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Development and Study of a High Speed HCCI Combustion Engine

[1]Gajanand Choubey, [2]Prof. Mahendra Prajapati, [3]Anand kumar
[1]M.Tech Scholar, Department of Mechanical Engineering, Millennium Institute of Technology, Bhopal, India
[2]Assistant Professor, Department of Mechanical Engineering, Millennium Institute of Technology, Bhopal, India
[3]Research Scholar, Department of Mechanical Engineering, National Institute of Technology, Patna, India

***Abstract*— This paper provides a comprehensive overview of HCCI engine technology, encompassing its fundamental principles, operating characteristics, benefits, challenges, and current research trends. HCCI engines operate by igniting a homogeneous mixture of air and fuel through compression, eliminating the need for a spark plug. This combustion approach combines the efficiency of CI engines with the ability to control combustion timing, similar to SI engines. The paper delves into the thermodynamic and chemical processes governing HCCI combustion, highlighting the role of factors such as temperature, pressure, and fuel properties.**

***Keywords*— HCCI, Combustion Engine, SI, CI, Spark.**

I. INTRODUCTION

In the pursuit of cleaner and more efficient automotive technologies, Homogeneous Charge Compression Ignition (HCCI) engines emerge as a beacon of innovation, aiming to bridge the gap between the efficiency of diesel engines and the lower emissions of gasoline engines. This detailed introduction to HCCI engines spans their fundamental concepts, inherent advantages, prevalent challenges, and the forefront of research aimed at making this technology a viable alternative for the future of internal combustion engines.

At its core, HCCI technology leverages the concept of auto-ignition, where a premixed air-fuel charge ignites spontaneously under the pressure of compression, without the need for a spark plug or the direct injection of fuel into the combustion chamber at the point of ignition. This mechanism is fundamentally different from that of conventional spark ignition (SI) and compression ignition (CI) engines, promising a unique blend of advantages, including reduced emissions and increased fuel efficiency. The principle behind HCCI involves achieving a homogeneous mixture of fuel and air throughout the cylinder, which upon compression, reaches a temperature and pressure where it combusts uniformly across the combustion chamber.

The innovation of HCCI engines lies not just in their operational principle but also in their potential to significantly reduce nitrogen oxides (NOx) and particulate matter (PM) emissions. The lower peak combustion temperatures inherent to the HCCI process limit the formation of NOx, a major pollutant associated with conventional engines, especially under high-temperature conditions. Moreover, the homogeneous nature of the air-fuel mixture ensures a more complete combustion, reducing emissions of unburned hydrocarbons (HC) and carbon monoxide (CO), which are prevalent in incomplete combustion scenarios. These environmental benefits are coupled with the efficiency gains of HCCI engines, which operate closer to the ideal Otto cycle efficiency due to their lean-burn characteristics, leading to lower fuel consumption and enhanced thermal efficiency.

However, the transition from traditional combustion technologies to HCCI is fraught with challenges, primarily centered around the precise control of combustion timing and the engine's operational range. Unlike SI and CI engines, where ignition timing can be directly controlled via spark or fuel injection timing, HCCI combustion timing is inherently linked to the engine's thermal state and the reactiveness of the fuel-air mixture. This sensitivity introduces complexity in achieving consistent and controllable combustion, especially across a wide range of operational conditions. The difficulty in precisely managing auto-ignition leads to challenges in extending the HCCI operational range to accommodate the full spectrum of engine loads and speeds encountered in real-world driving.

Additionally, the operational characteristics of HCCI engines pose challenges in cold start conditions and during transient operations such as acceleration and deceleration. The exact conditions required for auto-ignition are difficult to maintain during these dynamic states, necessitating advanced control strategies and engine designs to ensure reliable and

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responsive performance. This complexity is compounded by the need for HCCI engines to seamlessly transition between different combustion modes, ensuring optimal performance and emissions across all driving conditions.

Addressing these challenges has spurred extensive research and development efforts, focusing on advanced engine control algorithms, variable valve actuation technologies, and innovative combustion strategies. Real-time engine management systems that utilize sophisticated sensors and control algorithms are at the forefront of these developments, aiming to dynamically adjust engine parameters to maintain optimal combustion conditions. Technologies such as variable valve timing (VVT) and lift (VVL) play a crucial role in enhancing the flexibility of HCCI engines, allowing for precise control over the intake and exhaust processes to modulate the engine's thermal environment and mixture reactivity.

Moreover, the exploration of dual-fuel and stratified charge strategies offers promising avenues to extend the operational range and improve the controllability of HCCI combustion. By carefully managing the distribution and reactivity of the fuel-air mixture within the cylinder, these approaches aim to achieve a balance between the low-temperature combustion benefits of HCCI and the operational flexibility required for practical applications.

