Refrigeration effect and energy efficiency ratio (EER) calculation of 1/2 cycle refrigeration system on LPG-fueled vehicles

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Abstract. This paper presents a lab-scale experiment on the prototype of the ½ cycle refrigeration system of an LPG-fueled vehicle. LPG before being sent to the engine is used as a heat absorbing medium. The experiment was carried out at 0.15 MPa evaporation pressure and 1-6 g/s of LPG flow rate which representing of Light Duty Vehicle (LDV) fuel consumption. The results of this study indicate that ½ cycle refrigeration system capable of producing refrigeration effect of more than 1.2 kW with EER of 2.72.

1. Introduction

In recent decades, Liquefied Petroleum Gas (LPG) has become a substitute alternative to gasoline that is widely for SI engines, in addition to alcohol and Compressed Natural Gas (CNG). In fact, the utilization of LPG as a vehicle fuel has been more than 100 years [1]. Although 60% of the world's LPG is produced from oil refineries [2, 3], the trend of LPG usage for transportation sector shows a significant increase. In 2015, based on World LPG Association's annual report, global LPG consumption reached 26.4 million tons with an increase of 24% when compared to 2009. Until now, the number of LPG vehicles operating in the world is not known with certainty, but WLPGA reported more than 27 million [4].

LPG has an energy content (High Heating Value, HHV) which is slightly higher than gasoline, which is 46.23 MJ/kg (depending on percentage propane to butane). LPG has a relatively high energy content per unit mass, although per unit volume is low [5]. As a result, LPG tanks have larger volumes than gas tanks to accommodate the same energy. LPG car trials show about 15% reduction in greenhouse gas emissions (per unit distance), fewer NOx emissions, and almost zero particulate emissions when compared to gasoline [6]. However, due to its physical properties, LPG engine performance is generally below the performance of gasoline engines [7-10].

With the latest generation of converter kits, where LPG is inserted into the intake manifold or even directly into the combustion chamber in the liquid phase, and with advanced injection settings, LPG engine performance is equivalent to gasoline [4]. In LPG engines with first-generation converter kits (converters and mixers), the best performance only can be obtained under partial conditions even with
the unique design of mixers and ignition timing [11, 12]. However, along with the development of research activities, recently, found a hybrid system. LPG not only functions as fuel but serves as a refrigerant before it supplied to the engine (figure 1). Cooling effects generated through lab-scale tests show promising results, which more than 1.2 kW [13, 14].

![Diagram of LPG fuel system](image)

**Figure 1.** Illustration of hybrid system on LPG fueled vehicle (a) and P-h diagram on ½ cycle refrigeration concept (b).

A half cycle refrigeration system on LPG-fueled vehicles is a harvesting cooling effect without compressor and condenser. As an advantage, LPG in a cylinder is a pressurized liquid. Then LPG is expanded in an evaporator. LPG evaporates with the heat derived from the airflow that crosses the evaporator. Finally, LPG flows the engine under low-pressure vapor. In this case, the price per liter of LPG in the tube already includes the cost of compression on the refinery.

In the previous study [13], a 4 g/s LPG flow rate expanded from 0.6 MPa to 0.15 MPa was capable of producing a cooling effect of 1.2 kW with a humidity reduction of about 10%. This test can generate COP up to more than 6.0. Compression work to calculate COP is considered as energy to increase the pressure of LPG from atmospheric to 0.7 MPa (gauge). Meanwhile, studies conducted by Shah and Gupta [15] in a domestic refrigerator resulted in a maximum COP of 5.08. Denominators for
calculating COP by Shah and Gupta use total energy to compress LPG per unit mass obtained from PCRA energy audit.

Furthermore, since there is no compressor work in ½ cycle refrigeration, the energy to compress the LPG into the cylinder is neglected. Instead, the performance of the system is calculated by the Energy Efficiency Ratio (EER) method. In this case, the input work is considered as electrical energy to flow the air across the evaporator by an electric blower.

2. Method

In this study, an LPG tank was removed from the vehicle then assembled with an expansion valve, an evaporator, and supporting equipment as shown in figure 2 [13].

