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EFFECT OF AIR JET AT THE VARIOUS RATE OF FUEL INJECTION IN A DIRECT INJECTION DIESEL ENGINE*

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Abstract– In the present work, the simultaneous effects of fuel injection rate and injection of air jet into the combustion chamber on exhaust emissions, combustion process and performance parameters in a direct injection diesel engine were investigated. In order to create an air jet, a design was presented in which a secondary chamber (air cell) was created inside the cylinder and was joined to the main chamber by throats. The obtained results showed that creating the air cell had no major effect on the power and specific fuel consumption, and brought about the reduction of emitted smoke particles from the combustion chamber in all four conditions of 100% load, 75% load, 50% load and 25% load. In comparison with the base engine, the rates of oxides of nitrogen (NOx) emissions decreased at 100% and 75% loads, yet increased at 50% and 25% loads. The outcomes of the current study were compared with those existing in the relevant literature and displayed acceptable behavior.

Keywords– Air jet, air cell, combustion, emission, diesel engine, injection rate

1. INTRODUCTION

Diesel engines refer to a range of engines which can, without the need for electric sparks, ignite the fuel. These engines have high fuel efficiency and more durability compared to spark ignition (SI) engines. The main emissions from these engines are smoke (Soot) and oxides of nitrogen (NOx), whereas unburned hydrocarbons and emitted carbon monoxides are low and negligible. Nowadays, there are strict regulations against exhaust emissions from diesel engines in most countries throughout the world. A large number of experimental and numerical researches have been accomplished so as to reduce these pollutants and to increase the efficiency of diesel engines.

Numerical simulations of combustion systems by means of advanced computational models have made it feasible to study various combustion conditions which are experimentally costly and difficult.

Numerical simulations are classified into two main models: thermodynamic models and flow field models. In contrast to thermodynamic models, flow field models can be employed to explore the processes of injecting drops, local temperature distribution and in-cylinder pressure in any time and place [1]. Choi wook et al [2] attempted to investigate flow field in a single cylinder diesel engine and demonstrated that high Reynolds k-ε model was appropriate for this field. Using numerical models, Hou and Abrams modeled intake and exhaust steps in addition to compression, combustion and expansion in diesel engine [3].

Many researches have been done in order to simultaneously reduce soot and NOx emissions. Kawazoe et al [4] employed air injection inside combustion chamber by means of a cylinder pump and

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managed to decrease exhaust smoke pollutant significantly; however, this led to reduction in engine power. Creating air jet by an air-accumulation generator in a direct injection diesel engine, Nagano et al [5] efficiently reduced exhausted smoke and NOx emissions. Choi et al [6] examined the effect of increasing the ratio of fuel-air mixture on the emissions by means of high-pressure injection of gaseous carbon dioxide and nitrogen into the combustion chamber. Results indicated that nitrogen injection into the chamber improved the mixture and increased Soot oxidation. Furthermore, delay in both fuel injection and injected gas showed significant reduction in the rate of smoke. Carbon dioxide injection also caused reduction in exhausted emissions.

The main problem in diesel engines is maintaining engine power along with simultaneous decrease in soot and NOx emissions. Since these two pollutants have opposite behaviors, decrease in one of them involves increase in the other [7]. On the other hand, studies have shown that reducing both these emissions mostly causes decrease in engine power [8]. Uludogan et al [9] employed numerical KIVA Code and investigated the impacts of the number of injectors and multiple injection in a direct injection diesel engine. Increasing the number of injectors resulted in simultaneous decrease in Soot and NOx emissions as well as increase in engine power at the same time. Reitz et al [10] demonstrated that utilizing exhaust gas recirculation accompanied by multiple injections significantly reduced soot and NOx without negative effects on specific fuel consumption. Mather and Reitz [11] offered a design in which an air cell was created inside the piston and connected to the main combustion chamber by throats. The obtained numerical results indicated that the amount of both Soot and NOx as well as engine power reduced simultaneously. Jafarmadar et al [12] quantitatively investigated creating an air cell inside the piston and insulating it in order to improve engine performance parameters. In the present work, AVL Fire U. 8.3 software is used for numerical simulation of combustion, exhaust emissions, and precise modeling of spraying fuel jet and injecting droplets. The investigated engine is a direct injection diesel engine Mt. 4.244 made by Motor Sazan Iran Company and its specifications are given in Table [1]. Figure 1 shows the test room of Motor Sazan Company. A hydraulic dynamotor that was directly connected to the motor shaft, has been applied to measure the performance parameters. A gas analyzing system has been applied to measure NOx by NDIR (Non-Dispersive Infrared Gas Analyses). The smoke has been measured by an AVL415S Smoke meter. The inlet airflow has been filtered and then measured by a flow meter. An accuracy sensor would measure the fuel consumption rate. A piezoelectric transducer would report the pressure changes by sampling the inner pressure of the combustion chamber. In this engine, the transducer has been adjusted so that the combustion chamber pressure has been reported for every 0.1 of the crank angle. In order to increase the experiment accuracy and reduce the possibility of error in the results, all the analyzing equipment has been calibrated before and after each test.

In order to explore the effects of air jet, an air cell is annexed to the main combustion chamber. It should be mentioned that compression ratio in both base and modified engines was equal.

