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A Simulation for Predicting Potential Cooling Effect on LPG-Fuelled Vehicles

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Abstract. Liquefied Petroleum Gas vehicles (LPG Vehicles) provide a potential cooling effect about 430 kJ/kg LPG consumption. This cooling effect is obtained from the LPG phase change from liquid to vapor in the vaporizer. In the existing system, energy to evaporate LPG is obtained from the coolant which is circulated around the vaporizer. One advantage is that the LPG (70/30 propane / butane) when expanded from 8 bar to at 1.2 bar, the temperature is less than -25 °C. These conditions provide opportunities to evaporate LPG with ambient air flow, then produce a cooling effect for cooling car's cabin. In this study, some LPG mix was investigated to determine the optimum condition. A simulation was carried out to estimate potential cooling effects of 2000 cc engine from 1000 rpm to 6000 rpm. In this case, the mass flow rate of LPG is a function of fuel consumption. The simulation result shows that the LPG (70/30 propane/butane) provide the greatest cooling effect compared with other mixtures. In conclusion, the 2000 cc engine fueled LPG at 3000 rpm provides potential cooling effect more than 1.3 kW, despite in the low engine speed (1000 rpm) only provides about 0.5 kW.

INTRODUCTION

Liquefied Petroleum Gas (LPG) is an alternative fuel that has entire property keys for spark ignition engines. LPG also produces lower pollutant than gasoline for all parameters (CO, CO_2, HC, and Nox) [1]. Up to now, studies on LPG-fueled vehicles generally investigate on the combustion characteristics [2], power characteristics [3], and exhaust emission characteristics compared to other fuels [4]. There has not been found studies on utilization of heat absorption during the LPG evaporation process in the vaporizer. Whereas, in the LPG fuel system with vaporizer-mixer device, LPG is dropped from 8-10 bar to 1.2 bar and it is changed phase from liquid to vapor. LPG entered vaporizer as a liquid and exits as a vapor. In this condition, LPG absorbs heat for evaporation process. In the existing system (Fig 1a), the heat absorption occurs has not been utilized and only discharged through coolant circulation. Meanwhile, heat absorption due to the LPG phase changes in vaporizer produces a potential cooling effect of about 430 kJ/kg LPG consumption.

On the other hand, the air conditioning system (AC System) becomes the main accessories and standard equipment on passenger cars to increase comfortability. However, the AC system causes significant power reduction due to compressor load and increases fuel consumption. Studies related to the over fuel consumption due to the imposition of the AC system were conducted by Center for Energy Studies (CENERG) together with the French Energy Agency (ADEME). Meanwhile, the National Renewable Energy Laboratory (NREL) also carried out extensive test series to evaluate the over fuel consumption due to the use of AC systems for various cars. Over fuel consumption of gasoline cars was reported up to 16-40% by CENERG and 35% by NREL. The CENERG and NREL studis are then reconfirmed by J. Benouali [5] with different types of cars and weather conditions. Two series of tests were performed in the climatic chamber and on the test bench showed that the fuel over fuel consumption is in between 1 and 2.45 *l*/100 km along the European MVEG cycle, representing 21 to 53% respectively.

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Efforts to reduce power losses and over fuel consumptions due to the imposition of the AC system have been carried out through a variety of ways. For example the application of absorption AC system to replace the vapor compression AC system [6] and utilization of exhaust gas to drive the AC compressor with a turbo system [7]. The other way is done by installing an external power source to drive AC compressor. A biogas-fueled engines with constant speed is mounted on a car to drive AC compressor [8].

Related to this study, one advantage of LPG in the tank as liquid and exit vaporizer as vapor. In the existing system, to vaporize LPG and to prevent from icing in the wall of vaporizer is done by circulating engine coolant surround the vaporizer (Fig 1a). A research conducted by Price shows that vaporizer was able to absorb the coolant temperature up to 7 ^{o}C with 6 g/s of LPG and 0.1 kg/s of coolant (with out auxiliary heat exchanger) [9]. However, vaporize LPG with engine coolant causing the LPG vapor could reach 50 ^{o}C when it exits. High temperatures increase the specific volume of LPG vapor so that reduce the air mass sucked into the engine. Meanwhile, LPG with a mixture of propane/butane in the ratio 70/30, at 1.2 bar evaporate less than -30 ^{o}C. These conditions provide opportunities to vaporize LPG with ambient air flow (Fig 1b), to produce a cooling effect and to reduce the specific volume of LPG as it exits the vaporizer.

