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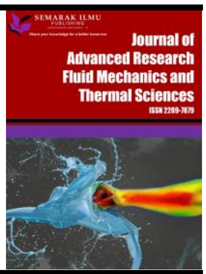

Effect of Injection Timing on the Dual Fuel Engine Performance Operated with Hydrogen and Nano-Biodiesel Blends

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ABSTRACT

In the current work, effect of nano-biodiesel blends and injection timing on the performance of hydrogen fueled dual fuel (DF) engine is presented. Hydrogen flow rate is maintained constant with a flow rate of 0.15 kg/h. For this B20 and nano-blends of Nigella sativa oil methyl ester (NLSTVAOME) and Jack fruit seed oil methyl ester (JKFSOME) fuel combinations are used. Nano-blends of respective B20 biodiesels are prepared using graphene amine (GA) nanoparticles with varied proportions ranging from 60 to 100 ppm using probe sonication method. Stabilization of the nano-blends are ensured with reference to quantity of nanoparticle, surfactant SDS (Sodium Dodecyl Sulfate) used and sonication time. Addition of the nanoparticles in the B20 biodiesel blends till 80 ppm showed considerable improvements on the performance of diesel engine with single fuel operation due to improved combustion compared to B20 biodiesel blends. Beyond 80 ppm the performance deteriorated due to non-homogeneous mixtures of nano-biodiesel blends. Injection timing (IT) for the modified DF engine IT is varied from 19 to 31°BTDC in steps of 4°BTDC. Further advancing the IT from 19 to 27°BTDC showed improved dual fuel engine performance with B20+GA80 blends of both biodiesels along with hydrogen induction when compared to B20 operation. Further mixing of air-hydrogen in the inlet manifold of dual fuel engine is studied using CFD analysis for varied hydrogen flow rates ranging from 0.10 to 0.2 kg/h in steps of 0.05 kg/h.

1. Introduction

Compression ignition engine has advantages over spark ignition engines because of its higher BTE with reduced carbon-based pollutants [1]. They are hence more suitable for transport, power generation and agriculture applications. Engine research involves reasonable BTE achievable with

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lower pollutants [2]. CI engines can operate on wide number of renewable and alternative fuels [3]. The vegetable oils are discovered as alternatives because to lower the petroleum import burden and encourage the indigenous fuels [4]. These fuels are sustainable, renewable and alternate fuels have several advantages and are eco-friendly, offering energy safety and saving in foreign exchange and deal ecological concerns, and socio-financial issues [5]. Utilization of these fuels makes the country self-reliant towards sustained energy. In this regard, hydrogen gas is a gaseous fuel and is the great promising substitutes to diesel. But this gas could be utilized in the CI engines on DF node. Its use in IC engine lowers the carbon-based emissions because it is carbon free gas. Hydrogen (H_2) gas is a promising renewable gaseous fuel and it has higher flame velocity, wider flammability limits and greater specific energy density. Hydrogen has a higher calorific value per kilogram compared to gasoline or diesel, as shown in various studies [6-9]. Several researchers have examined the performance of compression-ignition (CI) engines when fueled with different biodiesels [10-17]. The concept of dual-fuel (DF) engines has been explored by several investigators, involving the use of gaseous fuels with a small amount of pilot fuel to initiate combustion [18-22]. Some studies have reported the brake thermal efficiency (BTE) of diesel engines operating in DF mode using a combination of hydrogen (H_2) and diesel. These studies also provide comprehensive information on H_2 utilization techniques, advantages, disadvantages, properties, and the combustion of hydrogen in an engine." DF operation suffered from poor exploitation of gaseous fuels during the combustion at minimal and transitional loads and resulted in deprived combustion and pollutants. But at upper loads, the gaseous fuels performed better in the utilization of gaseous fuels, improved combustion with greater CO pollutants than typical diesel operation [23-26]. Among numerous combustion concepts explored on diesel engines in modern years the Reactivity Controlled Compression Ignition (RCCI) operation provides ultra-low smoke and NOx pollutants [27-32].

In general, nanoparticles (NPs) blended with diesel fuel have been found to enhance engine efficiency and reduce exhaust emissions. This improvement is attributed to NPs' larger surface area and higher thermal conductivity, which enhance heat transfer mechanisms and overall thermo-physical properties of the fuel [33].

Comparative studies have shown that using 40 ppm of Al_2O_3 nanoparticles in diesel (B20 blend) results in increased competence and decreased emissions at 80% load [34]. Conversely, blending B20 with CuO NPs led to a 3.9 % boost in brake thermal efficiency (BTE), 1.1% reduction in brake-specific fuel consumption (BSFC), a 12.78% reduction in smoke, and a 9.9% reduction in nitrogen oxides (NOx) emissions [35]. However, compared to pure diesel operation, B20 with NPs increased carbon dioxide (CO_2) emissions by 17.05%, decreased CO by 26%, and reduced HC by 28.56%, though NOx emissions increased by 14.19%.

Furthermore, studies have reported a positive impact of CeO_2 nanoparticles on emissions in biodiesel operation [36,37].

Computational Fluid Dynamics (CFD) analysis has been utilized to investigate the uniform mixing of different gaseous fuel combinations with air. These CFD simulations are followed by experimental studies to validate the analysis. The results consistently align with the experimental data, and the modeling has provided valuable insights into flow characteristics. This, in turn, has paved the way for optimizing geometric designs to achieve better mixing efficiency.

Previous research has demonstrated that the use of a mixing chamber, such as a gas-air mixer, doesn't result in power losses [38,39]. Additionally, the power output and efficiency of dual fuel engines are influenced by the amount of air introduced into the combustion chamber. Reducing the amount of induced air leads to a decrease in engine power and efficiency. As a result, it's important not to throttle the air intake side of dual fuel engines [40].

Various devices, such as throttle body injection mixers, venturi mixers, high-pressure mixers, venturi mixjectors, intake manifold injectors, and secondary fuel premixing controllers, are employed to blend gas and air before they enter the engine combustion chamber. CFD analysis is used to evaluate the mixing quality, as indicated by the Uniformity Index (UI) and color contours of methane mass fraction (MCh4), for compressed natural gas (CNG) and air [41-45].

