Design and analysis of multi fuel injector

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Abstract. In accordance with strict emission norms, the depletion of fossil fuels requires a fuel injection system that is efficient, responsive, and adaptable to various locally available fuels. Hence, electronically controlled fuel injector technology is the best option for fulfilling this requirement. Commercially, there are various types of fuel injectors which are mainly used for specific fuels such as gasoline, diesel, CNG, LPG, etc. This research outlined in this paper is based on the design of a multi-fuel injector which will be compatible to both gaseous and liquid fuels as a tremendous volume of research has been done in the usage of alternative fuels like hydrogen, JP-8, biogas, producer gas, acetylene, alcohol, and biodiesel. Since the government is primarily focused on green fuels and biogas fuels, the design of such a type of injector will become an excellent opportunity for the design of new products that will be compatible with automobile engines, gas-turbines, aerospace combustion furnaces, gas stoves, etc. An electronically controlled solenoid-operated multi-fuel injector was designed by utilizing the properties and parameters of liquid and gaseous fuel injectors. The designed Multi-fuel injector was modeled in Solid Works and simulated in ANSYS software. The simulated injector was tested with fuels, including gasoline, CNG, and acetylene. Due to a pressure limitation of 5 bar, the designed injector was tested only for low viscous fuels. The injector worked in the velocity range of 70 to 100 m/s. The usage of the Solenoid coil control enabled the injector to function with quick response, injected fuel quantity, and start of injection for various fuels.

1. Introduction

The present scenario in the initiative against emission pollution lies in the form of stricter emission controls and legislation norms. This motivates the researchers to improve the fuel economy and decrease the emission levels for the combustion equipment. In order to fulfill the new emission norms, it becomes mandatory to utilize the advanced technology of fuel injection systems in the replacement of the traditional carburetor system. The main difference between the fuel injectors and the carburetor is based on the fact that the carburetor depends on the low pressure induced by the flow of suction air through the venturi to draw the fuel for mixing with the air stream.

In the case of fuel injectors, the pressurized fuel from the fuel pump is injected through a small nozzle under high pressure. The quantity of fuel used in different combustion equipment is based on various external and internal factors, including engine load, injection timing, output power, type, quantity, and properties of the fuel, and ambient conditions. The opening and closing of the injector are done by electrical, mechanical, hydraulic, and electromechanical means. The adaptation of injectors comes across a significant drawback in the form of a fuel cycle to cycle injection.
control. One approach in overcoming the above problem is the employment of a solenoid valve in the unit injectors for controlling the opening and closing of the nozzle in order to vary the fuel quantity and the fuel injection timing during the cycles. The secondary problems are the rapid depletion of fossil fuel resources necessitating the search for an alternative clean-burning fuel that should be sustainable and environmentally friendly. The promising alternative fuels are natural gas, LPG, producer gas, biogas, alcohols, acetylene, and vegetable oils.

Gary et al. [1] vide US patent number 5,419,492 developed an electromagnetic unit fuel injector controlled by solenoid coil to provide precise metering and required timing injection of the fuel. Varde et al. [2] conducted an experimental study using a single-cylinder SI engine using electronic hydrogen fuel injector. The injector was calibrated to deliver a predetermined quantity of fuel in the intake manifold. The research concluded that the hydrogen injected for lean operations increased the thermal brake efficiency and avoided backfire when compared with the conventional operated engine. Verhelst et al. [3] conducted an experimental study on the V8 SI engine using hydrogen fuel on a timed multipoint injection system. The researchers suggested the utility of operating a hydrogen-fuelled engine in lean mode to avoid backfire. Heffel [4] used the commercially available natural gas fuel injector for usage with the hydrogen fuel in a diesel engine. The results showed that the pulse width modulated the injector-metered hydrogen fuel pressure between 2 to 20 bars. It was concluded that the natural gas injector performed within the necessary limits for hydrogen application.

Das et al. [5] designed and elaborated an electronically controlled gas injection system for injecting hydrogen and CNG in a SI engine. The design included vital components of gas injection systems such as optical sensors, electronic control circuits, and solenoid injectors. Using pulse width modulation solenoid injector, the researchers were able to inject the gaseous fuel. The methodology used was the timed manifold injection technique. This enabled the gaseous fuel to be injected at the required time and quantity. Lakshmanan et al. [6] designed an electronic injection system using a hydrogen injector for injecting acetylene in a CI engine. Using electronic control circuits, the researchers were also able to inject acetylene fuel using the Timed Manifold Injection (TMI) technique, which delivered the required quantity of gas during the suction stroke. The hydrogen injector was calibrated to inject the required quantity of acetylene.

