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THE EFFECT OF WALL TEMPERATURE TO THE COMBUSTION OF DIESEL/CNG MIXTURE

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ABSTRACT

The stringent emission regulations and the need to increase fuel efficiency makes controlled auto-ignition (CAI) based combustion an attractive alternative solution to these issues. However, the combustion control is the main obstacle to its development. Fuel combinations with substantial different in reactivity such as diesel/compressed natural gas (CNG) shows desirable combustion output and demonstrate great possibility in controlling the combustion. This paper will discuss the control method of diesel/CNG (DCNG) mixture combustion with a variation of wall temperature. The experiment was done in a constant volume combustion chamber with both fuels were directly injected into the chamber. The wall temperature was varied from 45 °C to 75 °C with an increment of 15 °C. The increment of wall temperature reduces the combustion performance of DCNG. It is caused by slower combustion rate of DCNG that indicated by its long combustion duration. Regardless the combustion performance reduction, it was found that the combustion delay of DCNG was not affected by the wall temperature.

Keywords: diesel-CNG mixture, controlled auto-ignition, thermal stratification.

INTRODUCTION

Stringent emission regulations and significant increase of fuel price highly affecting the growth rate of automotive technology development with the objectives of reducing fuel consumption and improves engine efficiency. Controlled auto-ignition based combustion system such as homogeneous charge compression ignition (HCCI) [1], stratified charge combustion ignition (SCCI) [2], premixed charge compression ignition (PCCI)[3], and reactive charge compression ignition (RCCI) [4] are the recent engine development with high efficiency, low emissions, and fuel consumption.

The timing of controlled auto-ignition based combustion system is determined by the chemical kinetics and the auto- ignition process. Both processes are highly affected by the instantaneous temperature condition of the mixture. However, a homogeneous temperature distribution in the combustion chamber is difficult to achieve due to the possibilities of temperature stratification to occur inside the combustion chamber is very high. It is either because of the operating conditions such as the intake air and combustion chamber wall temperature or because of the liquid fuel evaporation. These conditions become the main reason that drove the investigation on the thermal stratification effects on the HCCI combustion.

Hultquist *et al* [5] mentioned the temperature stratification which states that in the primary heat release stage of HCCI combustion, high charge stratification levels were detected. The authors also said that a distinct boundary between the unburned and burned charge may be due to temperature stratification. The temperature stratification may cause the instability in the engine as it creates hot spots in the charge that later may lead to knocking. However, thermal stratification can be utilized in controlling the combustion of HCCI as shown by Lim, OT *et al* [6]. They investigated the probability of using thermal stratification for better combustion of HCCI. They analyzed the effect of thermal stratification using a model created with CHEMKIN2 and modified SENKIN codes by Sandia National Laboratory. The results showed that the thermal stratification can reduce the rate of pressure rise. It was proved by the experimental work done with rapid compression machine (RCM) and found that the thermal and mixing stratifications could lengthen the combustion duration and reduce the pressure rise rate. The combustion duration was lengthened by dispersing the time of reaction starts to some area as shown by chemiluminescence images. However, the combustion duration in each zone was showing the same results as a homogeneous mixture. These results open the possibilities of HCCI control using thermal stratification, especially at high load conditions.

Sankaran, R *et al* [7] carried out a detailed analysis of the effect of non-uniform temperature distribution on HCCI combustion process using a two dimensional numerical method that applied full compressible Navier-stokes, species, and energy of reacting mixture equations coupled with the chemical kinetics of hydrogen-air oxidation. They found that the temperature distribution had a major influence on the location of the first ignition point and the subsequent combustion and heat release. The existence of both hot and cold core areas led to an increase in combustion duration. However, the existence of hot core region gave a better result as the combustion efficiency was higher due to the fast combustion rate at the early stages of the combustion with moderate combustion rate of the end gas while the cold core gave an undesirably slow combustion of the end gases that resulted in higher unburned hydrocarbon in the exhaust.