In this context, the effect of nano-biodiesel blends, CFD analysis of air-hydrogen mixing and IT on the dual fuel engine performance operated with hydrogen as induction fuel and nano-biodiesel blends as the injected fuel is carried-out. The practical implications of the present work basically involve sustained use of renewable fuels of hydrogen and biodiesel for diesel engine applications. This is because they address the ill effects of fossil fuels usage in internal combustion engines effectively. These include the addressing higher costs of fossil fuels, environmental degradation and ensuring local employment generation.

2. Methodology

2.1 Properties of Fuels Used

In the current work B20 blends of Jackfruit and Nigella sativa oils and their respective Nano-blends were prepared as injected pilot fuels respectively and hydrogen as inducted gaseous fuel. Nano-biodiesel blends were prepared using B20 blends of Jackfruit and Nigella sativa oils infused with Graphene Amine (GA) nanoparticles in varied proportions along with SDS surfactant. Table 1 gives the specifications of Graphene amine. Percentage of GA were varied from 20 to 100 mg in steps of 20 mg with optimized surfactant SDS. Figure 1 shows the nano-biodiesel blends prepared using ultra-sonication method. GA nanoparticles are sonicated in a probe-sonicator for 30 minutes and are dispersed into the B20 blends of the two selected biodiesels respectively. Optimal nanoparticle concentration is restricted to 80 mg as higher dosage beyond these results into agglomeration of the same in the fuel blends. Visual inspection and Zeta potential studies of the nano-biodiesel blends confirm this behavior which indicate settlement of the nano-particles and lower zeta potential values. In the present work, nano-biodiesel blends are synthesized by dispersing Graphene Amine nanoparticles in B20 biodiesel blends. Table 1 shows the specifications of Graphene amine nanoparticles. Non-homogeneous mixtures observed with higher dosage of nanoparticles is associated with dispersion issues of nano-particles in the base fluids. Factors like nanoparticle, surfactant, dispersion time, and dispersion medium affect the homogeneity of the Nano fluids. Optimization of these parameters need further research to ensure enhanced nanoparticle dosage in base fluids.

Table 1
Specifications of Graphene amine

Parameter	Description
Make	Ugray
Purity	97%
Size of the particle	2-3 nm
Density	0.241 g/cc
Specific Heat	2.1 kJ/kg K

Fig. 1. Nano-B20 biodiesel blends

The properties of B20 blends and their optimized nano-blends are shown in Table 2. The properties of hydrogen are provided in and Table 3.

Table 2
Properties of liquid fuels [7]

Properties	Diesel	JKFSOME (B20)	JKFSOME (B20GA80)	NLSTVAOME (B20)	NLSTVAOME (B20GA80)
Density (kg/m^3)	840	858	882	845	870
Calorific value (kJ/kg)	43,000	38,304	39,229	40,131	41,056
Flash point (°C)	54	115	112	90	88
Kinematic viscosity (mm^2/s)	2-3	4.32	4.82	3.7	4.32

Table 3
Properties of H_2 [7]

Properties	Values
Auto-ignition temperature (K)	858
Minimum ignition energy (MJ)	0.02
Flammability limits (% volume in air)	4-75
Stoichiometric A/F ratio on mass basis	34.3
Density at 15°C and 1 bar (kg/m^3)	0.0838
Net heating value (MJ/kg)	119.93
Flame velocity (cm/s)	265-325
Octane number	130

3. Experimental Test Rig

For the DF mode engine speed of 1500, compression ratio (CR) of 17.5:1, pilot fuel injection pressure (IP) of 260 bar, pilot fuel injector with 3-holes of 0.3 mm nozzle size and Toroidal combustion chamber (TRCC) combustion chamber is adapted. Table 4 shows the conditions of the engine used in the present study.

Table 4
Specifications of the experimental setup

Parameters	Values
Engine type	Kirloskar (TV1)
Injection system	Mechanical
No. of Cylinders	Single cylinder
Maximum engine speed	1500 rpm
Combustion chamber	Hemispherical
Nozzle holes	3
Injector nozzle dia.	0.3 mm
Compression ratio	17.5:1
Displacement	0.638 L
Cylinder bore × Stoke volume	87.5 mm × 110 mm
Injection pressure	200-300 bar
Injection timing	23°BTDC
Cooling system	Water cooled
Cylinder pressure transducer	0-360 bar

3.1 Hydrogen Utilization in a Nano-Biodiesel Fueled Engines

In the present work hydrogen is inducted into the intake manifold by engine suction. Figure 2 shows mixing ventures holder and different size ventures used. Figure 3 shows hydrogen supply arrangement provided to the dual fuel arrangement. The flow rate of hydrogen is set at 0.15 kg/h.

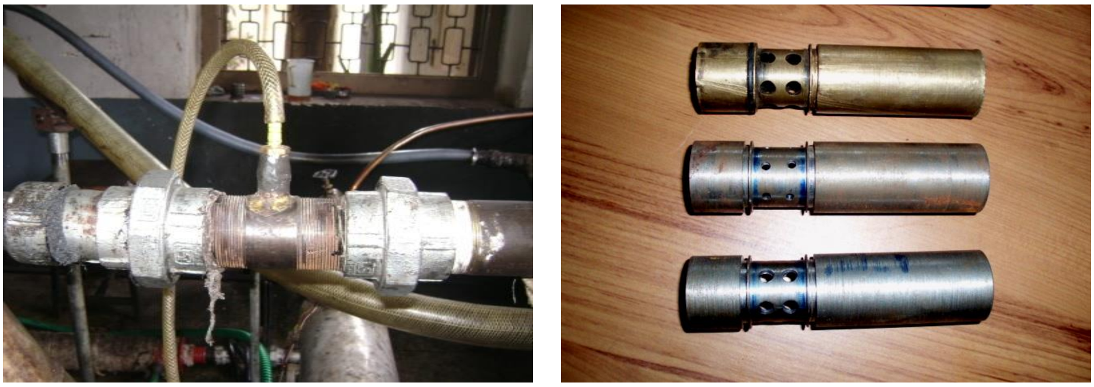


Fig. 2. Mixing ventures holder and different size ventures used

Fig. 3. Gas supply arrangement with dual fuel engine test rig

4. Results and Discussion

This section discusses the performance, emission and combustion characteristics of diesel engine operated in single and dual fuel modes. In single fuel mode of operation, the diesel engine is powered with two nano-biodiesel blends, while in dual fuel mode of operation along with injection of nano-biodiesel blends hydrogen is inducted into the engine cylinder.

