Advanced fuel injector design and modelling in IC engines to reduce exhaust gas emissions

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Abstract - *An idea of fuel injector is proposed that can improve the air-fuel mixing capability by spreading it more and creating swirl action without any modification in air flow manifold. For CI engine direct injection engine, fuel doesn't reach every region of combustion chamber injected by normal fuel injector. These left out regions have low air-fuel mixing velocity and hence are not mixed properly. In new fuel injector the motion of plunger is converted into rotational motion that spreads the fuel throughout in the combustion chamber. The related numerical research of the in-cylinder velocity, fuel/air mixing process, and emission characteristics of a diesel engine was performed. The numerical results showed that the new fuel injector had a positive effect on improving fuel/air mixing process by spreading the fuel more compared to normal fuel injector, which could improve the fuel utilization and reducing its consumption leading to reduction in harmful emissions such as NOx, CO and HC. The improvement in air-fuel mixing showed favorable reduction in NOx by 8.44%, reduction in CO by 8.69% and reduction in HC by 8.56%, showing that it has better performance than normal fuel injector.*

Key Words: Fuel injector, emission, IC engine, equivalence ratio

1.INTRODUCTION

Since pollution is caused by various sources, it requires an integrated and multi-disciplinary approach. The different sources of pollution have to be addressed in an integrated approach to achieve the objective of a cleaner environment. Air pollutants such as carbon monoxide, nitrogen oxides, particulate matter, volatile organic compounds, and benzene are emitted into the environment by motor vehicles. Air pollutants can contribute to urban air quality problems, such as photochemical smog and adversely affect human health. Incomplete combustion leads to high emissions, which is a substantial source of air pollution, especially for the soot. Due to the impact on air pollution, the government introduced several emission regulations [1]. Incomplete combustion leads to high emissions, which is a substantial source of air pollution, especially for the soot [2]. In-complete combustion is generally due to poor mixing of the air and fuel, insufficient residence time, insufficient temperature and low total excess air [3]. After-treatment devices can reduce the harmful emissions to meet the stringent emission regulations. For example, the diesel particulate filter (DPF) is an effective soot post-processing equipment, followed by SCR towards reducing NOx.

Improving air fuel mixing efficiency is the key area to reduce shoot and NOx. To achieve better air fuel mixing, swirl flow is generated that enhances turbulence intensity which controls cycle-to-cycle variation, combustion efficiency and exhaust emission in internal combustion engines. Swirl is used to speed up the combustion process in SI engines and to increase faster mixing between air and fuel in CI and some stratified charge engines [4-7]. Extensive research has been conducted to improve fuel air mixing capability. For example, to improve the in-cylinder fuel/air mixing process of heavy-duty diesel engines, optimize the combustion process and reduce the soot emissions, a new device named fuel split device was proposed. This device had a positive effect on improving fuel/air mixing process by splitting the fuel spray, which could in-crease air utilisation and lead to efficient combustion, multi-vortex structure could be formed during the fuel injection process, which could greatly improve the fuel/air mixing process that ultimately reduced HC, CO and soot emissions [8]. In another study, a bump combustion chamber was designed, which was characterized by some rings on the combustion chamber wall. With the bump ring, the spray generates a secondary jet after impinging the bump ring that decreases the wetting and rich mixture layer region on the wall, which led to the reduction of both NOx and soot emissions at low load [9]. In determining the effect of air fuel mixture on emission equivalence ratio becomes a major parameter. Higher equivalence ratios tend to result in less NO2, maybe because of lower concentrations of O2 for oxidising NO to NO2. A higher over-all equivalence ratio than the stoichiometric value results in lower NOx emissions. For all the overall equivalence ratios tested here, the NOx emissions tend to decrease around the richer-mixture equivalence ratio [10]. The optimization of the fuel/air mixing process on diesel engines is still of great interest. To improve the fuel/air mixing process, a new design of fuel injector is pro-posed in this study. In this concept of fuel injector, fuel is sprinkled throughout the engine as explained in Fig.1. With normal injection there are many areas left unaffected leading to less equivalence ratio, whereas in new fuel injector as fuel leaves orifice, it reaches more volume compared to normal injection. Followed by maximum volume coverage, new fuel injector guides the fuel to have swirl formation that leads to better air fuel mixing. In this study we compared the performance of 4-port fuel injector and new fuel injector based on equivalence ratio and its impact on emission such as NOx, CO and HC.

