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Second Law Analysis of Diesel Engine by Using Different Ignition Delay Models

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Abstract: ***A mathematical model is developed for comparing different ignition delay models for compression ignition engine fuelled with the diesel under different operating load. The model developed is single zone zero dimensional model. The different ignition delay models are used to compare the different. Once the heat release rate is modelled the pressure and temperature are predicted for every crank position. The diesel engine is considered as closed system for thermodynamics analysis. The cylinder gases are assumed as ideal gas the different developed ignition delay model is validated against the data obtained by experimentation at laboratory. This study again elaborated how properties of cylinder charge gases varying with the crank angle position. By performing the experimentation on diesel engine, experimental results have been compared with models given by Arrhenious, Wolfer, Watson and Hardenberg. It is found that experimental results are in good agreement with Arrhenious model. Heat transfer to the cylinder wall from cylinder gas has taken into account to find the gross heat release rate. Heat transfer coefficient correlation given by Hohenberg has been used to calculate convective heat transfer. Radiative heat transfer has been neglected. For predictive analysis two functions have been used, one for premixed part and Wiebe function for diffusion part. Different ignition delay correlation to predict start of combustion has been used, i. e. Watson, Wolfer, Arrehenius and Hardenberg and Hase. Simulated curve for ROHR has been tuned with experimental curve for various load conditions to find out the shape parameters of the functions. Correlation for these shape parameters are modified with adjusting coefficients, using the least square curve fitting method. The properties of in-cylinder gas have been calculated by various polynomial equations which are the main function of temperature. The ignition delay correlations are compared.***

Keywords: Ignition Delay Model, zero dimensional model, compression ignition engine, thermodynamics analysis, etc

1. Introduction

Investigations and reports that have used the second law of thermodynamics to analyze the combustion process in internal combustion engines have been published for more than 40 years. Representative results are presented for both compression-ignition and spark-ignition engines to illustrate the type of information obtained by use of second law analysis and instantaneous values for the engine availability or exergy and the overall values for energy and availability are described. A brief description of most of these methods is provided in this work. The use of second law analysis is not necessarily intended for general performance computations but for understanding the details of the overall thermodynamics of engine operations. The second law of thermodynamics is a powerful statement of related physical observations that has a wide range of implications with respect to engineering design and operation of thermal systems. The second law can be used to determine the direction of process, establish the condition of equilibrium, to specify the maximum possible performance of thermal systems and identify those aspects of processes that are significant to overall performance. Related to the analysis based on the second law of thermodynamics is the concept of availability or exergy.

Availability or energy is a thermodynamic property of a system and its surroundings and is a measure of the maximum useful work that the given system may obtain as the system is allowed to reversible transition to a thermodynamic state which is in equilibrium with its environment. A very important aspect of availability or exergy is the fact that a portion of a given amount of energy is available to produce useful work, while the remaining portion of the energy is unavailable for producing useful work. During the combustion process, thermal, mechanical and chemical processes are very important for availability analysis. An example of the thermal aspect of availability analysis is an ideal case where the system temperature is above the environmental temperature, and the availability from the system could be converted to work until the system temperature, equaled the environmental temperature while the remaining energy is an unavailable part of the energy. The mechanical aspect of availability analysis is a system which is at pressure above the environmental pressure. By utilizing an ideal expansion device, the energy of the system could be converted to work until the system pressure equaled the environmental pressure. A third aspect of availability analysis is a chemical aspect, which considers the potential to complete work by exploiting the concentration differences of the various species relative to the related concentrations in the environment. The consideration of the species concentration component of availability is often neglected due to the practical difficulties of implementing such a system and the relatively small amounts of work produced. Availability or exergy is not a conserved property and can be destroyed by irreversible processes such as heat transfer through a finite temperature difference, combustion, friction and mixing processes. The majority of different reports and studies have investigated the influence of heat transfer, combustion, friction and mixing processes on availability destruction suggesting different options to reduce energy degradation and increase portion of energy available for useful work. [2]

To interpret the second law analysis results, the desired output is brake work and increases in this quantity (for a given fuel flow) represent improved performance. All other availability terms represent losses or undesirable transfers from the system; decreasing these terms constitutes an improvement. These undesirable available energy transfer and destruction terms fall into five categories: (1) heat transfer, (2) combustion, (3) fluid flow, (4) exhaust to ambient, (5) mechanical friction. [12]

1.1 Modeling of combustion in DI diesel engines

The advantages of engine modelling are
a) Parametric studies of each variable can be done
b) Wide range of boundary conditions can be analyzed
c) Separation of each sub-process from other
d) Detailed information is available as output
e) Effective in terms of time and cost

1.2. Different Types of Models

Depending on the various possible applications, different types of models for engine combustion processes have been developed. Three different model categories are typically distinguished. In an order of increasing complexity and increasing requirements with respect to computer power,
1) Zero dimensional thermodynamic models
2) Quasi-dimensional phenomenological models and
3) Multi-dimensional computational fluid dynamics (CFD) models.

