Impact on performance and emissions of the aspiration of algal biomass suspensions in the intake air of a direct injection diesel engine

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Abstract

Recently, the production of sustainable biofuels from algal biomass has gained significant attention and been investigated as a potential replacement of fossil fuel. However, existing downstream processes for producing biodiesel from algae cells are complex, highly energy-intensive, and have high economic and environmental cost. Therefore, this work introduces an alternative and novel method of utilizing the energy content of microalgae that precludes lipid extraction by aspirating wet algal biomass suspensions directly into the intake air of an IC engine.

For all engine experiments, powdered algae cells were prepared as slurries at different biomass concentrations. The impacts of (i) varying the biomass concentration with constant suspension injection flowrate into the engine intake and (ii) varying suspension injection flowrate with constant biomass concentration were investigated.

A correlation between engine work produced during combustion and algal biomass aspiration was found. At constant flowrate and greater than 5% biomass concentrations, an increase of energy release during combustion from the aspirated algae could be observed. However, the aspiration of low concentration biomass suspension produced a negative impact on engine performance relative to water-only aspiration. The engine exhaust gas of nitrogen oxides (NOx) was reduced for all algae suspension tests relative to diesel-only combustion. However, the carbon monoxide (CO) emission level was much higher relative to diesel-only tests at high biomass concentrations and injection flowrate.

These findings demonstrate the possibility of utilising the energy content of algal biomass in combustion without lipid extraction, with added benefits of reducing NOx emissions.

Keywords

Microalgae, biofuel, *Chlorella sorokiniana*, intake aspiration, combustion

1. Introduction

Fossil fuels have been used for centuries and have played a crucial role in human development. However, with greatly increasing consumption of fossil fuel, many issues are beginning to affect sustainable economic development and national energy security. The most serious issue is potential release of carbon dioxide from burning fossil fuel and the effects on climate change. To control this situation, it is not enough to only reduce the greenhouse gas (GHG) emissions, but also optimise the efficiency of energy consumption. Therefore, the development of new renewable energy sources and the reduction of carbon emissions are of key importance.

Biomass is a diverse source of renewable energy. Its development and utilisation cannot only help alleviate the increasing depletion of energy resources but can also reduce emissions of fossil fuel carbon dioxide (CO_2), the most produced greenhouse gas [1]. The combustion of solid, liquid and gaseous biomass fuels to generate electricity and steam/heat via high-efficiency and low-emission conversion processes has been developed successfully [2]. Recently, microalgae have gained increasing attention from researchers and policymakers as it is considered one of the most promising sources of biofuels for total substitution of fossil fuels. Compared with other sources of biodiesel such as soybean, rapeseed and sunflower seed, microalgae has several advantages. These organisms have a high growth rate, high lipid content and low requirement for nutrition. Meanwhile, the cultivation of microalgae does not compete with food production and can also absorb CO_2 from the atmosphere, thus contributing to an overall reduction of GHG emissions.

Microalgae can be used in many applications such as food supply, biofertilizer, water treatment, capture of NOx and COx from flue gas and medical researches [3]. The most important contribution of microalgae to the energy field to date has been through the exploration of the biodiesel production from the lipids contained within microalgae cells, which is a process consisting of many steps; from the cultivation and harvesting of algae to the oil extraction and conversion of algal lipids into biodiesel. The downstream processes (harvesting and transesterification) comprise almost 60% of the total economic cost of producing biofuel from microalgae and hence it is crucial to reduce this cost [4]. Harvesting contributes 20% to the total cost but this is dependent on the type of harvesting technology used and the density of the microalgal broth [4]. By using cell rupturing techniques such as freezing and treatment with organic solvents, oil extraction costs can be reduced. However, mechanical methods are not recommended since microalgal cell walls are too thick to allow efficient oil extraction [5]. Even if the oil is extracted, using methanol and an acidic or alkaline catalyst in the transesterification reaction also creates obstacles, such as the presence of toxic chemicals, which require removal or treatment ahead of solvent recovery and recycling.

Due to a need for the integration of multiple steps of processing including harvesting, extraction and conversion of biomass to biodiesel, the high cost associated with algae biofuel production has meant that its economic viability remains uncompetitive relative to petroleum or bioethanol. Therefore, to improve the economics of producing microalgae-based biofuels, the greatest challenge to overcome is the downstream process. There is potential therefore in developing alternative approaches to utilising algal biomass in internal combustion (IC) engine, which avoid conventional routes of downstream processing.

Utilising algal biomass with less processing intensity will inevitably result in the use of wet biomass or slurries with a significant water content. The concept of introducing water into the air fuel mixture of IC engines can be traced back to the early 20th century, and has been used for the reduction of combustion temperatures and control of NOx emissions [6]. The easiest way to inject water into an engine is inlet air water injection (WI), also known as intake air humidification or fumigation [7]. Samec and Dibble [8] investigated the effect of water injection into the intake air of a boosted diesel engine and the results indicated that both water injection locations, at the manifold port and upstream of the compressor, resulted in similar levels of NOx reduction as compared to a direct injection of a water/fuel emulsion with a 40% v/v water in diesel mixing ratio. Although the results of water injection have found to be promising in the reduction of NOx emission, it is important to avoid water condensation and accumulation in the intake manifold, and also corrosion problems in the cylinder.

The use of solid fuel dusts, for example coal, in diesel engines has a long history of use, dating back to the 19th century. Rudolf Diesel first investigated the use of dry coal dust in a compression ignition (CI) engine in 1892 but stopped due to the difficulties in the handling of a powdered fuel and subsequent fouling of the piston riongs and lubricating oil [9]. Rudolf Pawlikowski then improved the engine feed system by adding a co-chamber, which can pre-ignite the solid fuel before injecting it into the combustion chamber [10]. Several German companies developed low speed engines utilising solid fuel dusts, operating between 100 and 1000 rpm due to the slow burning rate of coal dust [9]. However, in all cases it was found that the flowrate of direct injection coal dust limited the engine speed and resulted in high engine wear. Therefore, to overcome these issues, later work focused on the use of coal slurries, which mix the coal powder with fossil fuel, known as coal diesel slurry (CDS) or water (coal water slurry) [11]. This allowed the conventional diesel injection systems to be used during experiments and reduce the cost of engine modification.

A coal/diesel slurry was first tested by Hanse, who investigated the combustion of a mixture of 20/80%wt coal/diesel slurry with a coal particle size of 45 – 75 µm and 124 bars injection pressure in a four-stroke Hill engine (model 4R) at 1200 rpm. Due to the employment of a commercial injection system, the blockage of the injector needle was significant [11]. Tracy reported on the use of a 30/70%wt coal/diesel slurry with less than 20 µm particle size tested in a single cylinder four-stroke diesel engine. While the reduced particle size improved the coal slurry injection rate and engine operation, the wear of the engine was still 35 times higher than when operated with conventional fossil diesel [12]. Considering the high NOx and particulates level in exhaust emissions and significant wear of engine of using CDS [9], recent researches have mostly focused on coal-water based slurry (CWS) in IC engines.

Tataiah and Wood performed experiments on a four-cylinder Mercedes diesel engine with CWS in 1980. The results showed that the engine efficiency decreased at high speed and load, and higher emissions of CO and particulates, but lower NOx, were obtained when compared with pure diesel operation [13]. Dunlay et al. conducted tests with CWS (34% coal) on a 2-stroke Sulzer Bros crosshead diesel engine (model 1RSA76) and found out that the thermal efficiency is close to the results of pure diesel. However, the injector wear was significant due to slurry accumulation during the cold start of the engine [14]. In 2004, Wilson [15] from TIAX LLC company ran a Colt Pielstick PC2.6 two cylinder engine with a Kentucky coal-based CWS for one hour with no major problems. As an alternative to using coal slurry, Soloiu et al. [16] studied the use of a 10 μm charcoal slurry (25% by weight) on a Yanmar Nf-19 engine and found engine performance very similar to that with diesel, and net heat release even higher than in the case of pure diesel operation.