Fig. 1. Experimental setup

Table 1. Engine specifications

Number of cylinders	4-in line, Vertical
Number of intake valves	1per cylinder
Bore × Stroke (mm)	100 × 127
Cubic Capacity	3.99 liters
Compression ratio	17.5:1
Max power	82 bhp @ 2000rpm
Max toque	360 N.m @ 1300 rpm
Combustion system	Direct injection
Rotation	Clockwise, viewed from front
Fuel injection	DPA Pump
Cooling	Water cooled with oil cooler
Duration of injection (deg)	20
Number of nozzle orifice × diameter (mm)	5 × 0.276
Displacement (lit)	3.99
Rate of fuel injected (kg/hr)	15.22
Combustion chamber	Reentrant

For the 3D simulation, firstly engine cylinder is modeled by Solid works software. Considering the strategy applied in AVL Fire software for creating meshes, a surface mesh for the model needs to be created. Thus, the mentioned mesh is created by fame hybrid assistant tool in AVL Fire software while the piston is located in top dead center. Next, complicated 3D simulation of engine and creating moving mesh is carried out by means of fame engine plus tool in AVL Fire. Regarding that, the analysis is done on the closing cycle from intake valve closure (140 BTDC) to exhaust valve opening (130 ATDC), so the domain of the calculation includes the space of cylinder, which is divided into head, liner and piston bowl. Simulation of modified engine condition follows the above-mentioned process. In this condition, an air cell and four throats are added to the initial geometry. The diameter of the air cell is 55 mm and its height is 2 mm. The diameter of the throats is 1 mm. Figure (2) demonstrates the simulated engines in base and modified conditions.

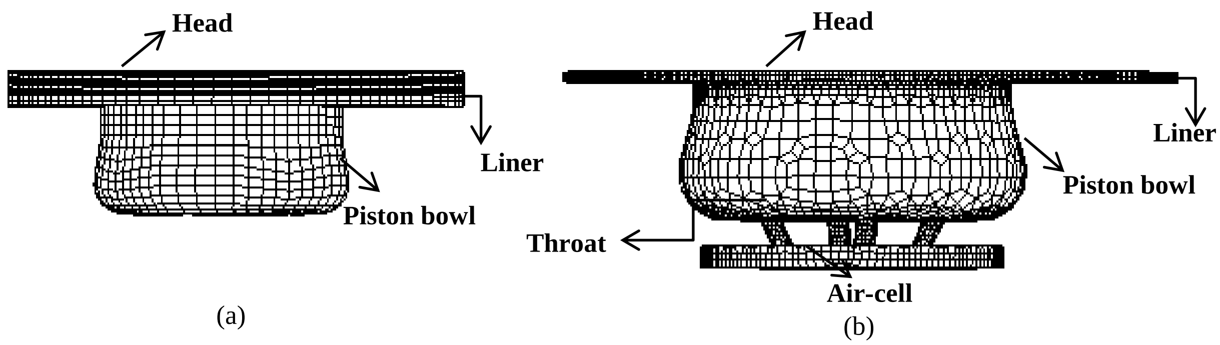


Fig. 2. Computational geometries for (a) baseline engine (b) modified engine

Inlet temperature at 300 K, initial pressure at 1.85 bar, and engine speed at 2000 rpm are set. In-cylinder swirl for both base and modified conditions are considered to be uniform, the amount of exhaust gas recirculation is assumed to be zero. In order to investigate grid dependency, combustion chamber pressure at 100% load condition for 22504 cells and 56321 cells is presented in Fig. 3. As can be seen in the figure, increasing or decreasing the number of the cells has no effect on the results.

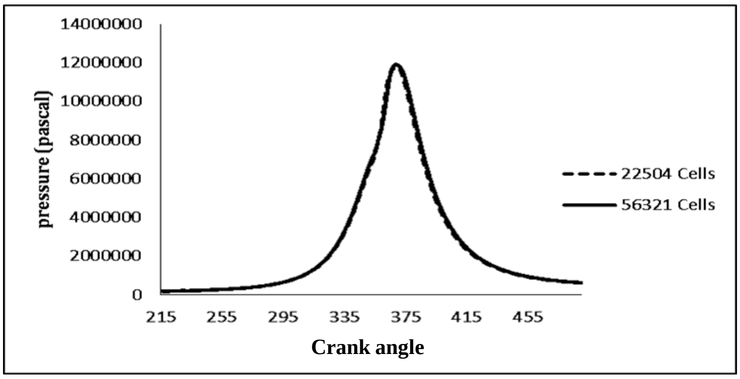


Fig. 3. Grid dependency based on the in-cylinder pressure

2. MODEL FORMULATION

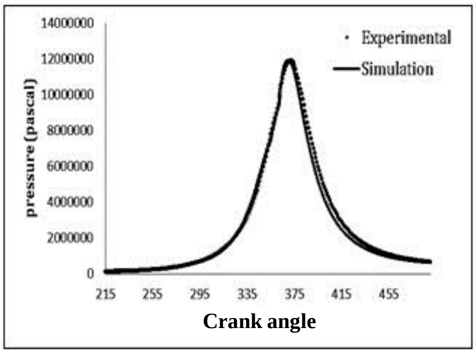
AVL Fire software, similar to other software operating according to infinitive volume method, carries out the discretization of equations of mass continuity, momentum and energy as well as the turbulence model, and then by utilizing an iteration algorithm, it solves the equations. Of course, this model has employed Shell auto-ignition model [13], Eddy breakup model [14], turbulence k-ε model [15], the Dukowicz model for transferring heat and evaporation of the fuel droplets [16], the Hiroyasu model for the formation of Soot emissions [17], and NSC model for Soot oxidation [18]. NOx formation is modeled by the Zeldovich mechanism [19]. Details of these models exist in the literature and they can be referred for further information.

3. RESULTS AND DISCUSSION

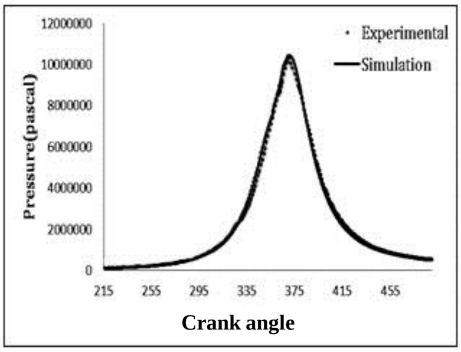
Calculations are carried out on an MT. 4.244 direct injection diesel engine at 100% load, 75% load, 50% load, and 25% load. Figure 4 depicts the comparisons of in-cylinder pressure in the base engine by experimental results. It is seen that there is a good agreement between the obtained and experimental results. It should be mentioned that the peak pressure discrepancy between the computational and experimental models is less than 2%.

