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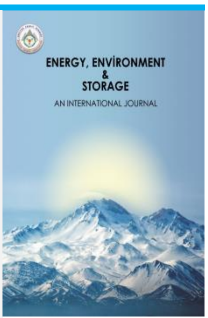

Effect of Excess Air Ratio on Emissions, Performance and Efficiency of Gasoline Fueled Engines: A Review

Happy Sinkala[1*], Saliha Özarslan[2], Abdallah Benarous[3,4]

[1]Graduate School of Natural and Applied Sciences, Mechanical Engineering Dept. Erciyes University, Kayseri, Türkiye

ORCID: 0009-0006-8871-6813

[2]Amasya University, Technical Sciences Vocational School, Automotive Program, Amasya, Türkiye

ORCID: 0000-0001-5696-9644

[3]Department of Mechanics, Technology Faculty, University Blida 1, Algeria

[4]LISICPE Laboratory, UHB University, Chlef, Algeria

ABSTRACT. This paper provides a comprehensive review of the fundamental impacts of excess air ratio (λ) on emissions and engine performance in spark-ignition engines. It examines pollutants such as oxides of nitrogen, unburned hydrocarbons, and carbon monoxide under both lean and ultra-lean conditions. In this paper, mainly the most prominent, up to date, and effective technologies such as ignition strategy, injection strategy, fuel blending, pre-chamber addition, are included. In addition to the effect the excess air ratio has on emissions, engine performance and efficiency are reviewed. This is done through the analysis of the Indicated Mean Effective Pressure, Coefficient of Variation, Fuel Consumption and Indicated Thermal Efficiency. The topics discussed relate to the primary categories listed above, but they are not exclusive to them. The paper concludes with a summary of findings and offers recommendations for future research directions..

Keywords: Guide, lean, emissions, performance, efficiency, fuel, combustion.

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1. INTRODUCTION

Fuel combustion has been widely used for many years to power transportation vehicles, produce electricity and heat for buildings and manufacturing operations. Nonetheless, given that energy cannot be produced, transported, or consumed without having a substantial negative influence on the environment, energy and environmental issues are tightly interlinked. Byproducts of fuel combustion, such as particulate matter (PM), carbon dioxide (CO_2), sulfur dioxide (SO_2), carbon monoxide (CO), and nitrogen oxides (NOx), have a negative impact on the environment. The poor quality of the air, the unprecedented climate change, and global warming are mostly caused by these pollutants. In an internal combustion engine, the burning of gasoline releases carbon monoxide, nitrogen oxides, and hydrocarbons.

A key environmental challenge today revolves around decreasing emissions from internal combustion engines while simultaneously enhancing fuel efficiency and engine performance. Numerous techniques, including better engine design, improved fuel characteristics, and enhanced combustion modes, have been employed to lower emissions and increase efficiency in engines.

One of the most important variables influencing engine exhaust emissions is the air-fuel ratio. The air-fuel ratio controls the amount of energy released, the amount of undesired pollutants generated during the process, and whether a mixture is combustible or not. Because of this, controlling the air-fuel ratio is still a top priority for engine control, particularly for the purpose of reducing exhaust emissions pollution [1]. Additionally, a three-way catalytic converter's performance depends on the quality of the mixture, therefore suitable control mechanisms are

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[*] Corresponding author: hapsink@gmail.com

needed to comply with emission regulations [2]. Since precise air-fuel ratio control is the cornerstone of low-emission technology for gasoline engines, researches have been conducted on air-fuel ratio control techniques to optimize three-way catalyst emission conversion efficiency and comply with global emission legislation [3–17]. Compared to engines operating under stoichiometric conditions, lean burn engines require higher levels of air-fuel ratio stability and control for lean operation; otherwise, misfires will occur, affecting engine power, economy, and emissions [18].

Not only is the air-fuel ratio a critical parameter in an internal combustion engine or industrial furnace for pollution control but it is significant for the purpose of performance tuning as well. The air fuel ratio has a significant impact on the engine's power and fuel efficiency. In a gasoline engine, the lean air-fuel ratio yields the lowest fuel consumption. The primary cause is the abundance of oxygen, which allows the fuel to burn entirely and produce mechanical work. On the other side, rich air fuel mixtures yield the most power.

From the above literature review, one realizes that air-fuel ratio is a crucial and noteworthy metric or indication for regulating or fine-tuning engine performance and factors that are directly related to air quality and reducing pollution. This paper will cover a review of the influence of an excess air ratio on engine performance and pollutant emissions. Since further charge dilution, i.e. ultra-lean conditions, affects the flame propagation speed, leading to combustion instability, different techniques used to overcome these limits and achieve a more stable combustion are mentioned. At stable ultra-lean combustion, the emission and performance characteristics of the engine are discussed.

2. EFFECT OF EXCESS AIR RATIO ON EMISSIONS, PERFORMANCE AND EFFICIENCY UNDER LEAN COMBUSTION

2.1 Effect of excess air ratio on emissions

The in-cylinder temperature, the air and fuel homogeneity, and the combustion mode all have a significant impact on emissions [19, 20]. Compared to SI mode, there are more emissions of CO and HC in HCCI mode. This is caused by trapped crevice gases, low in-cylinder temperatures, and incomplete oxidation brought on by the rapid combustion process. SI engines have higher NOx emissions than other engine types [20, 21]. It has been discovered that the HC and CO emissions in HCCI are primarily dependent on engine load, regardless of the air-fuel ratio. Engine speed has a smaller effect on CO emissions than it does on HC emissions [20].

Due to the sensitive nature of NOx generation to in-cylinder temperature and oxygen availability [22, 23], NOx emissions increase with in-cylinder conditions as well as fuel and air homogeneity, improved combustion, and better air/fuel mixing (λ=1.0 to 1.2). By burning fuel with an excess of air compared to the stoichiometric amount required for combustion per unit mass of fuel, it's possible to reduce in-cylinder temperature, thus leading to lower NOx emissions [24]. Conversely, a more diluted mixture cools the fresh charge and reduces the fuel rate even further, thereby reducing the heat release, average combustion temperature and deteriorates auto-ignition. Due to the considerably colder new charge, reduced fuel rate also results in incomplete combustion of HC and CO to CO_2 and low post-oxidation temperatures for the fuel/air mixture. HC and CO levels rise as a result [20, 25-26].

Ceviz et al. [28] investigated how engine emission characteristics were affected by an excess air ratio under lean operating conditions. According to their studies, at λ=1.2, an increase in the air excess ratio significantly reduced exhaust emissions relative to stoichiometric conditions by roughly 85% and 23% for CO and HC emissions, respectively.

