

CHARACTERISTIC OF LPG COMPOSITIONS IN THE FUEL LINE DURING DISCHARGING PROCESS

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ABSTRACT

Research and development activities on Liquefied Petroleum Gas (LPG) vehicles have increased LPG engine performance to that of gasoline engines. LPG evaporation in the fuel system also has a potential cooling effect that can be taken advantage of. The results from previous studies, however, do not explain the level of fuel in the tank at the time of data collection. LPG is a mixture of several molecules which have different properties. This paper presents an investigation of LPG composition characteristics in the fuel line during the discharging process. Samples were taken periodically on the fuel line by special gas syringes. Afterwards, the samples were injected into the Gas Chromatography-Mass Spectrometry (GC-MS) device. This series of tests, which was conducted on lengthy LPG tanks, showed that the propane and butane 2-methyl molecules are unevenly dispersed during the discharging of the tank. However, this study found that a change in LPG composition during the discharging process does not have significant influence on the energy delivery and the potential cooling effect.

Keywords: Cooling effect; Discharging process; Energy content; LPG composition

1. INTRODUCTION

In the last decade, the development of automotive propulsion technology has focused on electric vehicles (EVs) and fuel cells. EVs have been marketed in some countries as “green” cars. However, the market for EVs is much lower than that of conventional automotive propulsion systems, such as gasoline and diesel engine. This is due to the limited mileage and high total cost of ownership of EVs (Messagie et al., 2013). Bio-fuels from plants such as ethanol and biodiesel have also been developed, but their production will require competition for land used for crop production (World LPG Association 2015). Therefore, it is economical to substitute LPG engines for gasoline engines in some developed countries, while reducing the environmental impact of vehicles (Setiyo et al., 2016a).

LPG has been used as a fuel for road vehicles since the 1900s (Werpy et al., 2010). Initially, LPG vehicles produced lower power, ranging from 5% to 20% of the power produced by gasoline vehicles (Campbell et al., 2004; Ceviz & Yüksel, 2006; Watson & Phuong, 2007; Masi & Gobbato, 2012). Rapid research and development led to a significant reduction of these losses. For old LPG vehicles, the ignition timing adjustment was widely used to increase engine

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power to nearly the same level as a gasoline engine (Md. Ehsan, 2006; Bosch, 2010; Erkus et al., 2012; Lawankar, 2012; Setiyo et al., 2016b). The effect of LPG on emissions and engine performance has also been investigated by many researchers, including Murillo et al. (2005), Saraf et al. (2009), and Gumus (2011). The majority of researchers conclude that emissions from LPG engines are lower than emissions from gasoline engines.

A previous study showed that LPG can be used not only as a fuel but also has a cooling effect. Evaporating LPG in a vaporizer produces a cooling effect that can be used to help cool a car's cabin. An LPG fuel system was simulated in a model 2000 cm³ engine using various mixtures of propane and butane to determine the characteristics of the cooling effect. The simulation showed that the engine was able to produce a cooling effect of more than 1.0 kW at 3000 rpm. The different LPG compositions also affected the strength of the potential cooling effect (Setiyo et al., 2016c). This study was previously conducted by Mohan (2013) and Ghariya et al. (2013). The cooling effect of LPG evaporation was also observed in a domestic refrigerator by Shah and Gupta (2014), Nikam et al. (2015) and Mhaske et al. (2016).

However, studies related to LPG as a fuel and as a heat absorber did not report the level of fuel in the tank at the time of data collection. LPG level in fuel tanks decreases during the discharging process. Because LPG is a mixture of several molecules with different properties, the changing level of fuel in a tank could affect the performance of LPG as a fuel and as a coolant. This paper presents an investigation of LPG composition in the fuel line during the discharging process and its effects on energy combustion and cooling. This study uses LPG taken from one gas station in Semarang, Indonesia (ID. 41.502.02).

