Spectrum of Engineering Sciences
ISSN (e) 3007-3138 (p) 3007-312X Volume 3, Issue 7, 2025

STRUCTURAL AND DIMENSIONAL ANALYSIS OF THE PISTON AND EXHAUST VALVE OF TOYOTA XLI 1300CC BY USING VARIOUS ALTERNATIVE FUELS

Muhammad Awais[1], Muhammad Yaseen[2], Imdad Ali[3], Ramez Raja[4], Umair Ahmed Rajput[*5]

[1,2, 4 ,*5]Mechanical Engineering Department, Quaid-e-Awam University of Engineering Science and Technology Nawabshah, Sindh, Pakistan

[3]Industrial and Manufacturing Department Quaid-e-Awam University of Engineering Science and Technology Nawabshah, Sindh, Pakistan

[*5]engr.umair@quest.edu.pk

[*5]https://orcid.org/0000-0001-7943-1011

DOI: https://doi.org/10.5281/zenodo.16524228

Keywords
Toyota XLI, SEM, dimensional measurements, Alternative Fuels, Piston, Valves

Article History
Received on 21 April 2025
Accepted on 09 July 2025
Published on 24 July 2025

Corresponding Author: *
Umair Ahmed Rajput

Abstract
In this study, experimental investigations are conducted on engine components subjected to real- world operating conditions, ensuring the relevance and applicability of the findings. The fuels used in the Toyota XLI 1300cc engine are CNG, LPG, and LNG. Combustion of fuels has various impacts on the piston and exhaust valve, the structural and dimensional characteristics of the Toyota XLI 1300cc engine were characterized. Therefore, employing advanced characterization techniques such as Scanning Electron Microscopy (SEM), Energy Dispersive X-ray Spectroscopy (EDS), and precise dimensional measurements, the study provides a detailed analysis of the morphological changes, elemental alterations, and dimensional variations induced by the combustion of these alternative fuels. The observations revealed distinctive alterations in the microstructure and elemental composition of the piston and exhaust valve surfaces following exposure to CNG, LPG, and LNG combustion. Furthermore, dimensional measurements unveil potential changes in component geometry, shedding light on the mechanical consequences of adopting these alternative fuels.

INTRODUCTION

Engines are universal power sources for vehicles, electricity generation, and various industrial applications due to their advantageous combination of high power density and efficiency, The core of their operation lies in the combustion process, a crucial energy conversion method that directly transforms the fuel's chemical energy into heat [1]. This research is based on Toyota xli 1300cc engine, it is equipped with a 1.3L, 4- cylinder, engine that incorporates Dual VVT-I (variable valve timing) and MPFI.

This particular engine demonstrates enhanced fuel efficiency, along with a modest increase in both power (99-102 hp) and torque (95-99 lb. Ft) compared to its predecessors.

Mounting climate concerns and the depletion of fossil fuels have spurred a surge in research towards cleaner alternatives for internal combustion engines (ICEs). Gaseous fuels like liquefied petroleum gas (LPG), compressed natural gas (CNG), and liquefied natural gas (LNG) have emerged as promising candidates [2].

Natural gas/CNG is one of the most important and successful alternative fuels for vehicles engines combustion and emission fueled with natural gas/CNG have been reviewed by natural gas/CNG bi-fuel engine [3]. Liquefied Petroleum Gas (LPG) serves as a viable fuel option for Spark Ignition (SI) engines. It stands out as a substitute for energy resources obtained from crude oil. Over the recent years, LPG has garnered considerable interest, primarily due to its cost- effectiveness and its tendency to generate lower emissions when compared to traditional fossil fuels [4]. (LNG) is produced through the process of cooling natural gas to a temperature of −162 °C, transforming it into a liquid state while reducing its volume by approximately 600 times. This characteristic makes LNG highly compatible with vehicular applications. Historically, LNG has been employed as the primary fuel source, ignited through a minimal injection of diesel spray for the ignition process [5]. While these fuels offer significant environmental benefits, their use in IC engines can lead to premature wear and damage to critical components like valves and pistons. This research paper aims to explore the potential causes of such damage when using CNG, LPG, and LNG in IC engines. These fuels typically burn hotter than gasoline, leading to higher operating temperatures within the engine. This elevated heat can cause valve and piston components to warp, crack, and ultimately fail.

