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Fuel as secondary refrigerant on LPG fuelled vehicle: A thermodynamics analysis

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ABSTRACT

In LPG-fuelled vehicles, there is a potential cooling from LPG evaporation in the fuel line. Cooling power is obtained without reducing the caloric value of the fuel supplied to the engine. Thus, LPG functions like a refrigerant before it is burned in the combustion chamber. Consequently, there is a change in fuel efficiency. Therefore, this paper presents a new thermodynamic analysis of LPG-fuelled vehicles by harvesting cooling power in the fuel line. The research was conducted by simulating LPG mass flow rates of 1-6 g/s on 1998 cm^3 engine which represent the fuel consumption of passenger cars. The total fuel efficiency is calculated by summing the indicated thermal power added by cooling power to the fuel energy supplied. The results show that the cooling power from the fuel line can increase the total fuel efficiency of 3.16%.

Keywords: LPG fuelled vehicle; LPG evaporation; cooling power; total fuel efficiency.

INTRODUCTION

In the last few decades, LPG vehicle technology has rapidly developed [1]. Initially, LPG is supplied to the engine through a Converter and Mixer (CM) like a carburetor in the gasoline engine. CM LPG kit is the first generation but is still widely used today, especially applications on vehicles that are modified for LPG experiences. The engine performance with the CM LPG kits heavily depends on mixer design and adjustment on the converter. Output power from CM LPG kits is reportedly lower than gasoline due to volumetric efficiency factor [2-4]. Then, the LPG kit technology evolved into Vapor Phase Injection (VPI) as a second generation, where the amount of LPG supplied to the engine began controlled with electronics and pneumatic. VPI LPG kit leaves mixer and replaces it with injectors/splitters. The third generation of LPG kit evolves into Liquid Phase Injection (LPI), where liquid phase LPG is in a pressure regulated fuel rail. The third generation already involves many sensors; the LPG ECM controls the injectors to supply LPG from the fuel rail with a set amount to achieve the right mix, generating higher output power and lower emissions, compared to the previous generations. The recent technology is the fourth generation called Liquid Phase Direct Injection (LPDI), the liquid phase LPG is injected into the combustion chamber like Gasoline Direct Injection (GDI). The loss of volumetric efficiency in the first to third generation has been recoverable with LPDI. LPI and LPDI LPG kits are commonly used in vehicles designed for LPG applications. Meanwhile, CM and VPI are widely used on modified vehicles for LPG applications.

LPG was chosen because it has almost all the fundamental properties as an S.I engine fuel. In the complete combustion, emissions from LPG engine are lower than gasoline engines because of low carbon content, i.e., three carbon and four carbon for propane and butane, respectively [5,6]. The resistance to the knocking of LPG is also better than gasoline due to higher octane numbers which reported of 105-106, depending on the composition [7-9]. However, because the energy content per unit volume is smaller than gasoline, the output power generated by the LPG engine is lower than the gasoline engine. Many researchers agree that the decrease in output power is due to intake air displaced by fuel [10-13].

With continuous research activities, the output power and emissions from LPG vehicles can be improved at varying levels by adjusting the ignition timing, modifying engine component, and increasing the compression ratio [7],[14-18]. Other efforts to improve the output power and emissions are also done through LPG temperature management on the fuel rail [19] and modification on the valve lifter combined with injection duration management [20]. Recently, another study tested the LPG consumption compared to RON 95 gasoline in the same driving mode [21]. As a result, LPG consumption is lower at 1.16 MJ/km from the gasoline consumption in the same driving mode. From the articles studied by authors in present work, it can be concluded that LPG is still a promising fuel for the next few decades.