Soot production is another emission where the excess air ratio has a major influence. When lean homogeneous combustion occurs at a higher thermal efficiency (excess ratio of about 1.2), less fuel film forms on the piston head, which results in low PM concentration [29]. However, as the air is diluted, i.e. further increasing the excess air ratio, the reduction in both the temperature and released heat, and an increase in combustion phase, limits the oxidation of the soot. For this reason, increasing the excess air ratio above 1.4 shows a re-increase in the PM concentration [29].

2.2 Effect of excess air ratio on performance and efficiency

As indicated in the previous section, the excess air ratio showed to have an effect on the emissions. Likewise, the effect of excess air ratio is observed in engine efficiency and performance. The range of λ in which the correct mixture burns in typical spark-ignited engines is relatively small. Engine performance becomes unstable when the fuel mixture is reduced to the point that the excess air ratio value is greater than 1.5. This can lead to a variety of issues, including misfiring and a non-repeatability of engine cycle.

The indicated mean effective pressure (IMEP) is one of the primary factors defining the performance of an internal combustion engine. The test engines indicated mean effective pressure decreases as the value of λ increases, resulting in a decline in performance caused by the deterioration of the excess air ratio mixture [26, 30]. The reported findings by M. Kumar and T. Shen [31] demonstrate this with the maximum pressure decreasing as the excess air ratio increases throughout all operating conditions. Lowering the fuel levels causes the in-cylinder temperature to drop [31], which in turn causes the pressure to drop, hence Pmax decreases.

The coefficient of variation in indicated mean effective pressure (COV_{IMEP}) is a useful tool for measuring and expressing engine work instabilities, which are related to the macro-scale combustion process. By calculating the IMEP from successive engine work cycles, the COV_{IMEP} is found. The value of the COV_{IMEP}, which indicates the variation in combustion stability, rises as the excess air ratio expands [30, 32].

When the combustion stability is achieved, the Indicated Specific Fuel Consumption (ISFC) typically drops because there is less pumping loss as the extent of lean conditions rises. Other variables, on the other hand, might have an impact on ISFC, which might rise in certain circumstances. Park et al. [25] reported that the ISFC increased in the intermediate range of operating circumstances i.e. λ= 1.4 and 1.6. It's probable that the fuel injected early in the process caused moisture on the walls, leading to a film of fuel on the piston and cylinder surfaces. The increase in Total Hydrocarbon (THC) emissions might stem from some of the fuel injected early not fully engaging in combustion. Additionally, because of better fuel evaporation and air usage, a higher injection pressure was better for fuel efficiency. Nevertheless, owing to the cylinder receiving a lesser amount of energy i.e. fuel, the engine performance decreases. The ISFC is affected by the combustion phasing in a manner similar to the COV_{IMEP}, which is dependent on the ignition timing [26].

Under varying engine loads, equivalent brake specific fuel consumption (BSFC) decreases. However, the increasing λ reduces BSFC only up to a certain minimum, then it subsequently increases BSFC. For the different tested fuels, this was reported [23, 33], and according to the authors [23], the following variables might have contributed to this. First, when λ increases, the engine load was maintained by increasing the throttle opening angle and boosting the intake manifold pressure. This lowered the peak combustion temperature and, as a result, less heat is lost through the combustion chamber walls and less pumping work is required. In the meantime, increased intake pressure raises the fuel-air mixture's heat capacity ratio in the cylinder, enhancing the engine cycle's thermal efficiency. As a result, the equivalent BSFC decreases. However, when λ is increased to 1.5, poor constant-volume combustion and high air dilution rate cause misfires, which lower thermal efficiency and increases equivalent BSFC.

As was already mentioned during the combustion phase, the influence of air dilution on combustion increases the rate of misfires as well as the emissions of THC and CO, which lowers the value of total heat release and ultimately lowers thermal efficiency. Moreover, because of the poor combustion performance, this behavior will be notable at large λ. Conversely, the efficiency of combustion increases when the combustion phenomenon achieves stability thanks to better combustion and improved air- fuel mixing, after which it decreases as λ increases. Additionally, there is sufficient fuel as well as oxygen in the mixture for adequate oxidation (air-fuel mixing), which means that when more fuel oxidizes, there will be just a little excess of oxygen available.

Moreover, when λ increases beyond 1.4, there is insufficient fuel in relation to the excess oxygen present in the cylinder. This results in an improperly mixed mixture, or heterogeneous mixture, and hinders the smooth propagation of the flame front, causing partial combustion or misfires. These occurrences indicate the instability of the combustion phenomenon with lean-zone combustion and, ultimately, a decrease in combustion efficiency [26, 31].

In their study of the impact of excess air ratio on cyclic variability and engine performance characteristics under lean operation conditions, Ceviz et al. [28] concluded that lean burn combustion spark ignition engines can offer notable advantages in low load conditions, particularly when the engine is well-designed and the air-fuel mixture formation strategy is optimized. Under such circumstances, thermal efficiency increases by approximately 30%. However, specific fuel consumption and HC emissions start to increase once the excess air ratio exceeds around $\lambda = 1.25$. This also resulted in a more rapid increase in cyclic variability.

From the findings and as shown in table 1, it can be seen that increasing the fuel air ratio even further, or achieving ultra-lean combustion, may help the engine and power industries comply with the strict emission rules pertaining to nitrogen oxides (NOx). However, when λ grows from 1.4 onwards, the in-cylinder combustion phenomenon exhibits instability characteristic [23]. Additionally, inadequate ignition caused by a more diluted mixture can cause misfires in the engine. Misfires and ignition problems like these can cause rough operation, cycle-to-cycle variability, efficiency reduction, and an increase in emissions of unburned hydrocarbons. The narrow flammability limit will also restrict the NOx reduction.

In order to attain a short burn duration and good combustion stability in ultra-lean combustion, a number of attempts have been undertaken to provide a reliable ignition process and to improve fuel oxidation. The next sections review the different combustion and ignition techniques and works carried out to extend the excess air ratio and the effect it has on emissions, engine performance and efficiency under ultra-lean conditions.

