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Effect of Hydrogen Addition and Equivalence Ratio on Swirl Motion of Direct Ignition Engine

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Abstract

Objective: Reducing emissions and better quality of combustion are keen research areas in automobile. For better quality of combustion, modifications of engine features and utilizing novel fuels investigated in many researches. **Methods:** Hydrogen has very low ignition energy, high flame speed and helps to obtain ultra-lean-burn mixture. In this research work, the hydrogen mole fractions were added in the primary diesel fuel in the ranging from 10% to 90% with each interval of 10 % and varied equivalence ratio from 0.6 to 1.4 to examine the effect on velocity magnitude contour of air-fuel particles and swirl motion. **Results:** All the results were obtained through simulations by using ANSYS Fluent 17 for Internal Combustion (IC) Engines. The addition of hydrogen increases the turbulence intensity of the fuel and leads to better quality of combustion. In addition, the swirl motion decreased because of addition of hydrogen addition and increasing the equivalence ratio.

Keywords: Contour Velocity Magnitude, Diesel Fuel, Equivalence Ratio, Hydrogen, and Swirl Ratio.

1. Introduction

In recent years, due to the depletion of the fossil fuels and environmental degradation, the researchers are continuously struggling to ensure the continuous supply of fuels for the internal combustion engines and other fuel powered machines. The problem of environmental degradation rose from the environmental pollutants normally emitted from the industries and automobile emissions. The increased usage of conventional fuels in automobile engines is the foremost intention for such pollutants. Also, such conventional fuels consisting hydrocarbons which resulted the Carbon monoxide (CO), Carbon dioxide (CO2), Hydrocarbon Carbon (HC), Particulate Matter (PM) and other harmful emissions. Currently, many research groups in worldwide are focusing their research on unconventional automobile fuels to swap conventional (hydrocarbon) fuels. On contrasting with hydrocarbon fuels, hydrogen is recognized one of the most substitute fuel because of uncontaminated (less pollutant) burning qualities and overall good performance. The hydrogen as a fuel has several outstanding combustion properties when used in IC engine and also without carbon in the composition which makes it less pollutant. On such ground, we can conclude that a hydrogen engine doesn't emit toxic emissions: HC, CO and CO2; but since the main contents of hydrogen fuels are water (H2O) and nitrogen oxide (NOx) which probably assist the emissions in this way. Also, the hydrogen has a wide flammability range as compared to other fuels and can be used for an ultra-lean mixture. Additionally, on comparison with conventional fuels, the hydrogen fuel possessed very low ignition energy which means low amount of energy required for ignition during the combustion. This allows the hydrogen engines for igniting lean mixtures and confirms quick and better combustion. Furthermore, since hydrogen has a high flame speed and the engines using hydrogen fuels are more likely to the thermodynamically

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ideal engines. Such high flame speed rise the rate of pressure and makes instantaneous combustion. In addition, high auto-ignition temperature of hydrogen inspires the application in higher compression-ratios engines and can be employed in dual-fuel mode in CI engine.

Swirl is the rotational motion of the air with respect to the cylinder axis and strengthened by enhancing the flow rate of the supply through a valve by conferring a pipe to any of the 2-intakes. Past examinations have demonstrated that enhancing the swirl will decreases the exhaust emissions on the account of rising in-cylinder mixture[1–8]. But it cause reductions in the overall output power due to increment in heat and pumping losses[9–12]. Also, the inlet swirl flow effect on the dynamic combustion characteristics as it shifted central recirculation bulk upstream and formed unity with the zone of recirculation[14]. The increased the swirl intensity caused penetration of recirculation central zone within annulus inlet and caused flashback for the flame[14]. To reduce this flashback effect many researchers investigated and suggested for the alternative fuels. Some used various blend of fuels including natural gas, hydrogen and their mixture together. It is mainly because of the high flame speed of the hydrogen but also by increasing the swirl number; the flash back time effect can be reduced.

Several studies have been carried on IC engine fueled with hydrogen to examined and understood the in-cylinder combustion developments in different operating circumstances. But still, it is problematic to achieve good knowledge about it. Also the time required and experimental investigations consumed much more efforts and cost. In the previous couple of years various examinations concentrated on how to construct an engine models to understand and to achieve 3D Fluid Dynamics (CFD) process occurrences instead of the complex phenomena of in-cylinder processes and moreover to optimize engines progress and performance. Today CFD has become an indispensable instrument for designing and developing engineering devices including IC engines. CFD provides effective and productive evaluation of different technologies such as novel fuel preparation techniques, combustion models, alternative fuels and many more. With the current advancement of computer technologies and the development of admissible commemoration, engineers and researchers are capable to investigate comprehensively the chemical kinetics by using CFD technique to simulate IC engines. On the basis of previous whole highlighted research, the authors of this work keen to interest to find the effect of the hydrogen addition with different ranges along with the varying the wide range of equivalence ratio on the swirl motion and tumble motion of the flow dynamics during the combustion process in direct ignition engine. In this research work, diesel fuel is considered as the primary fuel and hydrogen as an additional fuel.

