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Quantitative Analysis of Coefficient of Performance of Liquefied Petroleum Gas Refrigeration System

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Abstract

This study addresses the significant environmental and energy efficiency challenges posed by traditional refrigeration systems. These systems emit greenhouse gases and rely heavily on electricity, making them unsuitable for regions with unreliable power supplies. To mitigate these issues and explore alternative applications for the high-priced LPG typically used in cooking, this research proposes using Liquefied Petroleum Gas (LPG) as a substitute for refrigeration. Focusing on the mathematical modeling and empirical testing of the Coefficient of Performance (COP) of an LPG refrigeration system, this study incorporates a comprehensive methodological approach, including theoretical models and a series of experiments that assess variables such as pressure drop, mass flow rate, and temperature change. These methodologies enabled the quantification of the system efficiency through a range of COP values observed from 0.02 to 1.78, demonstrating a progressive improvement in performance. The empirical data revealed the system's ability to achieve cooling effects down to -3.5°C, highlighting its potential for small-scale refrigeration in remote areas. A 22.12% average percent difference indicates that the current mathematical model for estimating COP shows some precision but leaves room for improvement. This discrepancy is significant because it suggests that the model does not fully account for all factors such as environmental variables. To enhance the model's accuracy, further research should focus on incorporating additional variables and refining the methodology.

Keywords*:* COP**,** energy**,** mathematical modeling, refrigeration, Sustainable Development Goals

1. Introduction

Refrigeration is broadly defined as the process of removing heat to cool a substance and maintain a body's temperature below that of its surroundings, while also reducing and eliminating waste (Jadyar *et al*., 2021). Refrigeration remains one of the most essential thermal devices for both household and industrial use worldwide, playing a significant role in global energy consumption, with its heat performance heavily influenced by the refrigerant used (Ahmad *et al*., 2020). According to Emani *et al.* (2017), refrigerants in refrigerators act as the operative medium, absorbing heat from the target area to generate a cooling effect. LPG refrigeration refers to a system that uses Liquefied Petroleum Gas (LPG) as the refrigerant instead of the conventional chlorofluorocarbons (CFCs) and hydrofluorocarbons (HFCs). Abbood *et al*. (2020) said that traditional home refrigeration systems often rely on CFC and HFC refrigerants, which significantly contributes to ozone layer depletion and global warming. The mechanism by which CFCs and HFCs damage the ozone involves the release of chlorine radicals, leading to the breakdown of ozone molecules, as explained by Raiyan and Rehman (2017). National Aeronautics and Space Administration (2015) highlighted the severe environmental threats posed by these substances, particularly their adverse effects on Earth's biodiversity. Fernando (2022) described hydrocarbons as organic compounds composed solely of hydrogen and carbon, which serve as key components of major energy sources such as crude oil and natural gas, known for their high combustibility and energy efficiency. Hydrocarbons, such as LPG, are recognized for their environmental compatibility, effective blending with mineral oils, and compatibility with standard refrigeration materials (Liu *et al*.,1995). The study on LPG refrigeration systems aligns with the United Nations' Sustainable Development Goals (SDGs), particularly SDG 7, which advocates for affordable and clean energy. By exploring the use of hydrocarbons, such as LPG, this study promotes energy efficiency, contributing to the reduction of greenhouse gas emissions and supporting SDG 13 on climate action. The development of environmentally friendly refrigeration technologies also fosters innovation in clean energy solutions, aligning with SDG 9, which focuses on industry, innovation, and infrastructure. Additionally, the use of sustainable refrigerants can improve access to modern cooling solutions, contributing to SDG 12 on responsible consumption and production by reducing the environmental impact of refrigeration systems (United Nations, 2015). The Air Conditioning and Refrigeration Industry Board (ACRIB) (2001) noted that LPG refrigerants are compatible with most lubricants and materials used in refrigeration systems, such as seals and gaskets, without requiring changes to evaporator and condenser sizes or pressures compared to fluorocarbon refrigerants. Iyer *et al*. (2006) observed no operational issues or lubrication degradation over 5,000 hours of using hydrocarbon mixtures as refrigerants. LPG, which consists mainly of propane and butane along with minor hydrocarbon components, is discussed by Rehman *et al.* (2023) as having a versatile composition. Its makeup can range from pure propane to various propane-butane ratios, with a notable mixture used in the Philippines being 40% propane and 60% butane, as noted by Rayos (2017). Satwik *et al*. (2016) describe LPG as colorless, non-toxic, denser than air, and initially odorless, with an odorant added for leak detection. Properties of some refrigerants can be seen in Table 1.

