Modification Design of Petrol Engine for Alternative Fueling using Compressed Natural Gas

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Abstract

This paper is on the modification design of petrol engine for alternative fuelling using Compressed Natural Gas (CNG). It provides an analytical background in the modification design process. A petrol engine Honda CR-V 2.0 auto which has a compression ratio of 9.8 was selected as case study. In order for this petrol engine to run on CNG, its compression had to be increased. An optimal compression ratio of 11.97 was computed using the standard temperature-specific volume relationship for an isentropic compression process. This computation of compression ratio is based on an inlet air temperature of 30oC (representative of tropical ambient condition) and pre-combustion temperature of 540oC (corresponding to the auto-ignition temperature of CNG). Using this value of compression ratio, a dimensional modification Quantity =1.803mm was obtained using simple geometric relationships. This value of 1.803mm is needed to increase the length of the connecting rod, the compression height of the piston or reducing the sealing plate's thickness. After the modification process, a CNG engine of air standard efficiency 62.7% (this represents a 4.67% increase over the petrol engine), capable of a maximum power of 83.6kW at 6500rpm, was obtained.

Keywords: modification design, engine, alternative fuelling, compressed natural gas

1. Introduction

The world today is lamenting the disastrous consequences of climate change and leading technologies are searching for alternative fuels [1]. The quest for alternative fuels does not only stem from environmental concerns but also as a result of the clamor for cheaper energy. According to the definition, alternative fuels are materials or substances which can be used as fuels, other than conventional fuels. Conventional fuels include fossil fuel, nuclear materials, artificial radioisotopes, etc. Some familiar alternative fuels include bio-fuel, alcohol fuels, ammonia, hydrogen, compressed air and compressed natural gas. Compressed natural gas (CNG) is a fossil fuel substitute for gasoline (Petrol), diesel or propane (LPG). It is considered the second most important energy source after oil [2]. Although its combustion produces greenhouse gases, it is a more environmentally cleaner alternative and it is much safer in the event of a spill. The use of CNG has several merits when compared to conventional fuels. Among these are low maintenance cost of CNG powered vehicles; elimination of fowling of spark plugs due to the absence of lead or benzene content; less likelihood to auto ignite since it's auto-ignition temperature is 540oC [3], and increase in the life span of lubricating oils due to non contamination and dilution of crankcase oil. Furthermore, CNG emits significantly less carbon dioxide (CO2), unburnt hydrocarbon (UHC), Carbon monoxide (CO), Nitrogen oxide (NOX), Sulphuroxide (SOX) [4]. Since CNG is a gaseous fuel, it mixes easily and evenly with air in the process of combustion.

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Some attempts have been made to develope CNG vehicles. Nissan CNG S-class van is the first CNG small van inline production that certified as an ultra low emission vehicle (ULEV) by ministry of transport in Japan [5]. The major points of developing dedicated CNG engine vehicles are reducing the exhaust emissions to comply with the emission standard such as ULEV, SULEV, Euro IV or Euro V, to achieve the greater cruising range by a single charge, to secure roomy luggage compartment by using space effectively and acceleration comparable to the gasoline model.

Another successful development of a prototype of a dedicated CNG engine-vehicle is a midsize sedan, done by the John Hopkins University Applied Physics Laboratory (JHU/APL), which is in conjunction with DaimlerChrysler and Lincoln Composites. It has a city/highway driving range of 480km, ample trunk capacity (354liters), and acceleration comparable to the gasoline model and achieving ultra-low exhaust emission. The 2.4-liter double overhead cam (DOHC) engine was modified for natural gas operation with high-compression pistons, hardened exhaust valve, a methane specific catalytic converter, and a multipoint gaseous fuel injection system. The chassis was repackage to increase space for fuel storage with a custom-designed, cast aluminum, semi-trailing arm rear suspension system, a revised flat trunk sheet metal floor pan, and by equipping the car with run-flat tires [5]-[7]. Shin et al [8] made design modifications that could transform a diesel engine to a Daewoo 11.1L CNG running engine. Kirpal Singh [9] provided the constituents of CNG conversion kit such as cylinder, vapor bag, high pressure pipe, refueling valve, pressure regulator, gas-air mixer, petrol solenoid valve.

