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Simulation Model of Hydrogen Fueled SI Engine

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Abstract- Limited reserves of fossil fuels and strict pollution norms have forced research towards searching alternate fuels. Hydrogen has great potential as an alternative fuel for Internal Combustion Engine. Understanding behavior of hydrogen fueled spark ignition engine and parameters controlling the performance is important. Simulation is an affordable solution as it saves time and money. In this paper, a mathematical model has been developed. The results acquired from the model and experimental results from literature have shown reasonable agreement. This model was used as a simulation tool for predicting performance of hydrogen fueled SI Engine under variable operating parameters. Finally, engine performances under variable compression ratio have presented.

Index Terms- Compression ratio, mathematical model, turbulent flame speed, laminar flame speed, hydrogen fueled internal combustion engine,quasi dimensional two zone model, brake power.

I. INTRODUCTION

There are limited fossil fuel reserves on the earth. However, consumption of fossil fuels, leads to severe air pollution. Therefore, developing Internal Combustion engines with improved efficiency and reduction in emission levels is the need of hour. So search for alternative fuel has become a prime important research task now days. Hydrogen is almost carbon free and light gaseous alternative fuel [1]. The use of hydrogen as an alternate fuel fulfills base norms as: High energy content, Availability, less pollution, safety, storage and transport. Hydrogen has justified its utility as compared to number of fuels in these norms.

Wide range of flammability ensures combustion of hydrogen in an IC engine over a broad range of air fuel mixtures [2]. Low ignition energy promotes combustion of lean mixture and assures prompt ignition. High auto ignition energy allows use of larger compression ratios in a hydrogen fueled engine than in a hydro-carbon engine. Hydrogen has peak flame speed at stoichiometric ratios. Under these conditions, the hydrogen flame speed is maximum (faster) as compared to gasoline. Hydrogen engine can match its performance with ideal engine cycle more closely. Fame velocity reduces considerably at leaner mixtures.

Diffusivity of hydrogen gas is very fast. This ability to spread in air is greater than gasoline and is useful because of two main reasons. First, it promotes the formation of a homogeneous mixture of air and fuel. Second, if any hydrogen leakage occurs, the hydrogen scatters fast, resulting in safer conditions. Review of hydrogen engine have shown that hydrogen operated IC engines are more effective, clean and cheaper in comparison with the fuel cells [3].

Computer simulation is an important tool in the development of internal combustion engines. It reduces time and cost in the engine development. Simulation extracts more data in comparison to data that can be got from experiments. The study of complex processes in the combustion chamber can be performed in a better manner. Few researchers have worked on simulation of hydrogen fueled SI engine.

Maher et al. [4] used two zone quasi-dimensional models to simulate the performance of a spark ignition engine fueled with a mixture of various fuels (ethanol, gasoline, hydrogen). The results gained from the study have shown the ability of the model to predict satisfactorily the performance and emissions, including the incidence of pre-ignition at various engine operating conditions. K.Subbarao et al. [5] compared the Eddy current entrainment model over the Reynolds parameter model in describing the combustion process in S.I engine fueled with hydrogen gas. They reported that Eddy Current Entrainment model was useful compared to the Reynolds Parameter model

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Ramchandran. [6] used two zone zero dimensional model to simulate the performance of a spark ignition engine with alternate hydrocarbon based fuels. The mass burning rate was predicted by using Wiebe's law. Farhad Salimi et al. [7] used a two zone quasi dimensional model for predicting performance of SI engine fueled with hydrogen gas. They have studied the effect of variation in spark advance, air to fuel ratio and valve timing. It was observed that maximum NOx concentration occurs near the equivalence ratio of 0.8.Due to high flame speed of hydrogen, small spark advance is required [5].