Figure 5 shows the comparisons of in-cylinder average pressure for both base and modified engines at four working modes of the engines. As can be observed the peak pressure increases as engine load increases. It is observed at 25% load, due to changes in the geometry of calculating domain and in the pattern of the flow field in the modified condition, peak pressure is 1.2% more than that of the base condition. The peak pressure has occurred at 5 ATDC for modified condition and at 2 ATDC for base condition. At 50% load condition, the value of the peak pressure in modified condition is 1.1% more than that of the base condition. The peak pressure occurred at 6 ATDC for modified condition and at 5 ATDC for base condition. At 75% load, the peak pressure in base condition is 1.6% more than that in modified condition, and the peak pressure has taken place at 10 ATDC for base condition and at 8 ATDC for modified condition. Also, at 100% load, it is observed that peak pressure in base condition is 1.1% more than that in the modified condition, and maximum pressure curve is recorded at 10 ATDC for base condition and at 8 ATDC for modified condition.

By decreasing the pressure inside the main chamber at expansion stroke, the reserved air in the air cell is injected into the main chamber and causes better combustion of the remaining fuel. By creating air jet, because of increasing combustion rate at final combustion stage, the exhaust temperature from the combustion chamber increases in all four working modes of the engines. This phenomenon is observable in Fig. 6. Increases in the exhaust temperature are as follows: 4.2% at 25% load condition, 6.1% at 50% load, 7% at 75% load, and 7.4% at 100% load.



(a)



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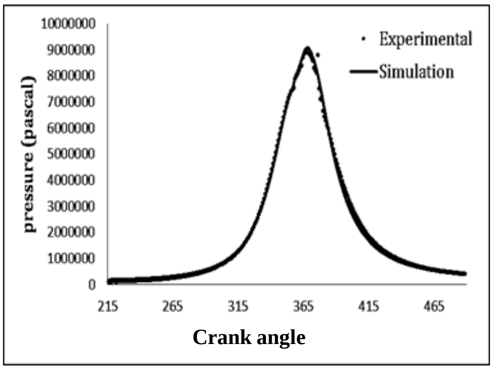

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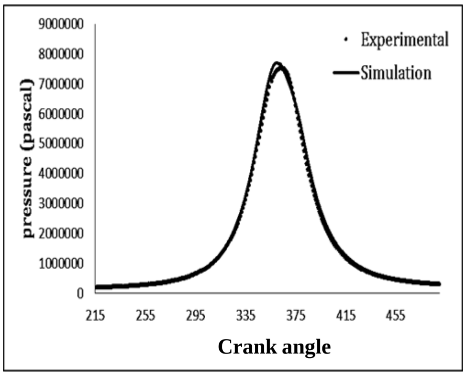
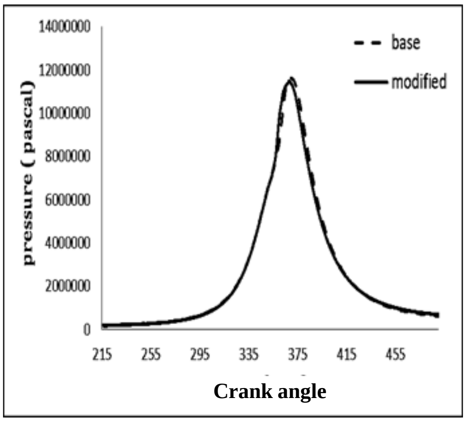
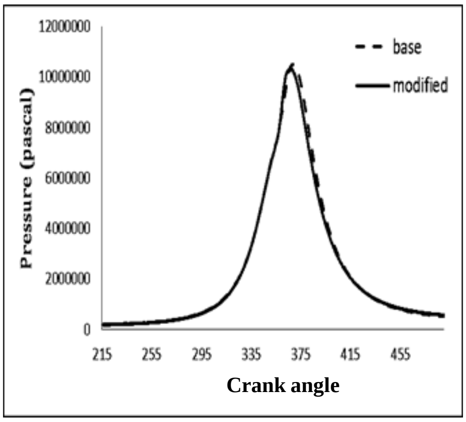


(d)

Fig. 4. Comparison of predicted and measured engine in-cylinder pressure for the at (a) 100% load and (b) 75% load (c) 50%load (d) 25% load



(a)



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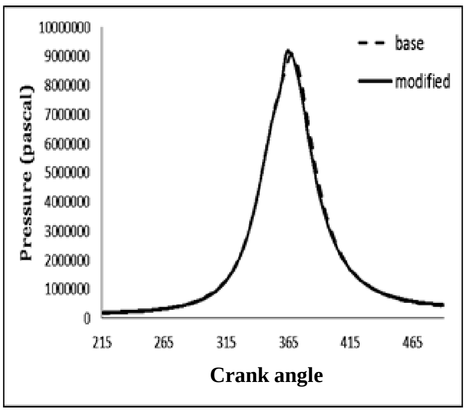

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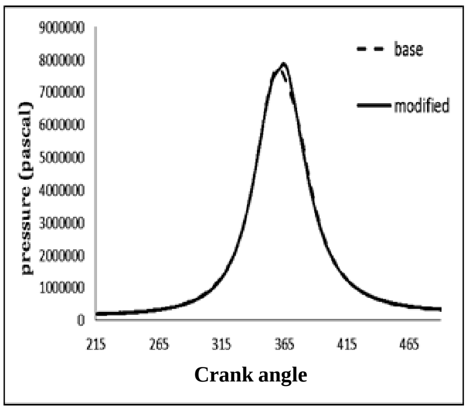