Compressed Natural Gas (CNG) was first used as a Vehicular fuel in Nigeria in 1989 when the Nigerian Gas Company initiated a pilot project to demonstrate the acceptability and viability of CNG utilization as automotive fuel [10]. However, many nations of the world have been operating natural Gas vehicles and not less than five million vehicles are currently powered by CNG worldwide.

2. Materials and Methods

To get petrol engine to run on CNG, two ratios are most essential. These are compression ratio and air-fuel ratio. The compression ratio is the ratio of the total volume between the cylinder head and the bottom dead centre (BDC) to the volume between the cylinder head and the top dead centre (TDC). The compression ratio needed to run CNG is higher than that needed to run gasoline. This is because of the relatively high auto-ignition temperature of CNG. The auto-ignition temperature is that temperature to which a substance must be raised before it burns. This higher compression ratio can be achieved by

(i) Increasing connecting rod length.
(ii) Installation of sealing plate with lower thickness.
(iii) Increase of piston compression height.
(iv) Decrease of engine block height

2.1. Compression ratio (Γv) determination:

An expression for the compression ratio would be derived based on the Otto cycle as shown in Fig. 1. It is pertinent to state that

(i) The compression process (1-2) is assumed isentropic
(ii) The combustion process (2-3) is assumed isochoric
(iii) The expansion process (3-4) is assumed isentropic
(iv) The exhaust process (4-1) is assumed isochoric

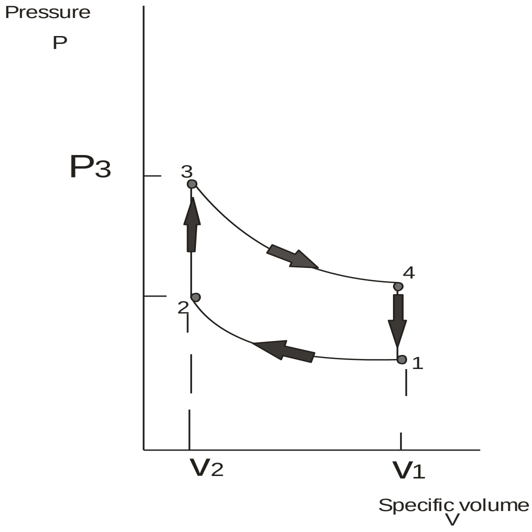

Fig. 1 Theoretical Otto Cycle

Based on our definition of compression ratio

$$\Gamma_v = v_1/v_2 \quad (1)$$

$$\Gamma_v = (T_2/T_1)^{1/(\gamma-1)} \quad (2)$$

2.2. Modification quantity (ψ)

The mathematical *basis* for this modification is that

$$(v_1+a)/(v_2+a) < v_1/v_2 \quad \text{for } a>0 \quad (3)$$

$$(v_1-a)/(v_2-a) > v_1/v_2 \quad \text{for } a>0 \quad (4)$$

The quantity ψ is needed to execute any of the four modification schemes mentioned earlier.

$$\Psi = h - L/(\Gamma_v - 1) \quad (5)$$

With the compression ratio determined from the previous section, these can be obtained analytically.

2.3. Clearance

This is obtained using

$$h = L/(\Gamma_{vp} - 1) \quad (6)$$

where h =Clearance height, L= Stroke Length and Γ_{vp}=Compression ratio of petrol engine.

2.4. Peak Pressure

It’s obtained from,

$$P = P_1(T_3/T_1)\Gamma_v \quad (7)$$

where P=Peak pressure, P_1= Inlet Pressure, T_3=peak temperature, T_1=Inlet pressure, Γ_v= Compression ratio of CNG engine.