Additionally, these fuels are generally drier than gasoline, resulting in reduced lubrication for valve stems and piston rings. This inadequate lubrication can accelerate wear and increase the risk of scuffing and seizure [6, 7]. As the availability of fossil fuels declines rapidly, there is a growing urgency to discover alternative energy sources to fulfill the increasing global demand for energy. It has become a priority worldwide to explore sustainable energy solutions, motivated by the immediate need to reduce the harmful environmental effects caused by traditional petroleum products. Recognizing the vital importance of transitioning to renewable resources, the global community acknowledges the significance of promoting innovation and adopting environmentally friendly technologies. This deliberate move toward sustainable energy not only tackles the impending energy challenges but also promotes environmental responsibility, ensuring a healthier and more robust planet for the well-being of future generations [8]. Enhancing the thermal efficiency of internal combustion engines requires a comprehensive approach to address heat dissipation through exhaust gases and optimize the combustion process. An essential strategy involves applying thermal barrier coatings to the piston. This application not only significantly improves the tribological performance of the piston but also concurrently reduces emissions and specific fuel consumption. Researchers have employed varied coating processes, strategically selected to enhance the wear and corrosion resistance of the piston system. This holistic method for improving engine efficiency emphasizes the significance of innovative solutions, showcasing a dedication to advancing sustainable and performance-oriented automotive technologies. Through ongoing exploration of coating methodologies, the automotive industry aims to usher in a new era of internal combustion engines marked by increased efficiency, diminished environmental impact, and extended component lifespan [9].

The increased combustion temperature inherent in CNG and LNG, as opposed to gasoline, can result in accelerated wear and tear on valves due to heightened thermal stress and the risk of overheating. Studies have indicated that CNG-fueled engines are more prone to issues such as valve seat recession and cracking. Consequently, these engines may necessitate more frequent valve adjustments or replacements [1, 10]. And relatively lower lubricating properties of CNG and LNG can give rise to lubrication challenges, especially concerning valve stems and guides. Research indicates that insufficient lubrication may result in heightened friction and wear, thereby contributing to the premature failure of valves [11] [12] [13]. The high-octane characteristics of CNG and LNG may give rise to backflash and pre-ignition concerns, particularly in engines not explicitly tailored for these fuels. These occurrences can induce excessive pressure spikes and thermal loads on pistons and valves, posing the potential risk of damage [14]. And the combustion of LPG has been associated with elevated carbon deposits on pistons and cylinder heads.

Research indicates that these deposits can result in issues such as piston ring sticking and scoring, adversely affecting engine performance and efficiency [15].

2.0 METHODOLOGY AND MATERIAL

Dimensional measurement test: This test assesses pistons and valves through precise measurements of dimensions like diameter and length, ensuring compliance with design specifications. This thorough process ensures accurate performance, longevity, and quality, essential for internal combustion engines in automotive or machinery applications.

Scanning electron microscopy test (SEM): The Microstructure Analysis Test, frequently performed using (SEM), investigates material microstructures at high magnification. SEM utilizes electron beams to generate detailed surface images, offering insights into composition, morphology, and microstructure. Essential for material studies in metallurgy and biology, it aids in research, quality control, and development. SEM's precise examination of surface topography renders it a powerful tool for materials analysis.

Analysis of deposits on piston and valves: Energy Dispersive X-ray Spectroscopy (EDS) serves as an analytical method extensively applied in materials science and associated disciplines for ascertaining the elemental composition of a given sample. When integrated with electron microscopy, such as (SEM), the EDS process involves directing a high-energy electron beam onto the sample, resulting in the expulsion of inner-shell electrons from atoms within the material. Following this,
electrons from higher energy levels descend to occupy the vacant positions, emitting X-rays that are indicative of the elements present in the sample. The emitted X-rays are subsequently detected and scrutinized by an energy-dispersive X-ray detector.
Through the examination of the energy and intensity of the detected X-rays, EDS furnishes valuable insights into the elemental composition of the sample. This technique allows for a deeper understanding of the spatial distribution of elements, enabling researchers to comprehend the chemical structure of materials at a microscopic level. EDS finds widespread application in materials characterization, offering assistance to scientists across diverse fields, including materials science, geology, and biology, in unraveling the elemental composition and inherent properties of the substances under investigation, the real time image of piston figure 2.0(a) and valve figure 2.0(b) are given below.

