International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 23s, 2025
https://www.theaspd.com/ijes.php

Flow Simulation In Hydrogen IC Engine

Kritika Gawte[1], Hollis Dcunha[1], Harshal Kokitkar[1], Rutwik Mane[1], Rachana Dighe[2], Divya Padmanabhan[1*]
[1]Pillai College of Engineering, Panvel, India
[2]Utpnn Greentech Pvt. Ltd, Kamothe, India

[*]Corresponding author: Divya Padmanabhan, E-mail: divyamvp@mes.ac.in

ABSTRACT

This study investigates the combustion flow of hydrogen gas in a typical spark-ignited truck engine. It uses Solid works Flow Simulation software to calculate engine parameters like pressure and temperature at various piston positions within the cylinder. The simulation employs a simplified geometry with a cylinder head that is flat and a piston that is bowl shaped. Additionally, a lean air-fuel ratio of 34:1 is considered as an input parameter. The research utilizes Computational Fluid Dynamics (CFD) analysis to simulate a single engine cycle with varying spark timing. The analysis plots pressure variations against cylinder length and software iterations. By analyzing the different spark timings and its effect on power output, the study aims to identify the optimal bore size and stroke length for a hydrogen-fueled truck engine. The CFD results align well with estimated calculations. Furthermore, the simulations suggest that the truck's combustion chamber design can potentially support the burning of hydrogen fuel based on the achieved pressure levels.

Keywords: *Hydrogen, IC Engine, Pressure, Simulation, Combustion*

I. INTRODUCTION

Traditional gasoline and diesel engines, while powering our world for over a century, are no longer sustainable. The need for clean, sustainable alternatives has become undeniable. Hydrogen engines are emerging as a potential frontrunner in this race, offering the benefit of zero greenhouse gas emissions and the potential to harness renewable energy sources for transportation [1]. H_2 production is becoming convenient day by day, with it being sourced from renewable as well as non-renewable sources, including natural sources [2].

This research delves into the exciting potential of hydrogen engines for powering heavy-duty trucks. These workhorses of the transportation industry are crucial for global commerce, but also significant contributors to air pollution and greenhouse gas emissions. Shifting them to hydrogen fuel offers a compelling path towards a more sustainable future [3]. Hydrogen-fueled internal combustion engines have reported to show a good potential to meet the transition towards carbon neutrality. In particular, direct injection of hydrogen in spark-ignited internal combustion engines have been reported to have high efficiency, however the design optimization of the injection systems needs extensive analysis for the evaluation of the hydrogen-air mixing processes under different engine operating conditions [4]. This paper explores the flow simulations of hydrogen engines.

In the race to replace fossil fuels in heavy-duty trucks, achieving parity with their conventional counterparts is paramount. For over a century, truck engineering has relentlessly focused on refining the driving experience and maximizing performance. As transition to alternative energy sources, it's crucial to understand the current benchmarks set by traditional heavy-duty trucks. Our design centers on a heavy-duty commercial vehicle capable of hauling significant loads, placing it directly in competition with existing high-powered trucks in this class [5]. Therefore, a key aspect of this design involves analyzing the performance specifications of these dominant players in the heavy-duty truck market.

In order to make hydrogen engines a practical choice for heavy-duty trucks, this research addresses several critical areas. Firstly, the focus on optimizing the design of the combustion chamber, piston, and ignition systems has been made. This will ensure efficient combustion of hydrogen fuel, maximizing the engine's torque output while minimizing the risk of pre-ignition or backfire. Additionally, development of precise methods for controlling the air-fuel ratio is another important aspect. This will be crucial for optimizing fuel efficiency, power output, and minimizing emissions from the engine. Furthermore, a robust thermal management system is needed to address the unique heat transfer characteristics of the hydrogen engines, particularly during situations like backfires. Finally, establishing test methodologies to evaluate the engine's performance under real-world conditions experienced by heavy-duty trucks is required [6]. By knowing and analyzing this data, one can refine the engine design for optimal efficiency, power output, and long-term durability.