(d)

Fig. 5. Mean in-cylinder pressure versus crank angle for (a) 100% load and (b) 75% load (c) 50% load (d) 25% load

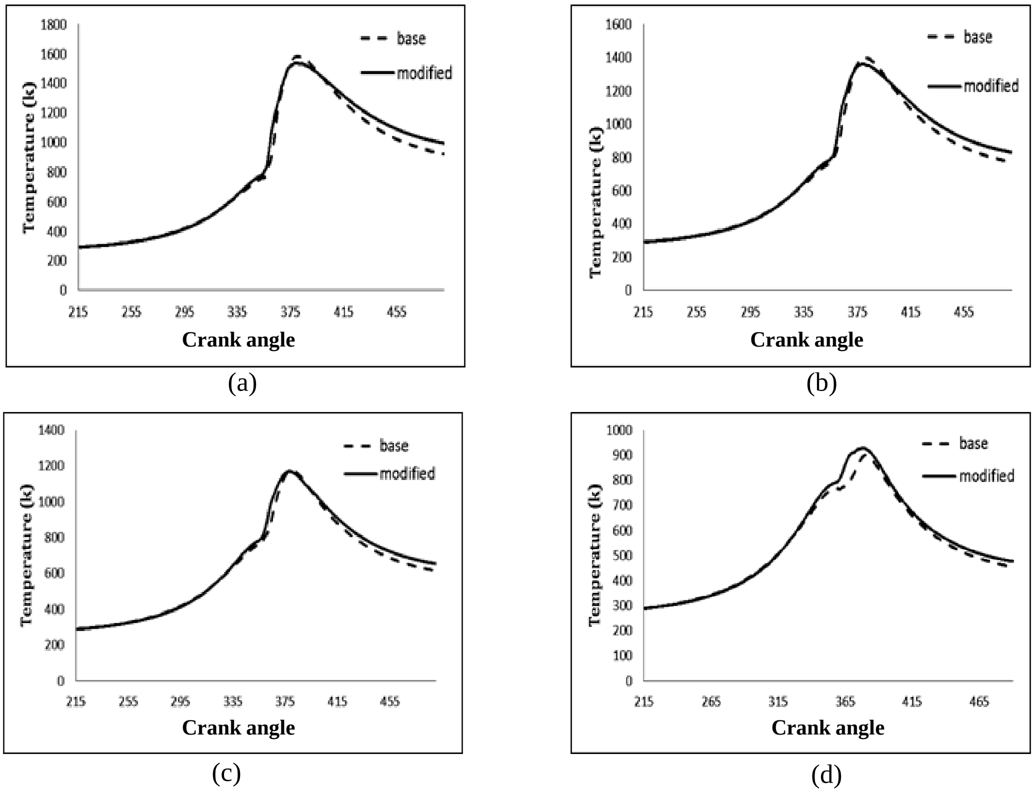

Fig. 6. Mean in-cylinder temperature versus crank angle for (a) 100% load
(b) 75% load (c) 50% load (d) 25%load

The process of combustion in diesel engines includes the stages of ignition delay, pre-mixed or rapid combustion, diffusion combustion, and late combustion [20]. Some factors effective in ignition delay are fuel type, temperature and combustion chamber pressure. At pre-mixed stage, the injected fuel during the delayed period burns at a high rate. Diffusion combustion is associated with the end of injection period, and injection stops at late combustion stage while the fuel is still being mixed inside the chamber by the gas movement; at this stage the rate of combustion basically depends on oxygen availability and the phenomenon of diffusion [21].

Figure 7 shows heat release rates at four working modes of the engines. At 25% load and 50% load, one can observe that ignition delay period for modified condition is 1 degree less than that for base condition. The reason for this phenomenon is that there are higher temperature and pressure in the modified condition during the ignition delay period. As can be seen in the figure, at the stage of rapid combustion at 25% load and 50% load for modified condition, heat release rate is higher than those for base engine and this is because of providing optimal conditions at the period of ignition delay (higher temperature and pressure).

During the diffusion combustion, due to insufficient air inside the main combustion chamber in modified situation, heat release rate for base condition is more than that for modified engine. At late combustion stage, owing to the entrance of oxygen from air cell into the combustion chamber during the course of expansion after 25° ATDC, the rate of available oxygen at this stage increases; combustion occurs more intensely during this period for modified condition than that for base engine.

At 75% load and 100% load, because of high pressure and temperature of combustion chamber at ignition delay period, heat release rate at pre-mixed stage in base condition is higher than that in modified engine. The behavior of heat release rate curve at diffusion combustion stage is similar to those at 25%load and 50% load. Also, at late combustion stage due to recirculation of air into the main combustion chamber, more intensified turbulence occurs in modified condition than in base engine. The effect of reserved air jet on main chamber in modified engine is seen as fluctuations in heat release rate at late combustion period.