Table 1 Summary of the effect of excess air ratio (lean burn) on performance, efficiency and emission characteristics

Author	Operation	Performance & Efficiency	Emissions
C. Park et al [25]	For a single injection, a lean mixture was formed. Engine speed of 3000 r/min Indicated mean effective pressure of 0.4 MPa Fuel injection pressure ranging from 10 MPa to 20 MPa.	Under lean burn - The Indicated Specific Fuel Consumption decreased owing to the reduced pumping loss - Possibility of misfire to occur as λ.	Due to further increase λ i.e. in lean burn - NOx decreased - THC emissions increased - the opacity increases
A. Jamrozik, W. Tutak [26]	A traditional, single-stage combustion process, Air-fuel mixtures with excess air ratios (λ) are managed appropriately, ensuring they do not exceed 1.5.	- λ goes beyond 1.5, misfire and non-repeatability of engine cycles occurred and engine efficiency decrease	At λ greater than 1.2 - NOx decreased At λ less than 1.5 - Both HC and CO decreased
C. Park et al [29]	The test parameters were set to 2000 rpm and 0.2 and 0.4 MPa for the brake mean effective pressure, in each case. The test settings included a spray-guided direct-injection system to ensure lean combustion.		-At λ about 1.5, the Particulate Matter (PM) increased dramatically - Increasing λ to higher than 2.0 leads a re-increase in the Particulate Matter concentrations
Martinez S [30]	The engine was run during the intake stroke at a fixed rotational speed of 1000 rpm, with the throttle wide open. The maximum brake torque setting for each case was taken into consideration when choosing the spark timing, and the excess air ratio was increased from 1 to levels that were almost at the flammability limit.	- When implementing lean combustion, IMEP dropped as λ increased. - Stable engine operation was maintained with COV values below 4% until λ = 1.5. Following this, there was a sharp rise in instability, peaking at about 6%. - Up to λ = 1.5, fuel conversion efficiency increases	-Emissions were not covered in the study
M. Kumar, T. Shen [31]	A traditional gasoline engine of the V6 type equipped with two fuel injection systems.	- As λ rises, less heat is released. - Combustion efficiency increases till λ = 1.4 and then decreases with additional λ increases -In-cylinder pressure decreases	- Because of improved combustion efficiency, NOx emission initially increases about λ=1.1 to 1.2 and then decreases as λ increases further.
Ceviz et al [28]	The engine speed 2500 rpm, at thirteen (13) different air-fuel ratios	- There is a noticeable decline in combustion quality as one approaches the lean operating limit. - Up to λ = 1.3, an increase in λ caused the cyclic variations to increase approximately linearly. The rate at which the cyclic variations increased after this value was extremely rapid. - Up to λ = 1.2, the specific fuel consumption reduced and the thermal efficiency increased as λ increased.	- CO emissions decreased (85%) dramatically down to λ =1.1 and continued to decrease as λ increased. - CO_2 emissions decreased linearly with the increase λ - HC emissions decreased (23%) up to λ =1.25, and started to increase after this point. - NOx emission reached maximum at λ =1.1. After this value, NOx emission decreased linearly
C.-W. Wu et al. [55]	A typical engine was used to evaluate ethanol–gasoline-blended fuel at different air-fuel ratios (λ).	- When the λ ratio is marginally less than one, the maximal torque output is attainable at all throttle valve openings. As λ increases, the cylinder's combustible vapor content decreases, resulting in a decrease in torque output.	For 100% pure gasoline fuel: - As λ approaches unity, CO emissions decrease, and may even reach zero under lean conditions. - At λ slightly larger than one, the amount of HC emission is minimum, owing to complete combustion. - With further increases, such as when λ surpasses 1.4, the level of HC emissions rises due to combustion becoming highly incomplete.

3. EFFECT OF EXCESS AIR RATIO ON EMISSIONS UNDER ULTRA-LEAN COMBUSTION

3.1 Ignition and Injection Strategy

The lean-burn limit is influenced by both the injection method and the ignition timing, as the latter determines the combustion phase. In lean operation conditions, late injection is effective than early injection at ensuring stable combustion with sufficient mixture formation. [2, 34-35]. With late injection, however, it is challenging to reduce the misfire tendency due to the huge amount of fuel injected under mid-load operating conditions. By utilizing converging-diverging nozzles with a specific aspect ratio in the pre-chamber, a supersonic hot jet technique allows combustion engines to burn ultra-lean mixtures. Increased fuel economy, decreased NOx emissions, and improved combustion efficiency are all shown benefits of supersonic jet ignition [36–19]. Additionally, it was noted that, in comparison to homogeneous combustion, the lean-burn limit was noticeably extended for stratified operation [37, 38]. In their study of the in-cylinder air-fuel ratio control problem for the lean burn mode of SI engines using cycle-based mode, Kumar et al. [31] discovered that stable combustion at an excess air ratio significantly extended to λ=2 can be achieved by fuel split injection, which enables the formation of an adequate stratified mixture in lean combustion conditions. The findings also indicate that combining lean combustion with intake tumble holds significant promise for conserving energy and reducing emissions in gasoline engines. Fig. 2 shows a continuous drop in CO_2. Experiments conducted by F. Zhou et al. [39] demonstrate that utilizing intake tumble notably extends the lean combustion limit while maintaining acceptable combustion stability. This approach increases the indicated thermal efficiency by 7.2% compared to the engine's initial state without tumble (at λ = 1), while the particular emissions of CO_2, CO, HC, and NOx can be decreased by, at most, 85.3%, 72.2%, 12.0%, and 5.8%, respectively as illustrated in figures 1, 2 and 3.

Microwave ignition has been shown to significantly increase the internal combustion engine's lean-burn limit [40]. The lean limit was demonstrated by Hwang et al. [41] in their experiments with the conventional spark ignition system at λ =1.28; however, the lean limit was extended to λ=1.57 by the microwave-assisted plasma ignition system. It was also proven that the air/fuel ratio is the main factor influencing CO emissions from internal combustion engines. Regardless of the ignition mode, as the lambda was increased, the CO emissions reduced. Simultaneously, a considerable decrease in CO emissions was found upon microwave activation. From Fig. 1, at a lambda value of 1.0, the CO emission dropped to 0.11% with microwave-assisted plasma ignition (520mJ) as opposed to 0.35% with traditional spark ignition. Microwave aided plasma ignition cut CO emissions by approximately 49% under lean operating conditions. Under lambda 1.0 conditions, the HC emissions from microwave-assisted plasma ignition (520mJ) and traditional spark ignition are 3108 ppm and 5175 ppm, respectively (Fig. 3). Furthermore, in lean operational settings, microwave-assisted plasma ignition could potentially reduce HC emissions by approximately 29%. This is attributed to the increased temperature and accelerated flame velocity generated by the microwave-assisted plasma ignition. Conversely, depicted in Figure 4, NOx emissions from the microwave-assisted plasma ignition system surpassed those from the conventional spark ignition setup due to the higher in-cylinder temperatures. In a lean condition, the average rate of growth in NOx emissions was 115%.