2.5. Cylinder Thickness

It's obtained from,

$$t = PD/2\sigma \tag{8}$$

where t= thickness, P= Peak Pressure, D= Bore, σ= hoop stress

2.6. Air standard efficiency

This is obtained from,

$$\eta = 1 - 1/\Gamma_v^{\gamma-1} \tag{9}$$

where η= air standard efficiency, Γ_v= Compression ratio of CNG engine, γ= ratio of specific heats

2.7. Specific Network

This can be obtained from,

$$w_{net} = C_v(T_3 - T_2)\eta \tag{10}$$

where C_v= specific heat at constant volume, T_3=peak temperature, T_2= post compression temperature, η= air standard efficiency

2.8. Mean effective pressure

This can be obtained from,

$$MEP = w_{net}/[v_1(1 - 1/\Gamma_v)] \tag{11}$$

where MEP= mean effective pressure, w_{net}=specific network, v_1= inlet specific volume, Γ_v= Compression ratio of CNG engine

2.9. Net Power Output

This can be obtained from,

$$\dot{W}net = PLANkS \tag{12}$$

where $\dot{W}net$= net power output, P= mean effective pressure, L= stroke length, A= bore area, N= speed in rps, k= number of cycles per revolution, S= number of cylinders

2.10. Mass flowrate of air /cylinder

This can be obtained from,

$$\dot{m}_{air} = \dot{W}net / (w_{net}S) \tag{13}$$

where $\dot{m}_{air}$= mass flow rate of air per cylinder, $\dot{W}net$= net power output, w_{net}=specific network, S= number of cylinders.

3. Results

To illustrate the relevance of the theoretical frame work laid down, petrol engine Honda CR-V 2.0 auto was used as a case study. The specifications are given in Table 1 and Table 2, some input data in table3 while the results are presented in

Table 4.

3.1. Specifications

The necessary specifications are in two categories. The first category pertains to the chosen petrol Engine Honda CR-V 2.0 Auto. These are presented in Table 1.The second category of specifications is found in Table 2. The table presents standard specifications in relation to CNG.

Table1 Specifications of Petrol Engine

Manufacturer	Honda Siel Cars India Ltd
Engine type	4 Cylinder in-line Petrol
Bore	86.00mm
Stroke	86.00mm
Compression ratio	9.8
Maximum power	103kW at 6500rpm
Maximum torque	184.4Nm at 4000rpm
Valve	4 Valves per cylinder, DOHC
Ignition and fuel system	Electronic PGM FI

Table 2 Properties of CNG [11]

Property	Value
Peak Flame temp(^{o}C)	1884
Auto-ignition Temp (^{o}C)	540

3.2. Input Data

In order to utilize the equations laid down, necessary input data have been established. These are presented in Table 3.

Table 3 Input data

Parameter	Value
Inlet temperature (T_1)	30^{o}C (303K)
Inlet pressure (P_1)	101.325kPa
Ratio of Specific heats for air (γ)	1.4
Peak flame temperature (T_3)	1884^{o}C (2157K)
Post compression temperature (T_2)	540^{o}C (813K)
Bore (D) X Stroke (L)	86.00X86.00 (mm)
Rotational Speed (N)	6500rpm

A closer look at Table 3 reveals that the Inlet temperature (T_1) corresponds to average thermal loading temperature under tropical conditions, the Inlet pressure (P_1) corresponds to atmospheric pressure, the Ratio of specific heat for air (γ) was chosen for the air standard cycle on the basis that the charge and exhaust products are predominantly air by mass, the Post compression temperature (T_2) corresponds to the auto-ignition temperature of CNG, the Bore (D)$\times$ Stroke (L) and Rotational Speed(N) correspond to those of the petrol engine to be modified.

3.3. Analytical Results

The relevant results obtained from the equations presented are shown in Table 4.

Table 4 Results (Continued)

Compression Ratio (Γ_v)	11.79
Clearance(h)	9.773mm
Modification Quantity(Ψ)	1.083mm
Peak Pressure(P_3)	85.02bar
Air Standard Efficiency(η)	62.7%
Specific Net work (w_{net})	606.7kJ/kg
Inlet air Specific Volume(v_1)	0.858m3/kg
Mean Effective Pressure (MEP)	7.726bar
Net Power output($\dot{W}net$)	83.60kW
Air flow rate/Cylinder($\dot{m}air$)	3.445×10-2kg/s
Fuel flow rate/Cylinder	2.02×10-3kg/s

4. Discussions

This section presents discussions regarding the output data (results). Table 5 displays comparative analysis on relevant performance indices. It may be necessary to state clearly that the values of these indices come from specifications while those of the CNG were strictly obtained using relevant equations presented.

