AN IMPROVEMENT OF PIEZOELECTRIC FUEL INJECTOR WITH SELF SENSING CONTROL AND VCI METHOD FOR BIODIESEL INJECTIONS

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Abstract

At present, some of the changes of global climates, power crisis, environmental pollution, noises and fuel consumptions are caused by fuel and fuel injector. Therefore, biodiesel has been introduced to overcome the above problems. In this paper, we design a piezoelectric fuel injector for biodiesel injection using analysis of spray pattern and ignition time, and control of corrosion in diesel engine. In IC engines, noises, emission and fuel consumptions can be decreased and process of diesel injections is controlled directly by using the piezoelectric fuel injector. The fuel has not been mixed entirely in the process of conservative piezoelectric fuel injectors. Hence, the some modifications are made by us in piezoelectric fuel injector design for biodiesel injections. The piezoelectric fuel injector is designed in three phases that are piezo actuator with self sensing control model, the thermal compensator and the body of valve to improve the work of fuel injector that can be used to reduce the fuel consumption. The computational fluid dynamics (CFD) and Reliability Centered Maintenance (RCM) methods are combined to analyze the spray pattern for reduction of ignition time delay. This kind of spray pattern analysis used to improve the accuracy and to reduce the complex operation during the injections of biodiesel in fuel injector. CFD method can use the numerical analysis to find the problem of functions of location of fuel injector, spark plug, valve body, four strokes and operation of piezoelectric fuel injector engine. After that, the RCM method can be exploited to expand the scheduled maintenance plans that are generated by CFD. Finally, The Volatile corrosion inhibitor (VCI) is applied on piezoelectric injector engine to eliminate the corrosion while using biodiesel injections.

Keywords: *Piezoelectric Fuel Injector, Biodiesel, Spray pattern, ignition time, Corrosion elimination*

I. Introduction

In petrol and diesel engines, the fuel injectors can be important part. Characteristically, injectors has been utilized in the petrol engine as solenoid valve, which are dependable for process of discharging and atomizing the fuel into the incoming air stream and enter into the ingestion ports in engines. The injectors performance of engine can reveal the work of engine that run goodly, badly or fail to run [1][2]. There can be numerous problems that can cause the failure of injectors like congested fuel injectors, unclean fuel injectors, fuel injector's needle valve does not open correctly, and fuel injector's needle valve is not place correctly [3]. Fig.1 shows the design of fuel injector that has valve spring, electrical attachment, plunger, fuel filer, solenoid, spray tip and pressurized fuel.
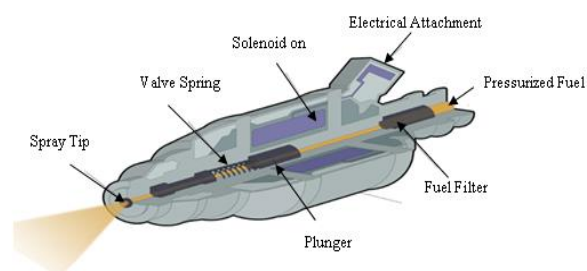

Fig.1. Design of Fuel Injector

For the diesel engine, injector's accurate process is needed to get suitable worked indicators; it can also be considerably manipulate the environmental safety of piston combustion engines by containing a significant force on the drain gases' toxicity. The

fault of diesel engine's fuel injector can affect the fuel injection quality and poorer the process of combustion in engine directly that directs to the worsening of the diesel engine's work [4][5]. By the needle movement inside the body of fuel injector, the injection has been controlled and fuel flow of the injector is started and stopped by needle movement [6]. In piezoelectric fuel injectors, the piezoelectric stack injectors can allow the speedy needle movement and the prospect of rate determining can also been permitted. The number of potential injections and response time of fuel injector is enhanced in cycle of combustion process by improved piezoelectric based fuel injectors [7]. Well controllable force densities have been provided by the piezoelectric actuator per unit stroke contrasted with other kinds of actuators like pneumatic or hydraulic. Furthermore, the fast response time of piezoelectric stack actuators can create those to good candidates for utilize in fuel injectors of diesel engine [8].