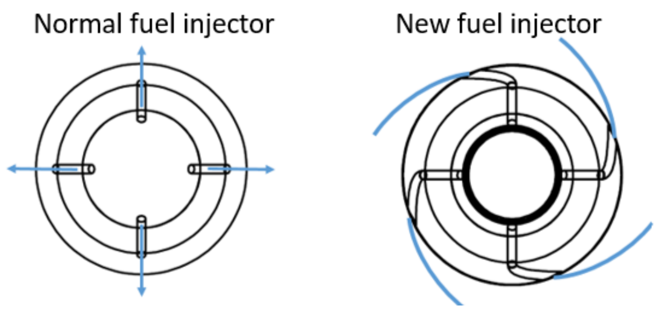


Fig -1: Path trajectory of new vs normal fuel injector

The primitive features of design and the transient nature of the flow through these systems makes it very difficult to analyse them experimentally. Simulation tests are often used to analyse the flow inside the injectors and provide the physical flow processes visibility that occurs in them and the entire fuel system. To have a good alternative, computational flow dynamics analysis (CFD) of flow through the injector was performed. Depending on the computing solver, there are many ways to simulate the movement of the elements [11]. However, such an approach increases the difficulty of mesh generation for complex shapes of injectors. It is possible to carry out the whole analysis including the geometry preparation and model discretization in Ansys Fluent software. Injector designing is still challenged by con-stant striving to improve eco-nomic and ecological aspects in combustion engines, alternative-fuel supply and varied injection pressure. This paper focuses on the development of the model of diesel fuel injector, using Ansys Fluent. To carry out the simulation in the simplest way possible, a 2D section of the engine was taken to simulate two different conditions. In the first condition, normal injection was simulated, and in other conditions new fuel injector was simulated. New fuel injector has a rotational phenomenon where the fuel injector rotates at a particular angle to spread the fuel throughout the engine. CFD tools are often applied to simulate parameters of the flow inside the engine, which are difficult and sometimes impossible to mea-sure experimentally. In the numerical simulation, we evaluated the impact of the equivalence ratio using a model we developed using MATLAB.

2. DESIGN

An ideal fuel injection system can precisely provide the right amount of fuel under all engine operating conditions and hence can precisely control air–fuel ratio, which allows, for instance: easy engine operation even at low engine temperatures (such as a cold start), precisely governed engine speeds, good fuel efficiency, and the lowest achievable exhaust emissions. For internal mixing operations, fuel injectors can be classified into two basic types of injection,

Direct Injection: Direct injection means that an engine only has a single combustion chamber and that the fuel is injected directly into this chamber as shown in fig. 2 [12]. This can be done either with a blast of air. Direct injection is well-suited for a huge variety of fuels, including petrol and diesel fuel.

Indirect injection: In an indirect-injected engine, there are two combustion chambers: a main combustion chamber, and a pre-chamber [13] that is connected to the main one, as shown in fig. 2. The fuel is injected only into the pre-chamber (where it begins to combust), and not directly into the main combustion chamber. Therefore, this principle is called indirect injection.

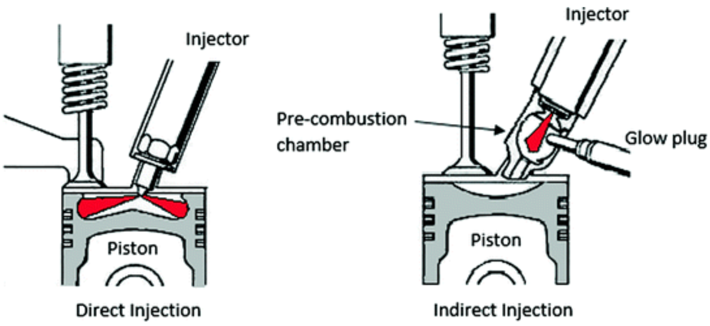


Fig -2: Direct vs Indirect fuel injection.

