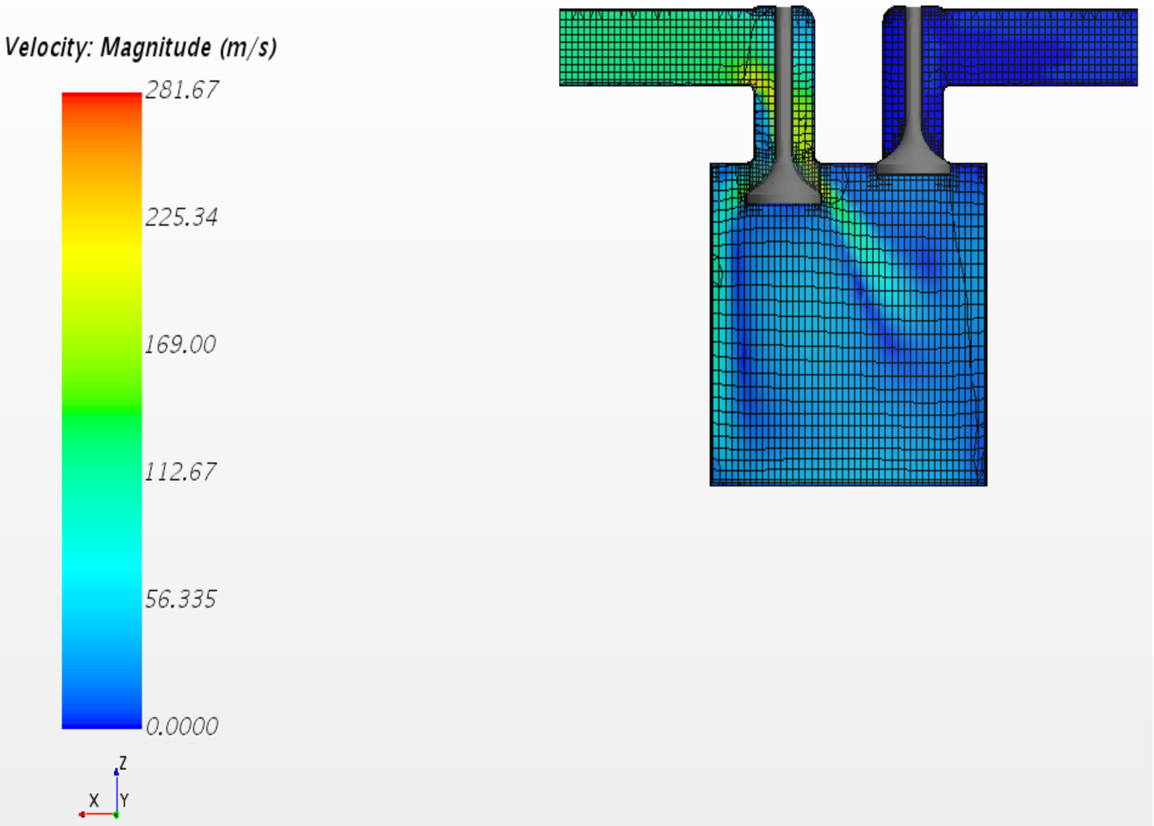

Figure 15. (a) Suction process.

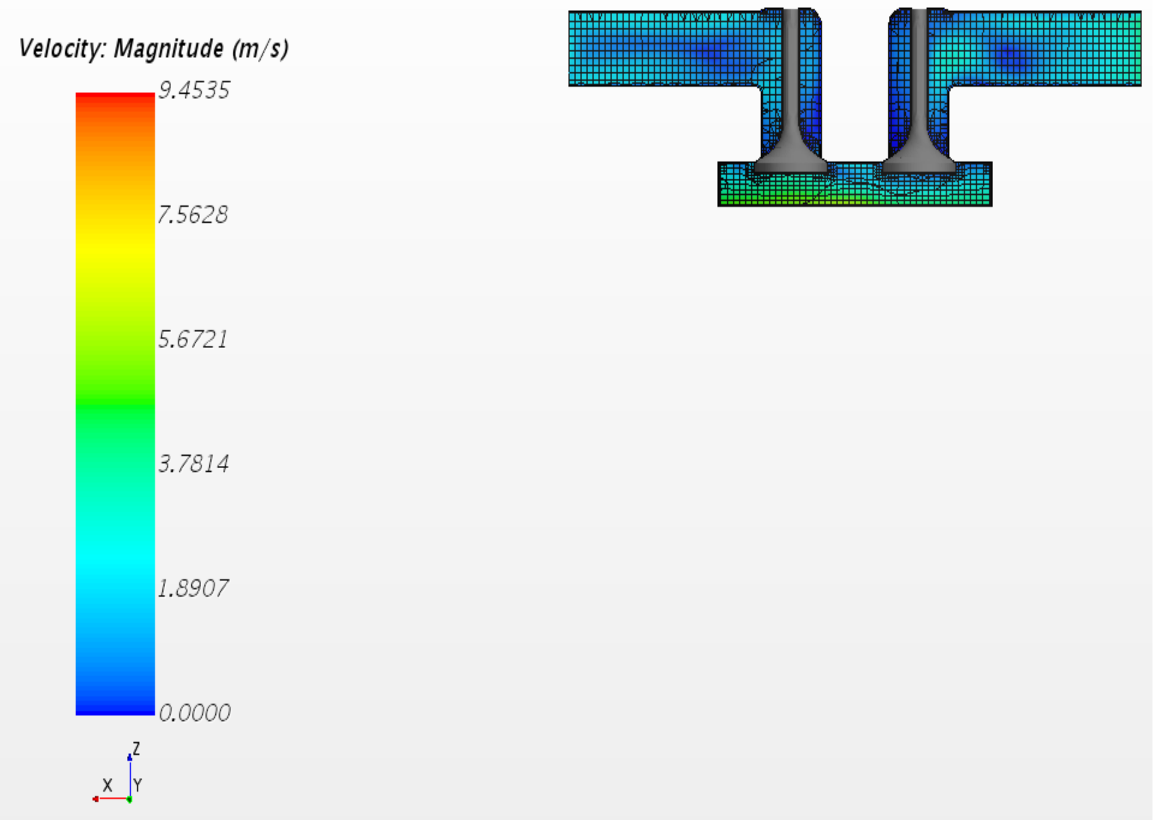

Figure 15. (b) Compression process.