II. METHODOLOGY

HCCI engine is highly efficient and it also produces low NOx emission. It is difficult to operate these engines at high load and high speed. So for fundamental understanding of HCCI engine at high speed and high load experimental studies are required to be conducted.

In present work experimental studies are carried out to determine the following aspects:-

- Variation of pressure with the crank angle rotation.
- Variation of temperature with the crank angle rotation.
- Variation of HRR with the crank angle rotation.
- Variation of ISFC with load.

The experimental setup is shown in figure 1and 2.

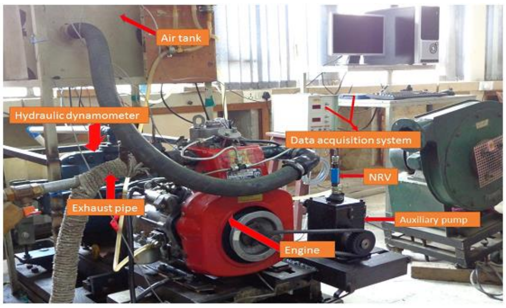

Figure 1: Experimental test rig

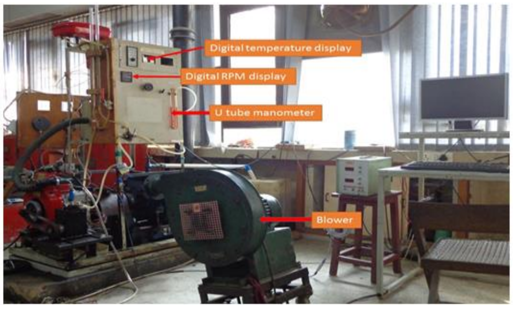

Figure 2: Experimental test rig

Pressure measurement: In an HCCI engine laboratory experiment, pressure measurement and calibration are crucial for understanding combustion characteristics, optimizing engine performance, and validating computational models. Here's a step-by-step guide to pressure measurement and calibration in an HCCI engine lab experiment:

Selecting Pressure Transducers:

Choose pressure transducers suitable for measuring the cylinder pressure during HCCI combustion. These transducers should have high accuracy, fast response times, and the ability to withstand high temperatures and pressures typical in HCCI engines.

Common types include piezoelectric pressure transducers, which offer fast response times and high sensitivity, and strain gauge pressure transducers, which are robust and suitable for long-term measurements.

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Mounting Pressure Transducers:

Install pressure transducers in the combustion chamber of the HCCI engine. Ensure proper sealing and positioning to minimize signal distortion and protect the transducers from heat and mechanical stress.

Use specialized mounting hardware and adapters designed for high-pressure applications to secure the transducers to the engine cylinder head or spark plug ports.

Flow measurement

In a laboratory experiment focused on measuring fuel consumption in an HCCI engine, accurate flow measurement and calibration are essential for assessing engine efficiency, optimizing combustion strategies, and validating computational models.

Speed measurement

For measuring the speed of the engine RPM sensor was installed.

Load measurement

In a laboratory experiment involving an HCCI engine, load measurement and calibration using a hydraulic dynamometer are crucial for assessing engine performance, characterizing power output, and validating computational models.

III. RESULT AND DISCUSSION

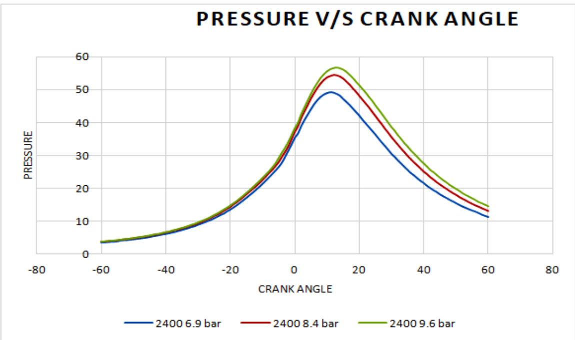

Figure 3: Pressure v/s crank angle

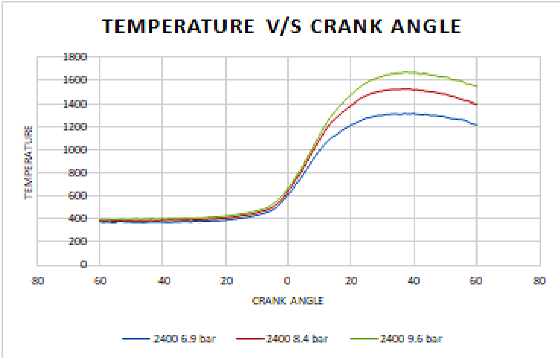

Figure 4: Temperature v/s crank angle

In this graph temperature increases on increasing the load while speed of the engine was kept constant. When the load was 6.9 bar maximum amount of temperature came 1312ºC. At the same time if load was increased to 8.4 bar and 9.6 bar the values of maximum temperature were 1523ºC and 1675ºC respectively. On increasing the load maximum temperature increase because at higher load more amount of power required for this more amount of fuel has to be supplied hence temperature at higher load increases.

