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A Computational Study Evaluating the In-Cylinder Flow Parameters of a Hydrogen-Fueled Powered-Internal Combustion Engine

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Abstract
This research focuses on analyzing the movement of gases within the cylinder parameters of two-dimensional combustion chambers in hydrogen-fueled four-stroke engines with internal combustion. We employ computational fluid dynamics modeling to study and understand the intricate dynamics involved. CFD simulation was performed using commercial CFD programme. In this investigation, the engine speed was changed from 1000to 3000rpm, with a range comparable Ratio of 0.6 to 1.0 and a crank angle of 720 degree at the level of monitoring condition, the influence of engine speed and ratio of equivalent on flow field features and volumetric efficiency is explored increased engine speed results in a more efficient Hydrogen diffusion techniques and greater uniformity of the mixture of air and fuel structure. The in- cylinder thermodynamics and pressure distribution, and additionally, the symmetry of Hydrogen fractions of mass of different engine speeds, show the flow field characteristics. The collected data demonstrate the highest in- cylinder temperature and pressure attained at engine speed 3000rpm were 650k and 5.8mpa, Respectively, it is clear that engine speed and equivalency ratio are highly connected to volumetric performance. Results from this study reveal that volumetric effectiveness increase exponentially with engine speed while decreasing with equivalency ratio. The findings from this simulation can be utilized to investigate the homogenization of air-fuel mixture structure, ultimately enhancing engine combustion efficiency.
Keywords: CFD, hydrogen, internal combustion engine, volumetric performance.

1) Introduction

In today's ever-evolving world, where cutting-edge technologies emerge daily, the energy consumption of transportation is on a relentless rise. An essential driving force behind this surge is petroleum fuel, which plays a vital role in both energy production and serving as the primary fuel for transportation. The availability of petroleum is declining rapidly, and the worsening air quality is raising concerns about the future. However, hydrogen, as an alternative fuel, possesses unique qualities that give it a significant advantage over other forms of fuel. Not only is hydrogen a clean substitute for petroleum fuels, but its potential as a car fuel also paves the way for the development of ecologically friendly transportation systems. Extensive research [1-7] has been conducted on hydrogen-fueled internal combustion engines. As society becomes increasingly concerned about energy scarcity and environmental protection, efforts are being directed towards enhancing engine fuel economy. Consequently, there is a growing development of hydrogen-fueled engines, accompanied by a wide range of fuel delivery methods [1,3, 6, 8-11].

The growing presence of automobiles on the road leads to the generation of residue and pollution as a result of emissions. It has been widely recognized that hydrogen serves as an outstanding fuel for internal combustion engines [12]. An essential step in comprehending the underlying physical phenomena during the motor cycle is the identification of the flow field within a cylinder of an internal combustion engine, covering the intake, compression, expansion, and exhaust strokes. The performance of an engine is greatly influenced by the way the air-fuel mixture moves inside the cylinder. Consequently, car manufacturers and researchers are currently giving a lot of attention to studying the flow patterns inside the cylinders of internal combustion engines.

Thanks to the progress in engine simulation technology, the virtual representation of an engine has become a feasible choice [13]. CFD programs are extensively employed nowadays, and these software tools can be utilized for engine simulation [14-15]. The integration of Computational Fluid Dynamics (CFD) in engine enhancement projects has led to significant reductions in both time and costs when designing and developing engine combustion systems [16]. Accurate modeling and analysis of cylinder flow play a crucial role in achieving successful combustion, minimizing emissions, and simulating optimal engine performance. Understanding the flow pattern inside the cylinder of an internal combustion engine is extremely important to enhance our knowledge and optimize engine performance. The turbulent flow within the cylinder greatly affects the combustion process, fuel efficiency, emission levels, and overall engine functionality. The main goal of this study is to utilize CFD analysis to explain the movement of fluid within an internal combustion engine powered by hydrogen. Additionally, we will examine the flow properties inside the engine cylinder. By conducting dynamic simulations, we can visualize the characteristics of the flow field during engine operation. Furthermore, we aim to investigate how engine speed and equivalency ratio affect the flow field properties inside the cylinder and the volumetric efficiency.

