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Design of Injector for Hydrogen Operated S.I. Engine

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Abstract—Current era is the era of fossil fuels. Today most of the vehicles are using fossil fuels as the main fuel. But these fuels are exhaustible; they will exhaust after some days. So engineers and scientists are looking for various alternative fuels. Hydrogen is one of the fuels which are abundantly available in nature and it possesses essential properties for being used as alternative fuel for fossil fuels. But hydrogen also possesses some properties such as low viscosity and low density. So injecting hydrogen is one of the challenges. So for injecting hydrogen in the combustion chamber injector is needed. Currently some hydrogen injectors which are operated by using solenoid as an actuator are available in the market. But the main problem deals with them are injection delay and the problem of backfire and pre-ignition. So, piezoelectric hydrogen injectors could be the best option to overcome such problems**.**Piezoelectric injectors use piezoelectric stack actuators which give quick response as voltage is applied**.**Using this actuator precise injection is done. This tends in reducing the injection delay by means of which problems like backfire and pre-ignition can be overcome.So in this paper, work related to the design of hydrogen injector using piezoelectric actuator for diesel power generator will be presented along with mechanism developed, design calculations.

Index Terms— Hydrogen, Injector, Piezoelectricity, Actuator, Alternative fuels, Injection delay,Piezo stack.

1 INTRODUCTION

TODAYS' era is the era of fossil fuels. Today most of the vehicles are using fossil fuels such as gasoline, diesel, etc. as main fuel. But the main problem dealing with these fuels is the exhaust emission of automobiles is changing the climate of atmosphere and causing damage to human life as well as to the environment. For the growth of civilisation, the use of automobiles is increasing day by day, so it is impacting badly on the atmosphere as well as increasing fuel crisis. Therefore, scientist and engineers are in search of other alternative automotive fuel. An intense research effort is going on in the field of engine to develop new vehicle engine with improved efficiency and decreased harmful emission. As compared to conventional, fossil hydrocarbon fuels, hydrogen eliminates emissions of pollutants such as carbon monoxide (CO) and unburnt hydrocarbons, which are injurious to health risks in largely populated areas. The only non-trivial pollutant from hydrogen engines is nitrogen oxides (NO_x). However, some characteristics of hydrogen fuel, such as a high flame speed and extensive lean burn operation possibilities, allow significant reductions in NO_xas compared to when using conventional fuels. [1] So hydrogen could be used as a best alternative fuel.

1.1 Why Hydrogen?

It is clear that the transportation sector is in need of some other energy carriers. As a means to chemically store energy, hydrogen has been advanced as an interesting energy storage or carrier. There are many ways to produce hydrogen and the possibility of producing energy from hydrogen with very fewer emissions. Also, hydrogen has the potential to be used for creating renewable energy. One of the ways is to produce hydrogen when the demand for renewable energy production exceeds than energy demand, and convert it back to (electrical) energy or store it when the demand of production reduces.

With hydrogen available as a fuel, there are two options for using it to power vehicles. First is the fuel cell powered vehicle (FCV). Fuel cells using hydrogen are attractive for their potential efficiency, particularly at part load (important for passenger cars), their emissions (only water vapour), quiet running and modularity. But their cost and durability concerns are the major problems. The second option is to use hydrogen in an internal combustion engine. [2]

Using hydrogen as a fuel for internal combustion engine is one of the best options. I.C. Engines are fuel flexible. They can be run on different fuels with some changes. H_2ICEs requires low purity of hydrogen as compared to fuel cells, which makes it cheaper fuel; also low emissions from engine increase peak and part load efficiency compared to most commonly fuelled ICEs.

H_2I.C.E.s are useful for:

- reducing local pollution,
- reducing global emissions of carbon dioxide,

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- increased efficiency compared to current, fossil-fuelled ICEs,
- can be made fuel-flexible,
- They are tolerant for fuel impurities, enabling them to use hydrogen from most sources, without the need for expensive purification.[2]

Based on the type of hydrogen supply system, hydrogen internal combustion engine can be classified into four forms:

- Carburettor type
- Intake manifold fuel injection
- Port fuel injection (PFI), and
- Direct cylinder injection.

