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Performance Analysis of Formaldehyde Addition in CNG (HCCI) Engine

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ABSTRACT: In this paper, the effects of formaldehyde addition on the performance of compressed natural gas homogeneous charge compression ignition engine, CNG (HCCI) were investigated. In this study, the four-cylinder, four-stroke engine was used. The results obtained from the use of various percentage of formaldehyde addition in CNG (HCCI) engine were compared to those of numerical and theoretical analysis. The results indicated that when addition fuel additive as the formaldehyde in CNG engine were used, engine performance parameters such as torque and power, brake mean effective pressure and brake specific fuel consumption are optimum condition at 0.13% formaldehyde addition in CNG (HCCI) engine and these parameters are decreased with increasing more than 0.13% formaldehyde addition amount in the engine. It is also shown that the air/fuel mixture will ignite earlier using this additive so it is conceivable to reduce inlet mixture temperature resulting in better performance due to higher volumetric efficiency.

KEYWORDS: natural gas, HCCI, formaldehyde, additive, engine performance

I. INTRODUCTION

Most of the energy used in the world is supplied by fossil fuels. Burning of the fossil fuels generates waste materials, mainly emissions to the atmosphere in the form of combustion fuel gases and dust, as well as some ash and/or clinker. These waste materials have hazardous effects on the environment, some of them locally, others with more widespread or even global impact . It is well known that vehicles with natural gas present lower pollutant and carbon dioxide emissions compared to gasoline vehicles. Natural gas engine has many advantages, such as higher efficiency and lower heat losses but as the engine runs close to the so called lean limit, problems may occur- such as misfiring.

Homogeneous charge compression ignition (HCCI) engines are being considered as a promising alternative to the existing spark ignition (SI) and compression ignition (CI) engines. HCCI engines have the potential in reducing the emissions of nitrogen oxides (NOx) and particulate matter (PM), while maintaining high thermal efficiency. The HCCI engine concept promises to combine the advantages of both CI and SI engines, while minimizing their drawbacks.

One of the key difficulties in the implementation of HCCI technology in production engines is that ignition cannot be directly actuated. The timing of auto-ignition of HCCI combustion is determined by the cylinder charge conditions, rather than the spark timing or the fuel injection timing that are used to initiate combustion in the SI and CI engines, . Myanmar has since resolved to do more researches and experiments to use alternative fuels like natural gas. In literature, it is reported that many research groups recently have been working on natural gas fuelled engines worldwide via experimental work or through simulation studies and formaldehyde is one the most common additives which has been utilized in many researches.

Fiveland et al. investigated in the influence of initial temperature, initial pressure of mixture, natural gas composition, heat transfer model, equivalence ratio and compression ratio on ignition behavior of an HCCI engine. Kentaro et al. showed that formaldehyde strongly affects production/consumption rate of hydroxyl radicals and therefore it can be used to control the combustion of an CNG (HCCI) engine. Numerical results of Morsy et al. have indicated the effects of using formaldehyde on advanced autoignition in natural gas fuelled engines. Mansha et al. has implemented the oxidation mechanisms of methane in IC engine and predicted the combustion temperature and pressure in the

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combustion chamber of the IC engine. In another study, the authors developed the kinetic mechanisms of CNG and simulation based investigation of CNG combustion was carried out Chen et al. figured out formaldehyde would reduce the exothermic of low temperature combustion reaction of diethyl ether and therefore leads to advanced combustion.

In the present study the COMSOL Multiphysics 4.3b and theoretical formula are used to model complex combustion phenomenon and performance analysis in compression ignition HCCI (CNG) engine. This paper utilized a single zone zero dimensional model to investigate the effects of using formaldehyde as an additive on performance of a single cylinder engine. High computational speed, appropriate precision for calculating parameters such as start of combustion, combustion temperature and pressure trends are the main reasons of using this model. The effects of various percentage of formaldehyde addition on temperature and pressure trend of combustion mixture start of combustion and engine performance characteristics: engine power, engine torque, specific fuel consumption and brake thermal efficiency are described in detail by numerical and theoretical. The studies have been done for different initial temperatures of inlet air/fuel mixture.

