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A Comprehensive Review on Design Modifications for Emission Reduction in Two-Stroke Spark Ignition Engines

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Abstract
Two-stroke spark ignition (SI) engines are renowned for their high power-to-weight ratio and simplicity, making them popular in motorcycles, small generators, and garden equipment. However, their inherent design results in significant hydrocarbon and particulate emissions. This paper presents a comprehensive review of recent design modifications aimed at reducing emissions in two-stroke SI engines. Various techniques such as direct fuel injection, advanced scavenging systems, stratified charging, exhaust after-treatment, and lubrication improvements are evaluated. The review also discusses computational simulation approaches and their role in optimizing engine design for minimal emissions.

Keywords: ***Two-stroke, Lubrication, Emission, Spark ignition.***

1. Introduction

Two-stroke spark ignition (SI) engines have historically been favored in applications requiring high power output from compact and lightweight machinery, such as motorcycles, lawn equipment, and small marine engines. Their mechanical simplicity, low cost, and high power-to-weight ratio have made them attractive compared to their four-stroke counterparts. However, these advantages come with significant environmental drawbacks. The fundamental operating principle of two-stroke engines often leads to incomplete combustion and the loss of unburned fuel during the scavenging process, resulting in elevated emissions of hydrocarbons (HC), carbon monoxide (CO), and particulate matter (PM).

The environmental implications of these emissions have become increasingly critical due to stringent global regulations and growing public awareness. Traditional two-stroke engines are now being phased out or heavily regulated in many regions. In response, engineers and researchers have pursued various design modifications to mitigate emission levels while preserving the performance benefits of two-stroke technology. Innovations such as direct fuel injection (DFI), improved scavenging designs, stratified charging, and exhaust after-treatment systems have demonstrated promising results.

This review paper aims to consolidate recent advances in emission-reducing design modifications for two-stroke SI engines. By evaluating both experimental outcomes and simulation-based studies, this work provides insights into the effectiveness, challenges, and future potential of these technological solutions.

2. Review of Literature

This section presents the earlier work done by various authors or researchers in Emission Reduction in Two-Stroke Spark Ignition Engines.

Research by High pressure direct fuel injection systems has shown transformative emission benefits. In 2021, experiments demonstrated that introducing a high-pressure injector timed to avoid scavenging losses improved brake thermal efficiency by 16.3%, and reduced CO by 27.5% and unburned HC by 88.5% compared to carbureted counterparts. Similarly, Zhang & Cao (2025) assessed two-stage injection using methanol–gasoline blends in DISI engines, reporting ~20% fewer particulate emissions with optimal injection ratios.

In hybrid injection strategies, Mohamed et al. (2024) examined dual-injection in biogasoline-fueled SI engines, achieving significant reductions in PM and gaseous pollutants through split injection timing and staged control . In dual-fuel contexts, MDPI et al. (2024) showed that increasing GDI pressure in

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EPI+GDI engines led to ~60% fewer particulates and a 36% drop in PM mass.
Computational simulations further refine spray/charge control. In 2020, Gong et al. demonstrated via CFD that 10-hole non-uniform spray nozzles in methanol DI engines produced superior stratified mixtures, reducing unburned fuel and CO emissions while raising peak pressures drastically. Earlier, Esposito et al. (2021) validated a 3D-CFD gaseous emission model against cycle-resolved SI-DI data, facilitating accurate prediction of in-cylinder species under varied conditions.
Beyond gasoline, hydrogen and alternative fuels are gaining attention: Performance analysis (2023) showed that hydrogen-gasoline dual-fuel SI engines can dramatically lower CO_2 and HC emissions thanks to hydrogen's rapid flame speed and clean combustion profile. Concurrently, Hydrogen-fuelled ICE bibliometric review (2024) highlighted advances in EGR, H_2 dosing, and intake strategies, underscoring their role in minimizing NO_x and improving efficiency.
In the realm of lubrication, Dueholm et al. (2023) demonstrated in marine two-stroke engines that electronically controlled common-rail oil injection systems provide precise dosing, improving performance and reducing emissions by limiting over-lubrication.
Lastly, although largely in four-stroke contexts, Kalvakala et al. (2024) used CFD to model gasoline-ethanol blending's impacts on soot and NO_x under compression ignition—techniques which could transfer to two-stroke optimization