It should be noted that phenomenological models are the most practical to describe diesel engine combustion (Stiesch 2003). This is because the injection process, which can be relatively well predicted with the phenomenological approach, has the dominant effect on mixture formation and subsequent course of combustion. Therefore, these models are widely used as predictive tools for carrying out parametric studies during engine development. The need for improving these models was also established by incorporating developments happening in engine designs. A phenomenological model consists of sub-models for combustion and emissions. The combustion in modern DI diesel engines is mainly divided in two phases
a) A small ignition delay event in which pre-flame activities
b) Main heat release

Combustion Model
The combustion starts almost at the onset of fuel injection because the ignition delay in modern DI diesel engines is very small with high compression ratio and highly retarded injection timing, which enable substantial reduction in noise, NOx and HC. The heat release estimated with this assumption predicts satisfactorily the important instantaneous parameters used by a designer e.g. heat transfer, fuel consumption, and the performance turbocharger and piston. On the same tenor, with the drop in norms for HC and NOx, ignition delay, however small it may be, cannot be neglected while estimating emissions.[13]

Ignition delay
In direct injection diesel engines, estimation of ignition delay is of great importance because of its effect on startability, noise and formation of NOx. The ignition delay in a diesel engine is defined as the time interval between the start of injection and the start of combustion. This delay period consists of physical delay, wherein atomization, vaporization and mixing of air fuel occur and of chemical delay attributed to pre-combustion reactions. Both physical and chemical delays occur simultaneously
a) Physical delay, wherein atomization, vaporization and mixing of air fuel occur and
b) Of chemical delay attributed to pre-combustion reactions.

Higher temperature at the beginning of injection by increased compression-ratio reduced the delay period substantially. Numerous ignition delay correlations have been proposed based on experiments carried out in constant volume bombs, steady state reactors, rapid compression machines and engines. Wolfer (1938) developed the earliest correlation for predicting ignition delay. The equation was in the form of an Arrehenius expression representing a single stage reaction. Kadota et al (1976) related results of combustion bomb experiments to an Arrehenius type expression by introducing dependence of equivalence ratio. Lahiri et al (1997) modified this equivalence ratio to fuel-oxygen ratio, attempting to make it suitable for oxygenated fuels. However, these correlations fail to predict the ignition delay under unsteady diesel engine conditions as they are based on experiments conducted in a constant volume bomb. On the other hand, a few correlations have been developed considering engine data (Hardenberg et al 1979, Watson et al 1980). These correlations also were not successful in yields, satisfactory predictions under widely varying operating conditions as they have ignored the effect of mixture quality. Recently Assanis et al (1999) have compared these correlations and found better predictability using the Watson correlation (1980). They improved the correlation by introducing the equivalence ratio and tuning the empirical constants. They postulated that the introduction of the dependency of ignition delay on overall equivalence ratio makes the correlation more dynamic.
The time taken for visible fire to appear in the pre-mixed zone of spray is a strong function of pressure and temperature of the ambient. In addition, the physical properties such as Cetane number, viscosity of fuel, nozzle-hole size, injected quantity and injection pressure contribute to the delay phenomenon in diesel engines (Chandorkar et al 1988). In this chapter, a phenomenological models considering droplet formation, evaporation of fuel and preflame reaction are presented for prediction of delay period and location of the ignition accurately within the experimental errors and errors in the input to the calculations.

1) General equation for the ignition delay is as follows:
2) $$\int_{t_{si}}^{t_{si}+\tau_{id}} \left(\frac{1}{\tau}\right) dt = 1 \qquad \text{.....(1)}$$
3) where,
t_{si} = start of ignition,
τ_{id} = ignition delay period,
τ = ignition delay at conditions pertaining at time t. [13]

1.3. Ignition Delay Correlations

Ignition delay in direct injection diesel engine is of great interest to researchers and engineers because of its direct impact on the intensity of heat release immediately following auto ignition, as well as its indirect effect on engine noise and pollutant formation. The delay period is composed of a physical delay, encompassing atomization, vaporization and mild, coupled with a chemical delay, a result of pre-combustion reactions in the fuel/air mixture.