2. LITERATURE REVIEW

In general, LPG is a mixture of propane (C₃H₈) and butane (C₄H₁₀) and a small part of ethane (C₂H₆) or pentane (C₅H₁₂). This mixture is stored as a liquid in pressurized cylinders at 0.6–1.2 MPa (Adolf et al., 2015). The percentage of propane and butane in LPG is different in winter and in summer, with a higher percentage of propane in winter (Price et al., 2004; El-Morsi 2015). Butane provides more energy than propane per volume by 12% when burned at temperatures above freezing. However, propane is more reliable when stored at low temperatures. In atmospheric conditions, the boiling point of propane reaches -44°C while butane is only 0°C. The liquid density of propane and butane is different as well, with 489.45 kg/m³ for propane and 571.99 kg/m³ for butane (The Engineering Toolbox n.d.). Propane, butane, and mixtures of the two also produce different levels of vapor pressure (Younglove & Ely 1987; AES, 2012). The greater the composition of propane in LPG, the higher the vapor pressure.

2.1. LPG Composition of Household LPG Cylinders

In household LPG cylinders, propane and butane compositions from cylinder to burner during the discharging process has been investigated by Zainal et al. (2006). This study showed the ratio of propane to butane was not equal during the discharging process. At the initial stage of discharging, there were no butane molecules flowing from the cylinder. Butane molecules take some time to flow alongside propane molecules. The higher percentage of propane, the longer the time required. For all mixtures, the vapor is largely composed of propane at the beginning of the discharge process. During this process, the temperature drops inside the cylinder. As a result, a layer of ice forms on the cylinder wall, which demonstrates the heat-absorbing nature of evaporating LPG.

2.2. LPG Applications in Vehicles

In vehicles, LPG tanks are placed lengthwise on the rear trunk or mounted in the chassis. LPG tanks on vehicles are also equipped with a submerged tube as an outlet for the fuel. The tube is

mounted on a multi-valve unit. It enables LPG to flow into the vaporizer in liquid form. In this way, LPG travels from the tank to the fuel line without phase change. Thus, the pressure of LPG before it enters the vaporizer is only slightly lower than the pressure inside the tank. This phenomenon is different from the household LPG cylinders for cooking, as described by Zainal et al. (2006).

Commercial LPG in the automotive market must meet a standard that is not defined by the exact composition of the LPG but limited fuel properties only (European Committee for Standardization, 2008). In Indonesia, the specification for LPG systems in road vehicles was regulated by the Government through the Director General of Oil and Gas in 2009. However, the regulation is not explained clearly and merely limits the minimum composition of C₃ and C₄. By examining the differences in tank geometry and position (as previously studied by Zainal) as well as the uncertain compositions of LPG, this study will investigate the composition of LPG in the fuel line during the discharging process.

3. METHODOLOGY

3.1. Experimental Set Up and Apparatus

In this study, the LPG tank was removed from the vehicle and filled to 85% by volume (100% by mass) at the gas station. The tank was placed on a digital scale and allowed to stand for one day. A shut-off valve was installed in the pipeline between the LPG tank and the expansion valve. An expansion valve was mounted on the evaporator inlets to decrease the pressure and to regulate the LPG flow rate, and a flow meter was installed on the exit side of the evaporator for monitoring the LPG flow rate. Ambient air flows through the evaporator via an electric blower to help the LPG evaporate. LPG flowed from the tank to the fuel line by activating a shut-off valve. Samples were taken during the discharging process for every 2 kg of weight lost (1.4 g/s). The samples were then analyzed by a Gas Chromatography-Mass Spectrometry (GC-MS) device TQ-8040. The experiment set up and test equipment is presented in Figure 1.