Table 5 Comparative analysis

Parameter	Petrol engine	CNG engine	% Increase
Engine Type	4-Cylinder in-line Petrol	4-Cylinder in-line CNG	------
Bore X Stroke	86.00X86.00	86.00X86.00	------
Compression Ratio	9.8	11.79	20.3
Efficiency (%)	59.9	62.7	4.67
Max Power at 6500rpm (KW)	103	83.6	-18.8

4.1. Compression Ratio

The compression ratio of the Petrol Engine Honda CR-V 2.0 Auto is 9.8 while that of the CNG engine is 11.79. This increase of compression ratio by 20.3% is due to the fact that CNG has a higher auto-ignition temperature than petrol. To achieve the required geometry of the combustion chamber for a compression ratio of 11.79, the modification quantity(ψ)=1.803mm is needed to increase the piston’s compression height by 1.803mm, increase the connecting rod’s length by 1.803mm or reduce the sealing plate’s thickness by 1.803mm.

4.2. Peak Pressure

The peak pressure of 85.02bar is a useful parameter if there is need for cylinder wall thickness evaluation. The thickness is a function of this pressure and material properties. This relatively high value of the peak pressure is due to the relatively high peak flame temperature (2157K) of CNG.

4.3. Air Standard Efficiency

The air standard efficiency for the petrol engine is 59.9% while that of the CNG engine is 62.7%. This 4.67% rise in efficiency is attributed to the higher compression ratio of the CNG engine.

4.4. Maximum Power Output

The original petrol Engine is capable of 103kW. Our CNG is only capable of 83.6kW both running at 6500rpm. This reduced power can be attributed to reduced mass of induced charge in the relatively smaller combustion chamber of the CNG engine. The reduced mass possesses reduced energy content hence the reduction in netpower output.

4.5. Mass Flow Rate of Air per Cylinder

This parameter $\dot{m}_{air}$=3.445×10^{-2} kg/s is useful in the design of inlet manifold and the design of throttle valve geometry.

4.6. Mass Flow Rate of Fuel per Cylinder

The parameter $\dot{m}_{fuel}$ =2.019×10^{-3}kg/s is useful in the programming of Injectors.

4.7. Modification Quantity

The modification quantity (Ψ)=1.803mm was obtained and it's necessary for increasing piston's compression height, increasing connecting rod's length or decreasing sealing plate's thickness

4.8. Modification Diagrams

The modification diagrams are shown in Figs 2 to 5 below.

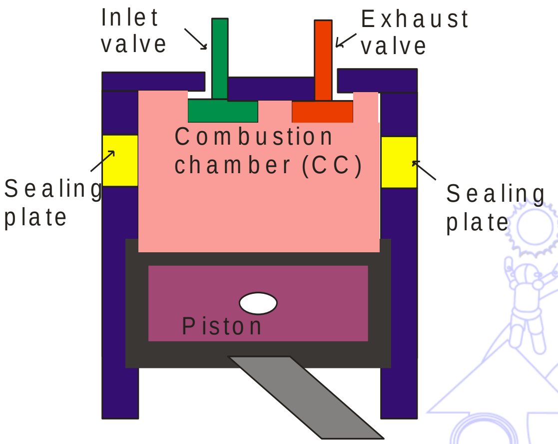

Fig. 2 Sealing Plate before modification

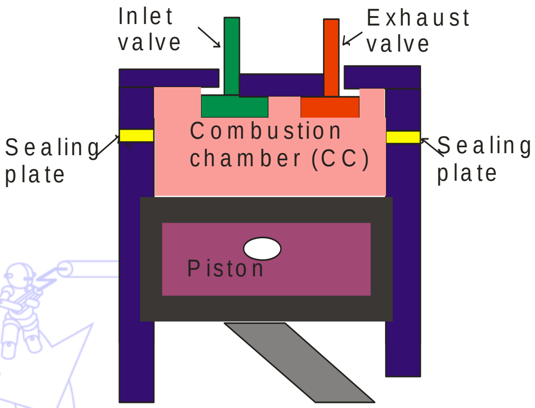

Fig. 3 Sealing plate after modification

As stated in section (vii), sealing plate modification requires decrease in sealing plate's thickness. This decrease in thickness has the overall effect of shrinking the combustion chamber (CC). By comparing Fig 2 and Fig 3, it is observed that the sealing plate thickness of the CNG engine is smaller than that of the petrol engine. Therefore, the combustion chamber for CNG engine is much smaller than that of the petrol engine because CNG engines run at higher compression ratios than Petrol engines.