For diesel engines, biodiesel can be another fuel that is getting great awareness universal as it decreases the confidence on the power crisis, products of petroleum, air pollution, noise pollution and changes of global climate changes. In diesel engines, blends of biodiesel have been utilized without any foremost alteration. Though Vegetable oil esters give convinced benefits such as lower thermos tip, lower thickness, higher vapor pressure and easier processing comparative to animal greasy acid esters, therefore they can be non-feasible and non-economical due to the high-priced cost [8][9]. Conversely, these kinds of viable fuel injectors do not characteristic injection needle's direct control and, therefore, face issues in precise control of injection time. In this paper, piezoelectric fuel injector with self sensing piezo actuator is designed and VCI is used on injector for injections of biodiesel to reduce the ignition time delay.

2. Related Works

Analysis of a double-layer magnetic circuit structure has been designed in [1] for a high-force density mixture fuel injector. Generally, models of fuel injector contain demerits such as a magnetic diffusion and major leak fluctuation. Consequently, a finite-element technique was utilized to point the design and reduction of leakage flux from the electromagnet pole to the escort pipe. A spark plug fuel injector (SPFI) has been enhanced in [2] which

are the spark plug and fuel injector combination with the try to translate a few gasoline port injection spark explosion engine to direct injection of gaseous fuel. In applications of diesel engine, an optimal number of holes were presented for better productions and performance of engine [3]. A theoretical design and control of a new gasoline direct injector (GDI) has been proposed in [4] employing Terfenol-D, the huge magnetostricitve material, as an actuation part. Electromagnetic and examination of fluid have been skilled to examine the power of some parameters like input fuel pressure, length of nozzle, and funnel angle of needle of the injector. The use of an optically available high-pressure sector test fix in combination with optical test techniques was illustrated in [5] as part of the improvement process of a lean injection combustion model. In diesel engines, experiments with signals of an input voltage equivalent to those exploited established the fuel injector's prototype performance. The prototype has been verified for 250-, 400-, 600-, and 800-μs investment times and just demonstrated a response delay due to hysteresis that has been decreased employing the closed-loop control with the incorporation of the electronic control unit (ECU) in [6].

A new ultrafast time-sequence driving technique was introduced in [7] for piezoelectric stacks that has been exploited in fuel injectors. This method has exposed the reduction of piezoelectric stack's response time by consider the dissemination of stress wave in the piezo-stack. An effort resulting was summarized in withina- cycle assessment of injected fuel in fuel injector for rate shaped outline in [8]. Simplify an actually base, experimentally-validated simulation form; a decreased order model has been introduced. The quality of combustion, drain emissions and tribological biodiesel impacts on CI engines with definite focus on the power of physico-chemical assets of biodiesel examined in [9]. Current efforts in extenuating difficulties associated to operations of diesel engine due to utilization of biodiesel were pointed in [10]. An electronic board operation has been described for motivating solenoid diesel injectors and the experimental setup depending on the Common Rail injection system, for fuel injectors' description with 100% biodiesel fuel during analysis of spray discharged in a dormant velocimetric chamber.
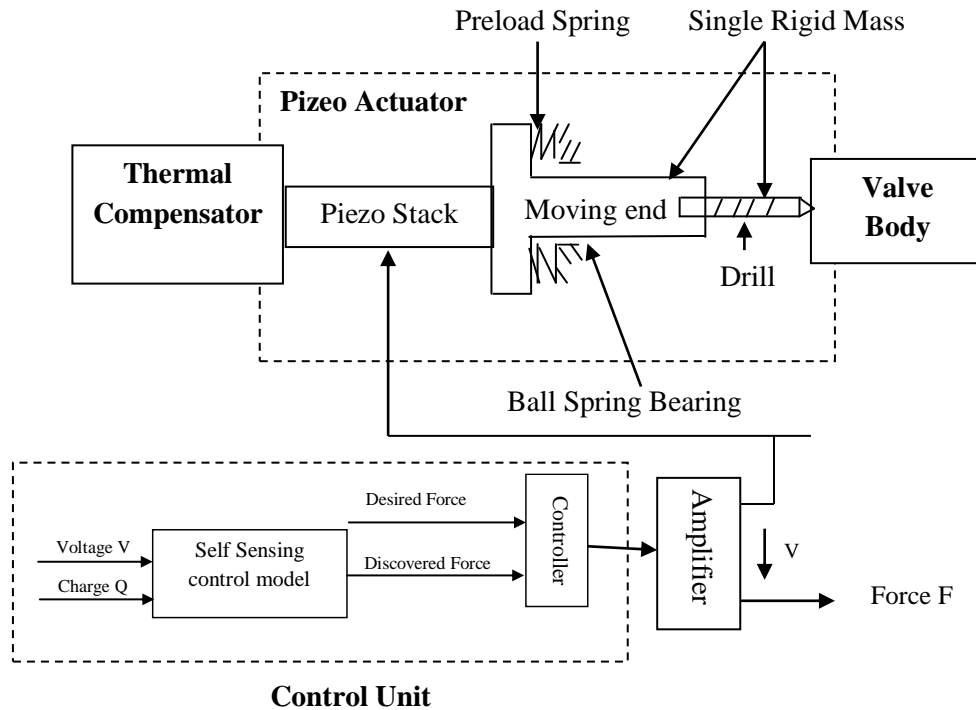
3. Methodology