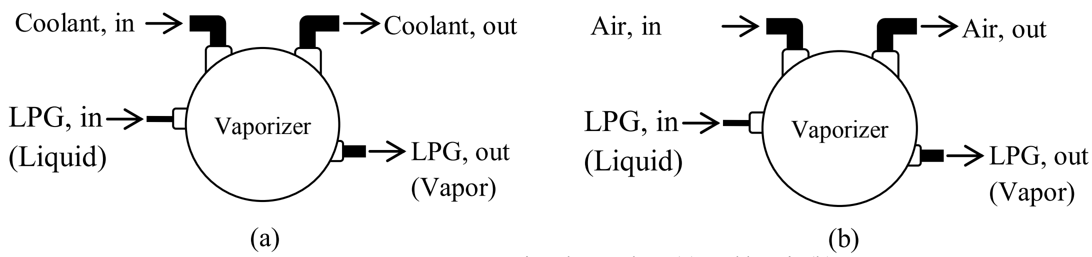

FIGURE 1. LPG vaporizer by coolant (a) and by air (b)

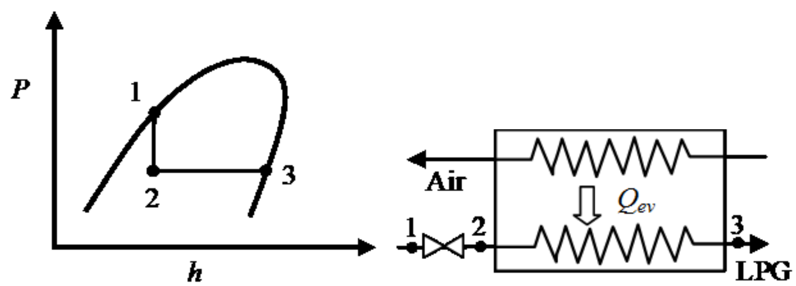

FIGURE 2. LPG phase change and heat transfer in the vaporizer

Under the first law of thermodynamics and an assumption that no heat is transferred from the vaporizer body to the environment, the amount of heat transfer from air stream to LPG is given in the following equation.

$$Q_L = Q_a \quad (1)$$

$$Q_L = \dot{m}_a \cdot C_{p,a} \cdot \Delta T_a \quad (2)$$

Where, Q_L is total heat transfer from air stream to LPG (Watt), $\dot{m}_a$ is air flow rate across vaporizer (kg/s), $C_{p,a}$ is specific heat of air at constant pressure (kJ/kg ^{o}C), and ΔT_a is temperature difference of air as enter and exit vaporizer (^{o}C). The amount of heat energy needed to vaporize LPG (Q_{EV}) can be formulated as follows.

$$Q_{EV} = \dot{m}_L (h_g - h_f) \quad (3)$$

Where Q_{EV} is total heat transfer from air stream to LPG (Watt), m_L is LPG flow rate in vaporizer (kg/s), and $(h_g - h_f)$ is enthalpy difference of LPG from liquid to vapour (KJ/kg). The air and LPG flow rate are given in the following equation.

