CFD Analysis of I.C. Engine Processes

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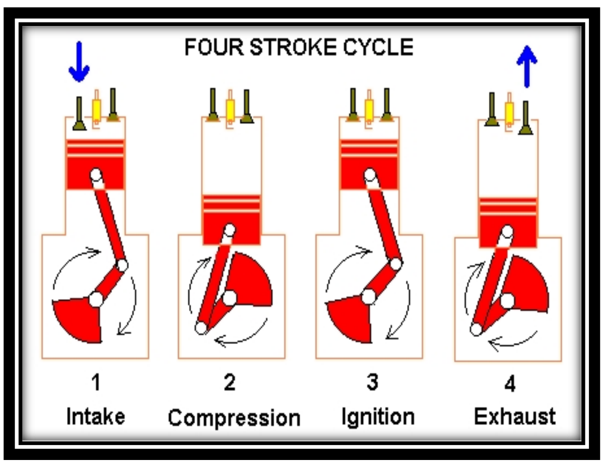
Abstract- *Modeling is a process of developing and using the appropriate combination of assumptions and equations that permit the critical features of the process to be analyzed. In case of spark ignition engine, fuel and oxidizer are mixed at the molecular level prior to ignition. Combustion occurs as a flame front; propagating into the unburnt reactants called as premixed combustion. Premixed combustion is usually occurs as a thin, propagating flame that is stretched and contorted by turbulence. The effect of turbulence is to wrinkle and stretch the propagating laminar flame sheet, increasing the sheet area and, in turn, the effective flame speed. The objective of project work is to do combustion modeling of single cylinder spark ignition engine of 124.7 cc ignitor bike by using computational fluid dynamics for predicting the turbulent flame speed at different equivalence ratio.*

I. INTRODUCTION



Combustion process is a chemical phenomenon which involves exothermic chemical reaction between the fuel and the oxidizer (air) [1]. The term combustion is saved for those reactions that take place very rapidly with large conversion of chemical energy into sensible energy. When a combustible fuel-air mixture is ignited with a spark, a flame propagates with a velocity determined by the kind of fuel-air mixture and the external conditions. Accordingly; the velocity of flame propagation depends on whether the vessel is taken as a reference or the unburned gas is taken as reference. Usually, the former is referred to as the flame travel speed, while the latter is known as the flame propagation speed or the flame velocity. Turbulent flame speed for C.I and S.I engine can be predicted by using non- premixed combustion, premixed combustion and partially premixed combustion models. . K. A. Malik [1] developed a theoretical model for turbulent flame speed, based on turbulent transport process for spark ignition engine. This model was then taken into account and the effect of turbulence was generated by (i) the expanding flame front and (ii) the inlet valve geometry. Abu-Orf [5] developed a new reaction rate model and validated the r e sul t s for premixed turbulent combustion in spark ignition engines. The governing equations were transformed into a moving coordinate system to take into account the piston motion. The model behaved in a satisfactory manner in response to changes in fuel type, equivalence ratio, ignition timing, compression ratio and engine speed. Garner and Ashforth [2] studied experimentally the effect of pressure on flame velocities of benzene-air and 2,2,4-trimethyl-air mixture below atmospheric pressure. They found that the flame velocity increases with the decrease in pressure The predicted turbulent flame speed values were compared with the experimental values in the speed ranges 600 rpm to 1160 rpm and fuel air equivalence ratio from 0.8 to 1.25 which were found to be in good agreement with each other. Abu-Orf [5] developed a new reaction rate model and validated the r e sul t s for premixed turbulent combustion in spark ignition engines. The governing equations were transformed into a moving coordinate system to take into account the piston motion. The model behaved in a satisfactory manner in response to changes in fuel type, equivalence ratio, ignition timing, compression ratio and engine speed. Sunil U. S. Moda [8] did a computational investigation of heavy fuel feasibility in a gasoline direct injection spark ignition engine. He developed a computational model to explore the feasibility of heavy fuel in a gasoline direct injection spark ignition engine. A geometrical model identical to that of the Pontiac Solstice 2008 was developed using ANSYS and Gambit 2.4. In accordance with the various literatures, the combustion modeling of single cylinder four stroke spark ignition engine of 124.7 cc was done and the turbulent flame speed was predicted using pre-mixed combustion.