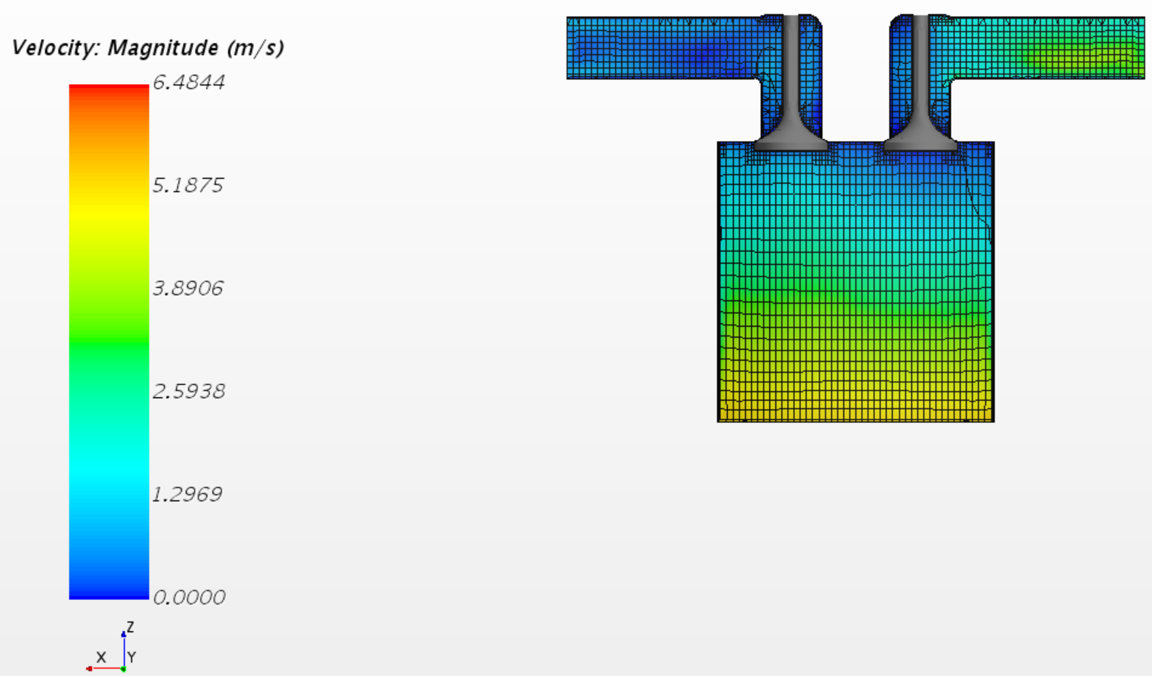

Figure 15. (c) Expansion process.

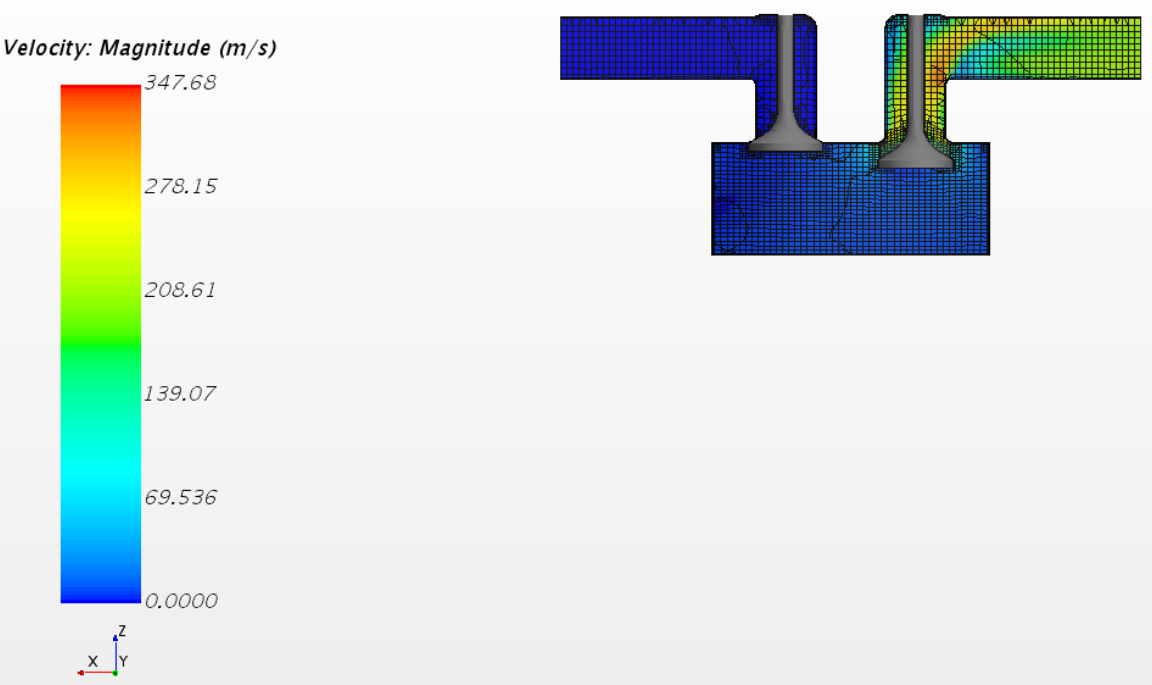

Figure 15. (d) Exhaust process.

Cylinder pressure vs crank angle

The cylinder pressure is identified at the three different speeds 1000 rpm,2000rpm,3000 rpm. In this analysis absorbed that the cylinder pressures were varied with respected to speed. The cylinder pressure increases gradually from 1000 rpm to 2000 rpm. The maximum pressure at 1000, 2000 & 3000 rpm were 56, 57 & 53 bar. The cylinder pressure been increased at 2000 rpm as compared to 1000 and 3000 rpm. However, when the engine speed increases from 2000 rpm to 3000 rpm, the peak cylinder pressures should not attain more than 57 bar pressure. This is due to; at 3000 rpm the rate of combustion is low as compared to remaining rate of combustion at 1000 and 2000 rpm. During analysis observed that when the engine speed is increases from 1000 rpm to 2000 rpm, the cylinder pressure was raised by about 1.75%. Similarly, when the engine speed increases from 2000 rpm to 3000 rpm, the cylinder pressure was lower by about 8.77%. Figure 16 (a-d) shows the different pressure vs crank angle.

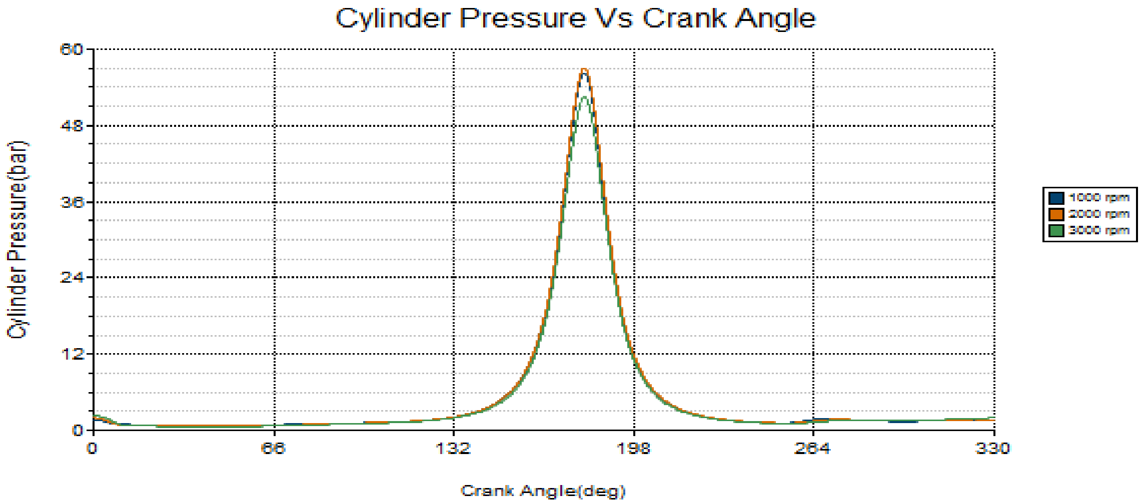

Figure 16. (a) Variation in the cylindrical pressure with respect to crank angle at various speeds.

