Analysis and simulation of combustion and emission on small engine

M Siti Sabariah¹, A S Syafiqah Nabilah¹, A B Rosli¹*, Z Z Junaidi¹ and M T Mustafar

¹ Faculty of Mechanical Engineering, Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia

*Corresponding Author’s Email: rośli@ump.edu.my

Abstract. Liquefied Petroleum Gas (LPG) has become an interesting topic in the automotive industry to develop the engines with clean emission characteristics. The usage of gasoline as a fuel to power up the vehicle will contribute to the heavy environmental problem. A single cylinder four-stroke spark ignition (SI) engine that fueled by LPG and gasoline are used to predict and analyze the combustion process in the cylinder. A zero dimensional models are most suitable analytical models for engine cycle simulation. The simulation program has been developed using MATLAB software by implementing a single-zone thermodynamic model. The first law of thermodynamics is applying into this model and Annand’s model was used to compute the convection and radiation of heat transfer within the cylinder. The engine performance parameters computed including the in-cylinder pressure, gas temperature, net heat release, mass fraction burn, brake power, torque, indicated specific fuel consumption. Then, exhaust emission in the cylinder was predicted by the formation of emission model. The results of engine performance are compared between gasoline and LPG as a fuel. Results show LPG engine has contributed to the lower HC and NOx emissions compared to gasoline. It proved that the development of simulation program is useful to calculate the engine performance at different operating points.

1. Introduction

The price of oil is fluctuating and the increasing environmental issue has led to the use of alternative fuels such as compressed natural gas (CNG) and liquefied petroleum gas (LPG) for internal combustion engine. Many researchers have conducted the studies on using alternative fuel in internal combustion engine in order to study the engine performance by using alternative fuels (Kalra, Veeresh Babu et al. 2014). The use of gasoline and diesel in internal combustion engine is substituted for alternative fuel, which one of the alternative ways to save our raw non-renewable sources.

Liquefied Petroleum Gas (LPG) is one of the alternative fuels that used in the spark ignition (SI) engine instead of gasoline. LPG is produced as byproduct of natural gas and it created from the refining petroleum. It consists of either propane (C₃H₈), butane (C₄H₁₀) or mixture of propane and butane but also contain small portion of propylene and butylene. Instead of using LPG in vehicles, it also can be used as fuel in the heating appliances and cooking equipment (Sulaiman, Ayob et al. 2013).

In this study, the type of engine used is a single cylinder four-stroke spark ignition (SI) engine. The combustion process for fuel and air are homogeneously mixed together in the carburetor. Homogeneous mixture is then mixed with residual gases inside the cylinder and it is compressed. The combustion process is begins near the end of compression stroke and the spark is produced by an electrical discharge across the electrodes of a spark plug. The combustion process is consists of three stages which ignition
and flame development, propagation of flame and after burning. Figure 1 shows the variation of pressure caused by combustion process in a practical engine.

![Combustion stages in a spark ignition (SI) engine.](image)

**Figure 1.** Combustion stages in a spark ignition (SI) engine.

Source: V Ganesan 2008

In terms of engine performance, the engine that fueled by LPG could run with high compression ratio in order to increase the thermal efficiency because LPG has a high octane rating (RON) (105 – 112) as compared to gasoline (91-97) (Sulaiman, Ayob et al. 2013). In addition, the probability of occurrence for knocking in the engine is increased due to high compression ratio. Besides, the power output generates by the engine that powered by LPG as fuel is poorer as compared to gasoline engines. This is because the fuel supplied into cylinder acts as a vapor (Lee, Ryu et al. 2005).

Then, the development of a simulation program for the actual process thermodynamic cycle of spark ignition (SI) engine is attempted and the single zone thermodynamic model, which is a zero dimensional model, has been applied in this simulation. By dealing with combustion performance, the heat release rate of the fuel within the combustion chamber is computed from a thermodynamic model. The rate of heat release is used as an input data for the calculation of in-cylinder pressure. Then, the simulation has been used to calculate the performance of spark ignition (SI) engine (Pourkhesalian, Shamekhi et al. 2010).