The two time scales are not simply additive, but are occurring simultaneously. Detailed ignition models exist (e. g., Agarwal and Assns, 1998), but due to the complexity of the in-cylinder physical and chemical process, can only provide ignition delay trends for practical fuels.

Some researchers justified the use of second law of thermodynamics to the engine analysis. They called it a very potent tool to for better insight and optimization of diesel engine. For diesel fuels a reasonable estimate of the delay, ID is achieved by Wolfer. The time taken for visible fire to appear in the pre-mixed zone of spray is a strong function of pressure and temperature of the ambient. In addition, the physical properties such as cetane number, viscosity of fuel, nozzle hole size, injected quantity and injection pressure contribute to the delay phenomenon in diesel engines. For diesel fuels a reasonable estimate of the delay, ID is achieved by Wolfer, [13]

$$ID = 3.45 \exp(2100/T_m)*P_m^{-1.02} \quad \text{.....(2)}$$

Where, T_m and P_m are the mean temperature and pressure of the ambient during ignition delay.

Classical Arrhenius type model for Ignition Delay and its extension to other fuels values of pressure and temperature are necessary to predict ignition delay. If this equation has to be developed as design tool, then it is necessary to predict pressure and temperature precisely for required engine operating condition. Considering pressure and temperature at TDC position will ignore effect of injection timing.

The Arrhenius type of equation is used to describe ignition delay [13]

$$\tau_{id} = a.\Phi^{-k}.P^{-n}.\exp\left(\frac{Ea}{Ru.Tcyl}\right) \quad \text{.....(3)}$$

Where,

τ_{id} = Ignition delay
Φ = Equivalence ratio
E_a = Activation energy
T_{cyl} = Cylinder charge temperature
R_u = Gas constant
a, k and n = Empirical constants

Watson developed equations for fuel energy release appropriate for diesel engine simulations. In their development, the combustion process starts from a rapid premixed burning phase (represented by function f1), followed by a slower mixing-controlled burning phase (represented by function f2), with both functions empirically linked to the duration of ignition delay (~τid) and the duration of combustion (Δθcomb).

The Watson model is given by [14]

$$t_{id} = A(BP)^{-N}.P_{SOC}^{-B}.\exp\left(\frac{E}{RuTsoc}\right) \quad \text{.....(4)}$$

The constants A, N and B are adjustable.
The Cetane number of biodiesel is better than that of diesel. Therefore, the Cetane number truly represents the compression ignition quality of fuel. Therefore, this parameter needs to be incorporated while developing a new model for predicting the ignition delay especially with fuels containing oxygen. Here, the correlation developed by Hardenberg and Hase can be employed. It is given by, [13]

$$\tau_{id}(A) = (0.36 + 0.22\overline{S_p})\exp[E_A(\frac{1}{\bar{R}T} - \frac{1}{17190}).(21.2/(P-12.4))^{0.63}] \quad \text{.....(5)}$$

Where,
$\overline{S_p}$ = piston speed (m/s)
$\bar{R}$ = Universal gas constant (8.3143 J/mol)
E_A = Apparent activation energy
$E_A = \frac{618840}{CN+25}$
CN = Cetane number