3. Emission Characteristics of Two-Stroke Spark Ignition (SI) Engines:

Two-stroke SI engines are known for higher emissions compared to four-stroke engines due to their unique operational cycle. During scavenging (the process of expelling exhaust gases and introducing a fresh air-fuel mixture), some of the fresh charge escapes directly through the exhaust port before combustion, leading to unburned hydrocarbon (HC) emissions. This fuel short-circuiting is a major source of pollution.
Additionally, carbon monoxide (CO) is produced due to incomplete combustion, often caused by poor air-fuel mixing and rapid cycles. Particulate matter (PM) is also generated, particularly in engines using oil-fuel mixtures, as burning lubricating oil contributes to soot and deposits. These emissions not only degrade air quality but also fail to meet modern environmental regulations.

Table 1: Types of Emission

Emission Type	Conventional 2-Stroke SI Engine	Modified/Optimized 2-Stroke SI Engine	Remarks
Hydrocarbons (HC)	Very High	Moderate to Low	Reduced with direct fuel injection and better scavenging
Carbon Monoxide (CO)	High	Moderate	Improved combustion efficiency lowers CO
Particulate Matter (PM)	High	Low	Improved oil control and cleaner combustion
Nitrogen Oxides (NOx)	Low to Moderate	Slightly Increased	Lean-burn and higher temperatures may raise NOx slightly
Carbon Dioxide (CO_2)	Moderate	Slightly Lower	Better fuel efficiency reduces CO_2 emissions
Oil-Related Emissions	High (due to premix lubrication)	Low (with auto-lubrication systems)	Reduced with synthetic oils and controlled lubrication

4. Design Modification Techniques

There are various modifications techniques in which some of them are describing below:

4.1 Direct Fuel Injection (DFI)

It is a significant advancement in reducing emissions from two-stroke spark ignition engines. In conventional carbureted two-stroke engines, the air-fuel mixture enters the combustion chamber during the scavenging phase, which often leads to a portion of unburned fuel escaping directly through the exhaust port. DFI addresses this problem by injecting fuel directly into the combustion chamber after the exhaust port has closed. This ensures that only air flows during scavenging, minimizing fuel loss and significantly reducing unburned hydrocarbon (HC) emissions. DFI systems can be mechanical, air-assisted, or electronically controlled, with electronic fuel injection (EFI) offering precise timing and quantity control for optimal combustion. In addition to emission reduction, DFI improves fuel economy, enhances throttle response, and allows better engine calibration under varying loads and speeds. However, its implementation requires more complex and costlier components, including high-pressure injectors and advanced engine control units (ECUs).

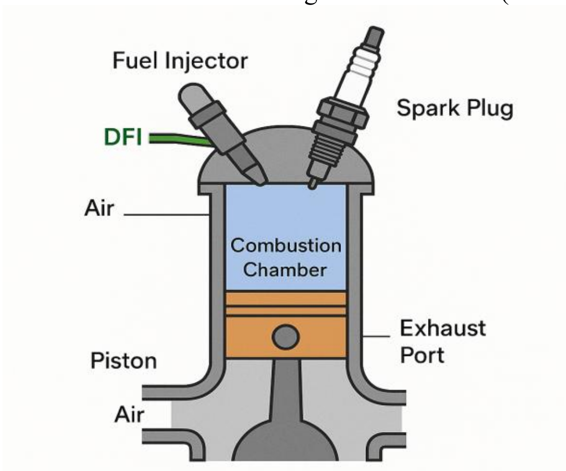

Fig. 1: Fuel Injection in Two-Stroke SI engine

4.2 Advanced scavenging techniques

It is a crucial design improvement in two-stroke spark ignition (SI) engines that enhance the removal of exhaust gases and the intake of fresh air or air-fuel mixture, without significant loss of unburned fuel. Effective scavenging improves combustion efficiency and reduces emissions, especially hydrocarbons (HC). Here are the main types.

