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# FUNDAMENTAL STUDY ON COMBUSTION CHARACTERISTICS OF DIRECT INJECTION GASEOUS FUEL

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## ABSTRACT

The development of a more efficient engine is an important agenda in the automotive industry and the shrinking source of fossil fuel drives the search for alternative fuels as a replacement for gasoline in car engines. Some of the problems faced by a direct injection engine used today is heat loss to the walls of the combustion chamber. The objective of the study is to determine the combustion characteristics such as the combustion temperature, enthalpy, total energy and local heat flux which use direct injection for various alternative fuels like methane, propane, hydrogen and compressed natural gas. Variables such as the mass flow rate of air, air temperature, ambient pressure and type of fuel are studied to determine the heat loss which occurs so that this data can be used in future researches that involve more specific applications. This study is done using computer simulations with the aid of computational fluid dynamics software. The model used in this study includes non-premixed combustion, P1 radiation, energy equation and large eddy simulation. The results showed that increasing air temperature leads to an increase in heat flux due to more dominant pre-mixed combustion at higher temperatures. An increase in ambient pressure also causes an increase in the mixture density and this leads to a lower heat flux due to narrower combustion. Different fuels show different combustion characteristics. Hydrogen showed the highest heat flux while methane showed the lowest heat flux. This study is a form of fundamental research which allows the data obtained to be used in the development of high efficiency internal combustion engine.

**Keywords:** combustion characteristics, hydrogen, methane, heat flux, CFD.

## INTRODUCTION

Combustion is an important aspect and become the key point in designing process of an internal combustion engine. A chemical reaction occurs when the fuel reacts with oxygen in the air to produce heat. The current energy demand all over the world is primarily based on fossil fuels (Xiao *et al*. 2013). However, the reserves of fossil fuels become increasingly exhaustible. Therefore, alternative fuels were studied to obtain higher efficiency result and overcome the problems. Besides the gasoline, spark ignition engine can also use other fuels such as hydrogen, methane, propane and compressed natural gas. With rising petroleum prices and global warming being a dominant environmental issue, it seems that the use of alternative fuels in the future is inevitable (Li *et al*. 2010). The heat loss from the engine cylinders is an important aspect in ensuring the achievement of the optimum engine efficiency. Benefits of alternative fuels are that they emit less air pollutants and they are very economical compared with conventional fuels (Ali *et al*. 2010). Combustion characteristics for each alternative fuels need to be studied to determine their applicability in combustion engines as well as the amount of heat energy that can be generate. Physical and chemical properties of fuel has an impact on the resulting power and fuel economy (Zhang *et al*. 2011).

In spite of the type of fuel, many criteria are being analyzed by engineers and researchers around the world such as the time of injection, ignition timing, fuel injector design, pressure and temperature in the engine cylinder, spark plug position, and the pattern of spraying fuel. Cylinder pressure and heat release analysis are important and standard tools for engineers and researchers when developing and tuning new engines (Shehata, 2010). However, research that is using actual testing engine has its drawbacks. By using the actual engine, the potential of study is limited because it is difficult to control the parameter. For example, the pressure cannot be determined and fuel composition difficult to change. With the actual engine, the pressure will change constantly such other parameters like temperature and volume.

One of alternative to overcome this issue is to use a constant volume vessel to simulate burning with computational fluid dynamics software (CFD). Through this approach, we can set parameters such as pressure and other variables can be studied more easily. Simulation for a single burning can also be done due to the absence of combustion processes in a cycle of expansion and compression as in the actual simulation engine. The main purpose of this simulation is not to get the exact values or data as the same as in the actual engine. It is more to get the interrelationship among different variables to find the most optimal conditions for the highest efficiency engine. Various variables are tested in order to know the heat loss that occurs and make the factors that affect heat release understandable.

Current research is focusing in the investigating the process of constant volume combustion vessel by varying ignition delay through varying fuels, temperature and pressure (Mansor *et al*. 2012). All known research,

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prototype and production gasoline direct injection engines worldwide are reviewed as to performance, emissions and fuel economy advantages, and for areas requiring further development (Zhao *et al.* 1999). Factors that may affect the combustion characteristics of the engine must be examined to determine favorable conditions to achieve a low heat loss and high heat release. In the design of an internal combustion engine, accurate estimates of heat transfer is a vital important (Jafari and Hannani, 2006). Understanding the heat transfer mechanism from the combustion gases to the walls inside an internal combustion engine is key in the search for higher efficiencies, higher power outputs and lower emissions (Demuynck *et al*. 2012).