Figure 2.0 (a) Piston **Figure 2.0 (b) Valve**

ISSN (e) 3007-3138 (p) 3007-312X Volume 3, Issue 7, 2025

Real time images of piston and valve

3.0 RESULTS DISCUSSION

3.1 SEM and EDS of piston, SEM analysis revealed crucial insights into the microstructure of the pistons when subjected to different alternative fuels. High-resolution images displayed the presence of various surface features, including microcracks, pits, and irregularities the images captured at various magnifications showcased distinctive surface morphologies, which may be attributed to the combustion characteristics of alternative fuels. Notably, the presence of certain deposits or wear patterns provides valuable information about the interaction between the piston material and alternative fuels, The magnified images of piston by SEM are given below. Figure 3.1(a) is x50 magnified with 500 micrometer spot size, figure 3.1(b) is x100 magnified with 100 micrometer spot size and figure 3.1(c) is x150 magnified with 100 micrometer spot size and all the magnified pictures are taken from 10kV accelerating voltage.

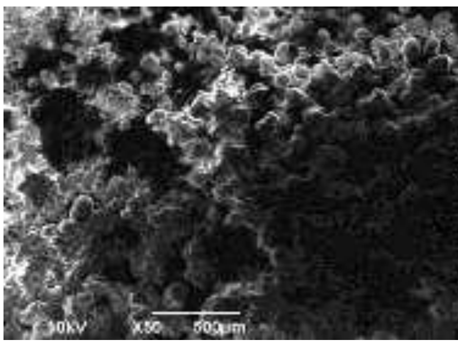

Figure 3.1 (a)

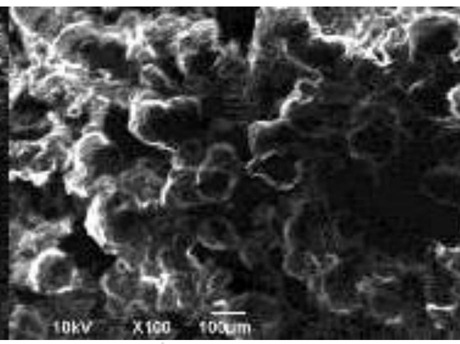

Figure 3.1 (b)

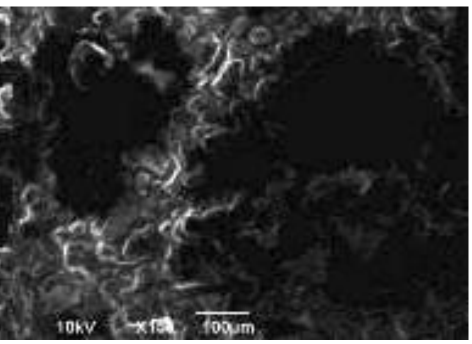

Figure 3.1 (c)

The utilization of EDS analysis played a crucial role in determining the elemental composition of the deposits identified in SEM images. Elemental mapping facilitated a thorough comprehension of any chemical alterations taking place on the surfaces of the pistons. Discrepancies in the elemental composition can be linked tothe chemical characteristics of alternative fuels, providing insights into possible reactions or degradation mechanisms, we can see in Figure 3.1

(d) there is 80.46% of carbon, 15.5% of oxygen, and 1.39% of silicon deposit at piston used by alternative fuels.