1.1 Mathematical model of SI engine.

Engine model used is a quasi-dimensional two zone model. The combustion chamber is divided into two zones. Zone 1 contains burned products and zone 2 contains unburned mixture separated by a flame front based on model of Al-Baghdadi [4]. A system of first order differential equation was established in terms of pressure and temperature with respect to crank rotation during compression, combustion and expansion stroke .The basic equation for the engine model is derived from the conservation of energy applied to the cylinder volume

$$dE = -\delta Q - \delta W + \sum_i hi\ dmi \text{--- (1)}$$

1.1.1 Compression and expansion

Pressure and temperature variation w.r.t crank angle during compression and expansion were calculated using equations.

$$\frac{dP}{d\theta} = \frac{1}{V}[-\left(1+\frac{R}{Cv}\right)P\ \frac{dV}{d\theta} - \frac{R}{Cv}\frac{dQcr}{d\theta} + \frac{R}{Cv}\frac{dQht}{d\theta}] \text{---- (2)}$$

$$\frac{dT}{d\theta} = T.\left(\frac{1}{P}\frac{dP}{d\theta} + \frac{1}{V}\frac{dV}{d\theta}\right) \text{--- (3)}$$

1.1.2 Combustion

During combustion a flame nucleus is formed and the combustion chamber is divided into two zones, unburned zone denoted by b and an unburned zone denoted by u. .Pressure throughout the combustion chamber is assumed to be uniform. The rate of change of cylinder pressure P, unburned and burned gas temperature Tu and Tb are derived from conservation of mass and energy and the ideal gas equation as follows.

$$\frac{dTu}{d\theta} = \frac{1}{Nu\,Cpu}\frac{dQhtu}{d\theta} + \frac{Vu}{Nu\,Cpu}\frac{dP}{d\theta} - \frac{1}{Nu\,Cpu}\frac{dQcru}{d\theta} \qquad \text{--- (4)}$$

$$\frac{dTb}{d\theta} = \frac{P}{Nb\,R}\left[\frac{dV}{d\theta} - \left(\frac{R\,Tb}{P} - \frac{R\,Tu}{P}\frac{MWb}{MWu}\right)\frac{dMb}{d\theta} - \frac{Vu\,R}{P\,Cpu}\frac{dP}{d\theta} - \frac{R}{P\,Cpu}\frac{dQhtu}{d\theta} + \frac{R}{P\,Cpu}\frac{dQcru}{d\theta} + \frac{V}{P}\frac{dP}{d\theta}\right] \text{--- (5)}$$

and $\frac{dQcr}{d\theta}$ is energy loss to the crevices.

Neglecting change in the gas constant during expansion.

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$$\frac{dP}{d\theta} = \left[\frac{P\frac{dV}{d\theta}\left(1+\frac{Cvb}{R}\right)+\left(\frac{Cvu}{Cpu}-\frac{Cvb}{Cpu}\right)\frac{dQhtu}{d\theta}+\left(eb-eu.\frac{MWb}{MWu}\right)\frac{dMb}{d\theta}-\left(Cvb.\left(Tb-Tu.\frac{MWb}{MWu}\right)\right)\frac{dMb}{d\theta}+\left(\frac{Cvb}{Cpu}-\frac{Cvu}{Cpu}\right).\frac{dQcru}{d\theta}+\frac{dQcr}{d\theta}-\frac{dQht}{d\theta}}{\left[\frac{Cvu\,Vu}{Cpu}-\frac{Cvb\,Vu}{Cpu}+\frac{Cvb}{R}V\right]} \right]$$

---- (6)

Mass burning rate [8] required in the equation (6) is modeled as

$\frac{dMb}{d\theta} = \rho_u A_f\, St$ - --- (7)

1.1.3 Laminar Flame speed

A number of researchers have already worked on laminar flame speed and derived their own correlations. Flame speed is an important factor during the combustion phenomenon careful selection of accurate formulation is required.

Amongst all researchers Iljima and Takeno's formula [9] gives fairly accurate results because the formula consists of the equivalence ratio, pressure and temperature.