During the same period, the intake air aspiration of coal dust into a CI engine, with continued direct injection of diesel fuel, was also investigated. Marshall and Shelton operated a 1400cc Nordberg diesel engine at 1750 rpm with coal dust intake aspiration for 45 hours, and the results showed several issues, including significant wear, crankcase oil contamination and an efficiency drop [11]. Rich and Walker continued this study but at a lower speed of 1000 rpm and found thermal efficiency to drop from 27% (pure diesel) to 11% (diesel and coal dust) [11]. Between 1989 and 1994, Adiabatics Incorporated company tested dry coal dust and coal slurry with a Thermal Ignition Combustion System (TICS), which was developed by Kamo et al. [17] to enable better control of the engine speed and load through more precise delivery of the coal dust and lower the injection pressure and nozzle wear. This system achieved improved engine performance than previous tests through the direct injection of coal dust via the TICS system.

The physical similarities in the particle size of the coal dust and algae powder makes it a suitable candidate as a source of fuel for combustion engines. However, there is no report of the use of algal biomass as a slurry in this way. This paper presents a novel method of utilising algal biomass directly as a second fuel source for an IC engine, through the engine testing of intake air aspirated algae slurry with a variety of biomass concentrations and injection flowrates.

2. Experimental Methods

2.1 Preparation of algal biomass slurry

A wild type strain of *Chlorella sorokiniana* was obtained from the Chinese Academy of Tropical Agricultural Sciences. Algae cells were cultivated in Tris Acetate Phosphate (TAP) medium and spray dried (200 °C inlet and 82 °C outlet) to remove all the water content in and outside of the cells. The biomass suspensions was blended with Reverse Osmosis (RO) water and prepared in four concentrations: 5%, 7.5%, 10% and 20% (w/v). All the suspensions were properly mixed in 1L beakers on a magnetic stirrer and then transferred into 1L Duran bottle.

2.2 Apparatus

The single cylinder direct injection diesel engine used for all experiments was based on a 2L Ford Duratorq head, with the original combustion chamber geometry preserved and a compression ratio of 15.8:1. The specification of the research engine and associated system has been described previously in further detail [18]. The engine was operated naturally aspirated and the intake pipe modified to mount a liquid spray gun 250 mm upstream of the engine intake valve and deliver the water and biomass slurry into the engine intake manifold.

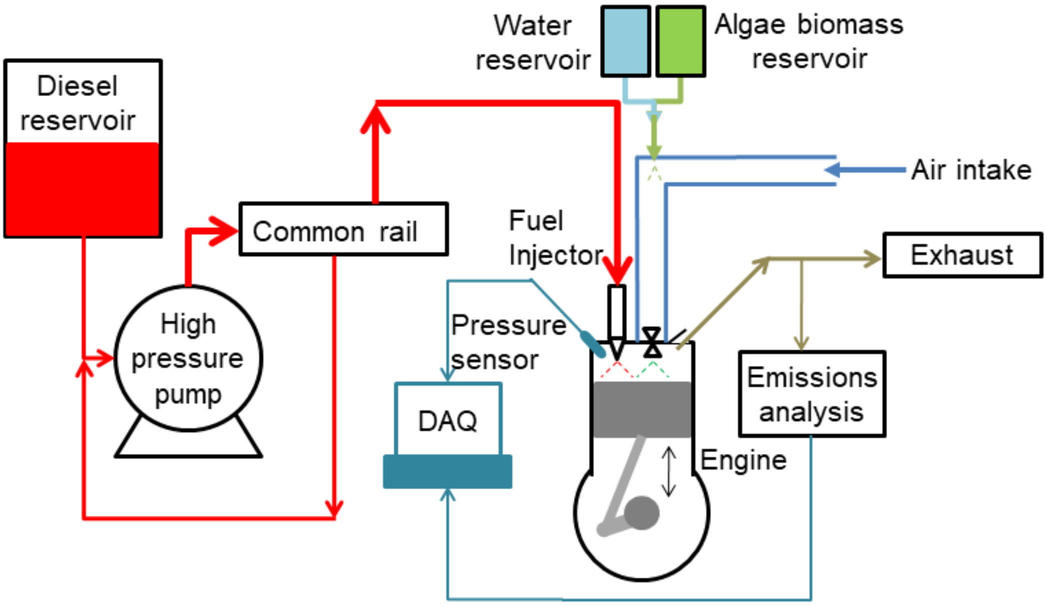


Figure 1. Schematic showing operation of the algal biomass aspiration system and test engine set-up.

A schematic of the algae aspiration system is shown in Figure 1. The spray gun was utilised with a supply of compressed air at 1.2 bar, and was gravity fed, necessitating that two reservoirs for RO water and algae suspensions respectively were installed 200mm above the spray gun, isolated with two independent control valves. This allowed the injection system to be flushed with RO water between every test run. The spray nozzle was modified to produce a circular spray pattern. Further details of the engine and control apparatus are given in Table 1.

During the experiments, several parameters were controlled and recorded by a PC data acquisition system (National Instruments). A piezoelectric pressure transducer (Kistler 6056AU38) with charge amplifier (Kistler 5011) was used for measuring and logging the gas pressure in the engine cylinder at every 0.2 crack angle degree (CAD). A piezoresistive pressure transducer (Druck PTX 7517-3257) was installed in the intake manifold (at 160 mm upstream of the intake valves) to measure the in-cylinder pressure at bottom-dead-centre of every combustion cycle. The same PC data acquisition system utilised for logging in-cylinder pressure was also used to measure various control and experiment temperatures using K-type thermocouples. The net apparent heat release rate was derived from the in-cylinder pressure (MATLAB) measured during post-processing, using a one-dimensional and one-zone model assuming homogeneity and ideal gas behaviour of the cylinder contents.

Engine head model	Ford Duratorq
Engine bottom end model	Richardo Hydra
Number of cylinders	1
Cylinder bore	86mm
Crankshaft stroke	86mm
Swept volume	499.56cc
Compression ratio	15.8:1
Maximum cylinder pressure	150 bar
Peak motoring pressure at test conditions	45 bar
Piston design	Central ω-bowl in piston
Oil temperature	80 ± 2.5 °C
Water temperature	80 ± 2.5 °C
Fuel injection pump	Single-cam radial-piston pump (BOSCH CP3)

Injectors	6-hole solenoid controlled (DELPHI DF1 1.3)
Electronic fuel injection system	1 µs accuracy (EMTRONIX EC-GEN 500)
Shaft encoder	0.2 CAD resolution

Table 1. Engine specification

Exhaust gas sampling occurred 180 mm downstream of the exhaust valves to determine concentrations of gaseous species. Gaseous species (CO, CO_2 and NOx) sampled via a heated line, were measured by an automotive gas analyser system (Horiba MEXA 9100 HEGR).

2.3 Experimental conditions

Due to the changing viscosity of the water and algae suspension with varying biomass content, and in order to maintain a constant injection volumetric flowrate for all experiments, the spray gun was calibrated by adjusting the release valve and measuring the actual volumes of water and biomass suspension sprayed out during 1 minute. This calibration procedure was conducted before every test. The water and algae suspensions were delivered into the engine intake air with flowrates of 40, 49.2, 56 ml/min. During the tests, the engine was set to a constant speed of 1200 rpm and constant start of diesel fuel direct injection (SOI) of 5 CAD BTDC (before-top-dead-centre). The injection duration was varied as necessary to maintain a constant engine indicated mean effective pressure (IMEP) of 4 bars when operated with a reference RO water only aspiration at an injection flowrate of 40, 49.2, 56ml/min. Water only tests were used to establish a baseline to investigate the effect of aspirating algae suspension on engine performance and emissions.

3. Results and Discussion

3.1 Effects of algal biomass concentration in aspirated suspensions on combustion and emissions

In order to investigate the impact of the aspirating algae cells directly into the air intake on the efficiency of combustion and emissions levels in a diesel engine (Section 2.2), dry algae powder (*C. sorokiniana*) was utilised to form a algal suspension with reverse osmosis (RO) water containing 5% w/v, 7.5% w/v, 10% w/v and 20% w/v dry algal biomass. A reference RO water was also prepared with no biomass content.