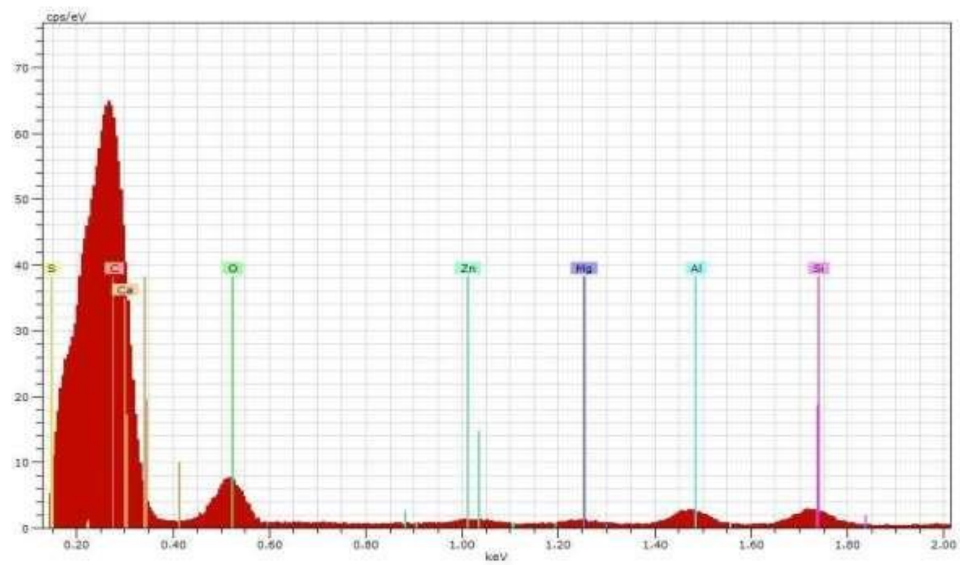

Figure 3.1 (d) EDS of Piston

In table 3.1(1) that is given below has shown the amount of deposition of carbon, oxygen, magnesium, Aluminum, Silicon and Sulphur with their percentages.

Spectrum: Acquisition

Element	Series	unn. C [wt.%]	norm. C [wt.%]	Atom. C [at.%]	Error [%]
Carbon	K-series	71.54	71.54	80.46	22.6
Oxygen	K-series	18.35	18.35	15.50	6.4
Magnesium	K-series	0.52	0.52	0.29	0.1
Aluminium	K-series	1.76	1.76	0.88	0.1
Silicon	K-series	2.89	2.89	1.39	0.2
Sulfur	K-series	1.15	1.15	0.49	0.1

Table 3.1(1)

3.2 SEM and EDS of Valve

The investigation of valves exposed to various alternative fuels using SEM yielded vital insights into alterations in microstructure. Detailed images captured at different magnifications showcased distinct surface features, such as microcracks, pits, and irregularities. These morphological changes, observed underdifferentfuelconditions,are probably linked to the specific combustion traits associated with alternative fuels, Figure 3.2(a) is x270 magnified with 50 micrometer spot size, figure 3.2(b) is x100 magnified with 100 micrometer spot size and figure 3.2(c) is x50 magnified with 500 micrometer spot size and all the magnified pictures are taken from 10kV accelerating voltage.

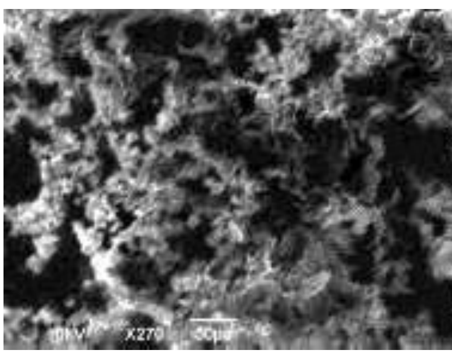

Figure 3.2(a)

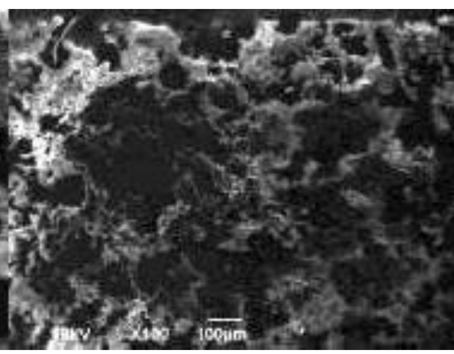

Figure 3.2(b)

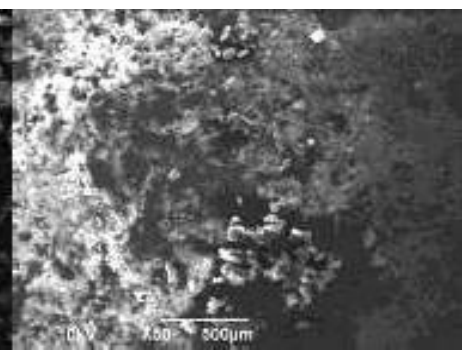

Figure 3.2(c)

The utilization of EDS analysis played a critical role in discerning the elemental composition of deposits observed in SEM images. Elemental mapping provided a comprehensive grasp of the chemical alterations taking place on valve surfaces. The associations between fluctuations in elemental composition and the chemical characteristics of alternative fuels offered valuable insights into potential reactions or degradation mechanisms at the microscopic scale. And we can clearly see in Figure 3.2(d) given below the deposition of carbon is 8.14%, 66.38% of oxygen, 2.47% of magnesium, 1.21% of aluminum, 2.81% of silicon, 2,97% of phosphorous, 3.39% of Sulphur and 2.94% of zinc.