2. Experimental Model

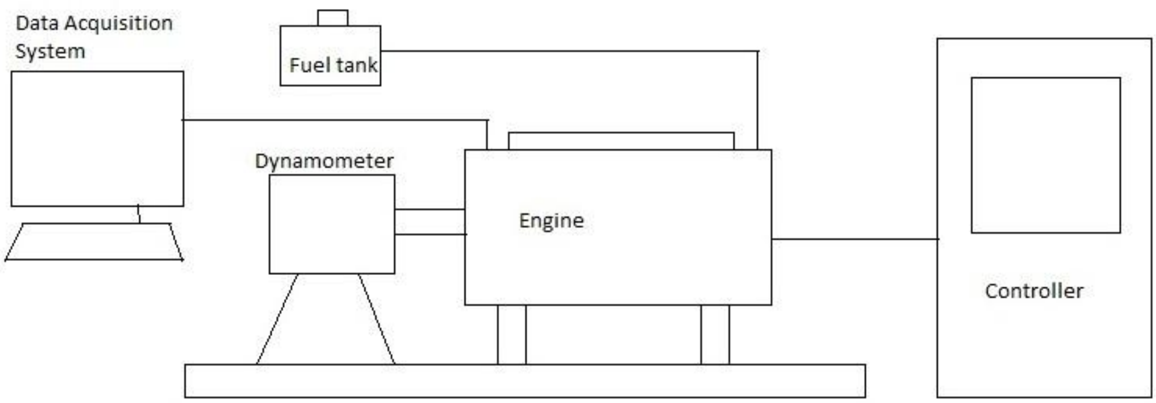

Figure 1: Block diagram of Experimental setup

1) **Specification of Experimental Setup**

Table 1: Engine Specification

Engine Model	*Single Cylinder Four Stroke Air Cooled Diesel Engine*
Engine Make	Comet
Maximum Output	5Bhp / 3.7kW@ 1500 rpm
Bore	80mm
Stroke	110mm
Compression ratio	16:1