Chen, J.H *et al* [8] concentrated their investigation on the effect of temperature in-homogeneities on the combustion regimes in HCCI combustion. They stated that the combustion regimes of

HCCI were classified into three categories; spontaneous ignition front propagation, deflagration, and detonation. They discovered that the spontaneous ignition propagation was inversely proportional to the initial temperature gradient while the deflagration region occurred at the colder temperature region mostly due to compressive heating. The occurrence of the temperature gradient gave rise to mass and heat transport at the combustion front as the regulating parameters of HCCI combustion, particularly at high-temperature gradient conditions. While for conditions where the temperature gradient was small, the spontaneous ignition regime was wider and resulted in a homogeneous like combustion with a rapid heat release rate.

Chang, J *et al* [9] used an experimental approach to characterize the sensitivity of a gasoline fuelled HCCI engine to the instantaneous temperature of the combustion chamber wall and the heat flux. They used two approaches for introducing the thermal stratification to the mixture, variation of intake air and engine coolant temperatures. They found that the combustion stability of the HCCI engine depended on the wall temperature rather than the intake air temperature. The changes in coolant temperature affected the bulk temperature of the mixture inside the cylinder while the local temperature of the mixture was mainly affected by the intake temperature. Their results showed that the cyclic variability of the HCCI combustion using controlled wall temperature was lower compared to controlled intake air temperature. Meanwhile, the effect of intake temperature was more on the local distribution of the temperature inside the cylinder caused a significant influence on the start of ignition compared to the wall temperature. Furthermore, the controlled inlet temperature also showed faster- burning rate and higher maximum pressure.

Strozzi, C. *et al* [10] presented their work regarding the study of the combustion processes of a homogeneous methane–air mixture subjected to thermal stratification within a rapid compression machine (RCM). The Chemiluminescence method was used as a tool to study the combustion process. The analysis of chemiluminescence images enabled the delineation of two propagation regimes, namely spontaneous ignition fronts and deflagrations. The first was observed for short ignition delays as the fluid featured a relatively large and homogeneous hot core zone. The second dominated the combustion process for longer ignition delays. Indeed, despite global homogenization of the temperature fields, the hottest zones were relatively narrow and surrounded by non- negligible thermal gradients, which favoured the formation of deflagration. The results thus clearly showed a strong correlation between the pre-ignition temperature field and the subsequent combustion process. The results were in good agreement with others previously obtained through chemiluminescence imaging for early and intermediate stages of combustion. It is more difficult to reach definitive conclusions for later instants.

Sjoberg. M, *et al* [11] used Ethanol and ethanol/gasoline blends to create partial fuel stratification to increase the thermal stratification in the cylinder. They found that the low sensitivity of the auto ignition reactions to variations in the local fuel concentration allowed the temperature variations to govern the combustion event. Sequential combustion events from leaner and hotter zones to richer and colder zones were observed; it lowered the overall combustion rate compared to fully homogeneous temperature. Combustion stability remained high, but engine-out NOx had to be monitored carefully. For the operation with a substantial reduction of the peak heat release rate, indicated specific NOx rose to around 0.20 g/kWh for an IMEP gross of 440 kPa. These results also were also confirmed, Liu. H. *et al* [12] using Chemiluminescence experiments that were conducted on a single-cylinder HCCI engine. The results indicated that different port injection strategies resulted in different mixture stratifications, thus affected the auto- ignition timing and combustion processes. Under higher intake temperature conditions, injection procedures had less effect on the combustion processes due to improved evaporating and mixing. Larger local temperature stratification can reduce the pressure rise rate through smoothing the reaction rates and extending the operating range in HCCI engines.

These previous investigations outlined that thermal stratification could control the combustion behaviour of CAI based engine. Therefore, this paper will explore the possibilities to implement thermal stratifications to the dual fuel combustion of diesel and CNG mixture.

