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Numerical CFD Analysis of a Direct Injection (DI) Four Strokes Single Cylinder Diesel Engine at Different Compression Ratios

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Nhad K Frhan[1,*] , Azwan Sapit[1,2], Mohd Azahari Razali[2], Mohd Faisal Hushim[2], Akmal Nizam Mohammed[1,2], Bukhari Manshoor[1,2], Amir Khalid[2]

[1] FAST Research Group, Universiti Tun Hussein Onn Malaysia, Parit Raja, Johor, Malaysia
[2] Faculty of Mechanical & Manufacturing Engineering, UniversitiTun Hussein Onn Malaysia. Parit Raja, Johor, Malaysia

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ABSTRACT

This study investigated the non-premixed combustion procedure by using ANSYS 18 software, with varied compression ratios as one of the effective engine design parameters and the theoretical cylinder pressure values were validated with the obtained result. Diesel and n-Heptane fuels were utilized to investigate their effects on combustion process. There are several combustion parameters such as, in-cylinder temperature, in-cylinder pressure, Heat Release rate (HRR), swirl ratio and tumble motion and all these parameters were compared for both the fuels. This work considered the compression ratios of 13, 15 and 17 to find out optimum value at which the combustion process was the best and attained stability. The obtained result reveals that with increasing compression ratio, the pressure and temperature within the cylinder were boosted up along with the increase in swirl ratio and heat release rate.

Keywords:
Direct injection diesel engine, combustion, in-cylinder pressure, in-cylinder temperature, compression ratio, CFD modeling

1. Introduction

Continuous optimization and enhancement of combustion diesel production engine have some environmental and economic significance and it encourages further improvement for substitute fuels. Usually for standard diesel fuel engine those fuels were considered that have higher boiling temperature and smaller cetane value so that emissions were less and the performance was better. In this regard biodegradable fuels, for example vegetable oil, can be used as a substitute to reduce the emission [1-4].

Accordingly, further study is essential to curb the effects of fuel properties like physical and chemical during combustion in forming the pollutant and also to give a clear understanding about this. Earlier researches were carried out on different kinds of engines to reveal precisely what happens at in-cylinder combustion zone. The diesel combustion process happens at higher pressure

[*] *Corresponding author.*
E-mail address: nihadkadem74@gmail.com (Nhad K Frhan)

and temperature for a shorter period when the pilot diesel liquid fuel interacts with the in-cylinder air flow and the chemical reaction occur. In situ diagnostic methods are required which have better radial and temporal resolutions to study this incident [3].

In Oakley *et al*., [4], diesel combustion was investigated implementing several techniques with the instruments having lesser resolutions for both temporal and spatial. To study in detail the formation of pollutant within the engines which are optically visible, new laser operated two dimensional (2D) non-intrusive imaging systems having higher spatial resolution were developed. When higher temporal resolution was applied for a particular type in this diagnosis, the obtained numerical data were even [5-6]. Soot was generated during the oxidation period when its particles increased in size and was possible to observe through elastic scattering, laser induced incandescence (LII), natural measurements and flame luminosity imaging. Detailed information of precursor types at the beginning time of soot construction and its chemical attributes were also obtained by flame emission and multi-wavelength light extinction methods [7-8]. The effect of compression ratio and the fuel's behavior of the combustion method was studied in this paper from the beginning when the fuel was inserted up to the combustion and the generation of soot. n-Heptane is a mono-component fuel. This was applied along with diesel fuel to find out the involvement of the aromatic compound within the latter one for soot generation and it was analyzed against the free aromatic of fuels.

Researchers and automobile manufactures gave attention to fuel-economy advantages of variable-stroke engines. Different compression ratios were realized by utilizing numerous techniques. When the head of the cylinder is at slopping position at an angle, it is described as a Tilting Cylinder position. This position explained the variation in compression ratios because it amplified the clearance volume. Several tilting angles matched the varied compression ratio values. With increased compression ratio values researchers obtained enhanced performance for the parameters such as BTHE and BSFC [7,13]. Emission and performance were most important parameters. An experiment was carried out on a diesel engine considering several engine designing features like compression ratio, injection timing, and use of Methyl esters of Jatopha [10,14] and Mahua Oil [9]. It revealed that the brake power and its thermal efficiency were augmented with the increasing compression ratio and the higher compression ratio was responsible to reduce the amount of specified brake fuel. The effect of variable compression ratios on emission in a diesel engine was also analyzed and it was confirmed that NOx content was boosted up sharply, whereas CO and HC contents were decreased with the increasing compression ratio [12,15].