3.2 Prechamber addition

The gasoline pre-chamber allows for the creation of ultra-lean mixtures with dilution ratios up to λ = 2.1. Similarly, burning of lean gas-air mixtures with an excess air ratio above the value of 1 (up to about 1.8) was obtained in the investigation of a two-stage combustion system [19]. Under these extremely lean circumstances, the NO_2/NOx ratio is almost 100% in terms of emissions [42]. When using a NOx storage catalyst, the high NO_2 to NOx ratio is advantageous.

Based on a SI stationary engine using a two-stage LPG-powered combustion system, Jamrozik et al. [26,43] discovered that the test engine's Air-Fuel mixture stratification method allowed lean mixture to burn with an overall excess air ratio of up to 2.0 thanks to the two-staged combustion system with pre-chamber. The centrally positioned active pre-chamber that allowed for independent regulation of the air/fuel ratio in the main combustion chamber facilitated the achievement of stable ignition and rapid flame propagation. Operating at an excess air ratio of up to 2.0, in turn, reduced NOx emissions from the exhaust as illustrated in Fig. 4.

3.3 Spark Discharge Interval

In SI engines, combustion initiation occurs through the spark discharge generated between the electrodes of the spark plug [44-46]. This discharge forms a high-temperature plasma kernel around the spark plug, facilitating the transfer of energy from the plasma to the combustible mixture. Subsequently, this initial flame kernel then becomes the propagating flame [32, 47]. According to Jung et al. [48], a rapid tumble motion in conjunction with a high discharge energy can further extend the lean limit, increasing maximal efficiency and lowering emissions. Under lean conditions, the longer discharge interval decreases the Cycle-to-Cycle Variation (CCV) of combustion, and Tsuboi et al. [49] indicated that achieving an operation at λ=2.3 was possible with a discharge interval of 0.4ms. However, their study highlighted that excessively long or short intervals between spark discharges lead to unstable lean operation, characterized by significant cycle-to-cycle variability in SI combustion, particularly for ultra-lean SI operation at λ ≈ 2.0. As consequence, an understanding of the phases of spark discharge is particularly important to find an optimum interval between spark discharges to minimize variations in combustion and ultimately increase the lean-stability limit. Nakata et al. [50] reported a similar finding, observing that the lean limit at a discharge current of 300 mA was extended to an excess air ratio of 1.96 due to the larger discharge current or longer discharge duration. According to Astanei et al, when comparing the efficiency of double spark plugs in enhancing the performance of combustion engines, the energy that the double spark plug (DSP) delivers to the discharge during long pulse durations is 20% more than that of the conventional spark plug. It was noted that even at equivalency ratios in the region of 0.65, where the usage of conventional spark plug (CSP) tends to cause misfires and extremely significant engine vibrations, the DSP can offer more stability for such very lean mixtures [51]. The high discharge stabilizes the initial stage of combustion by producing a large flame. Since the initial stage of combustion controls all combustion in a SI engine, a stabilized kernel flame forms quickly, which shortens the initial flame growth period and allowed for a decrease in combustion variations, which are represented by the CVV. [52, 53]

3.4 Fuel Blending

The use of the methods above, standalone or combined would greatly increase combustion stability under ultra-lean conditions. Other than that, the use of blended fuels, gasoline and ethanol for example, can enhance the combustion rate. In his research, Xiumin Xu [21] showed that the highest indicated thermal efficiency of ethanol/gasoline blends is higher than that of ethanol by 0.4% and 8.8%, respectively, at λ=1.2 and λ=1.4. Based on these findings, the EPI+GDI mode performs better in lean burn conditions.

A similar situation was seen in the LPG+Gasoline blending case [26, 43], where a pre-chamber Gasoline+LPG mix injection allowed for higher air ratio operation at high thermal efficiency.

Lower nitrogen oxide emissions were seen in the engine's exhaust gas after burning an ultra-lean mixture with an overall excess air ratio of up to 2.0 in the test engine. It did, however, result in a rise in hydrocarbon and carbon monoxide levels as shown in Fig. 1 and Fig. 3. It has already been demonstrated that using a leaner air fuel ratio and an appropriate catalytic converter can greatly reduce CO and (HC + NOx) emissions [54].

The performance and emissions of a conventional engine using gasoline-ethanol blended fuel were investigated by C.-W. Wu et al. [55] at different air-fuel ratios (λ). It was demonstrated that when the blended fuel's ethanol percentage increased, and as a result of oxygen enrichment, CO and HC emissions decreased. The highest quantities of CO_2 and the smallest amounts of CO and HC were obtained at an air-fuel ratio that was marginally larger than one. It was observed that the air-fuel ratio controlled CO_2 emission during lean combustion conditions, whereas CO_2 emission is compensated by CO emission under rich combustion conditions. It was also discovered that blended fuels had CO_2 emissions per unit horse power output that were either comparable to or lower than those of gasoline fuels.

