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Energy and Environmental Performance Enhancement of Radial Four-Stroke Diesel Engines by using Synergistic Staging Configurations

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Abstract: The effects of sectioning numbers on a 1500 RPM radial six-cylinder diesel engine with a 150 mm bore, 180 mm piston stroke, and a 15:1 compression ratio is examined in this study. The results of tests conducted under typical conditions (288 K, 1 bar) were evaluated for sectioning numbers ranging from 2 to 10. According to the specifications of the intake system, the gas velocity went from 15 m/s to 80 m/s, but the average intake manifold pressure stayed the same at 1.9 bar. The air-fuel ratio, cylinder pressure-temperature angles, and swirl ratios were all kept constant. As the number of sections increased linearly, the maximum gas force acting on the piston also increased, suggesting an improvement in performance. Improvements in combustion were indicated by an increase in exhaust gas temperature from 746 K to 775 K and a drop in average exhaust manifold gas pressure due to lower sectioning numbers, according to the exhaust parameters. According to ecological research, the best environmental performance is achieved with a sectioning number of 10, and emissions decrease as the number of sections increases. Complying with air pollution rules and demonstrating the advantages of sectioning modifications for increased engine performance and sustainability, this design decreased emissions.

Keywords: *Diesel engine, Engine performance, Swirl ratios, Sectioning numbers*

1. Introduction

The development of engines has played a pivotal role in the progress of modern society and technology. Starting with the primitive steam engines that fuelled the Industrial Revolution, these have evolved into the sophisticated internal combustion engines that power automobiles, machinery, and other devices today[1],[2],[3],[4]. Fundamentally, engines transform various forms of energy into mechanical labour, serving as critical components in power generation, transportation, manufacturing, and a multitude of other sectors. Constant innovation to achieve greater dependability, efficiency, and environmental sustainability has characterized their evolution, which has had a profound effect on the ways in which we live, work, and interact with the environment. Particularly indispensable to global transportation systems, internal combustion engines are installed in automobiles, lorries, ships, and aircraft [5], [6], [7]. By means of combustion, these engines generate the mechanical

The Internal Combustion Engine (ICE) and the Electric Compression Ignition Engine (ECE) are two discrete yet interrelated paradigms within the domain of power generation and propulsion. The selection among these technologies is contingent upon a multitude of criteria, each possessing distinct merits. In transportation and industry, the ICE continues to be indispensable owing to its high energy density and compatibility with pre-existing infrastructure, notwithstanding its lengthy historical background [8], [9], [10], [11]. Gasoline and diesel are examples of liquid fuels that possess the ability to store significant amounts of energy, enabling vehicles to traverse extensive distances without the need for frequent refuelling. The extensive variety of applications for ICE-powered vehicles is facilitated and practical by this firmly established infrastructure. Furthermore, ongoing progressions in internal combustion engine (ICE) technology, including hybridization, direct injection, and turbocharging, have substantially enhanced emissions management, performance, and efficiency [12], [13],[14],[15]. By expanding the capabilities of internal combustion engines (ICEs) in terms of power output and fuel efficiency, these developments compromise versatility across a range of fuel types and operating conditions, while simultaneously reducing environmental impact and operating expenses.

Due to its potential to cut emissions and promote sustainability, electric compression ignition engines (ECEs) are becoming a viable alternative to ICEs. ECEs can start combustion with electric power and zero emissions when powered by renewable energy. This electrification is part of global efforts to combat climate change and switch to greener transportation [16], [17],[18], [19, 20].

Radial design is a dynamic and adaptable paradigm in mechanical engineering. Its unusual circular arrangement of components around a central axis makes it versatile and beneficial in many industries, from aviation engines to hydraulic systems. Radial design is known for its compactness and space efficiency. Using a radial pattern

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around a central hub or axis saves footprint and increases usability. In aerospace, automotive, and marine, space and weight are crucial, therefore this efficiency is beneficial [21], [22]. Radial design has natural symmetry and balance, increasing mechanical stability and reducing vibration. Precision machinery and high-performance systems require stability since even tiny variations can affect performance and lifetime. Radial design solves space savings, mechanical stability, and performance optimization across sectors and applications [23].

Scalability and adaptability are two essential characteristics that stand out in the Radial design. These characteristics make it easier to incorporate additional components or subsystems, and they also streamline the process of upgrading and customizing the system. With this circular form, the configuration is simplified, which makes it easier to incorporate improvements as they are required [24], [25]. This is especially beneficial in dynamic contexts, where the requirements for the system may change over time or vary depending on the application being used. This flexibility not only improves operational efficiency but also offers a strategic advantage from a commercial point of view [26]. It enables agile reactions to changing demands and technology improvements, which is a significant benefit [27]. This study examines how synergistic staging arrangements can improve Radial Four-Stroke Diesel Internal Combustion Engine energy efficiency and environmental performance. This research analyses and simulates engine component arrangements and operational sequences to reveal synergies. This study advances sustainable internal combustion engine engineering by focusing on energy integration solutions and performance increases for environmental sustainability.

