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Deformation Analysis Of A Piston Crown In A CNG-Diesel Dual-Fuel Engine.

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Abstract: The piston in an internal combustion (IC) engine is subjected to several forces before transmitting power to the crankshaft. The main objective of this study is to analyze the stress distribution and deformation of a diesel–CNG dual-fuel engine piston when exposed to the gas pressure generated during combustion. An aluminum alloy piston was selected for the analysis, and suitable design parameters were assumed to develop the piston geometry. The stress and deformation caused by the maximum combustion pressure were analyzed using FEA-based software. The boundary conditions considered different peak combustion pressures corresponding to various CNG substitution rates acting on the piston. The results reveal that the piston crown experiences the highest deformation, with a maximum value of 0.075 mm, while the maximum Equivalent [von-Mises] Stress is found to be approximately 300 MPa, when tested with zero CNG substitution and pure diesel used and the lowest deformation of 00.062mm at 80% CNG substitution rate with maximum Equivalent [von-Mises] Stress is found to be approximately 240 MPa.

Index Terms – Piston Stress Analysis, Diesel-CNG Dual-Fuel Engine, Finite Element Analysis, CNG Substitution Rate

1. Introduction

Diesel engines are commonly used for transportation and power generation because of their high thermal efficiency and reliability. But the increase in fuel consumption and strict emission regulations have led to the use of cleaner alternative fuels. Compressed Natural Gas (CNG) is one of the alternative fuels which has become a major focus since it is a cleaner burning fuel with lower carbon and particulate emissions in comparison to traditional diesel fuel.

In diesel–CNG dual fuel engines, diesel is used as a pilot fuel for ignition and CNG as a main fuel providing most of the combustion energy. Dual-fuel technology helps in reducing fuel consumption while maintaining engine performance. Such systems are more appropriate for fleet-based and continuous load applications like buses and generators. However, dual-fuel engines also have several limitations such as combustion instability at different loads, incomplete combustion at high substitution ratios of CNG, and increased thermal and mechanical loading of engine components.

Most previous studies on diesel–CNG dual-fuel engines have mainly focused on engine performance, fuel economy, and emission characteristics, while limited research has been done on the structural and thermal behaviour of pistons under different CNG substitution ratios. Therefore, the present study aims to find out the effect of different diesel–CNG substitution ratios on maximum combustion pressure, stress distribution, and deformation of an IC engine piston using FEM-based structural analysis. The goal of the research is to determine the advantage of using CNG to improve reliability and reduce mechanical loading on the piston when operating in a dual-fuel operating mode.

Maximum combustion pressure after combustion corresponding to crank angle can be determined using the graph [fig. 1].

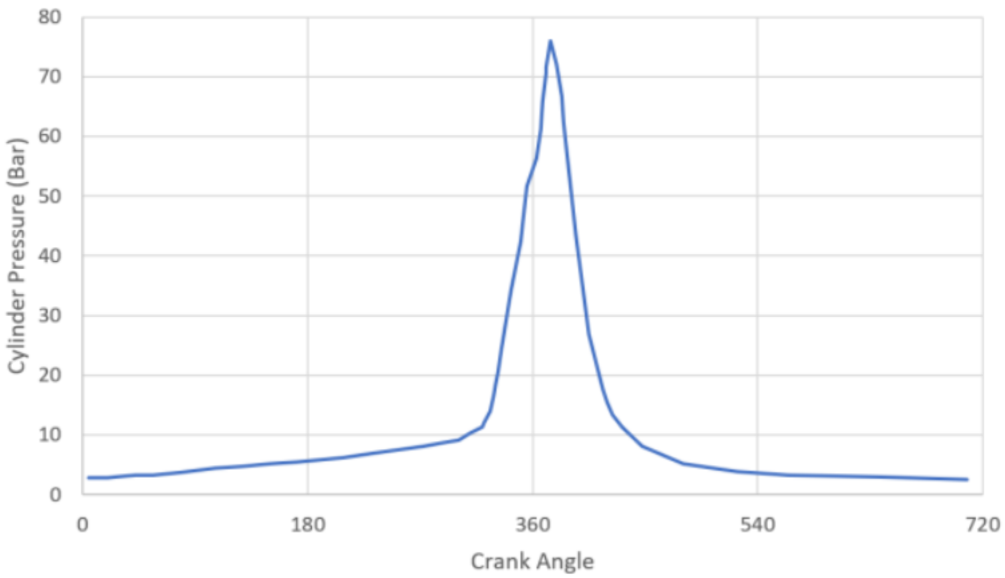

Figure 1: Variations of in-cylinder pressure in diesel engine with crank angle (Muhammad Usman Kaisan, 2021), (Torregrosa, 2007)