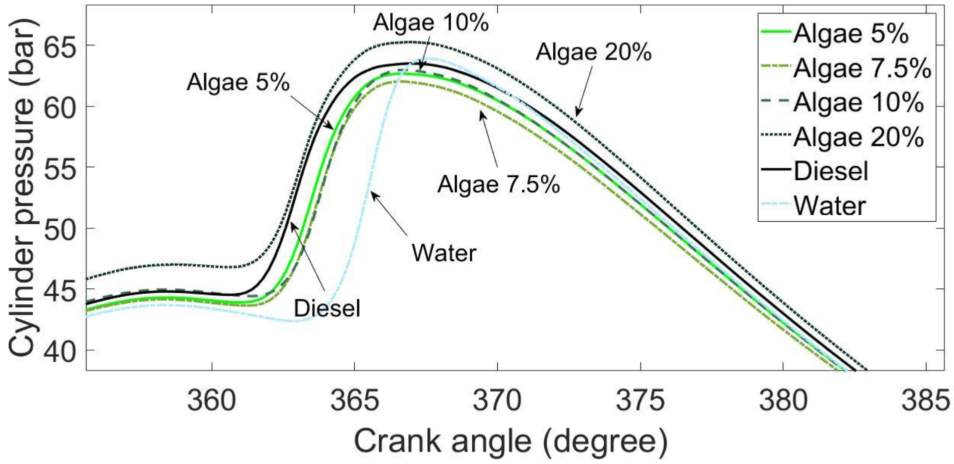


Figure 2. In-cylinder pressure with aspirated algal biomass suspensions of varying mass concentration

Figure 2 shows the in-cylinder pressure during direct injection diesel operation with intake air aspiration of varying concentration of algal biomass water suspensions and direct injection diesel operation without any water or suspension aspiration into the air intake at constant injection timing. It can be seen that the in-cylinder pressure rises due only to compression, and before the start of combustion, it is somewhat higher in the case of the aspiration of the algal biomass suspension with 20% biomass concentration. The manifold temperature reduced from an average of 37^{o}C for all other tests to 19^{o}C, suggesting the increased compression pressure to be likely attributable to an increased density of the intake air. In the case of water only aspiration, peak in-cylinder pressure occurs much later than diesel only and all the algae suspensions conditions result in lower peak in-cylinder pressure than fossil diesel only.

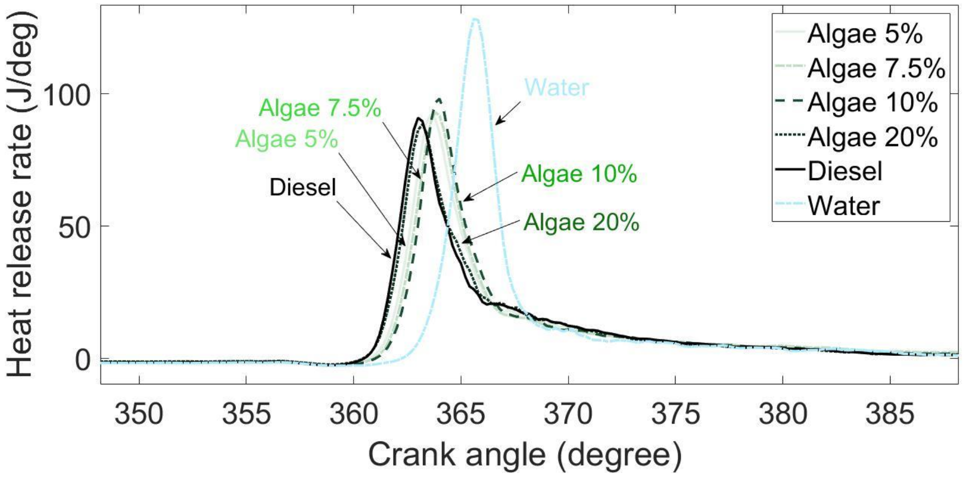


Figure 3. Apparent net heat release rate with aspirated algal biomass suspensions of varying concentration

Figure 3 shows the apparent net heat release rate (HRR) of varying algal biomass concentration suspensions aspiration and also fossil diesel only. It can be seen that at all conditions, combustion was predominate premixed, especially apparent in the case of water only aspiration. Meanwhile, following peak heat release rates during the premixed combustion phase, HRR in the case of aspiration of 20% algal biomass suspension has the trace most similar to diesel only and it also drops fast in the water only condition relative to other cases. It is likely due to the large number of algae cells in the suspension helped to maintain the premixed burn fraction and results in a similar diffusion-controlled combustion and HRR as diesel only.

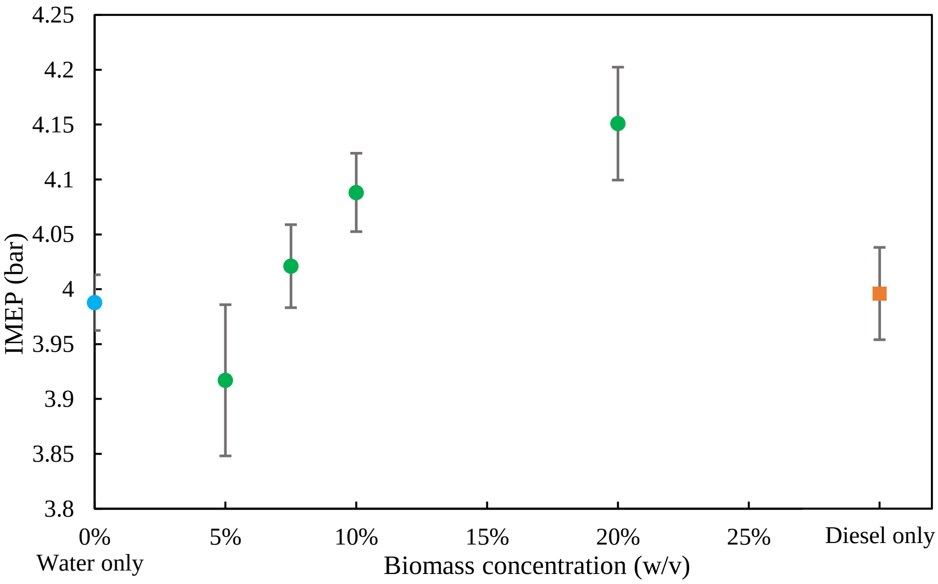


Figure 4. Engine IMEP with aspirated algal biomass suspensions of varying concentration. The error bars presented show plus and minus the standard deviation from the mean value.

Figure 4 shows the effect of varying the algal biomass concentration of the intake aspiration suspensions while maintaining a constant duration of fossil diesel direct injection on engine IMEP, and also reference fossil diesel without any water or suspension aspiration and where the diesel fuel injection duration was adjust to achieve an engine load of 4 bar IMEP. Immediately apparent in Figure 4 is an increase in engine IMEP with the biomass concentration of the aspirated suspensions. It can be seen that the 20% algae suspension resulted in the highest engine IMEP, and that from a biomass concentration of 5% to 20%, there is a linear increase in the engine IMEP with an increase of biomass content. However, also apparent is a decrease in IMEP at 5% algae content relative to water only (0%) aspiration. Notwithstanding this decrease with a 5 % biomass concentration suspension, this cautiously suggests that an increase in the concentration algal cells results in more useful energy towards the engine output.

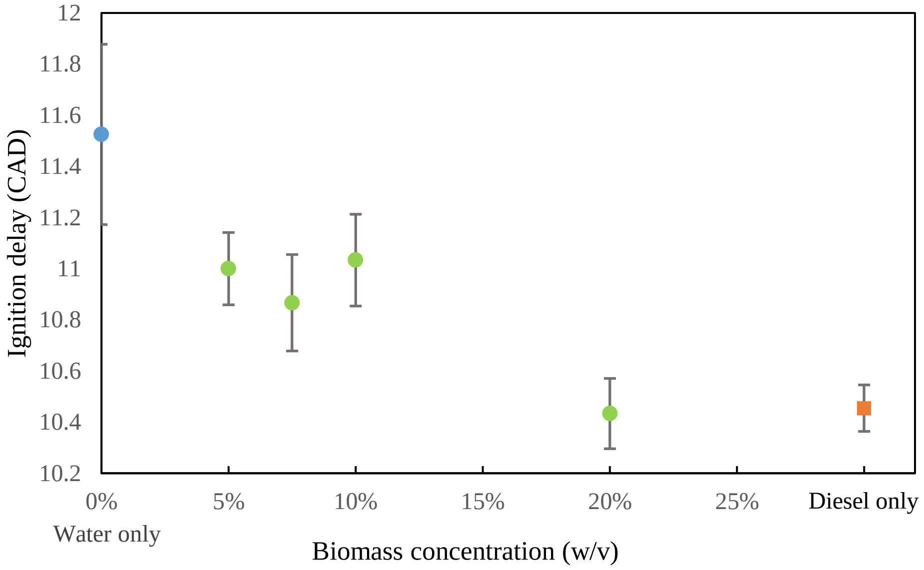


Figure 5. Ignition delay duration with aspirated algal biomass suspensions of varying concentration. The error bars present show plus and minus the standard deviation from the mean value.