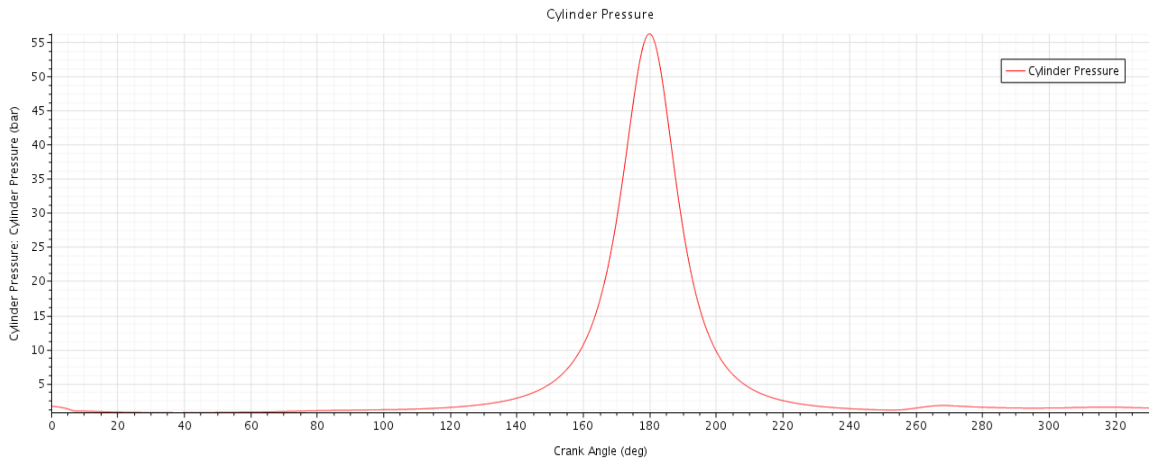

Figure 16. (b) Pressure vs Crank angle at 1000 rpm.

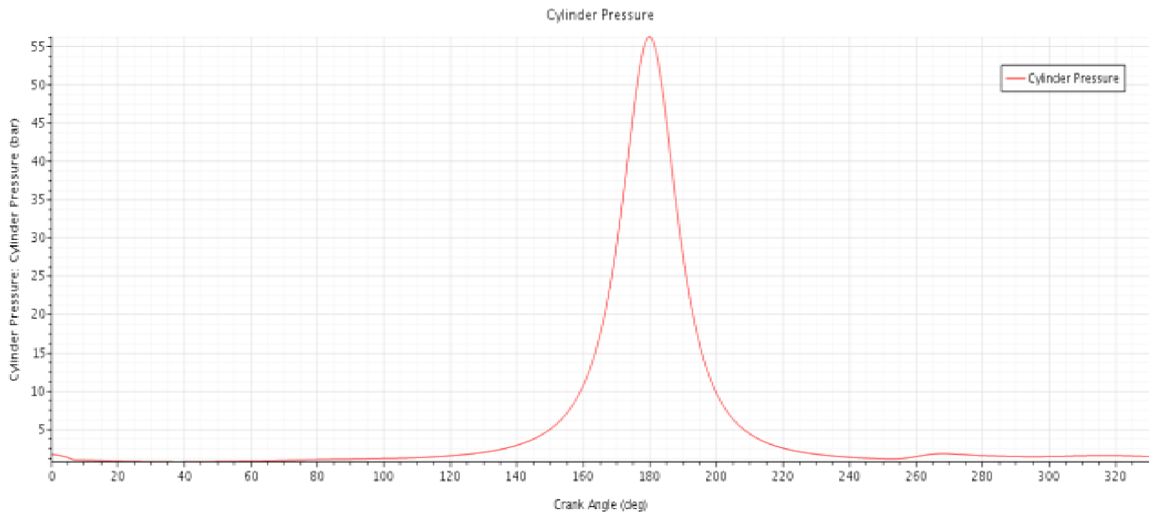

Figure 16. (c) Pressure vs crank angle at 20.

International Journal of I.C. Engines and Gas Turbines
Volume 7, Issue 2
ISSN: 2582-290X

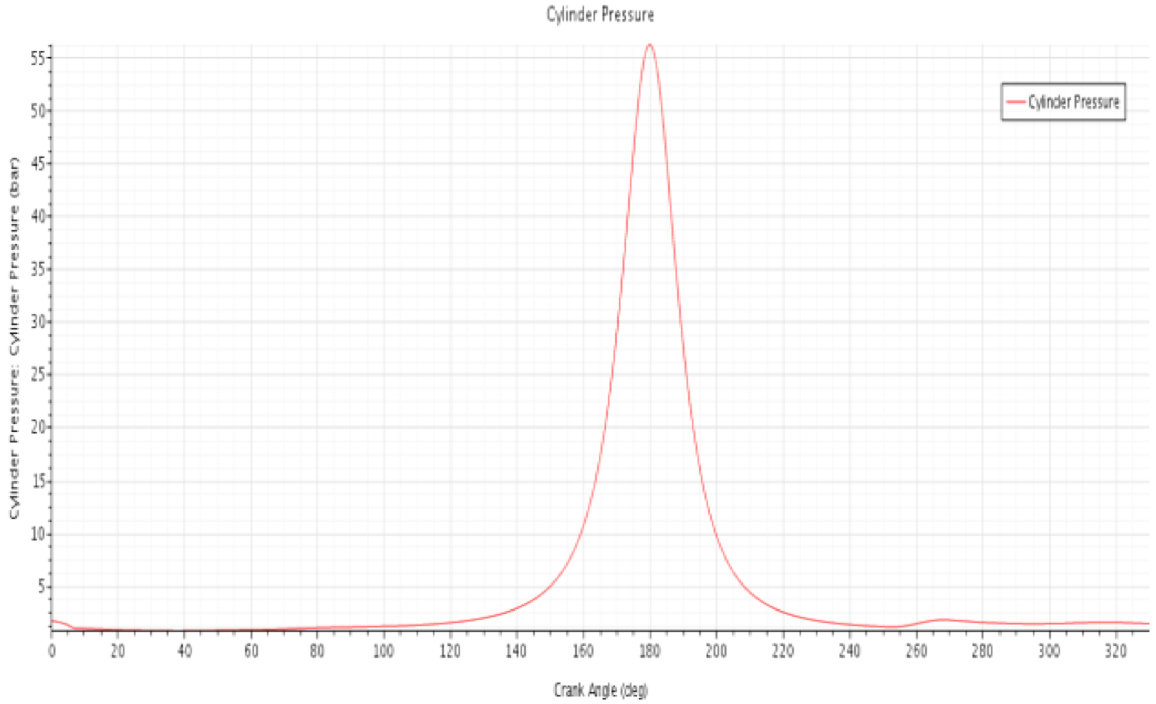

Figure 16. (d) Pressure vs Crank angle at 3000 rpm.

Cylindrical Temperature vs Crank angle

The variation of temperature in the cylinder with crank angle for three engine speeds is shown in the fig. The amount of temperature raise is depending up on the rate of combustion. In this analysis absorbed that the temperature inside cylinder was varied with respected to speed. The maximum temperature was attained at 3000 rpm and the value was 1399.3 K. Figure 17 (a-d) shows the different temperature vs crank angle.