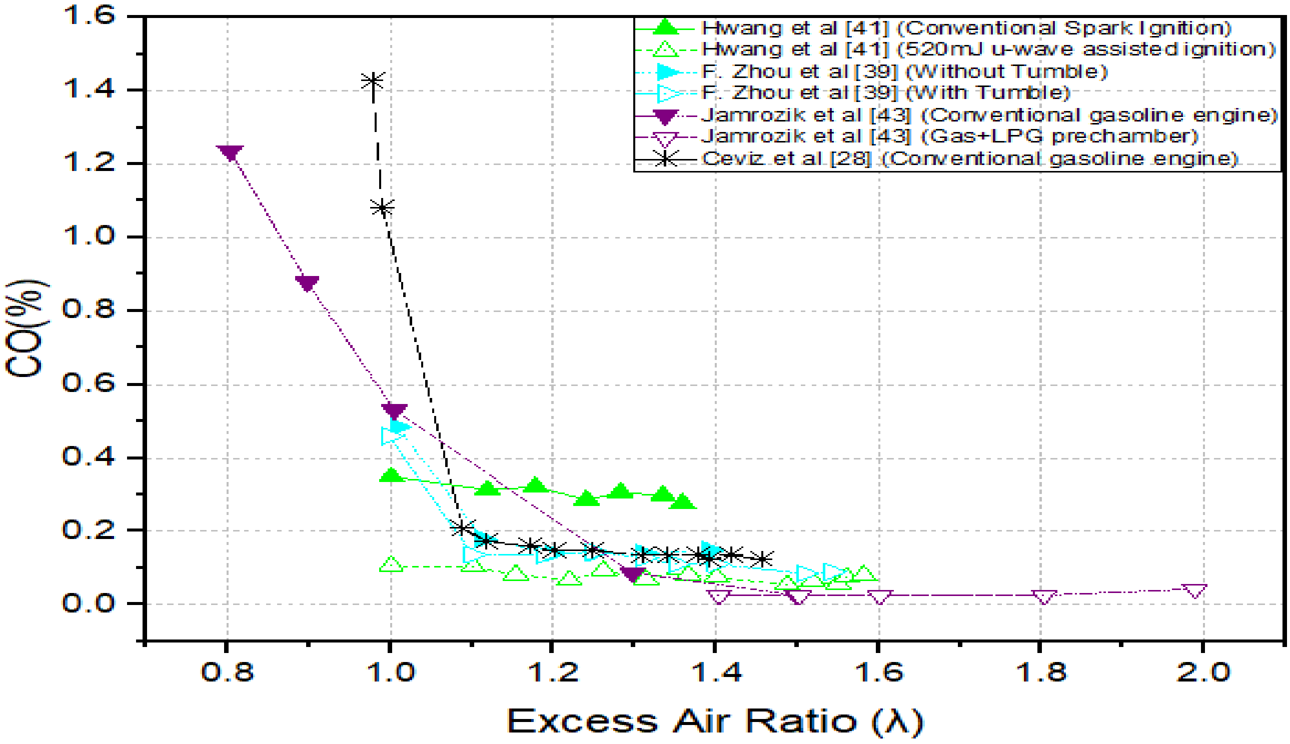

Fig. 1. The effect of excess air ratio on CO emissions

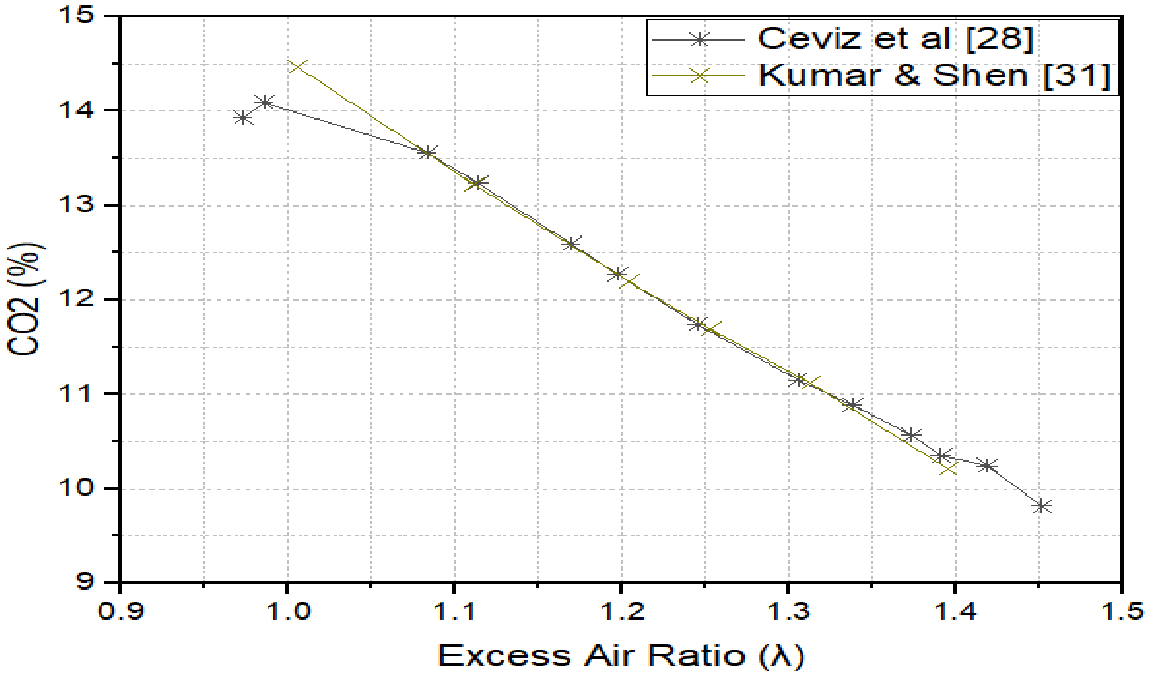

Fig. 2. The effect of excess air ratio on CO_2 emissions

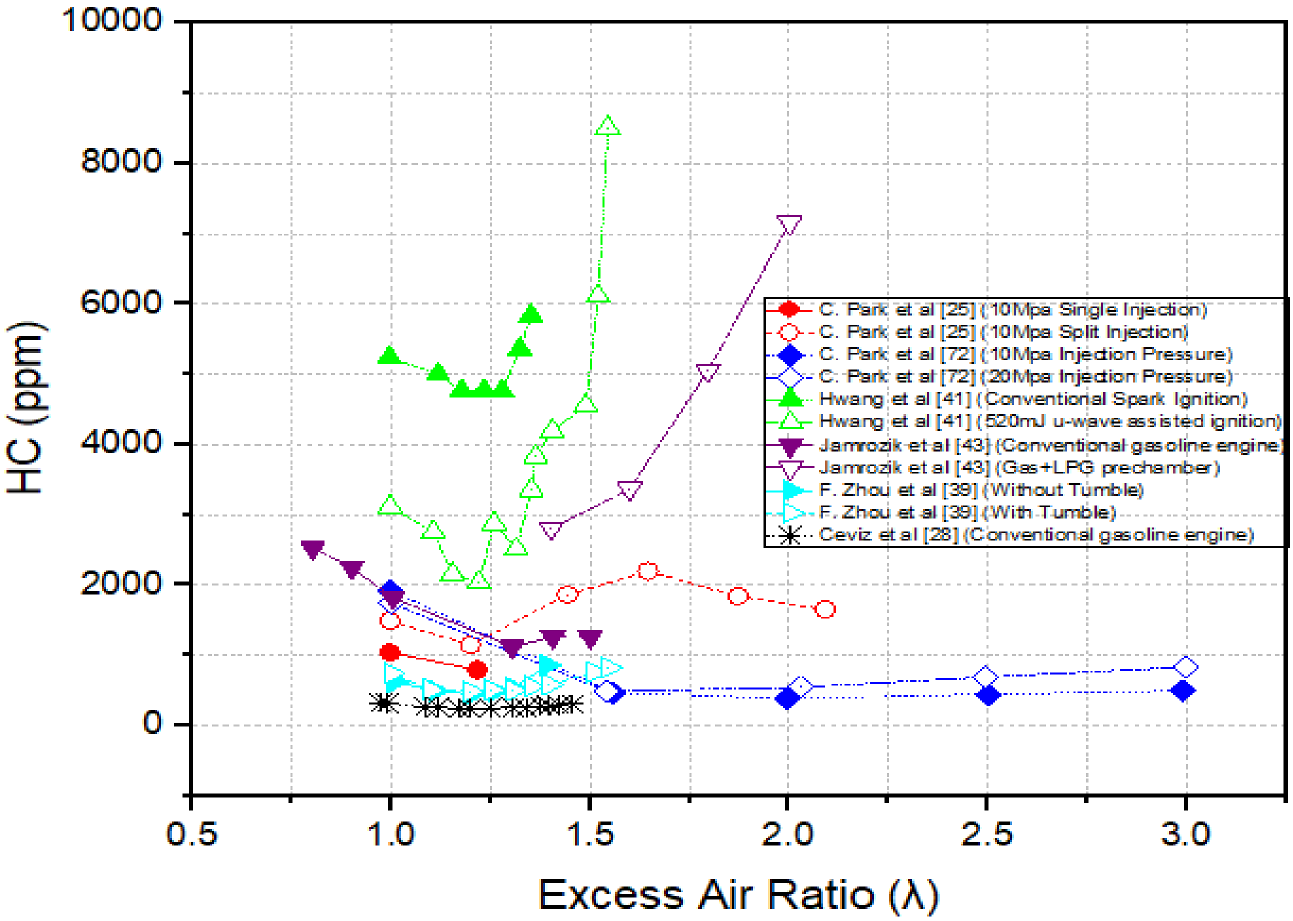

Fig. 3. The effect of excess air ratio on HC emissions

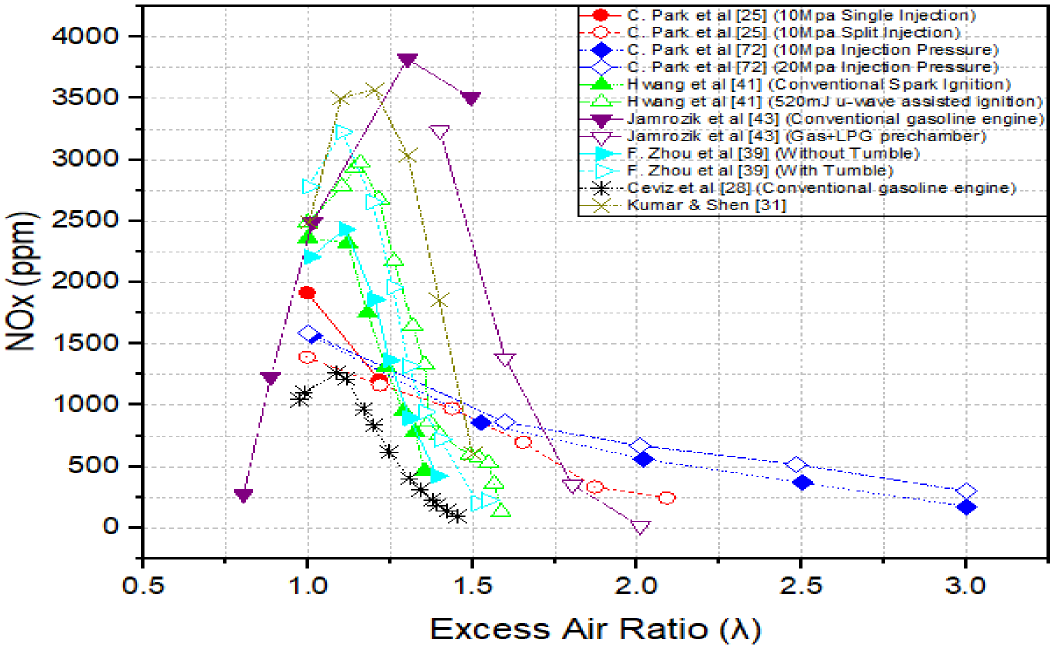

Fig. 4. The effect of excess air ratio on NO_X emissions

4. EFFECT OF EXCESS AIR RATIO ON PERFORMANCE AND EFFICIENCY UNDER ULTRA-LEAN COMBUSTION

Improving of efficiency and performance requires an expanded stable combustion range. Modern gasoline engine design aims to optimize efficiency and fuel economy while minimizing emissions to comply with regulations. Strategies such as downsizing, maximizing tumble flow, and increasing exhaust gas recirculation rates have shown to be effective [56-58]. Yet, there's still a need for ongoing improvement in engine designs and components to fully leverage these advantages. In particular, the ignition system has been an important aspect in the application of these strategies.

4.1 Microwave ignition

Numerous studies have summarized the fundamentals of plasma ignition and aided combustion [59–64], and it has been shown that microwave ignition significantly improves lean-burn mixed ignition performance [53, 65-66]. The utilization of microwave plasma ignition and assisted combustion technology results in a uniform distribution of flame intensity, increased propagation speed, enhanced combustion efficiency, extended lean burn flammability limits, and decreased emissions of pollutants. Moreover, multi-point ignition and stable combustion are achieved.

In comparison to a spark plug, a Multiple Microwave Discharge Igniter (MDI) operating as a 2point or 3point igniter significantly improved lean limit performance [58Hwange et al. [41] investigated the utilization of a novel microwave-assisted plasma ignition system in a direct injection gasoline engine. Their study revealed that the peaks of in-cylinder pressure and heat release rate were higher when employing microwave ignition compared to conventional spark ignition. The study's additional findings indicate that whereas the COVimep of conventional spark ignition may approach 20 at λ=1.35, it maintained a value below 15 at λ=1.5 when microwave ejection was used (Fig. 6). This is because the advanced combustion phase increased the in-cylinder pressure, which in turn enhanced the microwave-assisted plasma ignition's IMEP [67-70]. According to these findings [39], the microwave-assisted plasma ignition as shown in Fig. 5, can reduce the fuel consumption i.e. 2.05% increase in fuel efficiency in this case and avoid the lean limit flame out of a cylinder.