Aim and Objectives:

The aim is to investigate and analyze the in-cylinder flow parameters of a hydrogen -fueled internal combustion engine using computational methods.

Objectives:

1. To simulate the flow behavior within the cylinder of an internal combustion engine.
   - This objective involves creating a computational model of the engine and simulating the flow patterns within the cylinder during various stages of the engine cycle.
2. To evaluate the impact of hydrogen on fuel on the in-cylinder flow parameters.
   - This objective focuses on studying how the use of hydrogen as a fuel affects key flow parameters, such as intake air velocity, turbulence, swirl, and combustion characteristics.
3. To assess the effects of engine design and operating condition on flow parameters.
   - This objective involves analyzing how different engine design factors, such as intake system geometry, piston shape, and valve timing, as well as various operating conditions, impact the in - cylinder flow parameters.
4. To provide insights for optimizing the in-cylinder flow to enhance engine performance.
   - This objective aims to identify potential areas for improvement in the in-cylinder flow parameters in order to enhance the overall efficiency, combustion stability, and emissions characteristics of the hydrogen fueled internal combustion engine. By achieving these objectives, the study aims to contribute to a better understanding of the in-cylinder flow behavior in hydrogen internal combustion engine and provide valuable insight for optimizing their performance as well.

The Significance of United Nations on Sustainable Developmental Goals on the Research Topic

1. Clean Energy (Goal 7): This goal aims to ensure access to affordable, reliable, sustainable, and modern energy for all. It aligns with the study's focus on evaluating the in-cylinder flow parameters of a hydrogen-fueled internal combustion engine, which promotes the use of clean energy sources.
2. Industry, Innovation, and Infrastructure (Goal 9): This goal focuses on promoting sustainable industrialization, innovation, and resilient infrastructure. The study, which evaluates the performance of a hydrogen-fueled engine, aligns with the goal's aim to foster sustainable technologies in the transportation sector.
3. Climate Action (Goal 13): This goal is about taking urgent action to combat climate change and its impacts. The study's focus on hydrogen as a fuel source contributes to reducing greenhouse gas emissions and transitioning to a low-carbon economy.

4. Sustainable Cities and Communities (Goal 11): This goal aims to create inclusive, safe, resilient, and sustainable cities and communities. The research on hydrogen-fueled engines can contribute to sustainable urban transportation, reducing air pollution and improving the overall quality of life in cities.

2) Mathematical Model

One of the most fascinating areas of CFD is the simulation of internal combustion (IC) engines. The CFD simulation was performed on the engine's combustion chamber, which consists of the piston, intake, and exit valves, in a two-dimensional format. Table 1 is a summary of the engine specs. Crank angle (CA) is a measurement of the intake and exhaust valve's open and closing. Several techniques, including the carburetor, were used to create an external mixture for this investigation. Through the use of the GAMBIT preprocessing programme, computational fluid dynamic modelling was created. Triangular and quadrilateral components were used to generate the mesh for the 2D model, along with dynamic layering elements. Inlet and exit ports are examples of complicated geometries where an effortless glide from a minuscule mesh to a more robust coarse mesh is necessary that employ triangle components. The quadrilateral pieces are also used close to geometries where the border advances linearly. Therefore, the dynamic layers are employed above the piston, exhaust valve, and intake valve. Figure 1 displays the created CFD model. Furthermore, there are non-conforming connections in the space above the valve. Optimizing the layering approach to harness the full potential of the moving and deforming mesh (MDM) models is the goal of such meshing and domain decomposition.

Table 1. Engine specifications [17].