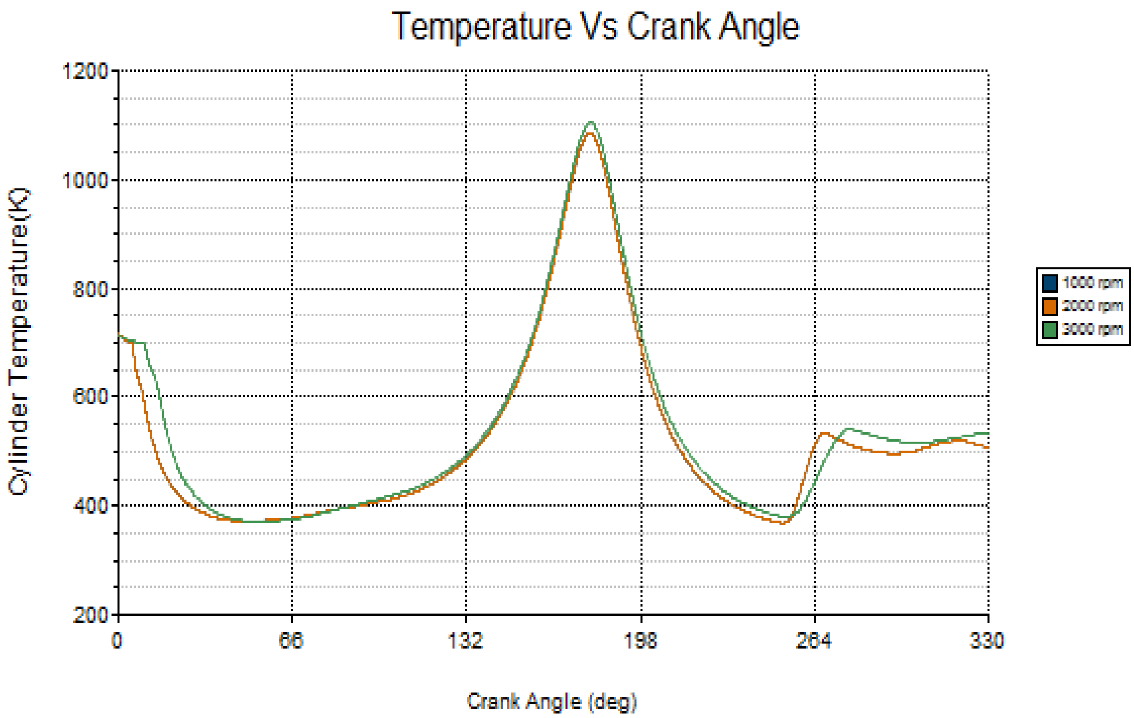

Figure 17. (a) Variation of temperature with respect to the crank angle at three different speeds.

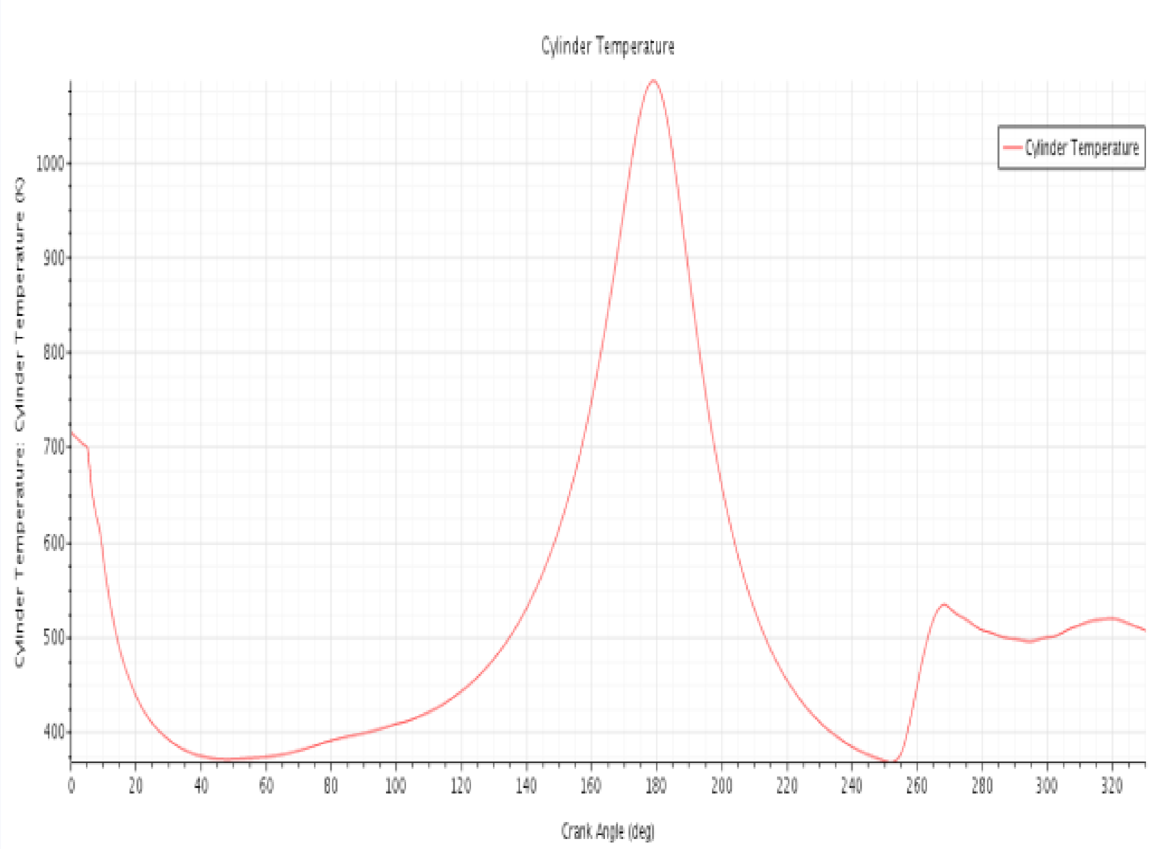

Figure 17. (b) Temperature vs crank angle at 1000 rpm.

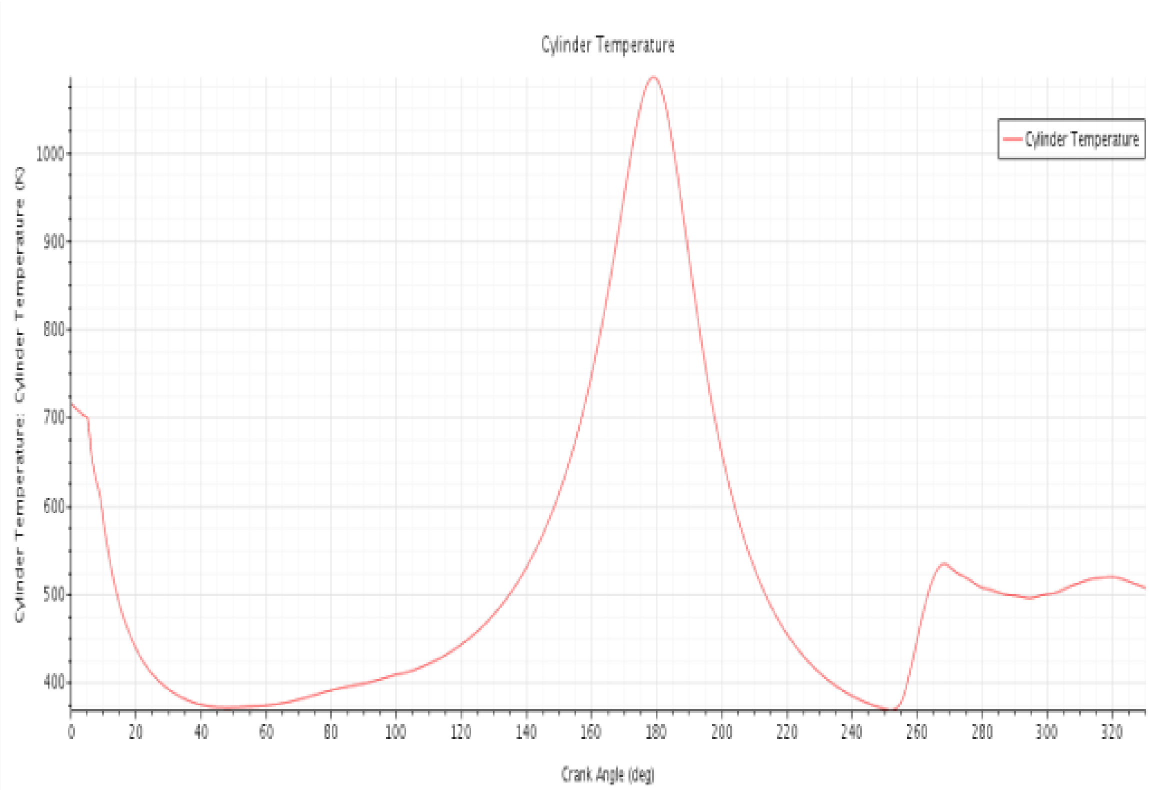

Figure 17. (c)Temperature vs Crank Nagle at 2000 rpm.