**2. Methodology**

Zero dimensional single zones thermodynamic are applied in this model. First law of thermodynamics was being the basis of the single zone thermodynamic model has been applied because the working fluid inside the cylinder is assumed as the thermodynamic system. Then, the energy released during the combustion process inside the cylinder is obtained from the first law of thermodynamic. Single Zone Thermodynamic consist of sub models such as heat transfer model, combustion model, frictional engine model and exhaust gas emission model.
The first law of thermodynamic model is defined as following:

$$\Delta U = Q - W$$  \hspace{1cm} (1)

The mixture of air-fuel inside combustion chamber is behaved as an ideal gas:

$$PV = mRT$$  \hspace{1cm} (2)

2.1. Combustion model

The Weibe function has been used in the construction of single zone model to determine the mass fraction burn inside the combustion chamber as a function of crank angle. It is defined as (Lounici, Loubar et al. 2011, Chaudhari, Sahoo et al. 2014, Ferguson, Kirkpatrick et al. 2015).

$$X_b(\theta) = 1 - \exp \left[ - a \left( \frac{\theta(i - \theta_b)}{\theta_b} \right)^{\frac{k+1}{k}} \right]$$  \hspace{1cm} (3)

2.2. Heat transfer model

Annand’s method is used for heat transfer model since the inner wall surface is separated into convection and radiation followed by Newton’s law of cooling. It can be defined as (K. Hareeesh, Rohith et al. 2014, G. P. Blair 1999).

$$\frac{dQ_w}{dT} = (h_c + h_r)A_w(T - T_w)$$  \hspace{1cm} (4)

Then, the convection heat transfer coefficient is computed using the Nusselt number (K. Hareeesh, Rohith et al. 2014).

$$h_c = \frac{k_{gas}Nu}{B}$$  \hspace{1cm} (5)

Nusselt number equation can be found out as (K. Hareeesh, Rohith et al. 2014, G. P. Blair 1999).

$$Nu = a \text{Re}^{0.7}$$  \hspace{1cm} (6)
Then, the radiation of heat transfer coefficient is given as (G. P. Blair 1999).

\[
h_r = 4.25 \times 10^{-6} \left( \frac{T_o^4 - T_w^4}{T_o^4 - T_w^4} \right)
\]  
(7)

2.3. Friction of engine model

Engine friction can be divided into various parts, inlet, throttling and pumping losses. However, some of the frictional losses of the engine that contribute fewer amounts can be neglected in calculation. Friction mean effective pressure (fmep) can be expressed as (V.Ganesan 1996):

\[
f_{mep} = 0.42 \times \left( P_{atm} - P_{inf} \right) \times \frac{L}{B^2} \times \left( 0.0888CR + 0.182CR^{1.33-0.3045P/100} \right)
\]  
(8)

2.4. Exhaust gas emissions model

2.4.1. Nitrogen oxide (NO\textsubscript{x}) emission model

The general equation for overall combustion reaction of fuel that react air is given as (Ferguson, Kirkpatrick et al. 2015):

\[
\varepsilon \left( \frac{1}{\lambda} \right) C + 2(1 - \varepsilon) \left( \frac{1}{\lambda} \right) H + O_2 + \beta N_2 \rightarrow n_1 CO_2 + n_2 H_2O + n_3 O_2 + n_4 N_2 + n_5 H_2 + n_6 CO
\]  
(9)

The extended Zeldovich mechanism was applied for the formation of NO\textsubscript{x}. This mechanism is described briefly as the following reactions:

\[
O + N_2 \xrightarrow{k_{s,f}} NO + N
\]  
(10)

\[
N + O_2 \xrightarrow{k_{s,f}} NO + O
\]  
(11)

2.4.2. Hydrocarbon (HC) emission model

The overall hydrocarbon (HC) emission mechanism that does not undergo normal combustion in cylinder can be expressed as (Hamrin and Heywood 1995):

\[
HC = \sum SF_{crev} \left( 1 - f_{oxy,cyl} \right) + SF_{wall} \left( 1 - f_{oxy,cyl} \right) \left( 1 - f_{oxy,exh} \right)
\]  
(12)

2.5. Engine performance

The indicated mean effective pressure can be defined as (Mc Graw-Hill 2008):

\[
imep = \frac{ip \cdot n}{V_d \cdot N}
\]  
(13)

The indicated power, \( ip \) inside the cylinder is given as (Pulkrabek 1997, 2008):

\[
ipo = \frac{WN}{n}
\]  
(14)
The brake mean effective pressure, bmep, is the average effective pressure that produced useful work transferred by the engine. It can be defined as (McGraw-Hill 2008):

\[ bmep = imep - fmep \]  \hspace{1cm} (15)

The indicated specific fuel consumption (ISFC) can be expressed as (V.Ganesan, 2003, 2008):

\[ isfc = \frac{\dot{m}_f}{ip} \]  \hspace{1cm} (16)

3. Result and discussion
In this study, the zero dimensional single zone thermodynamic models are developed as the simulation model for the combustion modelling by using MATLAB. The simulation results are compared between LPG and gasoline only based on simulation analysis.

Figures below show the results of the engine performance parameter by using various equations of thermodynamic models that solved numerically.

