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Internal Combustion Engines – A Comprehensive Study

M Suresh, Dr. R. Hari Prakash, Dr. B Durga Prasad
HOD, Dept. of ME, GKCE, Sullurpet, Principal, Dr. KVSRCEW, Kurnool,
Prof. & Head, Dept. of ME, JNTUA, Anantapuramu.

***Abstract*— internal combustion engines currently rule nearly all the road automobiles and a devastating majority of off-road practicalities. The internal combustion engines are likely to continue the chief major movers at least for the next few decades. The combustion produced engine emissions have been at the focus of attention of investigators, automotive engineers, ecologists and experts now for several years and it remains a lively area of engineering examination and education. This paper attempts to review the historical aspects, design, classification, application and working principle of internal combustion engine.**

***Index Terms*—IC Engines, combustion, fuel, heat release, emissions.**

I. INTRODUCTION

In the internal combustion engines, fuel endures combustion with air inside the engine discharging chemical energy in fuel as heat and it is transformed to mechanical work. Combustion of fuel increases temperature and pressure of the gasses inside the engine and these gasses establishes the working fluid [1][2]. As the high pressure gasses expand their action and moving components of the engine creates work. Working fluid before combustion for the duration of part of the internal combustion engine cycle is either mix of fuel and air or air only, whereas later in the cycle the combustion products establish the working fluid [3]. Most internal combustion engines are reciprocating type where pistons reciprocate back and forth inside the engine cylinders. The pistons through mechanical connections transform reciprocating motion to rotational motion and deliver power to circling output shaft [4]. Rotating internal combustion engines which do not use reciprocating pistons have also been designed. There are basically two types of internal combustion engines, which need a spark plug, and those that rely on compression of a fluid. Spark ignition engines take a combination of fuel and air, compress it, and ignite it using a spark plug. The tag `reciprocating' is given as the motion that the crank mechanism does. The piston-cylinder engine is essentially a crank-slider mechanism, where the slider is the piston in this case. The piston is stimulated up and down by the rotating motion of the two arms. The crankshaft revolves which makes the two links revolve. The piston is condensed within a combustion chamber [5]. The bore is the diameter of the cylinder. The valves on top characterize induction and exhaust valves needed for the ingestion of an air-fuel mixture and exhaust of chamber wastes. In a spark ignition engine a spark plug is essential to transfer an electrical ejection to ignite the mixture of fuel and air. In compression ignition engines the compressed air ignites at high temperatures and pressures because of spraying of fuel [6]. The lowermost point where the piston spreads is called bottom dead center (BDC). The uppermost point that the piston grasps is called top dead center (TDC). The ratio of cylinder volumes at BDC to that at TDC is called the compression ratio. The compression ratio is vital in many facets of both compression ignited and spark ignited engines, by describing the efficiency of engines. Compression ignited engines absorb atmospheric air; pressurize it to high pressure and temperature, at which combustion takes place [7]-[10]. These engines are high in power and fuel frugality. In this paper, the development of internal combustion engines, classification, applications, working principle and a sample simulation of internal combustion engines are presented. The rest of the paper is organized as follows. In section II, the brief review of works done on internal combustion engines starting from its inception to recent developments is presented. In section III, the principle of operation of 4-stroke and 2-stroke operations of both spark ignited and compression ignited engines are described. In section IV, a model of internal combustion engine is presented, simulated and the design parameters of the engines are listed and plotted as necessary. The section V concludes the paper.

II. REVIEW OF LITERATURE

The very first viable engine was engineered in 1860s by J. Lenoir working on coal gas – air combination. In this one cylinder engine, suction of air and fuel combustion and expansion of combustion products all happened in a single outward piston stroke. The efficiency of this engine was a maximum of 5% which is very low. In the same period of 1867, Nicolaus A Otto and E. Langen designed another engine in which combustion of gas and air accelerated a free piston and rack assembly on outward stroke that formed vacuum in cylinder. These engines have thermal efficiency of up to 11% [11]. The 4-stroke engine cycle that was recommended and model engine constructed by Otto in 1876 is considered the foundation of the modern automotive engines [12]. The triumph of Otto cycle engine provided inspiration for discovery and development of numerous novel types of reciprocating IC engines. Most distinguished amongst these are: 2-stroke engine and compression ignition (CI) engine. During 1880s, Dugald Clerk, Carl Benz and