2. Methodology

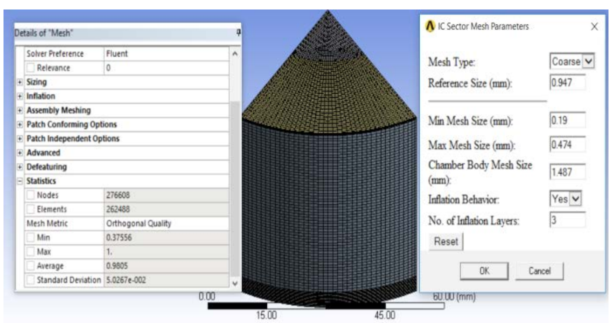
The combustion phasing and auto-ignition in HCCI engines is fundamentally determined by chemical kinetics. Chemical kinetics provides detailed reaction mechanism with higher accuracy for ignition and combustion of considered fuel used in HCCI engine. In this research work, the effect of hydrogen addition to natural gas on swirl ratio and tumble motion was investigated by conducting CFD for a non-premixed chemical profile. For the blending of non–premixed chemical profile ANSYS CHEMKIN software was employed while the output file is linked directly to CFD. The hydrogen addition varied from 0.1 to 0.9 (with each interval of 0.1) along with variations in equivalence ratio from 0.6 to 1.4 (with each interval of 0.2) to the blend of methane gas-diesel fuel.

2.1 Geometry, Decomposition and Meshing of the Combustion Chamber

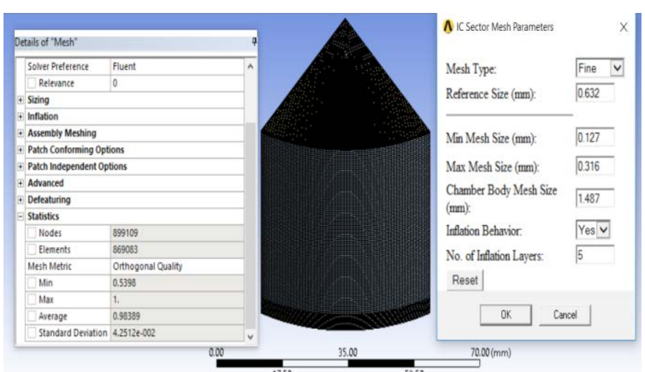
The 3-D hexahedral model for combustion chamber geometry was created by using ICEM software. However, ANSYS Fluent 17 for IC engine was used for the simulation purpose. Additionally dynamic meshing technique was used for the piston movement which had continuously changed the domain shape with time. Every occurrence in the boundary and moving mesh calculations were compared to different boundary and mesh geometries at all different Crank Angles (CA) during each engine cycle step. Dynamic meshing is an appropriate and valid method for apposite and exact CFD simulations of an internal combustion process[24] and on this ground it was employed to achieve CFD simulations of the combustion process. The development of grid generation was commenced from the mesh surface arrangement of the engine model established through Computer-Aided Design (CAD) tool. The surface data was converted into a finite volume mesh for the analysis purpose. However; the grid generator tool was used to produce hexahedral cells for the CFD analysis of computational mesh. Due to the computational domain complexity (in-cylinder, piston bowl and the intake of the port) different topologies with different zones were composed and it is a perfect method to match smooth, resulting in better meshing quality, refining meshes and a majorly for decreasing in meshing time.

2.2 Meshing Independency

To authenticate the accuracy of geometry, meshing independency is essential. In this regard, meshing size of the grid for geometry at the top dead center was generated as shown in Figure 1 (a) to (c). It is important to mention that almost all meshing domains were structural meshes while the piston bowl is of an unstructured mesh. The reason behind it is to boost the dynamic mesh update in case of piston move. Additionally, Figure 2 defines the pressure curve refinement[10] relating to the case highlighted in this research for validation purpose. Pressure curves for methane (Figure 2) and meshing case-2 (Figure 1 (b)) established a very good matching. Thus, for the rest simulation and computational time, such particular meshing was considered.