Table 1. Properties of some refrigerants (El-Morsi, 2015)

Refrigerant	R134a	R290	R600a
Chemical Formula	CH_2FCF_3	C_3H_8	C_4H_{10}
Liquid Density @ 20 °C (kg/m^3)	1225.3	500.1	556.9
Molecular Weight (kg/k.mole)	102.0	44.0	58.1
Explosive limits in air (% by volume)	Non-flammable	2.3-7.3	1.8-8.4
Ozone Depleting Potential	0	0	0
Global Warming Potential	1430	<20	<20
Boiling Point (°C)	-26	-42	-12
Latent Heat of Vaporization (kJ/kg)	216.87	423.33	364.25
Critical Temperature (°C)	101.1	96.7	134.7
Critical Pressure (MPa)	4.06	4.25	3.64

Table 1 presents a comparison of the properties of the refrigerants R134a (an HFC) and the hydrocarbons R290 (propane) and R600a (isobutane). R134a is non-flammable but has a high global warming potential (GWP) of 1430, indicating a higher impact on global warming. In contrast, R290 and R600a have much lower GWPs (<20), making them more environmentally friendly options; however, they are flammable, posing safety challenges. Hydrocarbon refrigerants are also characterized by lower density. According to Siddegowda *et al*. (2019), hydrocarbon refrigerants are identified as more energy-efficient alternatives to traditional hydrofluorocarbons like R134a, with energy savings ranging from 4.4 to 18.7% when switching to hydrocarbons. These improvements arise from hydrocarbons' lower density, which decreases the refrigerant charge requirement, resulting in lower emissions during operation and at the end of the refrigerant's life. The lower boiling points of hydrocarbons, such as R290 and R600a, enhance energy efficiency in refrigeration systems, allowing effective operation at lower temperatures. This was exemplified by Nasution *et al.* (2019), who showed that replacing another refrigerant with R290 in a room air conditioning system resulted in a notable 38% increase in the system's coefficient of performance (COP). Moreover, using a ternary mixture of R290/R600/R600a in a household refrigerator increase the COP by 14% compared to HFC-134a, highlighting the energy-saving potential of hydrocarbons in cooling applications. In a comparative study, Manohar *et al*. (2020) noted that LPG refrigeration systems offer lower cost and operational efficiency without requiring external energy sources, as these systems lack moving parts, which minimizes maintenance costs compared to conventional systems. Srinivas *et al*. (2014) also found that LPG provides more effective cooling than R134a, suggesting its potential as a suitable choice for cooling systems. Furthermore, Oyelami and Bolaji (2015) demonstrated improved performance of an experimental refrigerator using LPG compared to R134a. Despite its advantages, such as a higher COP and reduced environmental impact as noted by Manohar *et al*. (2020), LPG's flammability remains a concern. The Australian Institute of Refrigeration, Air Conditioning and Heating (AIRAH) (2013) and the ACRIB (2021) state that appliances with a factory-sealed design may use up to 150 grams of a flammable refrigerant in each cooling circuit without installation restrictions. Additionally, Quraishi and Wankhede (2013) found that refrigerators designed for R-134a had refrigerant charges between 105 to 150 grams, whereas those designed for hydrocarbon refrigerants could reduce this amount to approximately 70-90 grams, aligning with the standards set forth by ACRIB (2021).