## METHODOLOGY

The simulation of computational fluid dynamics (CFD) is being used in this study to obtain the temperature, enthalpy, energy and heat flux resulting from the combustion of methane. Combustion simulation conducted in cube-shaped vessel with constant volume generated through computer aided drawing (CAD) with a length of 1 m and a fuel valve diameter is 50 mm as shown in Figure-1. The diameter of the air inlet and outlet valves is 100 mm and 50 mm respectively.

Energy equation model, radiation P1, none pre-mixed combustion and large eddy simulation (LES) are used in the study. The first case is to study on the effects of air mass flow rate. Mass-flow rate of methane is 0.0018 kg/s which are based on the ratio of stoichiometric calculation. Fuel percentages from 4% to 10% are used to study the amount of air inlet for controlling the combustion. The second case is a study on the effects of air temperature into the vessel. Temperature range of 275 to 315 K was used. The third case is a study on the effects of pressure in the vessel. Injection pressure of 1 MPa is used in conjunction with a pressure vessel of 1 atm to 3.5 MPa. The fourth case is a study of combustion of different fuels such as propane gas, hydrogen and compressed natural gas. The total heat loss that occurs on the surface of the vessel wall is calculated in CFD software.

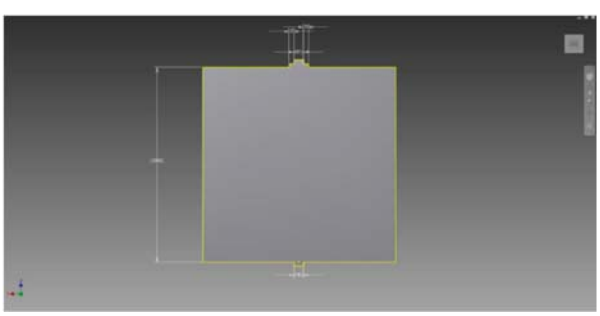

**Figure-1.** Constant volume vessel.

## RESULT AND DISCUSSIONS

### Methane Combustion Pattern

Large eddy simulation is used to determine the effects of the spiral flow, turbulent, flow field to the combustion of methane. Methane combustion pattern can be seen with a graphic contour that shows the isothermal plot and temperature data for combustion. Figure-2 shows the methane mass fraction. From the figure we understood that fuel burning looks stable and not skewed in other direction. This advantage will help to avoid heat loss thru vessel's wall. The heat flux occurs at different positions also can be seen. Methane combustion contour was shown in Figure-3. From the image, combustion area for methane with same temperature can be determined. The temperature for combustion decrease when it is close to the wall. The maximum temperature for the combustion is 2210K.

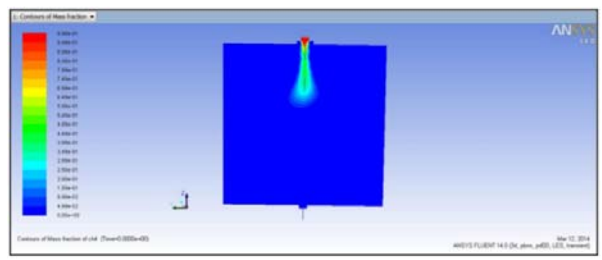

**Figure-2.** Methane mass fraction.

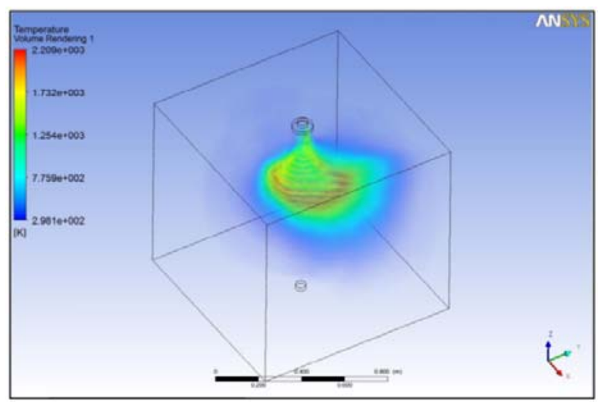


**Figure-3.** Methane combustion temperature.

Figure-4 shows the velocity streamline. It is clearly explains the combustion occurred in almost same velocity during the simulation. In addition, the fuel stream line at the top of vessel shows vortex in which it is effect from the LES model. Total heat transfer can be generated by Flux Report from the ANSYS Fluent application software. The total of heat loss to wall was 187, 152W where the maximum heat flux was 138W/cm$^2$.