Fig.2. Proposed Subassembly of piezoelectric injector

a. Design of piezoelectric injector for biodiesel injections

Initially, the three subassembly of piezoelectric fuel injector is designed separately and integrated for biodiesel injections such as actuator with self-sensing control model, thermal compensator and valve body. The approach is selected in order to permit the divide increase of every design, its validation and calibration using experimental test assemble of the three parts, therefore, the ultimate errors are prevented and simple to discover potential reasons of inconsistency between simulated and actual behavior. Fig.2 shows the proposed subassembly of piezoelectric injector for bio-diesel injections.

In piezoelectric fuel injector engine, the piezo actuator has been exploited to control the injections of fuel. A piezoelectric actuator can be an electrically controlled locating part that operations are depending on the piezoelectric results. In piezoelectric force sensors, the direct piezo effect has been utilized for design to giving an electric

charge as a result of mechanical sprain. But in this proposed design of piezoelectric fuel injector, we use a self sensing control model instead of force sensor to avoid the high cost sensor in piezo actuator. In common, the piezo actuators can be depending on the reverse consequence, that is and electrical field equivalent to the polarization direction can establish a crystalline material's extension with esteem to the similar direction. A torque has been made on electrical diploes by electrical field in the material structure that is assigned among the area to give modifications in the mono-crystalline partitions length.

In our proposed design of piezoelectric injector, the self sensing model is embedded in piezoelectric actuator instead of high cost force sensor. A detection model has been inferred that permits the calculation process in real time of the piezoelectric actuator extension. In this sensing model, force is started from the driving voltage V and current Q measurement. This kind of self sensing control model can be utilized to identify the force and the dislocation from the current and the voltage

measurements on the piezo actuator. In the self sensing control model for piezo actuator, the generated force can be an output and electrical current can be input.

The self sensing control model has been deduced the only dissimilarity being that the force becomes an output and the electrical charge becomes an input. By using an integrator, the electrical charge can be inferred from the considered current.

From the electrical charge, the Voltage V_H is calculated by using the following equation (1)

$$V_H = F(q) = x\left[1 - \sqrt{1 + \frac{q^2}{y^2}}\right] + zq \qquad (1)$$

The analytical expressions of generated force is given by equation (2)

$$a(q,V) = \frac{q}{\alpha} - \frac{C_p}{\alpha}\left[V - \left[x\left[1 - \sqrt{1 + \frac{q^2}{y^2}}\right] + zq\right]\right] \qquad (2)$$

