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Research Article

Effect of steam addition on the combustion, performance and emissions characteristics of an HCCI diesel engine

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ABSTRACT

Although homogeneous charge compression ignition (HCCI) diesel engines are the favored source of power with near zero oxides of nitrogen (NO_x) and particulate matter emissions owing to a higher degree of homogeneity and elimination of diffusion phase combustion, the main drawback is the uncontrolled start of combustion along with high CO and unburned hydrocarbon emissions. In the present work, experimental investigations were carried out on a single cylinder diesel engine operating in HCCI combustion mode using external air-fuel mixture preparation. The regulated percentage of steam is added inside the mixing chamber and the effects on the combustion, performance and emission characteristics were reported for various steam injection rates at different brake mean effective pressures. The results obtained show that the brake thermal efficiency was improved to 21.048% with the addition of 20% steam addition and the NO_x emissions were also reduced significantly.The emissions of CO and unburned hydrocarbon were found 0.7% and 93 ppmrespectively at the steam addition rate of 20%, however a rapid increase was observed if the steam injection rate was increased further. Overall, the present work shows that by the addition of steam, the CO and unburned hydrocarbon emissions can be reduced significantly along with NO_x emissions and also there is a greater potential to control the start of combustion.

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INTRODUCTION

The homogeneous charge compression ignition (HCCI) diesel engines are expected to be the favored source of power for heavy industrial and transportation sector with high power output and low exhaust emissions. The HCCI technology addresses the challenges in terms of NO_x (Oxides of Nitrogen) and particulate matter (PM) pollutants that result due to combustion of heterogeneous air-fuel charge [1-2]. However, HCCI engine has disadvantage of high CO and PM emissions [3]. The PM can be reduced by using Diesel Oxidation Catalysts (DOCs) and Diesel Particulate Filters (DPFs). DOCs are suitable only for non-road applications and are capable of reducing PM to 25% or more. DPFs, are more expensive and are able to reduce the formation of PM by up to 90% and work effectively on engines that are able to sustain high exhaust temperature [4]. Furthermore, in HCCI diesel engine there is no direct control on the

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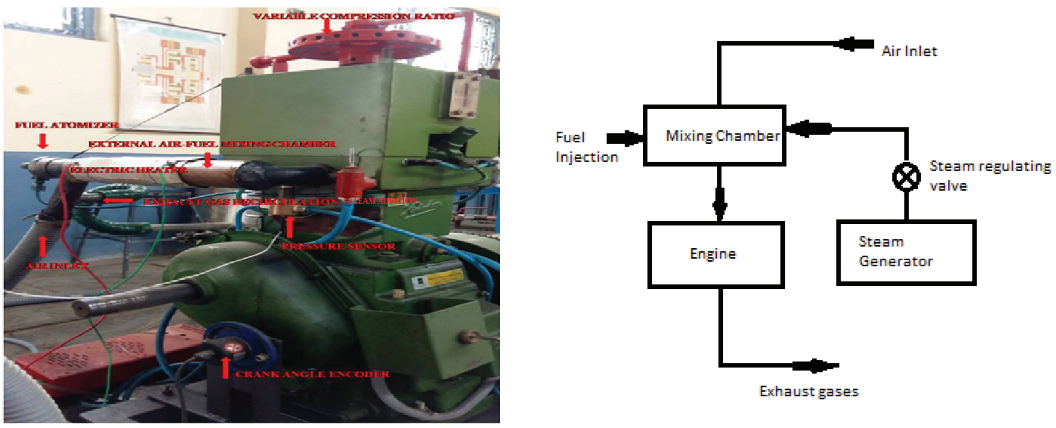
This paper was recommended for publication in revised form by Editor-in-Chief Ahmet Selim Dalkılıç combustion timing for better fuel economy and lower emissions. This implies that the auto-ignition time and following combustion phase of the HCCI engine are not controlled directly. The HCCI engine will be confined to a short working range due to the cold start, high-pressure rate, combustion noise, and even knocking combustion [2]. The start of combustion depends on various factors including the fuel properties, auto-ignition characteristics, the homogeneity of the fuel-air mixture and the temperature and pressure conditions within the combustion chamber. Several methods have been tried and reported to control the combustion phase of the HCCI engine including inlet air temperature, exhaust gas recirculation, variable valve timing, swirl ratio and compression ratio. NO_x emissions can be reduced significantly by using EGR technique but it has an adverse effect on particulate emissions and is also attained with a series of complex and sometimes opposite phenomenon taking place during combustion process [5]. The method of adding water in diesel engines helps significantly to reduce the in-cylinder temperature and consequently reduce the NO_x emissions [6-8]. The methods employed for addition of water in diesel engines mainly include direct water injection into the cylinder using separate injector, injecting diesel-water fuel emulsion and injecting water into the intake manifold. Addition of water into the diesel engines by using one of the above methods generally reduce the NO_x emissions either at low loads and high loads without any substantial increase in PM emissions and fuel penalty. This technique also improves the atomization of diesel fuel by increasing droplet micro-explosions. The use of water-in-diesel emulsion or direct water injection are the most efficient water injection technologies to reduce the NO_x emissions because the water is directly injected into the combustion zone, allowing a greater decrease in in-cylinder temperature. However, the drawback of water injection technique is that condensed water in the cylinder downgrades the quality of lubrication oil and raises the wear rate of moving parts of the engine. A recent technique to reduce the NO_x emissions and PM emissions simultaneously and also to improve the engine performance is the induction of steam into the inlet manifold. It is reported that with steam injection there is a decrease of up to 33% in NO_x emissions with an effective power increase of up to 3% and a decrease of up to 5% as a consequence of full-load conditions [9-14]. Murthy et al. [15] reported a decrease in NO_x emissions with an increase in soot emissions, thermal efficiency, effective power and specific fuel consumption at full load tests by injecting solar generated steam into diesel engine. The dissociation of water when using water injection technique increases the amount of OH radicals which reduce the formation of NO, HC, soot and PM and lead to an increase in effective efficiency and decrease in adiabatic flame temperature [16-26]. Researchers have also reported various techniques for improving the performance characteristics of diesel engines. K.S Kumar et al. [27] presented the experimental results for the investigation of lotus biodiesel with different blends as an ignition improver.