2. Meshing

The tetrahedral mesh was considered for this modelling at valves and bottom dead regions. The number of features generated at top dead center (TDC) and bottom dead center were nearly 340,000 and 445,000 respectively. The boundary in between hexahedral and tetrahedral meshes was shifted based on the number of features and this re-meshing added density volume to the mesh. The border movement profile was done through Fluent by assigning the movement of the piston. The piston reached the end as per its limit and was in hanging position and at this moment a waiting time was considered so that it restarted its movement and came back to the earlier position. In other words, the piston is moving down with the limit and then hanging and not accompanying the piston any more.

When the border was kept unchanged, an extra increment than the usual limit of the tetrahedral cells' dead volume's skewness was observed and the movement of the valves was responsible for this. At the top of the valves in ports the hexahedral mesh was used to dynamically update it with around 5000 and 135,000 features in TDC and BDC respectively. Altogether the number of features was nearly 345,000 and 580,000 and TDC and BDC. Mesh interface is nothing but its outside borders. The mesh geometry was definitely independent at TDC considering the discretized meshes with 200000, 300000, 400000, and 500000 cell volumes to make the meshes refined and more sensitive.

These grid sizes were utilized in the simulation for pure diesel fuel combustion to compare the curves of the air-fuel blend mass, fuel mass portion within the mixture, and in-cylinder temperature and pressure. Result revealed that the outcome was precise with grid size having 345,000 features at TDC without expanding the mesh density volume any further. This mesh was selected for all other simulations to save the computational time cost. Figure 1 exhibits the meshing and domain of the piston where structured mesh can be found in single row and others are unstructured meshes at bowel-piston. With the movement of the valves and piston, the mesh was dynamically updated as per the above theory.

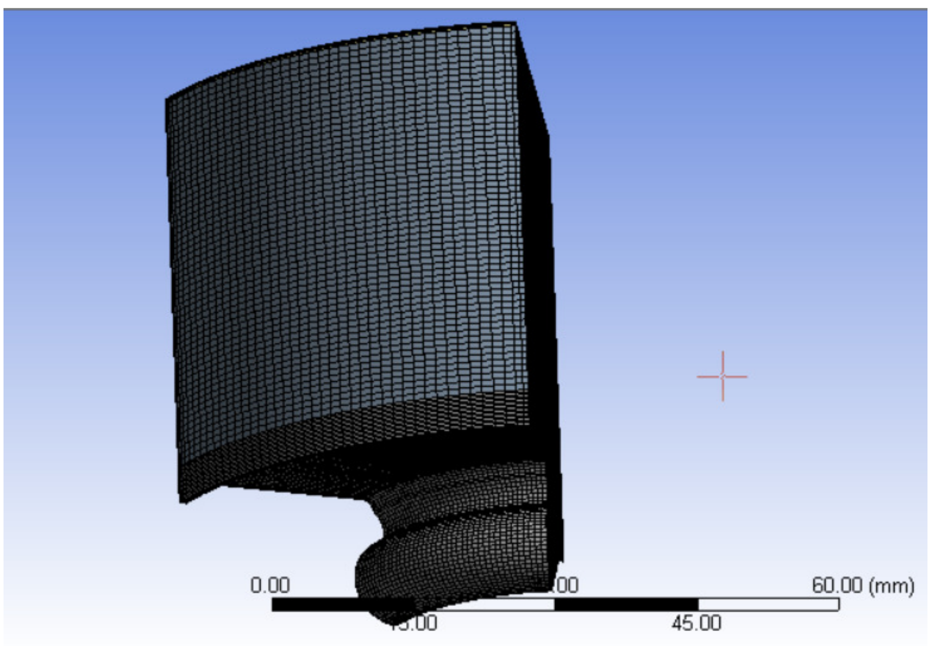

Fig. 1. Meshing domain of the piston

3. Modeling and Analysis

CFD stands for Computational Fluid Dynamics and is very useful software that investigates the heat transfer rate, amount of fluid flow and some other related incidents like chemical reactions, utilizing its analyzer tools and simulation is carried out in the computer. It founds its wide usage in all the sectors where it can be applied and few examples are given below.