Figure 5 shows the ignition delay during combustion with the aspiration of algae water suspension of varying biomass concentration into the engine intake air, and also that of reference diesel direct injection without water or suspension aspiration. The ignition delay is defined as the time between start of ignition (SOI) and start of combustion (SOC), where SOC is the incidence of positive heat release observed after SOI. It can be seen in Figure 5 that aspiration of all of the suspensions into engine, except that with 20% algae content resulted in a longer duration of ignition delay relative to diesel only. This is likely attributable to the water present in the algae suspension, which absorbs heat from the in-cylinder charge on evaporation and results in a higher specific heating value, reducing temperatures at TDC and slowing the rates of diesel low temperature branching reactions which culminate in fuel autoignition [19]. Notwithstanding the range of error present, it is interesting to note that an increase in the biomass suspension concentration appears to result in a reduction in the duration of ignition delay. It is anticipated that potential energy release from the aspirated biomass would only occur following autoignition of the fossil diesel, and so it is tentatively suggested that this effect of the aspirated biomass may in fact be through changes in local temperature distribution and heat transfer.

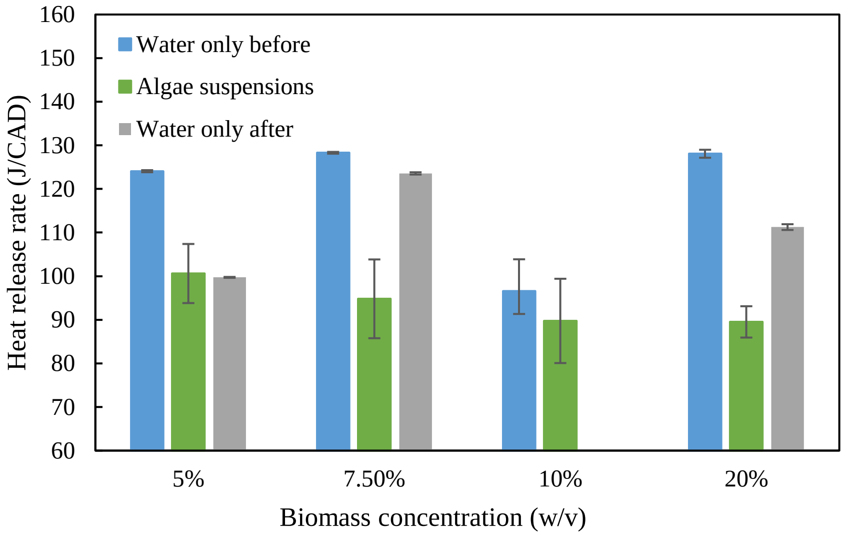


Figure 6. Peak heat release rate with aspirated algal biomass suspensions of varying concentration. The error bars present show plus and minus the standard deviation from the mean value.

Figure 6 shows the impact of varying the biomass concentration aspirated through the air intake on peak heat release rates, and also that from water only aspiration immediately before and after each test of algae suspension. In the case of 10% algal biomass aspiration, the water only test result after algae test could not be recorded due to the biomass accumulated inside engine after long period running and abnormal noise was detected during the operation. To ensure that the experimental conditions were consistent during each biomass aspiration test, the engine was operated with direct injection diesel only for several minutes after water only tests until the IMEP stabilised at 4 bar with same diesel fuel injection duration as previously observed. Apparent in most instances in Figure 6, is a reduction in peak heat release rate with aspiration of the algal biomass suspensions relative to water only, likely attributable to a smaller premixed burn fraction where a reduced duration of ignition delay (Figure 5) decreased the time available for fuel and air mixing prior to the start of combustion. Meanwhile, in the case of all biomass concentrations, results of water only tests before algae aspiration are always higher than those immediately after, which is suggestive of a possible accumulation of algal biomass in the engine intake system during aspiration as the manifold was only been cleaned after each change of algae concentration. Additional, aspiration of water only will also cause a side effect on the engine, but it was eliminated by running with fossil diesel only for at least ten minutes. This is to allow the IMEP to recover with the same injection duration.

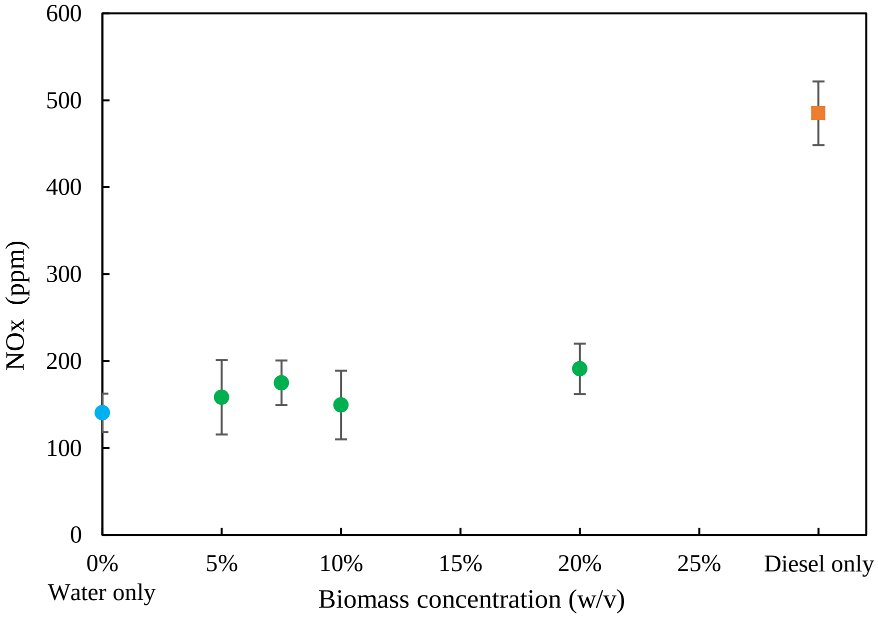


Figure 7. NOx exhaust emission level with aspirated algal biomass suspensions of varying concentration. The error bars present show plus and minus the standard deviation from the mean value.

Figure 7 shows the effect of varying algal biomass concentration on levels of NOx in the exhaust gas. It is clear to see that water only has the lowest NOx exhaust level and that there is a small increase with increasing biomass concentration. In all cases of intake aspiration, the level of NOx is much lower compared to diesel only. The formation of NOx during combustion in a diesel engine is related to the rates of thermal oxidation of nitrogen and has a strong positive correlation with in-cylinder temperature and peak heat release rates [20]. However, in Figure 2, it can be seen that in most cases intake aspiration resulted in a higher PHRR than the reference fossil diesel only, which exhibited the highest NOx exhaust level. Therefore, it is suggested the higher rates of heat release were insufficient to overcome the significantly lower in-cylinder temperatures as a result of the water evaporation and higher specific heat capacity of the in-cylinder charge [21].