The thermodynamic equation for measuring the performance of internal combustion engines is by Air Standard Efficiency (η_{ASE}) and Indicated Thermal Efficiency (η_{ITE}) [22]. η_{ASE} calculates the potential of thermal utilization based on adiabatic compression ratio regardless of the combustion process, given in Eq. (1). r is the engine compression ratio and k is the adiabatic index for air (1.4). Meanwhile, η_{ITE} compares the indicated power to the energy supplied in fuel energy given in Eq. (2). P_i is the indicated power and $\dot{q}_f$ is the energy supplied by fuel (mass flow rate of fuel [kg/s] × calorific value [kJ/kg]). Indicated Thermal Efficiency depends on the energy content of the fuel, combustion process, heat losses, and mechanical losses that occur.

$$\eta_{ASE} = 1 - \frac{1}{r^{(k-1)}} \tag{1}$$

$$\eta_{ITE} = \frac{P_i}{\dot{q}_f} \tag{2}$$

On the other hand, the air conditioning (A/C) system has become one of the main accessories in passenger vehicles to improve ride comfort. Initially, the A/C system only works to regulate the air temperature and humidity [23]. Now, many changes have been made to meet passenger comfort and health needs, save fuel, and improve environmental acceptance [24,25]. The general definition of the A/C system discusses heating and cooling. However, in this study only presents the A/C system that serves as a cooling and maybe dehumidifying. In its development, the cooling system on the vehicle is not limited only to passenger cars but to more extensive applications, including the refrigeration system for food transport vehicle [26-27].

To date, almost all A/C systems for commercial vehicles operate by the vapor compression system in which the compressor takes power from the engine. As compensation, fuel consumption and CO_2 exhaust emissions increased significantly to achieve comfortable temperature and humidity inside the cabin [28,29]. A study conducted by ADEME on a gasoline engine tested with urban cycles at 40 °C of environmental temperature showed that fuel consumption due to A/C systems increased 40% [30]. A similar study showed that fuel consumption with AC operation for sedans increased 20-25% [31]. Even, when the engine operates at idling, the wasted fuel for the A/C system more than at medium speed and high speed [32,33]. In another study, the wasted fuel due to the use of A/C systems for cabin cooling in Europe accounted for 3.2% of total global fuel consumption [34]. Although in different numbers, the A/C system on the vehicle becomes a significant load on the engine that needs fuel. On the other hand, almost all trends in automotive development are to increase efficiency and reduce emissions [35-37].

The heavy load of an A/C system is not only limited to compensate for the metabolic load of all passengers in the vehicle [38], but also other more thermal loads such as radiation load from windshields, engine load through the steering column, ventilation load, ambient load, and exhaust load transferred through the floor as shown in Figure 1. The thermal loads on the A/C system must be exchanged for cooling power on the evaporator. The refrigerant evaporates during flow in the evaporator and takes the heat from the circulated air stream. Assuming that the heat released by air is equal to the heat received to evaporate the refrigerant, cooling power can be calculated using Eq. (3). $\dot{q}_{ev}$ is the cooling power from the evaporator, $\dot{m}$ is the refrigerant mass flow rate, and Δh is the specific enthalpy different in the inlet and outlet evaporator.