II. COLD FLOW ANALYSIS

The CFD analyses performed can be classified into:

Port Flow Analysis: Quantification of flow rate, swirl and tumble, with static engine geometry at different locations during the engine cycle.

Cold Flow Analysis: Engine cycle with moving geometry, air flow and no fuel injection or reactions.

In-Cylinder Combustion Simulation: Power and exhaust strokes with fuel injection, ignition, reactions, and pollutant prediction on moving geometry.

Full Cycle Simulation: Simulation of the entire engine cycle with air flow, fuel injection, combustion, and reactions.

Cold flow analysis involves modeling the airflow and possibly the fuel injection in the transient engine cycle without reactions. The goal is to capture the mixture formation process by accurately accounting for the interaction of moving geometry with the fluid dynamics of the induction process. The changing characteristics of the air flow jet that tumbles into the cylinder with swirl via intake valves and the exhaust jet through the exhaust valves as they open and close can be determined, along with the turbulence production from swirl and tumble due to compression and squish. This information is very useful to ensure that the conditions in the cylinder at the end of the compression stroke are right for combustion and flame propagation. High turbulence levels facilitate rapid flame propagation and complete combustion during the power stroke. A well-mixed and highly turbulent air flow is critical to ensure the right air/fuel ratio throughout the combustion. CFD can also assess the level of charge stratification. Setting up the CFD model for cold flow analysis involves additional work in specifying the necessary information to compute the motion of the valves and piston in addition to the boundary conditions, turbulence models and other parameters. This includes specifying valve and piston geometry, along with the lift curves and engine geometric characteristics in order to calculate their position as a function of crank angle.

III. PREMIXED COMBUSTION

In premixed combustion, fuel and oxidizer are mixed at the molecular level prior to ignition. Combustion occurs as a flame front propagating into the unburnt reactants. The turbulent premixed combustion model, involves the solution of a transport equation for the reaction progress variable. The closure of this equation is based on the definition of the turbulent flame speed. Examples of premixed combustion include aspirated internal combustion engines, lean premixed gas turbine combustors, and gas-leak explosions. Premixed combustion is much more difficult to model than non-premixed combustion. But, the essence of premixed combustion modeling lies in capturing the turbulent flame speed, which is influenced by both the laminar flame speed and the turbulence.

3.1 Propagation of the Flame Front

In many industrial premixed systems, combustion takes place in a thin flame sheet. As the flame front moves, combustion of unburnt reactants occurs, converting unburnt premixed reactants to burnt products. The premixed combustion model thus considers the reacting flow field to be divided into regions of burnt and unburnt species, separated by the flame sheet. For computation of perfectly premixed turbulent combustion, it is common practice to characterize the progress variable c(for unburned gas c = 0 and for the product gas c = 1). The transport equation is as following [22].

$$\frac{\partial \bar{\rho}\tilde{c}}{\partial t} + \frac{\partial}{\partial x_i}\left(\rho \tilde{u_j} \tilde{c}\right) = -\frac{\partial y}{\partial x}\left(\overline{\rho u_j{}'' c''}\right) + \rho \widetilde{W}$$

Where, t is time. xj and uj the coordinate and flow velocity component respectively.
ρ is the gas density.
$\widetilde{w}$ is the mean rate of product creation.

3.2 Turbulent Flame Speed

The turbulent flame speed is influenced by the following factors:

- ✓ Laminar flame speed, which is, in turn, determined by the fuel concentration, temperature, and molecular diffusion properties, as well as the detailed chemical kinetics
- ✓ Flame front wrinkling - stretching and flame thickening. The former is influenced by large eddies and the latter is influenced by small eddies.