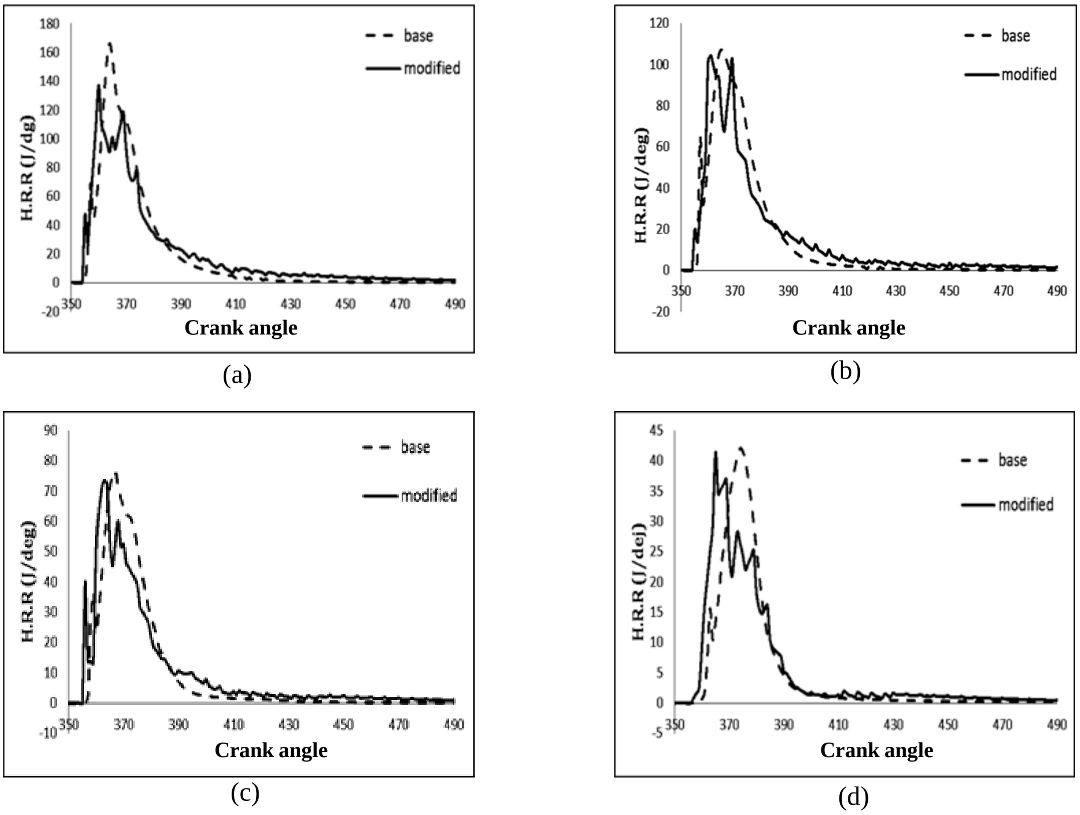

Fig. 7. Mean in-cylinder heat release rate versus crank angle for (a) 100% load and (b) 75% load (c) 50% load (d) 25% load

4. PERFORMANCE PARAMETERS

Table 2 depicts the variations of performance parameters, power, as well as indicated specific fuel consumption (ISFE).

Work per cycle by:

$$W=\int_{\theta 2}^{\theta 1} Pdv \quad (1)$$

Where θ1 and θ2 are closing intake valve and opening exhaust valve, respectively and dv is cylinder capacity stroke volume. The power of each cylinder is defined as:

$$p(KW)= \frac{W(N.M).N(rPm)}{6000\,\mathrm{n}} \quad (2)$$

Where n=2 is the number of crank rotation for each power stroke per cylinder and n is engine speed (rpm). Indicated specific fuel consumption is calculated as:

$$ISFC=\frac{\dot{m_f}}{p_i} \quad (3)$$

Where $\dot{m_f}$ is the rate of fuel injection into the combustion chamber. It should be mentioned that in Eq. (1) the work was only integrated at compression and expansion stages and the pumping work was ignored.

Table. 2. Operation characteristics for base and modified engine at part and full load conditions

		Work (kJ/cycle)	Indicated power(Kw)	$\dot{m}_{fuel}$ (gr/sec)	ISFC (gr/kw.hr)
Base	100% Load	1.28	21.38	1.16	195.12
	75% Load	0.94	15.66	0.87	198.36
	50% Load	0.61	10.16	0.58	205.2
	25% Load	0.27	4.61	0.29	219.60
Modified	100% Load	1.26	21.09	1.16	198
	75% Load	0.92	15.42	0.87	203.04
	50% Load	0.60	10.03	0.58	208.08
	25% Load	0.30	5.00	0.29	208.80

6. EMISSION ANALYSIS

NOx and Soot are the main exhaust emissions in diesel engines. Two major factors in the production of NOx are oxygen presence and high temperature regions [22]. Figure 8 shows the variations in NOx emissions. At 25% load and 50% load, the presence of high temperature regions as well as higher heat release rates at rapid combustion stage provide a more suitable background for further severance of nitrogen in modified engine than that in base engine. This phenomenon results in increases in the rate of exhaust NOx emissions from modified condition than those from base engine. The increase rate of NOx emission at 25% load compared with base condition is 27%, and at 50% load it is 2.5%. Low temperature regions as well as lesser pre-mixed combustion phase in modified engine compared to base engine at 100% load and 75% load bring about decrease of exhaust NOx emission in this condition. Decrease rate of exhaust NOx emission compared with base engine condition at 75% load and 100% load are 40% and 36%, respectively.