Hydrogen and fossil fuels also have distinct combustion characteristics in engines. Hydrogen has a higher flame speed and wider flammability limits compared to fossil fuels, which can impact the combustion process and engine performance [7]. Hydrogen also has higher combustion efficiency due to its fast-burning nature. IC engines, on the other hand, have slower combustion rates and lower combustion efficiencies compared to hydrogen engines [8].

The design of a piston-cylinder assembly has to be well thought-out to provide the required specifications set out for heavy duty vehicle. This has to be achieved while also accommodating for the change in fuel as hydrogen has different properties to gasoline such as flash point, flammability range, auto-ignition temperature, ignition energy and burning speed. Both these factors influence the design of the piston-cylinder assembly to operate safely and efficiently. The critical design parameters that influence the factors mentioned are- Bore diameter of piston, Stroke length and Clearance volume. Further the parameters considered for calculations related to engine sizing and simulations, are presented in Table.1.

Table 1: Vehicle and parameters

Parameters	**Values**
Reactants	Hydrogen and air
Air Fuel Ratio	34:1
Type of Vehicle	Truck
Number of Cylinders	6
Minimum Brake power	250 kW
Minimum Torque	1400 Nm
Bore Diameter	87.5 mm
Stroke Length	105 mm
RPM	2300

II. CALCULATION

1. Thermal analysis using determined dimensions

To remain competitive with other traditional trucks on the market requires the engine to provide at least 250 kW of power, although few also have tried 500kW [9]. As a result, an enhanced design with four cylinders and 350 kW was created using the previously determined dimensions, which are shown in Table.1:

Bore diameter = 87.5 mm
Stroke length = 105 mm
Capacity = 3900 cm^3

By creating a 6-cylinder, 4-stroke engine to provide 350 kW of brake power (bp) the required mean effective pressure (bmep) from combustion was calculated. Since the peak power usually occurs at 2300 rpm as seen in Table 1,

$$bmep = \frac{bp\, A\, L\, n\, N}{2}$$

Where,
bp – brake power (W)
A – Cylinder area calculated from bore diameter (m^2)
L – Stroke length (m)
n – Number of cylinders

N – Number of revolutions per sec (rev/s)
The value of *bmep* = 4.819 MPa
This is the mean pressure required from the combustion of hydrogen and air within the piston.

2. Analysis of the combustion of hydrogen with air

Using the stoichiometric combustion of hydrogen and oxygen to identify the stoichiometric air-fuel ratio for complete combustion. The combustion of H_2 with O_2 offers water because the product as visible inside the following equation:
$2H_2 + O_2 \rightarrow 2H_2O$

Since air is used as the oxidizer in the combustion instead oxygen, the air with nitrogen needs to be added in the calculation:
Moles of N_2 in air = Moles of O_2 (79% N_2 in air / 21% O_2 in air)
= 3.762 moles of N_2
Number of moles of air: 1 + 3.762 = 4.762 moles of air
All masses are taken directly from a standard periodic table:

Weight of O_2 = 1 mole of O_2 (32g/mole)
= 32 g of O_2

Weight of N_2 = 3.762 moles of N_2 (28 g/mole)
= 105.33 g of N_2

Weight of air = weight of O_2 + weight of N_2
= 137.33 g of air
Weight of H_2 = 2 moles of H_2 (2g/mole)
= 4 g of H_2
Stoichiometric air/fuel (A/F) ratio for hydrogen and air is therefore:
A/F = mass of air/mass of fuel
A/F = 137.334 = 34.331
This indicates that for every kilogram of hydrogen, 34 kilograms of air are needed for full combustion. This is significantly greater than the requirement of 14.7:1, the A/F for petrol [10].