4.1 Single Fuel Engine Operation: Effect of B20 Nano-Biodiesel Blends on Diesel Engine Performance

Engine optimization with B20 nano-biodiesel blends is done considering enhanced engine performance with reduced emissions.

4.1.1 Performance characteristics

Brake thermal efficiency (BTE)

Figure 4 shows the variation of BTE for nano-B20 blends of Jackfruit and Nigella sativa oils respectively infused with GA nanoparticles at full load single fuel engine operation. Addition of GA nanoparticles in biodiesel blends increases BTE as it assists in combustion activity associated with higher PP and HRR. As the percentage of GA increases from 60 to 80 mg the BTE increases due to effective combustion of the B20 biodiesel blends. Beyond 80 mg the nano-biodiesel B20 blends showed lower BTE due to non-uniform distribution of the GA nanoparticles in the blends. Compared to Jackfruit blends, Nigella sativa exhibited higher BTE due to its comparatively higher calorific value. Dual fuel engine performance is greatly affected by the pilot fuel injection timing. Advancing the fuel injection timing increases the delay period as more fuel is injected inside the engine cylinder. Further advancing the injection timing provides more time for uniform mixing of air-hydrogen and B20+GA80 biodiesel blend mixtures. This results in improved combustion with more fuel burning in premixed phase compared to diffusion combustion phase. Hence the brake thermal efficiency increases due to increase in in-cylinder pressure and heat release rate.

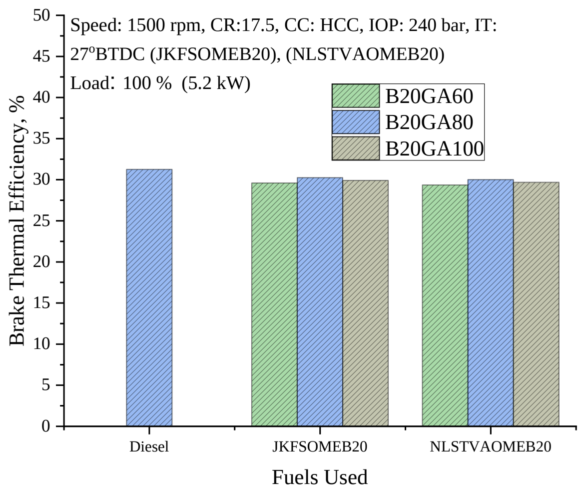


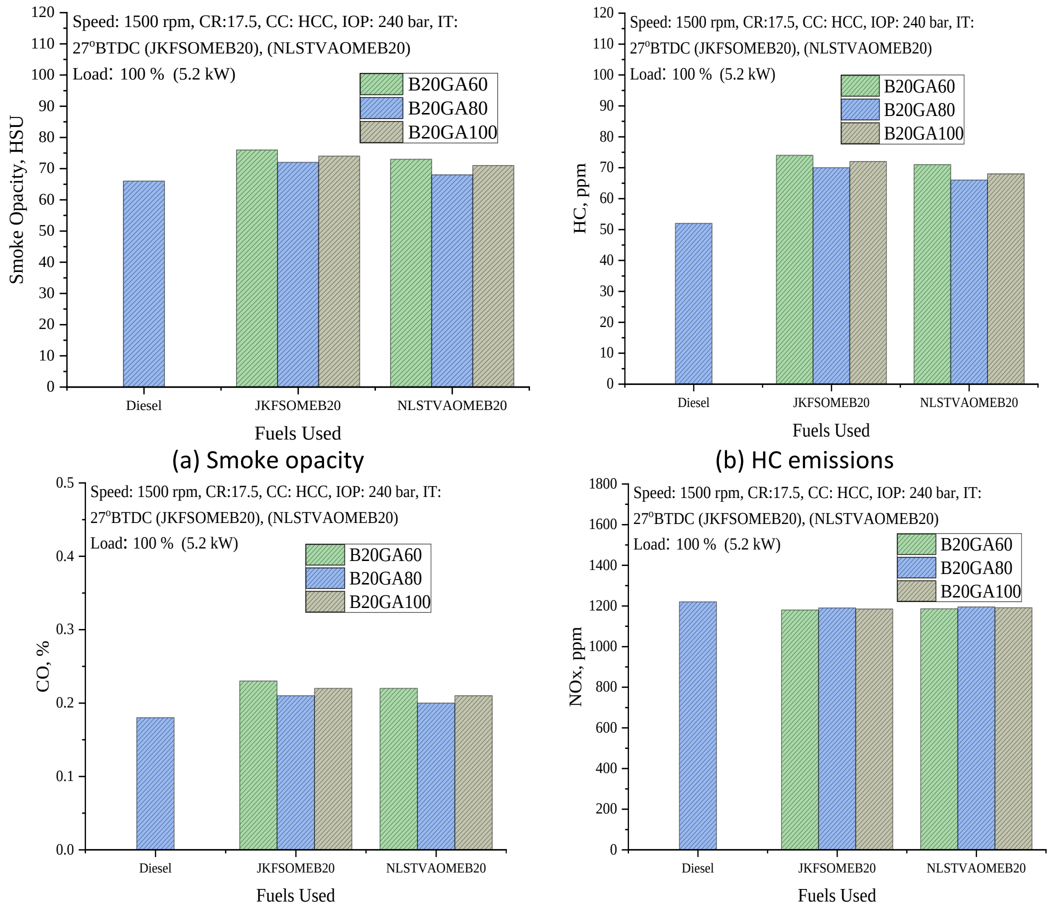
Fig. 4. BTE for Nano-B20 blends of biodiesels

4.1.2 Exhaust emission characteristics

This section shows the emission characteristics such as smoke, HC, CO and NOx of the diesel engine powered with B20 nano-biodiesel blends.

Figure 5 shows the variation of exhaust emissions for Nano-B20 blends of Jackfruit and Nigella sativa oils respectively infused with GA nanoparticles at full load single fuel engine operation. As the percentage of GA increases from 60 to 80 mg the exhaust emissions of smoke, HC and CO decreases due to enhanced combustion of the B20 biodiesel blends. On the other hand, NOx emission increased. Use of hydrogen induction increase NOx emissions of dual fuel engine along with injection of nano-biodiesel. This could be due to increase in-cylinder temperature, oxygen availability and residual time. Advancing the injection timing of nano-biodiesel blends further increases the NOx emissions. NOx emissions can be reduced using EGR (10-15%) as this dilutes the mixture, lowers the adiabatic flame temperature and suppresses the oxygen availability.