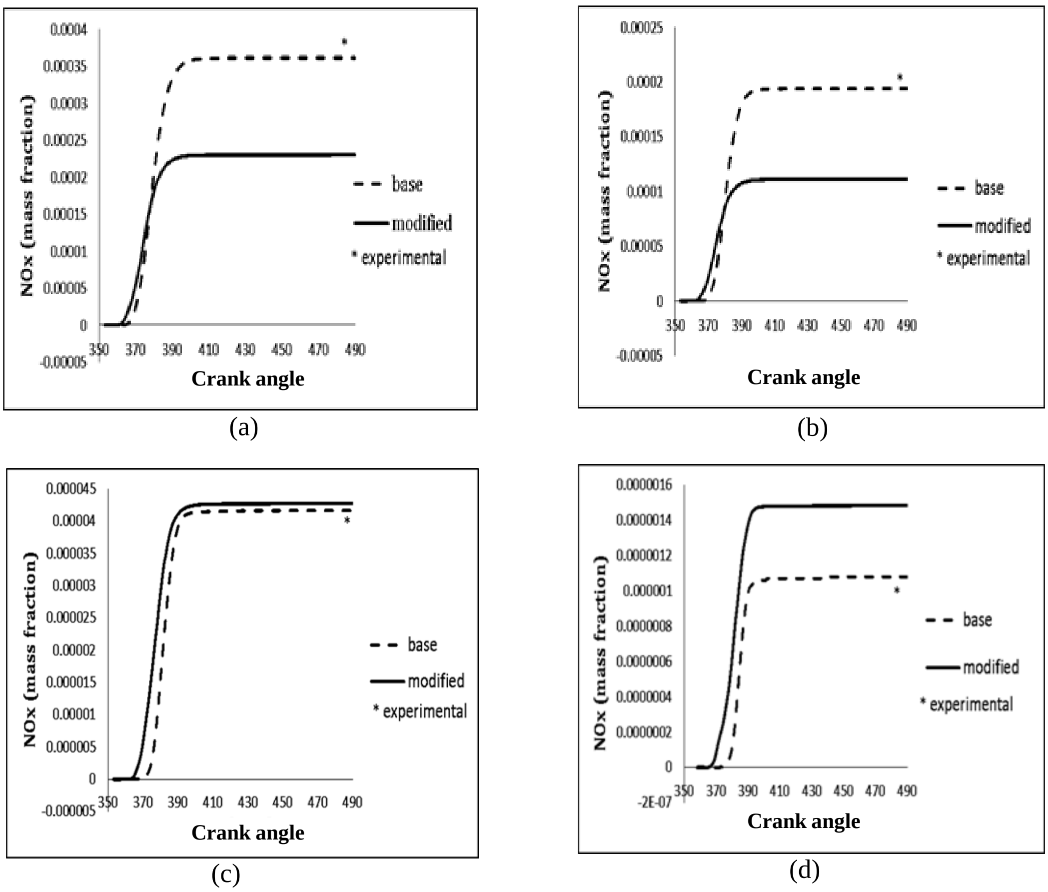

Fig. 8. results for NOx emission at (a) 100% load (b) 75% load (c) 50% load (d) 25% load

Figure 9 indicates variations in Soot emission. The rate of Soot formation begins from the start of combustion and at the peak of diffusion phase due to regions rich in fuel, overtakes its rate of oxidation, and then because of fuel reduction in the combustion chamber, its oxidation rate becomes faster [23]. Owing to increase in fuel-air mixture as well as increase in oxidation rate at the last stage of combustion in modified engine which originates from air injection into the combustion chamber by means of air cell during the course of expansion, the amounts of exhaust smoke from the modified engine in comparison with base engine at 25% load, 50% load, 75% load and 100% load have decreased 18%, 51%, 45%, and 53%, respectively.

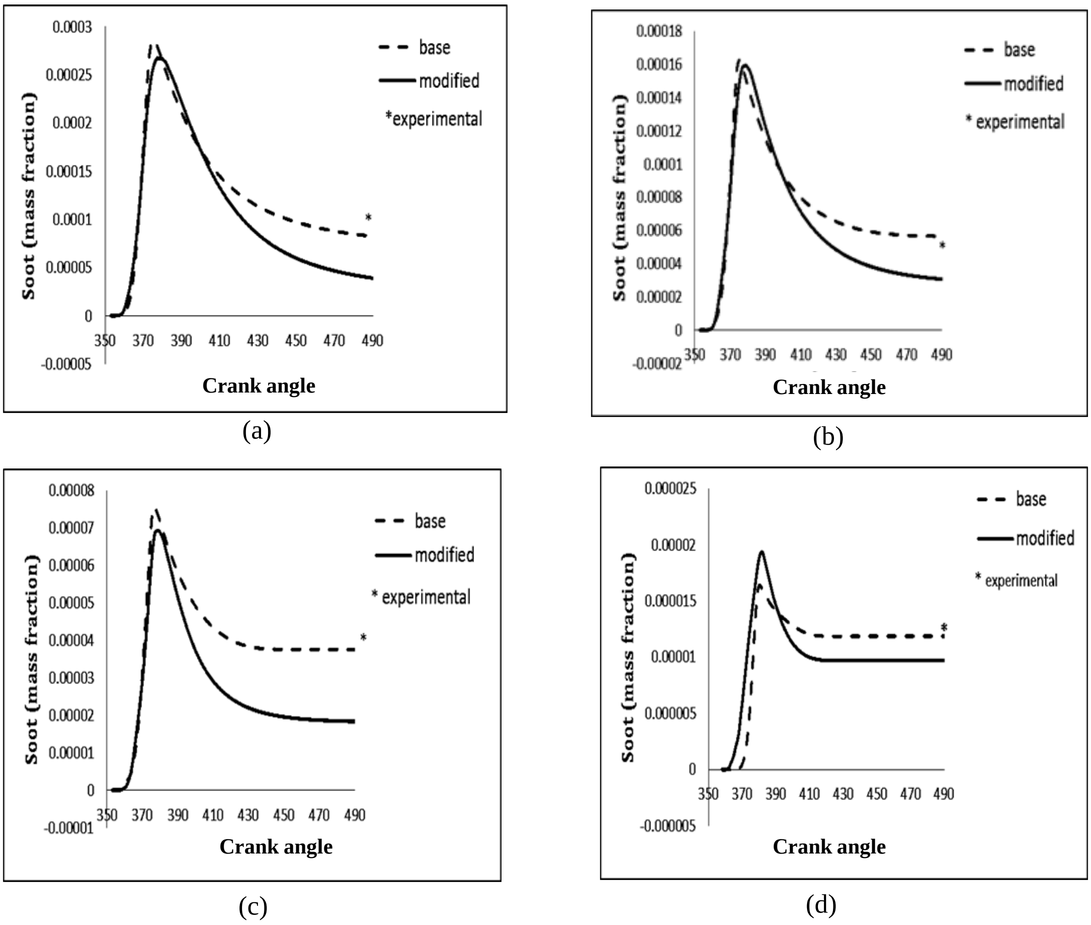

Fig. 9. Results for Soot emission at (a) 100% load (b) 75% load (c) 50% load (d) 25% load