Direct-injection diesel engines have been widely used on heavy duty applications. Recently they have become popular on light duty applications because of their inherent high thermal efficiency and low CO2 emissions. However, reduction of NOx and Particulate emissions emitted from direct-injection diesel engines is of urgent necessity since emission regulations have become stringent from a standpoint of preserving the environment. In order to reduce NOx emission, injection timing retard and EGR have been employed to reduce the initial burning rate by controlling the combustion temperature and oxygen concentration.[14] However, it is difficult to reduce both NOx and particulate emissions simultaneously. Some of authors have been reported that NOx emission could be reduced under fuel-rich and strong swirl conditions at the initial burning stage [14]. In our proposed design, we designed a direct injection fuel injector where the fuel in sprinkled inside the engine in a curved trajectory leading to swirl formation.

2.1 Design of new fuel injector

A fuel injector consists of few basic components such as Needle valve, Compression spring/ solenoid actuator, Nozzle and Injector body. The Nozzle is the part of the Injector through which the fuel is injected into the cylinder. Below Fig. 3 is a schematic cross-section representation the components of fuel injector.

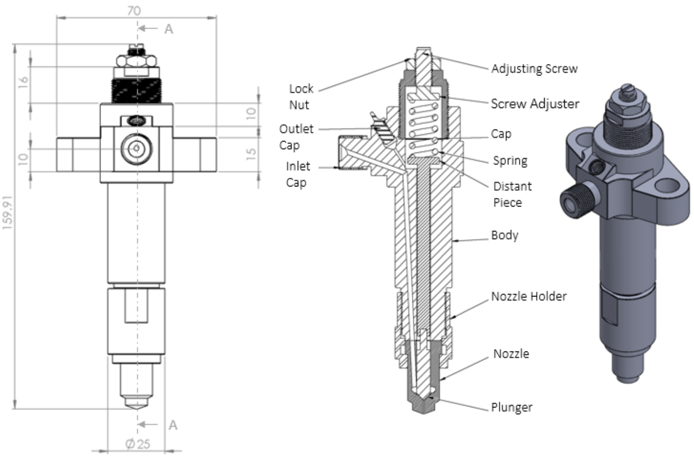


Fig -3: Normal Fuel Injector Cross-section view

Towards the aim to have maximum volume coverage, new fuel injector guides the fuel to have swirl formation that leads to better air fuel mixing. In this study we com-pared the performance of 4-port fuel injector and new fuel injector towards emission reduction. In the proposed new design of fuel injector, the nozzle part is modified where a rotor is added as shown in Fig. 4. As the plunger moves up, fuel supply is created and fuel enters the rotor from nozzle. The rotation of rotor is based on the principal of cam and follower mechanism. Plunger is designed to have a cam attached to it, making the entire plunger as cam. The rotor attached to nozzle has a follower path in it that is in contact with plunger's cam. The rotor's follower is given a curves path that the linear motion of plunger (up and down) is converted into rotational motion of rotor. As the plunger moves up, the fuel supply opens and parallelly rotor rotates sprinkling the fuel throughout the engine, covering all the regions where the normal fuel injector fails to reach. The structure of the nozzle is designed to have a bearing attached to it. The outer surface of bearing is in contact with nozzle body and the inner surface of bearing is holding the rotor, that causes it to rotate as the plunger makes its linear motion. The fuel injector is designed to withstand high temperature and pressure and hence the material most suitable for such condition is carburized or maraging steel [15].