$$\dot{q}_{ev} = \dot{m}\,\Delta h \tag{3}$$

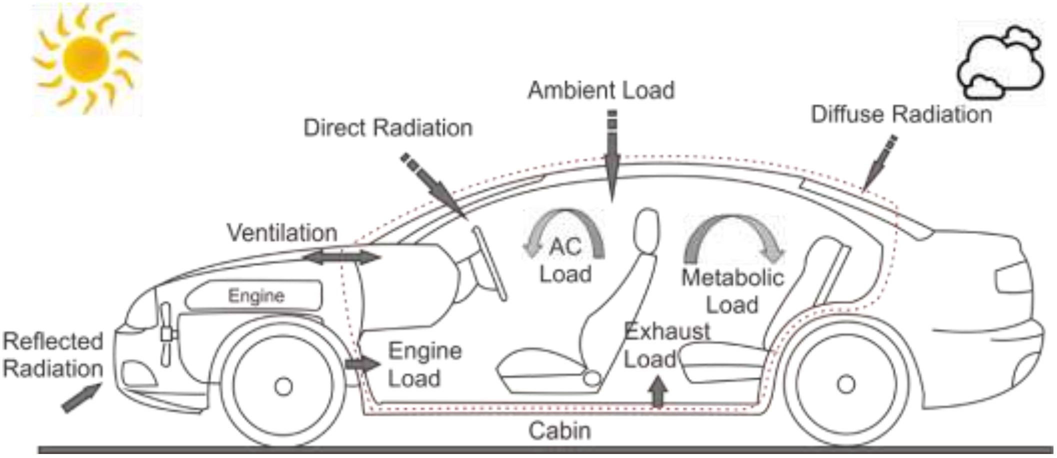


Figure 1. Thermal loads on a typical vehicle cabin

Several ways have been taken by many researchers to drive the A/C system, improve performance, and mitigate the high temperature inside the cabin, as presented in the author's previous study [39]. However, the use of alternative A/C systems such as absorption systems still produces lower cooling power and COP than vapor compression systems [40-43]. Therefore, seeking alternative cooling systems becomes a challenge as discussed in the author present work.

In 2004, an experimental study to calculate LPG requirements on a Ford Focus to produce equivalent power output when driven by gasoline was done by Price et al. [44]. Because LPG in a tank is liquid and enters the engine as a vapor, Price's study also discusses in detail the heat required to evaporate LPG (at varying mass flow rates) supplied from a portion of the engine coolant flow. As a result, there was a 7 $^{\circ}$C temperature drop from the engine coolant that crosses the evaporator with the flow rate of 0.1 kg/s at full engine load ($\dot{m}_{LPG}$ = 6 g/s). However, this potential has not been utilized; cooling recovery is still wasted with engine coolant. Although LPG can evaporate perfectly in the evaporator, the LPG temperature at the exit of the evaporator reaches more than 70 °C. With high temperature (superheated vapor), the energy density of LPG becomes lower and allows to reduce volumetric efficiency. In fact, the boiling temperature of LPG at evaporative pressure is below 0 $^{\circ}$C. It is possible to evaporate LPG with ambient air to produce cooling power.

The experiment to harvest the cooling effect from LPG flow is known as zero cost refrigeration [45]. The LPG pressure from the household cylinder is lowered using a capillary tube placed in a cooling box before LPG is delivered to the burner. Then, this concept is further discussed by Ghariya et al. [46] as the thermodynamic evolution of the cooling system. In the recent study conducted by present authors [47], LPG engines have been shown to produce cooling power above 1.0 kW in eco-driving mode. Assuming that LPG consumption is linear to the engine loads as presented by Masi and Gobbato [10], and the heat exchange in the evaporator occurs perfectly, its cooling power potential is hihger than the results of a recent study. LPG has a good capability as an alternative refrigerant that is more environmentally friendly, as has been tested by many researchers as a replacement for the refrigerant in domestic refrigerators or vehicles [48-52]. From previous studies, the thermodynamic analysis was performed separately for the engine (combustion) and cooling systems. Given that in this study, LPG before being used as a fuel used as a refrigerant, it is necessary to analyse and evaluate the thermodynamic equations which make it possible to create equations as a hybrid system.

METHOD

System Description

In a previous authors work [47], a model of a cooling system in an LPG fuelled vehicle was successfully tested as a secondary system as shown in Figure 2. First, Pressurized LPG is in a tank equipped with a deep tube (a) to guarantee LPG out of the tank in a liquid state. An expansion valve (b) is installed on the fuel line as a pressure reducer. An auxiliary evaporator (c) is installed after the expansion valve as a heat exchanger. As long as LPG flows in the evaporator, LPG evaporates by taking the heat from the air across the evaporator due to the drive from the electric blower (h). In this case, LPG functions like a refrigerant. As a result, the air temperature at the exit of the evaporator is lower than when it enters the evaporator that means produce a cooling power inside the cabin (g). Furthermore, LPG is received by the regulator (d) and forwarded to the mixer (e). Regulator functions to adjust the LPG flow rate based on the engine need. Finally, LPG goes into the engine (f) as fuel.