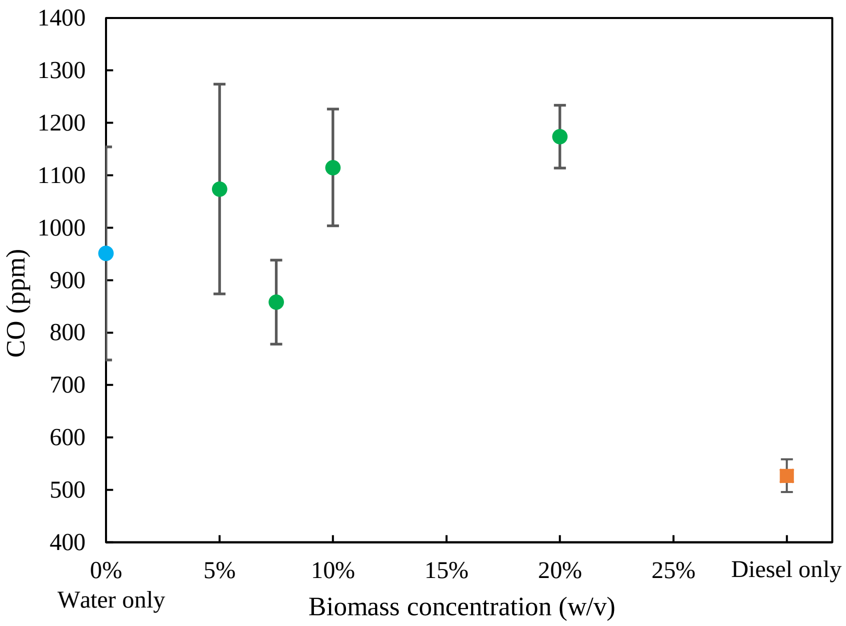


Figure 8. CO exhaust emission level with aspirated algal biomass suspensions of varying concentration. The error bars present show plus and minus the standard deviation from the mean value.

Figure 8 shows the effect of varying algae content suspensions aspirated via the air intake on exhaust gas levels of CO. Notwithstanding, the range of error shown, Figure 8 shows that with aspiration of water or algae suspensions, CO levels increased significantly relative to diesel only. A similar result of an increase in CO emissions during the combustion of water/diesel emulsion was observed in a study by Vigneswaran et al. [22]. This is likely attributable to the lower in-cylinder temperatures during water or suspension aspiration, as indicated by reduced levels of NOx emissions (Figure 7), resulting in higher levels of incomplete combustion.

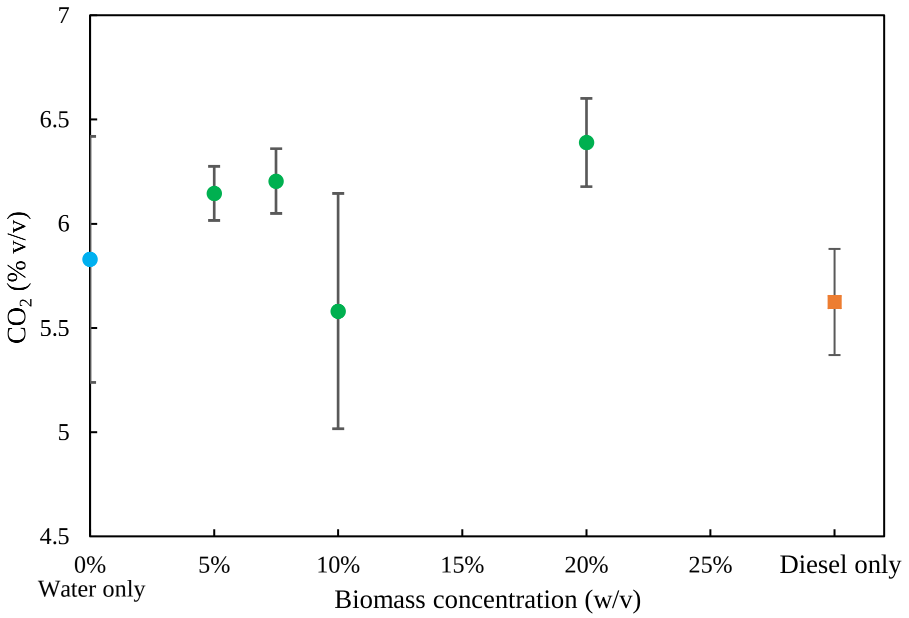


Figure 9. CO$_2$ exhaust emission level with aspirated algal biomass suspensions of varying concentration. The error bars present show plus and minus the standard deviation from the mean value.

Figure 9 shows the level of CO$_2$ in the exhaust gas with the aspiration of varying biomass concentration suspensions into the engine intake air. In order to maintain a constant load of 4 IMEP, a longer injection duration under the water only condition relative to diesel only combustion was required, and a concurrent increase in CO$_2$ levels can be seen in Figure 9. Notwithstanding the values of CO$_2$ recorded in the case of the 10 % w/v algae suspension, it is tentatively suggested that levels of CO$_2$ increased with biomass suspension concentration, in agreement with increasing IMEP (Figure 2), possibly attributable to greater combustion efficiency or the presence of more algal biomass available for combustion.

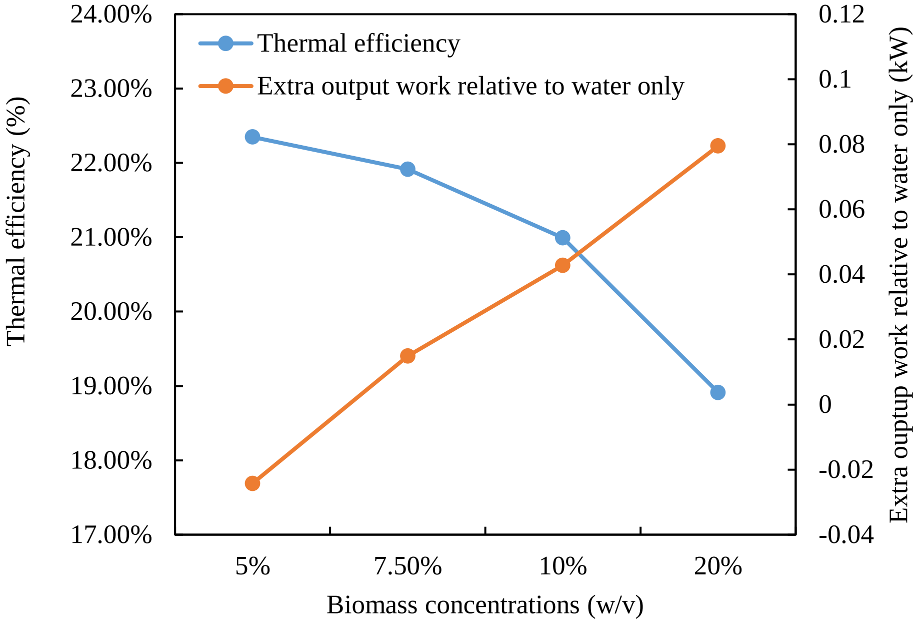


Figure 10. Thermal efficiency of diesel engine and extra output work relative to water only with aspirated algal biomass suspensions of varying concentration.

Figure 10 shows the impact of aspirated concentration of algal biomass suspensions on thermal efficiency of diesel engine and extra output work compared with water only condition. It can be seen that a reduction of thermo efficiency occurred with an increasing of the biomass concentration. With the increasing of CO emission relative to water only test (Figure 8), it suggests that more incomplete combustion occurred and decrease of the combustion efficiency during the algae combustion. Meanwhile, the extra output work from algal biomass was increased by increasing the biomass concentration and reached 0.8 kW relative to water only with 20% biomass concentration. However, 5% biomass concentration gave a negative impact on total engine output and the energy inputs from 7.5%, 10% and 20% algal biomass were 1.12, 1.5, and 2.99 kW (assuming 5% lost during combustion), which the extra outputs were only equivalent to 1.33%, 2.86% and 2.65% respectively of additional energy provided from algae.

3.2 Effects of algal biomass injection flowrates in aspirated suspensions on combustion and emissions

Following the engine tests of aspirated algal biomass suspensions with varying concentration, experiments investigating the aspiration of algal biomass suspension with varying injection flowrate (40, 49.2, 56 mL/min) were conducted with a constant biomass concentration of 5% w/v. Reference tests of water only and diesel only were also conducted.