2. Methodology: -

2.1 Material for piston: - Aluminum 2618 Alloy, Wrought

- **Material Composition: -**

Table 1

Element	**Composition [%]**
Copper	1.9 - 2.7
Silicon	0.25
Iron	0.9 - 1.3
Magnesium	1.3 -1.8
Titanium	0.04 - 0.1
Nickel	0.9 - 1.2
Others	0.05
Aluminum	92 - 94

- **Physical properties: -**

Table 2

Property	**Metric**
Density	2.76 g/cc
Melting Point	549 - 638 °C

- **Mechanical Properties: -**

Table 3

Properties	**Metric**	**Tensile**
Tensile Strength	372 MPa	54000 psi
Tensile Strength, Ultimate	441 Mpa	64000 psi
Shear Strength	262 Mpa	38000 psi
Fatigue Strength (completely reversed stress; RR Moore machine/specimen)	124 Mpa	18000 psi
Elastic Modulus (AA; Typical; Average of tension and compression)	74.5 Gpa	10800 ksi
Poisson's ratio	0.33	0.33

2.2 Mathematical model: -

The primary cause of stress development and deformation in a compression ignition (CI) engine piston is the high combustion pressure generated inside the combustion chamber during the power stroke. This pressure acts directly on the piston crown, creating mechanical stresses within the piston material. The present study focuses only on the mechanical stresses and deformation developed in the CI engine piston due to combustion pressure. Thermal stresses generated by the high-temperature expanding gases during combustion have not been considered in this analysis.

Pressure is the normal force exerted per unit area on a surface. In an internal combustion engine, combustion pressure is produced by the expansion of gases during fuel combustion, and this pressure acts on the piston crown to generate mechanical force. The pressure is mathematically expressed as:

$$P = \frac{f}{a}$$

Where:

- P is pressure
- f is the applied force
- a is the area over which the force acts.

Mechanical stress in a piston is defined as the internal resisting force developed within the piston material when it is subjected to external loads such as combustion pressure. In a CI engine piston, the combustion gases exert high pressure on the piston crown, producing compressive and tensile stresses within the piston body. Excessive mechanical stress may lead to deformation, fatigue, or failure of the piston material.

The mechanical stress developed in the piston can be calculated using:

$$\sigma = \frac{F}{A}$$

where:

σ = Mechanical stress (Pa or N/m^2)

F = Force acting on the piston (N)

A = Cross-sectional area of the piston (m^2)

Since the combustion force acting on the piston is generated due to pressure, the force can be calculated as:

$$F = P \times A$$

Where P is the combustion pressure acting on the piston crown.

Deformation in a piston refers to the change in shape or displacement of the piston material when it is subjected to combustion pressure and mechanical loading. In a CI engine piston, deformation mainly occurs at the piston crown due to the high pressure generated during combustion. Excessive deformation may affect engine performance and piston durability.

The deformation of a piston can be calculated using the relation:

$$\delta = \frac{FL}{AE}$$

where:

δ = Deformation or displacement (m)
F = Applied force (N)
L = Length of the component (m)
A = Cross-sectional area (m²)
E = Young's modulus of the piston material (Pa)

An empirical linearized relation was adopted to estimate equivalent combustion pressure variation with increasing CNG substitution for structural FEA analysis

$$Ps = Pd(1 - kx)$$

Where:

$Ps =$ Pressure at CNG substitution
$Pd =$ Pure diesel pressure
x = CNG substitution fraction
$k =$ pressure reduction coefficient

2.3 Geometrical and FE model of piston

The piston used for the analysis was designed according to the guidelines provided by previous researchers (Ku, 2021). The engine specifications are presented in Table 4. An aluminum alloy was selected as the piston material, and its properties are listed in Table 1,2,3. Aluminum alloy is considered suitable for applications involving speeds greater than 6 m/s. The equations used for calculating the piston dimensions were adopted from the book *Design of Machine Elements* by Bhandari. The calculated dimensions are provided in Table 4.