(a)

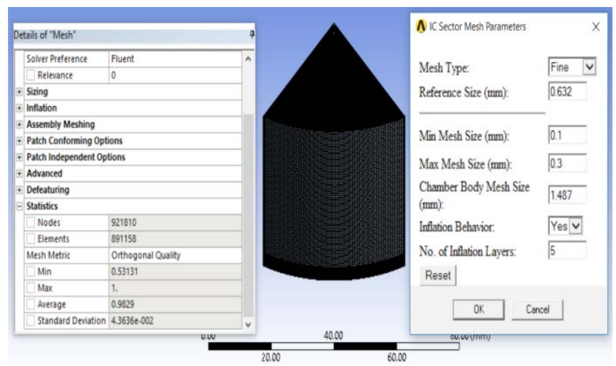


(b)

Figure 1. (a) Meshing Case – 1, (b) Meshing Case – 2, (c) Meshing Case – 3.

2.3 CUMMINS ISM370 Diesel Engine and Hydrogen Addition

CUMMINS ISM 370 is a turbocharging diesel engine with six heavy duty cylinders. The engine's specifications are tabulated in Table 1. An experimental study was conducted with addition of hydrogen in order to test the emission and combustion characteristics[15]. Such engine was considered in this research work, the load of the engine was running at different ranges from 10 % to 100 % with hydrogen fraction of 6 % added into the blended mixture.



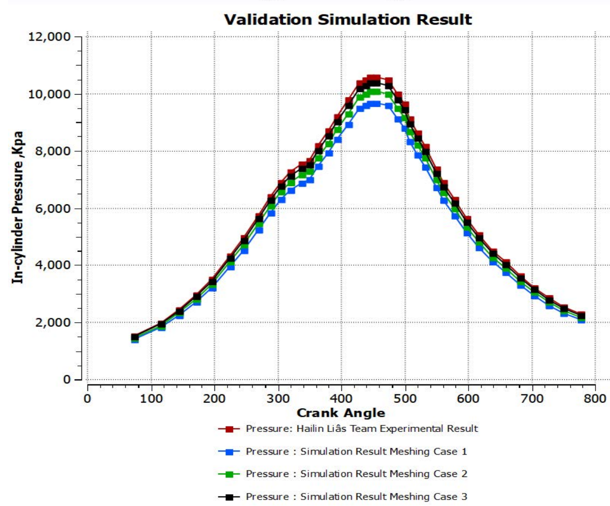


Figure 2. Cylinder pressure validation of pure diesel and 6 % hydrogen fraction.

3. Numerical Model Calibration and Validation

The simulation results were compared with the obtained results of pure diesel and 6% hydrogen fraction and are illustrated in Figure 2. It demonstrates the evaluation of released in-cylinder pressure along with engine's experimental result working on diesel fuel as a pure fuel and clearly shows that the general curve simulation tends to match well with the experiment resulted curves. By examining the comparison in Figure 2, the overall cumulative error is less than 5%. It is important that for tremendous agreement, the simulation results must have less or equal to 5% of the experimental results.

Table 1. Engine specification of the experimental study conducted in [15]

Parameter	**Quantity**
Hydrogen Fraction	6%
Speed Engine	1200 rpm
Load	70%
CR	16:1
Bore	125 mm
Stroke	147 mm
Capacity	10.8 L

4. Engine Specification

The engine model used for conducting this research has the following mentioned combustion and injector specifications in Table 2.

Table 2. Specification of the combustion engine

Parameter	Quantity
Engine cycle	Diesel – 4 stroke
Connecting Rod Length	200 mm
Crank Radius	20 mm
Rated engine speed	1800 RPM
Compression ratio	15:1
Minimum Lift	0.2 mm
Inlet valve closed	570 CAD
Exhaust valve open	833
Injector position	
x-position	0 mm
y-position	-12 E-05 mm
z-position	2 E-05 mm
Injection period	
Start injection	721 CAD
End injection	742.5 CAD
Injector Nozzle topology	
Diameter	254 E-6 mm
Cone angle	9 degree
Cone radius	17 E-05 mm
Number of injector holes	6
Injection angle	70

5. Mixture Boundary Condition

It is important that the values of and appropriate air should be injected with a certain proportion value of equivalence ratio (ϕ) and the fuel –air mixing must at. Moreover, oxidant air injected separately like co-flow outside the fuel flow. However; the mechanisms of the reactions (hydrogen, natural gas and air) and the overall composition of combustion reaction mixture were calculated by using model discussed in Kahraman[16] research work:

$$(1-\alpha)CH_4+\alpha H_4+\left(2-\frac{3\alpha}{2}\right)(O_2+3.76N_2)$$
$$\rightarrow(1-\alpha)CO_2+(2-\alpha)H_2O+x(O_2+3.76N_2)+3.76\left(2-\frac{3\alpha}{2}\right)N_2 \quad (3)$$

where, x is the excess air parameter

$$x=\frac{1}{\phi} \quad (4)$$

$$\alpha=\frac{n(H_2)}{n(H_2)+n(CH_4)} \quad (5)$$

where, denote the hydrogen mole fraction. (Methane +hydrogen) mole fraction equal to 1 and equivalence ratio is represented by ϕ.