Based on literature reviews, water injection into diesel engine has certain effects to reduce emissions and improve performance parameters. However, the water inside the cylinder cause to pronounced corrosion. Steam injection is the preferred method recently, in order to reduce this negative effect in the internal combustion engines [2]. In this study, in order to prevent the effects of corrosion caused by water, steam injection is performed phase into intake manifold of HCCI diesel engine. The steam is injected into the engine at rate of 10%, 20% and 30% of fuel mass. The experimental results for the effects of steam injection on the combustion, performance and emission characteristics obtained are given in comparison with the results of computational study.

MATERIAL AND METHODS

Experimental Setup

The engine used for the experimental work as shown in Figure 1 (a) is a Kirloskar made single cylinder naturally aspirated four stroke diesel engine having variable compression ratio. The main specifications of the engine are given in Table 1.



(a) (b)

Figure 1. (a) Engine setup, (b) Schematic of steam addition.

Table 1. Main specifications of the test engine

Type	Kirloskar, 4-Stroke, Water cooled, Naturally aspirated diesel engine
Number of cylinders	1
Rated Power @1500rpm (kW)	3.73
Bore	80 mm
Stroke	110 mm
Compression ratio	12:1 to 20:1
Connecting rod length	234 mm
Swept volume	552 cc

The inlet manifold of the engine was modified to allow the external homogeneous air-fuel mixture formation in order to run the engine in HCCI combustion mode. A copper plenum is attached in front of the inlet manifold pipe forming a fuel vaporizer unit to achieve the proper mixing of all the components of charge including steam addition as shown in Figure 1 (b). The length of this pipe is sufficient that enables the homogenization of charge components inducted. The fuel vaporizer unit consists of a nichrome heating element wound over it so as to vaporize the diesel fuel. A high pressure fuel injector is mounted on the vaporizer unit to inject desired amount of fuel. The fuel vaporizer unit is heated by supplying electrical energy and a temperature control unit is employed to ensure the proper temperature so as to form a fuel-air mixture at lean condition.

An external circuit for steam addition was incorporated to inject steam into the intake manifold. Steam was generated in the steam generator and the required quantity of steam was passed manually through the valve and fed into the mixing chamber of the intake system. The quantity of steam is measured by using orifice and U-Tube manometer and the flow is controlled by steam valve.

Experimental Procedure

The experiments are carried out by running the engine on HCCI combustion mode using diesel fuel with steam addition percentages of 0%, 5%, 10% and 20% at engine loads with brake mean effective pressures of 1, 2.3, 3.4, 4.4 and 5.5 bars.

Table 2. Instrument uncertainty

Measured quantity	Uncertainty (%)
Specific fuel consumption	± 1.5
Power	± 0.5
Thermal Efficiency	± 1
NOx emission	± 0.2
CO emission	± 1.5
Unburned HC	±2.1
In-cylinder peak Pressure	± 0.5
Crank angle encoder	± 0.2

The percentage uncertainties for the measurement various parameters were determined by using the percentage uncertainties of corresponding instruments involved in the experimentation. The instrument uncertainties for various measured parameters have been calculated and are given in Table 2.

The total percentage of the uncertainty for the overall experiment is calculated with the help of principle of propagation of errors. From the values in Table 2, the overall uncertainty is determined as

$$e_R = [(1.5)^2 + (0.5)^2 + (1)^2 + (0.2)^2 + (1.5)^2 + (2.1)^2 + (0.5)^2 + (0.2)^2]^{0.5} = \pm 3.23$$

The overall uncertainty in the present experimental work is less than 5%. In order to minimize the random errors, an experiment was carried out thrice at a particular set of conditions.

RESULTS AND DISCUSSION

Combustion Parameters

In-cylinder pressure and temperature

Figure 2 shows results for the in-cylinder pressure variations within the cylinder with varying crank angle for the HCCI diesel engine for different percentages of steam injection. The maximum in-cylinder pressure was found to decrease with an increase in percentage of steam injection. An amount of heat released during the combustion is absorbed by the steam due to its high specific heat resulting in decrease in peak cylinder pressure. However in some cases with lower amount of steam addition, it is observed that the maximum combustion pressure is slightly increased with steam injection owing to better atomization and shorter ignition delay. It is found that the combustion duration is shortened while increasing the amount of steam addition resulting in the decline in power output. The initial addition of steam advances the auto-ignition of the homogeneous charge and thereby reduces the ignition delay. However, further increment in the amount of steam addition increases the ignition delay. It has been found that the steam addition of 20% has the better performance and the overall combustion deteriorates when the steam addition is increased further.