II. RELATED WORK

Natural gas is well suited to the HCCI combustion concept because of minimal mixture preparation requirements and chemical stability. Many compounds such as propane, butane, hydrogen peroxide, and formaldehyde are used as an additive in natural gas fuelled (HCCI) engines. Formaldehyde is the simplest aldehyde in organic compounds category with chemical formula CH_2O. It is one of the intermediate species of natural gas combustion mechanism. It can increase the combustion reaction rates when used as an additive. Table 1 shows the physical properties of formaldehyde in comparison to major gases in natural gas composition. Formaldehyde is categorized as a hazardous material and it should be used under tight legislations.

TABLE I
Formaldehyde properties in comparison to major gases in natural gas composition

Properties	Formaldehyde	Methane	Ethane	Propane
Chemical Structure	CH_2O	CH_4	C_2H_6	C_3H_8
Molar Weight (g/mole)	30	16	30	44
Autoignition Tem; (K)	430	595	515	470
Explosive Limits (%)	7-73	5-15	3-12.5	2-9.5

A. *Procedure of Numerical Analysis*

The IC Engine model is appropriate for a closed system, representing the time between intake valve closure and exhaust valve opening in the engine cycle. The start time (or start crank angle) therefore represents the time of intake-valve closure. As a convention, engine events are expressed in crank rotation angle relative to the top dead center (TDC).

TABLE II
Specifications of the engine

Engine Specification	Variable Name	Value
Bore	D	0.1m
Stroke	S	0.103m
Connecting rod	Lc	0.103m
Crank arm	La	0.044m
Engine speed	N	3400rpm
Compression ratio	CR	11
Equivalent ratio	ER	0.5

In the developed zero-dimensional model, the whole combustion chamber is considered as a control volume. Energy and mass conservation equations should be solved simultaneously for this system [3]. The engine specification used in the simulation is given in Table 2.

Natural gas fuels, on the other hand, readily produce homogeneous mixtures and have the potential to serve as HCCI fuels. This model represents the combustion cylinder with a perfectly mixed batch system of variable volume. Single zone models are widely used because of their low computational requirements, accurate prediction of start of combustion [8].

B. *Theoretical Determination of Performance Characteristics*

This paper investigates for a four stroke (HCCI) engine, the influence of combustion condition on the brake power, brake torque brake thermal efficiency, specific fuel consumption, and brake mean effective pressure. The theoretical performance characteristics for the engine, obtained from derived equations, were also presented [1].

The engine torque, T is given by,

$$T = WR \quad (1)$$

where, W is the brake load in Newton and R is the torque arm in meters.

The actual power available at the crank shaft is the brake power, BP, given by,

$$BP = \frac{2\pi NT}{60} \quad (2)$$

where, N is the engine speed in revolution per minute.

The brake mean effective pressure (BMEP) is the mean effective pressure which would have developed power equivalent to the brake power if the engine were frictionless, and for a four stroke engine is given by ,

$$BMEP = \frac{2\times BP}{V_s Nn} \quad (3)$$

where, n is the number of cylinders and Vs is the swept volume.

The brake thermal efficiency, is the ratio of the brake power to the power supplied by the fuel, is given by,

$$\eta_{bth} = \frac{BP}{Q_{in}} \quad (4)$$

$$Q_{in} = m_f Q_{LV} \quad (5)$$

where, m_f is the mass flow rate of the fuel and Q_{LV} is the lower calorific value of the fuel.

The specific fuel consumption, BSFC is the total fuel consumed per kilowatt power developed and it is given by,

$$BSFC=\frac{3600\times m_f}{BP} \quad (6)$$

III. RESULTS AND DISCUSSION

A. *Numerical Analysis*

Firstly, the influence of inlet air/fuel temperature with adding additives has been studied. Fig 1 and 2 show the pressure and temperature trends for five different temperatures at inlet valve close (IVC).

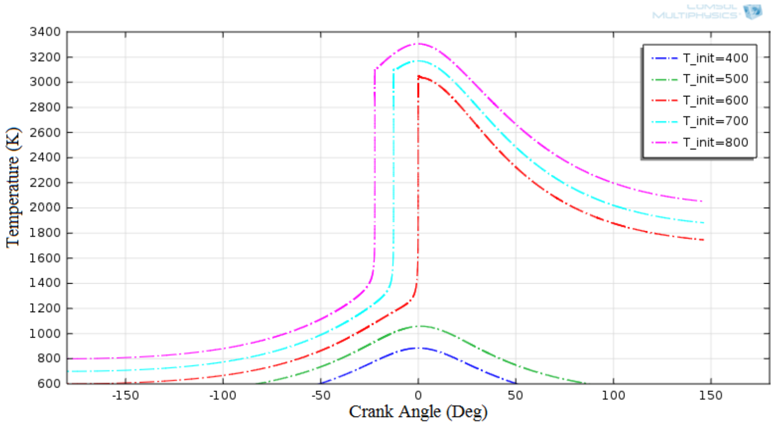

Fig. 1 Incylinder temperature variation for five different initial temperature at IVC