$s_l = s_{l0}\left(\frac{T_u}{T_0}\right)^{\alpha t}\left[1+\beta_p log\frac{P}{P_0}\right]$--- (8)

Where$T_u$is the unburned zone temperature, P is the pressure,T_0=291 (K),P_0=1. 013 bar

$\alpha t = 1.54 + 0.026(\emptyset - 1)$---- (9)

$\beta_p = 0.43 + 0.003(\emptyset - 1)$----(10)
And s_{l0}which is the laminar burning velocity(m/s) of hydrogen at 291(K) and 1 (atm)is calculated as follows.

$s_{l0} = 2.98 - (\emptyset - 1)^2 + 0.32(\emptyset - 1.70)^3$---- (11)

1.1.4 Turbulent flame speed

Number of methods for estimating the flame speed have been investigated by earlier authors. Out of that 'Damkohler and derivative' method is used during this paper. As per this method turbulent flame speed is formulated as follows

$s_t = s' + s_l$ ---- (12)

Where s' =s'_{TDC} (1-$\frac{\theta-360}{90}$)

$$s'_{TDC} = 0.75\dot{S_p}$$

$\dot{S_p}$is mean piston speed.

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1.1.5 Flame Geometry

Equation (7) requires an area of the flame front. Flame is assumed to be propagating in the semispherical shape center of semi sphere at the spark plug. Flame radius is estimated from flame speed.

1.1.6 Heat transfer model.

The engine model will use Woshni's correlation [10] to calculate the engine heat transfer. Flame travel is assumed in semi spherical shape.

$\frac{dQ}{d\theta} = A\ hc\ (T - T_W)$---- (13)

Where A =Total wall surface area
T=Mean gas temperature
T_W =Cylinder wall temperature averaged over the wall area
hc = Heat transfer coefficient averaged over a combustion chamber area
The Worshni's correlation can be summarized as
$hc(W/m^2K)$=
$3.26\ B(m)^{-0.2}\ p(kPa)^{0.8}\ T(K)^{0.55}\ W(m/s)^{0.8}$---- (14)

Table 1.1 Engine Specifications

Make	Datsu LT 200
Engine Type	Four Stroke
Number of cylinders	Single
Bore(mm)	68
Stroke(mm)	54
Compression ratio	8.5
Fuel system	Carburetor
Cooling system	Air cooled
Engine working temp. for gasoline (^{0}C)	120
Engine working temp. for hydrogen (^{0}C)	90

II. MODEL VALIDATION

To check accuracy of the model experimental results [11] are compared to the results of simulation.

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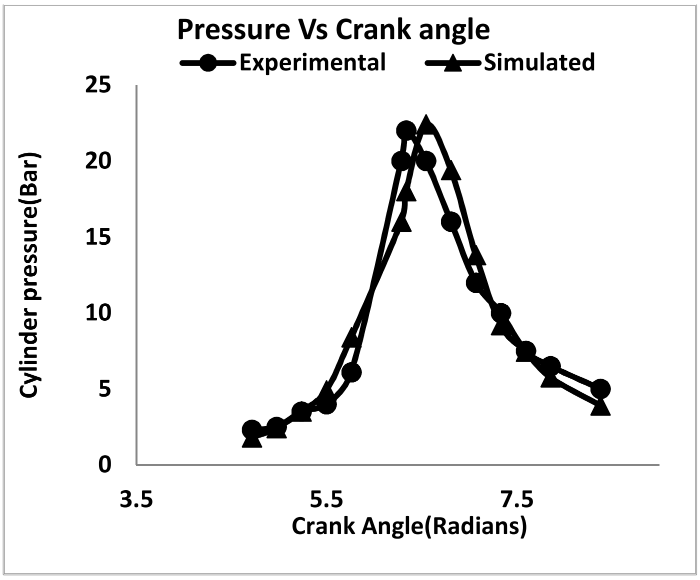

Figure 1 Cylinder pressure against Crank angle at 2200(rpm) and ϕ = 1

Engine specifications are as shown in Table 1, used during experimentation have been put into the model prepared in the MATLAB platform. Figure. 1 shows that simulated and experimental cylinder pressure is close to the results obtained from simulation of the model prepared. Figure. 2 shows the variation in Brake power at various speeds. Brake power increases with an increase in engine speed [12-13]. It indicates that there is good agreement between experimental and simulated results. Hence the model prepared can be used to predict the performance of engine under various operating conditions.