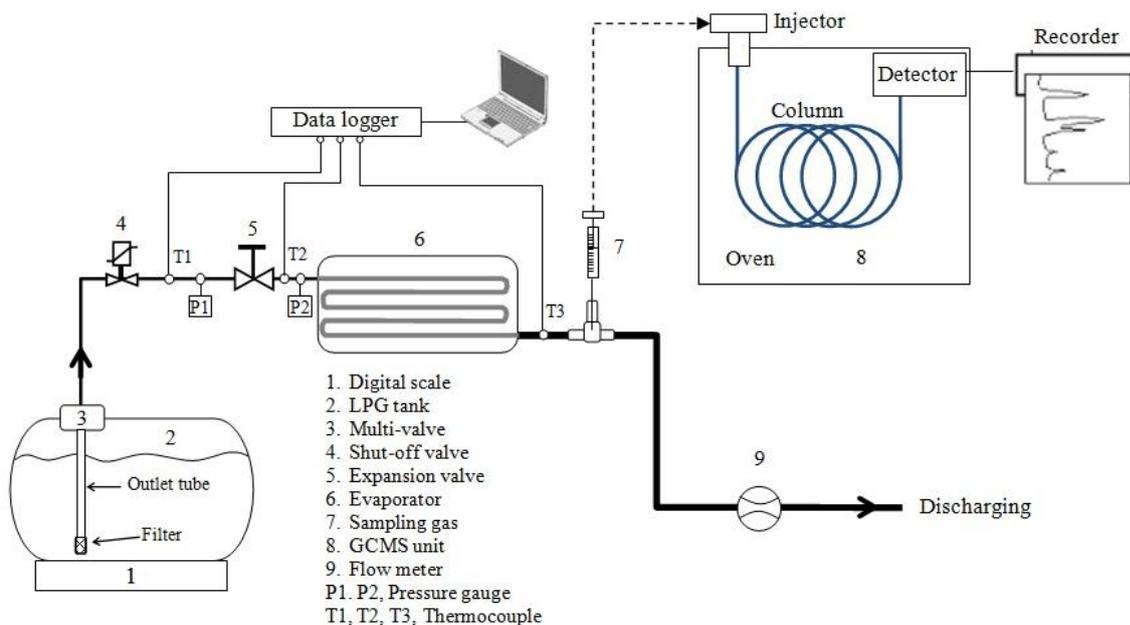


Figure 1 Experiment set-up and apparatus

3.2. Temperature and Pressure Measurements

During the test, temperature and pressure were recorded continuously to monitor the physical properties of LPG. PT-100 thermocouples recorded the LPG temperature before it passed through the expansion valve, after it passed through the expansion valve, and after it passed through the evaporator. The LPG temperatures were then fed to a TM4-N2RB series multi-channel modular temperature controller. The temperature data was processed and displayed on a personal computer through the Data Acquisition (DAQ) master software as Present Value (PV). The system's accuracy in measuring temperature is $PV \pm 0.5\%$ or $\pm 1^\circ\text{C}$. Next, the LPG pressure was measured in PV before and after the expansion valve by PSAN pressure transducers. The accuracy of the pressure measurements is $PV \pm 0.5\%$ F.S at 0°C to 50°C and $PV \pm 1\%$ F.S at -10°C to 0°C .

3.3. Composition Measurement

During the sampling process, LPG flow rate was maintained at 1.4 g/s by adjusting the expansion valve. Samples were taken at the evaporator outlets with a special gas syringe. The composition of LPG sucked into the gas syringe was assumed to be the same as the composition in the fuel line. Samples were taken at every 2 kg (10%) of weight lost. Next, the sample was injected into TQ-8040 series of GC-MS devices. Data from the GC-MS device were then processed and recorded by a personal computer.

Although the temperature and pressure of LPG were observed continuously in this experiment, samples were taken periodically at every 2 kg of weight lost. Therefore, attention to the temperature and pressure of LPG was focused solely on the LPG sampling points. The purpose of this was to ensure that the sample was obtained in its vapor phase so that it could be injected into the GC-MS device.

4. RESULTS AND DISCUSSION

4.1. Pressure and Temperature Distribution

In order to monitor the physical properties of LPG during the sampling process, pressure and temperature were recorded continuously at the points shown in Figure 1. The time from one sampling to the next was recorded using the DAQ master software. LPG pressure and temperature at the time of sampling are presented in Figure 2. During the discharging process, the temperature of air from the electric blower ($T_{air, in}$) was 35°C .