![Figure 2. Set up experiment and apparatus.](image)

This study uses LPG tanks with a maximum capacity of 40 liters equipped with multiple valves and shut-off valve. The expansion valve used is an adjustable expansion valve type to adjust the flow rate. In accordance with minimizing heat loss in the body expansion valve, the expansion valve is made of nylon that has a low thermal conductivity (0.24 W/m•K). The compact evaporator is chosen because it has the smallest pressure drop compared to the other types. In this study, used evaporator air conditioner of Peugeot 206.

Selection of electric blower is based on the estimated of maximum potential heat transfer [14]. It is assumed that the LPG mass flow rate for a passenger vehicle is a maximum of 6 g/s and the difference in enthalpy value at the outlet and inlet evaporator is 298.6 kJ/kg, then the total absorption of latent heat is 1.79 kW. Assuming the air enters the evaporator at 38 °C and 90% RH and out of the evaporator at 15 °C and 50% RH, the enthalpy at the inlet and outlet of the airbox are 143 and 29 kJ kg⁻¹, respectively (Δh = 114 kJ kg⁻¹). Thus, the need for maximum air flow rate is 1.79 kW/114 kJ kg⁻¹ = 15.7 g/s. Initial test results obtained that electric blower of 2A/3600 rpm produces air flow rate on the outside box of 16 g/s. Then, this value is taken because it is above the maximum requirement of 15.7 g/s.

3. Result and discussion

This section explains the refrigeration effect and discusses the energy efficiency ratio of the experiment results.
3.1. Refrigeration effect
During the air passes through the evaporator, the heat from the air will be absorbed by LPG for evaporation. As a result, the air becomes colder and drier. Dehumidifying occurs because some moisture in the air condenses. Therefore, the actual refrigeration effect is calculated based on equation (1).

\[ q_{ev} = m_a \cdot \Delta h \]  

(1)

Where \( q_{ev} \) is the refrigeration effect, \( m_a \) is the air mass flow rate, and \( \Delta h \) is the difference of specific enthalpy of air on the inlet and outlet airbox.

In this study, the specific enthalpy \((h)\) obtained from the online psychometric calculator. Location of data collection at altitude 380 m above sea level with the barometric pressure of 96,842 kPa. The changes in air temperature during the test are presented in figure 3. Meanwhile, the relative humidity of air during the test is presented in figure 4. The air at the inlet of the airbox is 32°C and 92 ± 1% RH. Then, the refrigeration effect at various LPG flow rates is presented in figure 5.

![Figure 3](image-url)  
**Figure 3.** Temperature drop during data collection at various LPG flow rate.

From figure 3, information can be given that the greater the flow rate of LPG the more energy is absorbed for evaporation. As a result, the cooling effect will increase as can be seen in figure 5. Then, due to cooling and decreasing the pressure of the airflow, it will cause a drop in the humidity as shown in figure 4.

![Figure 4](image-url)  
**Figure 4.** Relative humidity during data collection at various LPG flow rate.
3.2. Energy Efficiency Ratio (EER)

In addition to COP, the performance of the refrigeration system is also calculated by the Energy Efficiency Ratio (EER) [16]. EER is the ratio of actual refrigeration effect \( \dot{q}_{ev} \) to the total power input to produce refrigeration effect (equation 2). In the case of 1/2 cycle refrigeration, the power input is the electricity load to drive the electric blower \( w_b \). The concept of EER calculation on 1/2 cycle refrigeration system is presented in figure 6.

\[
EER = \frac{q_{ev}}{w_b}
\]  

(2)

The actual refrigeration effect (cooling and dehumidifying) of airflow on various of LPG flow rate have been presented in figure 5. In this study, the electric blower used is 220V, 2.0A. Thus, the electric blower \( w_b \) is 440 Watt. The EER data is presented in figure 7.
4. Conclusion
Lab-scale experiments on the prototype of the ½ cycle refrigeration system of an LPG-fueled vehicle have proven to produce refrigeration effect of more than 1.2 kW. Then, the EER calculation results show a non-linear curve to the LPG flow rate because the input work is constant. The actual EER value obtained from this study is 2.72. In conclusion, the ½ cycle refrigeration system promises to be applied to LPG-fueled vehicles as an effort to reduce fuel consumption and exhaust emissions.

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