Apparent heat release rate

The results for the variation of apparent heat release rate with crank angle position are shown in Figure 3. As depicted from figure the apparent heat release rate decreases with an increase in percentage of steam injection. However there is a decrease in ignition delay with increase in the amount of steam addition. The minimum ignition delay was obtained with a steam addition percentage of 20%. It may be noted that further addition of steam increases ignition delay and also deteriorated the development of peak pressure. This trend in the decrease in ignition delay was similar to the findings of F. Hadia et al. [28].

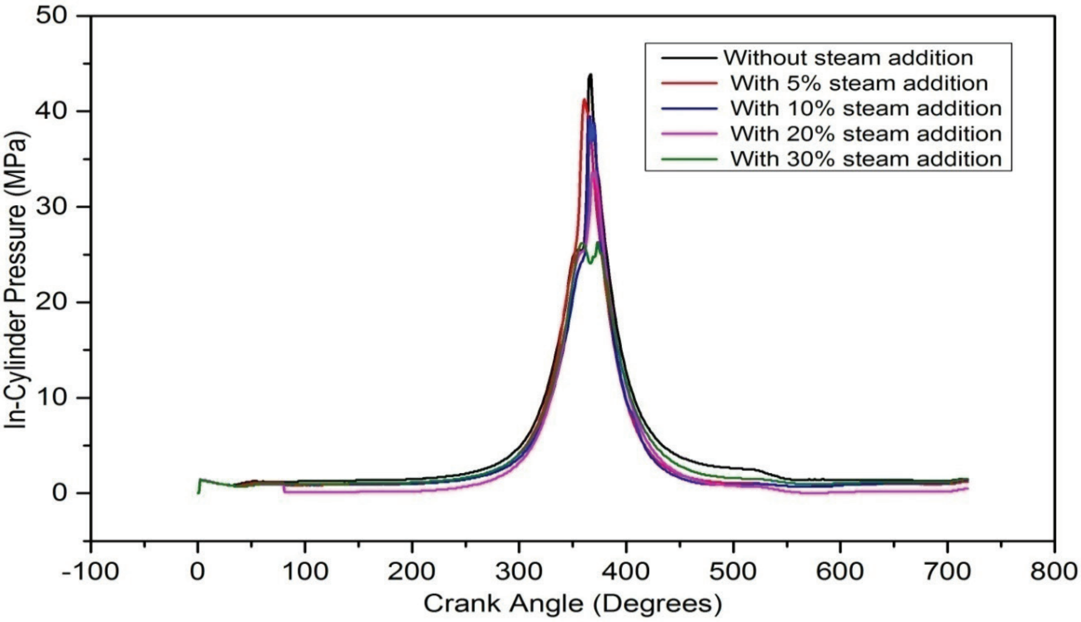


Figure 2. Experimental results for variation of cylinder pressure with crank angle position for various steam addition percentages.

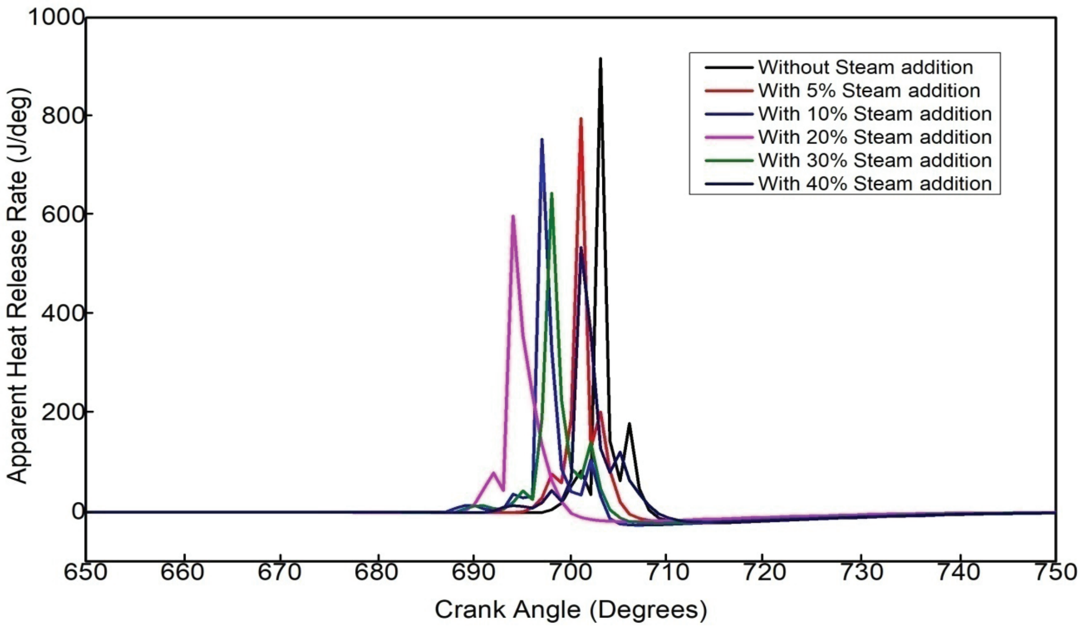
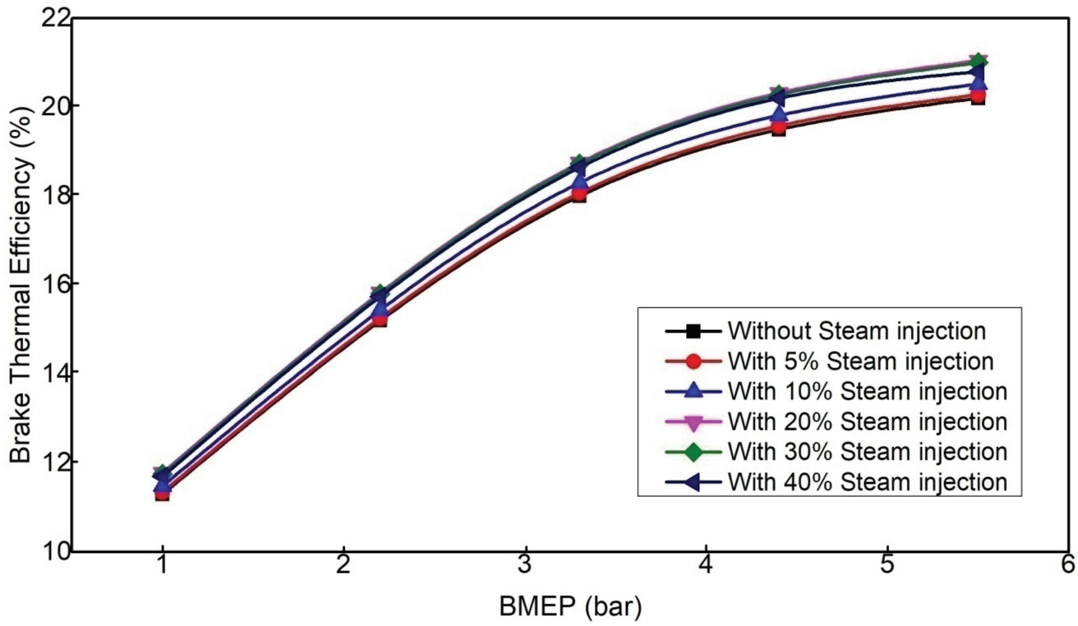