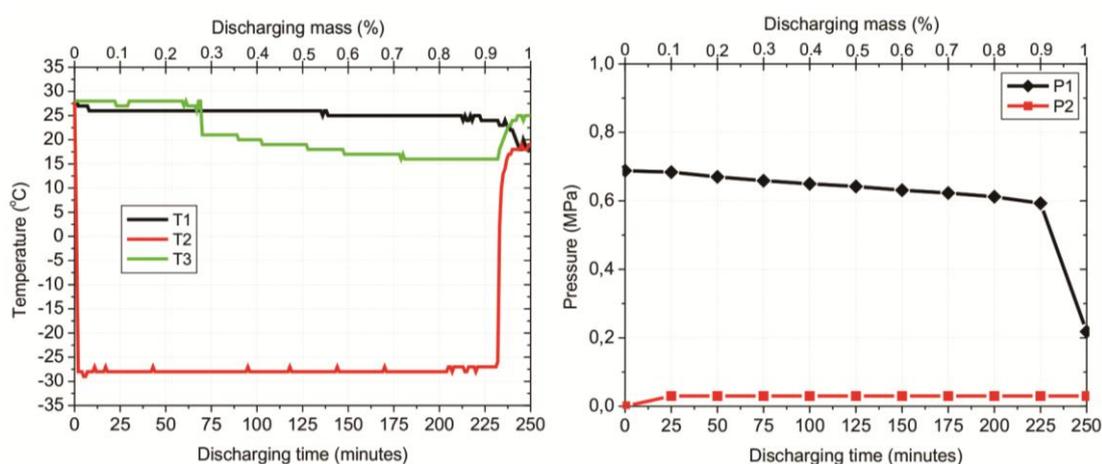


Figure 2 Temperature distribution (left) and pressure distribution (right) in the lengthwise LPG tank during the discharging process

From the data in Figure 2, the physical properties of LPG samples can be found by comparing the pressure and temperature at the time of sampling. Before entering the expansion valve, LPG was in a liquid state for sample number 1 to sample number 10. At this point (T_1, P_1), the temperature and pressure of LPG were 25–27°C and 0.59–0.69 MPa, respectively. However, for sample number 11, LPG was in a vapor state before entering the expansion valve. The temperature and pressure at this point were 18°C and 0.218 MPa, respectively. These conditions confirm that the end of the outlet tube is submerged during sample number 1 to 10. In addition, this data shows that LPG evaporation was completed in the evaporator. The heat exchange from LPG to the environment happens not only through latent heat transfer but also by sensible heat transfer. This phenomenon can be seen by comparing the temperature of LPG as it enters and exits the evaporator. LPG temperature exiting the evaporator has a much higher temperature than it does entering the evaporator. Finally, the data shows that LPG after the evaporator is superheated vapor. At this point (T_3, P_2), the samples' temperatures are in the range of 16–28°C while their pressure is at 0.03 MPa. Therefore, it can be concluded that LPG samples are taken in vapor forms.

4.2. Distribution of Molecules

Using the GC-MS device, a series of tests of the LPG composition during the discharging process was conducted. The results of these tests are presented in Figure 3 and summarized in Figure 4. A new composition of LPG obtained in this study is a mixture of propane and butane 2-methyl.

Based on the data shown in Figure 4, the characteristics of LPG composition during the discharging process can be observed. The series of test on LPG tank shows that the propane (CAS: 74-98-6) and butane 2-methyl (CAS: 78-78-4) molecules were unevenly distributed during the discharging of the tank. Six samples showed that the composition of propane was higher than butane 2-methyl (also called iso-pentane). Meanwhile, five samples showed that the composition of butane 2-methyl was higher than propane. This result is different than LPG compositions that were discharged from household LPG cylinders, which have an outlet valve located on the top of the cylinder. In household LPG cylinders, LPG evaporates inside the cylinder before it exits to the burner. Because the vapor pressure of propane is higher than butane, propane evaporates earlier than butane. In this study, LPG flowed from the tank to the fuel line in its liquid phase during the outlet tube is sinking in the LPG liquid. Evaporation occurs on the surface of the fluid and fills the space inside the tank. This is indicated by the fact that the pressure in the tank during the discharging process is nearly constant: it ranges from 0.59 to 0.69 MPa for up to 90% of fluid discharged (Figure 2). Since the liquid of LPG is lower than the end of the outlet tube, evaporation occurs entirely in the tank.