As seen in these figures, there is no combustion in the T_{IVC} = 400 K case because the mixture pressure and temperature do not reach the auto ignition limit. In such a case, it is usually noted that the engine is out of its operating range. In T_{IVC} = 500 K case, the combustion occurs slightly after TDC. By increasing the inlet temperature above T_{IVC} = 600K, the combustion occurs before TDC and the maximum value of pressure and temperature rises.

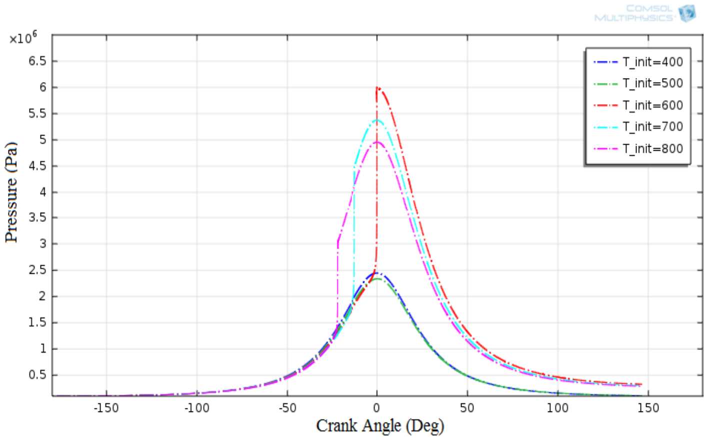

Fig. 2 Incylinder pressure variation for five different initial temperature at IVC

From these results, it can be seen that the ignition delay decreases with increasing initial temperature. The ignition delay time can be evaluated from the pressure gradient. Furthermore the combustion phenomenon is highly concerned to initial temperature and it can be used as a control parameter. Consistent with above simulation results, methane does not ignite at an initial temperature of T_{IVC} = 400 K and the ignition occur at TDC (crank angle zero degree) by giving initial temperature 600K. Additionally, ignition occur before TDC (crank angle zero degree) with increasing initial temperature.

Formaldehyde has a lower auto ignition temperature in comparison to other natural gas components; therefore it is logical that using formaldehyde as an additive would advance the CNG engine combustion. Table 3 shows the numerical results of combustion temperature at various percentage of formaldehyde addition by using COMSOL Multiphysis 4.3b.

TABLE III
Combustion temperature at various percentage of formaldehyde addition for CNG(HCCI) engine

Inlet Temperature , K	Combustion temperature (Effect of formaldehyde addition)				
	0%	0.11%	0.13%	0.15%	0.17%
400	850	860	870	855	840
500	1050	1100	1150	1050	1030
600	2300	2700	3000	2850	2820
700	2450	2900	3150	3050	2950
800	2750	3050	3300	3120	3050

For a detailed study on the effects of using formaldehyde as an additive on the performance such as power, torque, mean effective pressure, specific fuel consumption and brake thermal efficiency of an HCCI engine at various inlet temperature. Fig 3, 4, 5 and 6 show the effects of adding various percentage of formaldehyde on the engine performance at various inlet temperatures.