METHODOLOGY

The study performs extended experimental investigation on the auto-ignition behaviour of dual fuel (Diesel-CNG) in a constant volume combustion chamber (Figure-1). The combustion of the mixture will be compared to the single fuel (diesel) in order to assess the effect of the CNG addition to the combustion behaviour of the mixture.

A probe heater is used to increase the temperature inside the combustion chamber. Heater temperature is set at 800 °C in order to get a stable auto-ignition from the mixture of combustion chamber pressure equal to atmospheric. Furthermore, oxygen with purity 99.5% is used as the replacement of air in order to reduce the complexity of the reaction and to increase the auto-ignition occurrence probabilities. Diesel-CNG mixture was tested. Three wall temperature were tested namely 45, 60 and 75 °C. The combustion data for the mixture was obtained for lambda 1.

Three thermocouples were installed to monitor the wall temperature. The experiment started after the wall temperature for all thermocouples ranges ±3°C from the set point. Furthermore, heater and an air blower was used to maintain the temperature at its setpoint.

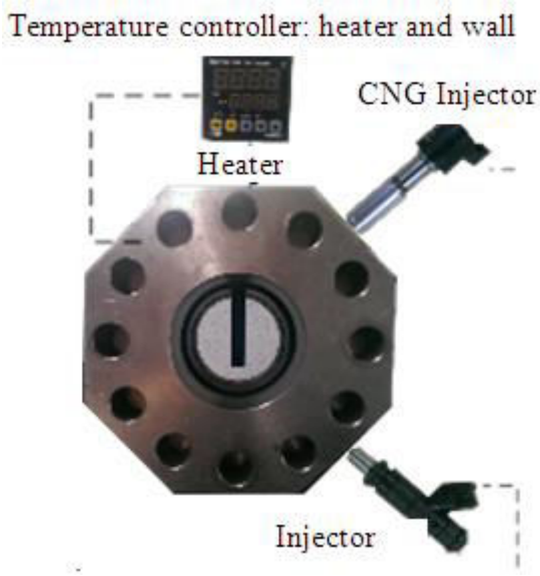


Figure-1. Fuel injector and heater arrangement in the CVC.

Table-1. Injector delivery rate.

Fuel	Injector delivery rate (g/s)
Diesel	4.2 @ 3 bar
CNG	7.2 @ 7.5 bar

The injector used is Siemens Deka 4 with 3 bar injection pressure and 4.3 g/s delivery rate for gasoline (manufacturer specification). Due to density variations of the fuels, the calibration process is carried out in the ambient condition for each file to measure the actual delivery rate of the injector. The calibration results are shown in Table-1. The CNG injector was using low-pressure CNG injector from an orbital with 7.2 g/s at injection pressure 7.5 bars. The injectors were placed 90° relative to each other and both are directly injected into the combustion chamber (Figure-1). Air fuel ratio (AFR) resulted from the above equation for each mixture is depicted in Figure-2. It ranges from 16.6 to 17.8. AFR was generated by calculating the stoichiometric reaction between the fuels and oxygen. The required fuel amount at constant volume (0.000492 m3) was determined and translated to the injector opening by dividing the total fuel required with the injector delivery rate.