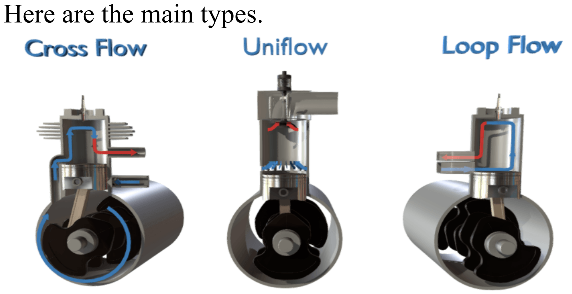

Fig. 2: Shows the types of Scavenging

Loop scavenging

It is a widely used technique in two-stroke spark ignition (SI) engines, particularly in small- to medium-sized applications due to its efficient and compact design. In this method, the fresh air-fuel mixture is introduced through two or more transfer ports located on the sides of the cylinder near the bottom. These ports are shaped and angled in such a way that the incoming charge flows upward in a looping motion, displacing the exhaust gases upward and out through the exhaust port located on the opposite side, usually at a higher elevation. This loop-like path helps minimize direct short-circuiting of the fresh charge while promoting effective removal of combustion residues. Although not as efficient as uniflow scavenging, loop scavenging offers a good balance between performance and simplicity. It improves cylinder filling and combustion stability, which contributes to reduced hydrocarbon (HC) emissions and better fuel efficiency when optimized properly through port timing and geometry.

Cross Flow Scavenging

It is one of the earliest scavenging techniques used in two-stroke spark ignition (SI) engines, where the fresh air-fuel mixture enters the cylinder from a transfer port on one side and pushes the exhaust gases out through an exhaust port located on the opposite side. This setup creates a horizontal sweeping motion of gases across the cylinder. To direct the incoming charge upwards and avoid direct loss of fresh mixture through the exhaust port, a deflector is often built onto the piston crown. While this design is mechanically simple and easy to implement, it suffers from relatively poor scavenging efficiency due to turbulence and potential mixing of fresh charge with residual exhaust gases. Additionally, the deflector piston adds weight and heat concentration, which can reduce engine durability. As a result, cross-flow scavenging is less common in modern two-stroke engine designs but remains relevant in certain low-cost or legacy applications.

Uniflow Scavenging

Uniflow scavenging is a highly efficient method used in advanced two-stroke spark ignition (SI) engines, where the gas flow moves in a single, streamlined direction—from one end of the cylinder to the other. In this technique, fresh air or air-fuel mixture enters the cylinder through ports located at the lower end (usually around the cylinder walls), while exhaust gases exit through a valve or port positioned at the top of the cylinder. This unidirectional flow ensures thorough evacuation of burnt gases and better retention of the fresh charge, minimizing short-circuiting and maximizing combustion efficiency. Because the incoming and outgoing gases do not directly mix or cross paths, uniflow scavenging results in lower hydrocarbon (HC) emissions, improved power output, and higher fuel economy. However, this method typically requires additional components like an exhaust valve and actuator mechanism, making the engine design more complex and expensive. Despite this, uniflow scavenging is widely favored in high-performance and emission-optimized engine applications.

Table 2: Comparison between various scavenging techniques

Feature	Loop Scavenging	Cross-Flow Scavenging	Uniflow Scavenging
Flow Direction	Looping upward within the cylinder	Side-to-side horizontal flow	Bottom-to-top unidirectional flow
Port Arrangement	Transfer and exhaust ports on	Transfer and exhaust ports on opposite	Transfer ports at bottom, exhaust valve at

	same side	sides	top
Piston Design	Flat or slightly domed	Deflector piston	Flat or domed piston
Scavenging Efficiency	Moderate	Low to moderate	High
Charge Loss (Fuel Escape)	Moderate	High	Low
Complexity	Simple	Very simple	Mechanically complex (requires exhaust valve)
Emissions (HC, CO)	Medium	High	Low
Engine Cost	Moderate	Low	High
Common Usage	Small to mid-size engines	Older or low-power engines	High-performance and emission-compliant engines

4.3 Stratified Charging

Stratified charging is an advanced combustion technique used in two-stroke spark ignition (SI) engines to reduce emissions and improve fuel efficiency. In this method, the air-fuel mixture inside the combustion chamber is arranged in layers or "strata," with a richer mixture concentrated near the spark plug and a leaner mixture or pure air in the surrounding regions. This stratification ensures that ignition occurs in a fuel-rich zone, allowing for stable and reliable combustion, even when the overall mixture is lean. By avoiding a uniformly rich mixture throughout the chamber, stratified charging significantly reduces unburned hydrocarbon (HC) and carbon monoxide (CO) emissions. It also minimizes fuel wastage and enables the engine to run efficiently at part-load conditions. Achieving stratified charging typically requires precise control over fuel injection timing and location, often through direct or staged fuel injection systems. Though it increases system complexity, the benefits in terms of lower emissions and improved fuel economy make it a valuable modification in modern two-stroke engine designs.