International Journal of I.C. Engines and Gas Turbines
Volume 7, Issue 2
ISSN: 2582-290X

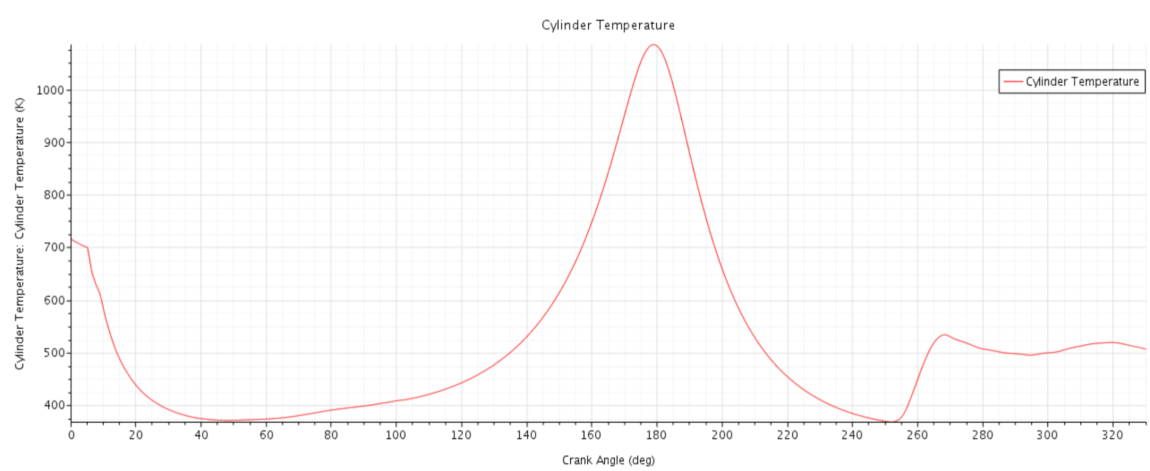

Figure 17. (d) Temperature vs Crank angle at 3000 rpm.

Turbulent kinetic viscosity vs Crank angle

variation of turbulent kinetic energy with crank angle for three engine speeds 1000,2000&3000rpm. Turbulent kinetic energy is very important parameter in CI engines. The turbulent kinetic energy gradually increases from 1000 to2000 and from 2000 to 3000 rpm. The maximum turbulent kinetic energy attained at speed of 3000 rpm. The turbulent kinetic energy is lower at lower speeds and higher at higher speeds. In analysis observed that the turbulent kinetic energy gradually increased during suction process and this turbulent kinetic energy again decreased in compression, combustion and end of the expansion. The turbulent kinetic energy increased only during exhaust process. The turbulent kinetic energy at the speed of 3000 rpm in the exhaust process the valve was 8424.3 j/kg. In analysis observed that when the engine speed increases from 1000 rpm to 2000 rpm, the turbulent kinetic energy was increased by about 269.13%. When the engine speed increases from 2000 to 3000 rpm the turbulent kinetic energy was increased by about115.98%. Figure 18 (a-d) shows the different turbulent kinetic energy with respect to the crank angle.

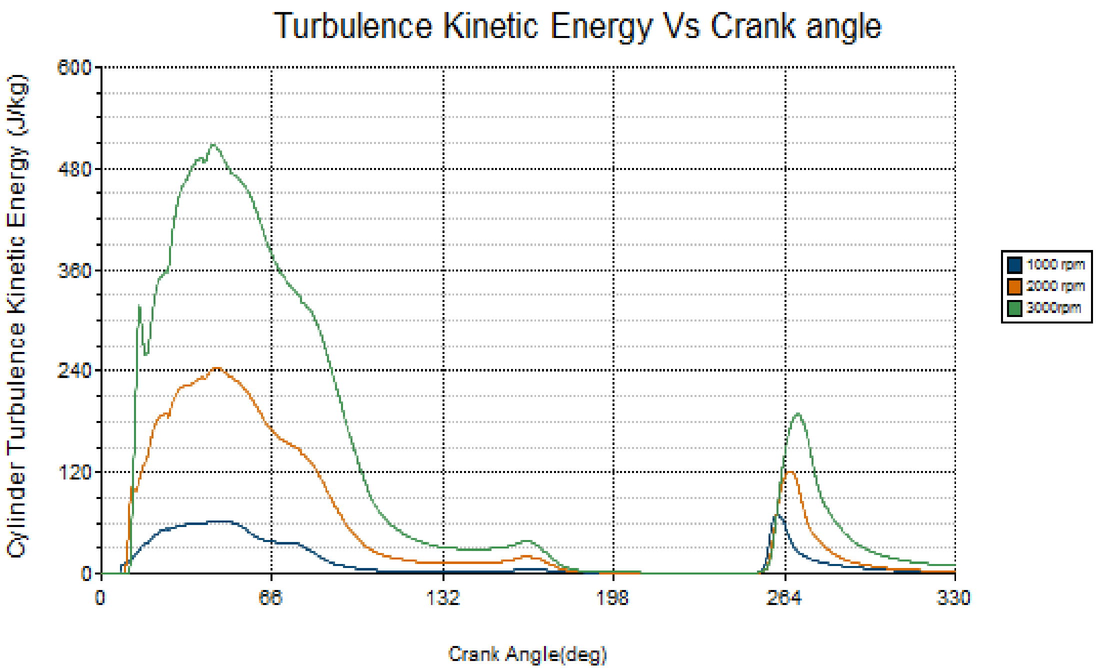

Figure 18. (a) Variation of Turbulent Kinetic Energy with respect to crank angles at Various speeds.

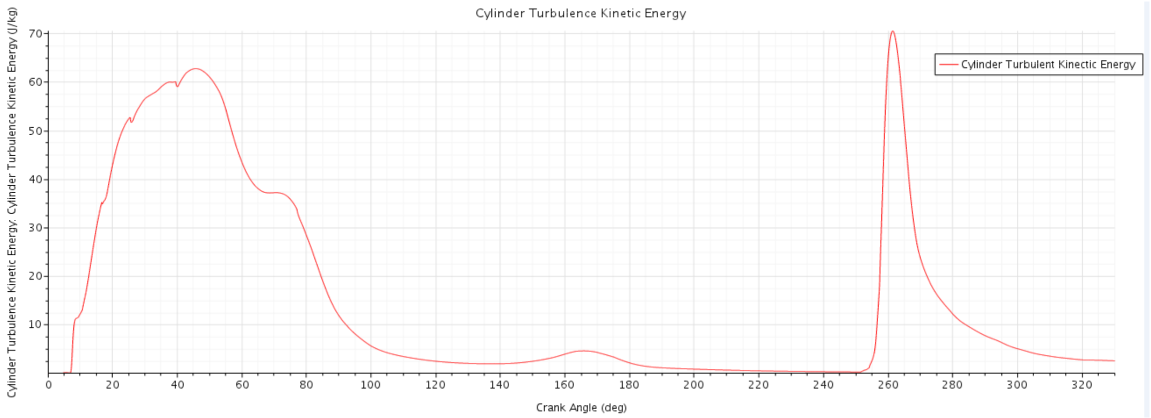

Figure 18. (b) turbulent kinetic energy vs crank angle at 1000 rpm.