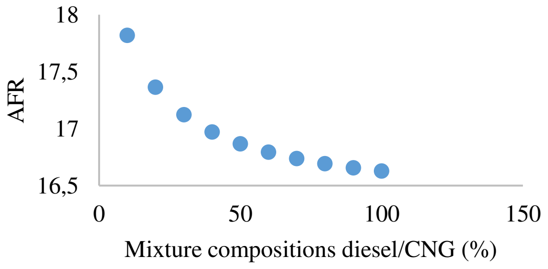
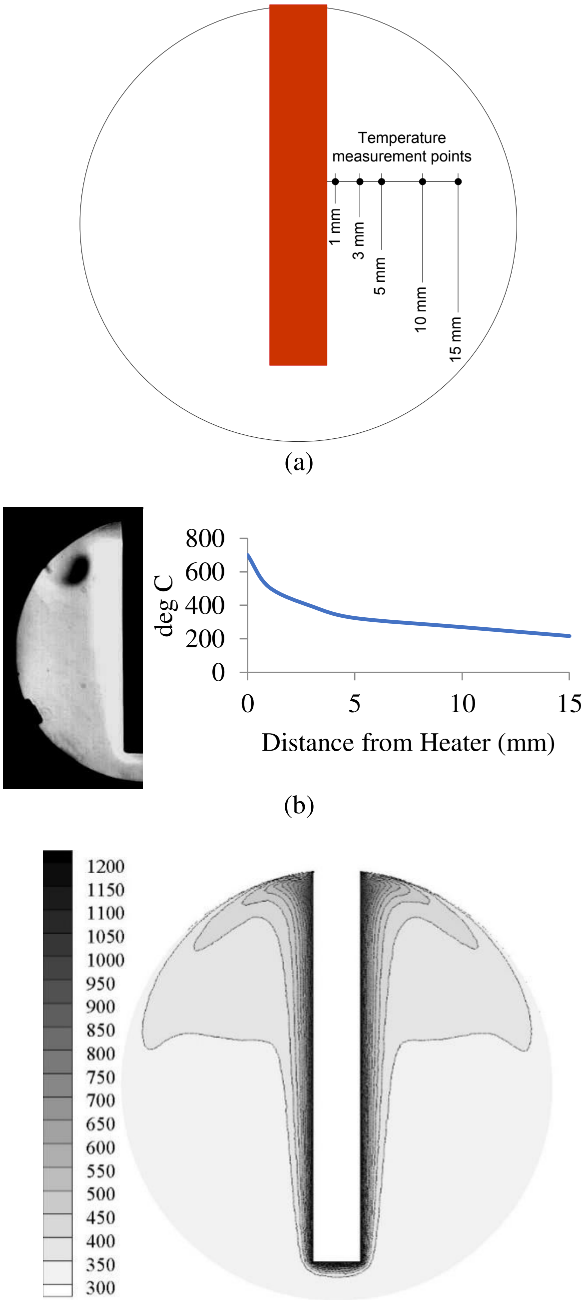


Figure-2. Lambda for various mixture compositions.

In this experiment, the fuels were injected at the same time to the chamber (0 ms injection gap) with 60/40 diesel/CNG composition.

The temperature profile in the chamber was acquired using simulation with ANSYS Fluent 15.0 and calibrated with experimental data measurement and image.



(a)

(b)

(c)

Figure-3. Temperature profile calibration, measurement points (a), temperature data and schlieren image (b) and simulation result.

The temperature profile shows that the upper region of the chamber having the widest high temperature region compared to the heater surrounding the area.

RESULTS AND DISCUSSIONS

The combustion phasing for diesel and DCNG is shown in Figure-4. For diesel, 30°C wall temperature decrement increases the combustion duration up to 50% longer from 1.5 ms to 3 ms. Kuboyama. T *et al* [13] stating that higher temperature stratification prolonged the combustion duration mainly at the main and final stage of combustions. Higher wall temperature will decrease the thermal stratification also will improve vaporization rate of diesel and higher average temperature in the chamber causing shorter combustion duration.

Shorter combustion duration of diesel is translated to higher combustion performance of diesel with higher wall temperature. The combustion efficiency and total heat release (THR) increases from 0.3 to 0.85 and 9 to 24.5 kJ respectively even though the maximum pressure relatively constant. Furthermore, the combustion delay significantly reduced from 19.7 ms to 10 ms.

DCNG, on the other hand, is showing less response to the changes in wall temperature on the combustion stages. The combustion efficiency, maximum pressure, THR, and combustion delay shows no difference for various wall temperatures. Insignificant effect of wall temperature to DCNG compared to diesel especially on combustion efficiency, THR and combustion delay mainly caused by the difference of vaporization process.