6. Results

The turbocharged heavy duty diesel engine was used for finding the effect of hydrogen addition to the diesel for finding the impact on swirl motion by varying the equivalence ratio. Diesel fuel was considered as the primary fuel while the hydrogen fraction was added from 10% to 90% in it. Since swirl caused high angular velocity when the piston reaches at the TDC thus cause the homogeneity of the charge which is important for the combustion. However; at this moment, hydrogen addition will help to speed up the combustion process as it has high flammability. Also, the equivalence ratio increases the fluctuation and vibration of the charge particles and this will also help to movement of the particles. This increment is desirable for the better mixture and the combustion process. On such arguments, this research was conducted to find the effect of hydrogen addition with varying the equivalence ratio to determine the dynamic flow characteristics of the charge.

6.1 Effect of Hydrogen Addition on Swirl Motion

Detailed research has been carried to examine the effects of H2 addition on the combustion, performance and exhaust emissions of diesel engines. In the beginning majority of the research work was conducted by employing small and single cylinder diesel engines[17]. In recent times, heavy duty, multi-cylinder, diesel engines with innovative technologies like cooled Exhaust Gas Recirculation (EGR) and common rail fuel injection are using for to examine the effect of H2 addition on the combustion, performance and exhaust emissions of it[18–21]. Majority of the past researches were to investigate combustion, performance and exhaust emission of H2-diesel dual fuel engines. The combustion, performance and emission parameters are totally relying on the dynamic flow characteristics of the fuel. In swirl motion. As the increment in the swirl intensity, the combustion duration decreases. However; premixed combustion left unchanged, on the other hand the increment in mixing on account of swirl, speed up the diffusion combustion and resulting to furthering combustion end timing[13]. For quite a while, swirling flow has been used to balance out the flame in high-velocity flows[23]. So for, numerous kinds of swirler, e.g., axial and radial swirlers have been established and approximately all diesel engines (light / heavy duty) have used such swirlers to balance-out the combustion. Also swirling flow creates a recirculation zone and generated hot and radical-rich yields to the reaction zone[24].

Figure 3 (a) to (f) shows the evolution contour of velocity for the combustion period to CAD through the in-cylinder engine. It can be clearly observed that the magnitude of velocity for charge particles decreased lightly in the direction of the circulation central zone of the in-cylinder engine. The main reason for that is the addition of hydrogen since it supports and helps the charge (air-fuel) for speeding up the combustion process[24]. Additionally, as the hydrogen have higher combustibility rate thus its addition caused the charge particles movement shifted upstream towards the central zone. For the movement of the charge particles, the Reynolds numbers have much more importance as in the beginning of the combustion process; the flame propagates with the initial velocity and flame possesses the laminar velocity. This laminar flame velocity depends on the chemical nature of the fuel and also on rich fuel condition. In the results showed in Figure 3 (a) to (f), it is observed that the laminar flame velocity is smaller in values and such is the reason behind the reduction in circulation fluid. Also two different movements in the fluid flow are observed and this is indication to lowers the combustion process time. However; the airflow was steered efficiently at the combustion plume where it has unique piston cavity with the laminar flame velocity and resulting good fuel/air mixture. Also it creates disinclination stress within fluid layers and circular motion beside the interaction which accelerates to decline the swirl fluid motion.