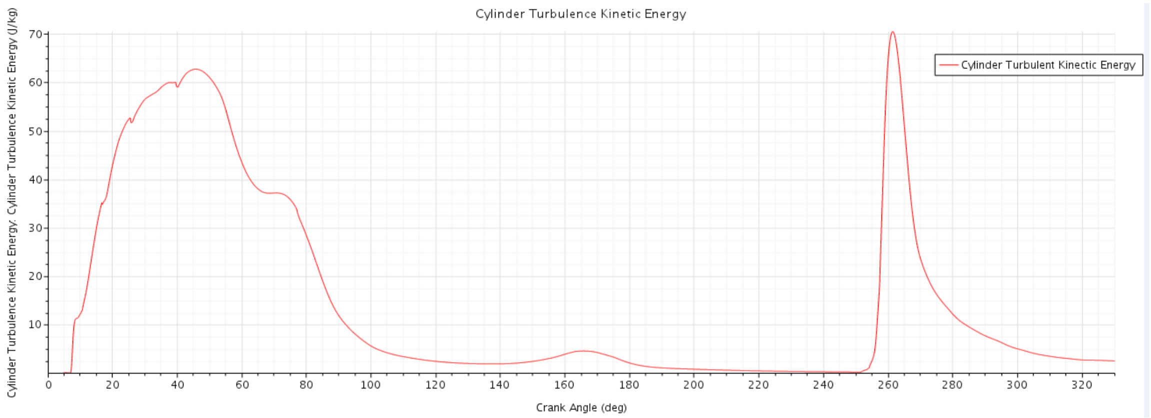

Figure 18. (c) Turbulent kinetic energy vs crank angle at 2000 rpm.

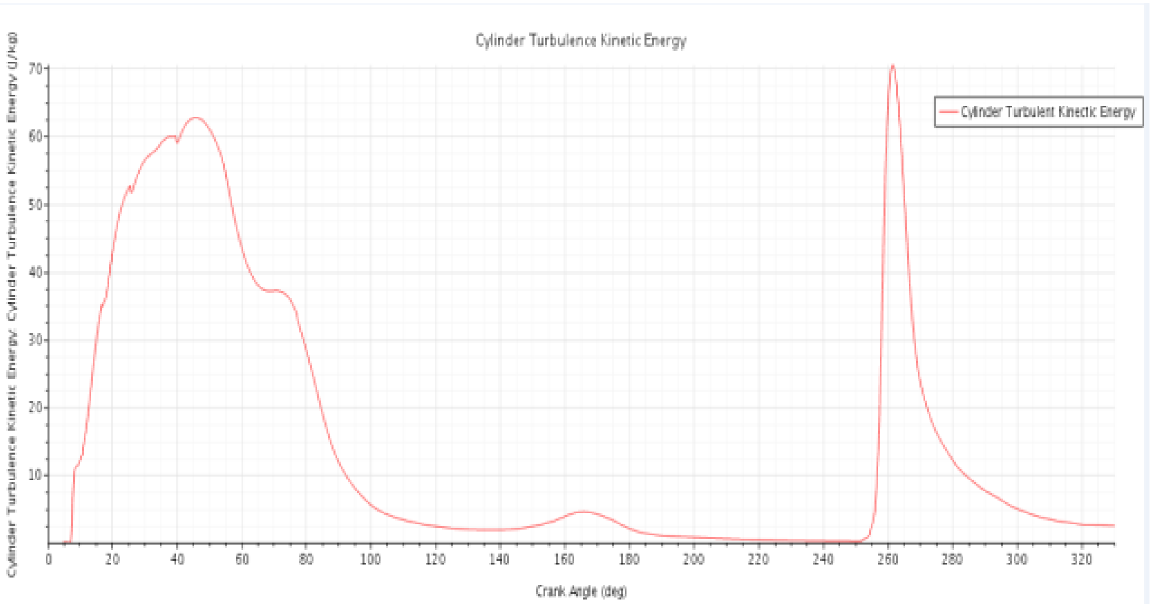

Figure 18. (d) turbulent kinetic energy vs crank angle at 3000 rpm.

Swirl vs Crank angle

The variation of swirl with crank angle at three engine speeds of 1000, 2000 & 3000 rpm. The engine effective combustion is depending up on the swirl. In this analysis observed that, the swirl is gradually increased from the engine speed of 1000, 2000 & 3000 rpm. The maximum swirl attained at the engine

International Journal of I.C. Engines and Gas Turbines
Volume 7, Issue 2
ISSN: 2582-290X

speed of 3000 rpm. When the engine speed increases from 2000 to 3000 rpm the swirl inside the cylinder was increased by about 73.49%. When the engine speed increases from 1000 to 2000 rpm the swirl inside the cylinder was decreased by about -63.74%. Figure 19 (a-d) shows the variation of Swirl with respect to crank angle at Various speed.

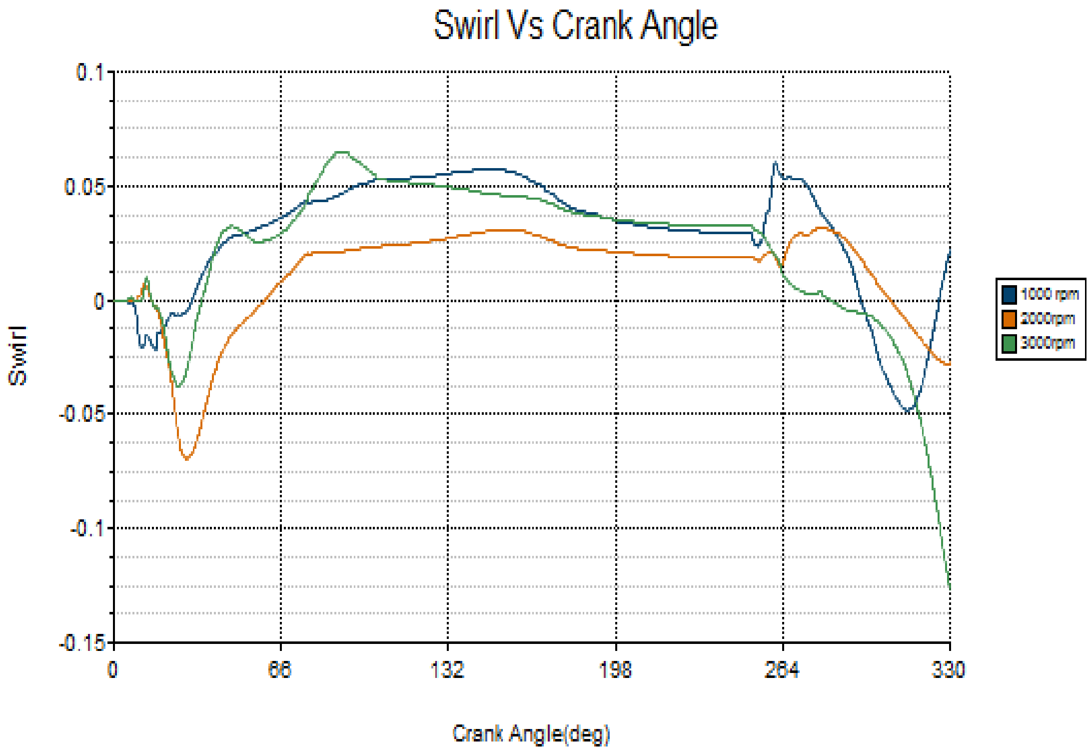

Figure 19. (a) Variation of Swirl with respect to crank angle at Various speed.