Beyond 80 mg the nano-biodiesel B20 blends showed higher emissions due to non-uniform distribution of the GA nanoparticles. Compared to Jackfruit blends, Nigella sativa exhibited lower emissions due to its comparatively higher calorific value and lower viscosity.



(a) Smoke opacity (b) HC emissions

(c) CO emissions (d) NOx emissions

Fig. 5. Exhaust emissions for Nano-B20 blends of biodiesels

Increase in BTE and lower emissions of smoke, HC, CO observed with Nano-biodiesel blends were found with 80 ppm dosage of GA. Accordingly, JKSOMEB20 GA80 and NSTVAOMEB20 GA 80 are optimized for dual fuel engine operation with hydrogen induction.

4.2 CFD Analysis of Air-Hydrogen Mixing in Inlet Manifold of Dual Fuel Engine

For modelling and analysis, cylindrical mixing chamber with air and hydrogen entry for different hydrogen flow rates ranging from 0. 1 to 0.2 kg/hr in strips of 0.05 kg/h are developed and tested. The mixing chamber in the CFD approach is equipped with inlets for air and hydrogen, ensuring a uniform mixture close to ambient conditions and the necessary pressure differential to drive the flow. ANSYS CFD and the FLUENT solver were employed for pre-processing and analysis. The CFD predictions of the hydrogen mass fraction were accompanied using a turbulent model based on the k-ε theory, implemented with a Reynolds-Averaged Navier-Stokes (RANS) code. The solver utilizes equations for Navier-Stokes, continuity, momentum, and energy.

4.2.1 Modelling and meshing

The cylindrical shaped mixing chamber with air and gas entry, has two inlets, one for hydrogen and the other for air as shown in Figure 6. The movement of a mixture of hydrogen gas and air has been modelled in three dimensions. In ANSYS CFD, a tetrahedron mesh is produced with a mesh size of 320771 elements and 115121 nodes. With 10 layers and a first layer mesh size of 0.272 mm and an expansion factor of 1.15, the grid is a structured mesh. Figure 7 shows meshing of mixing chamber for air and hydrogen.

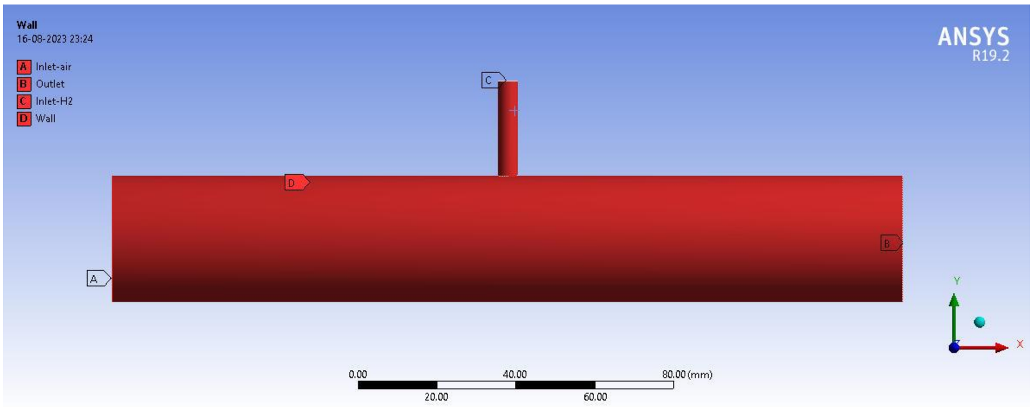


Fig. 6. Model of mixing chamber with air and hydrogen entry

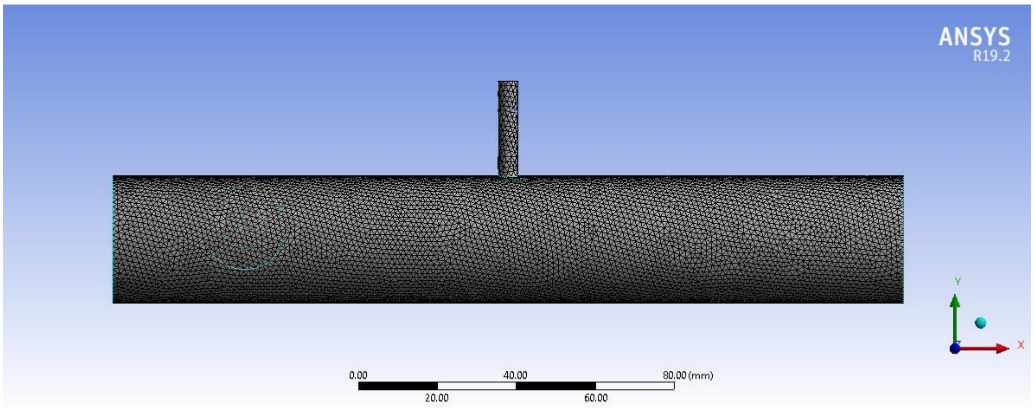


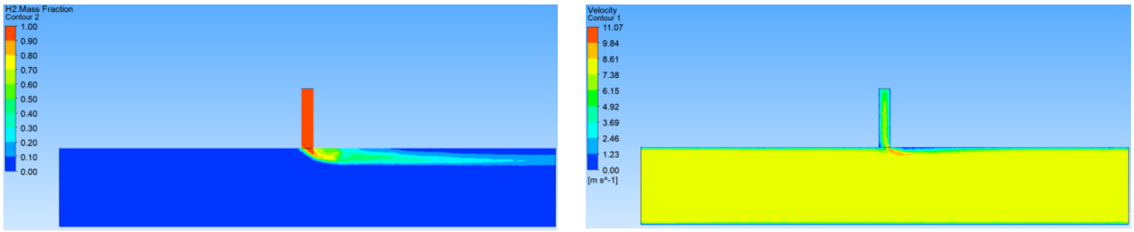
Fig. 7. Meshing of mixing chamber for air and hydrogen

4.2.2 Boundary conditions

Assuming a steady-state flow, the simulation treats the complete cylindrical mixing chamber assembly as the flow domain. When applying inlet boundary conditions to the air and hydrogen gas, buoyancy effects are not considered when determining the mass flow rate and pressure. Initial conditions assume an ideal mass fraction of zero for the flow rate via the air intake and a mass fraction of one for the hydrogen gas. At their respective inlets in the gas mixing chamber, the hydrogen gas and air are introduced at the necessary mass flow rates. The acquired results for mixing chamber with varying hydrogen flow rates for 0.1, 0.15 and 0.2 kg/h are explained in the following. CFD analysis of air-hydrogen mixing in the inlet manifold is done to ensure their uniform mixing from equivalence ratio calculation. Equivalence ratio refers to the ratio of actual air-hydrogen mixture to the stoichiometric mixture. As the quantity of hydrogen increases beyond 0.15 kg/h although uniform mixing occurs but the dual fuel engine performance deteriorated due to engine knocking.