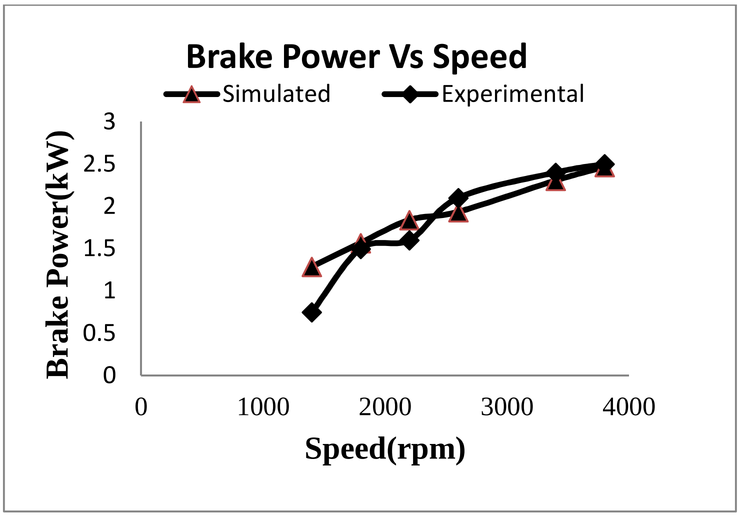

Figure 2 Brake power Vs Speed

III. COMPRESSION RATIO

After validating the model, it was used as a tool to explore the performance of engine with changes in operating conditions. In this present work same engine with variable compression ratio predicts the performance of the engine. Figure. 3 shows the variation in brake power with respect to various

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compression ratios at different speeds. Brake power increases with increase in compression ratio. Also brake power increases with increase in speed. Maximum Brake power is at compression ratio of 8.5 and speed 3800 rpm. Minimum brake power is at compression ratio of 7 and a speed of 1400 rpm

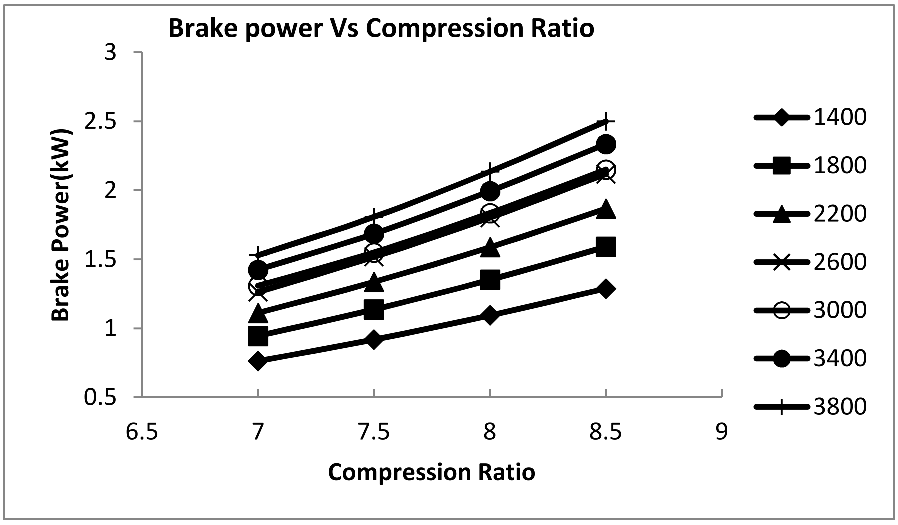

Figure 3 Brake power Vs Compression Ratio

IV. CONCLUSIONS

A mathematical model has been developed to simulate the performance of a spark ignition engine fueled with hydrogen gas as an alternate fuel. Results of simulation were compared with the experimental data. Three parameters brake power (kW) Vs speed of the engine and cylinder pressure (bar) Vs crank angle were compared between experimental results and simulation results. Experimental results and simulation results were closely associated.