2. Theoretical background

Radial engines are characterized by the presence of cylinders that are arranged in a radial pattern and are similarly spaced around a common crankshaft. Most of these engines are utilized in airplanes. For the most part, the radial arrangement is the one that results in the lowest weight per unit displacement. This is since the material that is needed in the crankshaft and crankcase is the least amount for a certain number of cylinders.

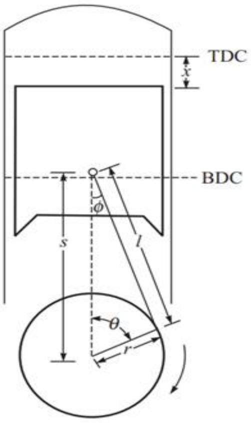

Fig. 1 Reciprocating engine Geometry

$$\boldsymbol{l.sin\emptyset = a.sin\theta}$$

$$\boldsymbol{sin\emptyset = \frac{a}{l}\, sin\theta}$$

Where, Φ is the angle between connecting rod and cylinder centre line, θ is the crank angle from TDC, a is the crank radius, and l is the connecting rod length. Then, the distance between crank and wrist pin axes (S), Piston displacement from TDC (X), volume of the cylinder instantaneously (V), instantaneous speed (Up), mean piston speed (ùp), and instantaneous acceleration (ap) cab given by the below equations.

$$\boldsymbol{S = a\, cos\theta + lcos\emptyset = acos\theta + \sqrt{l^2 - a^2 sin^2\theta}}$$

$$\boldsymbol{X = l + a - s = l + a - acos\theta - \sqrt{l^2 - a^2 sin^2\theta}}$$

$$\boldsymbol{V = \frac{V_s}{r-1} + \frac{\pi}{4}\, d^2 a \left[\frac{l}{a} + 1 - cos\theta - \left(\frac{l^2}{a^2} - \sin^2\theta\right)^{1/2}\right]}$$

$$\boldsymbol{U_p = 2\pi N \left[asin\theta + \frac{a^2 sin\theta cos\theta}{\sqrt{l^2 - a^2 \sin^2\theta}}\right]}$$

$$\boldsymbol{\overline{U_p} = 2LN}$$

$$\boldsymbol{a_p = \omega^2 a \left(cos\omega t + \frac{a}{l} cos2\omega t\right)}$$

Where the thermal efficiency of the diesel cycle can be expressed by the below equation.

$$\boldsymbol{\eta = 1 - \frac{m.C_v.(\Delta T1)}{m.C_p.(\Delta T2)}}$$

$$\boldsymbol{= 1 - \frac{1}{\gamma}.\frac{(\Delta T1)}{(\Delta T2)}}$$

The power produced within the chamber of an engine is referred to as the "indicated power." However, the actual available power is referred to as the break power. The frictional power is defined as the discrepancy that exists between the indicated and break powers. In general, as the initial pressure rises, the mean effective pressure of the diesel cycle engine additionally increases.

3. Result and discussion

In this investigation, a diesel engine employing a four-stroke configuration was chosen. The radial structure of the six-cylindered engine is chilled by liquid water. The engine revolution occurs at 1500 revolutions per minute, the bore diameter is 150 mm, the piston stroke is 180 mm, and the compression ratio is 15. The environmental parameters pertinent to this research comprise a standard temperature of 288 K and an atmospheric pressure of 1 bar. The objective of the study was to examine the impact of engine section numbers on engine performance. For each trial, the following section numbers were chosen: 2, 4, 6, 8, and 10. Each time the number of sections is altered, the engine's performance parameter is evaluated and detailed below. Since the static air pressure at sea level is equivalent to 1 bar at 288 K, the environmental conditions of this investigation are fixed using a variable injector pressure. The temperature is 288 K and the ambient pressure is 1 bar at rest. When all selected injector pressures are used, the exhaust back pressure equals 1 bar, and the total pressure after the induction air filter is set at 0.98 bar.

The intake system parameters for the chosen engine, denoted by sectioning numbers spanning from 2 to 10, are depicted in Figure 2. Regardless of the number of sections, the average intake manifold pressure remains unchanged at 1.9 bar. The values of the total effective valve port throat area, maximum velocity in the middle section of the intake, average intake manifold temperature, heat transfer coefficient in the intake manifold, and heat transfer coefficient in the intake port all demonstrate negligible variation, not surpassing 1 to 2 units. The corresponding values are 310 K, 130 W/(m²·K), 163 W/(m²·K), 52 m², and 18.4 cm². It is worth mentioning that the mean gas velocity within the intake manifold multiplies as the number of sections increases. It commences at 15 m/s with two sections and approximates 80 m/s with ten sections.