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some others developed 2-stroke IC engine where intake and exhaust proceeds concurrently near the end of the power stroke and commencement of compression stroke [13]. In 1892, R. Diesel developed a new type of engine where combustion was originated by injecting liquid fuel in high temperature air. James Atkinson, designed an engine that has lengthier expansion stroke than the compression stroke. Its mechanical design had poor structural strength and durability problems. Amongst the rotating IC engines proposed over many years, the engine designed by Felix Wankel, has been manufactured. It was first constructed in 1957 and was used in a production car manufactured by Mazda, a Japanese company in 1970s [14]. In 1860s hydrocarbon products brought from petroleum crude stared appearing in the market. As the plea of gasoline improved during 1920s and 1930 s, thermal cracking and catalytic cracking procedures were developed to transform heavier components of petroleum crude to gasoline, and the gasoline became main engine fuel for the 20th century. Thomas Migley of GM discovered an antiknock additive, tetraethyl lead in 1921 which became available in 1923 [15]. The electronic fuel injection schemes were introduced during 1990s in heavy duty CI engines. The peak fuel injection pressures have improved from about 40MPa in 1980s diesel engines to close to 200MPa in many contemporary diesel engine models. Other combustion ideas like homogeneous mixture combustion with compression ignition have fascinated attention of investigators in the post-2000 period [16]. Oil jolts of 1970s caused in implementation of vehicle fuel economy criterions. Investigation on alternate fuel reduced down in 1980s and 1990s as the prices of petroleum crude reduced significantly. In 1990s global-warming triggered chief worry and exertions to decrease carbon dioxide emissions, one of the major greenhouse gasses were originated. In 2002, worldwide transport energy demand was 1837 Million tons oil equivalent of which more than 50% came from petroleum crude. The transport contributed about 4914 Million tons of CO_2 that is about 20% of total global CO_2 emissions [17]. From mid-1990s the alternate power plant vehicles such as hybrid IC engine – electric vehicles and hydrogen fuel cell vehicles have become significant candidates to the conventional internal combustion engine vehicles by petroleum fuels. Global-warming alarms and the high petroleum crude prices are estimated to continue key factors behindhand rigorous accomplishments in the progress of alternative road transport power plants and fuels.

III. WORKING PRINCIPLE

The main application of an engine is to transform one form of energy in to other. In this sense the engine is a transducer. The fuel is converted into a mechanical energy. The fuel may be regarded as a form of chemical energy. The fuel and some quantity of air are mixed in one form or other and expansion of this mixture because of explosion creates mechanical energy. The light weight strong freely moving piston is used to hold the fuel air mixture in the cylinder. The bottom of the piston is connected to crankshaft. The crankshaft converts the up down movement of piston to rotatory movement. In either two stroke or four stroke compression or spark ignited engines, initially the piston has to move from TDC to BDC. For this movement an external source has to be used. This is done by a small motor in heavy vehicles kick in the motor cycles. Self-start motor cycles or any other self-start vehicles use a mini-motor for the initial up to down movement of piston [18]. The up to down movement of the piston extracts either only air or mixture of fuel-air into the cylinder. When the mixture blows the piston moves downward and as the burnt gasses exit through exhaust valve or port, because of the low pressure created of the exit gasses the piston gets attracted and makes an upward movement. For this to happen, the piston has to be light weight and freely moving. To resist the blow of the gasses the piston has to be strong enough. Hence the piston makes up-down movements till the fuel and air are supplied. The up-down movement of the piston is converted into rotatory movement by the crankshaft mechanism and the mechanical output is available at the crankshaft hence can be drawn by connecting the external load to crankshaft [19][20]. This section presents the working of 4-stroke and 2-stroke operations of both SI and CI engines. First consider the 4-stroke operation of SI engine. The first stroke is Intake stroke. In this stroke, the intake valve opens and admits fuel and air mixture in to the cylinder. The exhaust valve will be in closed position. Using a motor, initiating motor, the piston will be moved to the bottom location creating low pressure inside the cylinder, which will be filled with fuel and air mixture. The second stroke is compression stroke. In this stroke both the valves are first closed. The initiating motor moves the piston upward; hence the air fuel mixture gets pressurized. The third stroke is power stroke. In this stroke also the valves remain closed. The pressurized air fuel mixture will be burnt using a spark from spark plug and releases heat energy. The Hot working fluid (products of combustion) now gets expanded forcing the piston to get a downward movement. The last stroke is exhaust stroke, where the exhaust valve opens through which the exhaust products are displaced from the cylinder. Near the end of the stroke the intake valve gets opened and exhaust valve will be closed giving raise to beginning of the first stroke. The crank shaft at the bottom of the piston converts the un-down movement of piston to circulatory movement. The figure 1 shows the 4-stroke operation of SI engine.