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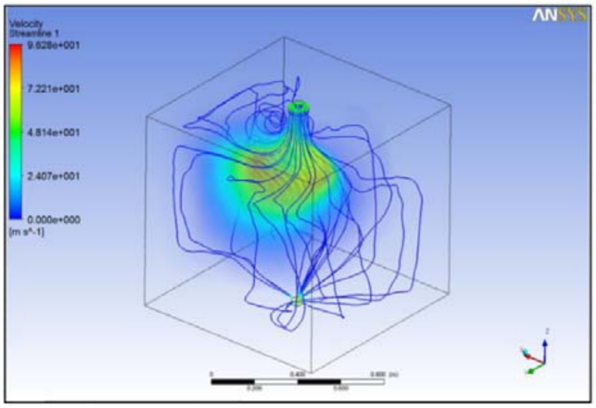

**Figure-4.** Methane velocity streamline.

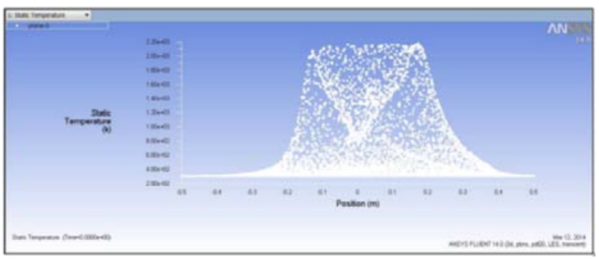

**Figure-5.** Methane static temperature.

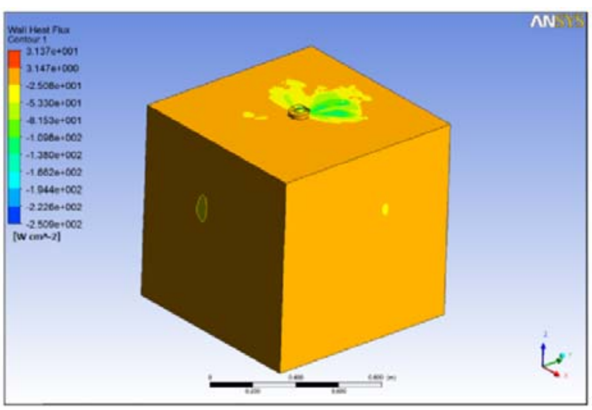

**Figure-6.** Wall heat flux.

Figure-5 shows the static temperature for the methane. Since the mass fraction not skewed to the right or left as shown in Figure-1, the highest temperature for fuel combustion located almost close to the center of fuel injection. This is a good sign in order to avoid the heat loss at the same time to maximize the efficiency. This phenomena also a good information and become a contribution to the internal combustion engine.

Figure-6 shows the wall heat flux for methane combustion. Location where the highest heat loss all around the vessel wall can be determined by referring to this figure. It is understood that the heat flux for this simulation not much different all over the wall.

**Effects for Percentage of Fuel**

Methane with percentage range of 4% to 10% is used to study the effects of different types of burning on maximum heat flux in the vessel. Stoichiometric combustion occurs at 5.5%. Lean combustion (<5.5%) and rich combustion (> 5.5%), the maximum heat flux are lower than the stoichiometry combustion even though the results of the study in Figure-7 showed that the highest maximum heat flux was 222.8 W/cm$^2$ at 5.75%. This condition is actually slightly more than the percentage of methane combustion in stoichiometry condition. Heat flux is highest in the stoichiometric combustion caused by heat release rate highest in complete combustion. Combustion shows the peak heat flux when it is in rich combustion but it will reduce when fuel percentage exceed the stoichiometric ratio. Experimental studies using the actual test engine gives a value of 150 W/cm$^2$ for methane combustion at 5.5% compared to 138 W/cm$^2$ from this study (Demuynck *et al*. 2012).

