Influence of Piston Bowl Shape and Number of Holes in Injector on Spray, Combustion and Emissions of a Diesel Engine: a Numerical Research

Shahanwaz Khan, RajsekharPanua, Probir Kumar Bose

***Abstract:**Present study considers numerical simulation to explore the combine influence of piston bowl shape and number of holes on spray, fuel combustion and pollutant emissions of a diesel engine. The fluid flow behavior in combustor is extensively depends on piston bowl shape that affects the air fuel mixing, combustion and emissions. The number of holes in injector nozzle is a crucial constraint that influences the distribution of the fuel inside the combustor. To study the effect of piston bowl profile, three combustion chambers have been chosen for the same bowl volume and compression ratio of 17.5. The injector used for the study varied number of holes from 3 to 6 and the size of holes varied to maintain total area of nozzle holes constant. The investigation has been done on a compression ignition engine using the commercial CFD code AVL FIRE. The predicted results disclose that increasing number of holes considerably enhances combustion and improve emissions from piston bowls and the TRCC piston bowl predicts better performance.*

***Keywords:**Combustion, Spray, Swirl, Turbulence.*

I. INTRODUCTION

Diesel engines due to their better performance, efficiency and portability remain a primary option as leading propulsion system for ground transportation. In order to increase engine performance and reduce harmful emissions research efforts are focused on developing modern efficient diesel engine by improving the mixture formation and combustion processes. The improvement in air-fuel mixing is possible in compression ignition engines through changes in injector nozzle hole strategy and shape of combustor. Numerical investigation has been evaluated to analyze the impact of nozzle hole and shape of combustor on spray development, combustion and emissions in diesel engine. The ignition process in compression ignition engine is mainly depends on fuel injection system and perceptive of fuel distribution process. The shape of combustor and the number of holes in nozzle are the important controlling parameter effecting air fuel mixing in a CI engine and significantly influences the burning progression and pollutant emissions.

B. H. Lee et al. [1] proposed an best possible hole number for better performance, ignition and emissions in diesel engine and their result demonstrates that increased number of holes greatly affects evaporation, mixing, and ignition. S. P. Venkateswaran and G. Nagarajan [2] studied that the swirl and turbulence level of bowl with high re-entrance are much superior compared to baseline piston bowl and it generates enhanced performance and combustion which is helpful in reducing the specific fuel consumption and exhaust soot. L. Lin et al. [3] reported that to have better combustion with reduced pollutant emissions, it is necessary to have better distribution of fuel throughout the combustion chamber. Thus piston bowl shape, fuel injection and fluid dynamics are the important factors responsible for better combustion. A. R. G. S. Raj et al. [4] investigated that a central position of bowl on piston is better in terms of swirl, tumble and turbulence which play crucial role in developing suitable air movement, thereby enhancing the energy conversion process of the engine. J. Li et al. [5] investigated that Omega piston bowl is more efficient piston bowl profile in generating powerful squish in a short period which in turn improves the engine performance compared to other combustion chamber configurations . TRCC piston bowl have better performance, combustion and emission characteristics over other configurations of combustor [6-8]. S. K. Gugulothu and K. H. C. Reddy [9] investigated that a flat piston bowl enhances in-cylinder swirl and turbulence which improves air and fuel interaction. S. W. Park and R. D. Reitz [10] reported that injector nozzle hole layout influences effective fuel injection process which improves fuel consumption and pollutant emissions. V. Kumar [11] studied that modified piston bowl profiles enhances atomization in engine that resulted into homogeneous burning which reduces the fuel consumption compared to baseline engine. B. Kim et al. [12] examined the influence of modification in spray breakup model constant C2 with respect to spray angle and segmented time as a dependent parameter of density of fluid in combustor on combustion duration. C.P.A. Gafoor et al. [13] investigated that piston bowl geometry significantly affect the swirl and turbulence which intern enhance the quality of combustion. S. Jaichandar et al. [14] studied that combustion, performance and emissions diesel engine may enhanced by introducing tangential air passages to TRCC piston profile.