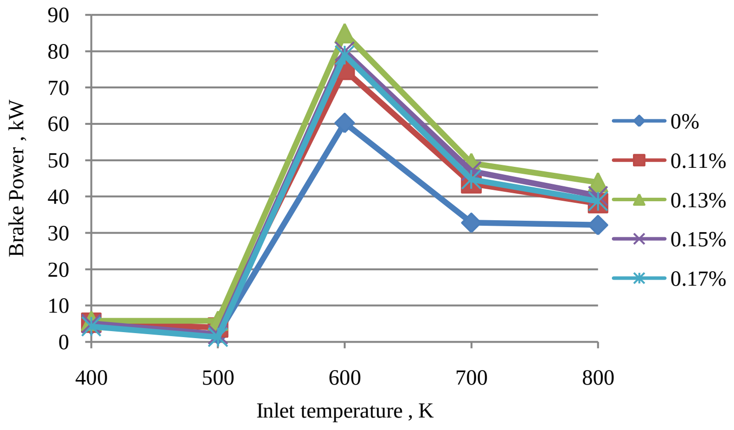

Fig.3 The effects of using formaldehyde on engine brake power

Fig. 3 shows the brake power variation on the effect of formaldehyde addition at various inlet temperatures. According to the brake power trends, the maximum value occurs at 600 K for each percentage of the formaldehyde. In figure, it can be seen that increasing formaldehyde from 0% to 0.13% causes increasing brake power from 5.823 kW to 84.903 kW at 600K. When the addition of formaldehyde percentage is more than 0.13%, engine brake power is decreased. On the other hand, engine power decrease because of higher incylinder maximum temperature and extended high temperature duration in the combustion stroke.

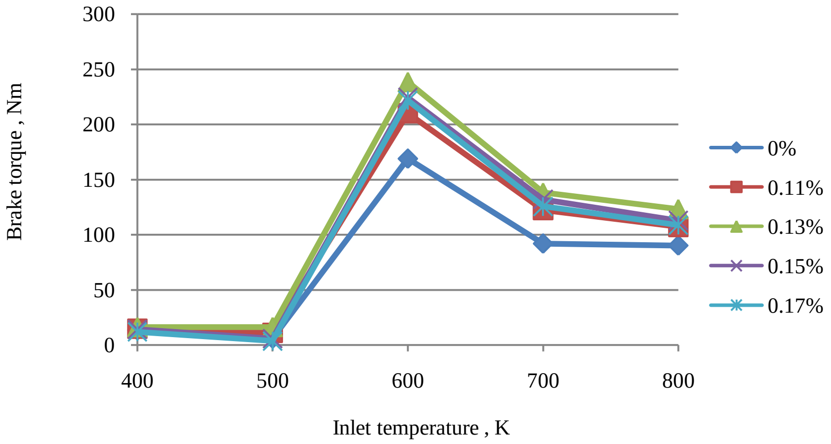

Fig.4 The effects of using formaldehyde on engine brake torque

The variation of brake torque on the effect of formaldehyde addition at various inlet temperatures is shown in Fig.4.According to the analysis , the maximum brake torque also occur 0.13% formaldehyde addition at inlet temperature 600K. Fig. 5 shows the brake mean effective pressure variation on the effect of formaldehyde addition at various inlet temperatures. From this figure, it can be seen that the mean effective pressure is highest at inlet valve close temperature 600K with 0.13% formaldehyde addition. The more percentage of formaldehyde addition, the less brake mean effective pressure.

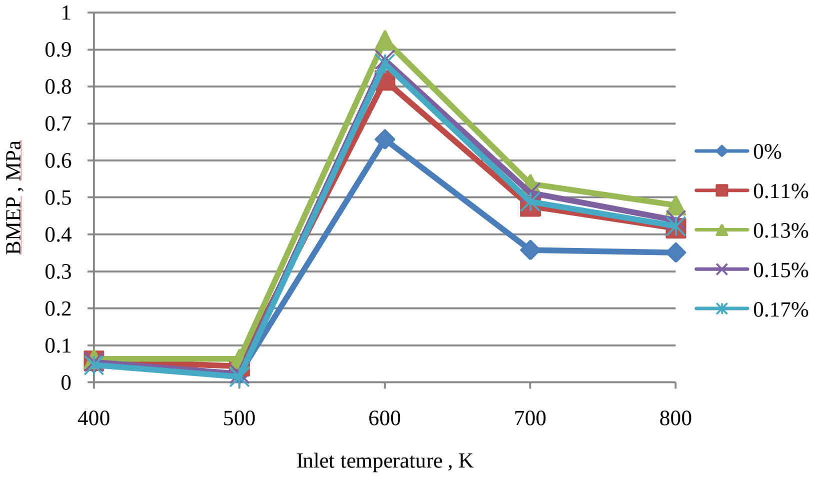

Fig.5 The effects of using formaldehyde on engine bmep

By comparison of engine power results, the reverse trends occur in brake specific fuel consumption (BSFC) in different cases. The minimum value of BSFC occur 0.13% formaldehyde addition and this value increase by adding formaldehyde over 0.13%. This result is shown in Fig.6.