Parameter	Value	Unit
Bore	88.00	mm
Stroke	90.00	mm
Connecting rod length	150.00	mm
Crank period	720.00	CA
Inlet valve open	340.00	CA
Exhaust valve open	120.00	CA
Inlet valve close	600.00	CA
Exhaust valve close	360.00	CA
Max. valve lift	9.50/9.50	mm

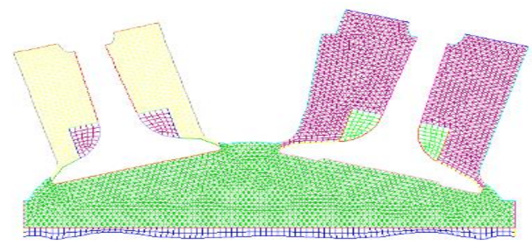


Figure 1. Computational Dynamic Model

Modelling flows when the geometry of the domain is changing over time owing to motion on the domain borders required the utilisation of the dynamic mesh model. At each time step, FLUENT will automatically update the volume mesh based on the updated locations of the boundaries [18]. This process is completely hands-free for the user. The goal is to determine the function that describes the movement of the piston with respect to the crank angle, which is crucial for accurately determining the optimal length of the connecting rod and the stroke length of the piston. The expression for the position of the piston is (1):

$$p_s = L + \frac{A}{2}(1 - \cos\theta_c) - \sqrt{L^2 - \frac{A^2}{4}\sin^2\theta_c} \qquad (1)$$

The position of the piston, denoted by 'ps', is measured in relation to the top dead centre (TDC) as 0 and bottom dead centre (BDC) as A. Meanwhile, the length of the connecting rod is represented by 'L', the stroke of the piston by 'A', and the position of the crank angle by 'c'.
To calculate the crank angle, simply apply the formula (2).

$$\theta_c = \theta_s + t\,\Omega_{shaft} \qquad (2)$$

The crankshaft speed is determined by the position of the shaft and the initial crank angle. The dynamic model was adjusted using layered quadrilateral and unstructured triangular elements. The updating process ensured that stationary areas remained intact. Referring to the profile that outlines the relationship between valve lift (in mm) and crank angle (in degrees) [18], the valve motion is defined.

The built-in functions and valve lift profiles provide an explanation of how each surface moves in relation to a reference point.

A. The Boundary and Starting Point: Examining the Surrounding Conditions

The simulation focuses on the combustion chamber as the flow domain, encompassing the inlet valve, exhaust valve, piston, intake port, and exhaust port. Three distinct varieties of boundary conditions have been applied. For both the pressure-inlet and pressure-outlet boundary conditions, the pressure setting is carefully set to atmospheric pressure. The pressure-inlet boundary condition is applied at the inlet of the intake port, whereas the pressure-outlet boundary condition is employed at the exhaust port's exit. For specific initial conditions, kindly refer to Table 2.

Table 2. Boundary and Initial Conditions

Variable (Unit)	Initial value
Pressure (pa)	0
X-velocity (m/s)	0
Y-velocity (m/s)	0
Turbulence kinetic energy (m^2/s^2)	0.01
Turbulence dissipation rate (m^2/s^3)	0.01
H_2 concentration	0
Temperature (k)	318
Cylinder wall temperature (K)	360

B. *Model Development*

In order to conduct this investigation, a comprehensive numerical model was developed. This model allowed the solving of equations related to the conservation of mass, momentum, and energy within a 2D control volume that was changing shape over time. To complete the simulation model, two additional sub-models were incorporated along with the main governing equations. To accurately represent the turbulent flow and velocity fluctuations inside the cylinder, the "-" turbulence model was taken into account. The species model is employed to imitate the motion of various species within a specific area, excluding any interactions between different species. 2. The fuel model refers to the specific types of fuel species utilized in an air-hydrogen mixture.

The technique of employing the dynamic mesh conservation equations is applied to solve both the governing equations and the sub model equations.