Looking for Fig. 2, there are two thermodynamic stages, the cooling stage ($1 \rightarrow 3$) and combustion stage ($4 \rightarrow 5$). The cooling stage consists of expansion process ($1 \rightarrow 2$) and evaporation process (2→3), while the combustion stage occurs by Otto cycle to generate indicated power (P_i). In this study, the performance of an LPG-fuelled engine was obtained from a study conducted by Masi and Gobbato [10] and the cooling effect performance was obtained from the previous author study [47]. FIAT 838 A1.000 engine with 1-6 g/s LPG mass flow rate was simulated. The LPG used in this study is a product of Pertamina (State Owned Enterprises of Indonesia) obtained from gas stations.

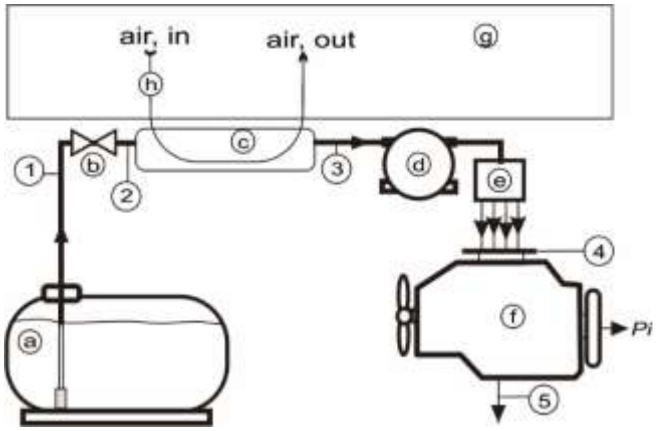


Figure 2. Concept of cooling recovery and energy delivery on LPG fuelled vehicle [53]

Then, an ideal thermodynamic diagram for the expansion valve and auxiliary evaporator work is shown in Figure 3. Specific state point (1) is liquid LPG pressurized 0.6 – 1.2 MPa at ambient temperature. LPG will be expanded to specific state point (2) at 0.15 MPa by isenthalpic expansion (h_1 = h_2). Furthermore, LPG will evaporate from point (2) to point (3) by taking heat from the air that crosses the evaporator. Meanwhile, the thermodynamic chart for Otto cycle is presented in Figure 4.

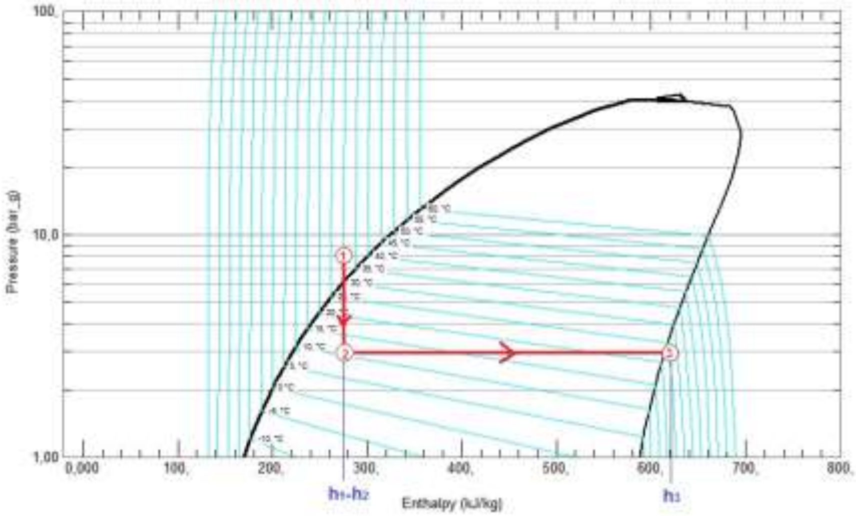
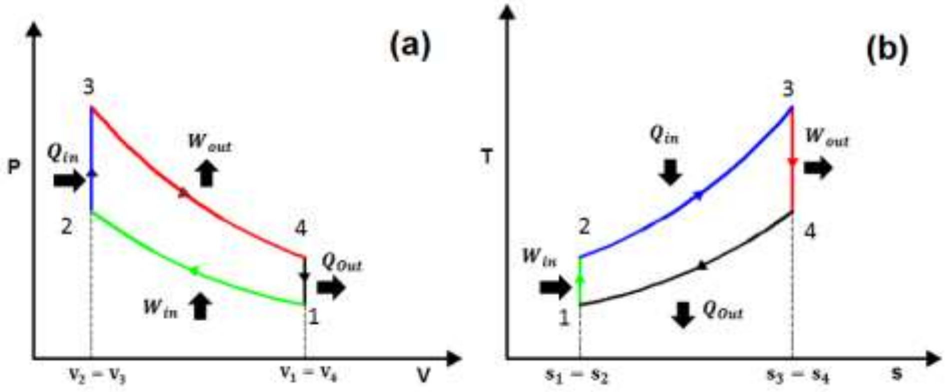