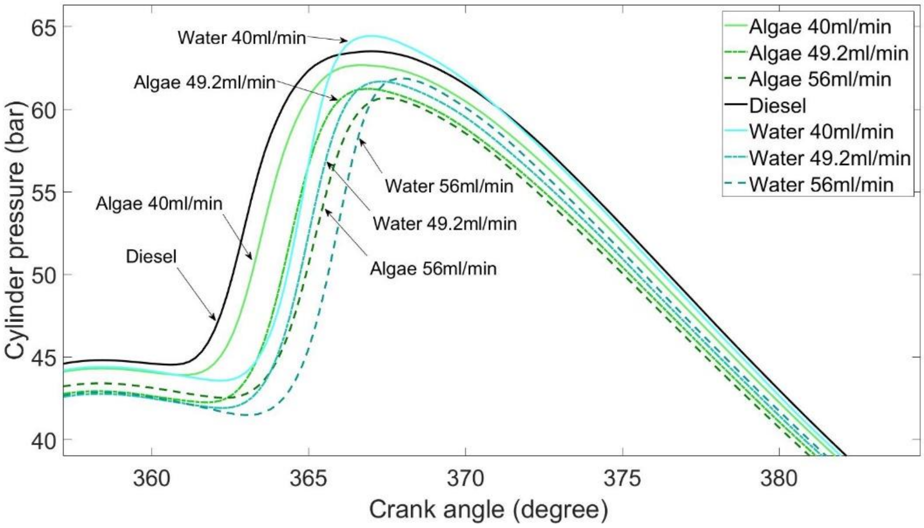


Figure 11. In-cylinder pressure with aspirated algae biomass suspensions and water of varying flowrate

Figure 11 shows the in-cylinder pressure of varying injection flowrate of aspirated algae suspension at 5% biomass concentration, and water only, at constant fuel direct injection duration. Except in the case of 40 ml/min water only, peak in-cylinder pressure occurs much later and is lower relative to diesel only. A flowrate of 56 ml/min algae suspension gives the lowest peak in-cylinder pressure, suggesting that the engine output was reduced due to the lower compression pressure achieved caused by the high flowrate of algal biomass aspiration.

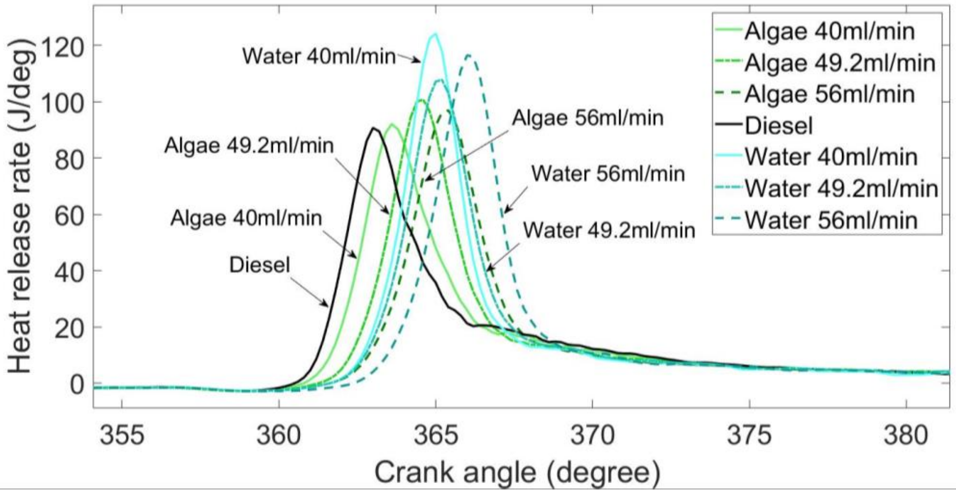


Figure 12. Apparent net heat release rate with aspirated algae biomass suspensions and water of varying injection flowrate

Figure 12 shows the apparent heat release rates of water and 5% biomass content suspensions aspiration at variable injection flowrates, and fossil diesel only. It can be seen from Figure 12 that premixed combustion dominates in all cases and algae suspension. In the case of 40 mL/min algae biomass aspiration, HRR reduces more slowly after reaching a peak heat release rate relative to algal biomass suspensions at higher flowrates, and water only. This suggests that an increase in water flowrate increases the premixed burn fraction, and thus there is a much smaller diffusion-controlled combustion and so a more abrupt decrease in HRR.

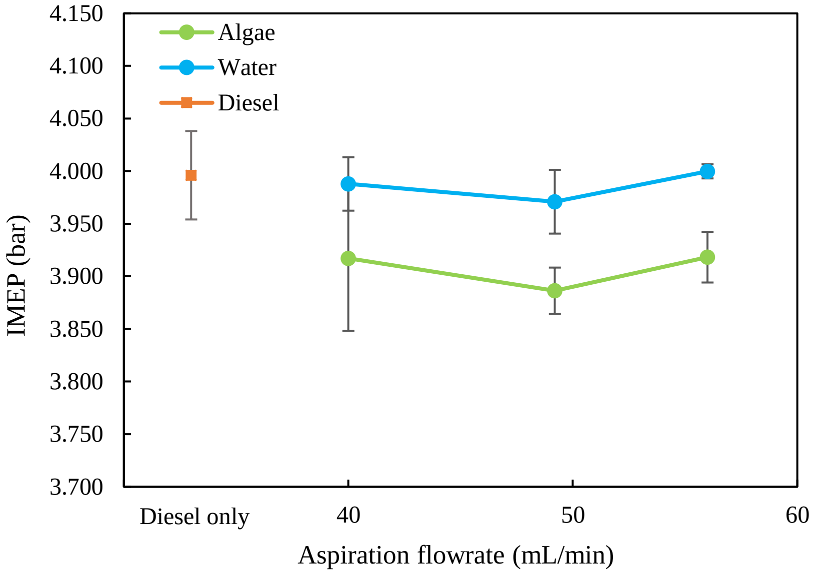


Figure 13. Engine IMEP with aspirated algae biomass suspensions and water of varying injection flowrate. The error bars present show plus and minus the standard deviation from the mean value.

Figure 13 shows the effect of varying the algae biomass and water injection flowrate of the intake aspiration suspensions while maintaining a constant duration of fossil diesel direct injection on engine IMEP. It can be seen that for the water only condition, the duration of diesel injection duration was increased to remain at 4 IMEP, and so there was no apparent effect of changing the flowrate of water only aspiration. Meanwhile, the aspiration of 5% algal biomass consistently reduced IMEP relative to diesel and water only cases, where the duration of diesel injection was kept constant. In addition, the exhaust gas temperatures in the cases with algae present had an average 15 °C increase relative to the water only case, which indicates that with 5% algal biomass content, combustion of the algal suspensions resulted in a greater amount of energy lost in the exhaust. However, no clear effect of increasing injection flowrate under constant algal biomass concentration condition could be seen, despite an anticipated change in the levels of suspensions present per combustion cycle.

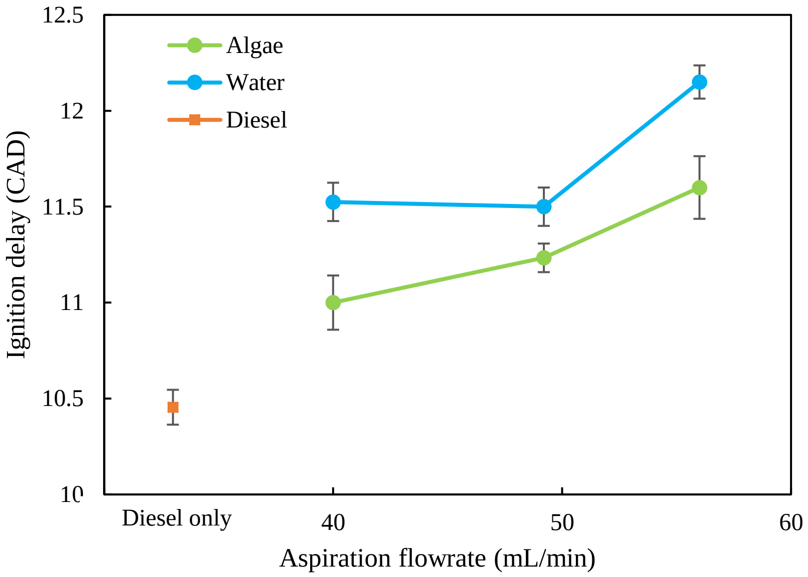


Figure 14. Ignition delay duration with aspirated algae biomass suspensions and water of varying injection flowrate. The error bars present show plus and minus the standard deviation from the mean value.