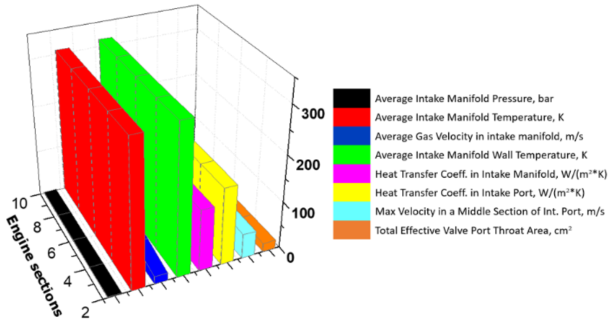

Fig. 2 Intake system parameters

Table. 1 presents the combustion parameters for the radial internal combustion engine being studied, illustrating the variations seen across different sectioning numbers. Several parameters remain constant regardless of variations in sectioning number. These include air-fuel equivalence ratio, fuel-air equivalence ratio, angle of maximum cylinder pressure, angle of maximum cylinder temperature, ringing-knock intensity, start of injection or ignition timing, fuel mass fraction evaporated during ignition, swirl ratio in the combustion chamber at top dead centre (TDC), swirl ratio in the cylinder at intake valve closing (IVC), and maximum air swirl velocity in the cylinder. The following parameters are regularly measured: 2, 0.5, 6, 28, 0.8 MW/m2, 13 S, 0.03, 0.1, 0.07, and 0.97.

In addition, the maximum gas force applied to the ascending piston grows in a linear manner as the sectioning numbers increase, going from 19941 kg at sectioning number 2 to 19784 kg at sectioning number 10. Increased sectioning numbers of the chosen engine are associated with greater operating efficiency, as seen by performance gains in other combustion metrics.

Figure 3 depicts the exhaust parameters of the radial internal combustion engine that was chosen for this research. The data indicates that when the sectioning number increases,

Table. 1 Investigated engine combustion parameters

		2	4	6	8	10
Air Fiel Equival. Ratio (Lambda) in the Cylinder	A/F_eq			2		
Fuel Air Equivalence Ratio in the Cylinder	F/A_eq			0.5		
Maximum Cylinder Pressure, bar	p_max	111.4	109.8	110.5	110.8	110.5
Maximum Cylinder Temperature, K	T_max	1675.5	1671.2	1669.9	1669.8	1670.5
Angle of Max. Cylinder Pressure, deg. A.TDC	CA_p.max			6		
Angle of Max. Cylinder Temperature, deg. A.TDC	CA_t.max			28		
Max. Rate of Pressure Rise, bar/deg.	dp/dTheta	3.88	3.8	3.86	3.9	3.7
Ringing / Knock Intensity, MW/m²	Ring_Intn			0.8		
Max. Gas Force acting on the piston, kg	F_max	19941	19653	19786	19836	19784
Custom Fuel Injection System						
Max. Sac Injection Pres. (before nozzles), bar	p_inj.max	1087	1074	1084.9	1085.9	1073
Mean Sac Press. for Total Fuel Portion, bar	p_inj.avr	697	687	694	695.4	686.4
Sauter Mean Diameter of Drops, microns	d_32	15.5	15.6	15.5	15.5	15.7
Start Of Injection or Ignition Timing, deg. B.TDC	SOI			13		
Duration of Injection, CA deg	Phi_inj	31	30.5	31	31	30.5
Ignition Delay Period, deg	Phi_ign	5.7	5.1	5.9	5.8	5.9
Start of Combustion, deg. B.TDC	SOC	7.3	7.8	7.1	7.2	7.1
Fuel Mass Fraction Evaporated during Ignit. Delay	x_e.id			0.03		
Combustion duration, deg	Phi_z	82.6	85	82	83	83.4
Swirl Ratio in the Combustion Chamber at TDC	Rs_tdc			0.1		
Swirl Ratio in the Cylinder at IVC	Rs_ivc			0.07		
Max. Air Swirl Velocity, m/s at cylinder R= 62	W_swirl			0.97		

there is a decrease in the average exhaust manifold gas pressure. This decrease is beneficial as it helps to alleviate the thermal strains on the cylinders during operation. By reducing thermal stress, it is possible to prolong the engine's lifespan and enhance its reliability.

In contrast, the average temperature of the exhaust manifold gas increases as the sectioning numbers increases. It begins at 746 K when the sectioning number is 2 and reaches 775 K when the sectioning number is 10. The rise in exhaust temperature suggests improved combustion processes and increased heat extraction, potentially leading to superior overall engine performance.