**Figure 3.** Cylinder Pressure versus Crank Angle

**Figure 4.** P-V Diagram for gasoline and LPG

**Figure 5.** Heat Transfer versus Crank Angle

Figure 3 shows the cylinder pressure as a function of crank angle. The higher cylinder pressure of gasoline is due to high volumetric efficiency of gasoline. So, more mass of air-fuel mixture inside cylinder and it tends to move more aggressively. Figure 4 shows the P-V diagram for gasoline and LPG. The cylinder pressure of gasoline is higher than LPG due to the high density of gasoline compared to LPG. The quantity of air-fuel mixture fuelled by LPG inside cylinder less caused it react
each other less aggressively and it caused the cylinder pressure decreased. Then, figure 5 shows the net of heat release respect to crank angle. The heat release of gasoline is higher than LPG because high density of gasoline could produce high burned gas during combustion process. This is because the cylinder temperature of gasoline is higher due to more burned gas released.

**Figure 6.** Mass of Fraction Burn versus Crank Angle

**Figure 7.** The Comparison of Brake Power versus Engine Speed for Gasoline and LPG

**Figure 8.** Comparison of Indicated Specific Fuel Consumption (ISFC) versus Engine Speed

Figure 6 shows the mass of fraction burn versus crank angle. As shown in the figure, the combustion of air-fuel mixture occurred earlier inside cylinder for LPG compared to gasoline. The mass fraction burn is slightly increased due to the combustion of air-fuel mixture occurred inside cylinder. Figure 7 shows the comparisons of brake power for gasoline and LPG versus engine speed. The decrease of brake power for LPG compared to gasoline is due to low volumetric efficiency and low density of LPG as its physical properties as a gaseous fuel. Figure 8, the Indicated Specific Fuel Consumption (ISFC) for Gasoline and LPG as a function of engine speed. It clearly shows that the gasoline requires more ISFC than LPG. This is because the low heating value and stoichiometric air-fuel ratio of gasoline. At high engine speed, the ISGC for both fuels are decreasing because of the presence of frictional losses of the engine. It has observed that ISFC of gasoline was always higher than LPG throughout the engine speed.
Figure 9 shows the graph of Oxide of Nitrogen (NO\textsubscript{x}) emission versus engine speed for gasoline and LPG. The high concentration of NO\textsubscript{x} at higher engine speed is due to high amount of oxygen presence inside cylinder. It caused the cylinder combustion temperature increased and high of residence time of NO\textsubscript{x}. The overall results of NO\textsubscript{x} concentration of gasoline is higher compare to LPG. Then, figure 10 shows the hydrocarbon (HC) emission as a function of engine speed. It clearly shows that the level of HC emission for gasoline is higher compare to LPG engine. The formation of HC emission is higher at low engine speed because of low volumetric efficiency. The less amount of oxygen presence to react with hydrogen and carbon and caused the presence of richer mixture.

4. Conclusion
The single zone thermodynamic models were developed as the simulation model for the engine combustion modeling of four stroke single cylinder spark ignition (SI) engine in MATLAB environment. LPG and gasoline are used as fuel to power the engine. The entire of engine geometry inputs, specifications of the engine, fuel inputs and atmospheric inputs have been calculated correctly before insert into simulation code to make sure the simulation program runs smoothly. The performance parameter such as brake power indicated specific fuel consumption, gas exhaust emissions as a function of engine speed have been compared between gasoline and LPG. It has clearly showed the power performance of LPG is poorer as compare d with gasoline. The reduction of power performance for LPG is 15 percent than gasoline. ISFC for gasoline is higher than LPG due to high heating value of LPG. For the combustion performance, the peak cylinder pressure is increase at high engine speed due to high
density of gasoline than LPG. Besides, the ignition timing also plays an important role in the combustion performance inside cylinder. By advancing the ignition timing, the combustion takes place just after the top dead center (TDC) and the cylinder pressure and gas temperature increases. In terms of exhaust gas emission, LPG engine has contributed to the lower HC and NOx emissions compared to gasoline. Therefore, it has proved that the development of a simulation program that related to the thermodynamic process occurring inside the engine is useful as the engine simulation model of single cylinder four stroke SI engines to calculate the engine performance at different operating points.

Acknowledgements
I would like to thank my supervisor, Prof Dato’ Dr. Rosli bin Abu Bakar. I also would like to thank my family, friends and colleagues for their great support.