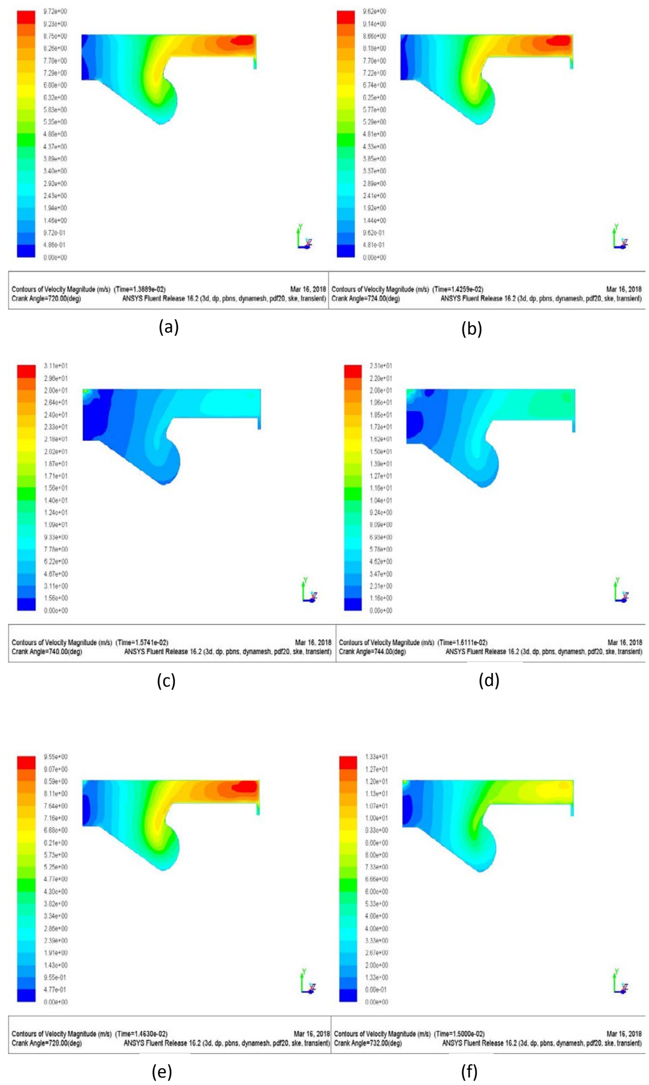


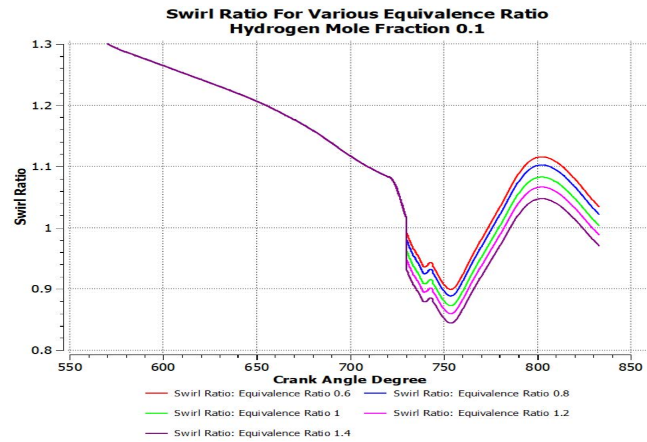
Figure 3. (a) - (f): Velocity magnitude contour of air-fuel particles.

Swirling flows are extensively considered as an appliance to maximize and betterment for the mixing of fuel during gas-phase with the air to improve the combustion efficiency and stabilizing the process during the higher concentrated combustion chamber[25,26]. Currently, several important calculations and data were achieved on the swirl affect problems on the combustion and flame stability. In swirl cases, the tangential velocity expands the velocity magnitude and

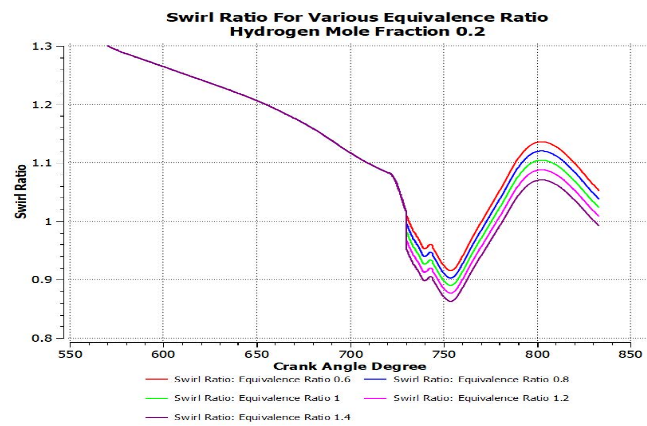
consequently builds the velocity gradient at the strong fuel surface. The swirl has enhanced the mixing of gases. However, the effect of swirl touches the nozzle and causing negatively impact on the performance of the nozzle. Figure 4 (a) to (i) showed represents the swirl ratio with respect to the variation of hydrogen volume fraction: 0%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80% and 90% together with equivalence ratio varied from 0.6, 0.8, 1, 1.2 and 1.4. If the circulation of bulk mixture fuel for combustion & the non-combusting processes reduced, the chemical reaction will moves upstream[12]. But the addition of hydrogen always supports the chemical reaction for speeding up the combustion and charge expands rapidly on account of faster heat release rates and impedes the circulation of fuel flow. Also the adiabatic flame temperature for the air-fuel blended rise due to the hydrogen addition.

In general, hydrogen addition improves the intensity of the combustion process which caused the reduction in movements of charge flow in the central zone. Such results were observed in Figure 4 (a) to (i) where the swirl ratio reduced with increment in the addition of hydrogen as compared to the non-addition of hydrogen.