- Vehicles and aircrafts for aerodynamics e.g. drag and lift
- Ships for hydrodynamics
- Power-plant for combustion in gas turbines and in internal combustion engines
- Turbo machinery for the flow movement inside the diffuser and rotating access
- Environmental engineering for the distribution of pollutants and effluents

CFD Icem is a very powerful 3D modelling and meshing software for measuring the flow and doing other CFD analysis. It holds a graphic interface for modelling components, meshing and boundary conditions definitions. This was applied when the entire engine parts were collected together. Each part was meshed separately after decomposition. This framework possessed the meshes of one domain facing another mesh that was paved or projected or mapped. However, the amount of grid points associated with the faces around the projection was similar towards the ray. This might result in the tiny mesh sizes by restricting the flow.

Each was initially meshed with another mesh of similar size. The internal combustion of the Engine was simulated through CFD software for its compatibility with physical models to develop the features such as, efficient simulating combustion and multiphase sprays module, liquid films development, also heat and mass transfer through the wall. It also provided transient and turbulence effects along with moving boundaries. Due to this, CFD software was already used in numerous industrial and research applications.

In this study, RNG t-Epsillon technique was utilized as the Turbulence model based on RANS equation to give a clear indication about the fuel and air flow. This physical model is extensively used for engine related application. Reitz-Diwakar model of 3D domain and the Shell auto ignition model were utilized for the Spray break-up of fuel and to determine the combustion rate respectively. All the boundary conditions and required input parameters were satisfied before starting the analysis. Several turbulence equations are available to solve the problem by incorporating them in the software. However, in this study only epsilon model was used since the flow is of turbulent mode. Initially the mesh motion of all the parts of the engine was checked and a cold flow simulation was carried out to make the mesh dependency precise.

4. Cold Flow Simulation

Cold flow is a primary simulation process, mainly opted for checking the mesh motion of the engine’s moving parts and making the engine model error free, in which the combustion process does not occur. The pressure and temperature rise in the cylinder during the crank angle movement were also measured. The clearance volume and the inlet and exhaust valves were clearly visible.

5. Simulation Engine Specification

The engine specification divided into two parts.

Engine geometry specification: the engine carried out in this study to simulate and deeply investigate emission and performance is shown in Table 1.

Table 1
Engine specification

Engine cycle	Diesel – 4 strokes
Connecting Rod Length	200 mm
Crank Radius	20 mm
Rated engine speed	1800 RPM
Compression ratio	13-15-17
Minimum Lift	0.2 mm
Inlet valve closed	570
Exhaust valve open	833

Injector specification: injection has a precisely properties in order to provide a high quality fuel penetration shown in Table 2.

Table 2
Injector specification

Injector position	
x-position	0 mm
y-position	-0.00012 mm
z-position	2E-05 mm
Injection period	
Start injection	721 CA
End injection	742.5 CA
Injector Nozzle topology	
Demeter	0.000254 mm
Cone angle	9
Cone radius	0.00017 mm
Number of injector holes	6
Injection angle	70

6. Results and Discussions

The interactions happened between varying engine design parameters (e.g., Compression ratio), with the results discussed in the following sections.

6.1 Cylinder Pressure

Maximum cylinder pressure was recorded during the power stroke. Due to the piston movement, the volume was a function of in-cylinder pressure, temperature, spray envelope of the inserted fuel and the ignition delay period. Generally, the cylinder pressure curve is drawn with reference to the crank angle. The starting and ending of the combustion was declared. Figure 2 demonstrates various maximum pressures obtained at different compression ratios (17, 15, and 13) for the diesel engine. This reveals that the rise in compression ratio is responsible for continuous increase of the maximum pressure value and it also indicates that maximum pressure was obtained at compression ratio 17. Figure 3 portrays the proportional relationship between in–cylinder pressure and the compression ratio for n-Heptane fuel for which the former was boosted by increasing in-cylinder pressure. The attained in-cylinder maximum pressures at compression ratio 17 for diesel and n-Heptane fuels were 62.5 bars and 55 bars respectively.