4.2 Spark Discharge Current

5% was the COV limit in the research conducted by Jung et al. [48]. The definition of the lean limit was thus the leanest condition that did not exceed the COV limit. In the absence of a discharge gap, the COV of IMEP reached 8.0% at λ =2.1. Yet, even at λ=2.1, the COV was reduced to less than 5% at a discharge interval of 0.4ms. With the exception of the high CCV conditions, the thermal efficiency increased as the extra air ratio increased. This effect can be explained by the decrease in heat loss. It is also possible that CCV suppression contributed to the increase in thermal efficiency at a discharge interval (Δti) of 0.4ms. Although the COV of IMEP reached 6.70%, an operation at λ=2.3 was attained and the maximum indicated thermal efficiency of 47.9% was achieved when the discharge interval was 0.4ms. According to Jung et al. [48] additional research on multiple spark discharge using a multi-coil ignition system to improve the thermal efficiency of lean SI engine operation, the indicated thermal efficiency increases fairly linearly with increasing λ for all discharge intervals taken into consideration. Additionally, for all but the Δti = 0.3ms example, the longer Δti is shown to have a greater the indicated thermal efficiency at each λ. Moreover, the lower COV of IMEP can be obtained by the longer Δti. The maximum the indicated thermal efficiency (≈47.0%) was thus obtained for operation with the multiple spark discharge of Δti = 0.2ms at about λ = 1.94.

4.3 Injection Strategy

When comparing the variation in combustion stability with the excess air ratio at different injection pressures for a single or split injection strategy, Park et al. [25] discovered that employing split injection extends the flammability limit with a high excess air ratio (e.g., λ = 2.0), while maintaining a COV_{IMEP} value of 5% as a benchmark for stable combustion. The study investigated how a split-injection strategy impacts the performance of stratified lean combustion in a gasoline direct-injection engine. The effect of the excess air ratio further expanding on the combustion stability was also studied and as λ expanded further, the COV_{IMEP} value increased as shown in Fig. 6. Improved stratified mixture ignitability with a twofold injection method reduces fuel consumption rate and COV_{IMEP} (Fig 5 and Fig 6 respectively), according to additional research [71]. Astanei et al came at a similar conclusion [51]. Furthermore, as the obtained results show, a high injection pressure is required to accomplish stable stratified lean combustion [25, 72].

4.4 Fuel Blending and Pre-chamber addition

Jamrozik et al. conducted a comparison between test results from a conventional gasoline engine featuring a single-stage combustion system and a slightly higher compression ratio of 9, and results from tests carried out on a dual-fuel engine equipped with a two-stage combustion system. In the latter, gasoline powered the cylinder while LPG fueled the pre-chamber [26, 43, 73]. The value of IMEP decreased by 16.7% in the engine with a conventional combustion system, but it decreased by 23.6% in the dual-fuel engine (LPG + Gasoline Prechamber) with the extension of the excess air ratio brought about by the addition of the prechamber. In comparison to the traditional engine, the dual fuel engine's higher IMEP decline also suggests a higher in-cylinder temperature decrease, which results in a lower maximum indicated thermal efficiency. On the other hand, an engine with a conventional combustion system experienced an increase in indicated thermal efficiency up to 34.2%, while a gas engine with a two-stage combustion system saw its maximum Indicated Thermal Efficiency (ITE) at λ = 1.8 (Fig. 7). This increase was followed by an increase in the excess air ratio λ up to 2.3. The COV_{IMEP} as shown in Fig. 6 indicated that further blending of the mixture to a maximum value of λ = 1.5 was linked with greater non-repeatability of engine cycles and decreased the engine's ITE [43].

Other engine performance experiments revealed that using fuel combined with ethanol and gasoline will result in a slight increase in torque output at small throttle valve openings [55].