Figure 3. Results for variation of apparent heat release rate with crank angle position for different steam addition percentages.

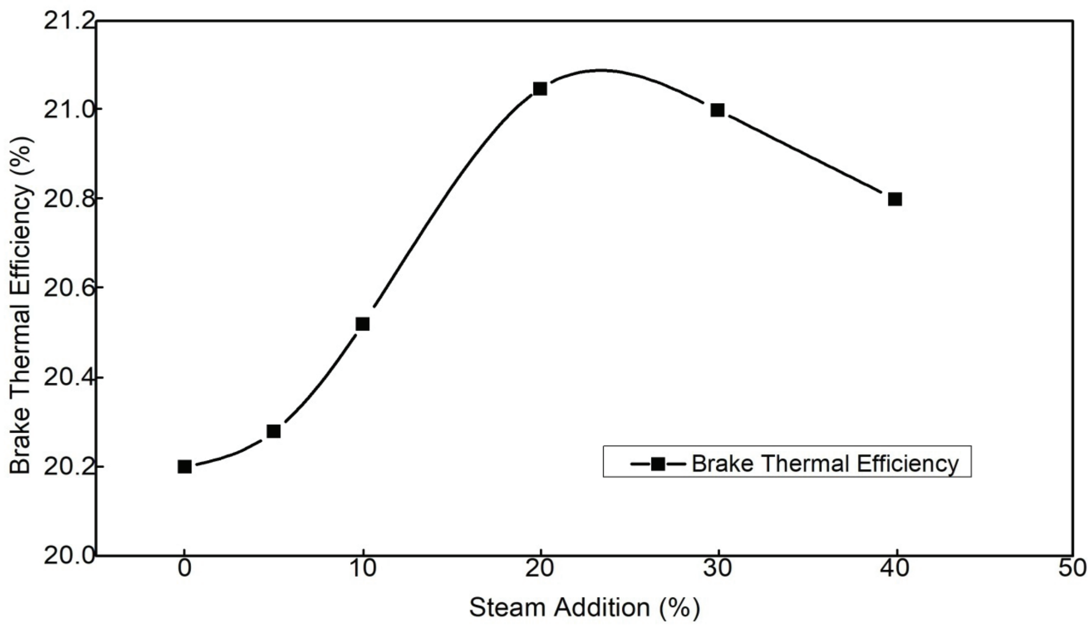
Performance Parameters

Brake thermal efficiency

Figure 4 (a) and (b) show the experimental results for the variation of BTE for the addition of different steam percentages with brake mean effective pressure and variation of brake thermal efficiency with the different steam addition percentages. In this investigation steam addition percentages of 5%, 10%, 20%, 30% and 40% were studied. The results show an improved brake thermal efficiency with the steam addition and the maximum brake thermal efficiency of 21.048% was achieved with a steam addition percentage of 20%. However further increase in the steam addition results in the deterioration of the efficiency and difficulty in combustion process. This improvement can be justified by three causes. One being the steam inducted into the intake manifold at a higher temperature of 140°C causing an increase in the inlet enthalpy of the engine. The other being the fine water droplets injected within the cylinder in contact with fuel may cause a very small surface stress.