6.2 Heat Release Rate (HRR)

This is a measure to describe the conversion of the fuel's chemical energy to the thermal energy after combustion. This directly impacted on the increment of pressure rate and consequently on the produced power. A part of the inserted fuel vaporized during its injection time and mixed with air for which the heat flow augmented and in return produced higher temperature. This was the reason behind the auto ignition. This air-fuel mixture was burnt rapidly at higher temperature and the initial stage of burning is known as premixed burning phase. HRR confirmed that the combustion procedure and the premixed burning phase were initiated and also provided the comparative information about the fuel's combustion rate.

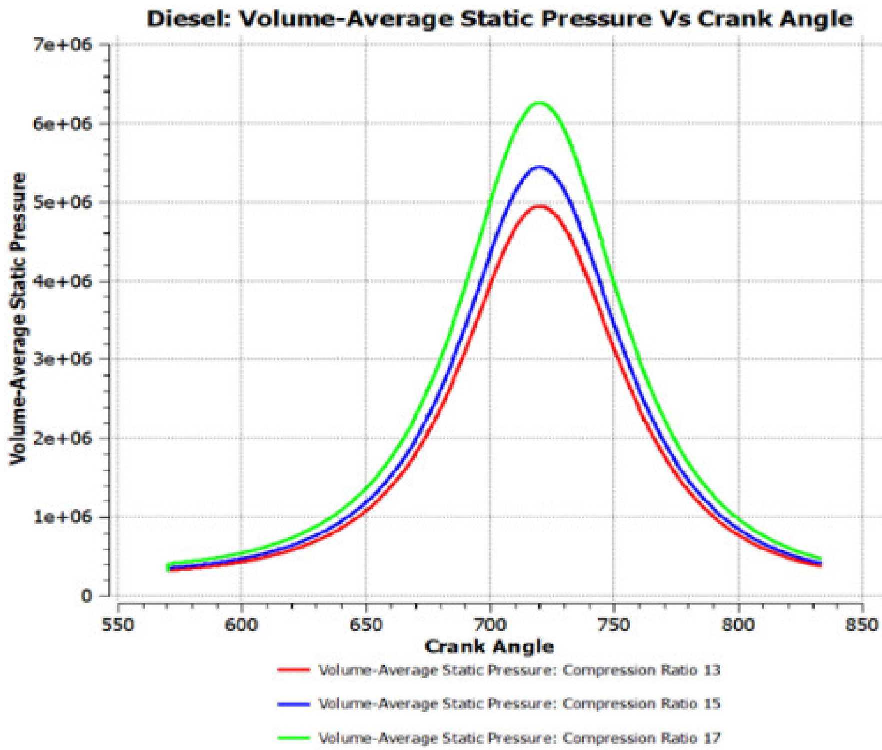

Fig. 2. The attained in-cylinder pressures at several compression ratios for Diesel fuel