Figure 10 shows speed vectors of modified engine at various crank angles. At compression stroke, the direction of flow at connecting throats of air cell is from the main chamber toward air cell. At this stage, air is reserved in the air cell at a high pressure. The obtained peak speed at angle 360 CA toward secondary chamber is 126 m/s. By fuel injection and start of combustion after top dead center, the speed of airflow at the throat reduces and at angle about 380 CA reduces to zero. Then, the flow direction changes toward main chamber. Inlet airflow into the combustion chamber through air cell causes fuller combustion of the remaining fuel at the final combustion stage as well as better oxidation of produced smoke at expansion stage.

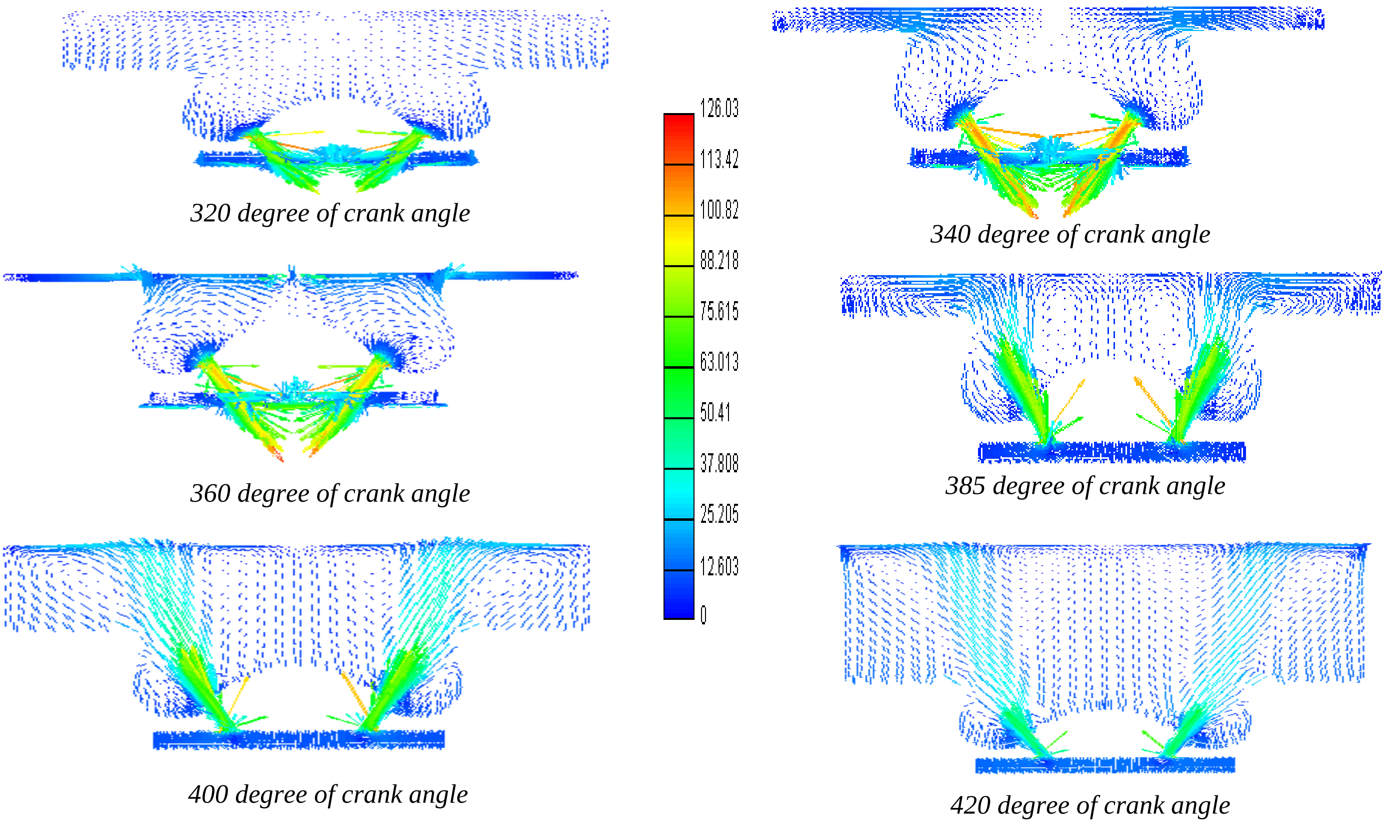

Fig. 10. Speed vectors (m/s) for modified engine in various crank angles

In Fig. 11, the contours of oxygen mass fraction, combustion chamber temperature, soot emission, and NOx emission for both base and modified engines at 390 degree of crank angle and 100% load are shown. As can be noted in the regions with high oxygen, the process of soot oxidation is done better and less smoke is seen there. Moreover, where there is not sufficient oxygen, oxidation happens at lower rate and more smoke remains in the combustion chamber. By injecting oxygen through air cell into the main chamber, due to oxygen availability and turbulence intensification, oxidation rate increases and regions with less smoke are observed. Higher amount of not oxidized soot emission is seen below the piston head (around the mouth of the throats) where re-circulated air from the air cell has less penetration. High temperature regions provide appropriate bed for NOx emission formation. Considering the temperature contour, it can be seen that by injecting air from air cell into the main chamber, temperature is reduced in the middle regions of the cylinder and the temperature of the side walls of the cylinder increases (because of increase in combustion rate in these regions), that is why in modified engine the amount of emission reduces in the middle regions of the combustion chamber and increases in the regions close to the cylinder walls.