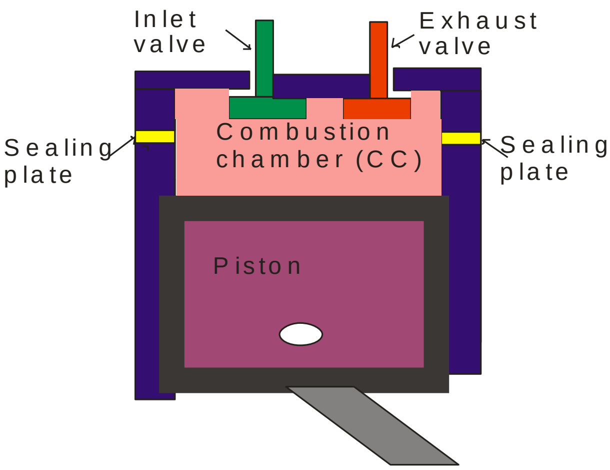

Fig. 4 Piston before Modification

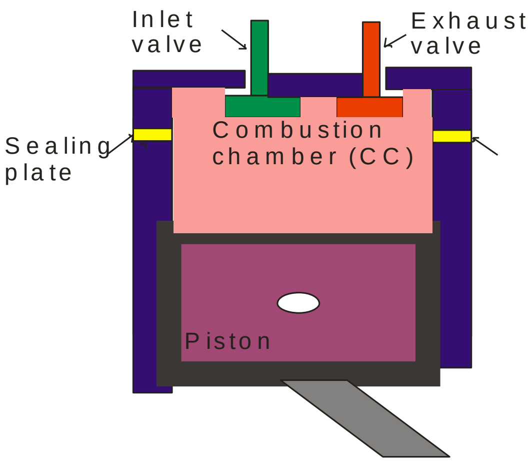

Fig. 5 Piston after Modification

As stated in section (vii), piston modification involves increase in the piston's compression height (perpendicular distance between the axis of piston pin and the piston crown). The compression height of the CNG's piston is longer than that of the petrol engine. This, as in the case of sealing plate modification, shrinks the CC of the petrol engine yielding a CNG engine of relatively small CC and high compression ratio.

5. Conclusion

In concluding this work, it is pertinent to state the extent of actualization of the aim. We have been able to modify a conventional petrol engine to run on CNG by first determining the optimal theoretical compression ratio (Γ_v) of 11.79. Next, the modification quantity (Ψ)=1.803mm was obtained and it's necessary for increasing piston's compression height, increasing connecting rod's length or decreasing sealing plate's thickness. To facilitate the modification design process, a suitable modeling and simulation application is necessary for quicker and more accurate results.

Notations

Symbol	Meaning
$\boldsymbol{\Gamma_v}$	Compression Ratio of CNG Engine
$\boldsymbol{\gamma}$	Ratio of Specific Heat Capacities
$\boldsymbol{\eta}$	Air Standard Efficiency
k	No of cycles per revolution of Crankshaft.
L	Stroke Length, m
A	Bore Area, m^2
N	Speed of Revolution per Second, rps
S	Number of cylinders
MEP	Mean Effective Pressure, Pa
$\mathbf{T}_i$	Temperature at State i, K
$\mathbf{P}_i$	Pressure at State i, Pa
v_i	Specific volume at State i, m^3/kg
H	Clearance ,m
σ	Hoop Stress, N/m^2
$\dot{m}_{air}$	Mass flow rate of air per cylinder, kg/s
$\dot{m}_{fuel}$	Mass flow rate of fuel per cylinder, kg/s
Ψ	Modification Quantity, m

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