

Research Article

Computation Fluid Dynamics Simulation of Spark Ignition Engine for Gaseous Fuels with Different Spark Time

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Abstract

Gaseous fuels offer several advantages such as clean combustion, high octane number, high availability, and attractive price. They have lower energy content than conventional fuels like petrol or diesel, however they can potentially deliver greenhouse gas emission reductions and air quality benefits compared to conventional fuels. The actual level of benefits in emission reductions varies greatly depending on the gas type, fuel quality, engine technology and driving behaviour. In the case of simulation the development of Computation Fluid Dynamics (CFD) methodology for IC (Internal Combustion) engine design represents a particular challenge due to the complex physics and mechanics, perhaps more than with any other widely-used mechanical device. Running the engine on gas is a prospect which is on offer for greener environment but in order to justify the possibilities thus a performance analysis need to be carried out. The trends in the variation of the parameters like Pressure, Temperature, Nitrogen Oxide (NOX), Carbon Monoxide (CO) emission are plotted against Crank Angle. The optimum Spark time during which the Power output is maximum has been analysed using the software.

Keywords: Spark Time (ST), Compression ratio, Stoichiometric Ratio, Crank Angle (CA) Air-Fuel ratio, Computational Fluid Dynamic (CFD), Propane.

Introduction

The internal combustion engine is a heat engine that converts chemical energy of fuel into mechanical energy. An internal combustion engines is distinct from external combustion engines, energy is released by burning or oxidizing the fuel inside the engine. In order to obtain more data about IC-engines with respect to its power developed, imep, peak pressure and its occurrence, CFD potentially offers a cost effective way of simulating results. Use of CFD simulation for the design of IC-engine is further advertised by the advancements made in combustion and turbulence. Making simulation study of an engine using STAR-CD engine simulation software helps in the calculation of engine power and other parameter variation with respect to the Spark time with least amount of time. The purpose of this work is to simulate the S.I Engine using gaseous fuels. Propane was used as a fuel in this analysis. The simulation was carried out using CFD Simulation software STAR-CD which uses an Unstructured Tetrahedral moving mesh grid under the transient condition. STAR-CD combustion simulation in perfectly mixed mixture is carried out using the 3- Zone Extended Coherent Flame Model (ECFM-3Z) (O. Colin et.al,2004) .The CFD simulation involves running the

engine with a constant Compression ratio, Equivalence ratio and varying Spark timing.The first section shows the use of the software for geometric modelling, allocation of cells in STAR-CD and trimming method involved in STAR-CD. The second section illustrates the mathematical background for the calculation of Peak Pressure. The Mathematically calculated results are in line with the software simulated results. The third part mainly focuses on the results obtained and the conclusion obtained from the Simulation Analysis. The maximum Power Output, Maximum Peak Pressure obtained are concluded for different Spark timing.

Geometrical Modeling

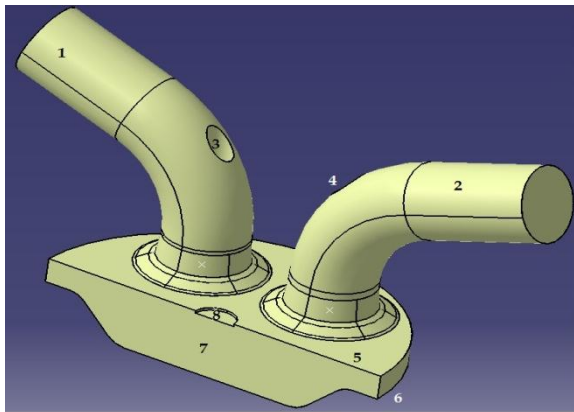
CATIA tool was used for modeling the engine. During model preparation the entire surface should be in closed position because trimmed method requires a completely closed surface for grid generation. As the actual engine configuration is 4 cylinder, for the ease of simulation only one cylinder was analyzed. Surface mesh generation is done using STAR-CCM+ which is then used in STAR-CD software for mesh generation and further analysis. Allocation of the parts like ports, valves, cylinder head, and piston was done using STAR-CCM+.The mesh used in the simulation was Unstructured Tetrahedral moving mesh grid. STAR-CD, together with es-ice, automates the setup and running of the sophisticated moving-mesh technology required for engine simulation. *Es-ice* is designed to facilitate moving-grid, transient analyses of

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internal combustion engines is capable of creating grids for two, three, and four or five-valve cylinders. It also generates 'events' input for pro-STAR and moves the mesh during the analysis. The computational mesh is then created using either the "Trimming" or "Mapping" method. In this analysis trimming method was utilized, as the method is easier in comparison with mapping method, which utilizes more time for creating the mesh. The initial and boundary conditions are generated using MATLAB, which is called as the Transient data, based on this data the simulation marches forward in an implicit method.