And the analytical expressions of displacement is calculated by using the following equation (3)

$$F(q,V) = \frac{K_E}{\alpha}q - \left[\alpha + \frac{K_E C_p}{\alpha}\right]\left[V - \left[x\left[1 - \sqrt{1 + \frac{q^2}{y^2}}\right] + zq\right]\right] (3)$$

The partial derivations of analytical expressions of force and displacement (2) and (3) can give a suggestion of the sensitivity of the self sensing control model comparative to the voltage and the current, correspondingly. The partial derivatives are given by (4), (5), (6) and (7)

$$\left|\frac{\partial a}{\partial q}\right| = \frac{y + C_p x}{y\alpha} \qquad (4)$$

$$\left|\frac{\partial a}{\partial V}\right| = \frac{C_p}{\alpha} \qquad (5)$$

$$\left|\frac{\partial F}{\partial q}\right| = \frac{\alpha^2 x + K_E C_p x + K_E y}{y\alpha} \qquad (6)$$

$$\left|\frac{\partial F}{\partial q}\right| = \frac{\alpha^2 + K_E C_p}{\alpha} \qquad (7)$$

This self sensing control model is attached instead of force sensor with the pizeo electric actuator to find the differing accelerations in a dynamics range and frequency of broad whereas demonstrating the linear response on the whole range of evaluation. This type of model can be suited for the evaluation of compression, shearing forces and dynamic tensile. This model has been designed with very high effectiveness and very dynamic forces can also be measured. Imbalances on rotating machine parts can also be detected by this self sensing control model without force sensor.

In the first subassembly, the piezo actuator with self sensing control model of fuel injector is integrated with the valve body in engine. The centre body of the piezoelectric actuator is the piezo stack in fuel injector. The different wafers of piezoelectric material squeeze in between electrodes have been assembled to form the piezo stack in piezoelectric actuator. The behavior of piezo stack can be differentiated by the some wafers, their region, their breadth and the piezoelectric material's uniqueness. At several assemblies preload conditions, the validation tests has been done on the valve body's needle, the force contact between the rigid block and the actuator is estimated. This first subassembly of this fuel injector design can reproduce the experimental tooling utilized after for the process of validation, wherever a dry injector has been exploited without employing the thermal compensator whose point has received by a rigid part of piezo-fuel injector process. This kind of experimental tooling can allow evaluating the displacement of piezo-actuator and the needle lift.

In second subassembly, thermal compensator model is integrated with the pizeo actuator with self sensing -valve body before validation process. This kind of model can also be validated by utilizing the similar tooling and the rigid component's position is taken by the thermal compensator model. The thermal compensator model's validation is used to validate the piezoelectric actuator with self sensing model using same apparatus. This model task can be to make sure the contact between the piezo-actuator and the needle lift in valve body separately from what operating situation. Probable reduction or development happens in a number of elements, occurred by thermal incline. Therefore, a lift loss or in a number of cases a missing injection are occurred during the activity of working process.

In the last subassembly of piezoelectric fuel injector, the valve body's hydraulic modeling and mathematical subsystems are attached, capable to explain oscillatory phenomenon happening in the liquid that has been implemented. In our design for biodiesel injections, the valve body can be the end part of the piezoelectric fuel injector. At the high pressure, gasoline flows inside the body of valve in

injector. A very accurate and comprehensive hydraulic analysis is done in order to measure the effect of ram, which happens while the working of cycles in valve body. This third model's validation can be carried out with high pressure and flow assessment employing the experimental tooling. Hence, the piezoelectric fuel injector is designed with self sensing model for bio-diesel injections.