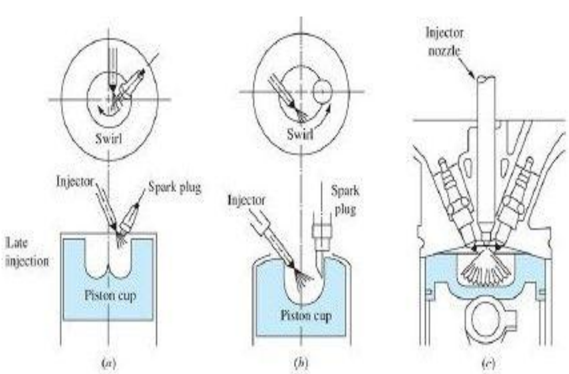

Fig. 3: Stratifying charging

4.4 Exhaust after-treatment systems

Exhaust after-treatment systems are emission control technologies applied to the exhaust stream of two-stroke spark ignition (SI) engines to reduce harmful pollutants such as hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxides (NOx) before they are released into the atmosphere. Since two-stroke engines inherently suffer from incomplete combustion and fuel short-circuiting, after-treatment plays a critical role in emission reduction.

The most common component is the catalytic converter, which facilitates chemical reactions to convert HC and CO into less harmful carbon dioxide (CO_2) and water vapor. Catalysts are typically made of precious metals like platinum, palladium, or rhodium, and operate at high temperatures to oxidize unburned fuel components.

Another technique is secondary air injection, where fresh air is introduced into the exhaust stream to support post-combustion oxidation of HC and CO. This method is simple but effective in improving catalytic converter efficiency.

In some designs, thermal reactors—insulated chambers that hold exhaust gases at high temperatures—are used to promote oxidation without a catalyst, though they are less common in modern systems due to bulk and thermal management issues.

Exhaust after-treatment systems are essential for compliance with modern emission regulations and are often used in conjunction with other engine modifications like direct fuel injection or improved scavenging. Their effectiveness depends on proper engine calibration and maintenance.

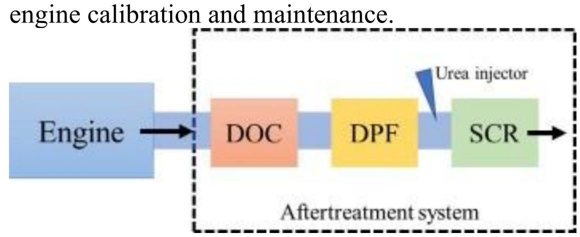

Fig. 4: Shows the Exhaust after-treatment systems

4.5 Lubrication System Improvement

Lubrication system improvement in two-stroke spark ignition (SI) engines is a key strategy for reducing particulate and hydrocarbon (HC) emissions while enhancing engine durability. Traditionally, two-stroke engines use total-loss lubrication, where oil is mixed with fuel (premix) or injected directly into the crankcase. A portion of this oil is burned during combustion, leading to high smoke and HC emissions.

To address this, modern designs implement advanced oil injection systems, which deliver precise amounts of lubricant only where and when it's needed—such as on bearings, cylinder walls, or the piston skirt. This reduces oil consumption significantly and minimizes the amount of oil that reaches the combustion chamber.

Another advancement is the use of low-ash or biodegradable synthetic oils, which burn cleaner than conventional mineral oils and produce fewer carbon deposits and smoke. Some high-performance engines now employ pressure-fed lubrication systems, similar to those in four-stroke engines, that use an oil pump and oil return path—although this adds complexity and cost.

Improving the lubrication system not only decreases environmental impact but also enhances engine longevity and efficiency by reducing friction and wear. These improvements, combined with emission control strategies, make two-stroke engines more viable for modern applications.