PFI has many advantages, such as uniform distribution of hydrogen between cylinders, which makes it easy for combustion, and requires minimum changes from a conventional engine structure. The volumetric energy density of hydrogen is lower than convensional fuels; so the injection volume of hydrogen should be much larger than conventional liquid fuel. It means that under high speed and heavy load, a large volume of hydrogen should be injected within a very short time. [4] By injecting hydrogen directly into the combustion chamber of an engine, the power output would be approximately double as that of the same engine operated in pre-mixed mode. The power output of such an engine would also be higher than that of a conventionally fuelled engine. Also, some problems such as inlet air manifold backfire and power de-rating will not occur by using direct injection. However, there are some challenges associated with direct injection of hydrogen in an engine, related to the properties of hydrogen. The main challenges are the high self-ignition temperature of hydrogen, the long auto ignition delay, and the high rate of pressure rise. On the other hand, hydrogen has advantageous properties such as a high flame speed, short quenching distance, high heating value, and high diffusivity. [2] To improve the performance of H_2ICEs, an understanding of the hydrogen combustion mechanism is required, including how operational variables influence the hydrogen ignition and combustion, and how they can be controlled.

Currently, for injection of hydrogen electrohydraulic injectors (EHI) and electromagnetic valve injectors (EMV) are used. EHI uses an actuator usually a solenoid and a hydraulic oil servo system to the lift needle and inject the fuel. While EMV uses solenoid actuator and a collapsing magnetic field to lift the needle and to inject the fuel. But both of them deals with the major problem of injection delay due to the low density of hydrogen. Nowadays piezo injectors are becoming famous for injecting the diesel because they show highest average mass flux, lower injection delay and faster fuel flow transient rate. The actuators used in piezo injectors works on the principle of piezoelectric effect. Also by designing the piezo injector for hydrogen fuelled operated engine problems such as backfire, pre-ignition and injection delay could be avoided. So it would be more beneficial to design an injector based on piezoelectric principle for the hydrogen fuelled engine.

2 Design Parameters

For designing the hydrogen injector following design parameters are important-

i. A/F Ratio.
ii. Number of injections per cycle.
iii. Pulse Width.
iv. Maximum Fuel Delivery.
v. Fuel Required.
vi. Hydrogen Flow.

For designing current injector $Air/Fuel$ (A/F) ratio was set to 16:1 because it is the standard ratio for using hydrogen as a fuel. Five injections per cycles are required for reducing injection delay according to that pulse width was set to 4ms for current selected case. From the calculations done for the currently selected case which mass flow rate of fuel found was 6.25×10^{-7}kg/cycle, and volume flow rate was $7.6219\times10^{-6}m^3$/cycle. Starting of injection is to be fixed at 10° BTDC and continued upto 10° ATDC.

3 Mechanism Developed

The working of piezoelectric injector is very simple. For starting the injection, voltage is applied to the piezo actuator, so it gets charged and expanded within the body of injector only and switches its force is without friction rapidly to the nozzle needle. The forces required to open nozzle needle cannot be generated by nozzle itself, so nozzle needle is triggered indirectly via amplification system. In another words,piezo actuator triggers a smaller fuel chamber in which pressure difference is shown in this small chamber that triggers the main fuel injector. Due to which the nozzle needle is get forced against the seat. As a result, needle opens, and fuel get injected. To stop the injection voltage is cut due to which piezo contracts which result in pressure reduction due to this nozzle needle get closed, and injection is stopped. In this way, piezoelectric injector works.