Aesoy [7] et al. modeled and simulated a high-pressure CNG gas injection system for a medium-speed engine. The gas injector optimized the injection rate, injector momentum, injector internal geometry, and injector nozzle. The researchers modeled the injector using the Bond graph modeling technique. They also conducted simulation studies for the dynamic behavior study. Deyang [8] filed his invention as patent WO 2013/188247, whose outcome was the utilization of single and multi-fuel injection with pressure intensification and variable orifice using gasoline and diesel. The research leveraged the different fuel properties and variable spray patterns. The invention was extended to the analysis of low viscosity fuels, including ethanol, LNG, and high viscosity fuels, including biodiesel, Jet Propellant -8 (JP-8) fuel.

The literature review revealed the lack of a sustained investigation in the simulation analysis of fuel injectors. Hence, thorough research needs to be done in the design of a multi-fuel universal gas injector for combustion equipment, including IC engines, gas burners, furnaces, and gas turbines, which have the ability to inject various liquid and gaseous fuels based on the local availability. The main objective of the current research is to design, model, and simulate a multi-fuel injector which can function using various fuels adaptable for different combustion equipment. The injector should be capable of producing the required power, adequate torque, and lower fuel consumption. They should also be capable of injecting the required quantity of the fuel at a specific time, especially during the suction stroke or during the compression stroke. The injection is also dependent on the location of the injector at the manifold or at the engine head for direct injection.

2. Fuel Injector
A fuel injector is a device that is used to inject or spray the fuel into the combustion equipment for the preparation of the stoichiometric air-fuel mixture, thereby providing efficient combustion. The fuel
injector is the heart of the fuel injection system. Based on the advancement of technology, various fuel injection arrangements exist based on the application requirement which includes, throttle body injection, MPF (Multi-point fuel) injection, Manifold injection, Port injection, and direct injection.

On the basis of fuel injected, the fuel injectors are classified as diesel fuel injectors and gasoline fuel injectors. The main difference between diesel injectors and gasoline injectors is that the diesel injectors provide a highly atomized diesel package while spraying the fuel inside the engine. But, in a gasoline injector, the injection of the required quantity is sufficient. This is because; gasoline is a highly volatile fuel that has the ability to form a homogenous air-fuel mixture for the combustion to take place.

On the basis of fuel metering for varying the combustion engine speed, the injectors are classified as mechanical controlled fuel injectors and electronically controlled fuel injectors. The mechanically controlled fuel injectors are controlled with the help of spring and plunger arrangement, which in turn drives the input from the cam and fuel distributor.

The highly pressurized fuel is transferred from the fuel pump to the fuel distributor. The fuel distributor, in turn, distributes the fuel to the fuel injector. The plunger spring located inside the main body of the injector always ensures the injector to be in a closed position. When the highly pressurized fuel reaches the injector tips, the nozzle is opened by pushing the plunger against the spring force. The decreased fuel pressure in the line closes the nozzle due to the domination effect of the spring force against the fuel pressure.

Figure 1 reveals the various components of the electronically controlled fuel injector, controlled by the solenoid coil, which in turn receives the signal from the optical sensor, or from the ECU. When the signal is received from the ECU, the solenoid coil gets energized. This opens the injector nozzle in the closed position by withdrawing the plunger against the spring force. When the signal is turned off, the solenoid coil is de-energized, which releases the plunger resulting in the closure of the injector nozzle with the help of the spring force. When compared with the mechanically controlled injector, exact metering of the injected fuel can be done in the electronically controlled fuel injector by varying the pulse width signal from the ECU. Table 1 provides the calorific values, density, and stoichiometric air-fuel ratio requirement of the various fuels.
Table 1. Fuel and properties.

| Type of Fuel | Calorific Value (MJ/kg) | Density (Kg/m³) | Stoichiometric air fuel ratio on mass basis (kg/kg) |
|--------------|--------------------------|-----------------|-----------------------------------------------|
| CNG          | 55.5                     | 0.716           | 17.2                                          |
| LPG          | 50.4                     | 0.498           | 15.8                                          |
| Acetylene    | 49.9                     | 1.097           | 11.1                                          |
| Diesel       | 45.6                     | 0.846           | 14.6                                          |
| Petrol       | 46.4                     | 0.737           | 14.5                                          |

Based on the fuel density, calorific value, stoichiometric air-fuel ratio requirement, power, and speed of the engine required, the fuel quantity and exact timing of the injection will be done by the ECU and the solenoid coil by varying the duration of the injector opening time and the start of the injection.