$$m_a = \frac{\rho_a \cdot \eta_v \cdot V_S \cdot n}{12 \cdot 10^{-7}} \quad (4)$$

$$m_L = \frac{\dot{m}_a}{AFR} \quad (5)$$

Utilization of LPG stream to produce a cooling effect (direct refrigeration) had been conducted by Hussain [10]. The result showed that this system produced higher COP than domestic refrigerator. Furthermore, the performance of a mix of propane (C_3H_8) and butane (C_4H_{10}) as a refrigerant had been studied by some researchers [11,12,13]. Referring to the potential cooling effect during the LPG phase change from liquid to vapor in the vaporizer [9], this study will examine the new concept in hybrid system (i.e. LPG fuel system and air-conditioning systems). In order to obtain a cooling effect (that can be used to cool the car's cabin), the flow of engine coolant in the vaporizer is replaced by air stream that flowed by an electric fan, so that LPG will evaporate by taking heat from the air stream. Cold air is flowed entering the cabin and produce cooling effect. Next, the process of heat absorption is shifted from the original vaporizer to an auxiliary evaporator which has larger area than LPG contact area with the coolant in the original vaporizer. This study is limited to discuss about potential cooling effect during the evaporation process in the vaporizer by a computer simulation. In this case, the LPG flow rate is a function of fuel consumption.

SIMULATION METHOD

Analysis of heat transfer in vaporizer is based on the following assumptions:

(1) Pressure and heat losses on the pipe and fuel system components are neglected;
(2) Pressure drop occurs in expansion valve is assumed as isoentalpi process;
(3) Kinetic and potential energy are neglected because a very small effect;
(4) Heat transfer coefficient of evapotaror material considered fixed;
(5) Property LPG is taken from the REFPROP-NIST;
(6) Air density 1.2 kg/m^3;
(7) Using a 2000 cc engine, and
(8) Cooling load of the car is ~ 2.57 kW, refers to the vaghela's Study [14].

From Eq. 3, Q_{EV} is a function of LPG flow rate ($\dot{m}_L$) and enthalpy difference from liquid to vapour$(h_g - h_f)$. While LPG flow rate is influenced by actual air mass which is sucked the engine ($\dot{m}_a$) and Air-Fuel Ratio (AFR). Reffering to the Massimo's study [15], AFR and volumetric efficiency are presented in the following table.

TABLE 1. AFR and volumetric efficiency

Engine speed, *n* (rpm)	Air-Fuel Ratio, AFR	Volumetric efficiency, η_v (%)
1000	13,1	80,1
1500	15,0	80,4
2000	14,7	81,7
2500	15,1	84,0
3000	15,8	83,0
3500	15,7	85,3
4000	15,2	89,0
4500	15,5	93,3
5000	16,0	93,2
5500	15,5	91,8
6000	15,5	89,0

Air flow rate on each of engine speed can be calculated using Eq. 4 by entering volumetric efficiency value (Table 1) and the assumption number 6 and 7. The air flow rate calculation and AFR value (Table 1) are then inserted into Eq. 5 to calculate LPG flow rate. Next, the potential Q_{EV} is calculated using the enthalpy value from REFPROP-NIST shown in Table 2.

TABLE 2. Enthalpy data of various propane/butane mixture at 1.2 bar

Propane/Butane Mass Fraction (%)	100/0	70/30	50/50	30/70	0/100
Liquid Phase Temperature (°C)	-38.21	-32.50	-26.97	-18.86	4.05
Vapor Phase Temperature (°C)	-38.21	-19.71	-11.69	-4.93	4.05
Liquid Phase Enthalpy, h_f (kJ/kg)	109.19	123.90	137.31	156.36	209.41
Vapor Phase Enthalpy, h_g (kJ/kg)	530.62	557.18	568.78	578.51	591.03
$h_g - h_f$ (kJ/kg)	421.43	433.28	431.47	422.15	381.62

RESULT AND DISCUSSION

Base on Eq. 4, 5 to 3 and using data in Table 1 and Table 2, on assumptions that have been determined, the amount of potential Q_{EV} is given in Table 3 dan Fig. 3 respectively.