(a)



(b)

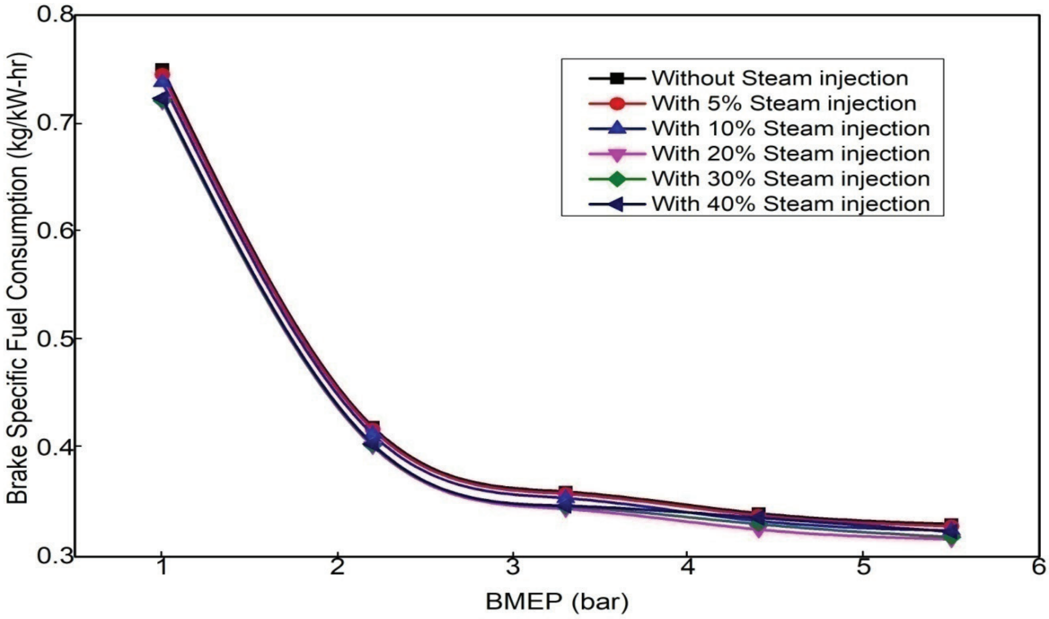
Figure 4. (a) Results for variation of brake thermal efficiency for different steam addition percentages with brake mean effective pressures. **(b)** Results for variation of brake thermal efficiency with different steam addition percentages.

Thus, the fuel in the cylinder is divided into much more fine droplets leading to a better fuel-air mixing owing to increased surface and better atomization with micro explosions. All these effects cause an increase in the combustion efficiency and thus increase the effective power and brake thermal efficiency.

The improvement in the brake thermal efficiency was also accompanied with a decrease in the brake power developed by the engine with an increase in steam addition percentage. It was observed that the brake mean effective pressure also reduced with an increase in the addition of steam percentage. The steam addition percentages beyond 20% were found to reduce the engine power significantly.

Brake specific fuel consumption (BSFC)

Figure 5 (a) and (b) show the variation of BSFC for different steam addition percentages with brake mean effective pressure and variation of BSFC with different steam addition percentages. The results show a slight improvement in the BSFC with the addition of steam in the inlet manifold of the engine. It is found that employing the steam



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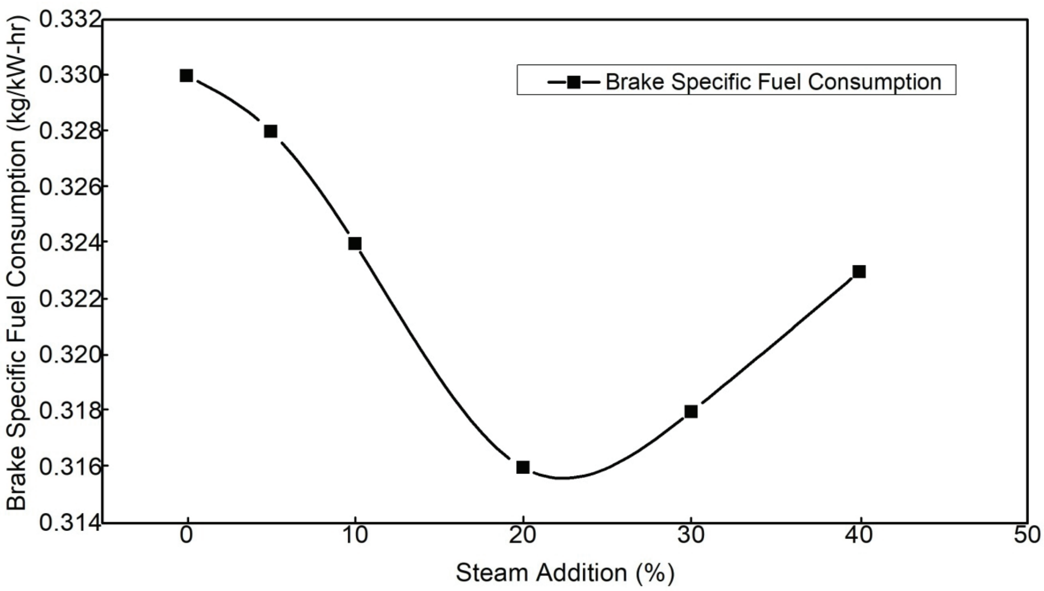


(b)

Figure 5. (a) Results for variation of brake specific fuel consumption for different steam addition percentages with Brake mean effective pressures. **(b)** Results for variation of brake specific fuel consumption with different steam addition percentages.

