Potential of ½ cycle refrigeration system for food transport application

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Abstract. Maintaining the quality of food products from an agricultural land and farms to the final consumer is usually conducted through the car-cooling box. However, as long as the refrigeration equipment takes energy from the car engine, it will significantly increase fuel consumption. Therefore, this paper presents the concept of 1/2 cycle refrigeration system on LPG-fueled vehicles to reduce fuel consumption due to the load of the refrigeration system. From the numerical study, the ½ cycle refrigeration system on LPG-fueled vehicles is potential to be applied on the car-cooling box as the secondary refrigeration system. This system provides a considerable potential cooling effect of 0.8 kW at LPG flow rate of 2.4 g/s.

1. Introduction

Food processing and distribution industries take full responsibility for maintaining the quality of agricultural products and farms from producers to consumers, or even to the dining table. The need for fresh vegetables and fruits is a great market demand [1]. In fact, it is impossible to provide agricultural land and settlements in one area. The need for large amounts of fresh food takes place in urban centers, industrial centers, and residential centers. Meanwhile, agricultural land to produce vegetables, fruits, or even farms is commonly far from the city. In some archipelago countries such as Indonesia, the availability of land supporting agricultural and farms activities is outside the needy island [2]. In fact, for a long time, fresh food has been transported from one country to several other countries, from one continent to another [3]. This is not only sufficient availability of land but more on geographical factors, where specific vegetable and fruits commodities can only be produced optimally on a certain high plateau or rainfall [4].

Currently, food preservation technology through refrigeration to withstand a few days or through freezing for several months becomes the need to support the distribution system. In order to maintain the quality of the product, a modern thermo-box not only regulates temperature, but has come to the arrangement of the relative humidity, the air velocity, and perhaps [1]. This is because the supply chain of foodstuffs from farmland, plantations, or farms can form short chains or very long chains according to the type and pattern of distribution. Figure 1 presents the complexities of cold chain development to maintain the quality of long-chain foodstuffs [5].
Figure 1. Cold chain development to maintain the quality of the farming product.

The standard transport of foodstuffs and agricultural products was governed by an agreement which was subsequently withdrawn by The Inland Transport Committee of the United Nations Economic Committee for Europe in 1970-1971 [6] which was amended several times and the last of 2016 [7]. This agreement is to facilitate international traffic related to food security by establishing recognized standards. The agreement was known as an ATP deal and was adopted in Britain in 1980 which was then used by many countries. This standard provides general information for controlled vehicles with controlled temperatures, such as road vehicles, trains, and marine containers [8]. Several types of transport equipment of agricultural and farms products are presented in figure 2 [5].

Figure 2. Transport refrigeration provides temperature control solutions during distribution of agricultural product.

On the one hand, a cooling capacity is required to transport foodstuffs to ensure their quality is maintained. However, as long as the refrigeration system is driven by a car engine with vapor compression system, it will take significant fuel and produce more exhaust emissions [9–11]. Waste of fuel is not only an effect on the increase in operational costs that cause the price of products to be more expensive but also gives an adverse effect on increasing global warming. This is also a concern for environmental practitioners, engineers, and stakeholders. In addition to the vapor compression system, the air cycle system has been piloted in food transport systems but has low performance [8].
2. Opportunity from LPG fueled vehicle
In previous studies, we have successfully harvested the cooling effect of the LPG evaporation process during LPG flowing in the fuel line from the tank to the engine through an additional evaporator. A numerical simulation has been done to calculate the potential cooling effect that can be obtained and the result is quite large reaching 1.5 kW at 3000 rpm for 2000 cc engine [12]. Then, the results of this simulation are re-verified more closely and the result is about 1.2 kW [13]. Finally, the results of the simulation were validated by lab-test and proven to produce of 1.2 kW cooling effect at LPG flow rate of 3 g/s representing the average consumption of 2000 cc eco-driving car [14]. The ½ cycle refrigeration concept of an LPG-fueled vehicle allows for a hybrid system with an air-conditioning system installed on the car as shown in figure 3.

Figure 3. Concept of Hybrid A/C system on LPG fueled vehicle.

3. Simulation on 1500 cc SI Engine
In this study, a 1500 cc LPG fueled vehicle was simulated for the transportation of agricultural products and food products with cooling boxes as shown in figure 4. In this case, there are two refrigeration systems, the fully cycle system driven by engine and 1/2 cycle system from LPG evaporation.