For a generic scalar (φ) within an unbounded control volume (V) with a moving boundary, the integral form of the conservation equation is represented as equation (3) [18]:

$$\frac{d}{dt}\int_V \rho\Phi dV + \int_{\partial V} \rho\Phi\left(\vec{u}-\vec{u}_g\right)d\vec{A} = \int_{\partial V} \Gamma\nabla\Phi . d\vec{A} + \int_V S_\Phi dV \qquad (3)$$

Where:

ρ denotes the mass per unit volume of the substance.,

The vector ū denotes the speed vector of the current,

The moving mesh's grid velocity is represented by $\bar{u}\rho$,

The diffusion coefficient, represented by Γ, measures the rate of diffusion,

SΦ represents the source term responsible for Φ.

The symbol ∂V is utilized to represent the boundary of the control volume.

Employing the formula for the initial backward difference with respect to time in equation 3 leads to the emergence of various conceivable expressions:

$$\frac{d}{dt}\int_V \rho\Phi dV = \frac{(\rho\Phi V)^{n+1} - (\rho\Phi V)^n}{\Delta t} \qquad (4)$$

The quantities at the current and next time level are denoted by 'n' and 'n+1' respectively. The volume at the (n+1) th time level, denoted as Vn+1, is calculated using equation (5):

$$V^{n+1} = V^n + \frac{dV}{dt}\Delta t \qquad (5)$$

Where 'dv/dt' represents the rate of change of volume with respect to time within the control volume. To comply with the grid conservation law, we must calculate the volume time derivative of the control volume using the formula (6):

$$\frac{dV}{dt} = \int_{\partial V} \vec{u}_g . d\vec{A} = \sum_j^{n_f} \vec{u}_{gj} . \vec{A}_j \qquad (6)$$

In equation (7), the dot product ūgh. Āj on each control volume face is calculated by multiplying the number of faces on the control volume, represented as nf, with the j face area vector, denoted as Āj.

$$\vec{u}_{gj} . \bar{A}_j = \frac{\delta V_j}{\Delta t} \qquad (7)$$

Where δVj represents the volume that is swept out by the control volume face j during the time step Δt. In a remarkable four-stroke engine, the stunning volumetric efficiency (V)plays a crucial role in determining the effectiveness of the gas alternating process. It quantifies the amount of air delivered by the intake valve (ma) during the intake time, comparing it to a reference mass required to adequately fill the engine's swept volume under specific atmospheric conditions. This relationship can be expressed as (8) in the following manner:

$$\eta_V = \frac{m_a}{\rho_a V_d} \qquad (8)$$

where ρ_a is the inlet air density and V_d is the swept volume.

This study utilizes volumetric efficiency to evaluate the engine's performance. To calculate the engine's volumetric efficiency, we convert the 2D inlet to a 3D inlet and consider the analysis geometry for each unit depth. By analyzing the mass flow history of the intake valve, we can make further assessments,

$$\text{Total volume of the air injected into the cylinder}$$
$$= \frac{\text{Mass flow rate} \times \text{time of flow}}{\text{air density}}$$
$$= \frac{\text{Area under mass flow history at inlet manifold}}{\text{air density}}$$

Hence,

$$\eta_V = \frac{\text{Area under mass flow history at inlet manifold}}{\text{air density} \times \text{swept volume}}$$

3) Outcomes and Discussion

A. Temperature and In-Cylinder Pressure Variation

Figure 2 showcases the changes in in-cylinder pressure as the crank angle varies across different engine speeds. It is clear that as the engine speed increases, the pressure inside the cylinder also goes up. At 3000 rpm and 1000 rpm, the maximum in-cylinder pressures reach 5.8 MPa and 2.3 MPa, respectively. The difference becomes more distinct when observing the peak pressure occurring at TDC. Additionally, the variation in temperature depends on the pressure, as described by the ideal gas equation of state. The temperature change within the internal cylinder aligns with the pressure profile in a consistent pattern. Figure 3 beautifully illustrates the correlation between in-cylinder temperature and crank angle. Moreover, it showcases the highest temperature achieved during an increase in engine RPM. At 3000 rpm, the maximum temperature reaches an impressive 650 K, whereas at 1000 rpm, it's 470 K. Interestingly, in both scenarios, the peak pressure occurs before reaching the maximum temperature.