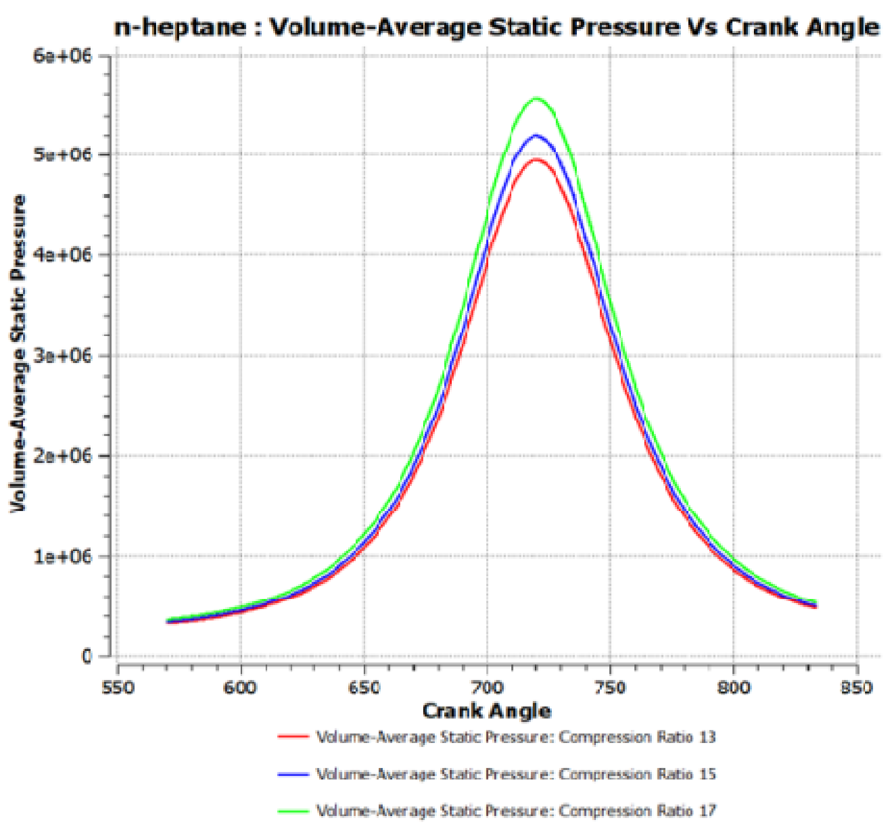

Fig. 3. The obtained in-cylinder pressures at numerous compression ratios for n-Heptane fuel

The time gap in between the combustion initialization and the beginning of fuel insertion within the cylinder is called ignition delay which is a vital factor of combustion process. When the compression ratio was reduced, the ignition delay was increased, leading to late heat release. The main reason behind different HRR values with changing compression ratios was the incomplete combustion. Figure 4 gives a clear image of combustion behaviour for the auto ignition process. The maximum HRR value was 0.68 kJ/Deg obtained at 735 with CR 17 for diesel fuel. Figure 5 shows the in-cylinder combustion process within the combustion chamber over four strokes for n-Heptane fuel. In this case, the maximum HRR was 0.9 kJ/Deg. Therefore, it is evident that the heat release rate for n-Heptane fuel is more than that of diesel fuel.

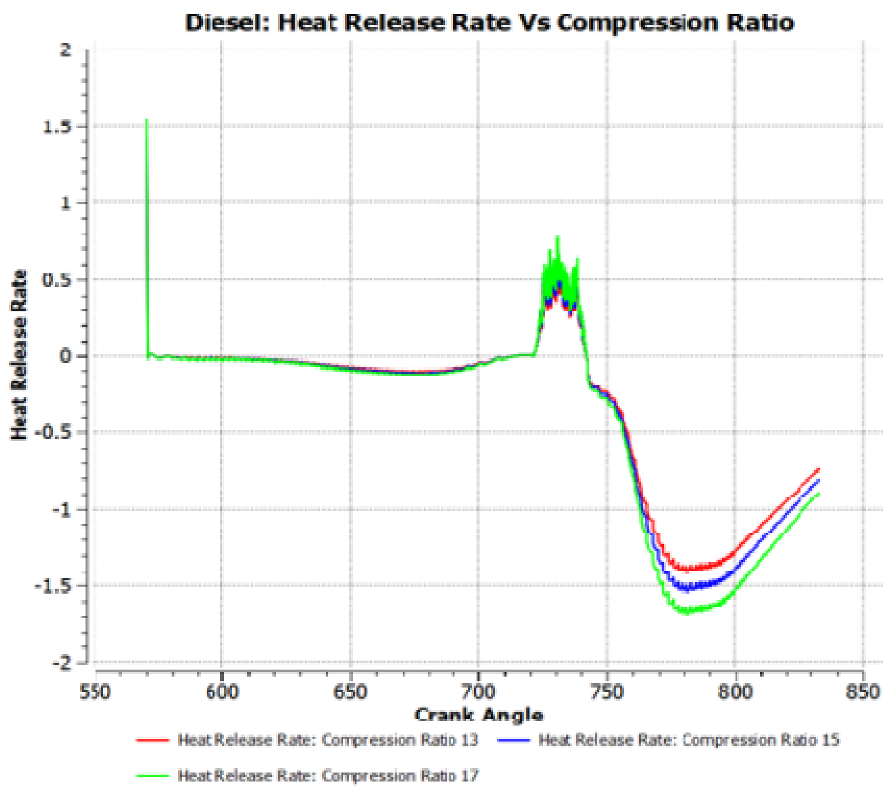

Fig. 4. Diesel: Heat release rate at different compression ratios

6.3 Swirl Motion

The massive fluid vortex within the cylinder is known as swirl where its rotational axis is parallel to the axis of the piston. However, it was assumed to be a solid part having continuous two-dimensional movement during compression and also at combustion period. Swirl preserved the entire angular momentum by keeping its decay at minimum during compression [3].