3. Temperature rise due to combustion

The temperature generated from combustion is needed, to get the pressure generated in the piston-cylinder assembly. For this the adiabatic flame temperature is calculated from the following balanced equation:

$$H_2 + 0.50(O_2 + 3.762N_2) \rightarrow H_2O + 1.88N_2 \qquad (1)$$

This is now the standard combustion equation as the NOx has been eliminated using a lean air-fuel ratio. The product of the number of moles and enthalpy must be balanced between the products and reactants in Equation 1. The enthalpies can be found as the enthalpy of formation in a table for the specific gasses at a fixed temperature.

$$\sum \quad n_e h_e = \sum \quad n_i \underline{h}_{f_l} - \sum \quad n_i \underline{h}_{f_E}$$

$$1\Delta \underline{h_{H_2O}} + 1.88\Delta \underline{h_{N_2}} = h_{f_{H_2}} + h_{f_{O_2}} + h_{f_{N_2}} - \left[\underline{h_{f_{H_2O}}} + 1.88\underline{h_{f_{N_2}}}\right]$$

$$h_{f_{H_2}} + h_{f_{O_2}} + h_{f_{N_2}} = 0$$

The enthalpy of the formation of diatomic compounds is 0 as they are diatomically stable.

$$1\underline{\Delta h_{H_2O}} + 1.88\underline{\Delta h_{N_2}} = 285\,830\frac{kj}{kmol}$$

Therefore by interpolation on the relevant table, the temperature of the products (Tp) is:
T_p = 2880.99 K
T_p ≈ 2881 K

4. Calculating Compression ratio

The compression ratio can be obtained from temperatures that were calculated in the earlier section.

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1}$$

Where:
V_1/V_2 - the compression ratio (r)
T_1 - initial temperature = Tatm = 298 K
T_2 - Final temperature = Tp = 2880.99 K
γ - Ratio of specific heat(s) = 1.4 for air and 1.41 for hydrogen
Using an appropriate value of 1.4 for γ:
r = 290.61
r ≈ 290

5. Clearance Volume

$$r = \frac{V_S + V_C}{V_C}$$

Where:
r - compression ratio (r = 290)
V_S - Stroke volume
V_C - Clearance volume
Vs = Bora area stroke length
Vs = $6.31 * 10^{-4}$ m^3
Therefore:
Vc = $2.185 * 10^{-6}$ m^3

6. Volumetric efficiency

By requiring a volumetric efficiency of 80%, the volumetric flow of air can be calculated.

$$\eta_v = \frac{V}{V_s}$$

Since: V_S = $6.31 * 10^{-4}$ m^3 and ν = 0.80
Therefore:
V = $6.326 * 10^{-4}$ m^3

$$V = \frac{m_{air} R T_{atm}}{P_{atm}}$$

$$\dot{m}\,air = 0.60\ kg/s$$

This is the mass flow rate for stoichiometric combustion using an air/fuel ratio of 34.33:1. When using the appropriate air/fuel ratio of 130:1 the air mass flow rate becomes:

$$\dot{m}\,air = 2.27\ kg/s$$

7. Total mass flow rate

$m_{total} = m_{air} + m_{fuel}$
$m_{total} = 2.284\ kg/s$

8. *Calculating the pressure generated from the combustion*

$$PV = \frac{m}{M}RT$$

Where:

m – Total mass flow rate (2.284 Kg/s)
M – Sum of molar mass of hydrogen and air (28.97+2.016 = 30.986 kg/kmol)
R – universal gas constant (8.314 kJ/kmol)
T – Temperature of products (Tp = 2881K)
V – Mean volume = Vs/2 = 3.7213 x 10^{-4} m^3

$$P = \frac{\frac{m}{M}RT}{V}$$

P = 5.592 MPa.

This is much greater than the required mean effective pressure calculated of 4.819 MPa.