On the basis of simulation results following conclusions are drawn:

- Brake power increases with increase in speed of the engine. Maximum Brake power is at speed 3800 rpm and minimum Brake power is at speed 1400 rpm.

- Brake power increases with increase in compression ratio of the engine. Brake power was observed maximum at a compression ratio of 8.5 at a speed of 3800 rpm and minimum brake power was reported at a compression ratio of 7 at speed 1400 rpm.

Nomenclature:

A/F air to fuel ratio
Cv Specific heat at constant volume
Cp Specific heat at constant pressure
e Specific energy
E Internal energy
hp Horse power
m Mass
 Mass flow rate
P Pressure
Pb Brake power
Q Heat transfer

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R Gas constant
T Temperature
V Volume
u Burning velocity
u_0 Root mean square turbulent velocity
W Work transfer
□ Crank angle
□ Specific heat ratio
□ Density
∅ Fuel to air equivalence ratio
□T Temperature exponent
□p Pressure exponent
hc Heat transfer coefficient averaged over combustion chamber area
$\dot{S_p}$ Mean piston speed
MW Molecular weight of gas mixture
A_f Flame front area
W Average cylinder gas velocity
N Number of moles
s_t Turbulent flame speed
sl Laminar flame speed

REFERENCES

[1] Ghazi A. Karim, “Hydrogen as a spark ignition engine fuel”, *International Journal of Hydrogen Energy*,;28 (5)569 – 577. 2003

[2] C.M. White, R.R. Steeper, A.E. Lutz, “The hydrogen-fueled internal combustion engine: a technical review”, *International Journal of Hydrogen Energy*;1292 – 1305.2006

[3] Verhelst S, Sierens R, Verstraeten S. A critical review of experimental research on hydrogen fueled SI engines. SAE paper, -01-0430.2006

[4] Maher A. R. Sadiq AL-BAGHDADI**, “** A Simulation Model for a Single Cylinder Four- Stroke Spark Ignition Engine Fueled with Alternative Fuels”,*Turkish J. Eng. Env.Sci.*;, 331 – 350,2006.

[5]K.SubbaRao, V.Ganeshan, B.S.Murthy K.V.Gopalkrishnan, “Modelling of Combustion process in a spark ignited hydrogen engine”, *International Journal of Hydrogen Energy*, ;,931 –933.1983

[6] SundeepRamachandran, “ Rapid Thermodynamic Simulation Model of an Internal Combustion Engine on Alternate Fuels”, Proceedings of the International MultiConference of Engineers and Computer Scientists Vol II IMECS 2009, March 18 - 20, 2009

[7]FarhadSalimi, Amir H. Shamekhi, Ali M. Pourkhesalian., “Role of mixture richness, spark and valve timing in hydrogen-fuelled engine performance and emission”, *International journal of hydrogenenergy* ;,3922–3929: 2009

[8] Heywood JB, “Internalcombustion engine fundamentals”,McGraw-Hill Book Company; 1988

[9] Iljima T, Takeno T., “Effects of temperature and pressure on burning velocity”, *Combustion and Flame*; 65:35–43.1986

[10] Colin R.Ferguson, Allan Kirkpatrick. Internal Combustion Engines, 2001.

[11]MuratKosar,BulentOzdalyan, M.BahattinCelik, “The usage of hydrogen for improving emissions and fuel consumption in a small gasoline engine”,*Journal of Thermal Science and Technology* 31, 22011

[12] R. Hari Ganesh, V. Subramanian, “Hydrogen fueled spark ignition engine with electronically controlled manifold injection: An experimental study”, Renewable Energy 33; 1324–1333.2008

[13]ErolKahraman, S. CihangirOzcanli, BarisOzerdem., “An experimental study on performance and emission characteristics of a hydrogen fueled spark ignition engine”, International Journal of Hydrogen Energy 32 2066 – 2072.2007