b. VCI Method to elimination of corrosion

After the subassembly of piezoelectric fuel injector, VCI method is applied on injector to avoid the corrosion when using bio-diesel. When using a bio-diesel the piezoelectric fuel injector is protected from the corrosion or oxidation by VCI corrosion inhibitor. It has capable of restraining the chemical reactions. The opposite of catalysts is considered that allow the definite reactions. The VCI process has been employed on injector instead of coating method. The substance of VCI method can be applied as oil formulation or spray on fuel injector. The injector surface is to be protected by this process during the evaporation. VCI can act as an active corrosion inhibitor technique. The water corrosion processes are dynamically influenced by VCI inhibitors while using the biodiesel in injector. Work of VCI method has been established in fig.3. The metallic surfaces of the fuel injector should be cleaned as possible to make sure the efficiency of this VCI method for prevention of corrosion.
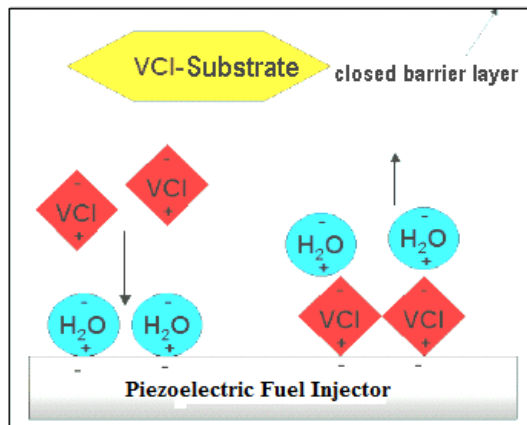

Fig.3. Work of VCI Method

The VCI method can take the ordinary temperature level separately to prevent the corrosion. Molecules of VCI are passed through pre-existing water films on injector surfaces. The protective layer is formed between the metal surface

of injector and the surrounding atmosphere continuously because VCI has stronger molecules than the water molecules. The water has been displaced from the metal surface of fuel injector. By using this VCI, the water vapor can be kept away from the metal surface of fuel injector and hence corrosion is prevented while biodiesel flows. The electrochemical processes are inhibited by VCI method which is resulted to restraining either the cathodic or anodic half-reactions. The VCI's period of action in fuel injector may be extended to two years. The protective action has been provided and compatibility difficulties must be verified in this process for effectiveness of this method.

Fig.4. Experimental Setup

Fig.4 shows the experimental setup for proposed piezoelectric injector to inject the biodiesel. An experimental setup has been developed for piezoelectric fuel injector with self sensing control model and VCI method. In this setup, piezo-actuator with self sensing model, thermal compensator and valve body integrated without force sensor. The mechanical loading condition of piezo-actuator can be changed dynamically. In the piezo- actuator, spring has been inserted in stiff manner to add a mechanical preload on piezo-actuator. The spring can be changed to adjust the condition of preload amplitude. The contact of piezo-actuator and needle of valve body has been ensured by thermal compensator. The effect is evaluated by the valve body of fuel injector. VCI is used to prevent the water corrosion while usage of biodiesel in fuel injector.

c. Analysis of Spray pattern using integration of CFD and RCM

The CFD method is combined with RCM method to analyze the spray pattern in piezo electric injector for biodiesel injections to the reduction of ignition time after the subassembly of piezoelectric injector. CFD can be a one method of fluid mechanics. After the subassembly of piezoelectric fuel injector, the CFD is applied to find the problems of injector. In proposed piezoelectric fuel injector for biodiesel injections, the numerical analysis and data structures have been utilized by CFD analysis to analyze and solve the difficulties that containing fluid flows. Fig.5 shows the experimental setup to analyze the spray pattern and ignition time of fuel injector for injections of biodiesel.

Fig.5. Experimental Setup for spray pattern analysis

In this experimental setup, the computer can be utilized to execute the calculations needed to simulate the interface of gases and biodiesel with piezoelectric fuel interface surfaces are described by conditions of boundaries. The bio-diesel has been injected into the piezoelectric injector with the volume of 33.97L. For the ignition system, an inductive spark has been used with adequate reside duration of 10 ms. For the CFD with RCM experiment, the spark gap has set at 0.6mm. In this work, the high speed supercomputers are used to attain better solutions for spray pattern of injector. Accuracy and flows of turbulent's simulation scenarios speed has been enhanced by using ongoing MATLAB software. By using a wind tunnel, the validation of experiments is executed. The specifications of fuel injector for spray pattern analysis have been summarized in table 1.