2) **Engine Cylinder Pressure at Various Loads**

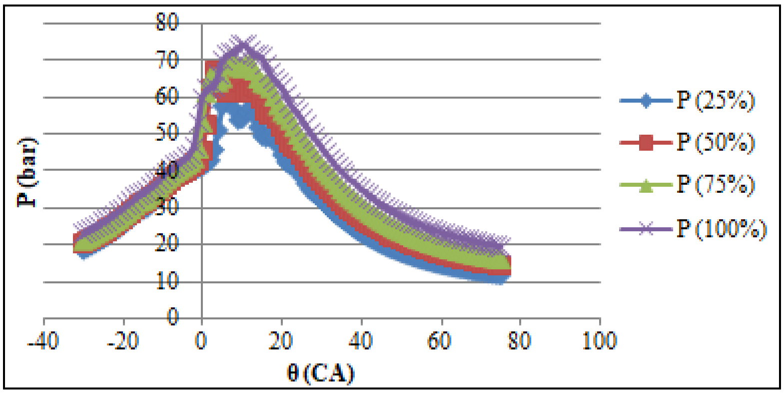

Figure 2: Experimental pressure vs. crank angle

3) **Mass Burn Fraction Calculation**

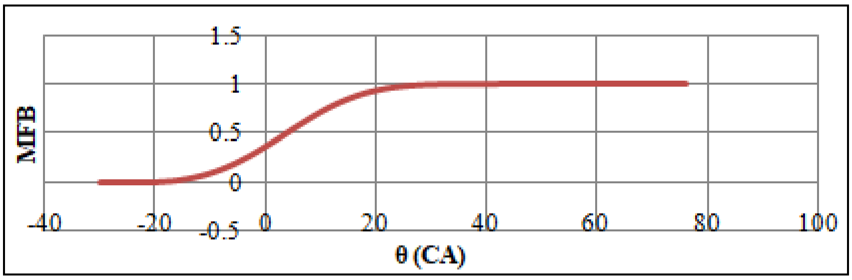

Figure 3: Mass fraction burn

4) **Work Availability**

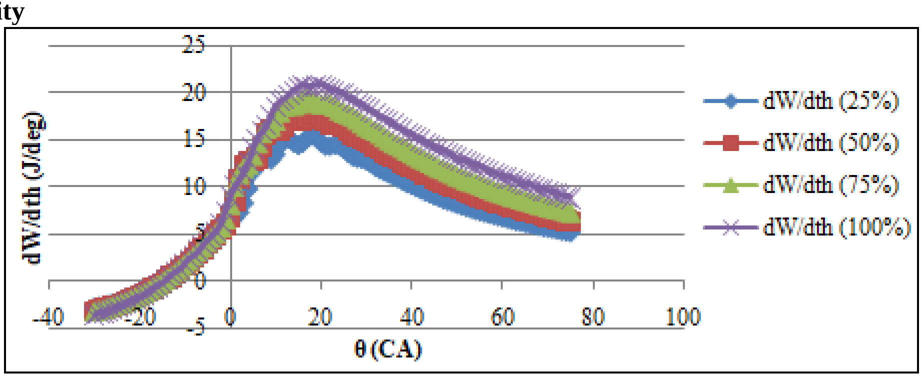

Figure 4: Work availability rate vs. crank angle

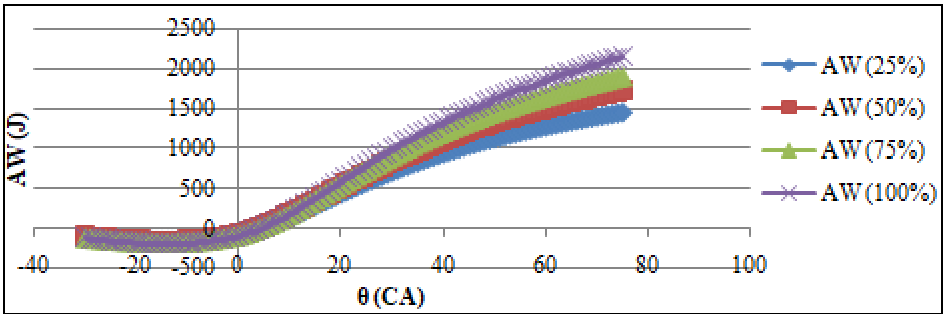

Figure 5: Cumulative work availability vs. crank angle

5) **Mathematical Analysis**

Heat release rate is modelled using Weibe model for heat release production. Once heat release rate is predicted, engine cylinder pressure curves for various heat release pattern can be calculated.

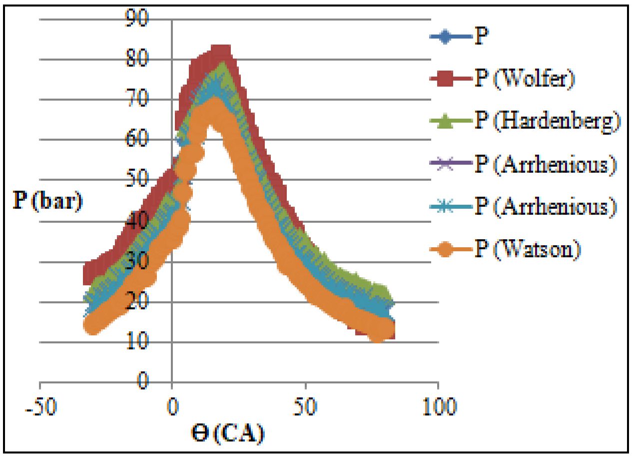

Figure 6: Comparison of experimental vs. predicted pressure for different ignition delay models vs. crank angle

3. Comparison of Experimental and Predicted Values of Pressure

Experimental and predicted maximum pressure and respective crank angle for 1500 rpm speed and various loads.

Models	Crank Angle (deg°)	Maximum Peak Pressure (bar)
Experimental	15	74.264
Wolfer	18	80.995
Hardenberg	19	77.272
Arrhenious	16	73.828
Watson	16	68.264

Experimental data is compared with different ignition delay models. Based on the results, it is found that the Arrhenious's correlation is best to calculate the engine cycle results.

4. Conclusions

Present study deals with experimental calculation and simulation of rate of heat release and pressure for the diesel engine. The single zone zero dimensional models for direct injection diesel engine for closed cycle for combustion process has been successfully developed. The model is effectively used to estimate the performance of the engine for given operating conditions. Detailed equations are given for the calculation of state properties. Following conclusion can be drawn from present study:

1) The Hardenberg and Hase model was found to be in very close relation with experimental values, as it is more calibrated than the other models. It gives the result values near to the accurate.
2) The Arrhenious model is also giving good relationship with experimental values. It uses equivalence ratio term which has good impact on the accuracy.

5. Future Scope

The existing model that has been presented in this dissertation can be modified and improve in the following items.

1) Single zone model used in this study follows experimental trends of the performance parameter. However program should be developed by using multi zone model to take into account special variation and to get more accurate results in terms of exact values of the output.
2) Using multi zone model, this study can be further extended to predict the effect of considered operating parameters on emission formation.
3) The accuracy in the model can be enhanced by tuning and verifying the parameter must be done.
4) The computational fluid dynamics can be used to predict the heat transfer from the engine cylinder.

If some of these improvements are done the complexity increases and therefore the computational time and simulation time will increase.

6. Applications

1) The simulation model developed in this study can be used to analyse the diesel engine with the slight changes the parameters of predicted heat release curve.
2) Simulation model can be used to analyse the heat release rate at effect of various parameters such as inlet pressure and temperature, injection timings, speed, load, air fuel ratio, compression ratio, etc.

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