Given the thorough investigations into the practical applications and benefits of LPG refrigeration systems, there appears to be a specific gap in the detailed mathematical analysis of the COP for these systems. The study by Nithiyanand *et al*. (2020) suggests the comprehensive evaluation of LPG's efficiency, while research by Shahare *et al*. (2021) identifies a need for further exploration into the efficiency of LPG refrigeration systems. This gap indicates the necessity for a more rigorous mathematical framework that can accurately describe the thermodynamic processes governing LPG refrigeration systems and predict their performance metrics, such as COP, with high precision. Such a framework would not only validate experimental findings but also enable the optimization of system design and operation to achieve higher efficiency and environmental sustainability. To bridge the existing knowledge gap, this study aimed to implement an LPG refrigeration system by designing the system, assembling its components, developing a mathematical model to compute the COP, and evaluating its performance.

2. Methodology

2.1 Working Principle

Heisler (2002) describes the refrigeration process in which the refrigerant enters the evaporator as a liquid and exits as a vapor after absorbing heat from the refrigerated space. This transformation enables the system to remove heat from the cold compartment. In an innovative approach, LPG is utilized as an alternative refrigerant to freon. According to Elgas (2019), within an LPG cylinder, the substance coexists as both liquid and vapor: the top part holds pressurized vapor, while the bottom part contains liquid LPG. Typically, these cylinders are filled to 80% of their capacity, maintaining a balance of 80% liquid and 20% vapor, as outlined by ES Systems (2021). For refrigeration to occur, the LPG must be in liquid form and at a reduced pressure. In this study, the LPG tank was inverted to extract the liquid LPG into the evaporator. Normal LPG cylinder pressure ranges from 70 to 50 psi, but it needs to be reduced to 15 psi to achieve refrigeration, as noted by Sathayan *et al*. (2018). To facilitate this pressure reduction, a throttling device was installed at the evaporator's inlet, which was connected to the inlet hose. Adhav *et al*. (2017) emphasize that the cooling effect is produced by circulating LPG through the evaporator coil, which is located within the evaporator compartment in this study. After passing through the evaporator coil and transforming into vapor, the LPG is directed to a burner via a hose. Continuous operation of the burner stove is essential for maintaining the flow of LPG from the cylinder, thereby ensuring the refrigeration effect within the setup. The evaporator compartment utilized in this setup was filled with water to maintain the cooling temperature of the refrigerator, particularly during periods when the burner is not in use, compensating for the absence of LPG input. The setup, complete with labeled instruments and materials, is illustrated in Figure 1.