Piston Dimensions: -

Table 4

Description	Property (mm)
Thickness of piston	10.28
Radial thickness of ring	3.44
Minimum axial thickness of ring	3.44
Top land thickness	12.34
Thickness of other land	3.44
Maximum thickness of barrel	11.10
Thickness of piston barrel at lower end	3.88
Outer diameter of piston pin	38.54

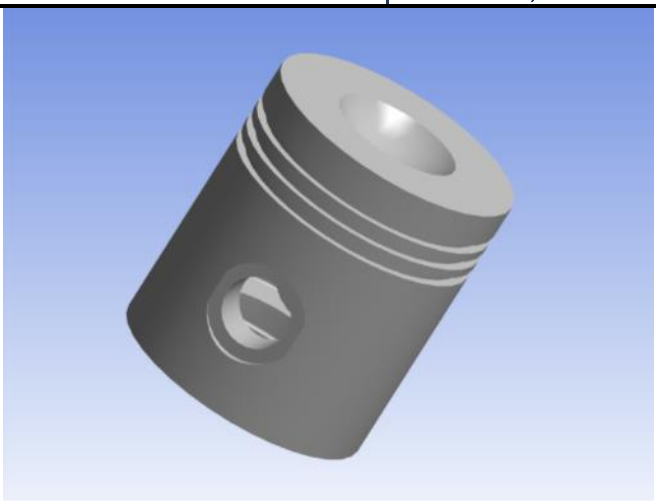

Figure 2: 3D model of the Piston

2.4 Meshing: -

Mesh consists of 114755 number of elements and 171495 number of nodes. Nonlinear mechanical mesh has been chosen for analysis of mechanical stress. Cross section of mesh geometry can be seen in figure 5.

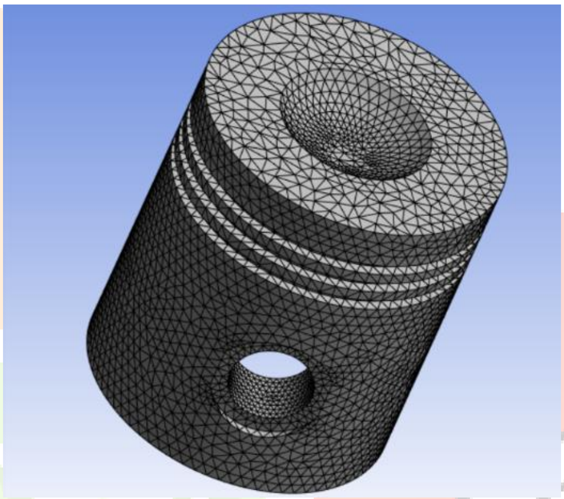

Figure 3: Mesh model of Piston

2.5 Boundary condition

The Boundary condition for deformation and stress analysis where the pressure of 6 MPa has been used as the force exerted by hot gases on surface of the piston in 100% diesel used. Figure 1 shows the value of pressure range that can be used for diesel engine piston. For the static analysis, the piston pin location has been chosen as fixed support. Different values of pressure based on the CNG substitution rate have been chosen for the input in simulation. The maximum pressure after combustion acts only on the crown of the piston. The value of maximum pressure is dependent upon the CNG substitution rate.

2.6 Methodology: -

The methodology involved selecting a suitable piston material, which is an aluminum alloy in this study. The piston geometry was designed using data and design procedures obtained from the machine design handbook. A 3D model of the piston was then developed, and the geometry is illustrated in Figure 2. The developed model was imported into FEA-based software, where meshing was performed. The generated mesh contained 114,755 elements and 171,495 nodes. The model was subsequently analyzed by applying the boundary conditions which are various values of maximum pressure after combustion inside the combustion chamber after various CNG substitution rates. All computations were carried out using Finite Element Analysis (FEA). After completion of the iterations, the obtained results were evaluated and compared with findings reported in previous literature.

3. Results and Discussion

3.1 Deformation Analysis: -

Figure 4 clearly shows the deformation generated on the piston crown due to the pressure exerted by the hot working gases. This deformation is produced under diesel-only combustion conditions. This is the first case of deformation analysis, in which the pressure acting on the piston crown is purely due to diesel combustion, with a pressure of 6 MPa or 60 bar. This baseline pressure value has been taken from the Dahal [2023]. It can be clearly observed that the maximum deformation obtained is 0.075 mm.