To arguments on the variation of equivalence ratio, generally the oxygen concentration reduced along with the an increment in equivalence ratio and this is the major reason for the ignition delay[25]. Also, the high heat capacity on account of hydrogen addition causes extension in ignition delay and during that the fuel accumulation rises due to prolonged ignition delay[26]. In general spectrum, majority of the fuel always prepared for the combustion during the pre-mixing segment and confronting the combustion reaction intensity must increases along with the rising in ignition delay.



(a)



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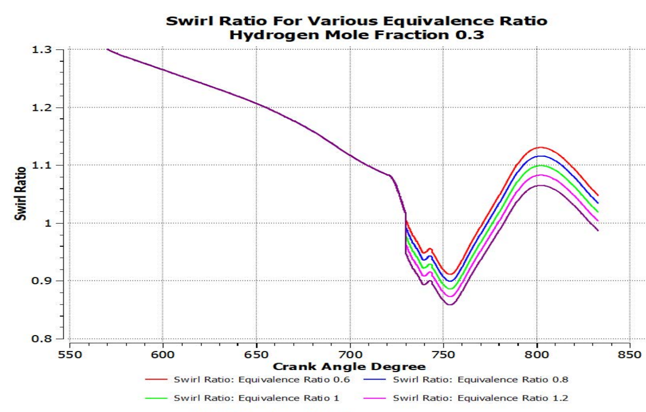

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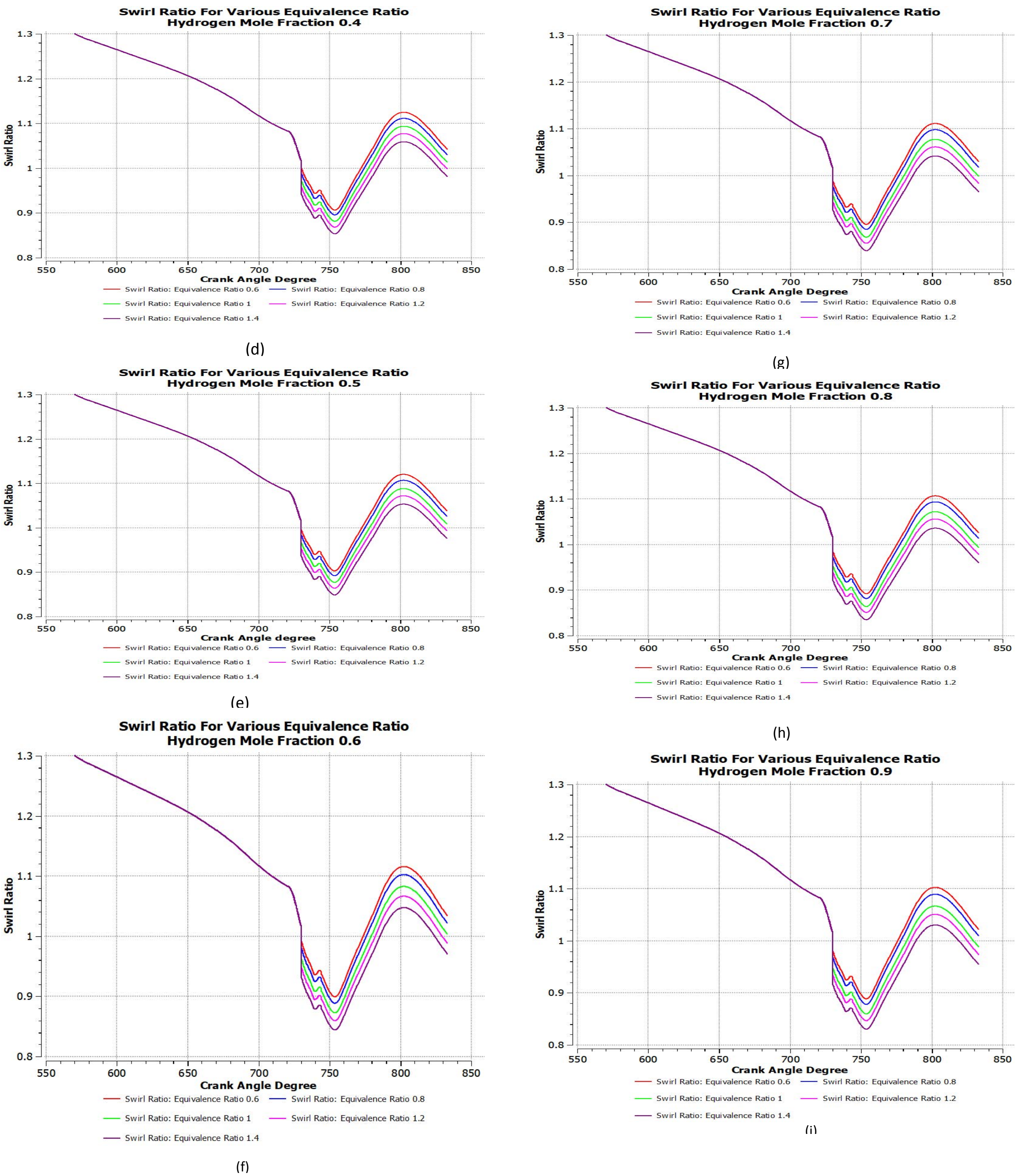