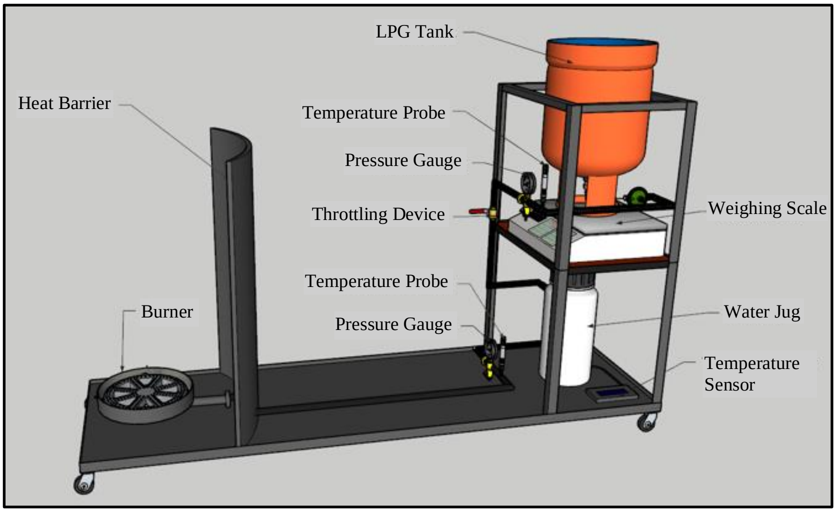

Figure 1. LPG Refrigeration Set-Up with labeled parts

2.2 Selection of Materials

This study adopted methodologies from Shah and Gupta (2014), utilizing components such as an LPG tank, an expansion valve, an evaporator, and a burner, as the system has already been proven and tested. A 2-liter insulated plastic water jug was selected as the evaporator compartment due to its excellent insulation properties, attributed to the polyurethane material, as noted by Demharter (1998). Its local availability also made it a practical and cost-effective choice for the system, enhancing its suitability for the design. To accommodate the inlet and outlet of the evaporator coil, holes were drilled into the jug 2 and 8 inches from its top. The evaporator coil, made from copper tubing, was shaped into a coil within the jug's cylindrical wall as shown in Figure 2a to minimize friction loss and simplify the coiling process. Copper tubing was selected for its excellent heat transfer capabilities, corrosion resistance, and affordability (Abbood *et al.*, 2020). The coil consisted of 18 loops of 3/16" tubing with a diameter of 3.5-inch and a height of 9 inches, optimizing the flow of LPG through the system. A ball valve was utilized as a throttling device at the evaporator's inlet to effectively manage the system's pressure drop. This valve was selected for its adjustability and widespread availability. For the exhaust of LPG, an iron-cast stove, measuring 22 inches by 16 inches by 9.5 inches, was employed. The system also incorporated commercial-grade gas and liquid hoses with a 3/8" diameter, chosen for their cost-effectiveness and compatibility with readily available fittings. Mobility and ease of handling were ensured by using an 11-kg LPG tank from Prycegas, a local supplier. The researchers also developed an innovative setup that allowed the system to be easily relocated, employing welding and cutting of angle bars in the construction of this set-up. Figure 3 shows the actual set-up of the LPG refrigeration system.

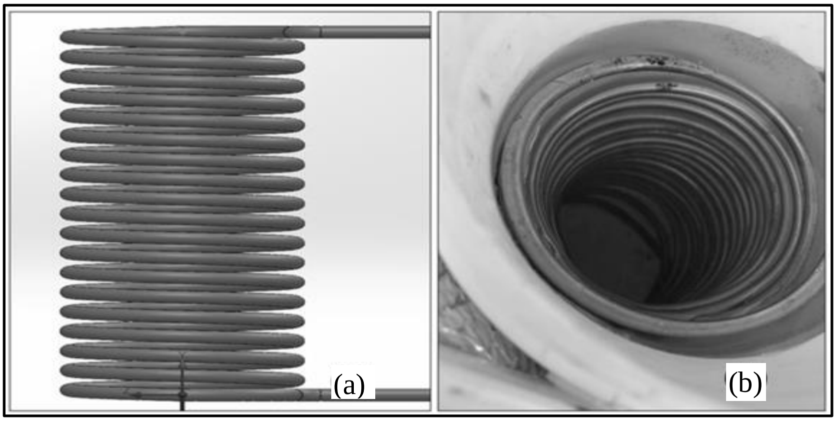

Figure 2. 3D drawing of a cylindrically coiled Copper Tube (a); Actual Copper Tube coiled inside the Evaporator Chamber (b)