The turbulent flame speed is computed,

$$U_t = Au'\left(\frac{\tau_t}{\tau_c}\right)^{1/4}$$

Where,
A = model constant,
u = RMS(mean root square) velocity (m/s)
$\tau t = l_t / u^1$ turbulence time scale(s)
$\tau c = \alpha / U^2{}_1$= chemical time scale (s)

IV. CAD MODELING AND MESHING

The geometry of the engine of 124.8 cc is modelled in SOLID EDGE software. To simplify the meshing, the geometry cleanup is done in ANSYS meshing module software. A SOLID EDGE model is imported into FLUENT and the geometry clean-up is performed. The simple geometry is meshed and specific zone names and types are assigned.

Table 1 Specification of the engine.[9]

Input Parameter	**Value of Parameter**
Type	Air cooled, 4-stroke, O.H.C engine
Cylinder arrangement	Single cylinder 80˚ inclined from vertical.
Bore	52.4 mm
Stroke	57.86 mm
Displacement	124.7 cc
Compression ratio	9.2:1
Inlet Valve Opening (IVO)	5˚ BTDC
Inlet Valve closing (IVC)	30˚ ABDC
Exhaust Valve Opening (EVO)	30˚ BBDC
Exhaust Valve closing (EVC)	0˚ TDC

4.1 Geometric Model

The fluid model that was designed in SOLID EDGE is shown below. It was designed according to the specification obtained from Workshop ma n u a l of HONDA ignitor, Service Department, Hero Motocorp Ltd.

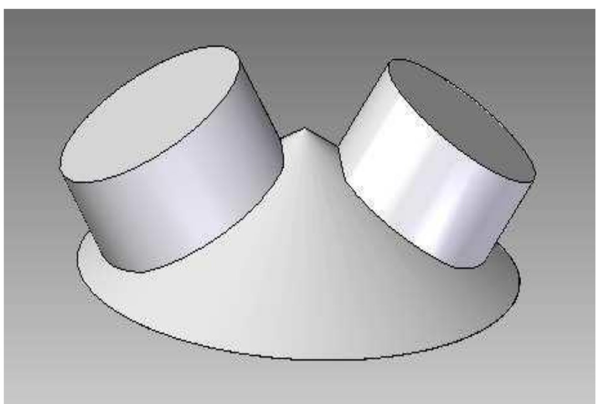


Fig.1 Solid edge model created from real Engine.

4.2 Mesh Motion

The mesh motion which is the basic for all the simulations is achieved in ANSYS mesh module. The mesh created is based on the crank angle specified and the results obtained from the dynamic mesh generation agreed with the actual cylinder movement to a considerable extent. The valve profiles help to exactly replicate the actual valve motion in the computational environment. Figure 2 and 3 show the mesh motion with respect to the crank angle.

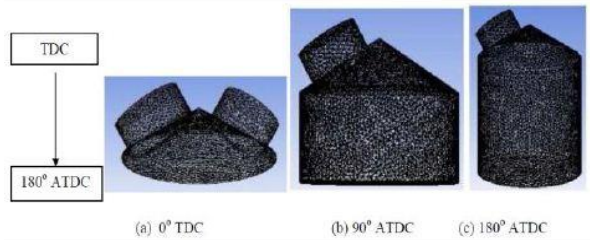


Fig. 2 Mesh motion for first stroke

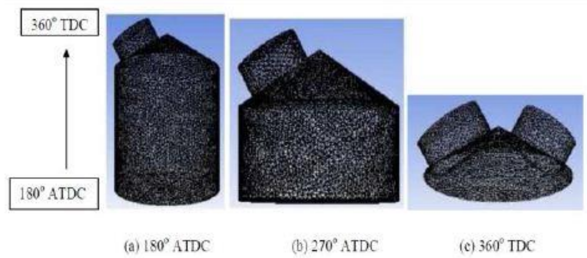


Fig.3 Mesh motion for second stroke

V. HYPOTHESIS

The combustion analysis includes hypothesis of the model (flame structure, species diffusion, chemical species involved, burnt gases chemical reactions, and chemical equilibrium) and analysis of the working cycle for calculation of pressure, temperature and volume for suction, compression, combustion and expansion process.