Figure 4. Hybrid cooling box vehicle for transporting fresh food products.
4. Result and discussion

This section discusses the simulation result on potential cooling effect and contribution to the refrigeration load in the following subsections.

4.1. Potential cooling effect

In this study, the potential cooling effect calculated by the following assumptions: (a) The LPG used is a mixture of 50% propane and 50% butane; (b) The expansion process takes on iso-enthalpy; (c) LPG before expansion valves is 30 °C, 8 bar_g and exits the evaporator at 24 °C, 2 bar_g; (d) LPG mass flow rate is estimated at 2.4 g/s, calculated on stoichiometric mixtures for 1500 cc engine and 3000 rpm with volumetric efficiency is estimated from previous studies [12]; and (e) LPG properties are obtained from REFPROP-NIST. The P-h diagram of 1/2 of the refrigeration cycle based on the assumption of assumption is shown in figure 5.

![P-h diagram](image)

**Figure 5.** P-h diagram of ½ cycle refrigeration on LPG fueled vehicle.

From figure 5, specifics state point (1) represents LPG in a fuel pipe before the expansion valve as a pressurized liquid. Then, specifics state point (1) to (2) is the expansion process at the inlet evaporator. Assuming the expansion process is iso-enthalpy, then $h_2 = h_1$. The LPG evaporates in the evaporator at a constant pressure. Because the LPG used is a mixture of propane and butane, the temperature of LPG increases during the evaporation process at a constant pressure known as gliding temperature. LPG exit evaporator (specifics state point 3) in the form of saturated vapor. The enthalpy value for each state point ($h_1$, $h_3$) is obtained from REFPROP-NIST as shown in table 1.

**Table 1.** Enthalpy data at each specifics state point ($h_1$, $h_3$).

| Temperature (°C) | Pressure (bar_g) | Density (kg/m³) | Enthalpy (kJ/kg) | Entropy (kJ/kg·K) |
|-----------------|------------------|-----------------|-----------------|-------------------|
| 1               | 30.000           | 8.000           | 208.33          | 274.85            |
|                 | 24.000           | 2.000           | 0.5597          | 620.65            |
|                 | 3                |                 |                 | 2.5029            |
Using the first law of thermodynamics, the heat released by air (cooling effect) is the same as the heat used to evaporate the LPG. Therefore, the potential cooling effect that can be harvested is defined in equation (1) and equation (2) [13, 15].

\[
q_{\text{into LPG}} = q_{\text{loss by air}} \tag{1}
\]

\[
q_{\text{ev}} = m_{\text{LPG}} (h_3 - h_1) \tag{2}
\]

Where, \(q_{\text{ev}}\) is the potential cooling effect (kW), \(m_{\text{LPG}}\) is flow rate of LPG (kg/s), and \(h_3, h_1\) are the specifics enthalpy of LPG in the outlet and inlet evaporator, respectively. Using the enthalpy data from table 1 and the LPG flow rate of 3 g/s, the potential cooling effect that can be harvested can be calculated as \(q_{\text{ev}} = \frac{0.024kg}{s} (620.65 - 274.85)(\frac{kJ}{kg}) [kW] = 0.83 [kW]\).

4.2. Contribution to the refrigeration load
We found that refrigeration load for a small-size cooler box car is using Hwa Sung Thermo HT-100 II with refrigeration cooling capacity of 3,224 kW [16]. This means that the potential cooling effect harvested from the LPG fuel system provides approximately 25.7 % of the refrigeration capacity requirement for medium-size cooler boxes. However, this potential varies according to the mass flow rate of LPG and the quality of the vapor formed in the evaporator. With one condition, LPG entering the expansion valve must be liquid.

5. Conclusion
From the numerical study, the ½ cycle refrigeration system on LPG-fueled vehicles is opportunities to be applied on the food transportation box as the secondary refrigeration system. This system provides a considerable potential cooling effect of more than 0.8 kW at LPG flow rate of 2.4 g/s. However, this number is an estimated number at a stationary condition of 3000 rpm. In fact, it is impossible to drive a vehicle at a constant high speed so that the potential cooling effect that can be harvested depends on driving mode, in this case, the LPG flow rate from the tank to the engine. This work will be continued by creating a prototype that resembles the original to test the reliability of the system.

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