The air must be in motion within the cylinder before injecting the fuel to make the air-fuel blend appropriate and this is crucial for better combustion. The detailed information about the in-cylinder air movement was obtained through simulation. The piston speed was kept constant at 1500 RPM. At the middle of the engine cylinder, a clockwise vortex was generated beneath the intake valves so that the high speed air did not hit the walls of the cylinder, which instead moved towards its center. A stretched vortex was generated towards the wall when the high speed air struck the cylinder wall. Figure 6 show the behaviour and provide detailed information about swirl of air –fuel blend inside combustion engine. The obtained swirl ratio had a negative attitude during injection period enclosed by (700° -750°) crank angle. Consequently, when the time period of maximum HRR was over, the swirl ratio tried to increase and was about 50° crank angle ATDC.

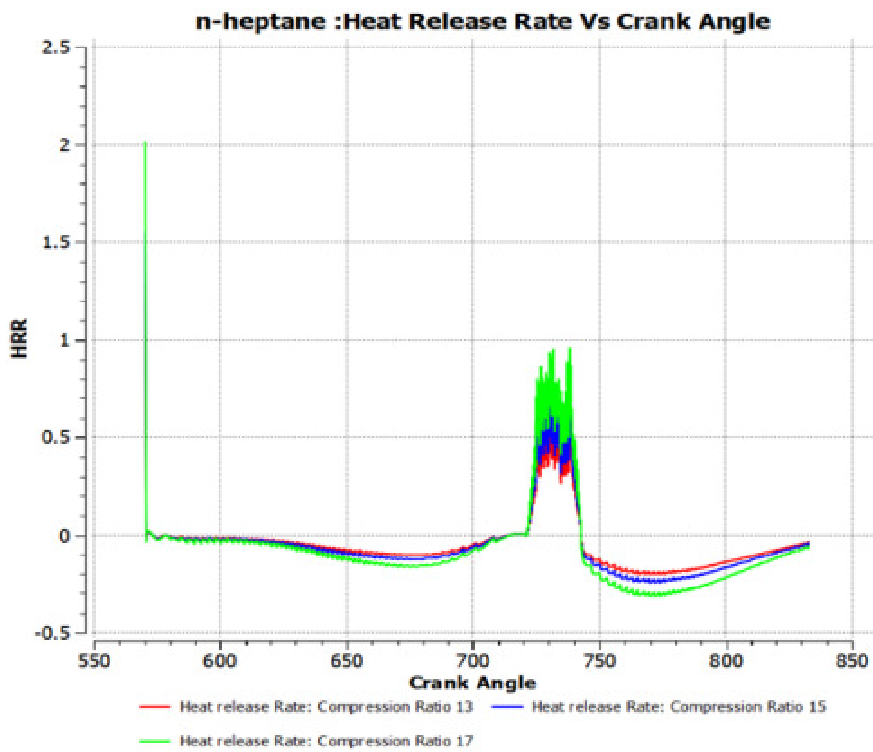

Fig. 5. n-Heptane fuel: Heat release rate at different compression ratios

6.4 Tumble Motion

Tumbling motion was generated as an axis enclosed by the clearance area either of the piston top crown or of the cylinder head due to the huge vertical surge at the time of intake where the relation between its rotational axis and the axis of the cylinder was normal, similar as barrel rotation. It was the main reason to produce squishing wave in the in-cylinder working fluid when the piston arrived close to TDC and hence, termed as barrel or vertical swirl. The tumbling motion was expected in the cylindrical coordinates because tumble flowed both in axial and radial direction. If an intake jet has only the tangential and the axial components in the cylindrical coordinate.

Swirl and tumble flow interacted through the compression stroke for which squishing wave of air was formed. Figure 7 explains the nature of the tumble flow within the cylinder and also describes how it varies. Tumble value was negative during the initial time of injection and attained its lowest value at nearly 740° after TDC when the injection time was over. A remarkable modification in the curve was observed when the ratio started to rise.