It is evident from above literature, very few analysis have been performed on the basis of piston bowl shape along with number of holes on fuel spray, ignition and emissions in

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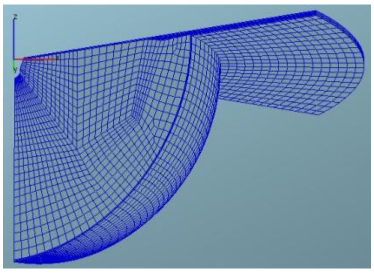
compression ignition engine. Hence, to have better perceptive of these issues, it is necessary to explore the influence of piston bowl shapes and the number of nozzle hole in injector. The central theme of present attempt is to improve the fuel distribution, atomization, evaporation and fuel-air mixing through efficient spray and air motion in combustor. The detailed in-cylinder spray, combustion and emission characteristics have been studied to find out an optimal piston bowl shape and hole number in fuel injector.

II. MATERIALS AND METHODS

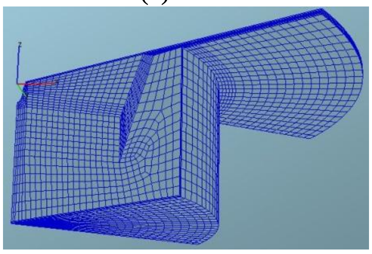
Diesel engines combustion, performance and emissions are mainly influenced by spray progression, fuel atomization and evaporation which in turn are robustly influenced by the fluid dynamics through injector nozzle. In order to study the impact of hole number in injector associated with modification of piston bowls, hole numbers varied from 3 to 6 and the size of nozzle orifice varied from 0.2121 to 0.3 mm so that the total discharged area of the holes remains constant. The detailed injection strategies for different injectors have been shown in Table 4. The fuel mass flow rate was circulated across the nozzle holes such that the total amount of fuel mass injected into the combustor remains constant. A centrally located injector has been considered for all the studies.

A.Piston Bowl Shapes

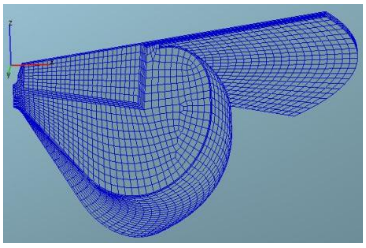
In present numerical analysis, to analyze the influence of piston bowl geometry on fluid motion, ignition and emissions of diesel engine, the combustor shape was customized to have Cylindrical combustion chamber (CCC) and Toroidal re-entrant combustion chamber (TRCC) apart from the baseline Hemispherical combustion chamber (HCC). For all three combustion chambers, the bowl volume remains constant to have same compression ratio. Furthermore, the cell size of each created medium mesh for all combustion chambers was considered to be same. The created meshes for three investigated piston bowls with 60° sectors were illustrated in Fig. 1. The technical specifications have been illustrated in Table 1 for the test engine.



(a) HCC



(b) CCC



(c) TRCC

Fig. 1.Generated meshes of three piston bowls with 60° Sector.

Table 1 Technical specifications of engine.

Engine type	4-Stroke, Single Cylinder, Water cooled, Diesel Engine
Bore X Stroke	87.5 X 110 mm
Compression ratio	17.5:1
Length of connecting rod	234 mm
Rated power	5.2 @1500 RPM
Rated Speed	1500 RPM
Outlet diameter of hole	0.3 mm
Number of nozzle hole	3
Injection timing	23° before TDC
Injection Pressure	210 bar
Combustor shape	Hemispherical
Inlet valve closing	35.5° after BDC
Exhaust valve opening	35.5° before BDC

B. Solution Algorithms

In the present investigation commercial CFD code AVL FIRE, specially developed for in-cylinder simulation has been applied to study the in-cylinder processes. It uses implicit temporal discretization technique based on finite volume approach to solve the governing equations of fluid movement. The SIMPLE algorithm has been considered for pressure velocity coupling intended for the solution of flow field. The discretization of continuity equation has been done based on central differencing scheme and upwind differencing scheme is considered for discretization of momentum, energy and turbulence equations. The applied different sub- models for this present analysis have been listed in Table 2.

Table 2 Considered models for simulation.

Breakup model	WAVE
Turbulencemodel	*k-ζ- f*
Evaporation model	Dukowicz
Wall interactionmodel	Walljet1
Combustion model	ECFM-3Z
Soot model	Kinetic Model
NO model	Extended Zeldovich

C.Boundary and Initial Conditions

In present study, no-slip boundary condition is applied at the wall boundaries like piston bowl, cylinder liner and cylinder head. Continuous boundaries are employed as cyclic symmetry boundary condition and moving wall

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boundary condition is employed to piston bowl. Wall boundary conditions were considered to cylinder wall and cylinder head. The near wall cells are treated as standard wall boundary conditions. The initial conditions for CFD calculation specified at intake valve closing are illustrated in Table 3.