Considering that the test is static, the electronegativity of molecules is the simplest explanation for this phenomenon. Propane and butane 2-methyl are non-polar molecules, in which the electrons are spread evenly, so they do not show positive and negative poles in the molecule. The only atomic bonds in propane and butane 2-methyl are C-H and C-C. The electronegativity of carbon (C) and hydrogen (H) is almost the same, with 2.5 for C and 2.2 for H. Therefore, the C-H bonds in propane and butane 2-methyl are almost perfectly covalent. The electronegativity difference is less than 0.5, so propane and butane 2-methyl are non-polar. Thus, there is no electrostatic force from propane to butane 2-methyl making its easy to mix.

4.3. Effect on Energy Combustion

A numerical simulation was used to predict the characteristics of the energy delivered to the combustion chamber, High Heating Value (HHV), the results of which are shown in Figure 4. The composition of propane and butane 2-methyl during the discharging process is distributed unevenly. The energy content (HHV) of propane and butane 2-methyl is different, 50.33 kJ/kg

for propane and 48.57 kJ/kg for propane (Damirel, 2012). The curve of energy delivered during the discharging process is presented in Figure 5.

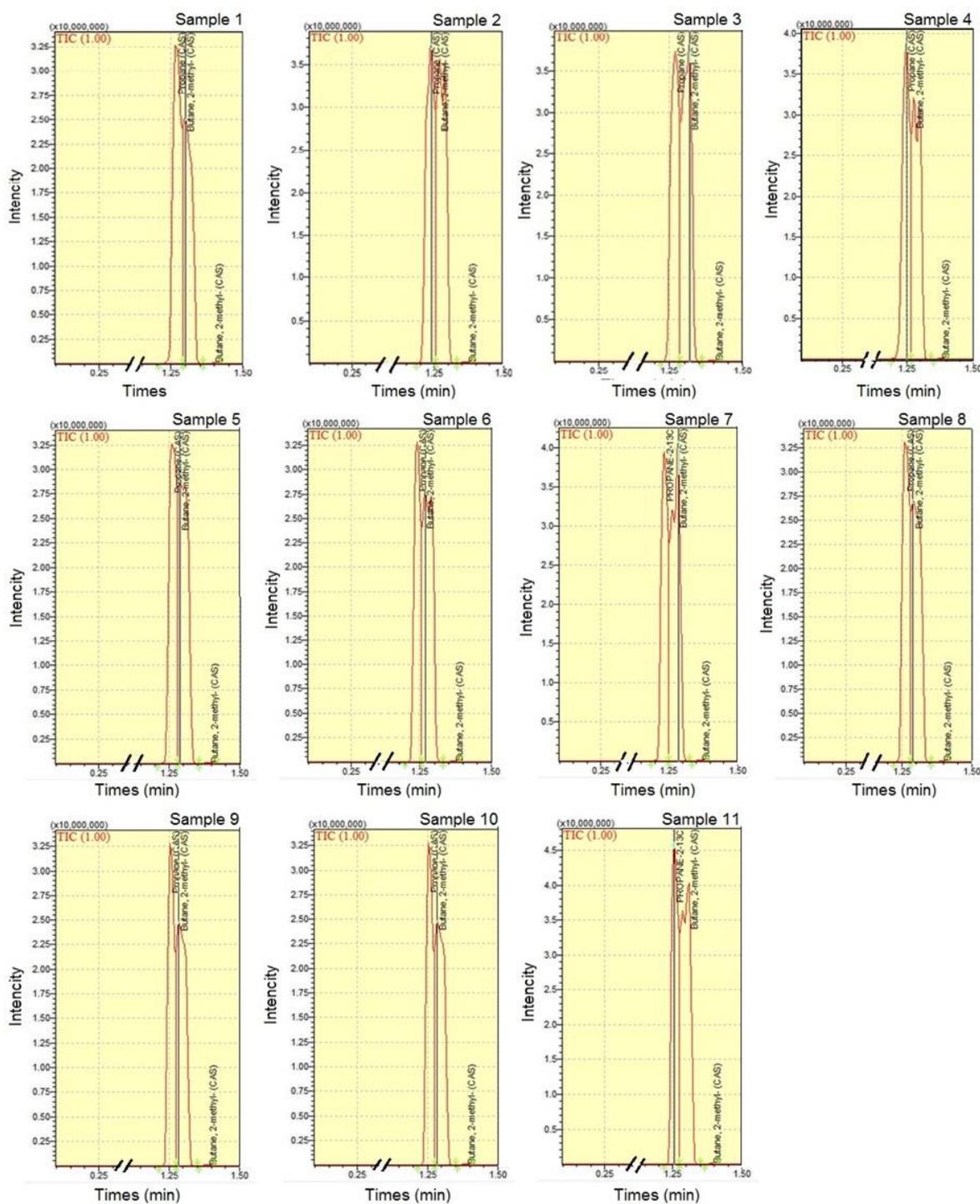