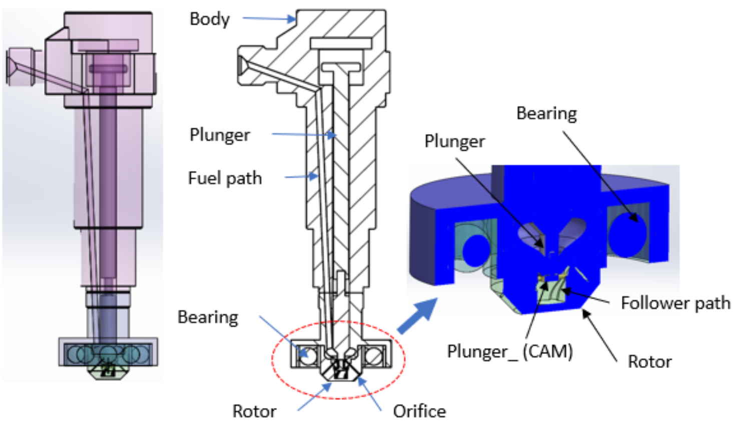


Fig -4: New Fuel Injector Cross-section view

3. SIMULATION METHODOLOGY

3.1 Geometry Modelling

In order to carry out simulation using Ansys Fluent 21, a simplistic 2D model was created using Solidworks 2017. This 2D model was created based on the cross section as seen from the top of a diesel engine's combustion cavity, as mentioned in Table 1 [16]. The 2D CAD representation of the same which has been used for modelling has been mentioned in Fig.5. The dimension of combustion region used under this study is mentioned in Fig.6, representing bore and combustion cavity region.

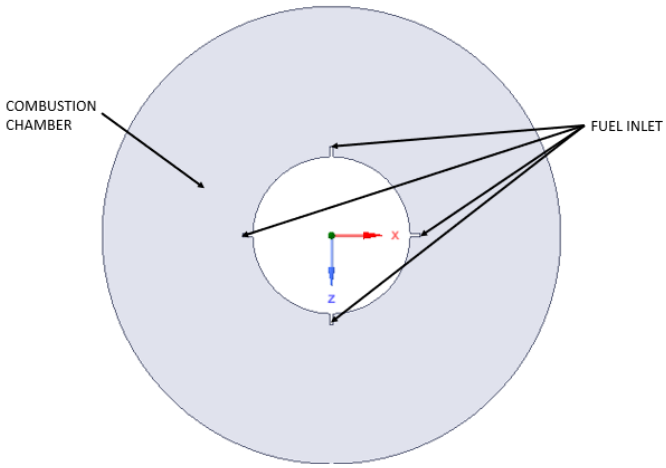


Fig -5: 2D CAD representation of combustion chamber

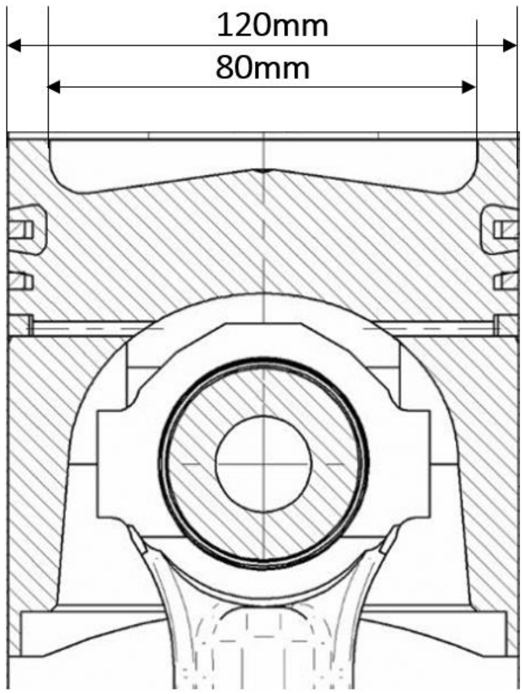


Fig -6: Front view -cross section of combustion chamber

Model	PS10
Power HP/kw	10/7.35
Speed RPM	1000
Bore MM	120
Stroke MM	139.7
Cubic Capacity CC	1580
Compression Ratio	1:18
Fuel Consumption (max)	1970 g/hr (2.37 Lit/hr)
Injection Pressure (MPa)	150
Lubricating oil consumption	10 cc / hr max
Fuel	HSDO / LDO
Lubricating oil	YENTROL-32B / SAE-30/40
Net Weight Kg	320
Gross Weight Kg	410
Packing Size	105 X 70 X 114 CMS

Table -1: Engine parameters

After simulation, pressure contours were taken at the center of BTP fluid volume as shown in above Fig. 13. As stated in last paragraph, the same can be observed through pressure contours. Pressure at the inlet is maximum for pattern 2 (A2 and B2) as the area is less at the entrance and as it approaches exit, pressure reduces.