2.1. Methodology
In order to achieve the above objective, the multi-fuel injector was initially designed by considering the various parameter variations among the different fuels. Then modeling and simulation were done. In the simulation, the injector was subjected to various fuels, including gasoline, CNG, and acetylene, for understanding the dynamic working of the designed multi-fuel injector. The following section explains the design, modeling, and simulation procedure carried out for the realization of the objective.

2.2. Design of fuel injector
The various parts of the injector are injector body, spring, coil, spindle, and nozzle are shown in figure 1. The major difference between the gaseous fuel injector and the liquid fuel injector is the working pressure as the liquid fuels are highly viscous in nature than the gaseous fuels. Liquid fuels are to be injected at very high pressure in order to atomize the fuel to form a homogenous combustion mixture for combustion to take place. The present design is done for low viscous fuels for reducing the complication in the design process.

2.2.1. Spring. This is the most important component of the injector as it defines its capacity. If the spring very stiff, then higher pressure will be required to allow the fuel through the injector. A powerful pump will be required to pump the fuel to the injector. The design was carried out using the standard design data book. [9] and the research work is done by Sai et al. [10]. The designed multi-fuel injector is based on the spring design, which consists of fuel delivery by means of a small compression produced by the spindle in the spring. The spring is an open-end type with the outer diameter (D) as 4.8 mm and coil diameter (d) as 0.8 mm. The initial pressure is 5 bar.

Spring stiffness for the injector was calculated using the outer diameter of the spring and the force acting on the spring using the following formula.

$$s_s = K \left( \frac{8F_d}{\pi D^3} \right)$$  \hspace{1cm} (1)

Where ‘K’ is the Wahl’s factor which was calculated using the following formula where C is the spring index,

$$K = \frac{4C-1}{4C-4} + \left( \frac{0.615}{C} \right)$$  \hspace{1cm} (2)

Spring index is the ratio of the spring diameter (D) to the wire diameter (d).
Deflection $(y)$ of the spring is based on the calculation of spring travel when a load $(F)$ is applied, where ‘$n$’ is number of coil in spring and ‘$G$’ is shear modulus of spring.

$$y = \frac{8FC^3n}{dG}$$  \hspace{1cm} (4)

Total number of coils in the spring is given by the following equation,

$$\eta' = n + 2$$  \hspace{1cm} (5)

Pitch length of the spring is calculated using the following formula where $L_f$ and $L_s$ are indicating the free and compressed length, respectively.

$$p = \left[ \frac{L_f - L_s}{n} \right] + d$$  \hspace{1cm} (6)

2.2.2. Injector body. The material was selected as carburized steel AISI1050. The thickness of the nozzle body was taken from the standard values indicated in the literature review. The canal diameter, along with the cross-sectional area, is calculated using the following equations. As shown in figures 2, 3 and 4.

$$p_{inj} = \frac{F_s}{A_{can}}$$  \hspace{1cm} (7)

$$A_{can} = \left( \frac{\pi}{4} \right) D_{can}^2$$  \hspace{1cm} (8)

where ‘$p_{inj}$’ denotes the injection pressure, ‘$A_{can}$’ represents the canal area, ‘$D_{can}$’ represents the diameter of the needle and $F_s$ represents the force on spindle.

2.2.3. Spindle. The spindle design is based on the dimensions obtained from the spring design. The diameter of the spring and that of the spindle are the same. The spindle is electromagnetic due to its connection with the copper coil. Hence, the spindle movement can be controlled using the Electronic Control Unit (ECU).
2.2.4. Nozzle. The nozzle plays a major role in the fuel atomization. The various types of nozzles are the single hole, multi-hole, pintle, and pintaux nozzles. The Pintle nozzle type is selected, and the material is maraging steel. This part of the injector will be directly exposed to the combustion chamber of the equipment.

2.2.5. Solenoid Coil. The solenoid coil is made of copper, which is wound on the spindle. When the coil is activated, the plunger is attracted to the coil against the spring force, thereby opening the hole of the injector, which is always in closed condition by the injector nozzle. The coil will be connected to the ECU, which will control the timing of each cycle.

2.3. Modeling and Simulation of Injector

The modeling of the fuel injector was done using the SOLIDWORKS 2015 SP5 software. The spring is the vital component of the injector. The designed multi-fuel injector was modeled using SOLIDWORKS in STEP format, which is compatible with simulation in ANSYS R18.1 version. The analysis using computational fluid dynamics involves three stages, which are the initial processing, solving, and post-processing. The file was uploaded to ANSYS, and meshing was performed for the flow parameter analysis of the fluids to be used in the injectors. The model was meshed into 1, 20, 114 nodes and 5,86,091 elements.