5.1 Flame Structure

The main assumption made for this work is that the combustion of fuel occurs in a premixed regime, even for very lean or very rich combustion. The region of fuel consumption is supposed to be very thin and we assume that it separates unburnt from burnt gases and also that no fuel remains in the burnt gases. This assumption can be easily justified because the high temperature existing in the burnt gases leads to fuel molecules decomposition.

5.2 Chemical Species Involved

It is assumed that the unburnt gases are only composed of fuel, molecular oxygen and nitrogen, carbon dioxide and water. Also it is assumed that the existence of other components in the fresh gases will add one transport equation per added component, which is not cost effective. The burnt gases are supposed to be composed of molecular and atomic oxygen, nitrogen, and hydrogen, carbon monoxide and dioxide, OH and nitrogen monoxide [10].

5.3 Burnt Gases Chemical Reactions

All the reactions computed in the burnt gases are supposed to be bulk reactions. That means that no local structure of the reaction zone is taken into account and that these reactions are only function of the mean local quantities computed in the burnt gases. The reactions are solved using conditioned burnt gases properties [10].

5.4 Chemical Equilibrium

A single step oxidation of methane with oxygen to form carbon dioxide and water vapor is considered. The following species has been used for methane combustion fuel O, O2, H_2, OH, CO, CO_2 .

$$CH_4 + 2O_2 = CO_2 + 2H_2O$$

VI. THEORETICAL ANALYSIS

A S.I. engine works on the principle of Otto Cycle. The theoretical analysis was done on the basis of equations obtained from Otto cycle and also from various other literatures. For instance:

At site condition of engine:
Atmospheric pressure P1 = Pa = 1.01 x 105 bar
Suction temperature T1 = 25˚ C = 298K
Where Mch = 1.00 Kg.
V1 = 0.8736 m3
Similarly, the other values that were obtained are shown in the table below:

Table 2 Result of Theoretical Analysis**.**

P_1:	**1.01 bar**
T_1:	**298 K**
V_1:	**0.8736 m^3**
P_2:	**21.1208 bar**
T_2:	**677.8635 K**
V_2:	**0.0950 m^3**
P_3:	**86.8834 bar**
T_3:	**2788.4885 K**
V_3:	**0.0950 m^3**
P_4:	**4.1548 bar**
T_4:	**1225.85 K**
V_4:	**0.8736 m^3**
Γ compression:	**1.37**
Γ expansion:	**1.37**

VII. COMPUTATIONAL ANALYSIS

The computational analysis was performed in FLUENT. The values that were obtained using the theoretical analysis were considered as boundary conditions.

7.1 Input Parameters

Following parameters are taken as input to fluent:

1. Valve opening and closing position, which includes Inlet valve opening position, Inlet valve closing position, Outlet valve opening position and Outlet valve closing position.
2. Pressure and Temperature at inlet and outlet.

Table 3 Properties of Methane Gas

Property	Value
Density	0.6679 kg/m3
C_P	2222 J/kg-k
Thermal conductivity	0.0332 w/m-k
Viscosity	1.087e-05 kg/m-s
Molecular weight	16.04303 Kg/Kg mol

Engine Parameter:

a. Crank shaft speed = 1500 rpm to 3000 rpm
b. Crank period = 720˚
c. Crank angle step size = 0.5˚
d. Piston stroke = 0.0578 m
e. Connecting rod length = 0.124 m

7.2 Output Obtained

Turbulent kinetic energy, turbulent intensity, turbulent flame speed, density and temperature at different region of cylinder are obtained from FLUENT which are presented in the results and discussion.

VIII. CONCLUSION

The following can be concluded from the results: The aim of this project is to do combustion modeling of single cylinder four stroke spark ignition engine of ignitor bike having compression ratio of 9.2 and displacement of 124.7 cc using computation fluid dynamics for predicting turbulent flame speed by using premixed combustion model. The methane gas will be considered as a fuel in this study. The single oxidation of methane with oxygen to form carbon dioxide and water vapor is taken in to use. Prediction of turbulent flame speed at different equivalence ratio and engine is done in FLUENT software.

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