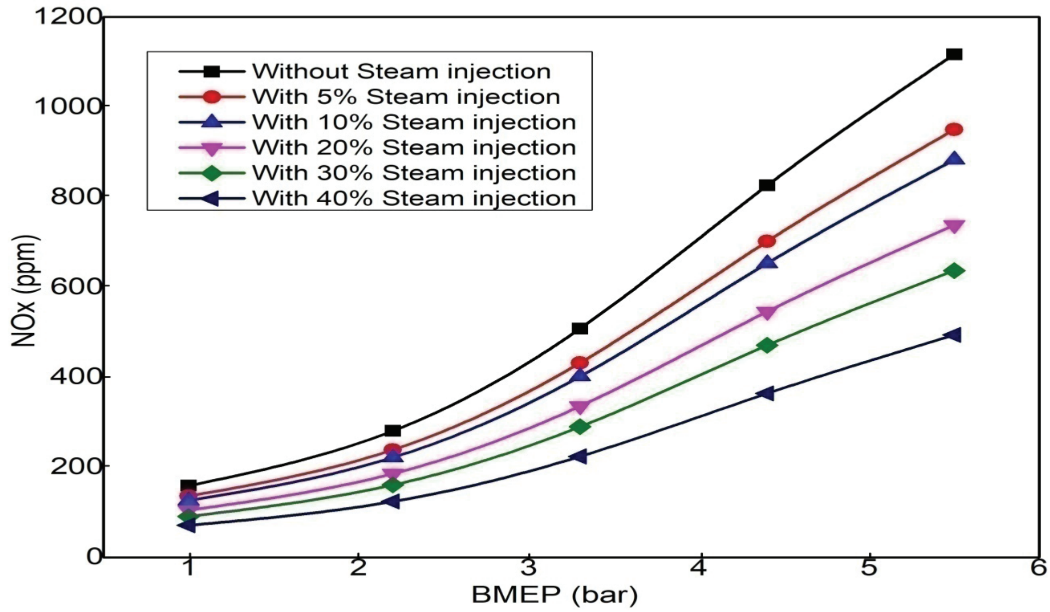
addition results in an increase in BTE with reduced BSFC. The reduction in BSFC can be attributed to the short combustion duration because of properly mixed homogeneous charge [28-30].

Another reason for the improved BSFC with the addition of steam may be due to the presence of oil-water interface having lower interfacial tensions leading to the fine atomization and increasing the contact of fuel droplets with the air. Depression of thermal dissociation may also be attributed to the reduction in BSFC.

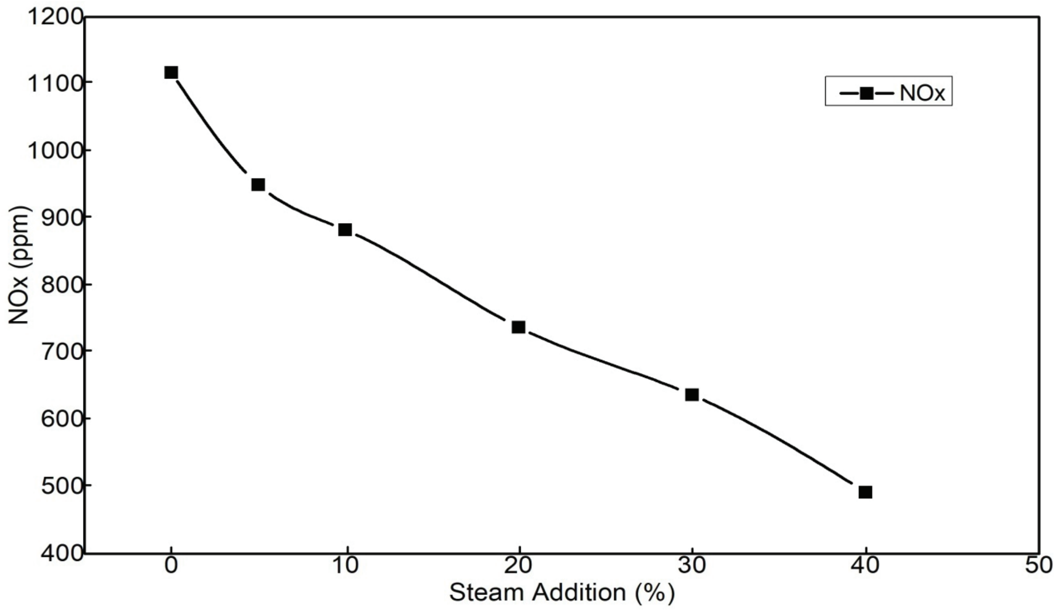
Emission Parameters

NO_x emissions

The NO formation rate is strongly dependent on the maximum in-cylinder temperature and the length of combustion duration at maximum temperature. When steam is added into the cylinder, the maximum temperature in the cylinder is reduced, thereby reducing the formation of NO and NO_2. Figure 6 (a) and (b) show the experimental results for the variation of NOx emissions for different steam addition percentages with brake mean



(a)