Table 3 Initial conditions for calculation.

Initial temperature	335 K
Initial pressure	1 bar
Cylinder head temperature	425 K
Piston temperature	525 K
Liner temperature	375 K
Residual gas ratio	0.05
Fuel	Diesel

D. Mesh Independence Study

Mesh independence study has been done using hemispherical piston bowl to decide the optimum mesh size with 120° sector (based on 3 holes injector). The coarse, medium and fine mesh contains 14854 cells, 29525 cells and 45700 cells respectively at TDC position. To clarify the grid independence, simulations have been done for three meshes at constant speed of 1500 rpm at full load. The calculated ignition pressure results comparison have been shown in Fig. 2. It have been found that further refinements on the mesh size, the influence on calculated ignition pressure curves from the medium to fine mesh is negligible. Therefore, to save computational cost, medium mesh has been adopted throughout the investigation.

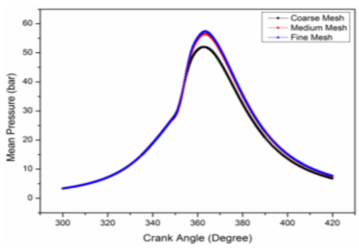

Fig. 2. Combustion pressure prediction considering coarse, medium and fine meshes.

E.Model Validation

To verify the numerical stability of the software code, the simulation results are compared with experimental measurement carried out on a diesel engine having 3 holes nozzle in injector and hemispherical combustor. It is obvious from Fig. 3, the cylinder ignition pressure of predicted and experimental results are capable to precisely forecast the in-cylinder ignition characteristics within permissible tolerance limits.

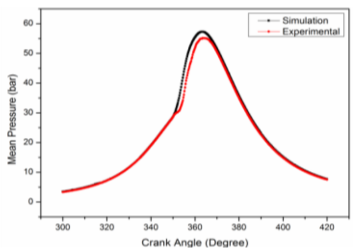

Fig. 3. Validation results of cylinder pressure at full load operation.

III. RESULTS AND DISCUSSIONS

In present investigation, to observe the influence of piston bowl profile and number of nozzle holes on fuel spray progression and combustion quality. The impact of these parameters on combustion was analyzed using combustion pressure, cylinder temperature, heat release rate and emissions at full load condition. The mixture formation and combustion processes have been carried out from inlet valve closure (IVC) to exhaust valve opening (EVO) of the engine.

The predicted ignition pressure distribution with crank angle among three piston bowls against the injector nozzle holes have been shown in Fig. 4. It has been found that TRCC bowl depicts highest combustion pressure compared to CCC and baseline HCC geometry. The improved air movement due to profile of combustor during fuel injection is favourable for fuel-air assimilation process and burning in TRCC piston bowl. It was also found from the figures that increase in number of holes from 3 to 6, ensured better fuel-air mixing process in the combustor, leads to better combustion and hence increased cylinder pressure.

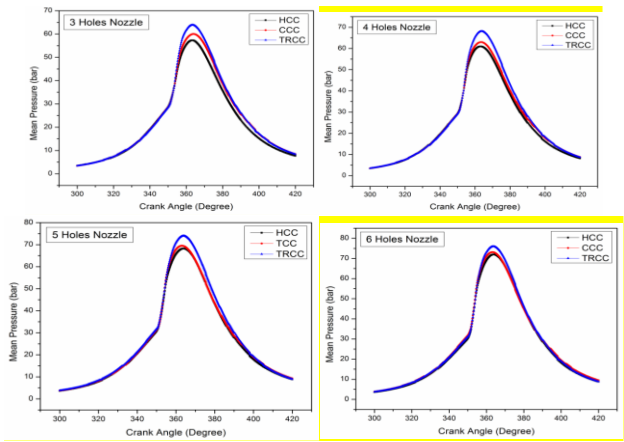

Fig. 4.Predicted in-cylinder pressure in three piston bowls for different nozzle holes.