4.2.3 H_2=0.1 kg/h flow rate

Figure 8(a) and Figure 8(b) show hydrogen mass fraction and velocity contours for hydrogen flow rate of 0.1 kg/h. The contour of the mass fraction of the hydrogen has its color scale with red for 1 (100% hydrogen gas) and blue for 0 (100% air). It is observed that air and hydrogen gas mixing happen in the pipe outlet. The mass fraction of hydrogen at the outlet area's average weight was found to be 0.42. The equivalence ratio for this case is found to be 0.60.

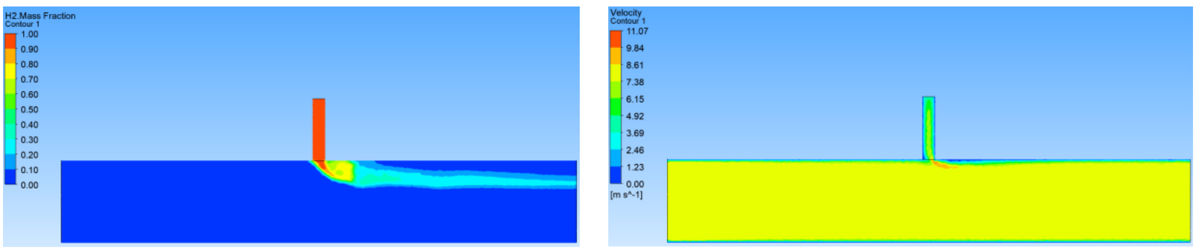


(a) (b)

Fig. 8. (a) Hydrogen mass fraction contour, (b) Velocity contour

4.2.4 H_2=0.15 kg/h flow rate

Figure 9(a) and Figure 9(b) show hydrogen mass fraction and velocity contours for hydrogen flow rate of 0.15 kg/h. It is observed that air and hydrogen gas mixing happen in the pipe outlet. The mass fraction of hydrogen at the outlet area's average weight was found to be 0.46. The equivalence ratio for this case is found to be 0.70.

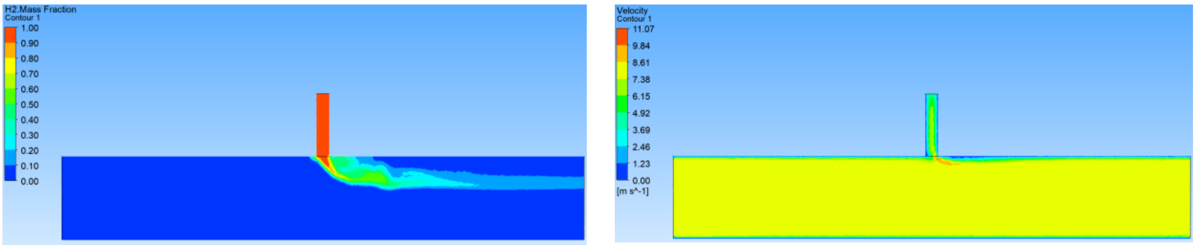


(a) (b)

Fig. 9. (a) Hydrogen mass fraction contour, (b) Velocity contour

4.2.5 H_2=0.2 kg/h

Figure 10(a) and Figure 10(b) show hydrogen mass fraction and velocity contours for hydrogen flow rate of 0.15 kg/h. It is observed that air and hydrogen gas mixing happen in the pipe outlet. The area weighed average of mass fraction of hydrogen gas at outlet was found to be 0.45. The equivalence ratio for this case is found to be 0.68.



(a) (b)

Fig. 10. (a) Hydrogen mass fraction contour, (b) Velocity contour

4.3 Effect of Injection Timing on Dual Fuel Engine Performance

Optimization of IT of nano-biodiesel blends are done with enhanced engine performance and reduced emissions of smoke, HC and CO emissions respectively.

4.3.1 Brake thermal efficiency

Effect of IT on BTE of dual fuel engine fuelled with diesel/hydrogen and nano-biodiesel/hydrogen for pilot injected fuels in dual fuel mode are shown in the above Figure 11. BTE of the hydrogen-run dual-fuel improves with the advancement of IT of pilot fuel. Advancing the IT from 23° to 27° BTDC results in increased BTE for all the fuel combinations considered. Further advancing the IT beyond 27° BTDC i.e., at 31° BTDC, the BTE decreased as more fuel burns in the diffusion combustion phase. This is because advanced IT causes biodiesel to be injected into the combustion chamber earlier than ordinary IT. This allows the biodiesel enough time to mix evenly with the hydrogen and air and burns it more effectively. In comparison to JKFSDOB B20+GA80-hydrogen and NLSTVAOB B20+GA80-hydrogen, dual fuel engine operating with JKFSDOB B20+GA80-hydrogen exhibits higher BTE. This is primarily because, hydrogen being common inducted gaseous fuel, the B20+GA80 blends have higher caloric values and lower viscosities. Nano-biodiesel provides enhanced combustion activity due to the addition of nanoparticles as they have large surface area compared to their volume. This provides improved catalytic combustion of the fuel blends and hence the engine performance is improved. As the percentage of GA increases from 60 to 80 mg in the B20 biodiesel blends combustion performance is increased, beyond which it decreases due to increased fuel blend viscosity and affect fuel atomization leaving the injector [46].