Figure 4. (a) to (i): Effect of hydrogen addition on swirl ratio.

Therefore, the bulk of air-fuel circulation obstructs when equivalence ration increased which results to decrease in swirl ratio.

Figure 4 (a) to (i) also demonstrates the combined effect of hydrogen's addition along with equivalence ratio on the swirling ratio. From the results, the swirl ratio decreased at the commencement of compression stroke. It is because that the compression precludes and diminishes the bulk fuel recirculation[25]. Also, the swirl ratio continues to decrease further in the next stroke and it can be observed in the results shown in Figure 4 (a) (i) as sharp curve through the combustion process. Conclusively, the addition of hydrogen and by increasing the equivalence ratio, the swirl ratio decreased and helps to improve the combustion.

7. Conclusion

Effect of Hydrogen Addition and Equivalence Ratio were carried on Swirl and Tumble Motion on a CUMMINS ISM 370 Direct Ignition Engine (Turbocharged Diesel Engine). In advantages of hydrogen as a combustible gas, it is very light and has higher flammability. Also, because of having hydrogen H2 and some water particles H2O, it is considered as environmentally friendly fuel. Since the research work is not so much rich in this era, still hydrogen is considered as the debatable for using it as a fuel. The main hindrance in it is the production of hydrogen gas is costly and time taking but on other hands: looking in to its attractive characteristics for combustion, it is one of the prominent fuels for combustion in automobile. Arguing on its attractive characteristics, it is light and can be easily atomization during the compression stroke on account of turbulence effect and laminar flame velocity. Swirl motion is main reason for achieving the better turbulence intensity and can affect the combustion process.

On the basis of results in this research work, we concluded that increasing the hydrogen mole fraction results enhance the laminar flame velocity and achieving better turbulent intensity. This increased turbulent intensity cause to increase the flame burning criteria. In other words, hydrogen improves the combustion quality and confiscates the barrier in interaction between the supply (air-fuel) and the hindrances in bulk of fluid circulation. Also as the hydrogen mole fraction increases, the swirl ratio decreases while by increasing the equivalence ratio an increment in ignition delay time was found.

8. References

1. Dembinski H, Angstrom H-E. Swirl and Injection pressure impact on after-oxidation in diesel combustion, examined with simultaneous combustion image velocimetry and two colour optical method. SAE Paper 2013-01-0913; 2013.
2. Lopez JJ, Martin J, Garcia A, Villalta D, Warey A, Domenech V. Characterization of in-cylinder soot oxidation using two-color pyrometry in a production light-duty diesel engine. SAE Paper 2016-01-0735; 2016.
3. Ge H-W, Shi Y, Reitz RD, Wickman DD, Zhu G, Zhang H, Kalish Y. Heavy-duty diesel combustion optimization using multi-objective genetic algorithm and multi-dimensional modeling. SAE Paper 2009-01-0716; 2009.
4. Sun Y, Sun K, Lu Z, Wang T, Jia M. Selection of swirl ratio in diesel engines based on droplet trajectory analysis, SAE Paper 2017-01-0813; 2017.
5. McCracken ME, Abraham J, Swirl-spray interactions in a diesel engine, SAE Paper 2001-01-0996; 2001.
6. Shundoh S, Kakegawa T, Tsujimura K, Kobayashi S. The effect of injection parameters and swirl on diesel combustion with high pressure fuel injection. SAE Paper 970627; 1991.
7. Kang KY, Reitz RD. The effect of intake valve alignment on swirl generation in a DI diesel engine. Experimental Thermal and Fluid Science. 1999; 20(2):94–103. https://doi.org/10.1016/S0894-1777(99)00034-5
8. Benajes J, Martín J, García A, Villalta D, Warey A. Swirl ratio and post injection strategies to improve late cycle diffusion combustion in a light-duty diesel engine. Applied Thermal Engineering. 2017; 123:365–76. https://doi.org/10.1016/j.applthermaleng.2017.05.101
9. Olmeda P, Martin J, Garcia A, Villalta D, Warey A, Domenech V. A combination of swirl ratio and injection strategy to increase engine efficiency. SAE Paper 2017-01-0722; 2017.
10. Miles PC. The influence of swirl on HSDI diesel combustion at moderate speed and load. SAE Paper 2000-01-1829; 2000.
11. Lahane S, Subramanian KA. Impact of nozzle holes configuration on fuel spray, wall impingement and NOx emission of a diesel engine for biodiesel–diesel blend (B20). Applied Thermal Engineering. 2014; 64(1–2):307–14. https://doi.org/10.1016/j.applthermaleng.2013.12.048
12. Benajes J, Molina S, Rudder KD, Maroteaux D, Hamouda HBH. The use of micro-orifice nozzles and swirl in a small HSDI engine operating at a late split injection LTC regime, Proceedings Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering. 2006; 220:1807–17. https://doi.org/10.1243/09544070JAUTO383