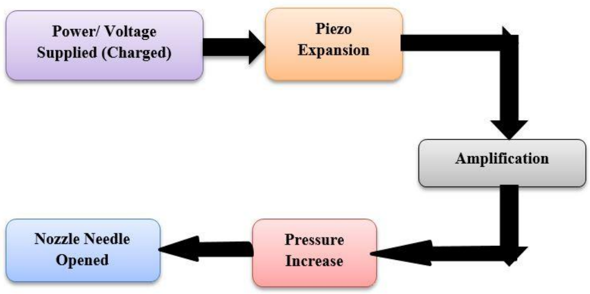

Fig.1. Flow Diagram for Start of Injection

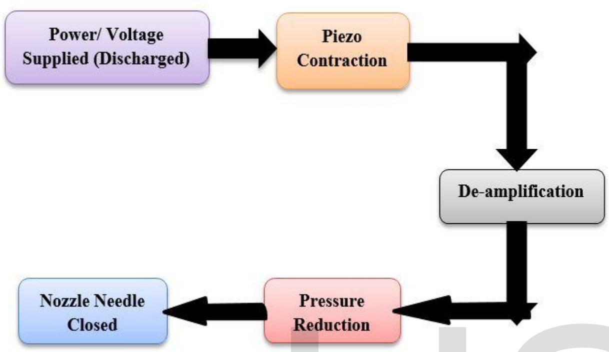

Fig.2. Flow Diagram for Stopping Injection

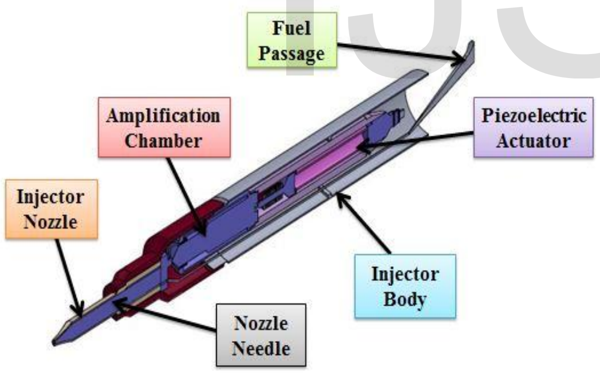

Fig. 3.Proposed Diagram of Injector.

4 Design of Components

4.1 Case Selected

Here injector has been designed for the Engine of Generator having following specifications.

Engine Type- Four-stroke Single Cylinder S.I. Engine
B.P. = 2 kW
RPM = 2000
P_m = 20.4061×10^5 N/mm^2
I.P. = 2.6 kW
D = 44 mm
L = 53 mm
η_v = 85 %
$\dot{V}_d$= 1.3431×$10^6 mm^3$/sec
$\dot{m}_a$ = 1.3985×10^{-3} kg/sec
$\dot{m}_f$ = 8.74× 10^{-5} kg/sec
$\dot{v}_f$ = 1.065× $10^{-3} m^3$/sec

4.2 Piezoelectric Actuator

The piezoelectric actuator is a smart material that undergoes mechanical deformation when an electrical load is applied. The type of piezoelectric actuator that is used for fuel injection is the multi-layer stack, which consists of many thin layers of piezoelectric material bonded together. Here Ring type stack actuator has been used.

For the actuator NoliacPiezoceramic material NCE-51F was used because of its following properties.

Transverse Piezoelectric charge constant (d_{31}) = -208×$10^{-12} m/v$

Longitudinal Piezoelectric charge constant (d_{33}) = 443×$10^{-12} m/v$

Dielectric loss factor (δ) = 0.015

Relative Dielectric Constant (ε^T) = 1900

Density (ϱ) = 7850 kg/m^3

Young's Modulus (E) = 16×$10^{12} N/m^2$

Actuator Specifications-

Outer Diameter = 6 mm
Inner Diameter = 2 mm
Height = 20 mm
Voltage Applied = 200 Volts
Stroke = 30 μm
Blocking Force = 1060 N

4.3 Amplification Chamber

Amplification system is to be designed for increasing pressure of hydrogen to be injected.

Design of Amplification Chamber-

Injection pressure of hydrogen is 3 bars and it to be increased by compressing the hydrogen gas. Here the force applied by actuator on piston is 1060 N diameter of piston (D_p) selected is 20mm. The pressure increased by compression is calculated as-

$$P_{Am} = \frac{F_A}{A_{Am}}$$

P_{Am} = 33.7 bar.

Total volume of fuel to be injected = 7620mm^3.

Here, amplification chamber is designed for storing 5000 mm^3 of fuel and remaining 2620 mm^3 fuel is stored in fuel canal.

So, Length of Reservoir (L_{Am})= 16 mm.

4.4 Nozzle Design

The needle that is commonly used in fuel injection consists of 2 components. The first component consists of a needle seat which is usually part of the housing unit. The second component is the needle, used to seal the nozzle shut.

4.4.1 Needle Design-

The needle is made up of Stainless steel -301 having density (ϱ) = 7888.77 kg/m^3.