3.2 Meshing

For the sake of optimizing computational time and efforts, a 2D cross section in-side the combustion chamber was sliced out for our study. This cross section was meshed using quadrilateral dominant meshes using Ansys Fluent Meshing, as shown in Fig.7. The size of each mesh was kept at 0.1mm to accurately capture the mixing phenomenon between air and diesel. Since quadrilateral meshes have the advantage of capturing local geometry more accurately, it was considered as opposed to triangular meshes [17]. Besides, layers of inflation layers have been added (as shown in Fig.8) to-wards the inlet walls as these help in capturing the near wall phenomenon more accurately [18].

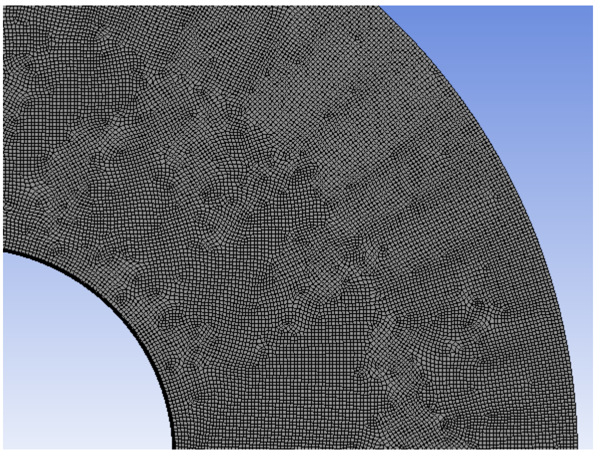


Fig -7: Meshing model

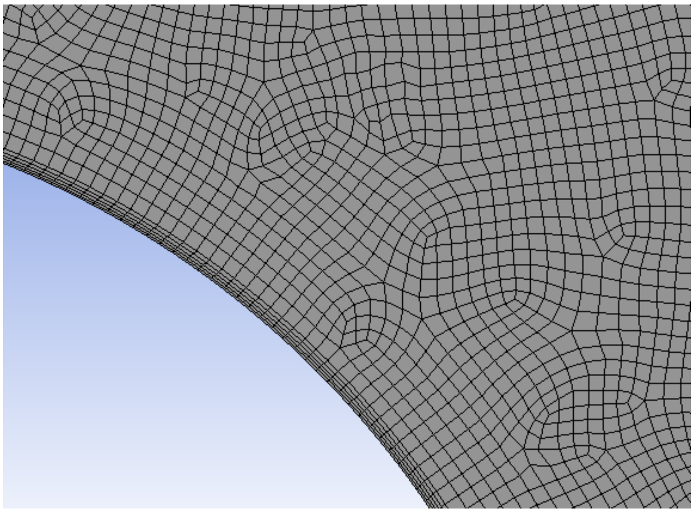


Fig -8: Inflation layer added in geometry

3.3 Boundary Conditions

All For most IC engine simulations, the validation of the engine parameters is carried out using a 3D model of IC engine. However, this requires a lot of computational power and resources. Hence, in order to save computational efforts, the simulations for the given case were performed in 2D using Ansys Fluent CFD models. To achieve the results as close to as an actual IC engine simulation, a comparison was made between the simulation results of the new proposed design of IC engine with advanced fuel injector and an existing diesel IC engine, details of which have been mentioned in Table 1. The boundary conditions used during simulation have been mentioned in Table 2:

Parameters	Values/Model
Solver Type	Pressure based
Solver Time	Transient
Turbulence model	RNG k-ε
Combustion model	Species Transport
Turbulence chemistry Interaction model	Eddy dissipation

Table -2: Simulation boundary conditions

A pressure-based solver with transient conditions was considered. During the process of air fuel mixture inside the combustion chamber, turbulence is created. Hence, a turbulence model, which is RNG k-ε was considered. In many cases STD k-epsilon model is used for diesel combustion simulations. But STD k-epsilon model sometimes gives large turbulence viscosity values which in turn produces an unrealistic flow behavior. Thus, in order to get a realistic flow behavior, RNG k-ε turbulence model is preferred. This is because some additional constants have been introduced in the RNG k-ε model which neutralizes the large values of turbulence viscosity, thereby producing a much more realistic flow behavior [19]. The equations used for a typical RNG k-ε model has been shown in (1) and (2).