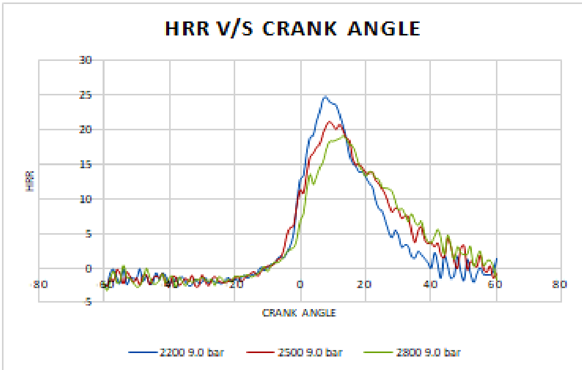

Figure 5: HRR v/s crank angle

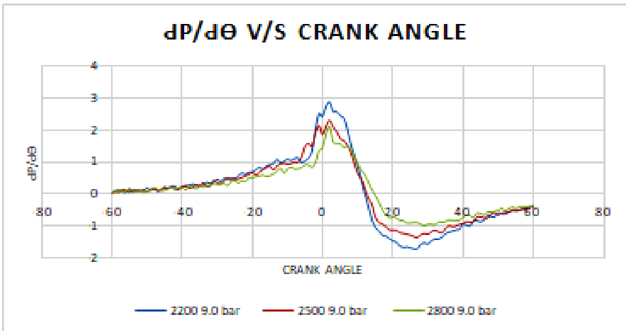

Figure 6: Rate of pressure rise v/s crank angle

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This is the graph between rate of pressure rise and crank angle at certain load and different speed. Maximum value of pressure rise is near TDC. Maximum values of pressure rise are 2.88, 2.32 and 2.09 J/degree at 2200, 2500 and 2800 rev/min respectively.

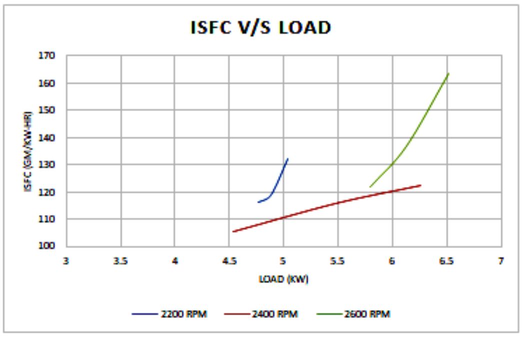

Figure 7: ISFC v/s load

This graph shows that near to 2400 rev/ min ISFC is minimum. When we increase of decrease the speed at any particular load its value increases. Hence by this graph it can be said that near to 2400 rev/min performance of the engine is optimum and at any other speed its performance will be lower.

While doing the experiment many difficulties were found. Each time it had been resolved. The difficulties found were as follows:-

- For making homogenous combustion we are using auxiliary pump. Fuel line from main pump and from auxiliary pump were connected by connector. When fuel was supposed to be supplied from the auxiliary pump it would not happened. It was found that there was flow of fuel in reverse direction in the fuel line connected to auxiliary pump. It was observed by fuel level increase in burette that connected to auxiliary pump. The reason behind this pressure developed by main pump was greater compared to auxiliary pump. So we connect an NRV in the auxiliary fuel line. By adding this the problem associated to that was resolved.
- Initially the auxiliary pump was connected to main fuel supply line which was connected to injector, by two numbers of such fuel line and main injection pump was connected to main supply line by one fuel line. It was found that since both the fuel line which were connected to main supply line were not equal hence to start the engine was very difficult. So after that both the line were made of equal length. The problem was resolved and both the line were made to connect with main supply line by two numbers of fuel line.
- When both the line (auxiliary fuel line, fuel line from main injection pump) was connected to main supply by two numbers of fuel line. It was found that there was time lag in fuel supply due to extra length added to fuel line. Hence the injection was very late. So, to resolve this problem both line were made to connect with main supply line by single fuel line.

IV. CONCLUSION

It has been observed that for HCCI mode of combustion in high speed engine fuel has to be supplied slightly earlier so that late combustion can be avoided. Otherwise also there will be wastage of power since maximum heat release after TDC as observed. Fuel line should not be altered very much because it causes time lag due to which difficulties arises in HCCI mode of combustion. At the same speed if we increase the load then pressure, temperature and HRR all increases. If the load is kept constant and increase in the speed causes shifting of peak pressure, peak temperature and maximum value of heat release rate towards right. Engine when operate at optimum condition at that speed the value of ISFC is lowest.

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