TABLE 3. Potential cooling effect of various propane/butane mixture

Engine speed, n (rpm)	Volumetric Efficiency, η_v (%)	Air Flow rate, $\dot{m}_a$ (kg/s)	LPG flow rate, $\dot{m}_L$ (kg/s)	Potential Cooling Effect, Q_{EV} (kW) of various propane/butane mixture				
				100/0	70/30	50/50	30/70	0/100
1000	80,10	13.1	0.001223	0.0160	0.515	0.530	0.528	0.516
1500	80,40	15.0	0.001608	0.0241	0.678	0.697	0.694	0.679
2000	81,70	14.7	0.002223	0.0327	0.937	0.963	0.959	0.938
2500	84,00	15.1	0.002781	0.0420	1.172	1.205	1.200	1.174
3000	83,00	15.8	0.003152	0.0498	1.328	1.366	1.360	1.331
3500	85,30	15.7	0.003803	0.0597	1.603	1.648	1.641	1.606
4000	89,00	15.2	0.004684	0.0712	1.974	2.030	2.021	1.977
4500	93,30	15.5	0.005417	0.0840	2.283	2.347	2.337	2.287
5000	93,20	16.0	0.005839	0.0932	2.461	2.530	2.519	2.465
5500	91,80	15.5	0.006515	0.1010	2.746	2.823	2.811	2.750
6000	89,00	15.5	0.006890	0.1068	2.904	2.985	2.973	2.909