![Figure 5(a). Modeling.](image)

![Figure 5(b). Meshing.](image)

The meshing of the component is shown in figure 5(b). The boundary conditions for the analysis are the inlet, outlet, and the wall of the fluid flow path.

3. Result and Discussion

The multi-fuel injector was designed, modeled, and simulated using ANSYS. The property density of fuel varied from 0.7 to 1.1 kg/m³, and the calorific value varied from 46 kJ/kg to 56 kJ/kg. The velocity of the fuel was taken in the range of 70 m/s to 100 m/s. The following section demonstrates the analysis done using ANSYS for the mentioned fuels. The low viscous fuels such as Petrol, CNG, and acetylene were tested for compatibility in this modeled injector.

Figures 6(a) and 6(b), figure 7(a) and 7(b) represents the velocity and pressure analysis of petrol and compressed natural gas used in the fuel injector. Based on the ANSYS analysis, the maximum velocity obtained using compressed natural gas in this injector is 1.8903+003 m/s as and maximum pressure obtained in this injector using compressed natural gas is 7.349e+005 Pa.
Figure 6(a). Velocity analysis of Petrol fuel.

Figure 6(b). Pressure analysis of Petrol fuel.

Figure 7(a). Velocity analysis of CNG.
Figure 7(b). Pressure analysis of CNG.

Figure 8(a). Velocity analysis of Acetylene fuel.

Figure 8(b). Pressure analysis of Acetylene.

Figure 8(a) and 8(b) represents the velocity and pressure analysis of acetylene gas in the fuel injector. The pressure and velocities of the input fuel were taken as 5 bar and 100 m/s, respectively. The highest velocity of acetylene through this injector obtained from the analysis was found to be 5.835e+003 m/s. The maximum compatible pressure derived from the fuel flow in this injector was
9.016e+006 Pa. The flow of fuel from the inlet to the outlet in the analytical results establishes the compatibility of the designed injector to the acetylene gas.

Hence, the performed analysis aptly justified the design injector’s compatibility with multiple fuels, including liquid and gaseous fuels.

4. Conclusion
A multi-fuel electronically controlled fuel injector was designed, modeled, and simulated for usage using low viscous fuels such as gasoline, CNG, and acetylene. The selected fuels were analyzed using the ANSYS-CFD, and the fuels were found to be compatible with the designed fuel injector in the velocity range of 70 to 100 m/s. The Injector was confined to operate at a maximum of 5 bar pressure. The liquid fuel pressure was contained within the required pressure values using the fuel pump. The gaseous fuel pressure was contained using the gas regulator. With the help of the Electronic Control Unit (ECU), the volume of fuel to be injected and the timing of the fuel injection into the engine cylinder can be controlled and adjusted as per the requirements. The designed multi fuel-injector is still in the developmental stage. Further research needs to be undertaken for accommodating high viscous fuels.

5. References
[1] Gary L Gant 1995 Force Balanced Electronically Controlled Fuelnector US patent number 5,419,492
[2] Varde K S and Frame G M 1984 A Study of combustion and engine performance using electronic hydrogen fuel injection International Journal of Hydrogen Energy 9 327-332
[3] Verhelst S and Sierens R 2001 Hydrogen engine-specific properties International Journal of Hydrogen Energy 26 987-990
[4] James W Heffel, Michael N Mcclanahan, Joseph M Norbeck 1998 Electronic Fuel Injection for Hydrogen Fueled Internal Combustion Engines SAE Technical Papers
[5] Das L M, Rohit Gulati, and Gupta P K 2000 A comparative evaluation of the performance characteristics of spark ignition engine using hydrogen and compressed natural gas as alternative fuels International Journal of Hydrogen Energy 25 783-793
[6] Lakshmanan T and Nagarajan G 2010 Experimental investigation of timed manifold injection of acetylene in direct injection diesel engine in dual fuel mode Energy Journal 35 3172-3178
[7] Vilmar Aesoy and Eilif Pedersen 2011 Modeling and Simulation for Design and Testing of Direct Injection Gaseous Fuel Systems for medium speed Engines SAE International 2401
[8] Deyang Method, System, and Fuel Injector For Multi-Fuel Injection With Pressure IntensificaTion and A Variable Orifice patent WO 2013/188247
[9] PSG Tech Design Data Book, 2007, Kalaikathir Publication Coimbatore India
[10] Sai Krishna T K S, Kasanagottu Shouri and Repala Deepak Kumar 2013 Design, and Analysis of Electronic Fuel Injector of Diesel Engine International Journal of Scientific & Engineering Research 4