Table 1 Specifications of piezoelectric injector engine

Parameters	Specifications
Number of cylinders	1
Compression ratio	10.5:1
Cylinder bore/mm	81mm
Number of valves	4
Displacement	400 cm^3
Stroke	91.3mm
Inlet ports	Tangential and swirl inlet port
Combustion chamber	Disk-Shape
Ignition technique	Inductive Spark

For computational resources, the spray modeling is very complex with their important necessities. Therefore, the fast computers are used to give the better simulation results for spray pattern in fuel injector. Fig.6 shows the spray pattern modeling of fuel injector.
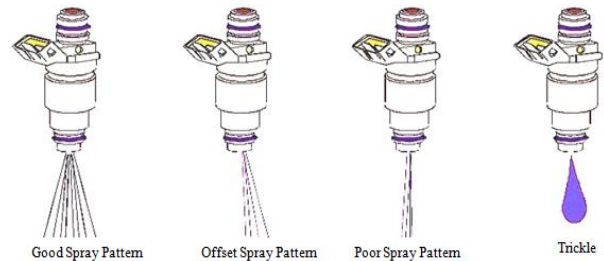

Fig.6. Spray patterns of fuel injector

In this paper, spray patterns is characterized by the CFD method from piezoelectric fuel injectors for biodie Good Spray Pattern FD an Offset Spray Pattern on a thermal compensator, valve body, four-valve, wall guided piezoelectric actuator which has a self sensing control model. Problem of functions of location of fuel injector, spark plug, valve body, four strokes and operation of piezoelectric fuel injector engine has been found by CFD using superfast computers. After that, the scheduled maintenance plans that are generated by CFD are extended by RCM. In RCM process, the failure mode is decreased and frequency of event is also

reduced by structured decision process to improve the spray pattern. The RCM is integrated with CFD to give the reliability of the spray pattern. This combination has been designed to find the every kind of failure modes in injector containing environment and working context. Process- based failure modes are also found by this method. In the RCM process, certifications can ensure the good level of spray pattern. In this spray pattern analysis, all the failures have been discovered and reported to the RCM. After that, the RCM eliminate or reduce the failures that are reported by the CFD. Hence, good spray pattern is improved by reducing all the failure modes of piezoelectric injector for biodiesel injections. This better spray pattern analysis is to reduce the ignition time delay.

4. Results and Discussions

In this section, the effect of proposed piezoelectric fuel injector for bio-diesel injections has been discussed with various parameters such as pressure and temperature of cylinder, rate of heat release and biodiesel burnt and Oxides of Nitrogen (NOx) Emissions.

Pressure and temperature of Cylinder

The comparison of cylinder pressures for proposed piezoelectric injector has been established in fig.7. From the chart, cylinder pressure is increased in case 1 that happens at about 600 CAD while the peak in-cylinder pressures for cases 2,3 and 3 can be lower correspondingly. After the 650 CAD, every cylinder pressure has the same pressure values.
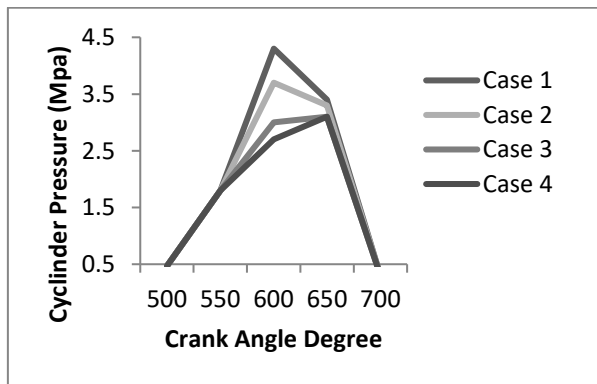