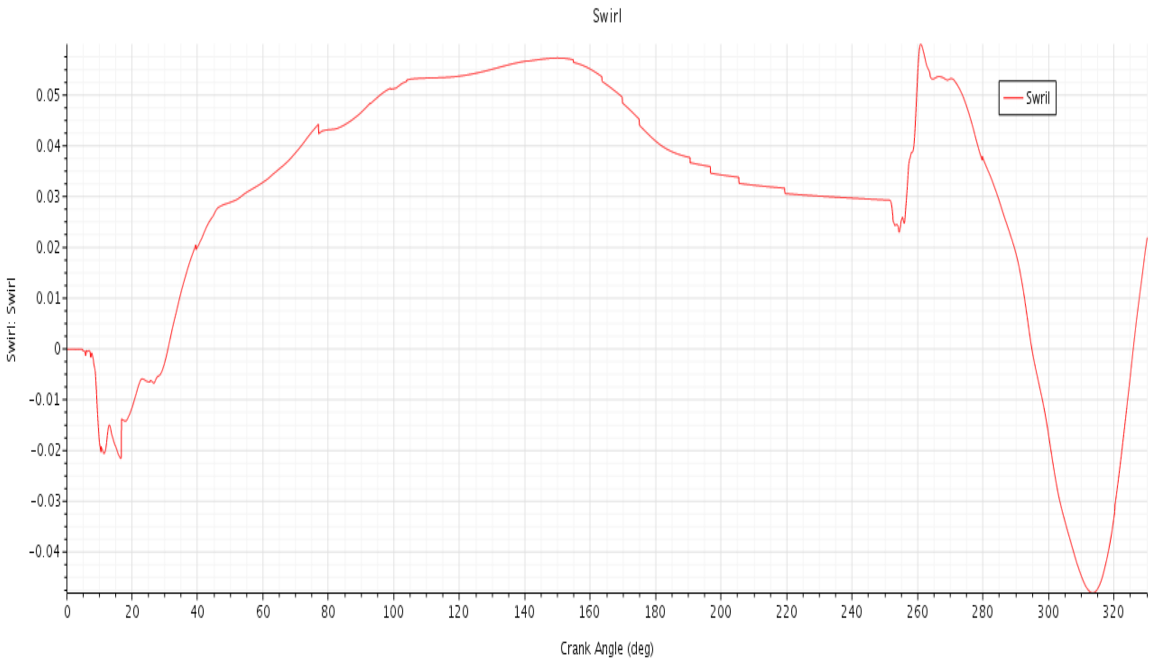

Figure 19. (b) Swirl vs Crank angle at 1000 rpm.

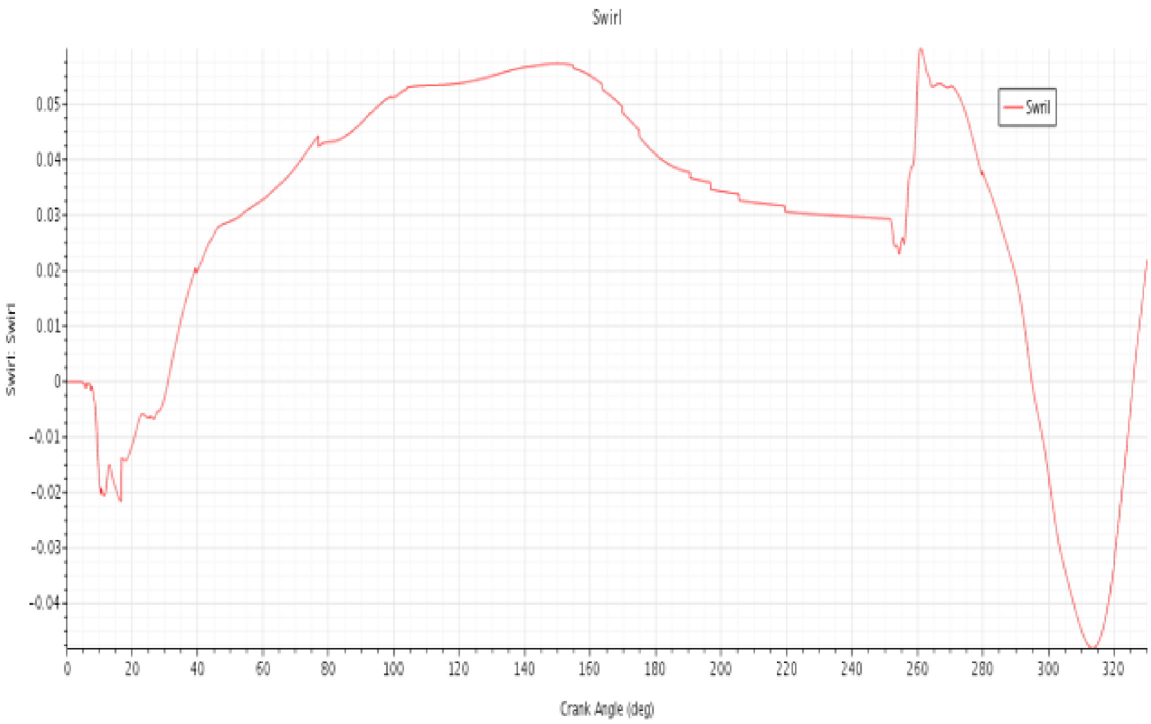

Figure 19. (c) Swirl vs Crank angle at 2000 rpm.

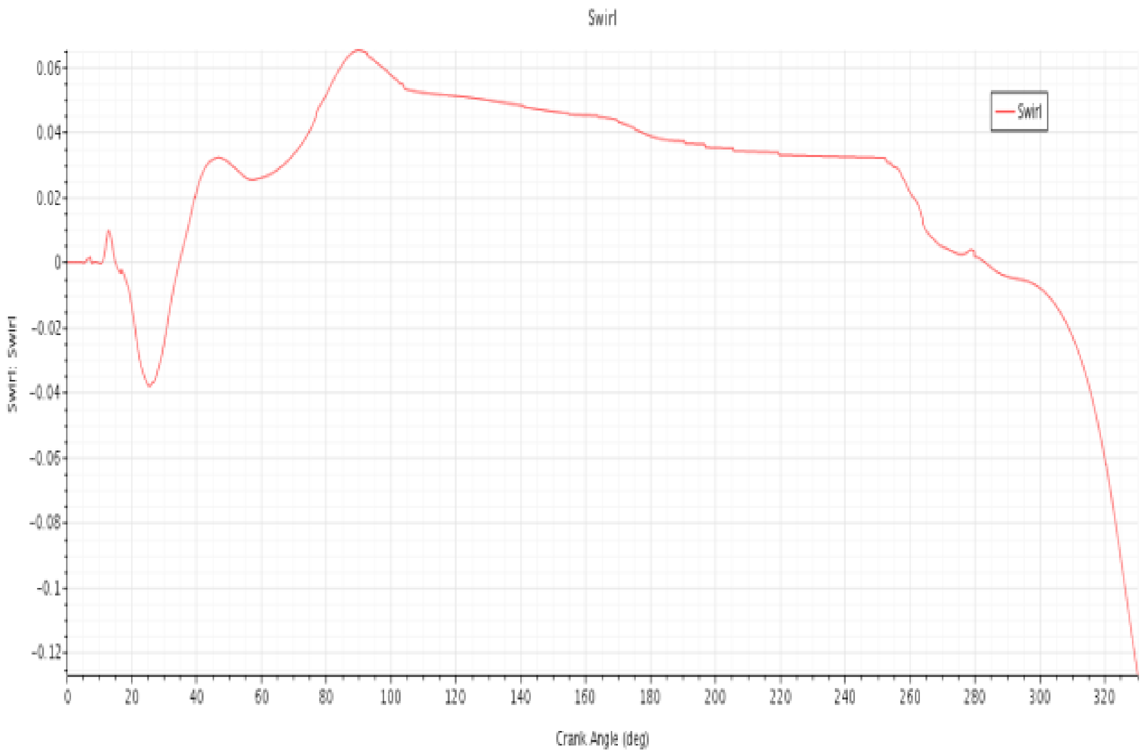

Fig 19 (d) Swirl vs Crank angle at 3000 rpm.