Figure 3. *P-h* diagram of the ideal expansion-evaporation process on LPG vehicle



(1-2= isentropic compression; 2-3= constant volume heat addition; 3-4= isentropic expansion; and 4-1= constant volume heat rejection)

Figure 4. *P*-*V* diagram (a) and *T*-*S* diagram for Otto cycle (b)

Energy Analisys

After the LPG properties at each specific state point shown in Figure 2, an energy analysis can be performed. By kinetic and potential energy are negligible, the mass and energy balance in LPG can be expressed by Eq. (4) and Eq. (5), respectively.

$$\sum \dot{m}_1 - \sum \dot{m}_4 = 0 \tag{4}$$

$$\sum \dot{q}_{f1} - \sum \dot{q}_{f4} = 0 \tag{5}$$

Now, with a hybrid system created, where LPG before being sent to the engine as fuel is used first as the refrigerant, there are two energy harvesting processes, engine brake power (P_i) by combustion systems and cooling power ($\dot{q}_{ev}$) by harvesting cooling effect from LPG evaporation in the fuel line. Thus, the total energy efficiency (η_{total}) available in the fuel can be given in Eq. (6) as follows.

$$\eta_{total} = \frac{\dot{q}_{ev} + P_i}{\dot{q}_f} \tag{6}$$

RESULTS AND DISCUSSION

Two curves of fuel consumption and engine brake power against the engine speed on a FIAT 838 A1.000 engine (11998 cm^3) fuelled by LPG have been reported by Masi and Gobbato [10]. Then, through further analysis of the two curves, there is a relationship between the output powers against the fuel consumption as shown in Figure 5, where the horizontal axis (*x*) represents LPG mass flow rate and the vertical axis (*y*) represents the engine brake power. The curve obtained is not linear because it is influenced by volumetric efficiency which varies with engine speed. With $x = \dot{m}$ and $y = P_i$, the polynomial equation is generated as $y = -0{,}34x^3 + 2{,}93x^2 + 9{,}84x$