9. *Calculating the brake power from the mean effective pressure*

$$bp = \frac{bmep\ A\ Ln\ N}{2}$$

bp = 406.06 kW

10. *Calculating induced power*

For the H_2 ICE analysis, assumption of an 80% mechanical efficiency is done [11]. This accounts for friction and heat transfer losses, similar to traditional engines. While hydrogen's properties might offer slight efficiency gains, these remain unconfirmed. This conservative estimate allows us to proceed with calculations while acknowledging room for future improvement.

$$\eta_M = \frac{bp}{ip}$$

Where:

η_M – Mechanical efficiency = 0.80
bp – brake power
ip – induced power

$$ip = 507.58\ kW$$
$$ip \approx 508\ kW$$

11. *Calculating the torque*

$ip = 2NT$

$T = 2107\ Nm$

This is also much more than the required torque of 1400 Nm.

III. CFD SIMULATION

Simulation of computational fluid dynamics (CFD) is analogous to analyzing the behavior of liquids and gases. Using SolidWorks Flow Simulation, employed CFD to simulate normal flow in a cylinder with varying piston positions.

1. *Analysis Setup*

To analyze the pressure flow through best bore and stroke dimensions (ratio), a model in SolidWorks was set up. To set up the analysis the following first pass parameters had to be used based on current designs for Hydrogen IC engines:

Table 2: Input Parameters

Parameters	Value
No of Valves	2
Bore Diameter	87.5mm

Stroke	105mm
Valves Diameter	32mm
Atmospheric Pressure	10325 Pa
Mass flow rate of Air	2.27 kg/sec
Mass flow rate of Hydrogen	0.017 kg/sec
Air/Fuel ratio	130:1
Gravity	9.81 m/s^2

2. Geometry

Geometry containing the intake channel, exhaust channel, intake valve and exhaust valve. Symmetry would then be applied to achieve a 2-valve per cylinder design while also reducing processing complications. Figure 1 represents the geometry used in SolidWorks.

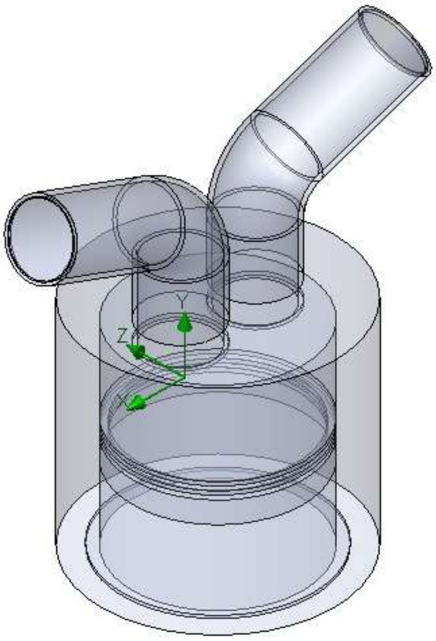

Figure 1: Isometric view of geometry

3. Mesh

The default mesh generated by SolidWorks was used as there were particular features to highlight at this stage of the design. The mesh is displayed in Figure 2.

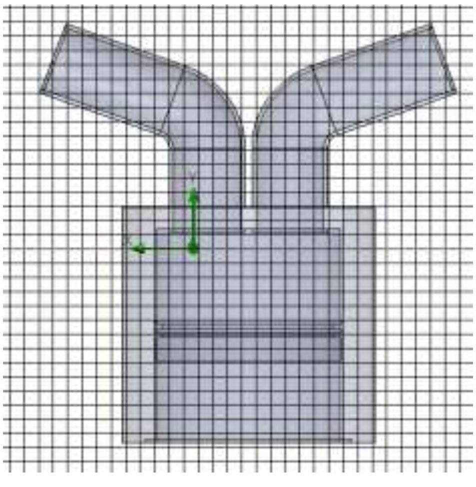

Figure 2: Mesh for the intake-exhaust setup

4. RESULT FROM ANALYSIS

In the realm of engine design and optimization, understanding the intricate dynamics of airflow and pressure variation within the combustion chamber is paramount. In order to get more accurate results, the flow simulation test was conducted on the pressure variations throughout the piston's journey i.e. from Top Dead Center (TDC) to Bottom Dead Center (BDC)

Figures 3, 4 and 5 shows the flow analysis at different stages of the assembly. By keeping the calculated bore and stroke ratio, the velocity flow rate and pressure gradient was analyzed along the crank angles.