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left(\alpha_k \mu_{eff} \frac{\partial k}{\partial x_j}\right) + G_k + G_b - \rho\varepsilon - Y_M + S_k \quad (1)$$

$$\frac{\partial}{\partial t}(\rho\varepsilon) + \frac{\partial}{\partial x_i}(\rho\varepsilon u_i) = \frac{\partial}{\partial x_j}\left(\alpha_\varepsilon \mu_{eff} \frac{\partial \varepsilon}{\partial x_j}\right) + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k + C_{3\varepsilon}G_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} - R_\varepsilon + S_\varepsilon \quad (2)$$

where,

k = turbulent kinetic energy

ε = rate of dissipation of turbulent kinetic energy

u_i = velocity in a given direction

α_k and α_ε = inverse effective Prandtl numbers for and

μ_{eff} = effective viscosity

G_k = generation of turbulence kinetic energy due to the mean velocity gradients

G_b = generation of turbulence kinetic energy due to buoyancy

Y_M= contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate

S_k and S_ε = user defined source terms

A direct repercussion of an increase in fuel-air equivalence ratio is the reduction of. Hence it is imperative to study the change in fuel-air equivalence ratio from the existing diesel engine to the proposed concept of new engine. In order to do that, a combustion study was done using the species transport model of combustion. In a diesel engine, a large part of the combustion occurs as a result of the turbulence occurring between the air and diesel mixtures. Hence, the turbulence chemistry interaction model needs to be accurately modeled. To do this, Eddy dissipation model was used.

In an eddy dissipation model, combustion occurs as soon as there is turbulence and no external source of ignition is required, quite similar to the way a diesel engine works. The reactants start to ignite once they are inside the combustion chamber or the computational domain [20].

Once the entire combustion is completed, the fuel-air equivalence ratio (represented by ϕ) for the existing model and the proposed new model can be compared to see the improvement. Fuel-air equivalence ratio can be calculated as per formula mentioned below:

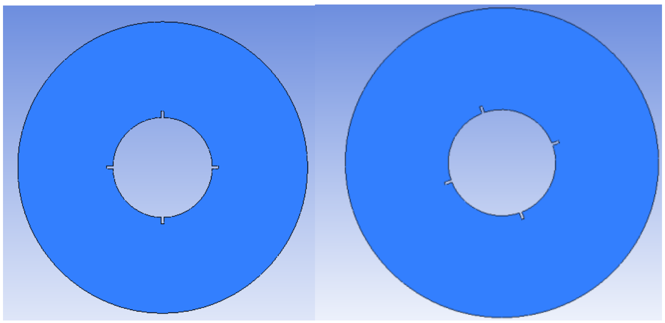
$$\phi = \frac{\text{fuel} - \text{to} - \text{oxidizer ratio}}{\text{fuel} - \text{to} - \text{oxidizer ratio}} = \frac{m_{fuel}/m_{ox}}{(m_{fuel}/m_{ox})_{st}} = \frac{n_{fuel}/n_{ox}}{(n_{fuel}/n_{ox})_{st}}$$

where m represents the mass, n represents a number of moles, subscript *st* stands for stoichiometric conditions.

Parameters	Values/Model
Mesh smoothing method	Diffusion
Layering method	Height based
Remeshing method	Method based
Minimum length scale	0.01mm
Maximum length scale	0.2mm
Maximum Cell Skewness	0.95

Table -3: Simulation boundary conditions

Further, in case of the proposed new model of the engine, the fuel injectors need to be given a circular motion. To do this, dynamic meshing has been used. Dynamic meshing enables to model such geometries where the shape of the computational do-main varies with time. The parameters used in dynamic meshing have been mentioned in Table 3. A pictorial comparison of a dynamic meshed domain with a regular computational domain has been shown in Fig. 9 (a,b) respectively.