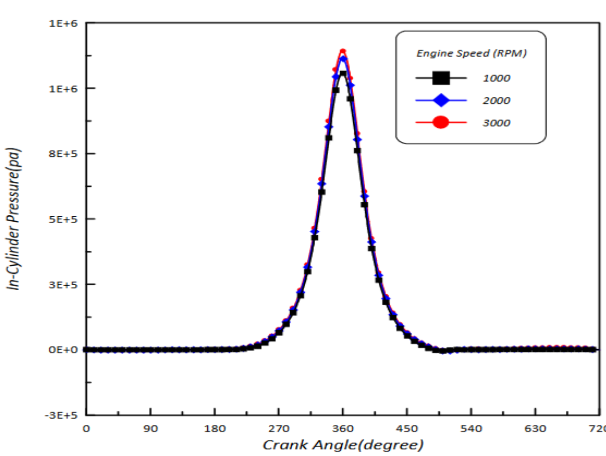


Figure 2: Variation of in-cylinder pressure against crank angle with different engine speed

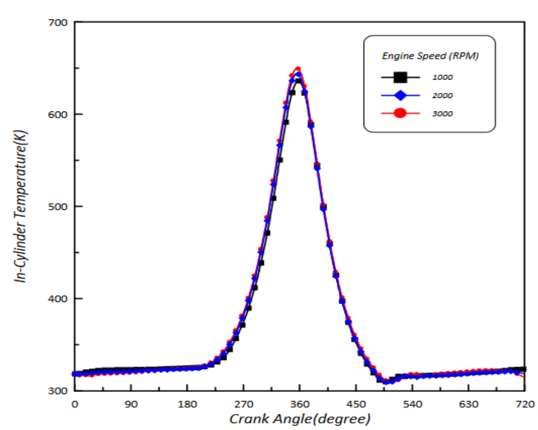
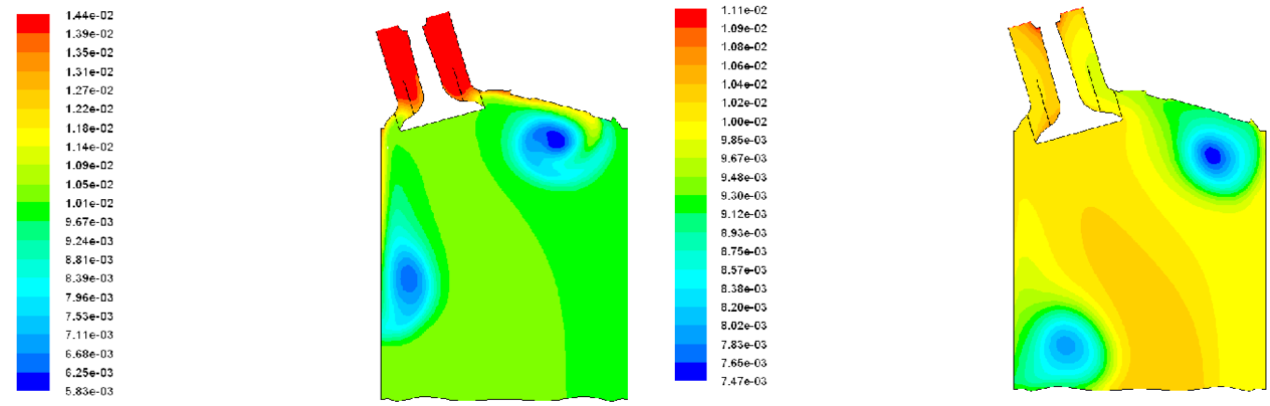