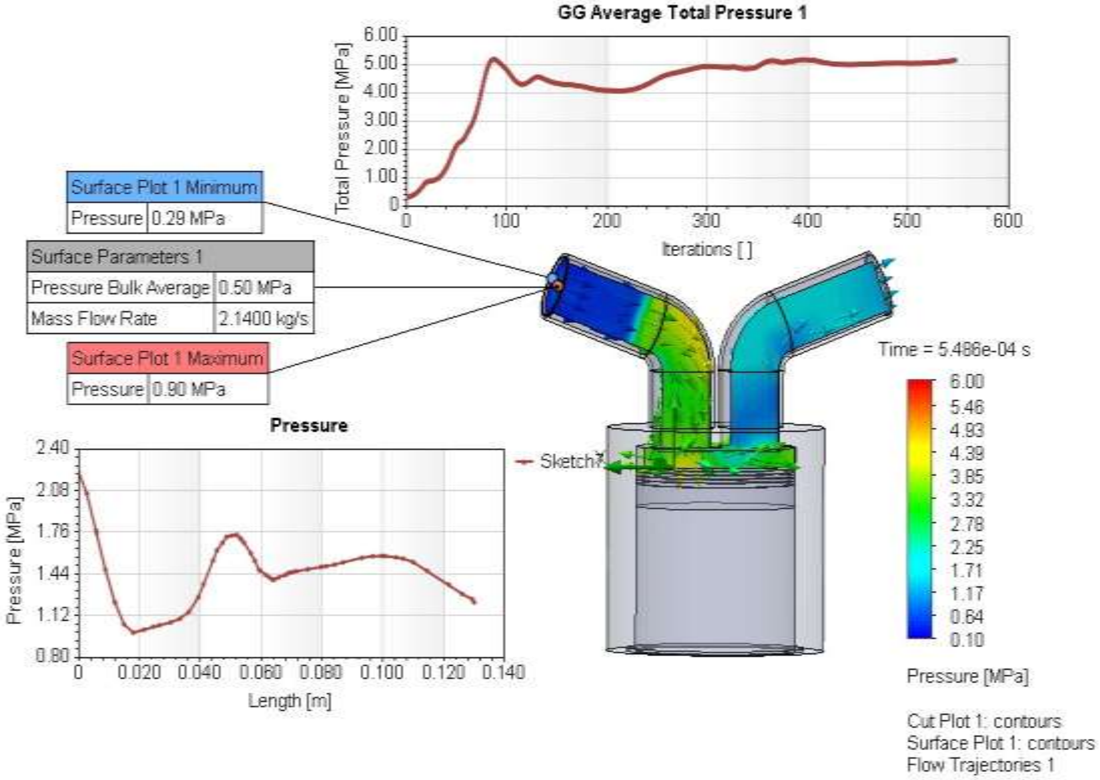

Figure 3: Normal Flow Simulation at TDC.