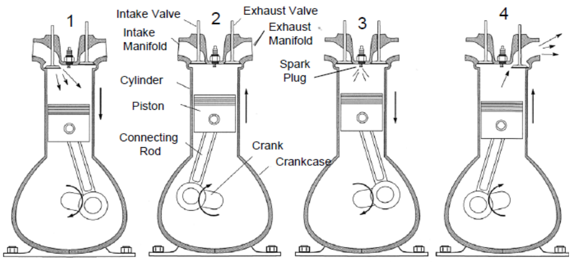

Fig. 1 4-strokes of SI Engine

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Now consider the 4-stroke operation of Diesel engine (CI). In diesel engine, the fuel will not be mixed with air in the intake stroke; the air alone will be sucked into the chamber and gets pressurized in compression stroke. In the power stroke, the pressurized air provides the environment to ignite the fuel sprayed by the fuel injector in to the combustion chamber. Fuel will be sprayed onto the pressurized air. The pressurized air takes less space compared to that of the air-fuel mixture of an SI engine combustion chamber, hence achieves higher compression ratio. But the combustion may not be homogeneous throughout the air filled chamber because of lack of allowed time for it to spread all over the air before it ignites or fires. The figure 2 shows the 4-stroke operation of Diesel engine.

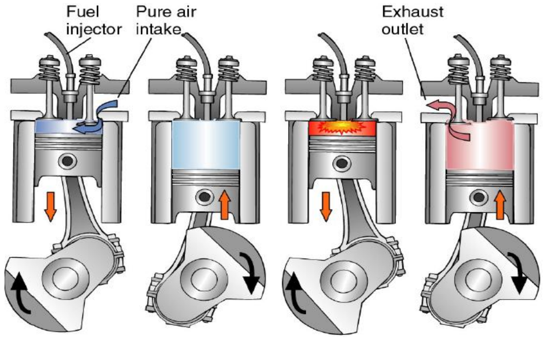

Fig. 2 4-strokes of Diesel Engine

Now consider the 2-stroke operation of SI engines. In first stroke, fuel-air mixture is introduced into the crank case through inlet port and the charge in the cylinder which is transported through the transfers port in the previous stroke is compressed, combustion initiated at the end of the stroke. In stroke 2, combustion products expand doing work and then exhausted. Power is delivered to the crankshaft on every revolution of the crank shaft.

IV. SIMULATION AND PARAMETERS OF ENGINE ENGINEERING

In this section the simulation results of an internal combustion engine with the following specification are presented. A list of key parameter is given in the table 1.

Working Cycle: Four-stroke Cycle
Fuel and Method of Ignition: Petrol, SI, Carburation
Number of Cylinders: 1
Cooling System: Liquid Cooling
Cylinder Bore: 150mm
Piston Stroke: 180mm
Nominal Engine Speed: 1500rpm
Compression Ratio: 14.4
Application: Overland
Cylinder Head Design: Two Valves