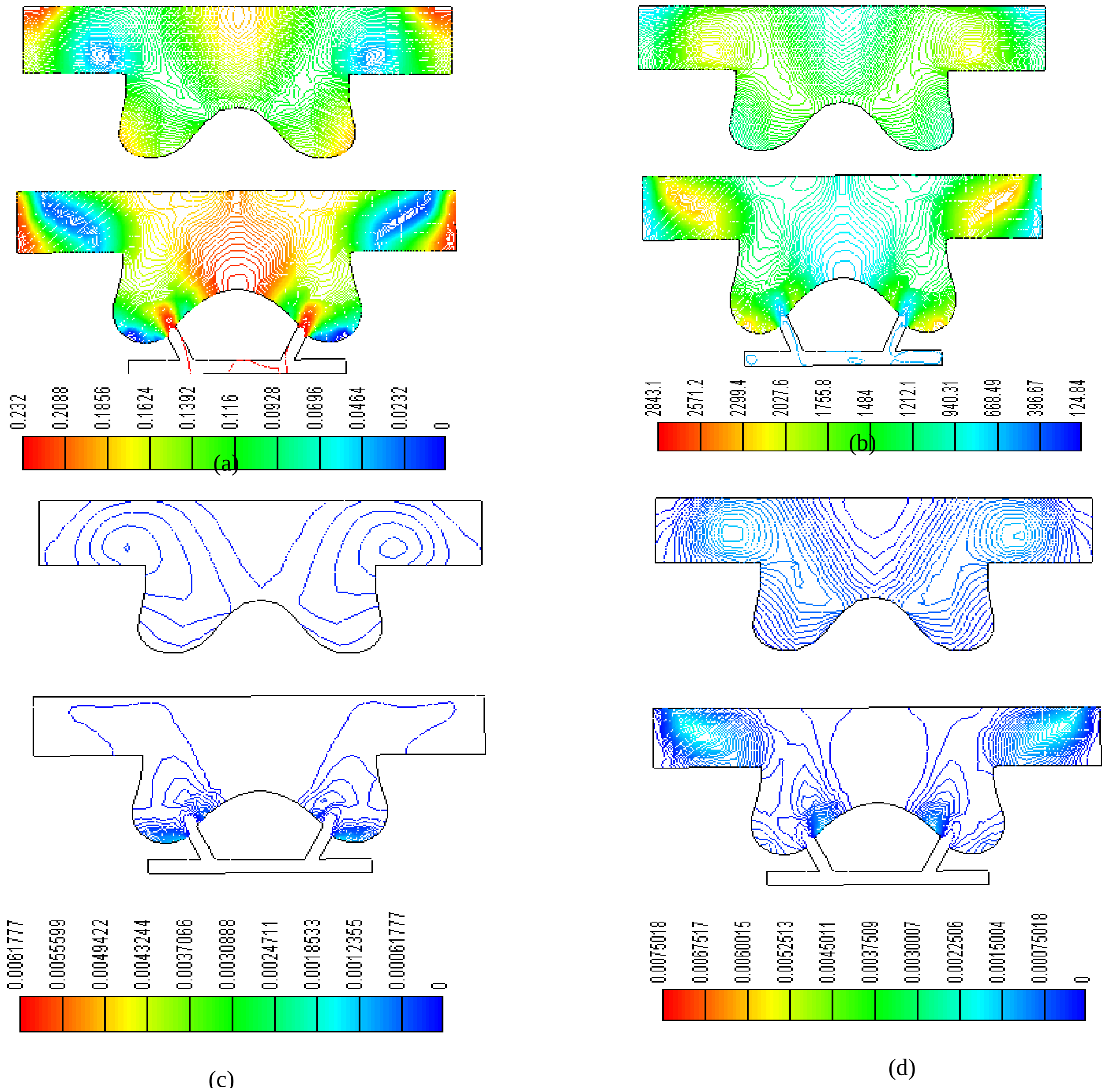

Fig. 11. (a) Temperature (k) (b) Oxygen mass fraction (c) Soot mass fraction (d) NOx mass fraction contour plots

7. CONCLUSION

In this paper, firstly the process of combustion, performance parameters, Soot and NOx emissions for engine MT. 4.244 at 100% load, 75% load, 50% load, and 25% load were simulated. The comparison of pressure curve inside the combustion chamber for base engine along with experimental results for four modes demonstrates a good correspondence between the obtained results and lab data. At the next stage, by adding air cell and four throats to the main combustion we dealt with the effect of air jet on the produced emissions, performance parameter and combustion process. The results show that at 100% load engine power reduces as little as 1.4%, ISFC increases 1.4%, and soot and NOx emissions decrease 53% and 36%, respectively. At 75% load engine power reduces 1.5%, ISFC increases 2.2%, and soot and NOx emissions decrease 45% and 40%, respectively. At 50% load engine power reduces 1.1% and the value of

ISFC increases 1.3%. The amount of NOx emission in modified engine increases 2.5% and soot emission reduces 50%. At 25% load, the power of modified engine increases 7%, and ISFC decreases 0.5%. NOx emission in modified engine compared to base engine increases 27%, and soot emission reduces 18%.
The significant results can be classified as follows:

1. Using air cell is an efficient way to reduce exhaust smoke emission from a direct injection diesel engine by means of increasing mixture as well as sufficient oxygen availability during diffusion combustion through air jet inside the combustion chamber in all four performance conditions.
2. Using air cell in this engine at 100% load and 75% load causes reduction in NOx emission, yet 50% load and 25% load the amount of this emission increases.
3. Equalizing compression ratio between base and modified engine can prevent power reduction and considerable increase of ISFC.

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