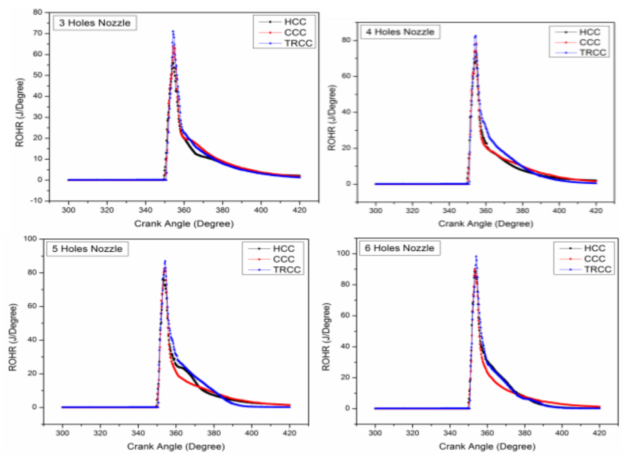

Fig. 5.Comparison of rate of heat release in piston bowls operating on different nozzle holes.

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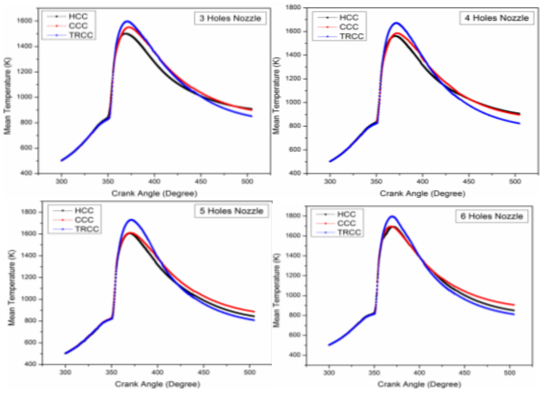


Fig. 6. Distribution of cylinder temperature in three piston bowls against nozzle holes.