Figure 3 Intensity vs. times of propane and butane 2-methyl during discharging process obtained from GC-MS (sample 1=0% and sample 11=100% of weight loss)

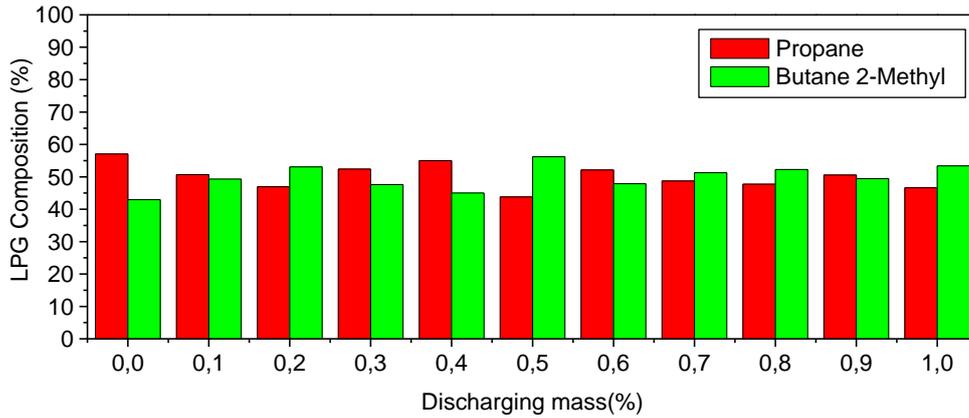


Figure 4 Distribution of LPG molecules during discharging process at 1.4 g/s from 0% to 100% of weight loss

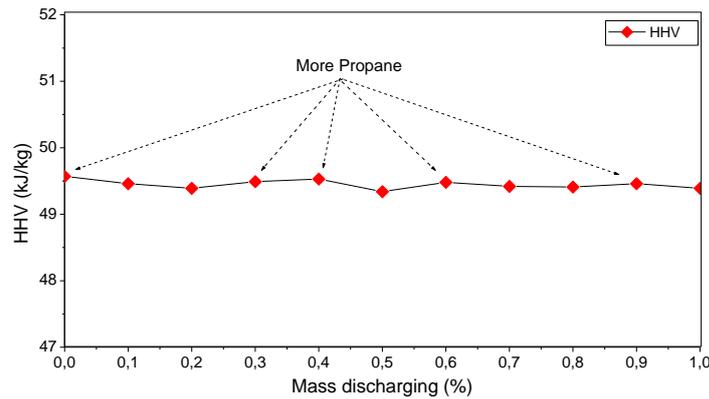


Figure 5 Energy delivered during discharging process

To determine the effect of changes in composition to the combustion, this analysis used the Wobbe index which is calculated by Equation 1 as follows.

$$I_W = HHV / \sqrt{SG} \quad (1)$$

where, I_W is Wobbe index, HHV is the higher heating value of fuel, and SG is the specific gravity. The SG of propane and butane 2-methyl of 0.45 and 0.62, then the I_W of propane and butane 2-methyl is 71.53 and 61.68. From Figure 5, one can see that the change of propane to butane 2-methyl during the discharging process is 43.78% to 57.05%, or $I_W = 65.99$ to $I_W = 67.29$. This means that the largest I_W to smallest I_W is only 2.32%. An I_W of less than 5% indicates that the change in the ratio of propane to butane-2 methyl does not have a significant effect on combustion (NREL, 1994; BP International Gas Union, 2011). The effect of LPG composition on diesel engine performance has been described in detail by previous researchers (Saleh, 2008; Elnajjar et al., 2013a; Elnajjar et al., 2013b).