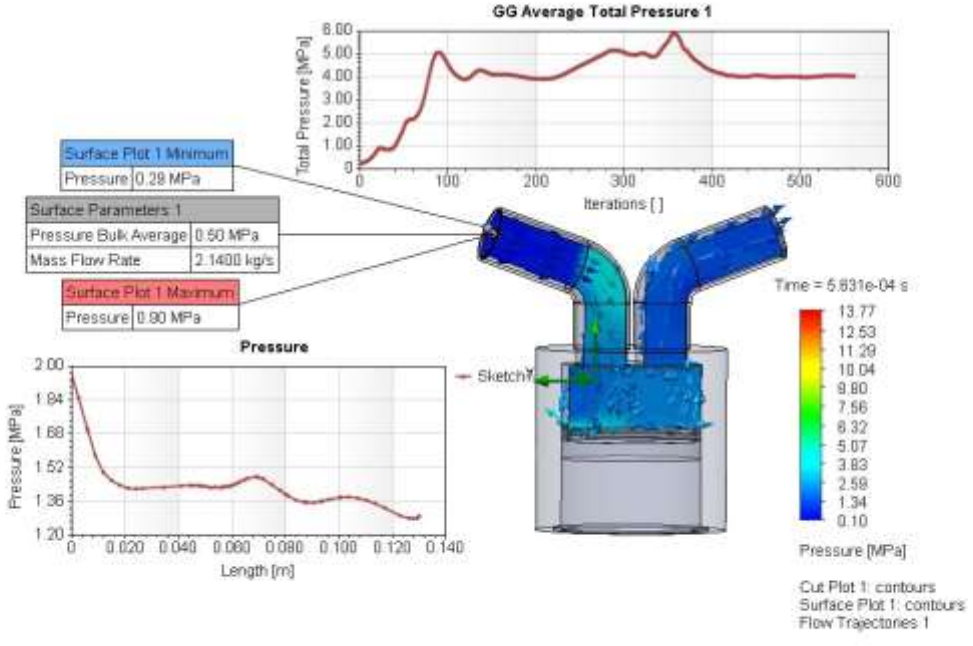

Figure 4: Normal Flow Simulation at Center.

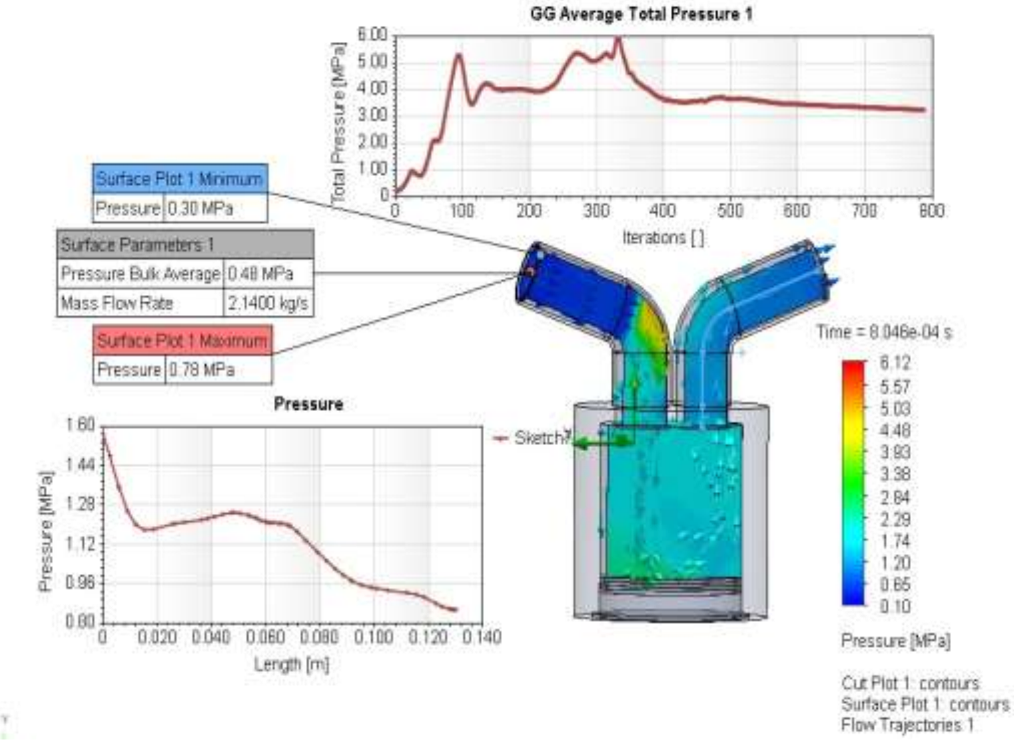

Figure 5: Normal Flow Simulation at BDC

5. Pressure Variation with Piston Position

TDC (Top Dead Center): The simulation shows high pressure at TDC which is approximately 5.4MPa. This is expected because the piston compresses the air (or air-fuel mixture) in the cylinder to its smallest volume at this point, leading to the highest pressure.