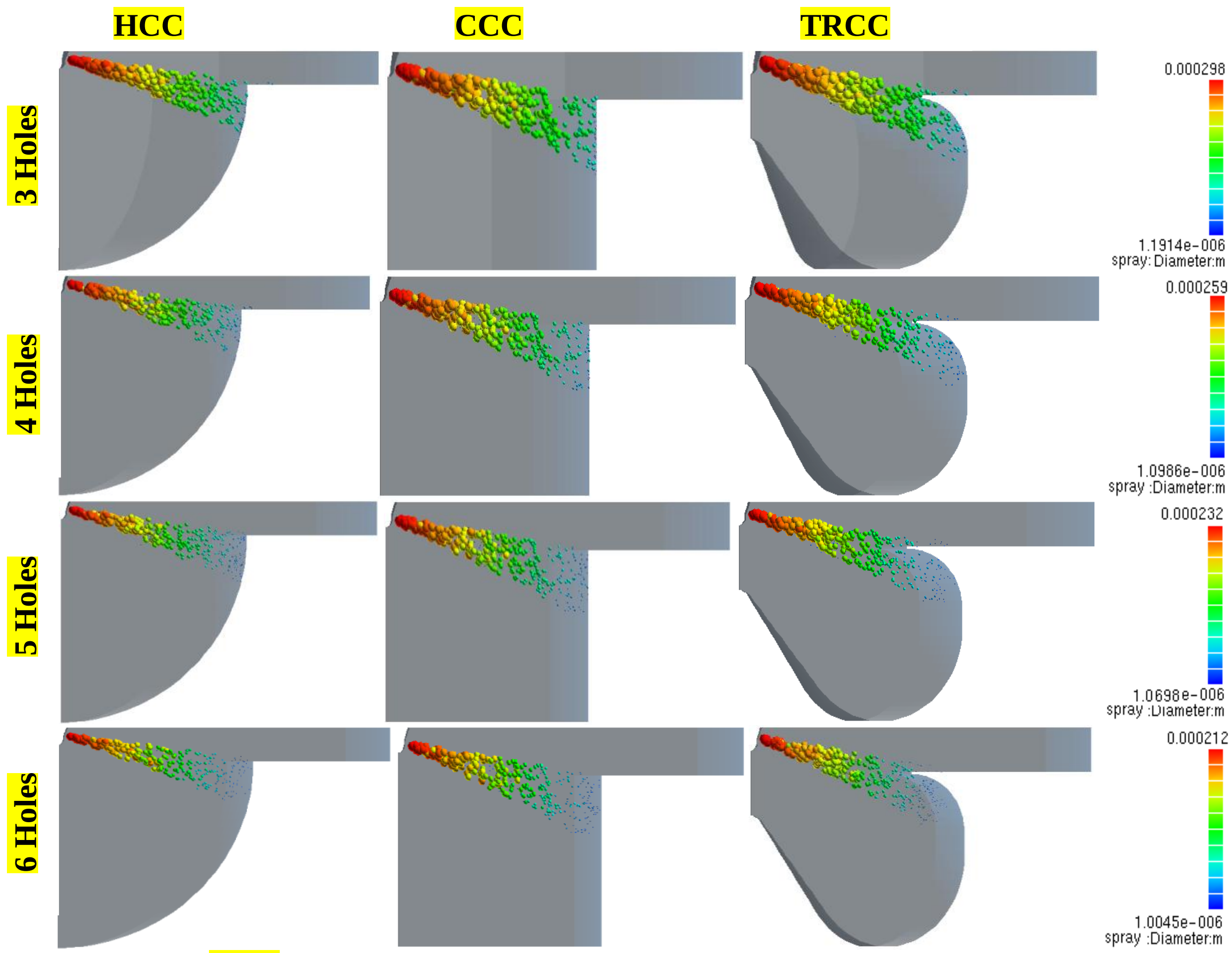


Fig. 7.Distribution of predicteddroplet size in combustors at 20° before TDC.

Fig. 5 demonstrates heat release rate variation among different combustors associated with the number of holes in injector. It was found that TRCC bowl profile predicts the highest value of heat release rate as compared to other piston bowls. The enhanced air motion into the fuel being injected due to increasing turbulence of TRCC piston bowl is liable for enhanced fuel-air assimilation and ignition. Also it has been found that injector having 6 holes nozzle shows highest heat release rate compared to other nozzle holes. The increased number of holes in nozzle will inject the same amount of fuel at more locations. This would have improved the fuel distribution, atomization and evaporation within the engine cylinder which promotes the combustion.

Fig. 6 shows the ignition temperature in various combustors against the number of holes. It have been found from the figures that the cylinder burning temperature magnified as the number of holes increases and the TRCC piston bowl shows higher temperature among the piston bowls. The higher turbulence in TRCC piston bowl prepares more homogeneous mixture of injected fuel with air, resulting in improved combustion responsible for higher temperature.