Table 1 Specification of the Engine

Engine model	Cummins NTC-495-G
Fuel	Propane
Number of cylinders	4
Bore/Stroke	130mm/152mm
Connecting rod length	308mm
Engine speed	1500rpm
Crank radius	76mm
Compression ratio	10:01
Maximum intake valve lift	9.6mm
Maximum exhaust valve lift	9.2mm



CATIA Model

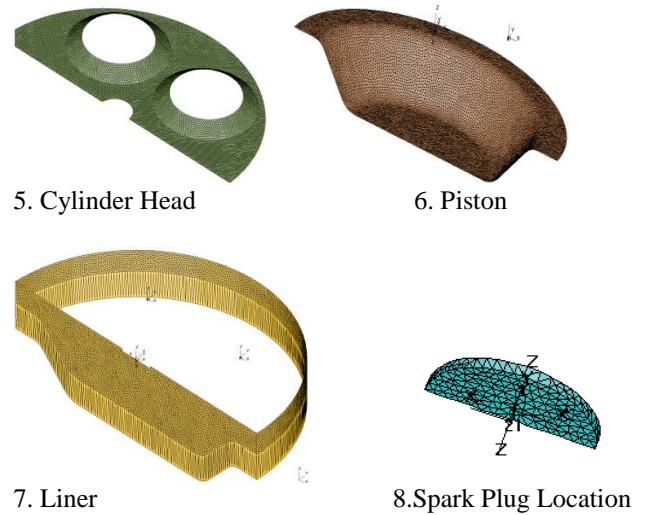
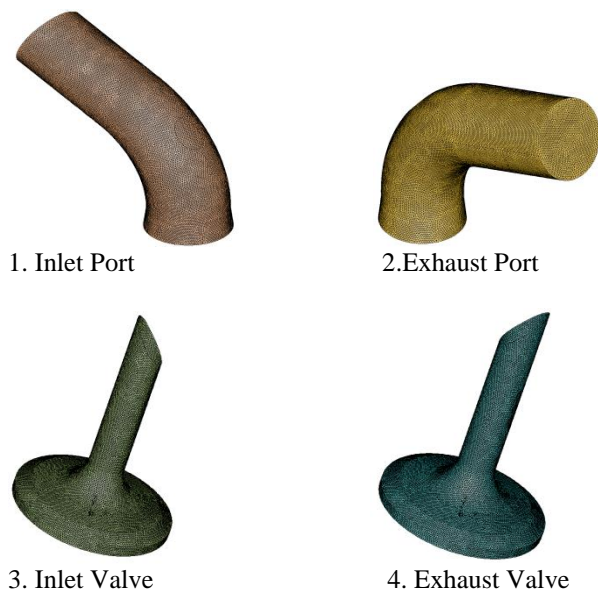


Fig 1 Parts Creation and Allocation of Parts in STAR-CD Software

Mathematical Background of Peak Pressure

As per the Air Standard Otto Cycle, considering only air inside the cylinder, theoretical calculation was carried out as below (John B.Heywood, 1988). The results are matched with the simulation and the obtained results are matched. The theoretical results obtained are with close match with the results obtained from the software. The software allows the simulation to be carried without the injection of the fuel which bear a resemblance to simulation of Motoring run, i.e., basically an Air standard cycle.

Assumptions used are

- Air is an ideal gas with constant C_p and C_v
- No intake or exhaust processes
- All internal processes are reversible