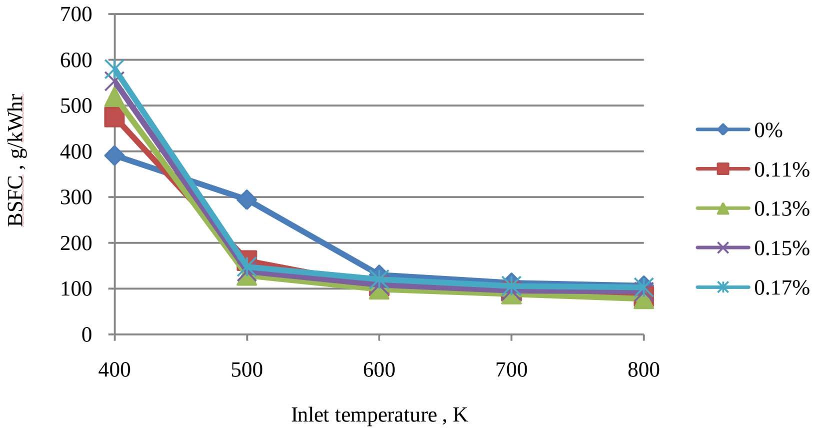

Fig.6 The effects of using formaldehyde on engine bsfc

B. *Comparison of Numerical and Theoretical Analysis on Engine Performance*

The parameters related to the performance of the engine, such as brake power, brake torque, specific fuel consumption and the thermal efficiency were evaluated by numerically and theoretically at different engine speed. All these parameters are comparing at inlet temperature 600K.

The comparison of the engine power for numerical and theoretical results with various engine speed are shown in Fig.7. The engine power is increase with the engine speed until 3500 rpm although engine power is decreased with engine speed over there. Further, it may be noticed that the numerical power produced is slightly higher than that of theoretical analysis. Because of the combustion temperature of theoretical analysis is lower than the numerical analysis. Brake torque variations with the various engine speed for two analysis are shown in Fig. 8. The figure shows that the brake torque increase with increasing the engine speed and the peak value is occur at 2000 rpm.

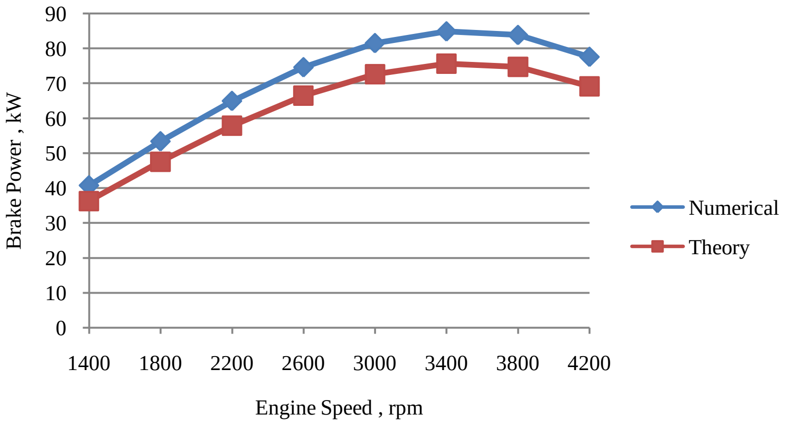

Fig.7.Brake power variation verses engine speed

The declination of the brake torque occurs beyond the 2000rpm engine speed. The higher the engine speed, the declination of the brake torque occurs. Because of engine volumetric efficiency is reduced and friction forces are increased by increasing engine speed.

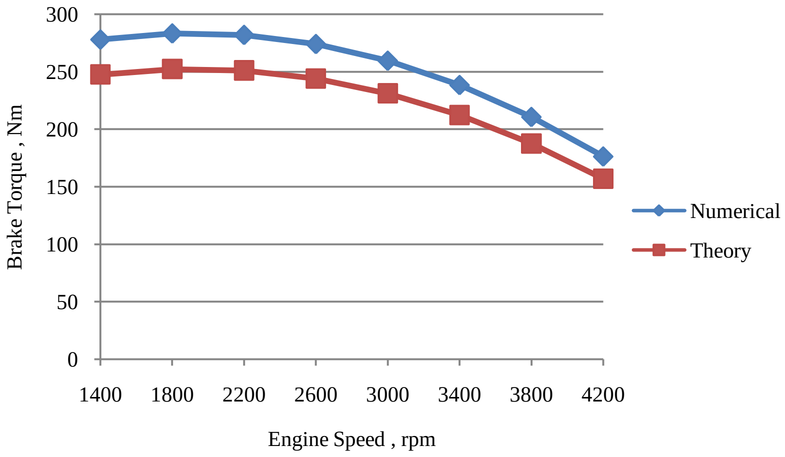

Fig.8 Brake torque variation verses engine speed

Fig. 9 illustrates the trends of BSFC with engine speed for two types of analysis at inlet valve closed temperature 600K for natural gas (HCCI) operations. It can be observed that BSFC drops down as the engine speed increase up to about 2000 rpm and then it increases when the engine speed exceeds 2000 rpm for both conditions. Higher BSFC at low engine speed is the result of great heat loss to the combustion chamber walls.