Diesel as single fuel requires higher vaporization energy compared to DCNG due to lesser fuel amount injected to the chamber. High wall temperature provides the required energy by higher average in-cylinder temperature and makes the vaporization rate faster. It translates to a significant reduction of combustion delay as well as combustion duration shown in Figure-4.

DCNG, on the other hand, requires lesser vaporization energy due to its lower diesel amount injected. Furthermore, CNG injection improved the mixing process and enhanced diesel distribution throughout the chamber and creates distributed and smaller droplets. This condition only allowed the initial flame of DCNG to occur at the chamber upper region as shown in Figure-5.

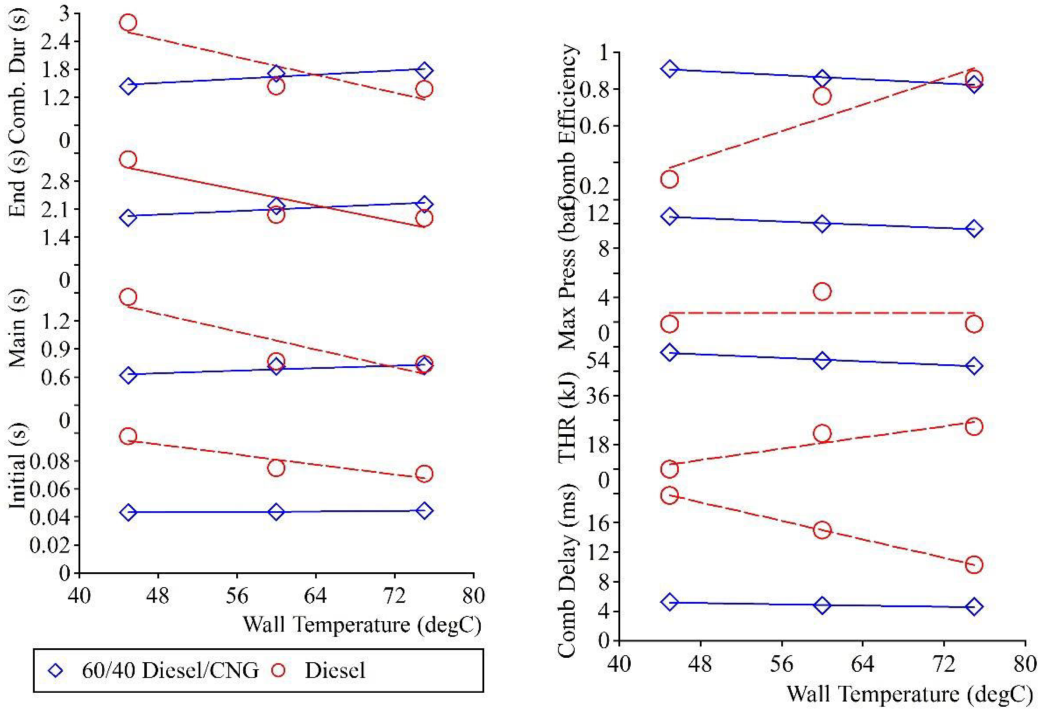
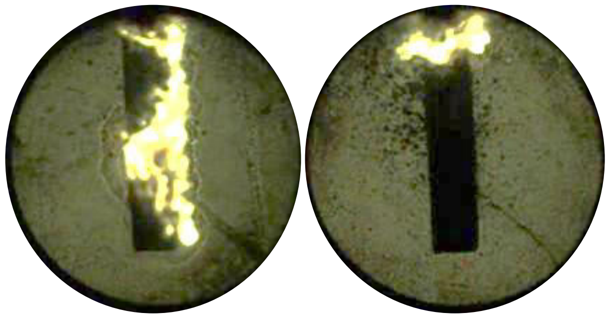


Figure-4. Wall temperature effect on the combustion of the dual fuel mixture, 60/40 of Diesel/CNG.