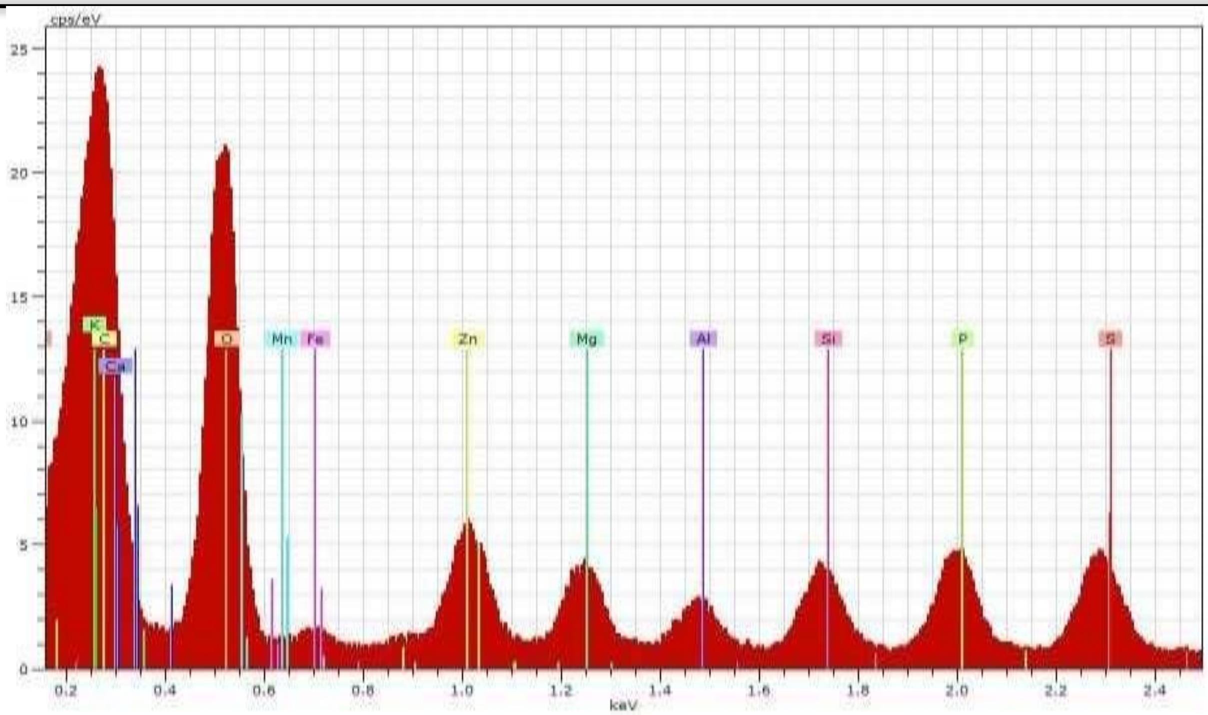

Figure 3.2 (d) EDS of Valve

In table 3.2 (1) that is given below has shown the amount of deposition of carbon, oxygen, magnesium, Aluminum, Silicon, Sulphur, Phosphorus, Potassium, Iron and Zinc with their percentages.

Table 3.2(1)

Spectrum: Acquisition

Element	Series	unn. C [wt.%]	norm. C [wt.%]	Atom. C [at.%]	Error [%]
Carbon	K-series	4.03	4.56	8.14	6.2
Oxygen	K-series	43.80	49.58	66.38	5.3
Magnesium	K-series	2.48	2.81	2.47	0.2
Aluminium	K-series	1.35	1.53	1.21	0.1
Silicon	K-series	3.25	3.68	2.81	0.2
Phosphorus	K-series	3.79	4.29	2.97	0.2
Sulfur	K-series	4.49	5.08	3.39	0.2
Potassium	K-series	0.89	1.01	0.55	0.1
Calcium	K-series	11.91	13.48	7.21	0.4
Manganese	K-series	1.22	1.38	0.54	0.1
Iron	K-series	3.20	3.62	1.39	0.3
Zinc	L-series	7.93	8.98	2.94	0.5
Total:	88.33	100.00	100.00		

3.3 Crack wear and tear of piston

In the course of our study, an analysis of the surface morphology of the piston has revealed distinct traits. The surface showcases intricate details, notably featuring discernible elements like cracks shown in figure 3.3(a). These irregularities on the surface offer valuable insights into how the piston's structurebehavesunderdifferent conditions. The discovery of cracks initiates a deeper investigation to understand their origins, how they propagate, and the potential consequences for the overall functioning and longevity of the piston within the engine system. Because of higher temperature in combustion chamber by using alternative fuels the wear and tear in piston can occur and we can clearly see in figure 3.3(b) that is given below.