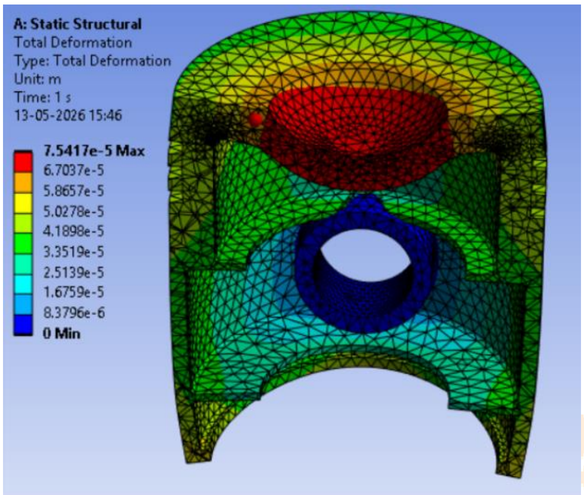

Figure 4

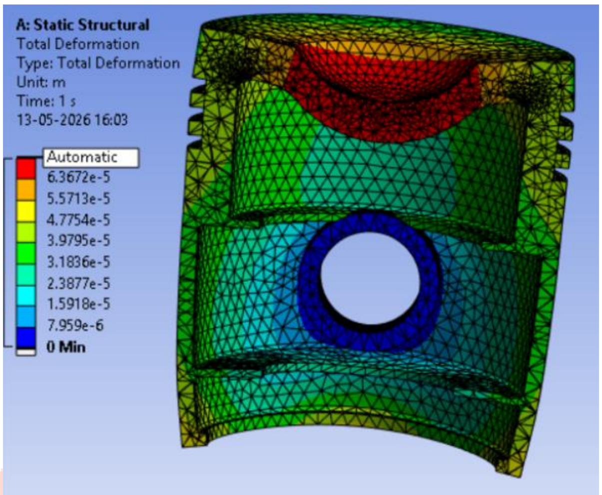

Figure 5

Figure 5 clearly shows the deformation generated on the piston crown due to the pressure exerted by the hot working gases. This deformation is produced when 25% CNG is mixed with the intake air, and combustion is initiated by 75% diesel. This is the second case of deformation analysis, in which the pressure acting on the piston crown is generated by the 25% CNG and 75% diesel fuel combination, resulting in a pressure of 5.7 MPa or 57 bar. This pressure value is calculated using the empirical relation stated above. It can be clearly observed that the maximum deformation obtained is 0.071 mm.

Figure 6 clearly shows the deformation generated on the piston crown due to the pressure exerted by the hot working gases. This deformation is produced when 50% CNG is mixed with the intake air, and combustion is initiated by 50% diesel. This is the third case of deformation analysis, in which the pressure acting on the piston crown is generated by the 50% CNG and 50% diesel fuel combination, resulting in a pressure of 5.4 MPa or 54 bar. This pressure value is calculated using the empirical relation stated above. It can be clearly observed that the maximum deformation obtained is 0.067 mm.