4.4. Effect on Cooling Effect

The function of the vaporizer in the LPG fuel system is to transfer heat energy to LPG and, in so doing, evaporate the LPG. Through the evaporation process, heat absorption occurs. In the original design, circulating engine coolant around the vaporizer prevents the ice formation layer on the vaporizer wall as the LPG evaporates. In this study, the test results showed that the LPG temperature after the expansion valve was below 0°C for all compositions, except for the last sample (see Figure 2). This provides an opportunity to vaporize LPG with ambient air to

produce a cooling effect (q_{ev}) for cooling the car's cabin. An enthalpy calculation from LPG stream based on experimental data is presented in Figure 6a.

Therefore, the potential cooling effect from LPG vaporizer can be estimated by enthalpy values (h) as shown in Figure 6. LPG flow rate through a 1998 cm³ engine running at 1000–6000 rpm is 1–7 g/s (Masi & Gobatto, 2012). Assuming that the heat released from the air stream is equal to the heat absorbed for evaporated LPG, the potential cooling effect can be calculated through the equation:

$$q_{ev} = \dot{m}(h_3 - h_1) \quad (2)$$

q_{ev} is the potential cooling effect in kW, \dot{m} is LPG flow rate g/s, h_3 is the enthalpy in P_3 , T_3 (exit evaporator) in kJ/kg, and h_1 is the enthalpy in P_1 , T_1 (entering expansion valve) in kJ/kg. Assuming the expansion process is enthalpic, then $h_2 = h_1$. The potential cooling effect of LPG vaporizer during the discharging process is presented in Figure 6b.

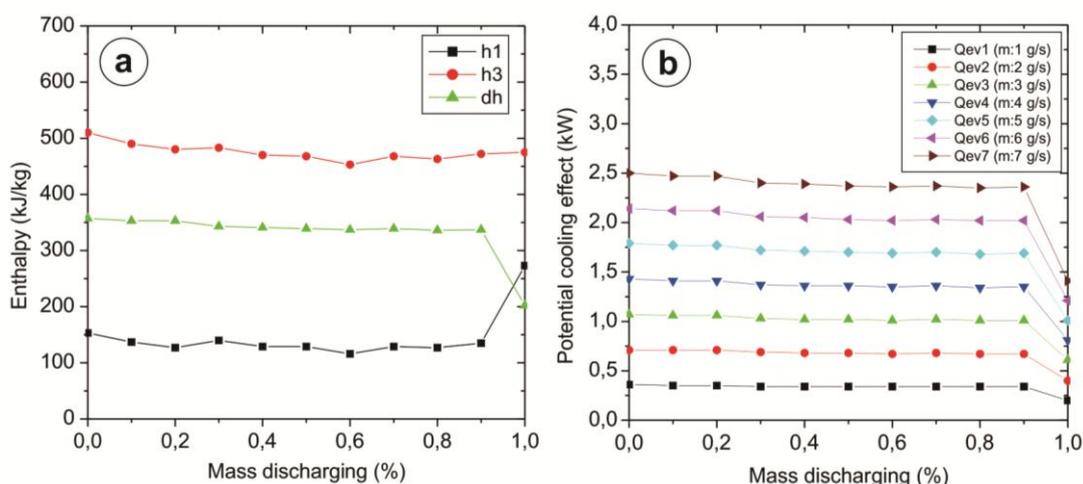


Figure 6 Enthalpy (h) during the discharging process (a) and potential cooling effects at various LPG mass flow rate during the discharging process (b)

Figure 6b shows that the LPG composition does not significantly affect the potential cooling effect. This can be seen during the discharging process with up to of < 90% of fuel discharged, even though the composition of propane to butane 2-methyl is changed. When over 90% of the fuel has been discharged, evaporation occurs in the tank so that the cooling effect from the evaporator is small. The experimental results show that the potential cooling effect is influenced by the temperature of LPG coming out of the evaporator.

5. CONCLUSION

Test results on the LPG tank indicate that propane and butane 2-methyl molecules are unevenly distributed during the discharging process of the tank. The changes in the composition of LPG during the discharging process do not significantly affect energy delivery (HHV) into the combustion chamber and the cooling effect. However, the large of the cooling effect is only obtained when the LPG exits the tank in its liquid phase.

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