Figure 3.3(a) Crack on piston

Figure 3.3(b) wear and tear of piston

3.4-Dimensional measurement of piston Accurate measurements of the dimensions of the piston were carried out while subjected to various alternative fuels, and comparisons were drawn against a baseline utilizing conventional fuels. The outcomes revealed significant modifications in the piston's dimensions, including size, shape, and surface characteristics. These changes imply potential influences of alternative fuels on the overall physical attributes of the piston. The first table Table 3.4(1) shows the size of the new piston. Then, we used the piston for 105,000 kilometers with alternative fuels, and you can find the new sizes in the second table Table 3.4(2). By comparing the two tables, we can see how the piston performed and if there were any changes in its size during the 105,000 kilometers traveled using alternative fuels.

Table 3.4(1) Dimensions of new piston

Diameter of piston	1 ring thickness(K1)	2 ring thickness K2	Oil removal ring thickness (M1)
75mm	1.2mm	1.2mm	3.0mm

Table 3.4(2) Dimensions of used piston

Diameter of piston	1 ring thickness(K1)	2 ring thickness K2	Oil removal ring thickness (M1)
74.4mm	1.24mm	1.25mm	3.02mm

4.0 CONCLUSIONS

In this extensive investigation centered around the Toyota XLI 1300cc engine, which is equipped with a 1.3L, 4-cylinder, engine and operates on alternative fuels such as CNG, LPG, and LNG, we conducted experimental assessments to evaluate the impact of these fuels on engine components in real- world operating conditions. Utilizing advanced characterization techniques, such as Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDS), enabled a thorough examination of morphological changes, elemental adjustments, and dimensional variations resulting from the combustion of alternative fuels. The analysis of piston and exhaust valve uncovered distinct modifications in microstructure and elemental composition after exposure to CNG, LPG, and LNG combustion. Issues identified encompassed accelerated wear and tear, challenges in lubrication, backflash, pre-ignition concerns, and the formation of deposits on pistons and valves. These findings emphasize the critical considerations needed when incorporating alternative fuels in internal combustion engines. The following results have been obtained after SEM, EDS and Dimensional measurement tests.

1) SEM analysis provided essential insights into the microstructure of the piston and valve under the influence of different alternative fuels. Detailed, high-resolution images highlighted the existence of diverse surface features, such as microcracks, pits, and irregularities, captured at various magnifications.

2) In EDS the results we got are 80.46% of carbon, 15.5% of oxygen, and 1.39% of silicon deposit at piston used by alternative fuels in piston, and the deposition of carbon is 8.14%, 66.38% of oxygen, 2.47% of magnesium, 1.21% of aluminum, 2.81% of silicon, 2,97% of phosphorous, 3.39% of Sulphur and 2.94% of zinc in valve.

3) The outcomes obtained from precise measurement tests indicate a reduction in piston diameter by 0.6mm, accompanied by an increase in ring thickness of 0.2mm. Furthermore, the oil removal ring demonstrated a slight increase of 0.02mm. These findings highlight noteworthy dimensional changes in the piston and ring components.

5.0 REFERENCES

C. Bae and J. Kim, "Alternative fuels for internal combustion engines," Proceedings of the Combustion Institute, vol. 36, no. 3, pp. 3389-3413,2017/01/01/2017,doi: https://doi.org/10.1016/j.proci.2016.09.0 09.

M. Melaika, G. Herbillon, and P. Dahlander, "Spark ignition engine performance, standard emissions and particulates using GDI, PFI-CNG and DI-CNG systems," Fuel, vol. 293, p. 120454, 2021/06/01/2021, doi: https://doi.org/10.1016/j.fuel.2021.1204 54.

H. Chen, J. He, and X. Zhong, "Engine combustion and emission fuelled with natural gas: A review," Journal of the Energy Institute, vol. 92, no. 4, pp. 1123-1136, 2019/08/01/ 2019, doi:https://doi.org/10.1016/j.joei.2018.06. 0 05.