(a) (b)

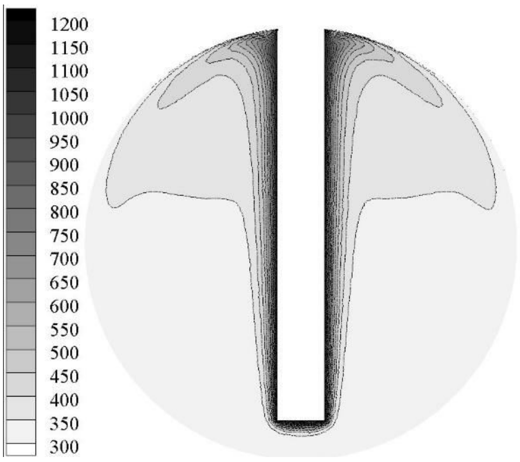
Figure-5. (a) Combustion of diesel (b) Combustion of DCNG at 1.5 ms after the start of combustion (SOC).

Figure-5 shows that the CNG content in the mixture is suppressing the initial autoignition of diesel to start in the upper region of the chamber. This region is the second hottest region after the heater surface.

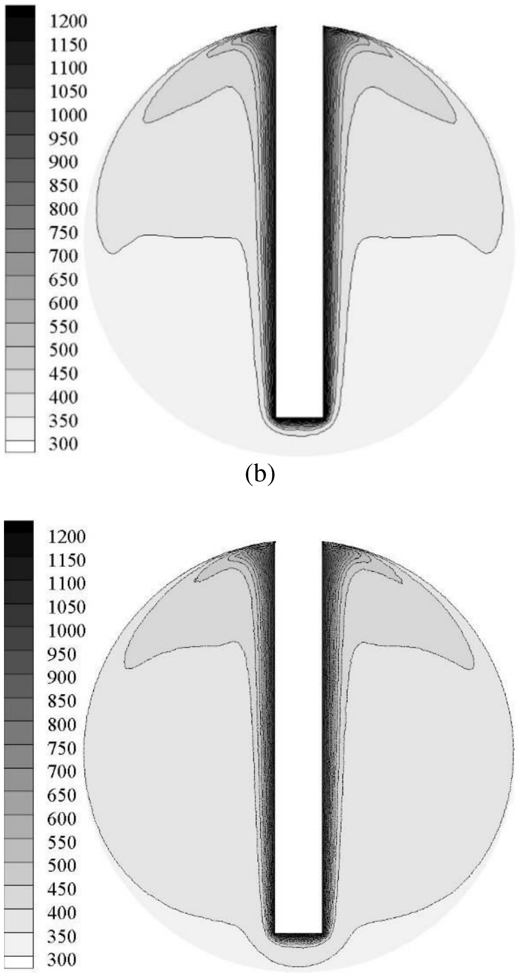
In the upper region, the temperature is strongly affected by the heater and less affected by the wall temperature as depicted in Figure-6. Therefore, the combustion delay and the initial combustion stage are almost constant for DCNG.

The main and final stage of the combustion duration shows slight increment with higher wall temperature which is contrary to diesel behaviour. CNG with its slower flame speed may contribute to the long combustion duration of the mixture [14].

In the contrary, the lower region of the chamber is highly affected by the wall temperature shown by Figure-6 that contributes to the significant difference in the initial and main combustion stage of diesel.



(a)



(b)

(c)

Figure-6. In-chamber temperature profile for wall temperature (a) 45 °C, (b) 60 °C and (c) 75 °C.

CONCLUSIONS

Wall temperatures have less effect on the combustion output of diesel/CNG mixture and its combustion delay. However, it increases the combustion duration of the mixture especially on the main and final combustion stage due to the slower flame speed of CNG.

Diesel, on the other hand, shows significant changes with the wall temperature variation. Higher wall temperature leads to shorter delay and combustion duration as well as increased combustion output.

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