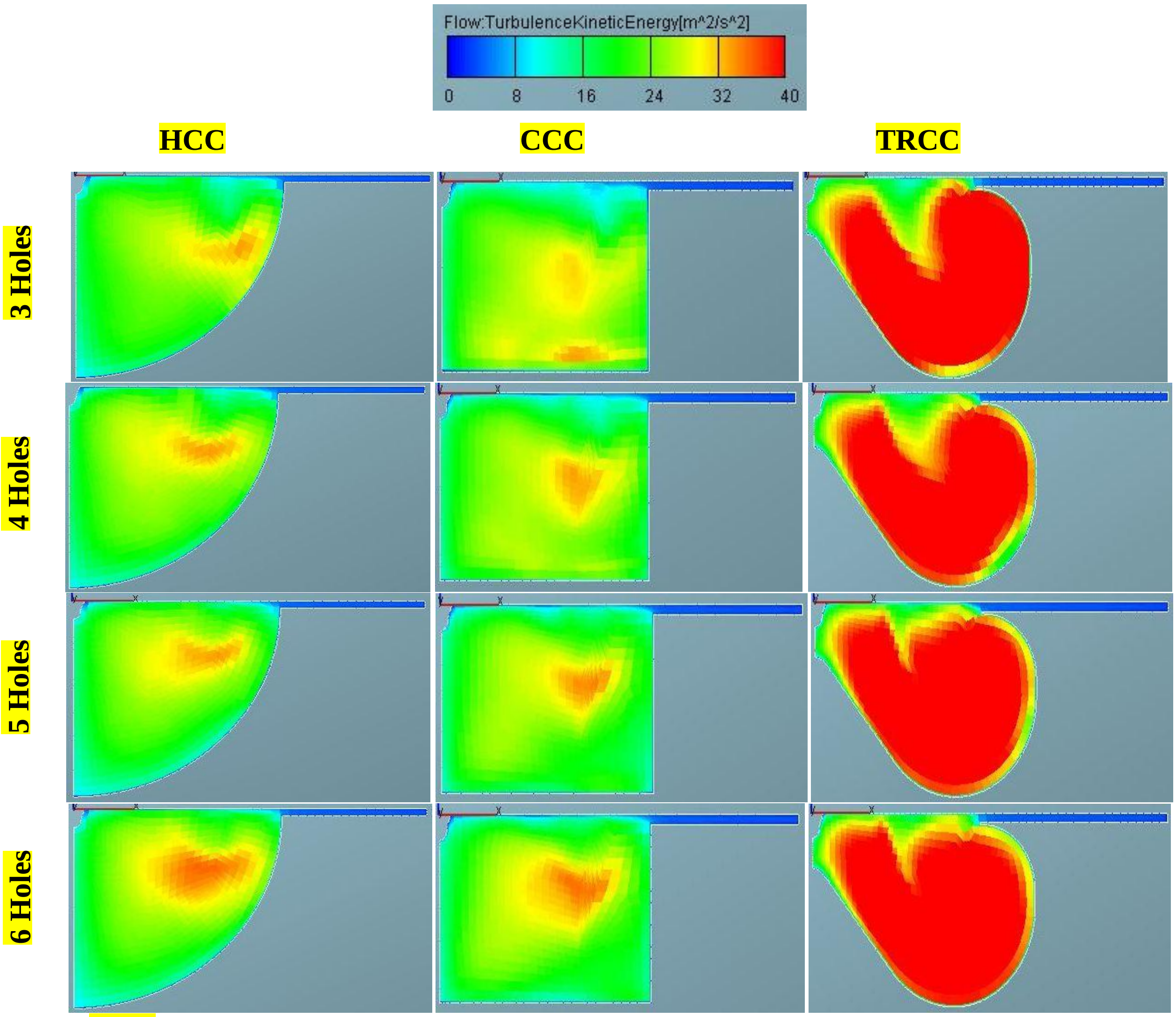


Fig. 8.TKE distribution in combustors with various numbers of holes at 5° crank angle before TDC.

The fuel interaction with combustor air and wall has important effect on fuel-air assimilation process. The injected fuel spray pattern among three investigated piston bowls has been shown in Fig. 7 for fuel injector with 3 to 6 holes nozzle. It has been observed from the figures that the increased number of holes reduces the size of the droplets and fuel is going to be injected at more locations for all three piston bowls. This would have improved the fuel distribution within the engine cylinder and decreases wall impingement. Fuel spray pattern and atomization characteristics are the driven keys to improve combustion and emission characteristics.

Fig. 8 represents the traces of turbulence kinetic energy at 5° crank angle before TDC among piston bowls operated under different number of holes in injector. The result implies that TRCC bowl shows larger region of peak turbulent kinetic energy compared to other piston bowls. Consequently, air-fuel interaction in the combustor could drastically be improved by increasing turbulence due to piston bowl profile.

Fig. 9 shows the mass fraction of NO emission from combustors at 15° crank angle after TDC operated under various numbers of holes in injector. The result implies that there is larger area of high NO emission in TRCC bowl compared to CCC and baseline HCC geometry. The increase in NO emission from TRCC piston bowl is due to higher in-cylinder ignition temperature resulting from better combustion due to improved mixture formation. Also it has been found that NO emission is increasing with the number of holes in fuel injector for all piston bowl geometries due to reduction in the sizes of the fuel droplet particles present inside the combustion chamber.