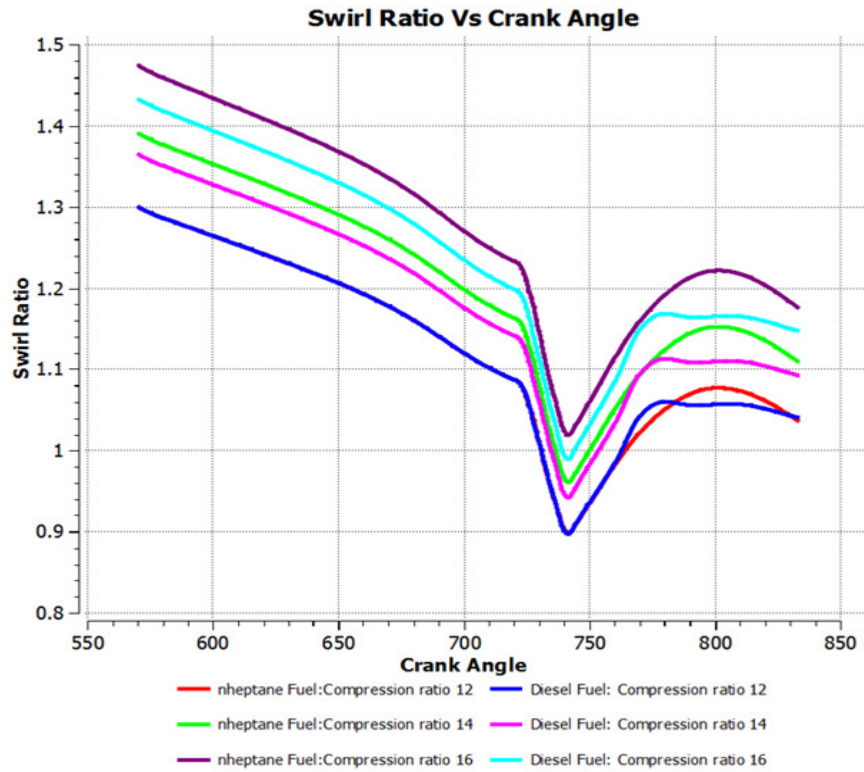

Fig. 6. Diesel, n-Heptane fuel: swirl ratio vs crank angle

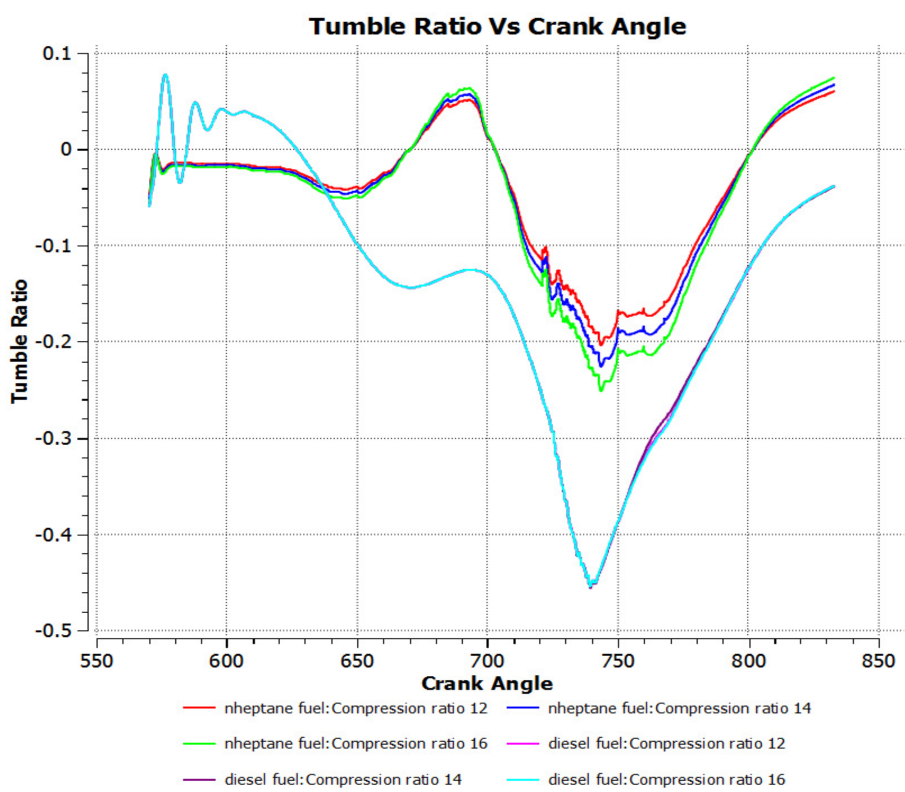

Fig. 7. Diesel, n-Heptane: Tumble ratio vs crank angle

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