Velocity vs Crank angle

The graphs Shows the velocity of Suction, Compression, Expansion and Exhaust at three different speeds like 1000 rpm, 2000 rpm, 3000 rpm. Figure 20 (a-b) shows the velocity vs Crank angle.

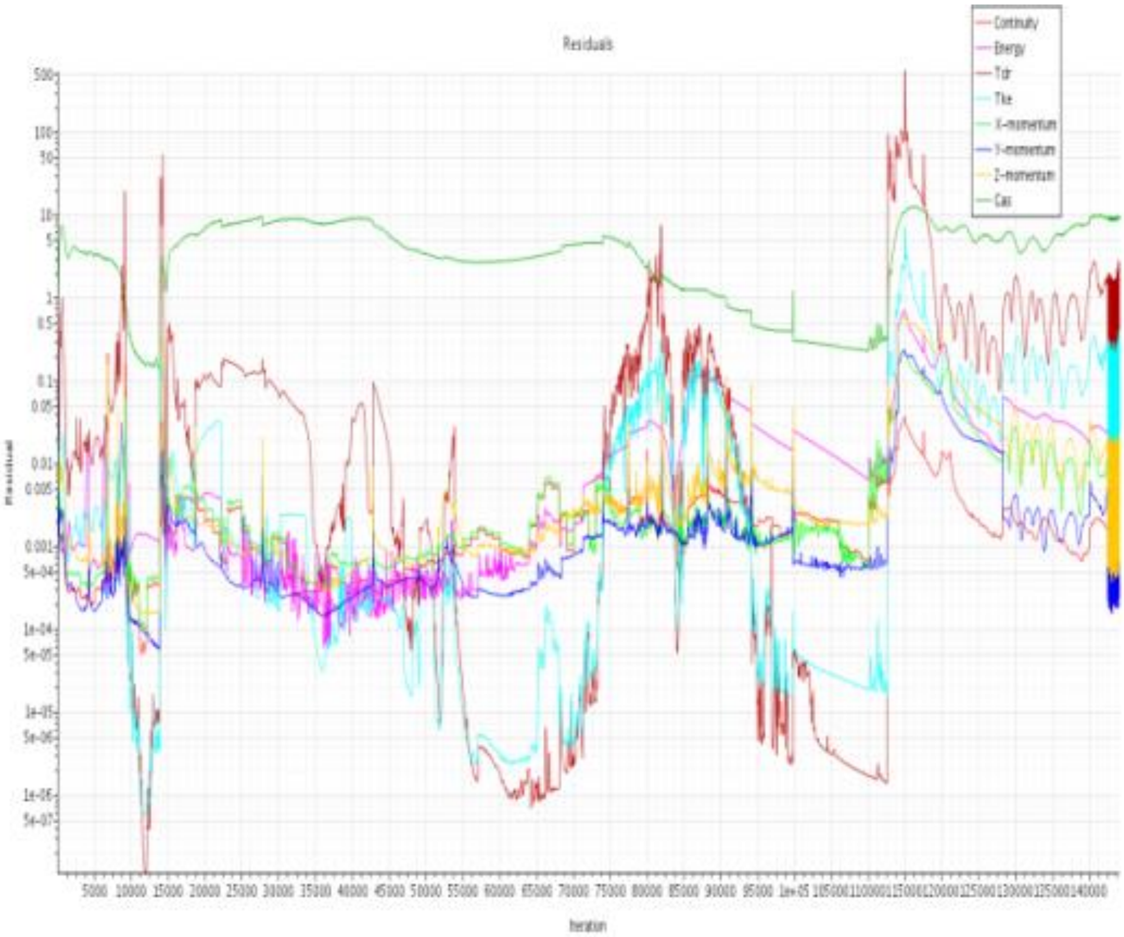

Figure 20. (a) Residual vs iteration.

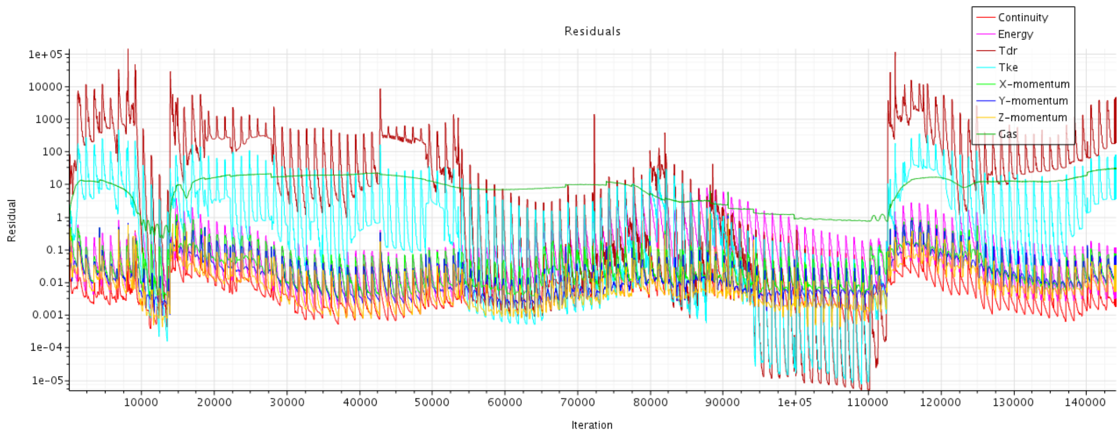

Figure 20. (b) Residual vs iteration.

CONCLUSION

In the present work STAR-CCM + was used as the CFD solver with the help of large eddy simulation (LES) model to evaluate the performance of the three-dimensional HCCI mode of the CI engine at different speeds. Performance of the HCCI engine is calculated by considering the various combustion parameters like Pressure, Temperature, Turbulent kinetic energy and Swirl (or) compound velocity.

- Through simulation Highest pressure inside the cylinder obtained at 2000 rpm which is 57 bar. The pressure at 1000 rpm and 3000 rpm are 56 bar and 53 bar respectively. However, with the increase in the rpm from 2000 to 3000 rpm the pressure inside the cylinder must be increased but it does not happen due to rate of combustion is low when compared to the 1000 and 2000 rpm

- The amount of temperature raise is depending up on the rate of combustion. In this analysis absorbed that the temperature inside cylinder was varied with respected to speed. The maximum temperature was attained at 3000 rpm and the value was 1399.3 K. When the engine speed increases from 2000 rpm to 3000 rpm, the temperature inside the cylinder increased by about 2.70%
- The Turbulent kinetic energy increases with the increase of the engine speed, it gradually rises in the order of 1000 rpm, 2000 rpm, 3000 rpm. The maximum turbulent kinetic energy obtained at 3000 rpm in the exhaust valve process which is 8424.3 kJ/Kg. The turbulent kinetic energy increased more in between 1000 rpm and 2000 rpm which was noted as 269.13% in simulation.

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