P-Pressure, 1-Inlet, 2-Compressed
 V-Volume, 1-Inlet, 2-Compressed

$$P_1 V_1^n = P_2 V_2^n$$

$$P_2 = P_1 (V_1/V_2)^n$$

$$P_2 = 1 \text{ bar} \times 10^{1.4}$$

$P_2 = 25.118 \text{ bar}$ against actual pressure obtained is 26.418 bar ,

Hence Variation = 5.175%

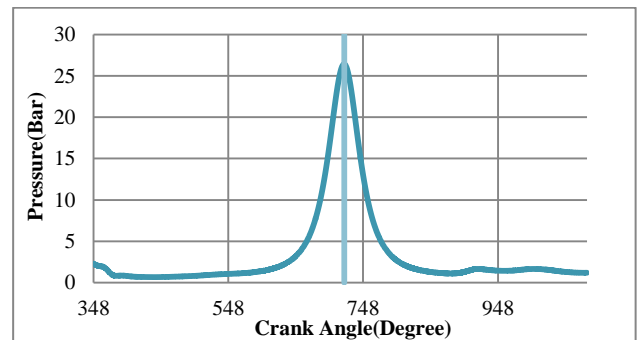


Fig 2 Crank Angle V/S Pressure Graph for a Cranking Curve

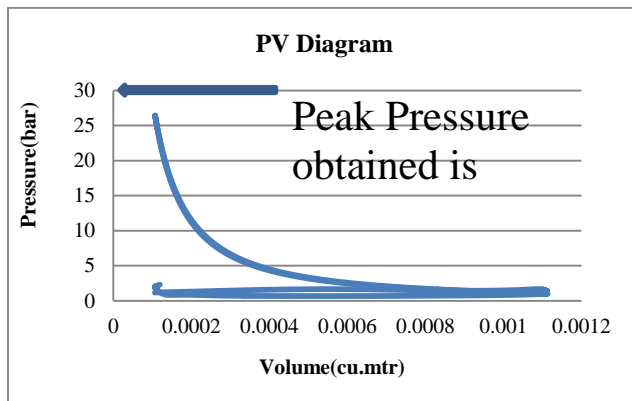


Fig 3 Pressure V/S Volume Graph for a Cold Run with Compression Ratio of 10

Results and Discussion

Pressure v/s Crank angle (P-θ plot)

The simulation is carried out using a set of fixed parameter i.e., Compression ratio 10, Equivalence ratio 1 and varying the Spark Time which results in the varying trend of parameters (John B.Heywood, 1988). These parameters are plotted against Crank Angle.

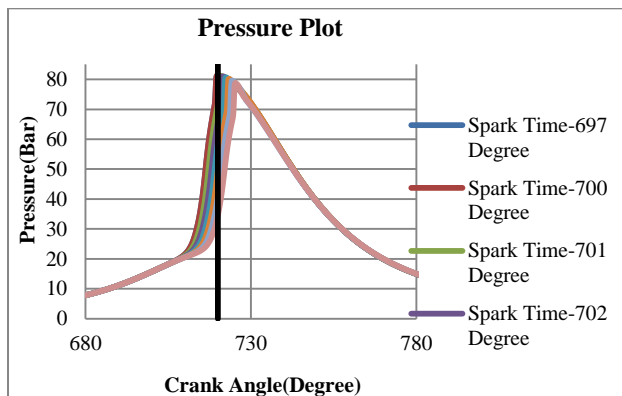


Fig 4 Variation of Pressure with respect to Crank Angle

The suction stroke is followed by Compression process initiated at 5000 CA position during which in-cylinder pressure increases by virtue of the compression work on the air-fuel mixture. At 7000 CA ignition of the combustible mixture takes place as a result of combustion temperature inside cylinder increases and attains a peak pressure and after combustion piston moves from TDC to BDC to deliver the power as a result of combustion. After the power stroke the burnt gases are let out to the atmosphere which causes decrease in pressure inside the cylinder, which is clearly shown in Figure 4. At the Spark angle of 7000 CA a maximum pressure of 81.350 bar was observed during the analysis as compared to the other Spark timing. However the occurrence of maximum pressure does not produce maximum work done and maximum Power output(Hakan Bayraktar et.al, 2005)

Temperature v/s Crank angle (T-θ plot)