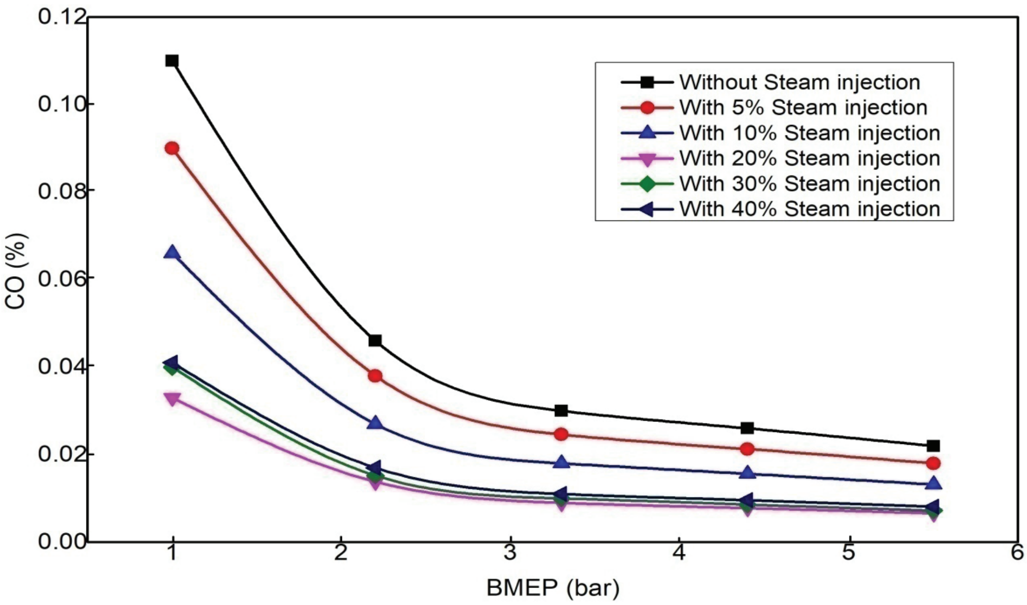
(b)

Figure 6. (a) Experimental results for the variation of NO_X for different steam addition percentages with brake mean effective pressures. **(b)**Experimental results for the variation of NO_X with steam addition.

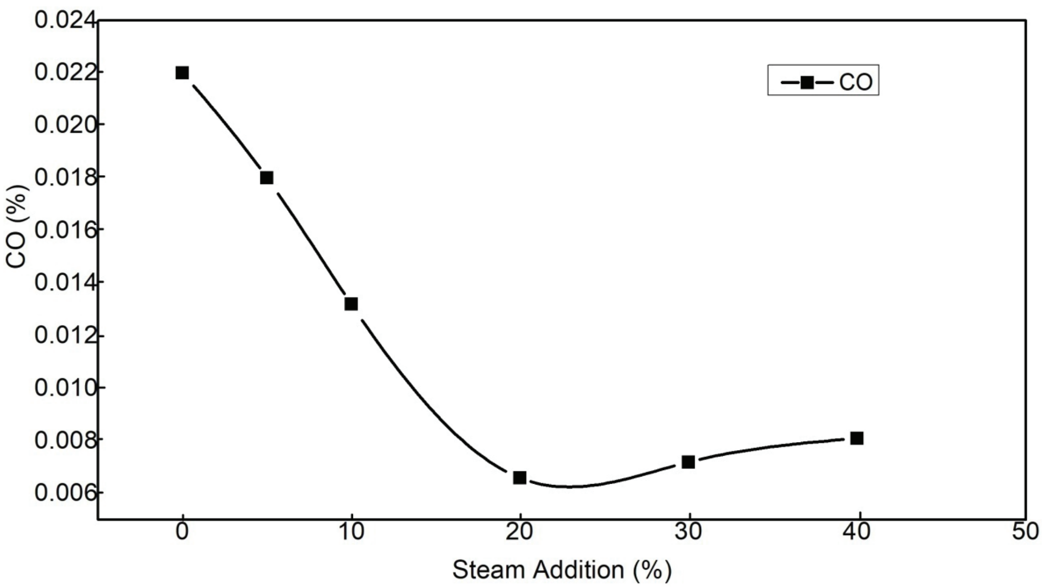
effective pressure and variation of NO_x emissions with steam addition percentages respectively. It is found that with an increase in the amount of steam addition there is a reduction in NO_x emissions. The reduced maximum combustion temperature due to relatively high molar heat capacity of water higher partial pressure of oxygen as well as the phase change during the combustion process results in a decline in the nitrogen oxides formation [31-34]. Improvement in the combustion efficiency mainly due to the micro-explosion phenomenon and reduced ignition delay leading to reduced combustion duration may also be attributed to the reduced NO_x emissions.

CO emissions

Figure 7 (a) and (b) show the results for the variation of CO emissions for various steam addition percentages with brake mean effective pressure and variation of CO emissions with steam addition percentages respectively. It can be observed from the results that the CO emissions are slightly reduced with increased steam addition quantity. The main reason being the improved combustion



(a)



(b)

Figure 7. (a) Experimental results for variation of CO for various steam addition percentages. **(b)** Experimental results for variation of CO for various steam addition percentages.

efficiency and properly mixed homogeneous mixture. The reduction in CO may also be attributed to the replacement of some fuel with the added steam due to reduced BSFC. The minimum CO emission was found with a steam addition percentage of 20%. There is a slight increase in the CO emissions when the steam is added beyond 20%. The main reason being the reduced combustion efficiency and increased BSFC.

Unburned hydrocarbons emissions

Figures 8 (a) and (b) show the experimental results for Variation of unburned hydrocarbons for various steam addition percentages with brake mean effective pressures and variation of unburned hydrocarbons with various steam addition percentages respectively. It was found that there is an improvement in the emission of unburned hydrocarbons with the addition of steam. The decrease in the emission of unburned hydrocarbons may be due to the