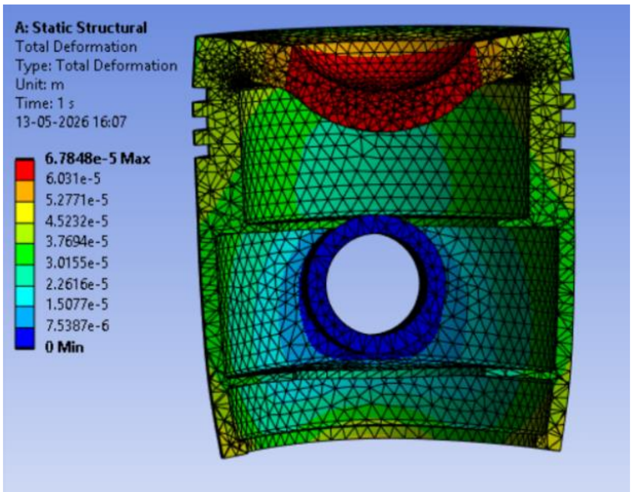

Figure 6

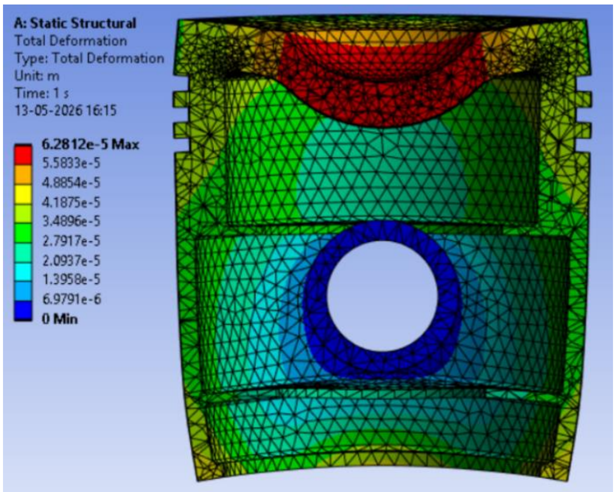

Figure 7

Figure 7 clearly shows the deformation generated on the piston crown due to the pressure exerted by the hot working gases. This deformation is produced when 80% CNG is mixed with the intake air, and combustion is initiated by 20% diesel. This is the fourth case of deformation analysis, in which the pressure acting on the piston crown is generated by the 80% CNG and 20% diesel fuel combination, resulting in a pressure of 5 MPa or 50 bar. This pressure value is calculated using the empirical relation stated above. It can be clearly observed that the maximum deformation obtained is 0.062 mm.

3.2 Equivalent [von-Mises] Stress Analysis: -

When any object is subjected to force or pressure, stresses are developed within the material. Various types of stresses are generated, and therefore Equivalent (von Mises) Stress analysis is performed. These stresses depend upon the pressure exerted by the hot combustion gases. The pressure exerted varies with different fuel substitution rates, and the stresses developed under different substitution rates are as follows:

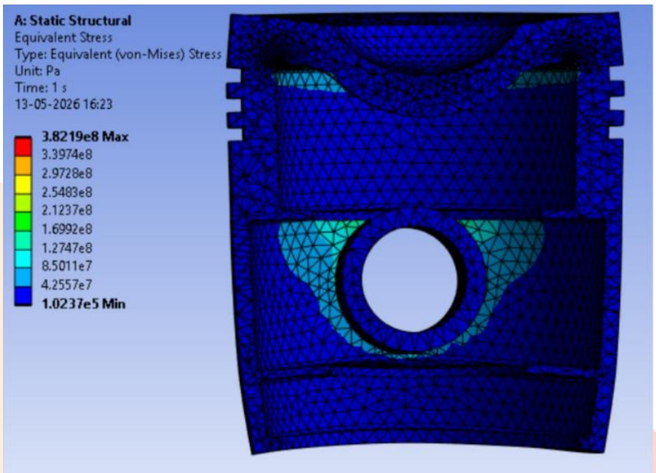

Figure 8

Figure 8: shows the maximum value of 300 MPa stress generated and the minimum value of 0.1 MPa with 100% diesel used.

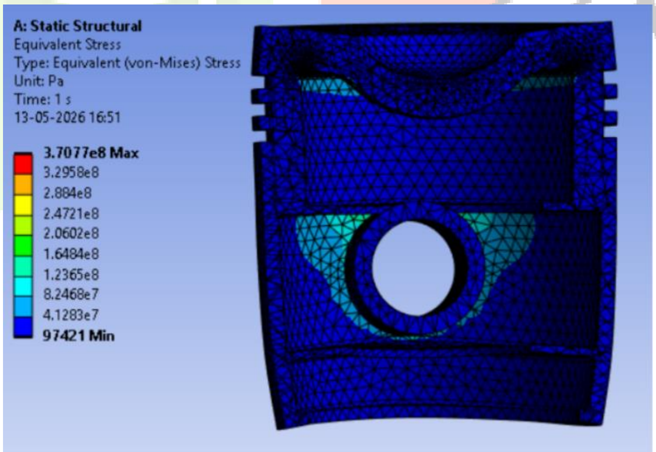

Figure 9

Figure 9: shows the maximum value of 250 MPa stress generated and the minimum value of 0.0974 MPa with 75% diesel with 25% CNG used.