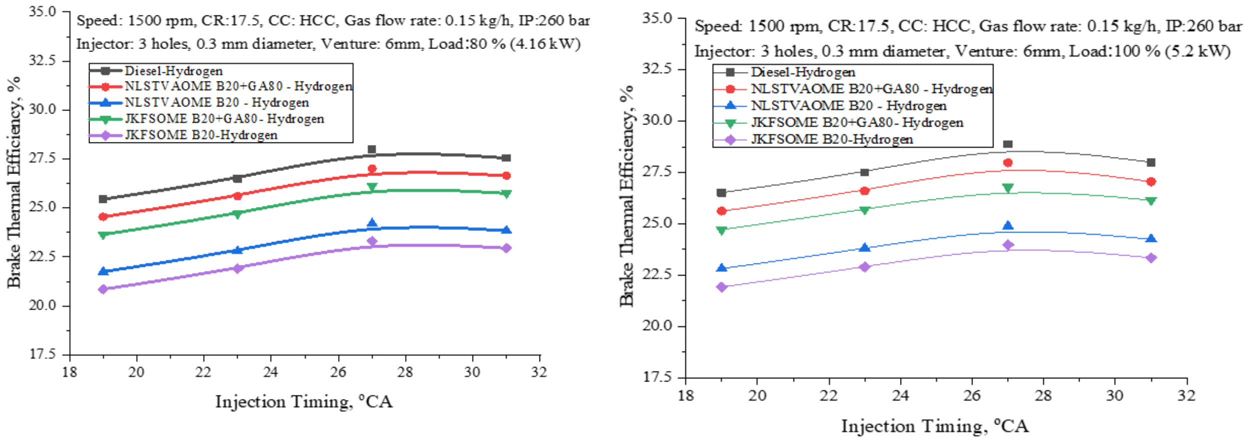


Fig. 11. Influence of IT on BTE

4.3.2 Smoke opacity

Effect of IT on smoke opacity behaviour of dual fuel engine fuelled with diesel/hydrogen and nano-biodiesel/hydrogen in dual fuel mode are shown in the Figure 12. Advancing the IT from 23° to 27° BTDC results in decreased smoke opacity for all the fuel combinations considered. Further advancing the IT beyond 27° BTDC i.e., at 31° BTDC smoke increased as more fuel burns in the controlled combustion phase. With advancement of IT of the pilot fuels of diesel and biodiesel the smoke opacity of the dual fuel engine decreases. This could be due to, higher combustion chamber temperature and higher in-cylinder pressure prevailing inside the engine cylinder which facilitates improved combustion associated with higher BTE. Hydrogen being common in dual fuel operation the properties of injected pilot fuels decide the magnitudes of smoke emission formation. The higher viscosity of the injected biodiesels results into incomplete combustion along with hydrogen induction compared to diesel. Dual fuel engine operation with JKFSDOB B20+GA80-hydrogen and NLSTVAOB B20+GA80-hydrogen shows lower smoke opacity than pure B20 biodiesel blends [47].

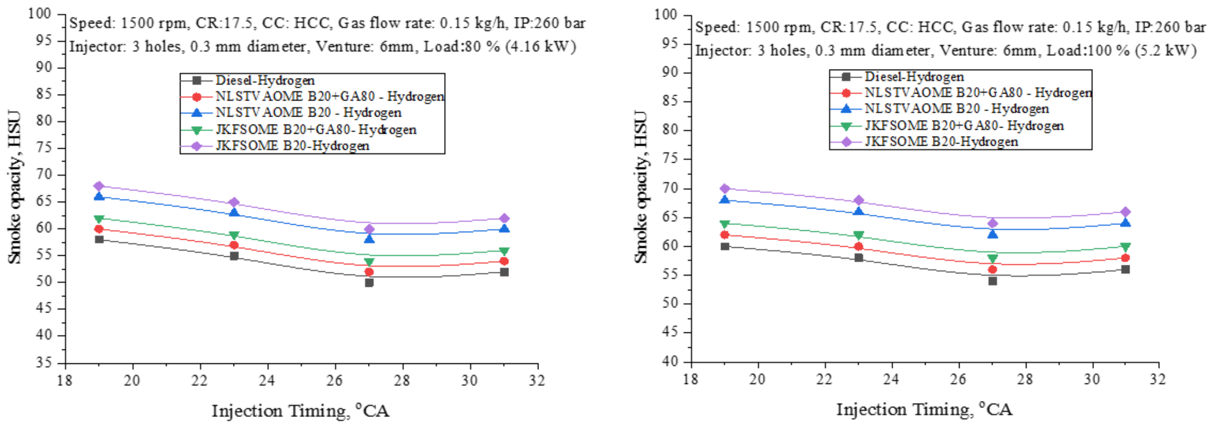


Fig. 12. Influence of IT on smoke opacity

4.3.3 HC and CO emissions

Effect of IT on HC and CO emissions behaviour of dual fuel engine fuelled with diesel/hydrogen and nano-biodiesel/hydrogen combinations in dual fuel mode are shown in the above Figure 13 and Figure 14. Advancing the IT from 23° to 27° BTDC results in reduced HC and CO emissions for all the fuel combinations considered. Beyond which HC and CO emissions increased. Further advancing the

IT beyond 27° BTDC i.e., at 31°BTDC, the HC and CO emissions increased as more fuel burns in the controlled combustion phase. Hydrogen being common in dual fuel operation the properties of injected pilot fuels decide the extents of HC and CO emission formation. The higher viscosity of the injected biodiesels results into incomplete combustion along with hydrogen induction compared to diesel due to higher wall wetting observed with the biodiesels. Dual fuel engine operation with B20 blends of JKFSDOB B20+GA80 and NLSTVAOB B20+GA80 with hydrogen induction in dual fuel mode operation shows lower HC and CO emissions than JKFSDOB B20, and NLSTVAOB B20 [48].