Dimensions of Needle-

Diameter (D_N) = 10 mm

Length (L_N) = 70 mm

Self-weight of needle (m_N) = ϱ×V_N

(m_N)= 0.0433 kg

Force exerted by needle due to self-weight (F_n) = m_N× g

F_N = 0.45 N

Force exerted by hydrogen at the Needle tip (F_H)= P_H× A_N

F_H = 265 N

Net force exerted by needle during lifting (W) = $F_H - F_N$

W = 265 – 0.45 = 264.55 N

4.4.2 Nozzle Design-

Nozzle also contains hydrogen which directly gets injected into the combustion chamber.

Inner diameter of Nozzle (D_{nI}) is selected as 16 mm.

Length of Nozzle (L_f) = 60 mm.

Volume of fuel in nozzle = 1700 mm^3.

4.5 Fuel Canal

Fuel canal is designed for storing 920 mm^3 of fuel. So, here diameter of fuel canal (D_f) was assumed as 6 mm.
Volume of Canal= 2620 mm^3
Length of fuel canal (L_f) = 32.5 mm

4.6 Spring Design

For injector helical spring is used which pushes the needle down for shutting down the injection.

For spring Stainless steel-302 material was selected having

Modulus of Rigidity (G) = 70.3 kN/ mm^2 &

Initial displacement (δ) was assumed as 2 mm.

$$\delta = \frac{8wD_s^3 n}{Gd_s^3}$$

C = 4

D_s= 10 mm &

$$C = \frac{D_s}{d_s}$$

d_s= 2.5 mm

n = 5

4.6 Injector Body

For injector body, Stainless steel-302 is selected as material because injector body has to sustain high temperature at the nozzle tip. So it must be temperature resistant and the melting point of stainless steel- 302 is high.

Thickness of body (t) = 3 mm

Diameter of Injector body (D_I) = Diameter of Amplification Chamber + 2× Thickness of body

D_I = D_P + 2×t

= 44 mm

Diameter of Injector body at Nozzle Section-

Inner diameter of Nozzle Body (D_{nI}) = 16 mm

Thickness of body (t_n) = 3 mm
Outer Diameter of Nozzle Body (D_{n0}) = D_n+ 2(t_n) = 25 mm.

5 Result & Discussion

So by designing the injector based on the concept of piezoelectricity following dimensions of various components are found.

Table No. 1

Dimensions of designed component

Sr. No.	Name of part	Dimensions (in mm)
1.	Diameter of plunger (D_p)	20
2.	Length of Amplification Chamber (L_{Am})	16
3.	Mean diameter of coil spring (D_s)	10
4.	Diameter of spring wire (d_s)	2.5
5.	Number of active coils (n)	5
6.	Diameter of Injector body (D_I)	44
7.	Diameter of Nozzle Body (D_n)	25

So, theoretical design calculations are done for the injector. Here ring type stack actuator is selected because by stacking different layers of piezo material it gives more loads and more displacement. Also, motto of selecting Noliac-51F piezo ceramic material for the actuator is, its properties such as high dielectric constant, young are modulus, etc. and its relative cost. Stainless steel is selected as a material for nozzle due to its properties of corrosion resistance and self-weightlessness. Here needle should be weightless or should have negligible weight as it should get lift by the pressure of hydrogen which is low. Injector body is made of Stailess Steel-302 because of its properties such as high melting point and is easily available.

6 Conclusion

In this way for the currently selected case injector is designed. Here direct injection method is used for injecting the hydrogen because it will avoid the problems of pre-ignition and backfire. For lowering injection delay, piezoelectric actuator is used as it has quick response time which is 0.5msec. So, theoretically, it can be concluded that injection delay will be reduced by implementing current design.

7 Expected Outcomes

Expected outcomes after completion of this project can be-

- Reduced injection delay.
- Back-fire as well as pre-ognition can be removed.

8 Acknowledgment

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Nomenclature

S.I.	Spark Ignition
NO_X	Nitrogen Oxide
I.C.E.	Tnternal Combustion Engine
BTDC	Before Top Dead Centre
ATDC	After Top Dead Centre
B.P.	Brake Power
R.P.M.	Revolutions Per Minute
P_m	Mean Effective Pressure
I.P.	Indicated Power
D	Bore Diameter
L	Stroke Length
η_v	Volumetric Efficiency
$\dot{V}_d$	Displaced Volume
$\dot{m}_a$	Mass flow Rate of Air per Seconds
$\dot{m}_f$	Mass flow Rate of Fuel per Seconds
$\dot{v}_f$	Volume flow Rate of Fuel per Seconds
mm	Milimetre

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