The model was simulated and the following results are obtained.

```
--- PARAMETERS OF EFFICIENCY AND POWER ---
 1500.0      - RPM       - rev/min
 36.567      - P_eng     - kW
 9.1967      - BMEP      - bar
 232.81      - Torque    - N m
 0.22199     - m_f       - g
 0.27319     - SFC       - kg/kWh
 0.29949     - Eta_f     -
 11.744      - IMEP      - bar
 0.38244     - Eta_i     -
 1.7603      - FMEP      - bar
 0.78311     - Eta_m     -

 --- ENVIRONMENTAL PARAMETERS ---
 1.0000      - po_amb    - bar
 288.00      - To_amb    - K
 1.0000      - p_Te      - bar
 0.98000     - po_afltr  - bar

 --- TURBOCHARGING AND GAS EXCHANGE ---
 0.98000     - p_C       - bar
 288.00      - T_C       - K
 0.04162     - m_air     - kg/s
 0.0000      - Eta_TC    -
 1.0403      - po_T      - bar
 712.81      - To_T      - K
 0.04432     - m_gas     - g/s
 0.99995     - A/F_eq.t  -
 1.0001      - F/A_eq.t  -
 -0.78680    - PMEP      - bar
 0.90791     - Eta_v     -
 0.03648     - x_r       -
 0.99998     - Phi       -
 0.77004     - BF_int    -
 0.17459     - %Blow-by  -

 --- INTAKE SYSTEM ---
 0.97827     - p_int     - bar
 290.93      - T_int     - K
 340.93      - Tw_int    - K
 101.53      - hc_int    - W/(m2*K)
 200.74      - hc_int.p  - W/(m2*K)

 --- EXHAUST SYSTEM ---
 1.0402      - p_exh     - bar
 712.79      - T_exh     - K
 8.6126      - v_exh     - m/s
 37.585      - Sh        -
 631.81      - Tw_exh    - K
 90.000      - hc_exh    - W/(m2*K)
 605.70      - hc_exh.p  - W/(m2*K)

 --- COMBUSTION ---
 1.0000      - A/F_eq    -
 1.0000      - F/A_eq    -
 110.84      - p_max     - bar
 2672.4      - T_max     - K
 6.0000      - CA_p.max  - deg. A.TDC
 11.000      - CA_t.max  - deg. A.TDC
 5.1968      - dp/dTheta- bar/deg.
 25.000      - Theta_i   - deg. B.TDC
 0.07560     - Phi_id    - deg.
 48.000      - Phi_z     - deg.
 1.9845      - m_w       -
 149.75      - ON        -

 --- ECOLOGICAL PARAMETERS ---
 5092.1      - NOx,ppm   - ppm
 37.181      - NO2,g/kWh- g/kWh
 0.0000      - SO2       - g/kWh
--- CYLINDER PARAMETERS ---
 1.1654      - p_ivc     - bar
 359.52      - T_ivc     - K
 35.816      - p_tdc     - bar
 832.42      - T_tdc     - K
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4.2912      - p_evo    - bar
1250.0      - T_evo    - K

 --- HEAT EXCHANGE IN THE CYLINDER ---
1593.5      - T_eq     - K
686.63      - hc_c     - Wt/m2/K
524.88      - Tw_pist  - K
413.00      - Tw_liner - K
485.99      - Tw_head  - K
425.22      - Tw_cool  - K
386.65      - Tboil    - K
12235.      - hc_cool  - W/(m2*K)
13438.      - q_head   - J/s
12966.      - q_pist   - J/s
8138.1      - q_liner  - J/s

--- MAIN ENGINE CONSTRUCTION PARAMETERS ---
14.400      - CR       -
42.000      - EVO      - deg.
16.000      - EVC      - deg.
16.000      - IVO      - deg.
40.000      - IVC      - deg.
```

TABLE I: Key Engine Parameters

Engine Speed	1500 rpm
Piston Engine Power	36.567 KW
Brake Torque	232.81 N m
Specific Fuel Consumption	0.27319 Kg/KWh
Indicated Efficiency	0.38244
Mechanical Efficiency	0.78311
Overall Thermal Efficiency	0.299493
Maximum Cylinder Pressure	110.84 bar
Maximum Cylinder Temperature	2672.4 K
Combustion Duration	48 deg.

Heat release rate, Concentration of NOx, Combustion zone temperature and Heat release fraction are plotted and are presented in figures 3, 4, 5 and 6 respectively.