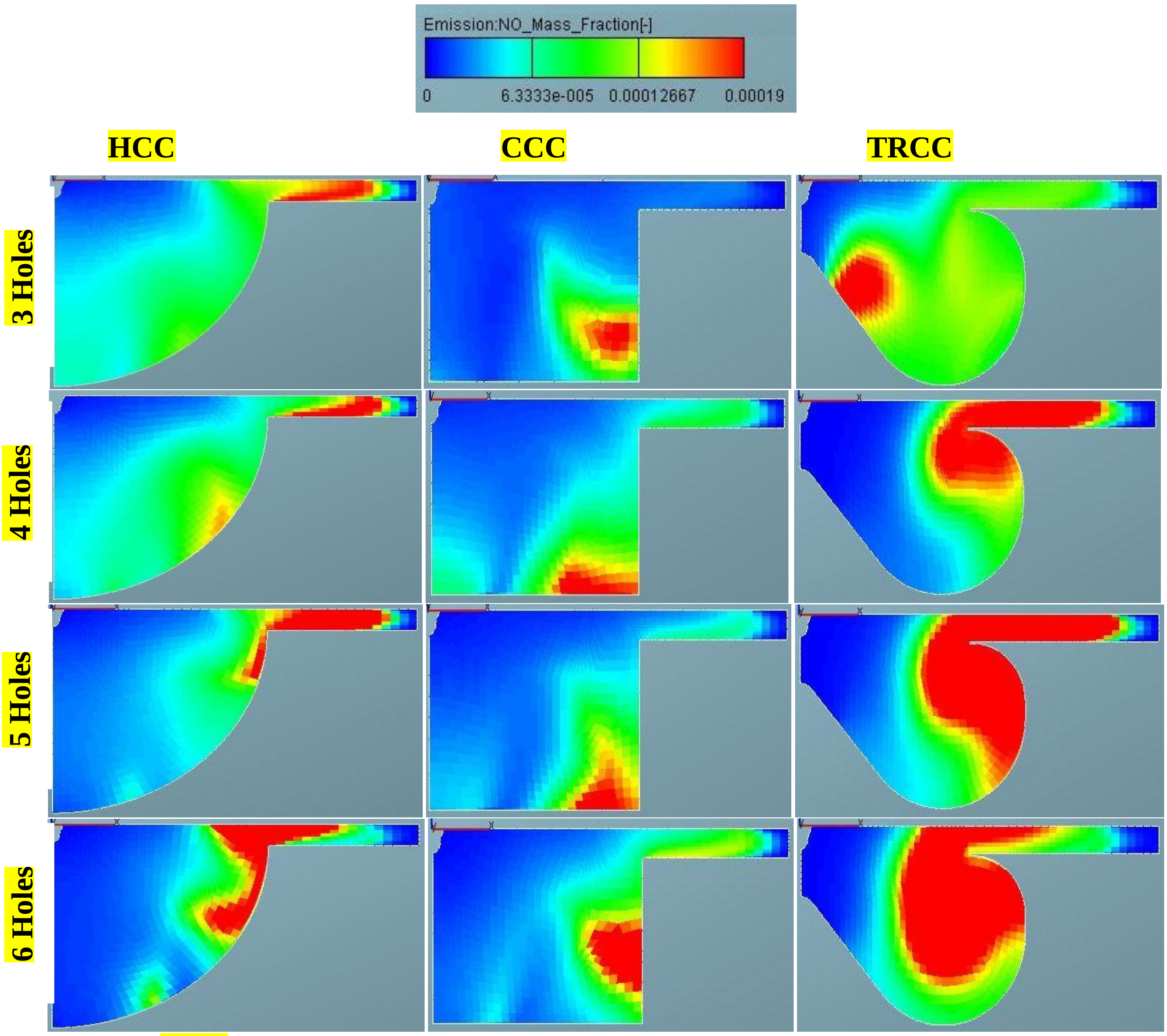
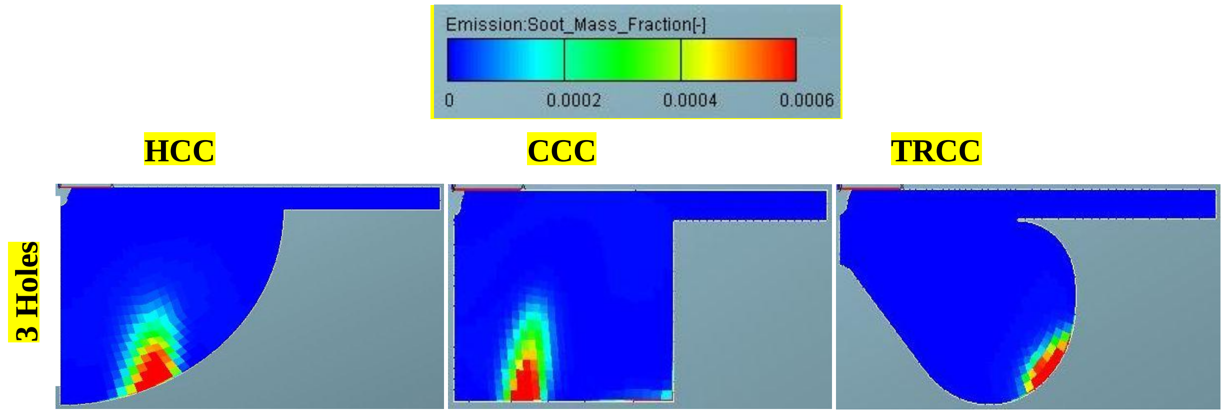


Fig. 9.Traces of NO emission contour of combustors at 15° crank angle after TDC.

Fig. 10 demonstrates contour of soot emission at 15° crank angle after TDC from combustors operated under different number of holes in injector. It has been observed from the contours that higher hole size injector mainly injects fuel on the combustor walls due to higher fluid momentum and thus have larger fuel rich regions as well. Hence soot emissions were found to be more with 3 holes and least with 6 holes injector. It is clear from the contour that in TRCC piston bowl soot oxidation is more and formation of soot is low due to high ignition temperature controlled by better fuel-air mixing process compared to CCC and baseline HCC piston bowls.