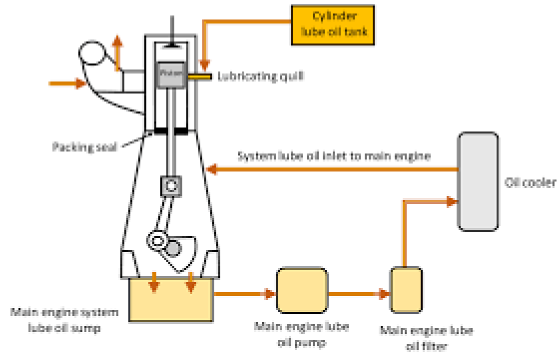

Fig. 5: shows the lubrication system

Table 3: Comparison between different design modification techniques

Design Modification Technique	Emission Reduction (HC/CO/NOx)	Fuel Efficiency	Technical Complexity	Cost	Overall Effectiveness
Direct Fuel Injection (DFI)	High (↓HC, ↓CO)	High	High	High	Very Effective
Advanced Scavenging	Moderate to High (↓HC)	Moderate to High	Moderate	Moderate	Effective
Stratified Charging	High (↓HC, ↓CO)	High	High	High	Very Effective
Exhaust After-Treatment	High (↓HC, ↓CO, ↓NOx)	Neutral	Moderate	Moderate	Effective
Lubrication Improvement	Moderate (↓HC, ↓PM)	Moderate	Low to Moderate	Low	Supportive but Essential

5. Discussion

The development and structural analysis of modified two-stroke spark ignition (SI) engines has become increasingly critical due to growing environmental concerns and stringent emission regulations. Conventional two-stroke engines are well-known for their simplicity, lightweight design, and high power-to-weight ratio. However, their inherent design, especially the overlapping of intake and exhaust phases, leads to significant unburned hydrocarbon (HC) and carbon monoxide (CO) emissions due to scavenging losses and incomplete combustion.

The reviewed literature from 2020 to 2025 highlights how direct fuel injection (DFI) has emerged as a highly effective strategy in reducing HC emissions. Studies such as Zhang & Cao (2025) and Mohamed et al. (2024) confirm that DFI, particularly in two-stage or hybrid forms, allows precise control over the injection timing and fuel quantity. This results in better air-fuel mixture formation and reduced short-circuiting of fuel during the scavenging process.

Advanced scavenging techniques, such as loop, cross-flow, and uniflow scavenging, have also been explored to improve combustion efficiency. Among these, uniflow scavenging stands out for its superior gas exchange characteristics and reduced backflow losses, as indicated by simulation studies and experimental trials.

Stratified charging and split injection strategies further aid in creating localized lean mixtures, reducing overall fuel consumption and minimizing knock tendency. These strategies allow engines to operate efficiently under varying load conditions while maintaining emission compliance.

Moreover, the integration of exhaust after-treatment systems, including catalytic converters and secondary air injection, complements in-cylinder techniques by oxidizing remaining pollutants. Alongside this, improved lubrication systems—using electronically controlled oil injectors and biodegradable low-ash oils—have been shown to reduce particulate matter and oil-derived HC emissions significantly.

Overall, combining these modifications has shown to significantly enhance engine performance, reduce emissions, and extend engine life. However, these technologies come with increased system complexity and cost, posing a challenge for mass-market applications, especially in low-cost segments like two-wheelers and small outboard engines.

6. Conclusion

This comprehensive review underscores the urgent need and promising potential of design modifications aimed at reducing emissions in two-stroke spark ignition (SI) engines. Traditional two-stroke engines, despite their advantages in simplicity and power density, are inherently prone to high hydrocarbon and particulate emissions due to overlapping intake and exhaust events. However, modern engineering innovations have paved the way for substantial environmental improvements without compromising performance.

Among the techniques explored, Direct Fuel Injection (DFI) stands out as one of the most impactful solutions, minimizing fuel short-circuiting and enhancing combustion control. Likewise, advanced scavenging methods—such as uniflow, loop, and cross-flow scavenging—optimize air-fuel exchange, further reducing unburned fuel losses. Strategies like stratified charging and split injection offer additional improvements by enabling leaner combustion and targeted fuel delivery.

The integration of exhaust after-treatment systems complements in-cylinder solutions, effectively lowering tailpipe emissions. Additionally, innovations in lubrication systems, including electronically controlled oil injection, significantly cut down oil-related emissions and support cleaner engine operation.

While these modifications have demonstrated considerable potential in both experimental and real-world scenarios, challenges related to cost, complexity, and retrofitting remain. Therefore, future research should focus on hybridizing these techniques, making them economically viable, and adapting them for mass-market use in small utility vehicles and developing regions.

Ultimately, the adoption of these design strategies holds the key to ensuring that two-stroke SI engines remain relevant, efficient, and environmentally sustainable in the modern mobility landscape.

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