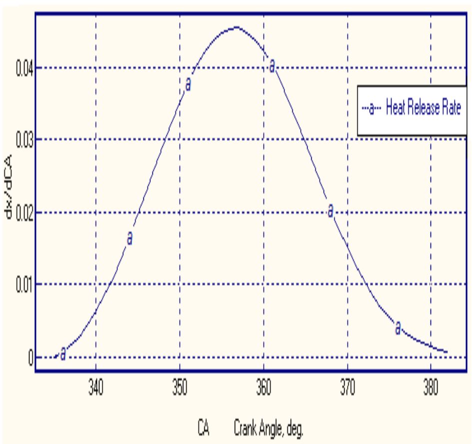

Fig. 3 Heat release rate Vs Crank angle

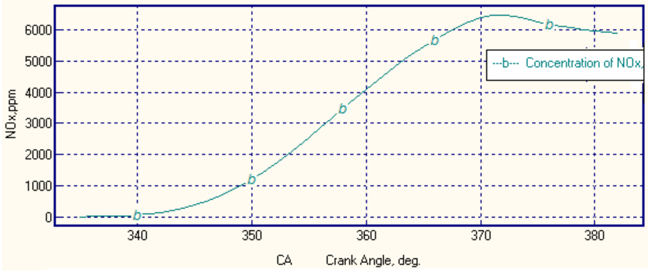

Fig. 4 Concentration of NOx Vs Crank angle

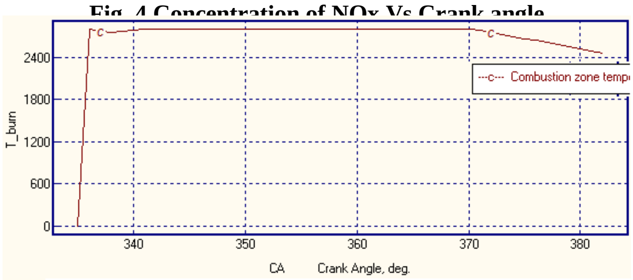

Fig. 5 Combustion zone temperature Vs Crank angle

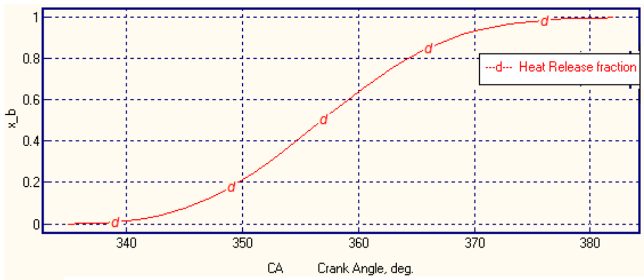

Fig. 6 Heat release fraction Vs Crank angle

VI. CONCLUSIONS

The focus of design of internal combustion engines in the early phase and till the end of the last century is on the effective utilization of fuel. Hence fuel efficient engines are built. But nowadays the focus is on minimizing the emissions that leads to environment friendly engines. To this end the SI engines are being explored using the concept of CI engines. To understand the overview of internal combustion engines, the paper summarizes the works carried out on the internal combustion engines from historical aspects to technical implements and improvements. In this paper the four stroke and two stroke operations of SI and CI engines are presented. The SI engine was simulated using a CFD implementation and results are listed and plotted.

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AUTHOR'S PROFILE

Suresh Muchakala received B.E in Mechanical engineering from AMACE, University of Madras, Kanchipuram in 1999 and M.Tech in Thermal Engineering from Jawaharlal Nehru Technological University, Hyderabad in 2005. Currently he is doing Ph.D on DISI Engines in Jawaharlal Nehru Technological University Anatapur. Since 2001, he held many positions like Asst. Prof., Asso. Prof., Examination Section In charge and currently he is working as the Head of the Department of Mechanical Engineering, all in GKCE, Sullurpet. His research interests include Thermal Engineering, CFD Solutions and IC Engines.

Dr.R.HariPrakash received B.Tech & M.Tech with distinction from Birla Institute of Technology Ranchi. He Obtained PhD from Indian Institute of Technology, Madras. He has 35 years of Industry/Research/Teaching at various levels. He worked as senior lecturer at Nanyang University, Singapore. He worked in NBKR Institute of Science & Technology Vidyanagar as Assistant professor and became Professor and Head of the Department. He is a Member of Board of Studies at JNTU Anantapur, S.V. University, Anna University, and Vellore Institute of Technology. He has published seven papers in National & four papers in International Journals. He worked as Principal of Gokula Krishna College of Engineering, Sullurpet, and Sri Venkateswara College of Engineering, Chittoor, Brahmaiah College of Engineering, Nellore and now he is the principal of Dr. KV Subbareddy College of Engineering for Women, Kurnool. He has authored the book "Operations Research" published by SCITECH publishers, Hyderabad. He is a Member of Indian Society for Technical Education, Indian Society for Non-Destructive Testing, Indian society for Automobile Engineering and American society of Mechanical Engineering, Fellow of Institute of Engineers. His areas of research specialization are Energy Management, Energy Distribution, Alternate source of Energy, Ecofuels.

Dr. B. Durga Prasad received B.Tech, M.Tech and Ph.D from the Department of Mechanical Engineering, JNTU Anantapur. Currently he is working as Professor & Head in the Department of Mechanical Engineering, JNTUA, Anantapuramu. He has more than 22 years of teaching experience He has published about 50 research papers in national and international journals and about another 40 research papers in national and international conferences. His research area includes Internal Combustion engines, Thermal Engineering, Alternate Fuels and Non-conventional Energy Resources.