Figure 14 shows the ignition delay during combustion with the aspiration of algae suspension and water only of varying injection flowrate into the engine intake air. It can be seen from Figure 14 that aspiration of the algal biomass suspension and water both resulted in an increase in ignition delay relative to diesel only. Similar results were observed in Zhao et al.'s research, where the ignition delay increased with the injection of liquid water at intake port of a diesel engine [23]. Furthermore, an increase in the flowrate of either further increased the ignition delay; this is to be expected as a higher flowrate of water or suspension would increase the level of in-cylinder cooling. However,at a constant injection flowrate, water only results in longer ignition delay than algae suspension. This is due to the algae cells displacing water and increasing the suspension density relative to water only, so the level of water present in-cylinder is relatively less than water only condition and therefore resulted in reduction of ignition delay.

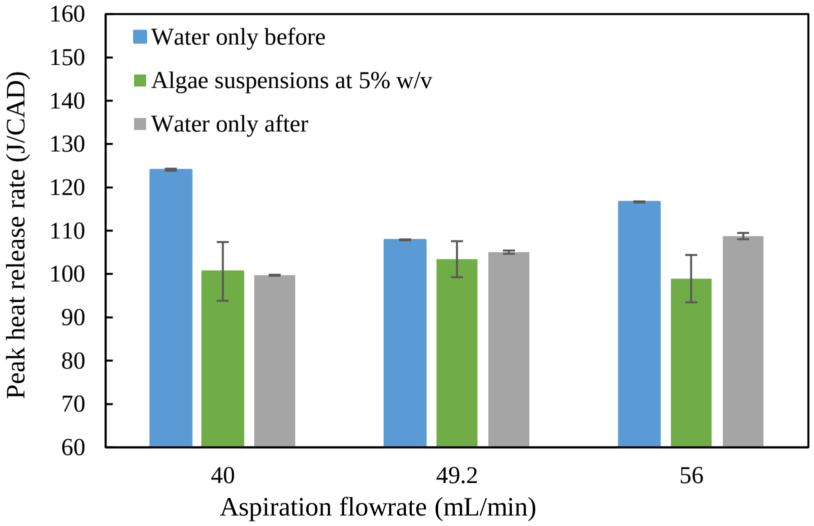


Figure 15. Peak heat release rate with aspirated algae biomass suspensions and water of varying injection flowrate. The error bars present show plus and minus the standard deviation from the mean value.

Figure 15 shows the impact of variable flowrate of algal biomass and water immediately before and after algae combustion test on peak heat release rate. In all the flowrate conditions, the results of water only after algae test has lower PHRR than the one before algae test, which suggest that there is a memory effect after combustion of algae suspension due to accumulation of algal biomass or water in the engine. This memory effect was eliminated as explained in Section 2.3. It can be seen in Figure 15 that the changes of algae aspiration flowrate do not have a clear impact on PHRR of the suspensions or of the subsequent water only tests, outside of the range of experiment variability shown.

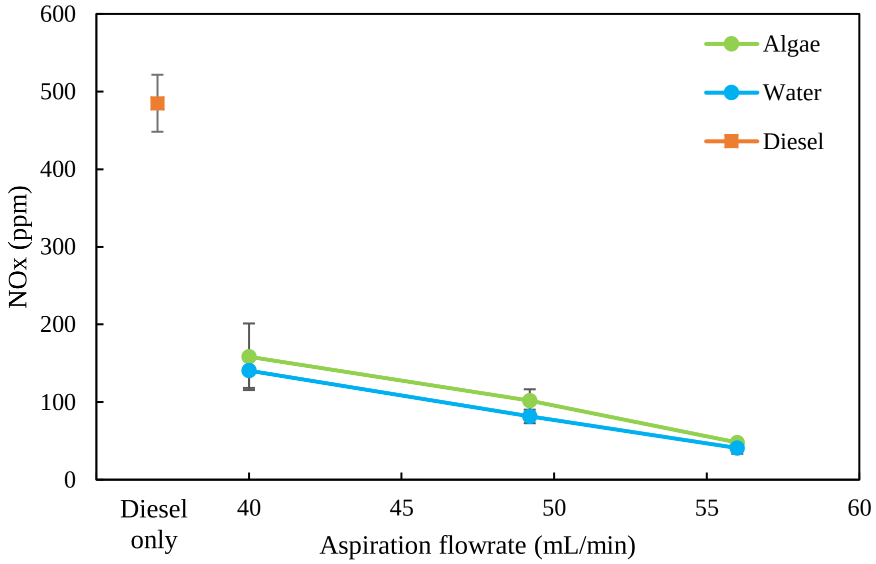


Figure 16. NOx exhaust emission level with aspirated algae biomass suspensions and water of varying injection flowrate. The error bars present show plus and minus the standard deviation from the mean value.

Figure 16 shows the effect of varying algae biomass and water injection flowrate on levels of NOx in the exhaust gas. It can be seen from Figure 16 that there is a linear decrease in NOx emission levels with increasing injection flowrate for water only and algae suspension. It is also clear to see that the tests with algae suspension or water have much lower NOx level in the exhaust gas relative to diesel only. Delivering more water into the engine per cycle would increase the total amount of water vapour and be expected to further reduce in-cylinder temperature, and thus decrease NOx production. Furthermore, under the condition of constant aspiration flowrate, algae suspension give higher NOx level than water only. According to the previous ignition delay results (Figure 14), aspiration of water only resulted in a higher ignition delay and lower NOx emission level relative to algae suspension, which suggests that the in-cylinder temperature in water only condition is lower than in the case of the algae suspension aspiration at all flowrates tested.

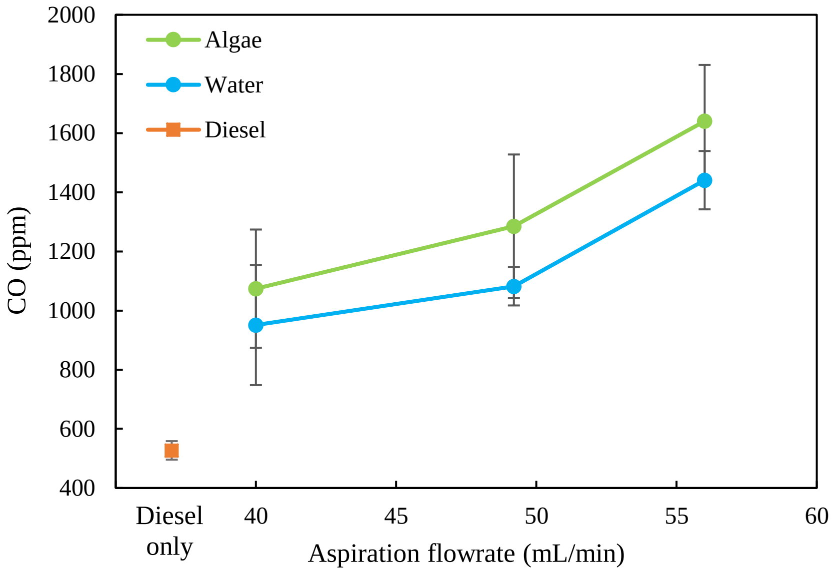
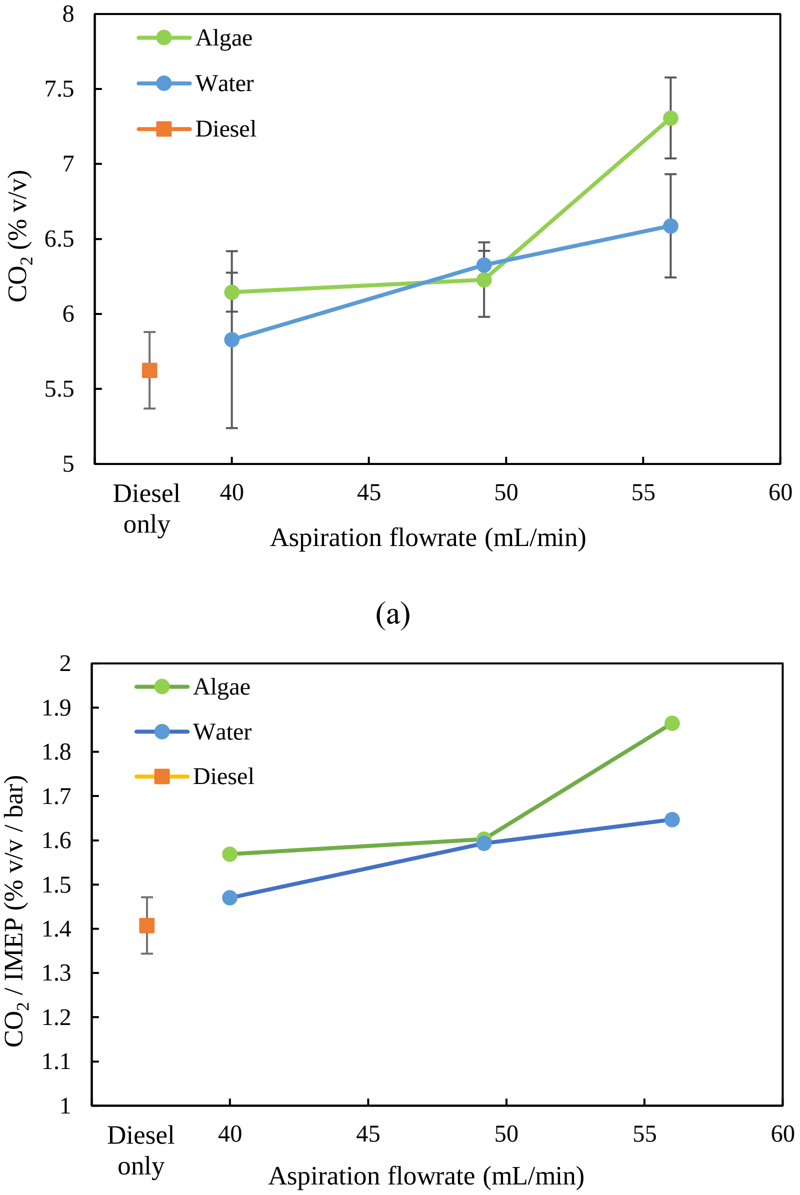