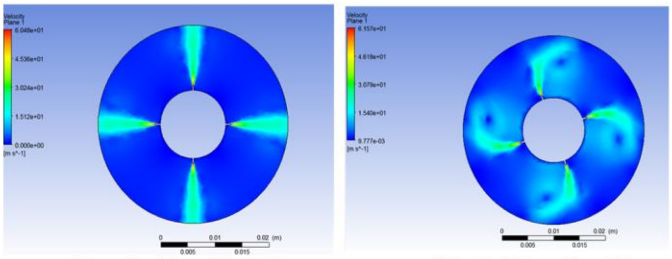
(a) (b)

Fig -9: This is a figure of mesh domains used for simulation, they should be listed as: (a) Regular meshed domain; (b) Variable meshed domain

4. DISCUSSIONS AND RESULTS

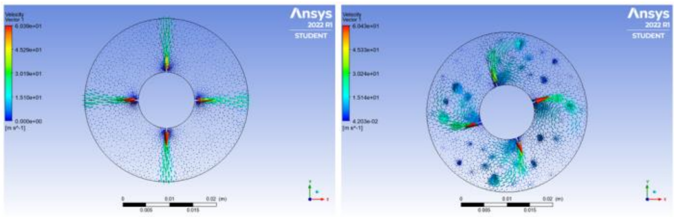
4.1 Equivalence Ratio

In order to investigate the air fuel mixing performance, the change in equivalence ratio was calculated based on the of normal injector and new designed injector. Fig.10 shows the difference in fuel spread between normal and new fuel injector. Upon deriving the area of fuel coverage, the new injector spreads the fuel more compared to normal fuel injector and so it is evident in the velocity contours shown in Fig.10(a,b). With better spraying of fuel, more area is being covered and followed by swirl formation leading to higher equivalence ratio.



a) Normal Fuel Injector ($\phi = 1.12$) b) New Fuel Injector ($\phi = 1.23$)

Fig -10a: Velocity Contours



a) Normal Fuel Injector ($\phi = 1.12$) b) New Fuel Injector ($\phi = 1.23$)

Fig -10b: Velocity Vector

With better fuel air mixing and change in equivalence ratio, combustion process is affected which also changes the amount of emissions being produced [21-23]. It can be expected to have cleaner burn [23] and higher Indicated mean effective pressure [22]. Higher Cylinder pressure during combustion phase is also achieved with better fuel air mixing [23]. With the same amount of fuel being supplied to both the setups, new fuel injector provided better mixing and spread as evident from equivalence ratio and fuel area coverage.

4.2 Emission

The development of new injector was to achieve better fuel-air mixing with an aim towards lower emissions. NOx emissions are mainly affected by temperature, oxygen concentration and reaction time [22]. As the better fuel-air mixing is achieved, oxygen concentration through the combustion chamber improves as the fuel spread is more. This give faster combustion reaction times and reduces the amount of NOx being produced [22]. Also, with better fuel-air mixing higher combustion temperature is achieved. Due to this more soot is oxidized and amount of soot formed will be reduced. The HC and CO mass will also be reduced due to the improved fuel-air mixture and faster rate of combustion [21-23].

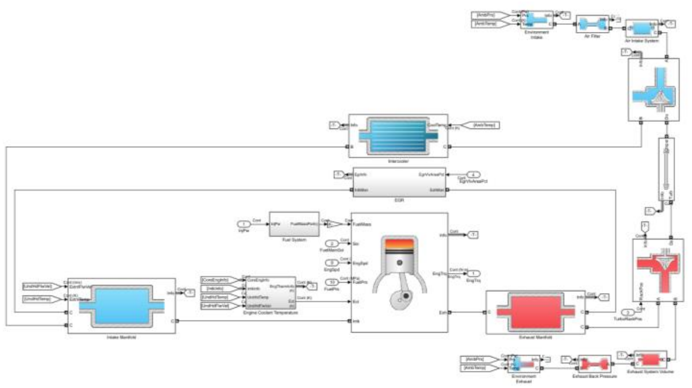


Fig -11: Simulink Model

With increase in efficiency [22], the amount of fuel being consumed will reduce, which might further reduce the emissions. So, to verify this an existing Simulink model was used [23]. A 4 cylinder diesel engine model was used for MATLAB simulation as shown in Fig.11, where the inputs to model where engine speed and load. First a normal injector emissions readings were noted at constant engine speed and RPM and then new fuel injector was simulated to observe the difference. A pattern in emissions throughout can noticed shown in Fig. 12, as with the same amount of fuel and injection period, the emission level in new fuel injector is less for all parameters compared to normal fuel injector.