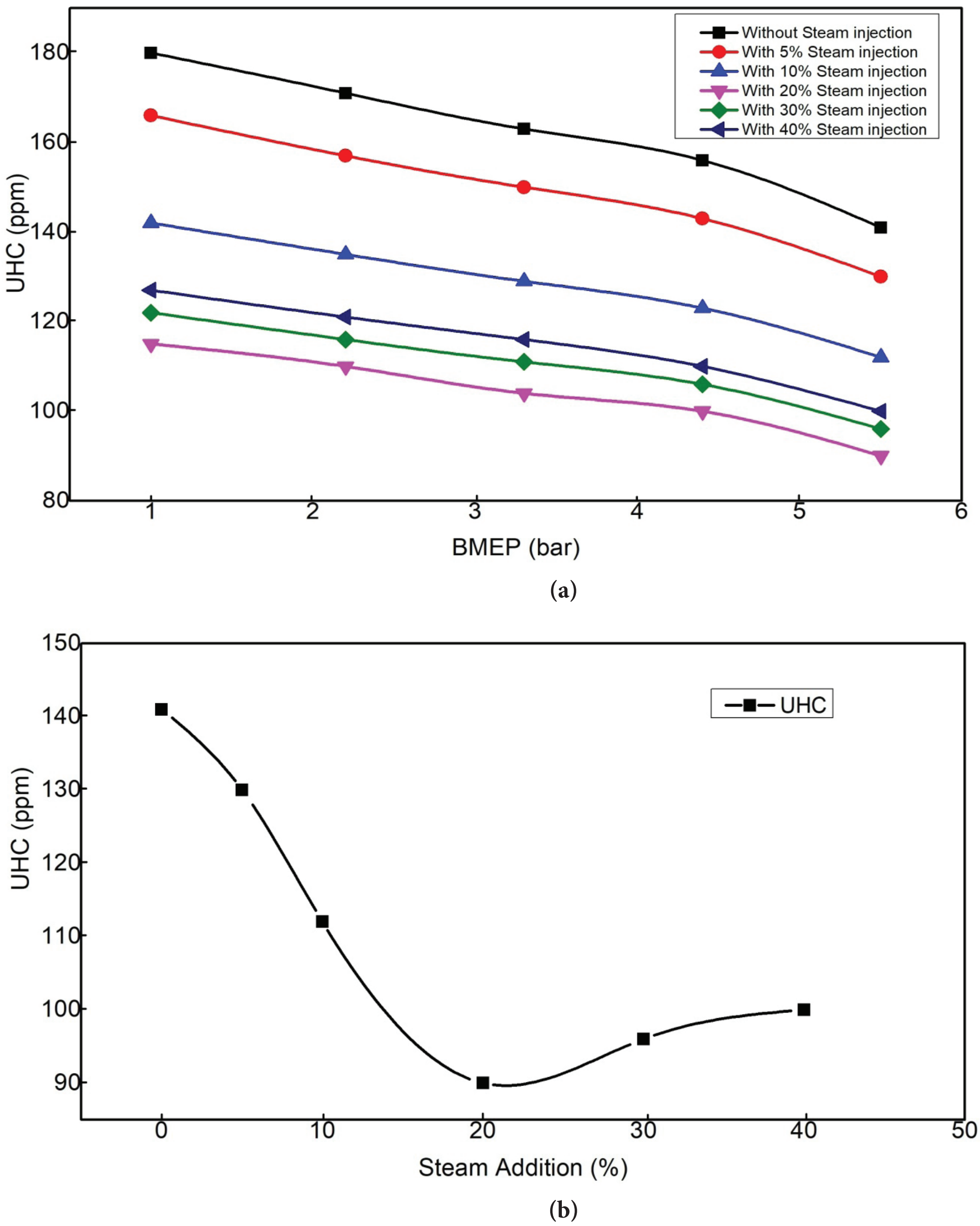


Figure 8. (a) Experimental results for variation of unburned hydrocarbons for various steam addition percentages with brake mean effective pressures. **(b)** Experimental results for variation of unburned hydrocarbons with various steam addition percentages.

complete combustion of the fuel during combustion process. The application of steam addition, the dissociation of water molecules may occur at higher combustion temperatures resulting in the formation of hydrogen and oxygen [35-41]. These oxygen atoms help in enhancing the oxidation of fuel. However it was found that the emission of unburned hydrocarbon was slightly deteriorated when the steam addition percentages were increased further beyond 20%. This increase in unburned hydrocarbon emissions may be attributed with the decrease in combustion efficiency and increase in BSFC. It follows that the variations in the emission ranges for standard and steam added HCCI engines remain within the limits of uncertainty while we consider the measuring accuracy.

CONCLUSION

In the current study, the effects of steam addition on the thermal and emission characteristics of a single cylinder HCCI diesel engine have been investigated computationally. The results obtained show that the brake thermal efficiency was improved to 21.048% with the addition of 20% steam addition. The NO_x emissions were also reduced significantly from 1100 ppm to 400 ppm. The emissions of CO and unburned hydrocarbon were found 0.7% and 93 ppm respectively at the steam addition rate of 20%, however a rapid increase was observed if the steam injection rate was increased further. Overall, the present work shows that by the addition of steam, the CO and unburned hydrocarbon emissions can be reduced significantly along with NO_x emissions and also there is a greater potential to control the start of combustion.

As a conclusion, steam addition is found to be an effective technique for reducing emissions and improving the performance of the diesel engines running on HCCI mode. HCCI technology has only recently acquired popularity and attracted automakers owing to a lack of supporting electronics and software in its early phases. The execution of the HCCI idea necessitates the development of several elements, including electronics, software, and materials. Thus, this technique could be implemented to the diesel engines in order to increase the usability of alternate fuels as a diesel engine fuel.

It is clear that this study could be used by the real-engine designers by considering the effects of steam injection into the inlet manifold of HCCI diesel engine.The execution of steam injection technique in HCCI engines necessitates the development of several elements, including electronics, software, and materials.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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