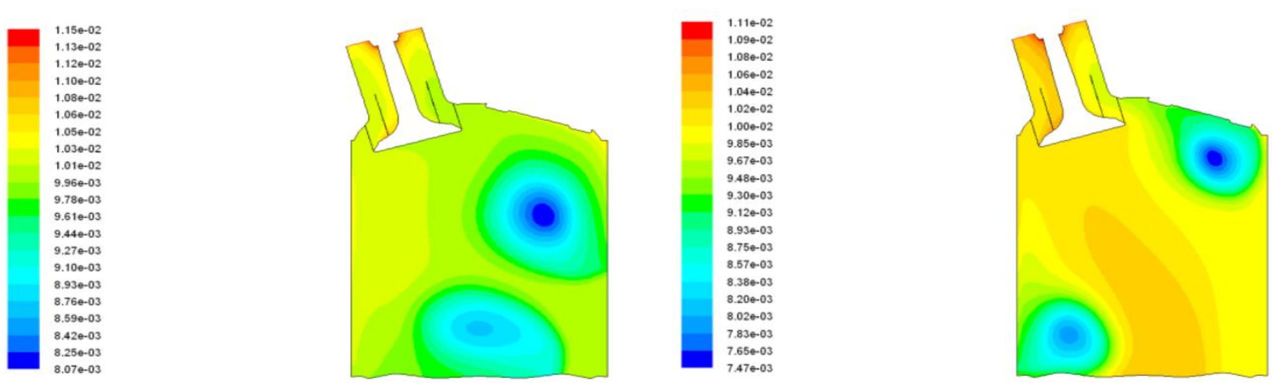
Figure 3. Variation of in-cylinder temperature against crank angle with different engine speed

influence of engine speed on the concentration and distribution of hydrogen species within the simulated area are closely monitored during the intake phase. The relationship between increased engine speeds and the diffusion process of hydrogen becomes evident, as it leads to a more efficient diffusion process and enhances the uniformity of the air-fuel mixture's structure due to the higher vacuum pressure in the combustion chamber.

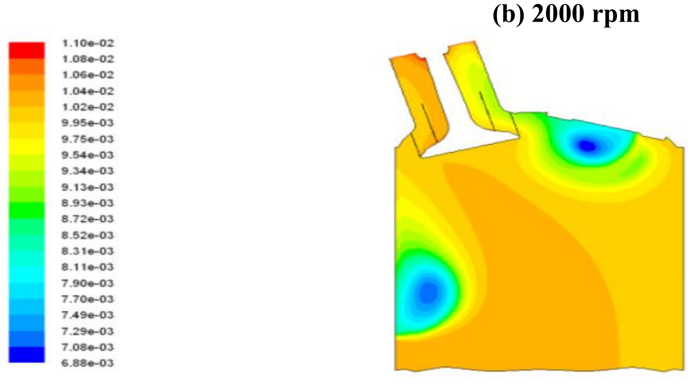


(a) Crank angle at 540^0 (b) Crank angle at 585^0

Fig. 4. Variation of hydrogen mass fraction



(a) 1000 rpm (b) 2000 rpm



(c) 3000 rpm

Figure 5. Hydrogen mass fraction for different engine speed

C. Modifications in Volumetric Efficiency

Figure 6 illustrates the fluctuation of volumetric efficiency concerning engine speed and equivalency ratio. - Generally, engines are more effective when they operate at their maximum volumetric efficiency. - Due to its low density of 0.0824 kg m-3 at 25°C and 1 atm, hydrogen fuel displaces a considerable amount of incoming air, thus emphasizing the significance of volumetric efficiency for hydrogen engines. According to research [11], the volumetric efficiency is significantly reduced. It becomes apparent that as the equivalency ratio increases for a specific engine speed, the volumetric efficiency decreases. This is a normal occurrence, as the increase in equivalency ratio leads to a decrease in the amount of air entering the combustion chamber per cycle. Additionally, it increases the amount of hydrogen in the charge. On the other hand, when considering the all-equivalence ratio, the volumetric efficiency increases with the rise in engine speed. The reason behind this phenomenon is that as the engine speed increases, the vacuum at the intake port intensifies, allowing a significant volume of air to enter the cylinder.