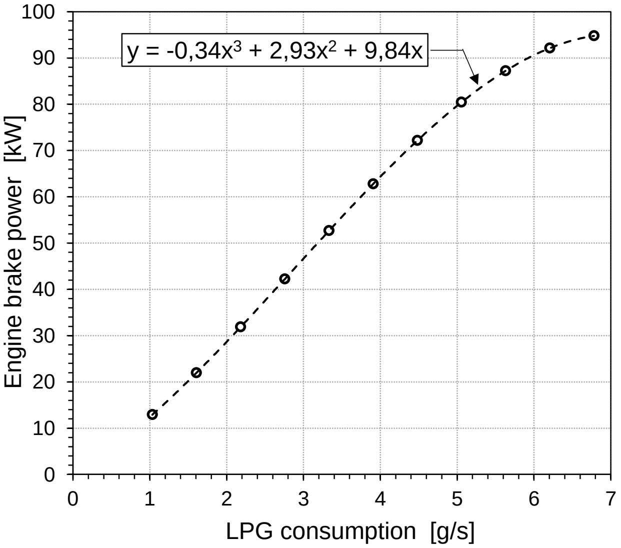


Figure 5. Engine brake power to fuel consumption on 1998 cm^3 LPG fuelled engine

Based on Figure 5, with the Lower Heating Value (LHV) of LPG is 46 MJ/kg [54], energy delivery to the combustion chamber can be calculated. Energy supplied to the combustion chamber ($\dot{q}_f$) is a multiplication of the mass flow rate with caloric value (LHV) which results in a linear curve in the form of a dashed line shown in Figure 6. Then, based on Eq. (2), the Indicated Thermal Efficiency can also be calculated as shown in Figure 6. The horizotal axis (x) represents LPG mass flow rate, the vertical left and right axis (y) represent energy supply and indicated thermal efficiency, respectively.

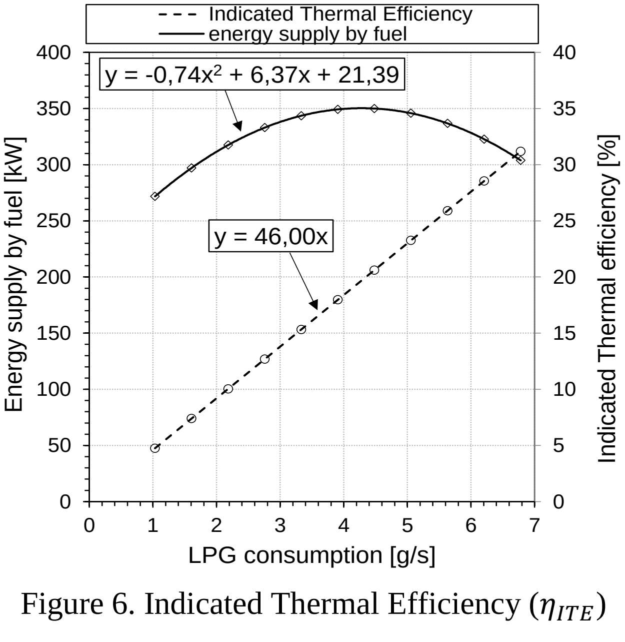


Figure 6. Indicated Thermal Efficiency (η_{ITE})

Furthermore, the cooling power of the LPG evaporation process on the fuel line at 0.15 MPa evaporation pressure is presented in Figure 7. The solid line shows the calculated cooling power without superheated, while the dotted line shows the measured cooling power. At LPG flow rate below 3 g/s, LPG exits the evaporator under superheated conditions, so that the heat exchange process occurs latently and sensibly. Meanwhile, in LPG flow rate above 3 g/s, evaporation of LPG inside the evaporator is not perfect because of limitation of heat transfer area, so cooling power is not linear with LPG flow rate.

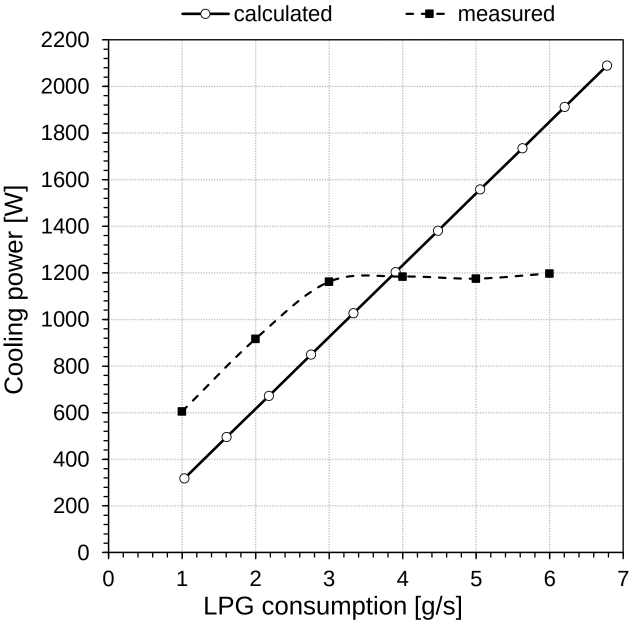


Figure 7. Calculated and measured cooling power in the fuel line at 0.15 MPa.