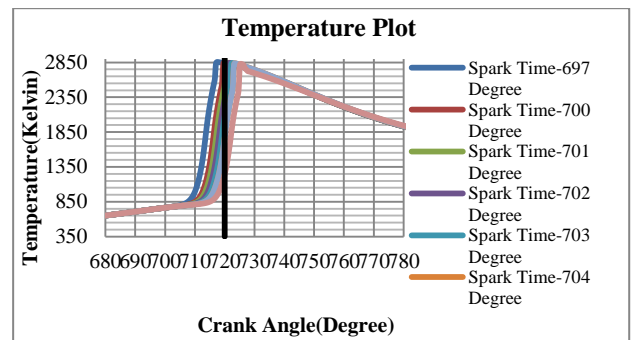


Fig 5 Variation of Temperature with respect to Crank Angle

The absolute temperatures for the Spark Time of 697 CA, 700,701,702,703,704,705 and 706 are shown in the Figure 5. Temperature variation follows the Pressure variation trend. Since at the suction stroke in cylinder pressure is less for the first ignition in the cylinder and later it attains some increased temperature as it is succeeded by the previous combustion cycles. In the graph it is shown that temperature inside the cylinder is less before combustion and after the combustion at specified Spark Time the spark plug initiates the spark, due to this the gas mixture ignites and produces the products of combustion which causes temperature inside the cylinder to increase. As the Spark Angle is moved towards TDC correspondingly increases the Temperature inside the cylinder. The observation of maximum Temperature is obtained at a Spark Time of 697^oCA which is 2856.064K.

NO Emission

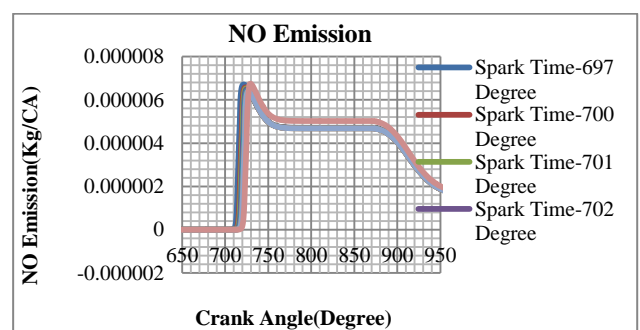


Fig 6 Variation of Nitrogen Oxide Emission with respect to Crank Angle

It was observed that retarding the ignition timing(moving the spark time towards TDC) causes reduction in NO formation, this was mainly due to the drop in the peak temperature during the combustion process. Maximum NO emission of 6.75×10^{-6} Kg/CA was obtained for a Spark Time of 706 CA as indicated in the Figure 6. On the other hand advancing the ignition timing causes rise in NO formation due to increase in pressure and temperature during the combustion process. As advancing the ignition

Table 2 Variations of Parameters with respect to Spark Time

Fuel	Spark Time (Degree CA)	bTDC	CR	Eq.Ratio	Peak Pressure(Bars)	Peak Pressure Observed at (Degree CA)	Temperature (K)	Peak Temperature Observed at (Degree CA)	Net Indicated Work(KJ)	Power(KW)	Power(hp)	IMEP(Kpa)
Propane	697	23	10	1	81.206	718.442	2856.064	717.542	0.97605	12.2023	16.364	483.784
Propane	700	20	10	1	81.350	719.942	2849.548	719.942	0.989092	12.3654	16.582	490.249
Propane	701	19	10	1	81.233	720.742	2846.887	720.742	0.992991	12.4141	16.648	492.181
Propane	702	18	10	1	81.011	721.542	2844.050	721.642	0.996125	12.4533	16.700	493.735
Propane	703	17	10	1	80.681	722.442	2841.142	722.542	0.999286	12.4928	16.753	495.302
Propane	704	16	10	1	80.201	723.342	2837.515	723.442	1.0003	12.5049	16.769	495.859
Propane	705	15	10	1	79.592	724.342	2833.894	724.442	0.998065	12.4775	16.733	494.696
Propane	706	14	10	1	78.837	725.342	2829.769	725.442	0.99927	12.4926	16.753	495.293

timing initiates the combustion process earlier in the cycle, which in turn, moves the location of the pressure peak near to TDC, thus increasing temperature during combustion process

^obTDC).A decreasing trend is observed as it is moved ahead of CA.Maximum Power output is obtained is

12.5049KW at 704 Degree CA (16 ^obTDC) with Net indicated Work of 1.0003KJ (Sulaiman et.al.2012)