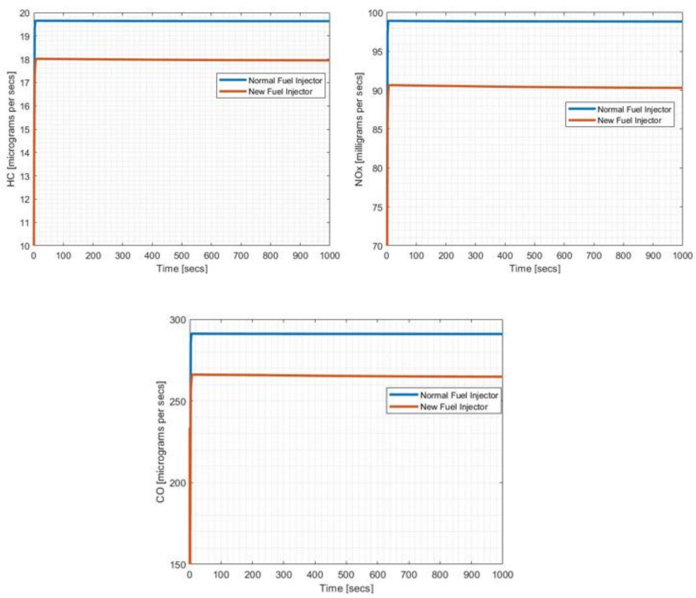


Fig -12: Emissions Output values

5. CONCLUSION

In this study, a new fuel injector concept was investigated to improve the fuel/air mixing process for diesel engine at. The in-cylinder velocity fields, fuel/air mixing process and emissions characteristics were analysed by numerical simulation. Compared to the normal fuel injector the rotational action of the rotor led air fuel mixing into a swirl action that ultimately led to an increment of 9.8% in equivalence ratio. The simulation was further analysed in MATLAB Simulink to observe its effect on emission. The improvement in equivalence ratio showed favorable reduction in NOx by 8.44%, reduction in CO by 8.69% and reduction in HC by 8.56% as shown in Fig.13. In essence, the concept of the new fuel injector led to increment in equivalence that ultimately led to reduction of NOx, CO and HC by 8.56% on an average.

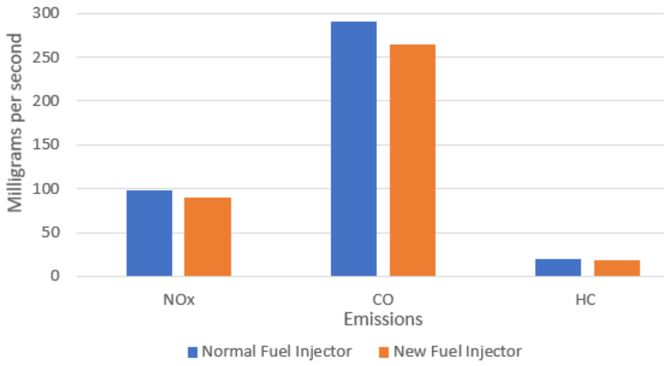


Fig -12: Emissions Comparison

- Schematic of an existing injector was studied to understand it operation. New design is proposed with modified nozzle part, where rotor is added housed in a bearing. To create a swirl type motion a cam and follower mechanism is used to convert the translation motion of injector plunger to rotatory motion of the rotor when the fuel is injected.

- A 2-D Model was created for cross section of diesel engine combustion chamber. A 2D simulation was done using Ansys Fluent with mesh size of 0.1mm to capture the mixing phenomenon between diesel and air. Furthermore, dynamic meshing was used to simulate rotatory motion of the improved injector. A comparison was made between the simulation results of the new proposed design of fuel injector and an existing Diesel IC engine. It was noticed that the fuel spread increased and was covering more area compared to normal injector. This resulted in increased fuel-air equivalence ratio.

- A study for change in emissions was done based on increased fuel air mixing and higher equivalence ratio. With better fuel air mixing and higher equivalence ratio, increased engine efficiency and lower NOx, CO and HC emissions were anticipated. The effects of increased efficiency on emissions were also studied using an existing Simulink model. With increase in efficiency the overall emission reduction was also noticed in the test model, which showed a reduction of 8-9% for NOx, CO and hydrocarbons (HC).

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