Fig.7. Comparison chart of Cylinder pressure

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Comparison of cylinder temperatures for pieo-electric injector has shown in fig.8. From the below chart 8, case 1 has high peak cylinder temperature 2550K while the peak cylinder temperatures for cases 2,3 and 3 can be lower correspondingly.
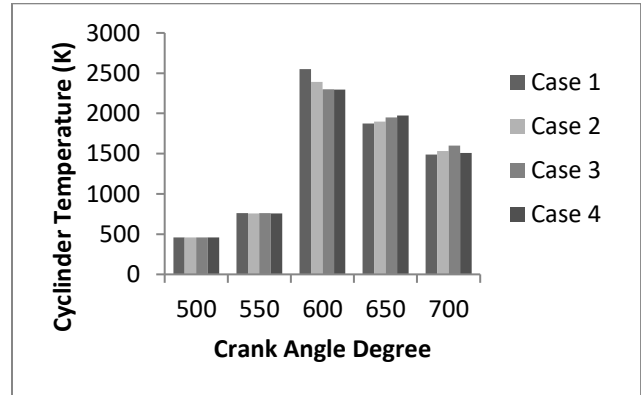

Fig.8. Comparison chart of temperature

Rate of heat release and biodiesel burnt

The comparison of rate of heat release for proposed fuel injector is shown in fig.9. From the chart 9, case 1 has taken 33 J of peak heat release rate while cases 2, 3 and 4 have taken lesser values of rate of heat release. Therefore, case 1 can directs to faster combustion process.
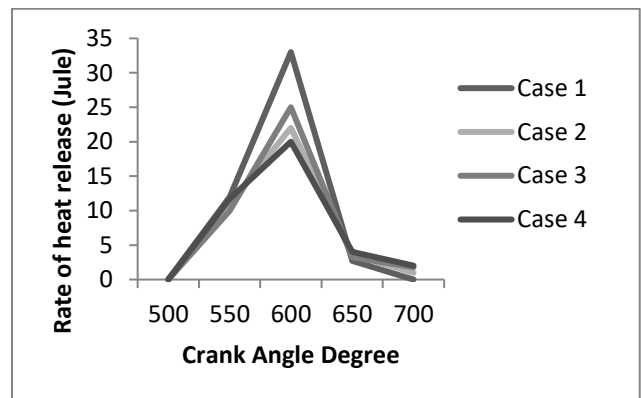

Fig.9. Comparison chart for rate of heat release

The percentage of bio-diesel burnt variation with crank angle has been established in fig.10 for the different cases. From the Fig.10, the center of combustion is 670 CAD while the c 2, 3 and 4 has taken 690, 683 and 688 CAD that can be very close to each other. Hence Case 1 has an enhanced and faster combustion than the other cases.
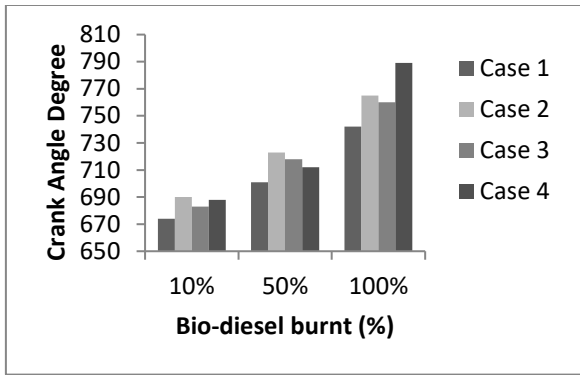
Fig.10. Comparison chart of bio-diesel burnt

Oxides of Nitrogen (NOx) Emissions

The comparison of NOx emissions has been established in fig.11 at the (850 CAD) for the different cases. The emission of NOx is increased as 0.9 mg in case1 than the cases 2, 3 and 4. Hence case1 has enhanced and faster combustion.
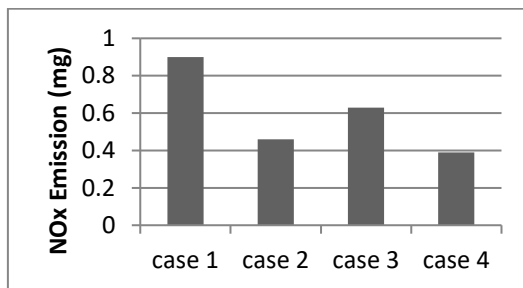