S. Simsek, S. Uslu, H. Simsek, and G. Uslu, "Improving the combustion process by determining the optimum percentage of liquefied petroleum gas (LPG) via response surface methodology (RSM) in a spark ignition (SI) engine running on gasoline-LPG blends," Fuel Processing Technology, vol.221, p.106947, 2021/10/01/ 2021, doi: https://doi.org/10.1016/j.fuproc.2021.10 6947.

X. Duan et al., "Effects of natural gas composition and compression ratio on the thermodynamic and combustion characteristics of a heavy-duty lean-burn SI engine fueled with liquefied natural gas," Fuel, vol. 254, p. 115733, 2019/10/15/ 2019, doi: https://doi.org/10.1016/j.fuel.2019.1157 33.

M. Pusterhofer, F. Summer, D. Wuketich, and F. Grün, "Development of a Model Test System for a Piston Ring/Cylinder Liner-Contact with Focus on Near-to- Application Seizure Behaviour," Lubricants, vol. 7, no. 12, doi: 10.3390/lubricants7120104.

O. P. Singh, Y. Umbarkar, T. Sreenivasulu, E. Vetrivendan, M. Kannan, and Y. R. Babu, "Piston seizure investigation: Experiments, modeling and future challenges," Engineering Failure Analysis, vol. 28, pp. 302-310, 2013/03/01/ 2013, doi: https://doi.org/10.1016/j.engfailanal.2012.11.005.

A. Singh Verma, S. Chhabra, A. Karnwal, A. Gupta, and R. Kumar, "A review on performance, combustion and emissions utilizing alternative fuels," Materials Today: Proceedings, vol. 64, pp. 1459-1464, 2022/01/01/ 2022, doi: https://doi.org/10.1016/j.matpr.2022.04.777.

S. Kumar and M. Kumar, "Tribological and Mechanical Performance of Coatings on Piston to Avoid Failure—A Review," Journal of Failure Analysis and Prevention, vol. 22, no. 4, pp. 1346-1369, 2022/08/01 2022, doi: 10.1007/s11668-022-01436-3.

P. Geng, E. Cao, Q. Tan, and L. Wei, "Effects of alternative fuels on the combustion characteristics and emission products from diesel engines: A review," Renewable and Sustainable Energy Reviews, vol. 71, pp. 523- 534, 2017/05/01/ 2017, doi: https://doi.org/10.1016/j.rser.2016.12.080.

M. Usman and N. Hayat, "Use of CNG and Hi-octane gasoline in SI engine: a comparative study of performance, emission, and lubrication oil deterioration," Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, vol. 45, no. 4, pp. 10983-10997, 2023/10/02 2023, doi: 10.1080/15567036.2019.1683098.

M. Usman, M. W. Saleem, S. Saqib, J. Umer, A. Naveed, and Z. U. Hassan, "SI engine performance, lubricant oil deterioration, and emission: A comparison of liquid and gaseous fuel," Advances in Mechanical Engineering, vol.12,s no.6,p. 1687814020930451, 2020/06/01 2014, doi: 10.1177/1687814020930451.

R. Mathai, R. K. Malhotra, K. A. Subramanian, and L. M. Das, "Comparative evaluation of performance, emission, lubricant and deposit characteristics of spark ignition engine fueled with CNG and 18% hydrogen-CNG," International Journal of Hydrogen Energy, vol. 37, no. 8, pp. 6893-6900, 2012/04/01/ 2012, doi: https://doi.org/10.1016/j.ijhydene.2012.01.083.

P. T. Nitnaware and J. G. Suryawanshi, "Effects of equal spark timing on performance emission and combustion characteristics of SI engine using hydrogen and CNG blends," Journal of the Brazilian Society of Mechanical Sciences and Engineering, vol. 38, no. 8, pp. 2245-2253, 2016/12/01 2016, doi: 10.1007/s40430-016-0508-8.

Weidenlener, H. Kubach, J. Pfeil, and T. Koch, "The Influence of Operating Conditions on Combustion Chamber Deposit Surface Structure," The international symposium on diagnostics and modeling of combustion in internal combustion engines, vol. 2017.9, p. C105, 2017, doi: 10.1299/jmsesdm.2017.9.C105..