Figure 17. CO exhaust emission level with aspirated algae biomass suspensions and water of varying injection flowrate. The error bars present show plus and minus the standard deviation from the mean value.

Figure 17 shows the effect of varying algae suspension and water injection flowrate aspirated via the air intake on exhaust gas levels of CO. It can be seen from Figure 17 that all the conditions of algae and water aspiration have higher CO emission levels relative to diesel only, and that there is increase in these with increasing aspiration flowrate. This observation is in agreement with previous studies where the water content of the combustion chamber reduced the in-cylinder temperature and resulted in more incomplete combustion, which will increase CO formation [24]. Meanwhile, at constant flowrate, combustion of the algae suspension produces more CO than water only. It is plausible that the size of aggregated algae cells (50 ~ 100 µm) are much bigger than the size of diesel droplets (10 ~ 20 µm) [25] and the presence of algae cells inhibits the air mixing with fuel, thereby causing incomplete combustion of the cells and producing more exhaust CO.



(a)

(b)

Figure 18. (a) CO_2 exhaust emission level with aspirated algae biomass suspensions and water of varying injection flowrate (b) CO_2 exhaust emission level normalized with respect to the engine IMEP. The error bars present show plus and minus the standard deviation from the mean value.

Figure 18 shows the effect of variable injection flowrate of algae suspension and water at constant biomass concentration on CO_2 emission levels in the exhaust gas. It can be seen that the algae test under 56 ml/min injection flowrate gives the highest CO_2 level. Notwithstanding the extent of the error bars shown, with the flowrate increasing, all the CO_2 levels in algae suspension and water aspiration test increase relative to diesel only

(Figure 18 a). It is likely due to the extension of fuel injection duration to maintain the IMEP at 4 bars and combustion of more algae biomass delivered into the engine produce more CO_2 emission. However, in Figure 18 (b) it can be seen that CO_2 emission during aspiration of water only and the algae suspensions remain higher than that during diesel only combustion when normalised with respect to engine IMEP, suggesting a decrease in the thermal efficiency of the engine under these conditions.

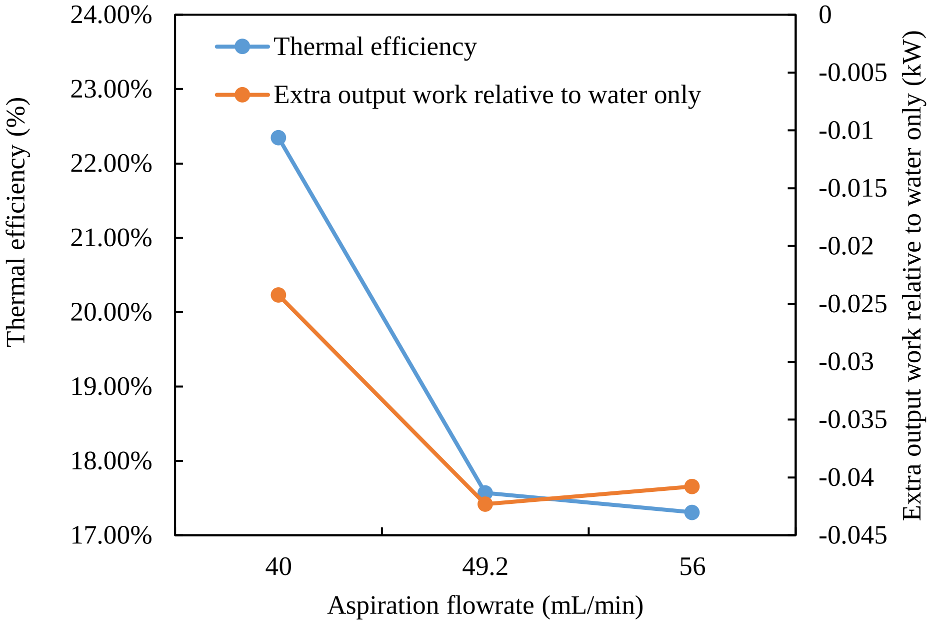


Figure 19. Thermal efficiency of diesel engine and extra output work with aspirated algae biomass suspensions of varying injection flowrate.

Figure 19 shows the effect of varying injection flowrate of algal biomass aspirated via the air intake on thermal efficiency of diesel engine and the extra output work relative to water only. In all flowrate condition, there were less extra output work of diesel engine than water only, which suggest that the algal biomass has negative impact on the engine combustion under low biomass concentration and results in reduction of total engine output. Meanwhile, a decreasing of thermal efficiency was observed with increasing of aspiration flowrate. Alone with the increasing level of CO emission (Figure 17), it indicates that the increasing of aspiration flowrate significantly affect the combustion quality and produced more incomplete combustion during engine operation.

4. Conclusion

The direct aspiration of algal biomass slurry in the air intake of a diesel engine was investigated as an alternative route of utilising the energy content of microalgae without a complete dewatering process to lower the cost and energy input of algae biofuel production. From the research of combustion and emissions characterisation of algae slurry in a modern compression ignition engine, the results can be summarised in the following conclusions:

1. At algal biomass suspension concentration of more than 7.5% w/v, an increase in IMEP was observed, suggesting a positive contribution of the aspirated algae biomass to useful work output.
2. However, at 5% w/v algal biomass concentrations, the presence of the algal cells resulted in a reduced IMEP relative to an equivalent aspiration flowrate of water only. It was possibly due to the greater degree of energy lost in the exhaust during the combustion of algae suspension.
3. All the engine combustion with the aspiration of water (with and without algae) reduced NOx emission levels relative to reference diesel. With increase of biomass concentration, NOx level increased. However, increasing aspiration flowrate resulted in a reduction of NOx emission.
4. Both of CO and CO_2 emissions levels increased in all cases, which indicates that the present of algae cells contribute additional carbon source to increase the CO_2 emission level. Meanwhile, the presence of the algae increases levels of incomplete combustion.

The experimental results proved the possibility of increasing the total engine output by aspirating algal biomass into the engine, however, it decreased the thermal efficiency of the engine combustion. In order to receive better result of delivering algal biomass into IC engine, the air intake should be redesigned to avoid any blind angle between the biomass injection point and combustion chamber. It also suggests examining the aspiration of algae suspension in smaller engine with large surface area to volume ratio to achieve better combustion efficiency. Moreover, it is not ideal to transport significant volume of algae suspension over a long distance due to the sedimentation of algae cells. Therefore, it is suggested that rather it could be used for stationary power generation nearby the algae cultivation.

Acknowledgements

This research was funded by a Fellowship award to PH by the UK Engineering and Physical Science Research Council (EP/M007960/1).

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