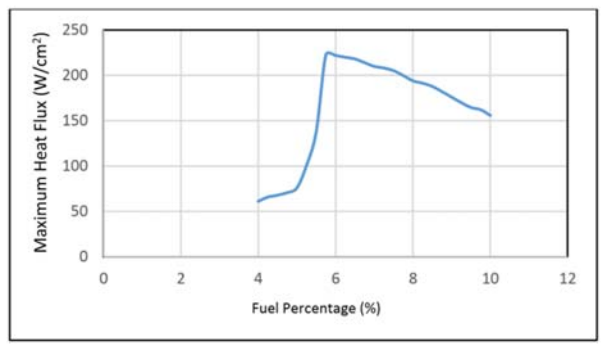


**Figure-7.** Maximum heat flux for case 1.

**Effect of Pressure in the Vessel**

Injection pressure of 1 MPa is used where the pressure in the vessel was 2.0, 2.5, 3.0 and 3.5 MPa. Generally, increased pressure in the vessels leading to lower heat flux. This is due to the density of methane-air mixtures are higher. Higher density leads to burning narrower in terms of combustion burning structure. Forming mixture becomes less efficient and therefore, the temperature and heat flux produced becomes lower. The result in Table-1 shows overall heat flux decrease when the pressure change from 0.1 MPa to 3.5 MPa, since the pressure is not high enough compared with the pressure in the vessel, the combustion is less because the fuel cannot enter the vessel smoothly. In order to improve the obtained data, the injection pressure greater than the pressure in the vessel should be used.

**Table-1.** Maximum heat flux and rate of heat loss for case 3.

| **Pressure of vessel** (MPa) | **Maximum heat flux** (W/cm2) | **Total rate of heat loss** (W) |
|---|---|---|
| 0.1 | 138.0 | 187152 |
| 2.0 | 121.2 | 122571 |
| 2.5 | 154.2 | 190703 |
| 3.0 | 272.8 | 296466 |
| 3.5 | 87.1 | 114802 |

**Different in Fuel Gas Combustion**

**Table-2.** Characteristics of different fuel combustion gas.

| **Fuel** | **Maximum Temperature** (K) | **Maximum Enthalpy** (J/kg) | **Maximu m Energy** (J/kg) |
|---|---|---|---|
| Methane | 2210 | 4.80e6 | 4.97e6 |
| Propane | 2240 | 2.38e6 | 2.44e6 |
| Hydrogen | 2370 | 1.18e6 | 1.29e6 |
| CNG | 2200 | 4.57e6 | 4.74e6 |

**Table-3.** Maximum heat flux and rate of heat loss for case 4.

| **Fuel** | **Maximum heat flux** (W/cm2) | **Total rate of heat loss** (W) |
|---|---|---|
| Methane | 138.0 | 187152 |
| Propane | 390.9 | 365386 |
| Hydrogen | 744.6 | 464802 |
| CNG | 312.5 | 325661 |

Combustion simulation was repeated with different fuels such as propane, hydrogen and compressed natural gas. The result of the simulation is shown respectively in Table-2 and Table-3. This data can be used as reference data for more details study in the future, such as the study of effects on heat flux when hydrogen added into the methane combustion.

**CONCLUSIONS**

Studies of combustion in computer simulations is conducted in four sets, which is the percentage impact of fuel, air temperature, pressure in the vessel and the type of fuel gas used. The total mass flow rate of methane was used as 0.0018 kg/s based on the stoichiometric ratio of methane. Other than fuel gas combustion pattern that shows in simulation result, the temperature, enthalpy, energy, local heat flux and the total rate of heat loss also obtained as the combustion characteristics for this study. Stoichiometric combustion produces the highest heat flux at 5.75% of methane in which the heat flux progressively higher when burning methane getting closer to stoichiometric combustion. Improved air inlet temperature leads to an increase in heat flux. Combustion at temperatures over 300 K showed high heat flux due to the premix combustion becomes more dominant than the diffusion combustion. Even though result shows decreasing trend in the overall maximum heat flux when the pressure change from 1 atm pressure to 3.5 MPa.

Study for the effect of the pressure vessel shows the unstable results due to injection pressure is not high enough. Different fuel combustion shows different characteristics where hydrogen showed the highest heat flux in contrast the heat flux of methane showed the lowest compared with propane and compressed natural gas.

**ACKNOWLEDGEMENT**

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