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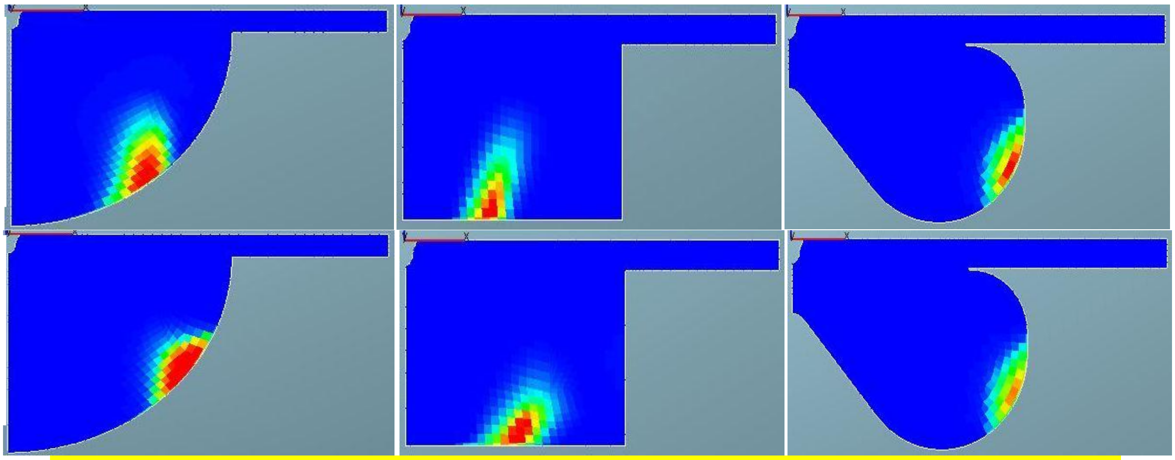

Fig. 10. Predicted soot emission contour of different combustors at 15° crank angle after TDC.

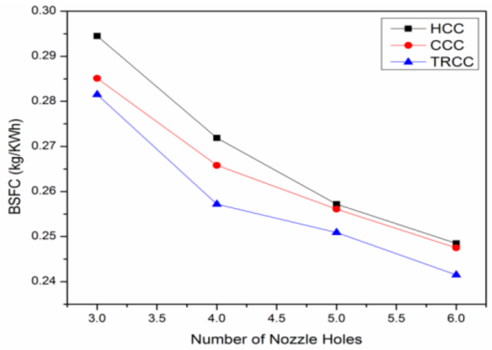

Fig. 11. Brake specific fuel consumption against nozzle holes using various piston bowls.

The brake specific fuel consumptions against number of holes for three piston bowls have been shown in Fig. 11. As the number of holes increasing, size of nozzle holes is decreasing to inject same quantity of fuel inside the combustor which enhances the atomization of fuel. The improved atomization and mixture formation ensures superior ignition resulting reduced specific fuel consumption of engine. The specific fuel consumption for CCC and HCC are higher than that for TRCC bowl profile. The increased turbulence in TRCC bowl improves fuel-air mixture formation responsible for more complete combustion resulting decreased specific fuel consumption.

IV. CONCLUSION

The numerical analysis has been performed to study the impact of piston bowl profile and number of holes in fuel injector on spray pattern, fuel-air mixing, ignition and emissions of a diesel engine at full load operation. The fluid flow phenomenon inside the combustor is robustly dependent on piston bowl profile and holes number in injector nozzle effects spray break up, atomization, air fuel mixing and evaporation of fuel. The general conclusions have been drawn from the investigation have been summarized as follows:

- Increasing number of holes in injector nozzle significantly improves spray characteristics, fuel distribution, atomization, fuel-air mixing and evaporation of fuel resulting better ignition with enhanced performance and emission as well.
- The six holes nozzle shows best combustion behaviour and engine performance among investigated nozzle holes, due to better distribution of fuel and decreased wall impingement.
- The enhanced air motion during injection due to increasing turbulence of TRCC piston bowl ensure better air fuel interaction within the engine cylinder which promotes the combustion.
- The higher turbulence in TRCC piston bowl due to its bowl shape improves combustion which in turn decreases the BSFC and promotes soot oxidation compared to CCC and baseline HCC piston bowls.

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