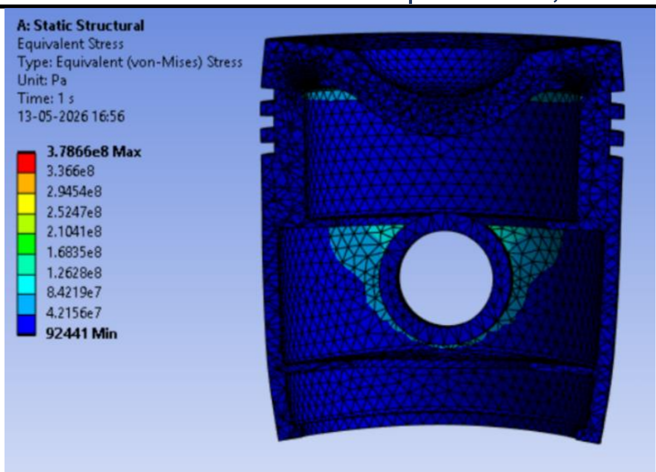

Figure 10

Figure 10 shows the maximum value of 240 MPa stress generated and the minimum value of 0.0924 MPa with 50% diesel with 50% CNG used.

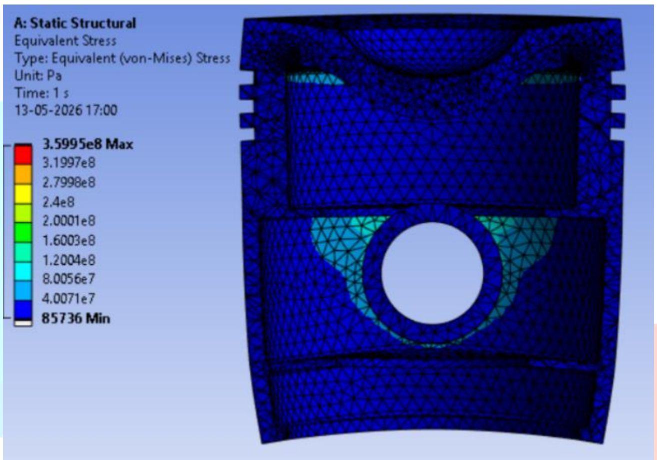

Figure 11

Figure 11 shows the maximum value of 240 MPa stress generated and the minimum value of 0.0857 MPa with 20% diesel with 80% CNG used.

A Comparative table [table 5] is made to show the values of maximum deformation and maximum and minimum values of Equivalent (von Mises) Stress with various CNG-Diesel substitution rates.

Table 5

Diesel	CNG	Deformation (max.)	Equivalent (von Mises) Stress [max.]	Equivalent (von Mises) Stress [min.]
100%	0%	0.075mm	300 MPa	0.1 MPa
75%	25%	0.071mm	250 MPa	0.0974 MPa
50%	50%	0.067mm	240 MPa	0.0924 MPa
20%	80%	0.062mm	240 MPa	0.0857 MPa

4. Conclusion

The present study investigates the deformation and stress analysis of piston crown used in diesel–CNG dual-fuel engine under different CNG substitution ratios using FEM-based structural analysis. The structural behavior of the piston crown under dual-fuel operation was evaluated for different combustion pressures, which correspond to different substitution ratios.

The analysis showed that the deformation and equivalent (von-Mises) stress developed in the piston decrease gradually with an increase in CNG substitution ratio. Under pure diesel operation, the piston experienced a maximum deformation of 0.075 mm and a maximum Equivalent [von-Mises] Stress of about 300 MPa due to the higher combustion pressure of 6 MPa. At 80% CNG substitution, the deformation was reduced to 0.062 mm, and the maximum Equivalent [von-Mises] Stress was reduced to around 240 MPa.

The study shows that as the CNG substitution increases, the peak combustion pressure and the mechanical loading of the piston crown decrease, which improves the piston reliability and reduces deformation and stress concentration. The study further shows the capability of analysis by FEM to evaluate the piston response under different dual-fuel combustion conditions.

5. Future Scope

1. The thermal analysis can be added in future work to study the effect of combustion temperature on the piston.
2. Different materials for the piston and the design of the piston crown can be investigated to improve the strength and reduce the deformation.
3. Fatigue and life analysis are performed to study long term durability under dual-fuel operating conditions.
4. The FEM analysis can be used to complement the CFD-based combustion analysis to predict the pressure and temperature more accurately.
5. The simulation results can be verified by experimental testing under the real engine conditions.

6. Acknowledgment

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