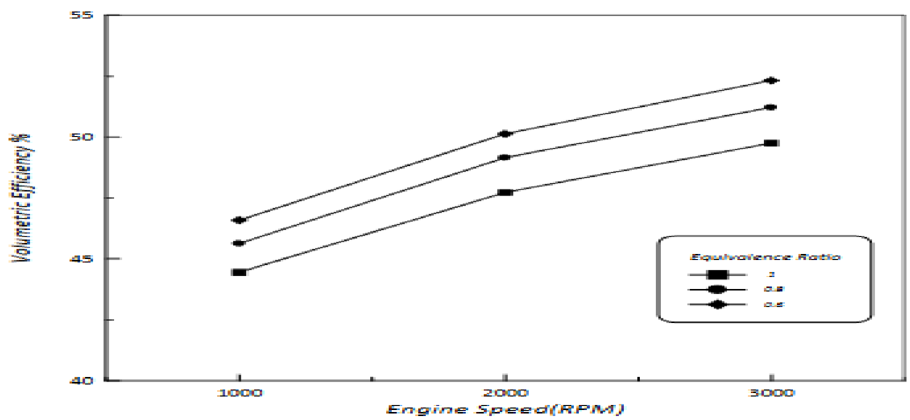
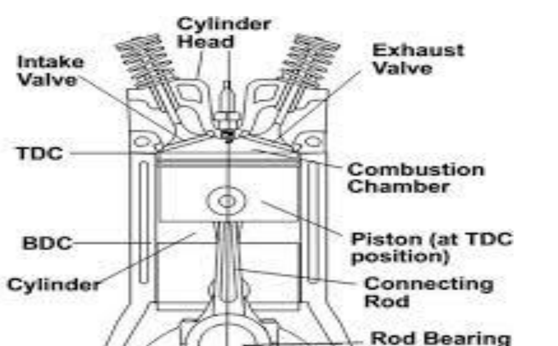


Figure 6. Variation of volumetric efficiency against engine speed and equivalence ratio



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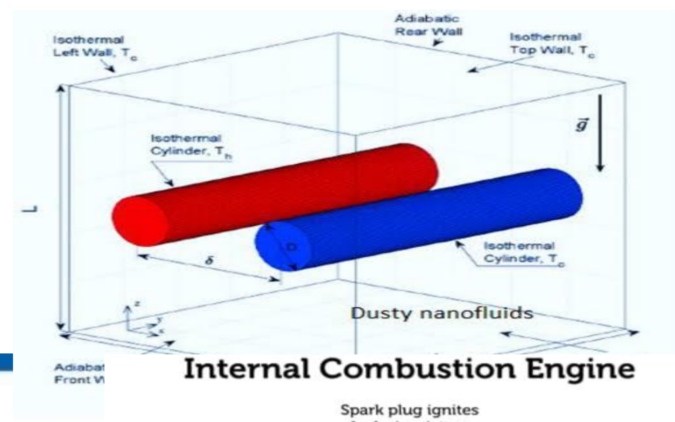