13. Park C, Kim C, Choi Y. Power output characteristics of hydrogen-natural gas blend fuel engine at different compression ratios. International Journal of Hydrogen Energy. 2012; 37(10):8681–7. https://doi.org/10.1016/j.ijhydene.2012.02.052
14. Zhou JH, Cheung CS, Leung CW. Combustion, performance and emissions of a diesel engine with H2, CH4 and H2–CH4 addition. International Journal of Hydrogen Energy. 2014; 39(9):4611–21. https://doi.org/10.1016/j.ijhydene.2013.12.194
15. Liu S, Li H, Liew C, Gatts T, Wayne S, Shade B, Clark N. An experimental investigation of NO2 emission characteristics of a heavy-duty H2-diesel dual fuel engine. International Journal of Hydrogen Energy. 2011 Sep; 36(18):12015–24. https://doi.org/10.1016/j.ijhydene.2011.06.058
16. Kahraman N, Çeper B, Akansu SO, Aydin K. Investigation of combustion characteristics and emissions in a spark-ignition engine fuelled with natural gas-hydrogen blends. International Journal of Hydrogen Energy. 2009; 34(2):1026–34. https://doi.org/10.1016/j.ijhydene.2008.10.075
17. Varde KS, Frame GA. Hydrogen aspiration in direct injection type diesel engine-Its effect on smoke and other engine performance parameters. International Journal of Hydrogen Energy. 1983; 8:549–55. https://doi.org/10.1016/0360-3199(83)90007-1
18. Shirk MG, McGuire TP, Neal GL, Haworth D. Investigation of a hydrogen-assisted combustion system for a light-duty diesel vehicle. International Journal of Hydrogen Energy. 2008; 33(7):237–44.
19. Bika AS, Franklin LM, Kittelson DB. Emissions effects of hydrogen as a supplemental fuel for diesel and biodiesel. SAEPaper: 2008-01-0648.; 2008.
20. McWilliam L, Megaritis T, Zhao H. Experimental investigation of the effects of combined hydrogen and diesel combustion on the emissions of a HSDI diesel engine. SAE Paper: 2008-01-0156; 2008.
21. Yoon S, Lee S, Kwon H, Lee J, Park S. Effects of the swirl ratio and injector hole number on the combustion and emission characteristics of a light duty diesel engine. Applied Thermal Engineering. 2018 Sep; 142:68–78. https://doi.org/10.1016/j.applthermaleng.2018.06.076
22. Lefebvre AH. Gas turbine combustion, Second Edition, Taylor and Francis, Philadelphia, USA; 1999. p. 125–31.
23. Uemichi A, Kouzaki K, Warabi K, Shimamur K, Nishioka M. Formation of ultra-lean comet-like flame in swirling hydrogen–air flow. Combustion and Flame. 2018 Oct; 196:314–24. https://doi.org/10.1016/j.combustflame.2018.06.019
24. Kim HS, Arghode VK, Linck MB, Gupta AK. Hydrogen addition effects in a confined swirl-stabilized methane-air flame. International Journal of Hydrogen Energy. 2009; 34(2):1054–62. https://doi.org/10.1016/j.ijhydene.2008.10.034
25. Abdelaal MM, Rabee BA, Hegab AH. Effect of adding oxygen to the intake air on a dual-fuel engine performance, emissions, and knock tendency. Energy. 2013; 61:612–20. https://doi.org/10.1016/j.energy.2013.09.022
26. Ji C, Su T, Wang S, Zhang B, Yu M, Cong X. Effect of hydrogen addition on combustion and emissions performance of a gasoline rotary engine at part load and stoichiometric conditions. Energy Conversion and Management. 2016; 121:272–80. https://doi.org/10.1016/j.enconman.2016.05.040