References
[1] V.Ganesan, (2003). "Internal Combustion Engines", Tata Mcgraw-Hill Publishing Company Limited.
[2] V. Ganesan (2008)."Internal Combustion Engines", McGraw-Hill Education (India) Pvt Limited.
[3] Al-Baghdadi, M. A. S. (2007). "A simulation model for a single cylinder four-stroke spark ignition engine fueled with alternative fuels." Turkish Journal of Engineering and Environmental Sciences 30(6): 331-350.
[4] Alkidas, A. (1999). "Combustion-chamber crevices: the major source of engine-out hydrocarbon emissions under fully warmed conditions". Progress in Energy and Combustion Science 25(3): 253-273.
[5] Chaudhari, A. J., et al. (2014). "Simulation Models for Spark Ignition Engine: A Comparative Performance Study." Energy Procedia 54: 330-341
[6] Elfasakhany, A. (2016). "Experimental study of dual n-butanol and iso-butanol additives on spark-ignition engine performance and emission". Fuel 163: 166-174.
[7] Ganesan, V. (1996). "Computer Simulation Of Spark-Ignition Engine Processes". Universities Press (India) Pvt. Limited.
[8] Gumus, M. (2011). "Effects of volumetric efficiency on the performance and emissions characteristics of a dual fueled (gasoline and LPG) spark ignition engine." Fuel Processing Technology 92(10): 1862-1867.
[9] Hamrin, D. A. (1994). "Modeling of engine-out HC emissions for prototype production". Massachusetts Institute of Technology.
[10] Hill, S. and L. D. Smoot (2000). "Modeling of nitrogen oxides formation and destruction in combustion systems." Progress in Energy and Combustion Science 26(4): 417-458.
[11] Hill, S. C. and L. Douglas Smoot (2000). "Modeling of nitrogen oxides formation and destruction in combustion systems." Progress in Energy and Combustion Science 26(4–6): 417-458.
[12] Isakower, S. and Z. Wang (2014). "A comparison of regular price cycles in gasoline and liquefied petroleum gas." Energy Economics 45: 445-454.
[13] Kakae, A., et al. (2011). "Sensitivity and effect of ignition timing on the performance of a spark ignition engine: an experimental and modeling study." Journal of Combustion 2011.
[14] Kalra, D., et al. (2014). "Effects of LPG on the Performance and Emission Characteristics of SI Engine-An Overview". International Journal of Engineering Development and Research, IJEDR.
[15] Marcus Klein, M. (2004) "A specific heat ratio model and compression ratio estimation".
[16] Lawankar, S., et al. "Experimental study of effect of ignition timing and compression ratio on NOx emission of LPG fuelled engine."
[17] Lee, K. and J. Ryu (2005). "An experimental study of the flame propagation and combustion characteristics of LPG fuel." Fuel 84(9): 1116-1127.

[18] Liu, E., et al. (1997). "A study on LPG as a fuel for vehicles". Research and Library Services Division, Legislative Council Secretariat Hong Kong.

[19] LIU, M. E., et al. (1997). "A Study On LPG As A Fuel For Vehicles."

[20] Masi, M. (2012). "Experimental analysis on a spark ignition petrol engine fuelled with LPG (liquefied petroleum gas)." Energy 41(1): 252-260.

[21] Paczuski, M., et al. (2015). "Liquefied Petroleum Gas (LPG) as a Fuel for Internal Combustion Engines."

[22] Irvin Glassman, Richard A. Yetter (2008). "Combustion." Elsevier Science. Edition 4.

[23] Sulaiman, M. Y., et al. (2013). "Performance of Single Cylinder Spark Ignition Engine Fueled by LPG." Procedia Engineering 53: 579-585.

[24] Yeom, K., et al. (2007). "Homogeneous charge compression ignition of LPG and gasoline using variable valve timing in an engine." Fuel 86(4): 494-503.

[25] G.P.Blair. (1999). Design and Simulation of Four Stroke Engines [R-186]. Society of Automotive Engineering Inc.

[26] S. Turns. (2011). An Introduction to Combustion: Concepts and Applications. Mc Graw-Hill Science/Engineering/Math. Edition 3.

[27] Fergusson, C. R. and A. T. Kirkpatrick (2015). Internal Combustion Engines: Applied Thermosciences, Wiley.

[28] Abdul-Wahhab, H. A., H. H. Al-Kayiem, A. R. A. Aziz and M. S. Nasif (2017). "Survey of invest fuel magnetization in developing internal combustion engine characteristics." Renewable and Sustainable Energy Reviews 79(Supplement C): 1392-1399.

[29] Doğan, B., D. Erol, H. Yaman and E. Kodanli (2017). "The effect of ethanol-gasoline blends on performance and exhaust emissions of a spark ignition engine through exergy analysis." Applied Thermal Engineering 120(Supplement C): 433-443.

[30] Hui Meng, L. W., Zongqi Han and Shubin Lei (2014). "Modeling and Simulation of Engine Power Based on MATLAB/SIMULINK." Advanced Materials Research 875-877: 929-933.

[31] Mariusz Ptak, S. K., Damian Derlkiewicz, Mateusz Słupiński, Marek Mysior (2017). "Liquefied Petroleum Gas (LPG) as an Alternative Fuel in Spark Ignition Engine : Performance and Emission Characteristics." Lecture Notes in Mechanical Engineering: pp. 441.