CO Emission

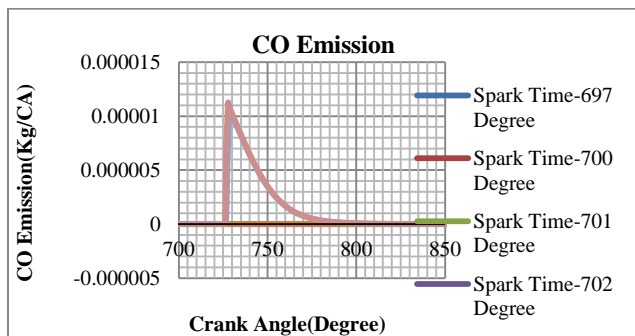


Fig 7 Variation of CO Emission with respect to Crank Angle

As the Spark Time is retarded (moving the Spark Angle towards TDC) the emission of CO increases, the maximum amount of CO emitted was 1.13×10^{-5} Kg/CA with a Spark Angle of 706 CA as indicated in the Figure 7. The quantity of CO emitted during the span of total analysis is very small, as the Compression ratio is 10 and Stoichiometric equivalence ratio of 1 is considered during the analysis. For fuel-rich mixtures CO concentrations in the exhaust increase steadily with increasing equivalence ratio, as the amount of excess fuel increases. For fuel-lean mixtures, CO concentrations in the exhaust vary little with equivalence ratio and are of order 10^{-3} (G.H. Abd-Alla et.al,2002).In premixed hydrocarbon-air flames, the CO concentration increases rapidly in the flame zone to a maximum value, which is larger than the equilibrium value for adiabatic of the fuel-air mixture.

Table 2 indicates the Power developed, imep and Net work obtained from the simulation for the Spark Time of 697,700,701,702,703,704,705 and 706 Degree CA The trend in the variation indicates, as the sparking angle is moved towards TDC the Power goes on increasing (Refer Figure 8 and Figure 9), upto 703 Degree CA (17

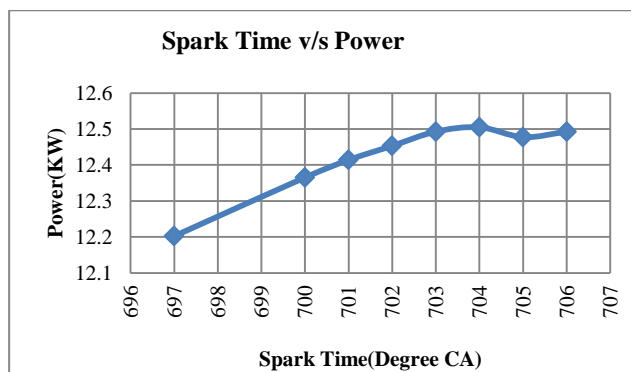


Fig. 8 Variation of Spark Time with power

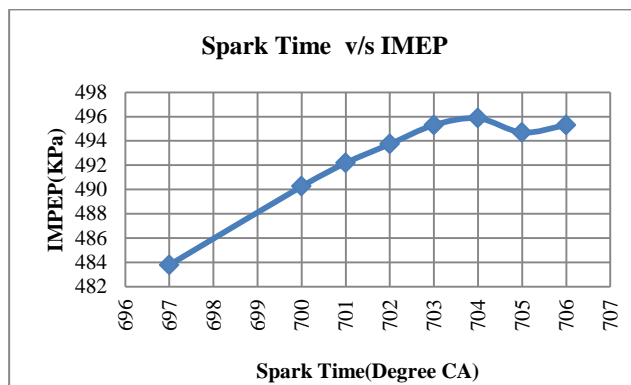


Fig. 9 Variation of Spark Time with IMEP

Conclusion

The CFD simulation work carried out using STAR-CD software for an IC Engine fueled with Propane (C₃H₈) gas with varying Spark Timing resulted the following conclusion.

- The maximum peak pressure of 81.350 bar at 719.942 ^oCA was obtained for Spark Time of 700 Degree CA(20 ^obTDC) as the occurrence of the pressure was

before TDC the Power Output and the corresponding Net Indicated Work was too low.

- As the variation of Spark Time was varied from 697 Degree CA to 706 Degree CA the Maximum Power output of 12.5049 KW and Net Indicated work of 1.0003 KJ was produced at a Spark Time of 704 Degree CA. This suggests that the optimum Spark Time for the analyzed engine is 704 Degree CA.
- The motored graph of Pressure with respect to Crank Angle was simulated using STAR-CD and the result obtained was compared with respect to the Theoretical calculated values. Variation observed was 5.175% which validates the CFD analysis process.
- ECFM-3Z model for combustion used in the study provides the analysis of all three zones of combustion (pre-mixed, mixed and post-mixed) which is not available in many of the CFD packages. Hence the results are accurate as compared to other combustion model.
- Generation of Mesh using STAR-CD is done in less time due to the combination of better static and dynamic mesh handling flexibility.

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