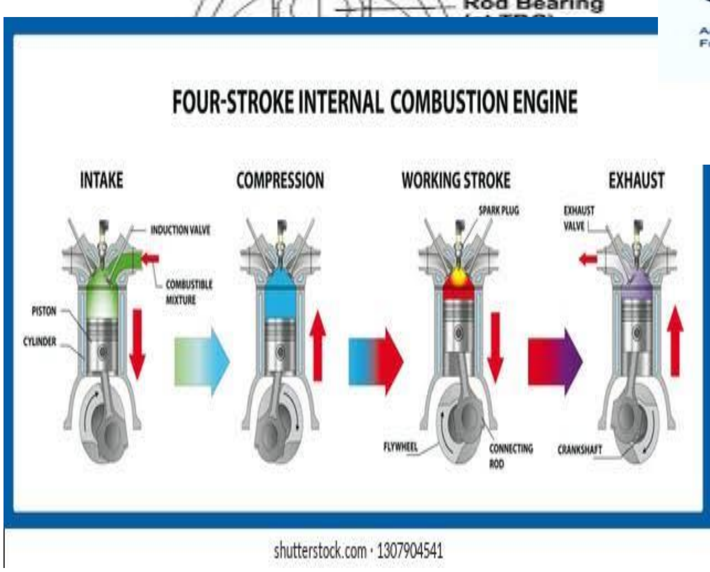

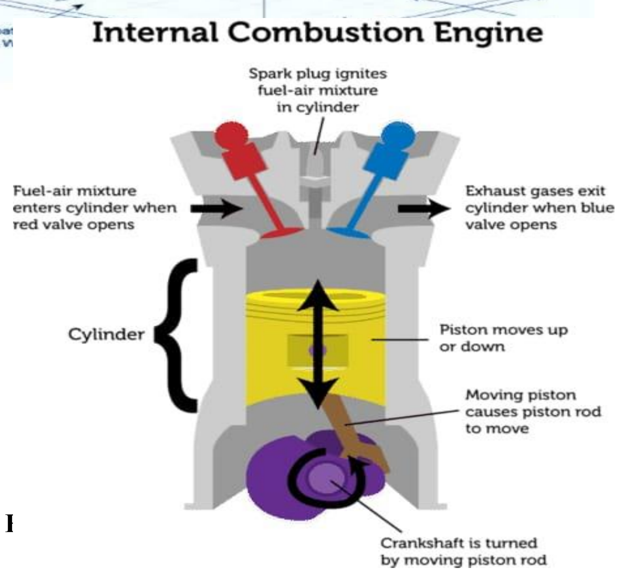

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Fig 11: Hydrogen Internal Combustion engine

Figure 12: New Hydrogen Combustion engine

Figure 7: Hydrogen internal combustion engine
This figure provides a visual representation of a hydrogen internal combustion engine. It showcases the various components involved, such as the intake system, cylinder, combustion chamber, and exhaust system. It helps to understand the basic structure of the engine.

Figure 8: four stroke internal combustion engine
This figure illustrates the working principles of a four stroke internal combustion engines. It shows the four stages of the engine cycle: intake, compression, power, and exhaust, understanding this process is crucial for comprehending the functioning of the engine.

Figure 9: Impact Properties Heterogeneity
This figure represents the impact properties heterogeneity of the Hydrogen fueled internal combustion engine .it provides information about the non -uniform distribution of properties within the engine structure and how it affects its performance. This can include variation in temperature, pressure, and fuel-air mixture distribution. By analyzing these figures, Researchers can gain insight into the internal working of hydrogen -fueled internal combustion engines. They can help in understanding the engine structure, operation, and the impact of heterogeneity on its performance.

Figure 10: Air fuel ratio internal combustion engine
The air-fuel ratio is a crucial parameter in internal combustion engines. It refers to the ratio of the mass of air to the mass of fuel being supplied to the engine's cylinders. When it comes to hydrogen-fueled internal combustion engines, understanding the in-cylinder flow parameters is essential for optimizing engine performance. Computational studies can provide valuable insights into these parameters. By evaluating the in-cylinder flow parameters, such as the velocity, turbulence, and pressure distribution, researchers can gain a comprehensive understanding of how hydrogen fuel behaves within the engine. This knowledge can help in designing efficient combustion processes, reducing emissions, and improving overall engine performance.

4) Conclusion

To forecast the properties of the flow field and volumetric efficiency, a thorough CFD model was created. To improve engine performance and the combustion process, it is possible to use the simulation's findings to assess the uniformity of the structure of the air-fuel mixture. To better comprehend the workings of the internal combustion engine powered by hydrogen, the findings have been obtained utilising dynamic simulations. open the door for more investigation on this subject. To create a comprehensive model of the internal combustion engine powered by hydrogen, the simulation may be expanded to include additional topics like injection and combustion.

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Conflicts of Interest:

The Authors declare that they have no conflict of interest.

Authors Contribution:

The first author wrote the draft under the guidance of the second author on the theme and content of the paper.

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