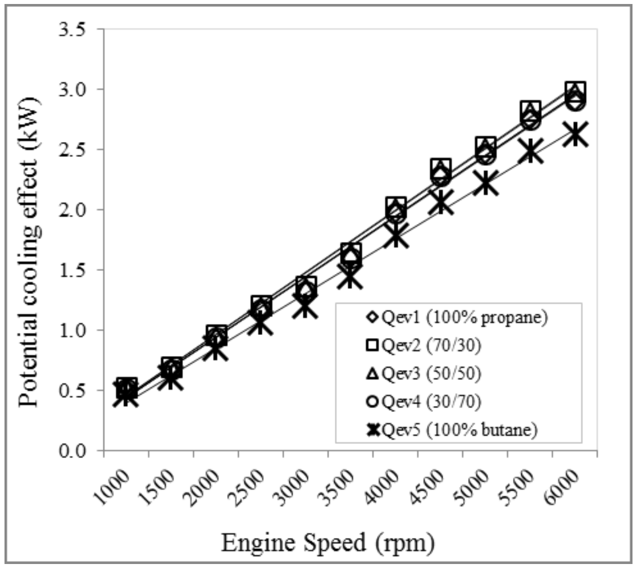

FIGURE 3. Potential Q_{EV} of various LPG mix

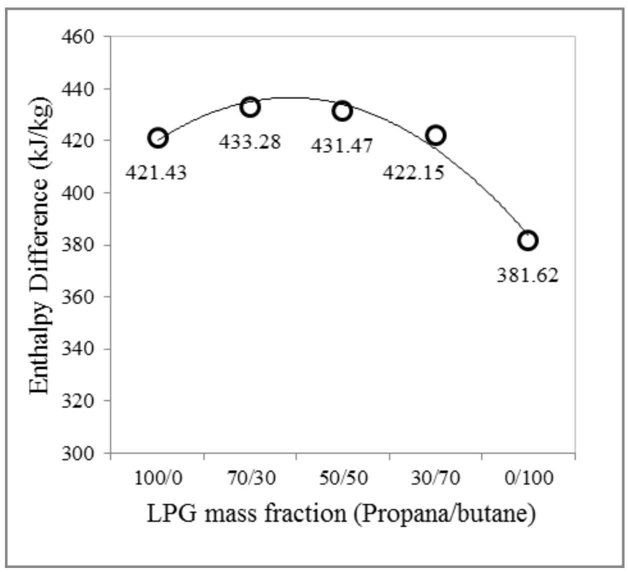

FIGURE 4. Enthalpy difference of various LPG mix

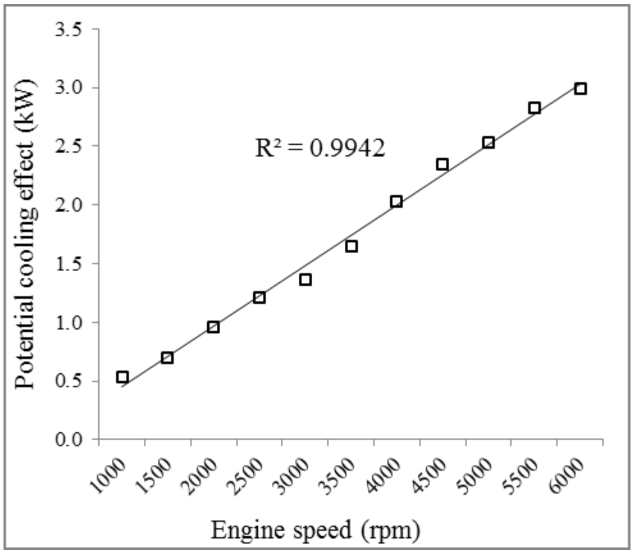

FIGURE 5. Q_{EV} regression of 70/30 propane/butane

Figure 3 shows that potential cooling effect from evaporation process of various LPG mix were nearly balanced, except for pure butane. Simulation results also showed that LPG with a 70/30 propane/butane gives the highest results. Although pure propane has the lowest boiling point, the amount of heat to change phase is lower than 70/30 propane/butane (Fig. 4). It is because Q_{EV} is affected by the enthalpy difference of the two phase of LPG. Another fact is that the enthalpy differences will decrease if butane fraction increases after a 50/50 mixture. In addition, potential of heat absorption also will be decrease if the boiling point of LPG increase. Moreover, the boiling point of pure butane at 1.2 bar is only 4 ^{o}C. If air is supplied at a 30 ^{o}C, it means that the only available potential difference is about 26 ^{o}C. Meanwhile, the mass fraction of propane is more than 50%, the potential difference of air temperature is over 56 ^{o}C (note: a 50/50 mixture of propane / butane 1.2 bar has liquid phase temperature of -26.97 °C).

The potential cooling effect increases proportionately to engine speed while on the other hand it does not form a straight line. This deviation is caused by the volumetric efficiency and AFR varied throughout the engine speed (Fig 5). Referring to the Vaghela's study [14], with the cooling load for a passenger car of 2.57 kW, this system is capable to provide more than 50% of cooling-effect on 3000 rpm. However, at low engine speed (1000 rpm), the system only able to provide potential cooling effect about 20% approximately (Fig 6). This is because at low engine speed, the flow rate of LPG is very small (about 0.001223 kg/s).

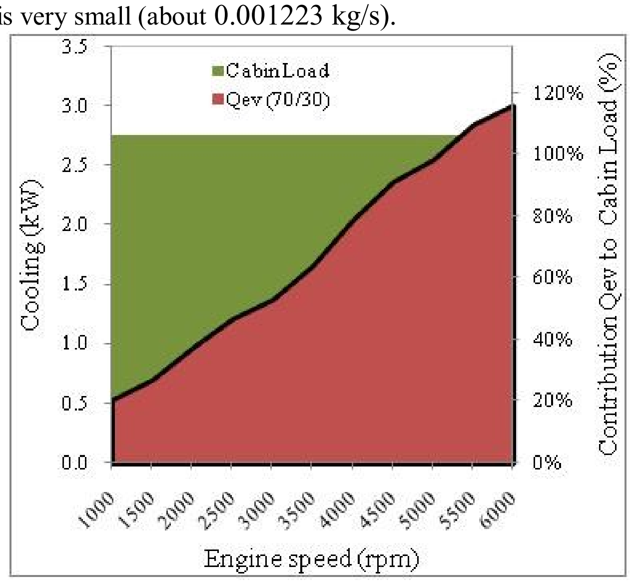

FIGURE 6. Contribution of Q_{EV} from LPG evaporation process to cooling load

CONCLUSION

The idea of replacing the coolant with air on LPG vaporizer provides the potential cooling effect by a significant amount. An important information was obtained that the cooling effect depends on the mass fraction of propane/butane. In this case, a 70/30 mixture of propane/butane provides the greatest potential cooling effect compared with other mixtures. The other information was also obtained that the potential cooling effect follows the volumetric efficiency and AFR. The simulation shows that 2000 cc engine fueled LPG at 3000 rpm provides cooling effect more than 1.3 kW, but at low speed engine only provides a low potention. This is because at low engine speed, the LPG flow rate is very small (about 0.001223 kg/s).

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