Fig.11. Comparison chart of NOx Emissions

5. Conclusion

In this paper, the pizeoelctric fuel injector has been developed with self sensing control model and VCI method for bio-diesel injections. The design of fuel injector was improved by subassembly of piezo-actuator with self sensing model, thermal compensator and valve body. In the design of piezo actuator, self sensing model has been attached in the replacement of force sensor to avoid the high cost sensor. The VCI method has been used on piezoelectric fuel injector to reduce the corrosion of metal surface of injector that is occurred by the water vapor due to the frequent usage of biodiesel. Finally, the spray pattern and ignition time was analyzed by combined CFD and RCM method. The functions failures were discovered by the CFD and reported to the RCM. Then, every failure mode has been eliminated by RCM. The ignition time delay

is reduced by good spray pattern. The spray pattern and ignition time has been simulated in MATLAM software using superfast computer. The better results of spray pattern analysis have been produced by computer for our proposed system. In future work, this kind of spray pattern and ignition time analysis can give idea about how to improve the fuel injector for all type of fuel such as diesel, petrol and bio-diesel.

References

1. Huai-Cong Liu, Sooyoung Cho, Hyun-Seok Hong, Ju Lee Ho-Joon Lee: *Design and Analysis of a Double-Layer Magnetic Circuit Structure for High-Force Density Hybrid Fuel Injector*. IEEE Transactions on Magnetics, Vol.53, No.11, 2017, p.1-5.

2. Taib Iskandar Mohamad. M. Harrison, Jermy, M., How, H. G.: *The structure of the high-pressure gas jet from a spark plug fuel injector for direct fuel injection*. Journal of Visualization, Vol.13, No.2, 2010, p. 121–131.

3. Lee, B. H., Song, J. H., Chang, Y. J., Jeon, C. H.: *Effect of the number of fuel injector holes on characteristics of combustion and emissions in a diesel engine*. International Journal of Automotive Technology, Vol.11, No.6, 2010, p. 783–79.

4. Mojtaba Ghodsi, Nasser Hosseinzadeh, Abdullah Özer, Hamid Rajabzadeh Dizaj, Yousef Hojjat, Nader Garjasi Varzeghani, Mohammad Reza Sheykholeslami, Soheil Talebian, Mohammad Hadi Ghodsi, Amer Al-Yahmadi: *Development of Gasoline Direct Injector Using Giant Magnetostrictive Materials*. IEEE Transactions on Industry Applications, Vol.53, No.1, 2017, p. 521 – 529.

5. Meier, U., Heinze, J., Lange, L., Hassa, C., Rackwitz, L., Doerr, T.: *Characterisation of the combustion performance of low emission fuel injectors with laser measurements*. CEAS Aeronautical Journal, Vol.3, No.1, 2012, p. 45–53.

6. Hirmand Nouraei, Ridha Ben-Mrad, Anthony N. Sinclair: *Development of a Piezoelectric Fuel Injector*. IEEE Transactions on Vehicular Technology, Vol.65, No.3, , 2016, p. 1162 – 1170.

7. Xuejie Ba, Qiaosheng Pan, Bin Ju, Zhihua Feng: *Ultrafast Displacement Actuation of Piezoelectric Stacks With Time-Sequence*. IEEE Transactions on Industrial Electronics, Vol.64, No.4, 2017, p. 2955 – 2961.

8. Jin Shen, Neha Ruikar, Dat Le, Gregory M. Shaver: *Model-based Within-a-Cycle Estimation of Rate Shaping for a Piezoelectric Fuel Injector*. 2013 American Control Conference, 2013, pp. 3625 – 3630.

9. Jo-Han Ng, Hoon Kiat Ng, Suyin Gan: *Advances in biodiesel fuel for application in compression ignition engines*. Clean Technologies and Environmental Policy, Vol.12, No.5, 2010, p. 459–493.

10. Visconti,   P., Ventura, V., Carlucci, A. P., Strafella, L.: *Driving electronic board with adjustable piloting signal parameters for characterization of Common Rail diesel injectors with pure Biodiesel*. IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC), 2016, pp. 1 – 6.