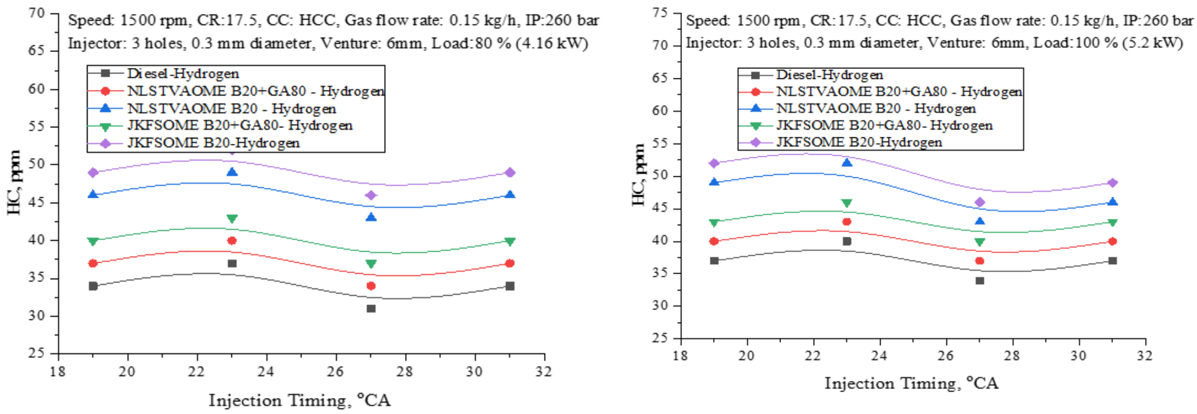


Fig. 13. Influence of IT on HC

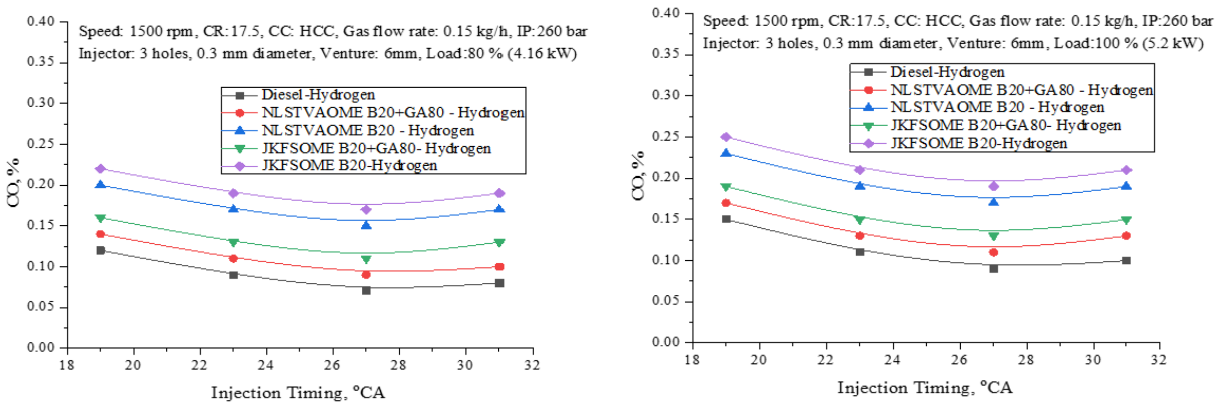


Fig. 14. Influence of IT on CO

4.3.4 NOx emissions

Figure 15 shows the effect of IT on NOx emissions behaviour of dual fuel engine fuelled with diesel/hydrogen and nano biodiesel/H_2 combinations in dual fuel mode. Formation of NOx emissions mainly depends on the in-cylinder temperature, oxygen availability and residual time. The NOx emissions with biodiesel operation are found to be lower in comparison to diesel mode. Higher calorific value of diesel compared to biodiesel and their blends results into higher BTE with more fuel burning in uncontrolled combustion. Hydrogen being common properties of the injected pilot fuels results into the observed NOx trends. It may be noted that advancing the IT from 23° to 27° BTDC results in higher NOx as more fuel is injected into the engine cylinder with higher ID. This further leads to increase in-cylinder temperatures with increased NOx emissions. Further advancing the IT beyond 27° BTDC i.e., at 31° BTDC, the NOx emissions decreased as lesser fuel participate in the controlled combustion phase with reduced BTE. Dual fuel engine operation with JKFSDOB B20+GA80 and NLSTVAOB B20+GA80 with hydrogen induction in dual fuel mode operation shows higher NOx emissions than JKFSDOB B20 and NLSTVAOB B20. The higher caloric value and lower viscosity of B20 blends ensures improved combustion and hence the NOx emissions increases [49].

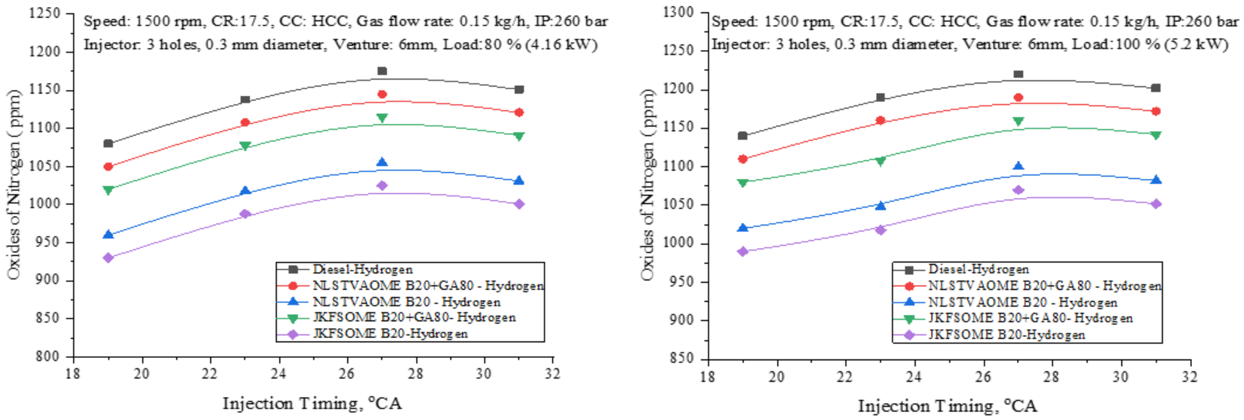


Fig. 15. Influence of IT on NOx

4.3.5 Ignition delay

Figure 16 shows the effect of IT on the Ignition delay (ID) behaviour of dual fuel engine fuelled with diesel/hydrogen and nano biodiesel/hydrogen combinations in dual fuel mode. Biodiesel/hydrogen DF engines show higher delay period compared to diesel/hydrogen combination due to their lower cetane number compared to diesel associated with more fuels burn in pre-mixed combustion. Hydrogen being common properties of the injected pilot fuels results into the observed ignition delay trends. It may be noted that advancing the IT from 23° to 27° BTDC dual fuel engine operation with all the fuel combinations showed decreased delay period as more fuel is injected into the engine cylinder. Dual fuel engine operation with nano-particles of JKFSDOB B20+GA80 and NLSTVAOB B20+GA80 with hydrogen induction in dual fuel mode operation shows lower delay period than JKFSDOB B20 and NLSTVAOB B20.