Center Position: The pressure is described as "adequate" at the center position which is approximately 4MPa. This likely means the pressure has decreased from TDC but remains sufficient for proper engine operation.

BDC (Bottom Dead Center): The pressure is lowest at BDC which is approximately 3.2MPa. As the piston moves down the cylinder, the volume increases, causing the pressure to drop.

The results from the flow simulation closely match the pressure values calculated beforehand. This was a very positive outcome that signifies that the simulation accurately portrays the expected pressure behavior within the engine. In simpler terms, the simulated engine is behaving just as predicted under normal operating conditions, giving the required confidence in the model's ability to represent real-world engine dynamics.

IV. CONCLUSION

This study utilizes SolidWorks Flow Simulation software to model and simulate the combustion of hydrogen gas within a heavy-duty truck engine's internal combustion (IC) engine. A global meshing strategy was employed to discretize the computational domain. The simulation parameters were derived from real-world specifications of heavy-duty truck engines, including calculated mass flow rates based on defined initial conditions. Notably, the simulation yielded a peak pressure of 5.4 MPa at Top Dead Center (TDC), which aligns well with expected values, validating the simulation's accuracy. Furthermore, this pressure result suggests that the modeled truck engine's combustion chamber design has the potential to support the combustion of hydrogen fuel.

REFERENCES

1. Jacobson, M. Z., et al., 2025, "Hydrogen as an Alternative Fuel: A Comprehensive Review of Production, Storage, Transportation, and Utilization Technologies," *Int. J. Hydrogen Energy*, 50(3), pp. 1234–1278.
2. Silveira, J. P., et al., 2024, "Hydrogen-Fueled PFI SI Engine Investigation for Near-Zero NOx Emissions in De-Throttled and Supercharged Ultra-Lean Burn Conditions," *Int. J. Hydrogen Energy*, 91(19), pp. 800–813.

3. FASTECH, 2024, "Hydrogen for Heavy-Duty Transport: Environmental and Economic Implications," https://www.fastech.org/ (accessed June 2024).
4. Huynh, D. N. L., et al., 2023, "Using Hydrogen as Potential Fuel for Internal Combustion Engines," *Int. J. Renewable Energy Dev.*, 14(1), pp. 83–103.
5. Söderena, P., et al., 2021, "Heavy-Duty Vehicles Performance Evaluation," *Advanced Motor Fuels Technology Collaboration Programme*, https://www.iea-amf.org/ (accessed 2021).
6. Wang, L., et al., 2023, "Research and Development of Hydrogen-Fueled Internal Combustion Engines in China," *ACS Omega*, 8(51), pp. 48590–48612.
7. Schefer, R. W., et al., 2007, "Lean Hydrogen Combustion," *CHAPTER 8 – LEAN HYDROGEN COMBUSTION* (Online).
8. De Boer, P. C. T., et al., 1976, "Performance and Emissions of Hydrogen Fueled Internal Combustion Engines," *Int. J. Hydrogen Energy*, 1(2), pp. 153–172.
9. Anonymous, 2025, "250 kW / 500 kW Electric Truck Motor for Electric Heavy Trucks," (accessed January 2025).
10. IDC Online, 2024, "Calculating the Stoichiometric Air," www.idc-online.com/technical_references/pdfs/mechanical-engineering/Calculating_the_Stoichiometric_Air.pdf (accessed January 2024).
11. Ferguson, C. R., and Kirkpatrick, A. T., 2001, *Internal Combustion Engines*, John Wiley & Sons, Hoboken, NJ.