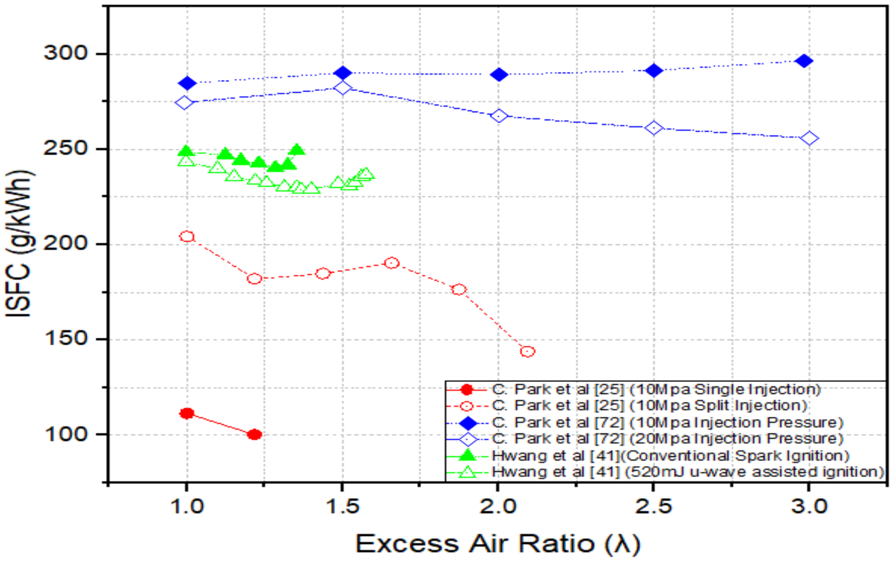

Fig. 5. The effect of excess air ratio on the specific fuel consumption

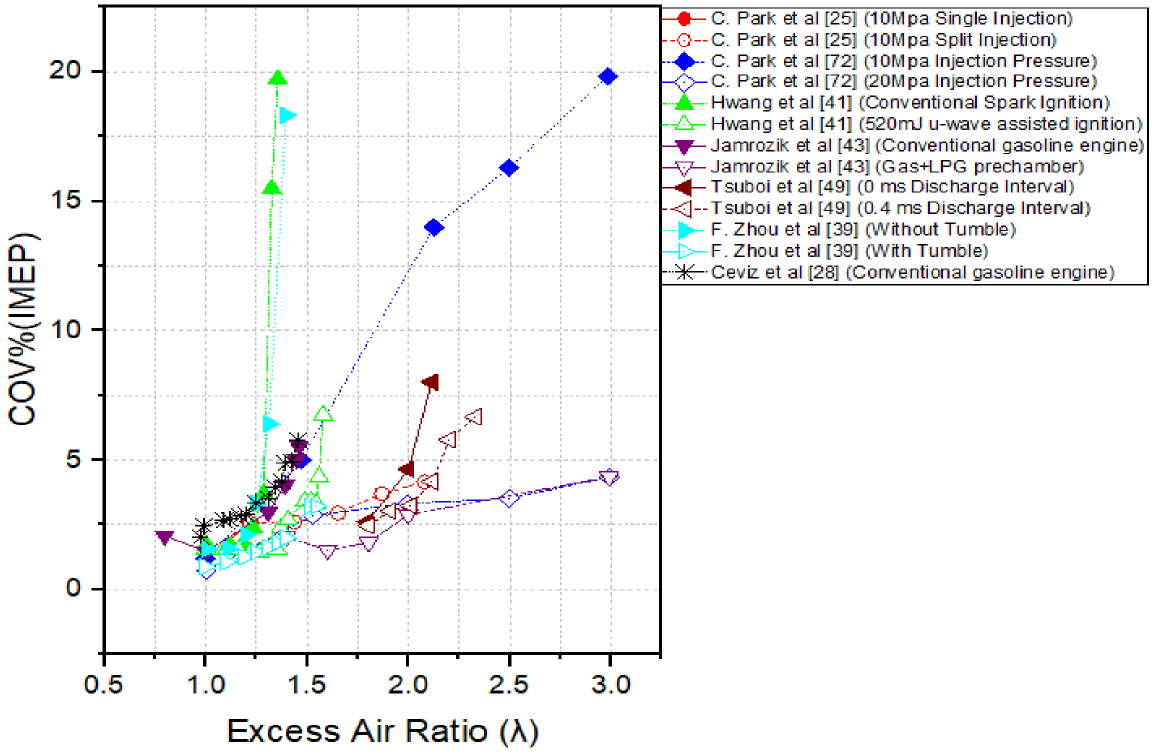

Fig. 6. The effect of excess air ratio on the coefficient of variation of indicated mean effective pressure

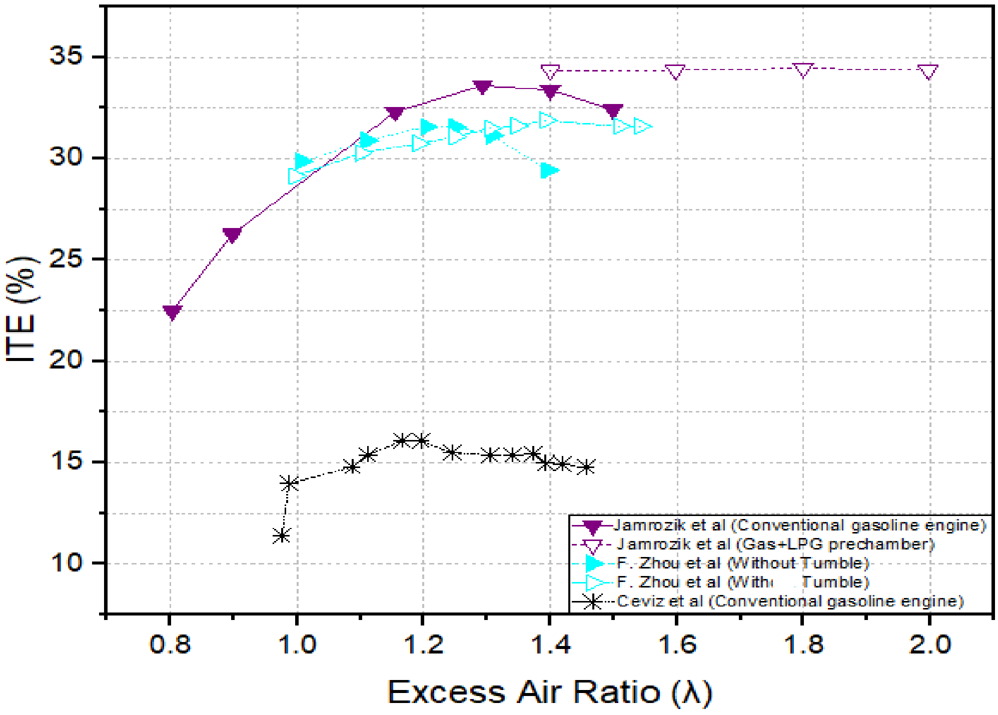

Fig. 7. The effect of excess air ratio on the engine indicated thermal efficiency

5. CONCLUSION

From the review, the importance of the air-fuel ratio in combustion has been discussed. In the case of excess air, its influence on emissions, engine performance and efficiency have been reviewed. Additionally, ultra-lean burn was considered as it seemingly showed to be a viable means to reduce Greenhouse Gases emissions. The effect of this combustion mode has on engine performance and efficiency is studied. The following are the conclusions from the review:

1. The air-fuel ratio is an important factor in combustion as it controls the amount of energy released, the amount of undesired pollutants generated during the process, and whether a mixture is combustible or not.

2. For lean burn, NOx emissions increase with improved combustion and better air/fuel mixing (λ=1.0 to 1.2). At this point, HC and CO emissions decrease. Further increasing the excess mass of air, the heat release and the average combustion temperature are reduced due to the more diluted mixture. This results in lower NOx emissions. However, in the case of HC and CO emissions, the incomplete combustion and combustion instability associated with high levels of excess air ratio causes a rise in these emissions.

3. The COV_{IMEP}, the value indicating combustion stability, since the indicated mean effective pressure decreases as the value of λ increases, resulting in a decline in performance utility caused by the depletion excess air ratio mixture, this value to increase. When the combustion stability is achieved, the Indicated Specific Fuel Consumption typically drops because there is less pumping loss as the extent of lean conditions rises. In the case of combustion instabilities, i.e. in higher excess air ratio values in conventional engines, the ISFC value increases.

4. The reduction in heat release under lean combustion results in the reduction in thermal efficiency. This showed that in this study there is a trade-off between efficiency and NOx emissions.

5. Given the specific range where fuel to air ratios must fall for ignition to occur, various methods, including adjustments to engine design, operational parameters, and improvement of fuels, can be employed to attain stable combustion. Achieving stable combustion, particularly in ultra-lean conditions, results in better efficiency, reduced fuel consumption, and lower emissions compared to a conventional spark ignition engine operating in lean combustion mode.

6. RECOMMENDATION

The different methods to achieve ultra-lean combustion outlined in this review can be improved. Especially in enhancing fuel properties by the use of fuel additives (ex. Nanofuels) or using different gasoline-biofuel blends. Hydrogen and Acetylene gas are also fuels that can be blended with gasoline to reduce emissions and also to investigate the performance of the engine under ultra-lean combustion.

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