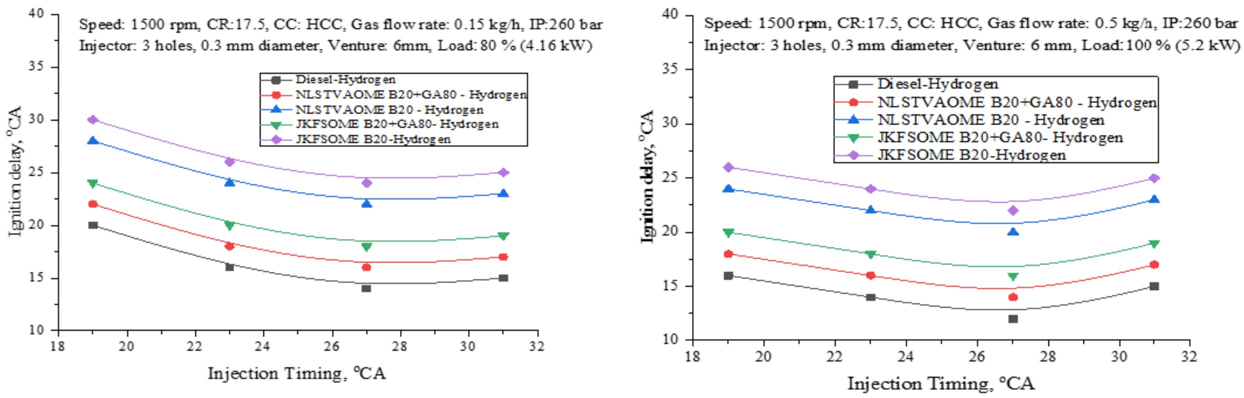


Fig. 16. Influence of IT on the ID

4.3.6 Peak pressure

Figure 17 shows the effect of IT on the Peak pressure (PP) behaviour of dual fuel engine fuelled with diesel/hydrogen and nano-biodiesel/hydrogen combinations in dual fuel mode. As the IT is advanced from 23° to 27° BTDC, the PP of dual fuel engine with all fuel combinations showed increasing trends as better combustion in the engine cylinder. Biodiesel-Hydrogen DF engines shows lower PPs compared to diesel-hydrogen combination. This could be due to higher cetane number for diesel compared to biodiesel and their blends which results into higher dual fuel engine BTE. Hydrogen being common properties of the injected pilot fuels results into the observed ignition delay trends. Dual fuel engine operation with B20 blends of JKFSDOB B20+GA80-hydrogen and NLSTVAOME B20+GA80-hydrogen shows higher PP than JKFSDOB B20 and NLSTVAOME B20.

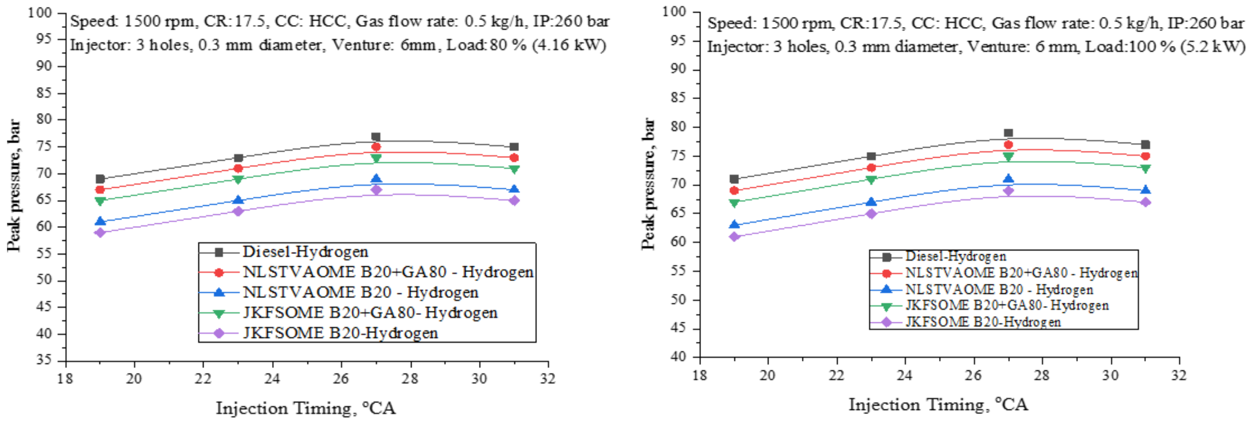


Fig. 17. Influence of IT on PP

5. Conclusions

Based on the obtained results on the performance of dual fuel engine powered with nano-biodiesel blends and hydrogen fuel combinations the following conclusions are drawn.

i. Use of renewable fuels in terms of diesel substitution by renewable biodiesel and hydrogen can address the environmental issues as well as freedom from high cost of fossil fuels usage.
ii. Hydrogen utilization in dual fuel engines is an effective method of addressing smoke, HC and CO emissions effectively.
iii. Higher BTE with inferior pollutants of smoke, CO, HC and lower ID for DF combustion when powered with hydrogen and nano-biodiesel B20 blends compared to pure B20 blends resulted with advancing of IT of pilot fuel.
iv. Increased time of pilot fuel injection to form uniform mixture of combustion and enables burning of fuel mixtures more efficiently and hence ensures enhanced engine performance.
v. NOx emissions of the DF engine with all fuels combination increased with advancing of IT more so pronounced with B20+GA80 fuel blends in-comparison with B20 fuels. NOx can be further controlled with EGR method.
vi. CFD analysis showed uniform mixing in inlet manifold of the dual fuel engine for 0.15 kg/h hydrogen flow rate compared to other flow rates.
vii. DF combustion powered with NLSTVAOB B20 along with hydrogen induction showed higher BTE, lower Smoke, HC, CO emissions as compared to JKFSDOB B20.
viii. Advancing IT, increases ID period as the ample fuel is injected inside the engine cylinder and at higher IT, the increased PP and lower ID are obtained for all fuel combinations.

The work is limited to use of hydrogen using induction method only. More advanced methods like port and direct injection of hydrogen can successfully overcome the drawbacks of induction methods like back-firing, reduced engine performance, reduced volumetric efficiency. The future work can focus on manifold and port injection of hydrogen as the induction technique has certain disadvantages like back-firing, reduced volumetric efficiency and lower engine performance.

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