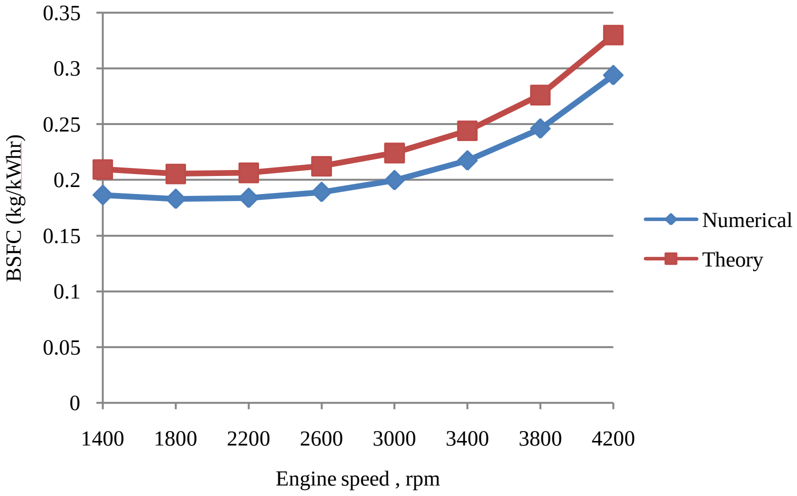

Fig.9 BSFC variation verses engine speed

The variations of brake thermal efficiency with engine speed for different analysis are shown in Fig 10. In all the cases, brake thermal efficiency is increased with engine speed up to 2000rpm. Because brake thermal efficiency is depend on brake specific fuel consumption.

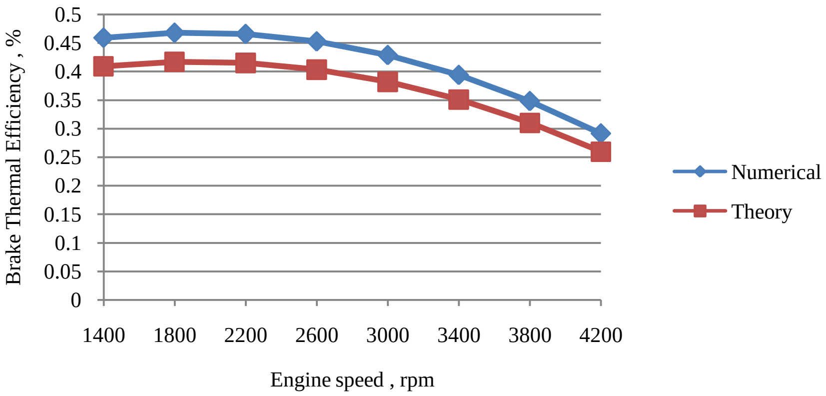

Fig.10 Brake thermal efficiency variation verses engine speed

IV. CONCLUSION AND DISCUSSION

Numerical and theoretical investigations carried out on a single cylinder, four stroke CNG (HCCI) engine. In the study of numerical analysis, simulations have been studied on the various percentage of formaldehyde addition in engine and at the inlet temperature changes. After that the CNG (HCCI) engine operation with numerical has been compared with theoretical analysis.

The temperature of inlet mixture strongly affects the combustion of HCCI engine. Therefore, the developed single zone zero dimensional model can predict start of combustion in HCCI engine with inlet temperature by using COMSOL Multiphysics software. And then, the engine performance analysis is carried out by adding various formaldehyde percentages. According to this analysis, it can be seen that 0.13% of formaldehyde addition at the inlet temperature 600K in the engine cylinder for the performance is the best for this engine. The performance of an CNG(HCCI) engine depends not only upon the combustion efficiency of engine but also the percentage of formaldehyde addition. The theoretically studied parameters show that there are reduction by 12% in brake power, brake torque, brake specific fuel consumption of engine compare with numerically. For further research, experimental study will be conducted to validate the simulation results for the mentioned parameters.

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