Furthermore, the other exhaust characteristics likewise demonstrate enhancements as the sectioning numbers increase. These improvements encompass enhanced exhaust gas flow, decreased back pressure, and potentially reduced emissions, all of which contribute together to boost engine efficiency and promote environmental sustainability. By optimizing these exhaust characteristics, the engine can attain enhanced fuel efficiency and reduced environmental footprint, in line with the objectives of sustainable engineering and eco-friendly transportation solutions.

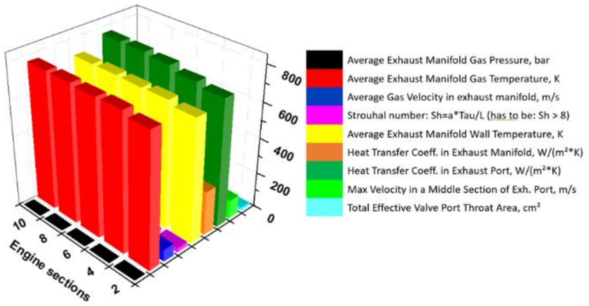

Fig. 3 Exhaust parameters of the selected engine.

Table 2 displays the ecological characteristics of the chosen radial internal combustion engine. The statistics unambiguously demonstrate that emission levels fall in direct correlation with the increase in the sectioning number.

Table. 2 Ecological parameters of the selected engine Ecological parameters

		2	4	6	8	10
Hartridge Smoke Level	Hartridge	9.3	9.9	9.4	9.4	9.2
Bosch Smoke Number	Bosch	1				
Factor of Absolute Light Absorption, 1/m	K,m-1	0.22	0.24	0.23	0.23	0.22
Specific Particulate Matter emission, g/kWh	PM	0.23	0.24	0.23	0.23	0.22
Specific Carbon dioxide emission, g/kWh	CO2	735	702	699	698	698
Fraction of wet NOx in exh. gas, ppm	NOx.w,ppm	866	744	858	850	840
Specif. NOx emiss. reduc. to NO, g/kWh	NO	6.2	5.1	5.8	5.7	5.6
Summary emission of PM and NOx	SE	1.8	1.5	1.4	1.3	1.1
Specific SO2 emission, g/kWh	SO2	0				

More precisely, the Bosch smoke number and the specific SO2 emissions do not change even when there are differences in the engine's configuration. The optimal environmental configuration is achieved when the sectioning number is set to 10. At this value, all ecological parameters reach their minimum levels, indicating a substantial decrease in the engine's environmental impact.

Augmenting the sectioning number not only raises emission levels but also improves the engine's overall ecological impact. This decrease in emissions leads to a more environmentally friendly atmosphere and is in line with strict legal guidelines for air pollution. The steady Bosch smoke number and particular SO2 emissions across different sectioning numbers indicate that these parameters are less responsive to changes in sectioning compared to other emissions. Nevertheless, the general inclination towards reduced emissions when using greater sectioning numbers highlights the advantages of improving engine design to promote environmental sustainability. The results emphasize the capacity of sectioning changes to greatly enhance the ecological efficiency of radial internal combustion engines.

4. Conclusions

Research on how different engine section numbers affect radial internal combustion engine performance has yielded some important results. To start, the research backs up previous claims that more engine parts equal better operational efficiency and performance measures. Higher sectioning numbers are associated with improved combustion processes and a linear increase in the maximum gas force supplied to the piston, both of which demonstrate this. Aligning with the principles of sustainable engineering and eco-friendly transportation, these advancements lead to greater engine efficiency and reliability.

Important metrics like intake manifold pressure, temperature, and heat transfer coefficients show almost no fluctuation across varied sectioning numbers, indicating that the intake system characteristics behave consistently. The combustion efficiency can be enhanced, nonetheless, since gas velocity increases within the intake manifold with increasing sectioning numbers, suggesting better air flow dynamics.

Some combustion parameters, like combustion efficiency and thermal stress on cylinders, improve with increasing sectioning numbers, while others, like combustion efficiency, remain constant independent of sectioning variations. Most notably, as the number of sections increases, the exhaust manifold gas pressure decreases, which means that the engine has less thermal strains and may last longer and be more reliable.

Results showing less back pressure, better exhaust gas flow, and less emissions corroborate the advantages of increased sectioning numbers in the exhaust parameter analysis. Not only do these upgrades make the engine more efficient, but they also help the environment by reducing the engine's impact on the environment. Sectioning number 10 yields the best environmental configuration, which significantly reduces emissions and meets air pollution control regulations.

The results show that radial internal combustion engines can be improved in performance, efficiency, and environmental effect by changing the sectioning. Sustainable and environmentally friendly transportation solutions can be achieved with the help of the findings, which offer useful insights for optimizing engine designs.

Author contributions

Saad S. Alrwashdeh: Conceptualization, Methodology, Software, Writing-Original draft preparation.

Ala'a M. Al-falahat Data curation, Validation., Writing-Reviewing and Editing.

Conflicts of interest

The authors declare no conflicts of interest.

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