An evaluation of the energy efficiency with and without cooling power harvesting is presented in Figure 8. The solid line shows energy efficiency without harvesting the cooling power in the fuel line, while the dashed line with the square box symbol shows the energy efficiency by harvesting cooling power. Smart method for harvesting the cooling power in the LPG fuel system can increase the average energy efficiency by 3.17%. As a comparison, in the previous authors' study, cooling power from the LPG fuel line was able to contribute to the vehicle A/C systems between 20-40%, depending on cooling load and driving conditions [47].

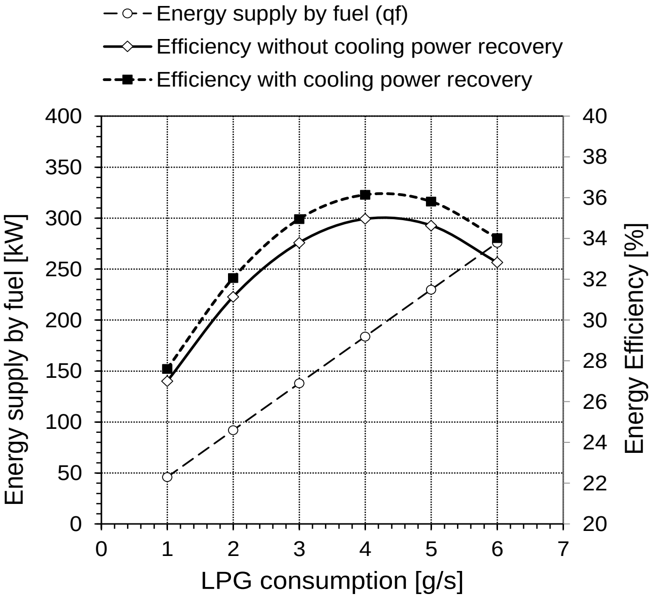


Figure 8. Calculated energy efficiency with and without cooling power recovery

Harvesting cooling power from LPG fuel system is prospective to be applied through the year in the tropical countries and during summer in countries with four seasons. Cooling power from LPG-fuelled vehicles can be developed independently or combined with an existing vapor compression A/C system as a secondary system. Combination models can be done in two ways: parallel and cascade, depending on the purpose of the application. The parallel model allows for greater cooling power without disrupting the existing A/C system when the secondary system is disabled. The cascade model makes it possible to obtain a lower evaporation temperature. However, if coupled with the cascade system, overall system performance will be disrupted when the secondary system is disabled. Given that in the cascade system, the cooling effect on the secondary system is used for lowering the condensation temperature.

CONCLUSION

The thermodynamic and prospective evaluation of a secondary AC system harvested in a fuel line of LPG fuel vehicles has been conducted. The energy stored in fuel originally only as fuel, has been developed as a secondary refrigerant to increase the useful energy. Cooling power from LPG evaporation process can increase the average total efficiency by 3.16%. The system has the prospect of being developed as a secondary system and combined with existing A/C systems through parallel and cascade methods. In conclusion, this system is promising to develop, present and in the future to increase total efficiency.

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NOMENCLATURE

$\dot{m}$	LPG mass flow rate	[g/s]
h	Specific enthalpy	[kJ kg^{-1}]
$\dot{q}_{ev}$	Cooling power	[kW]
$\dot{q}_f$	Energy supplied by fuel (mass flow rate × calorific value)	[kW]
P_i	Engine brake power	[kW]
r	Compression ratio	
k	Adiabatic index of air (C_p/C_V)	

ABBREVIATION

A/C	Air Conditioning
LPG	Liquefied Petroleum Gas
ASE	Air Standard Efficiency
ITE	Indicated Thermal Efficiency
COP	Coefficient of Performance
LHV	Lower Heating Value

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