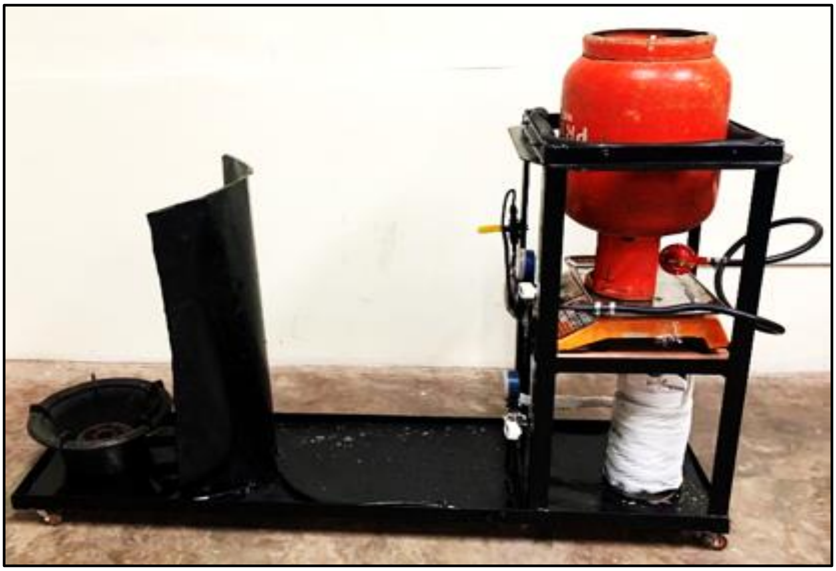

Figure 3. Actual Setup of LPG refrigeration System

2.3 Data Collection Instruments

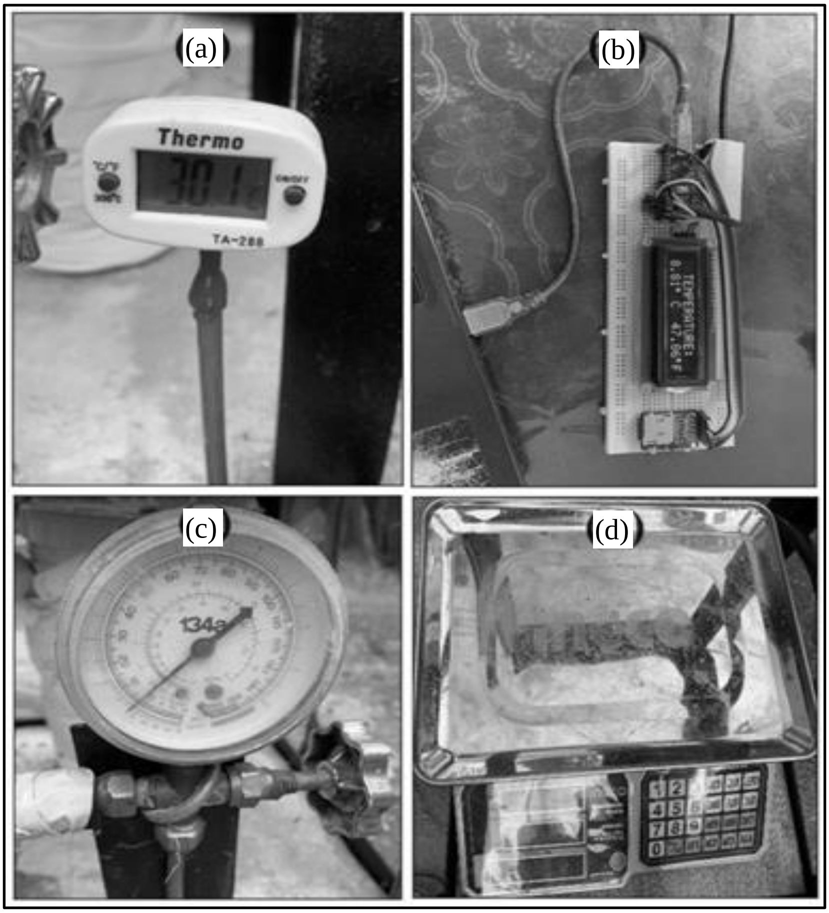

Figure 4. Data Gathering Instruments: Temperature Probe used in measuring the inlet and outlet temperature of the evaporator (a); Arduino Set used in measuring the Evaporator temperature (b); Pressure Gauge used in measuring the outlet and inlet pressure (c); Weighing Scale used for measuring the LPG mass (d)

In this experiment, the mass flow rate of the system was determined by weighing the LPG tank both when empty and when filled, using a scale as shown in Figure 4d. This step was crucial for monitoring LPG consumption during the experiment. To conduct the pressure tests, the system was adjusted to maintain a pressure of approximately 15 psi, which was measured using Bourdon-type pressure gauge, as illustrated in Figure 4c. The experiment involved two temperature probes attached to the inlet and outlet of the evaporator, as shown in Figure 4a to monitor the temperature of the water being heated or cooled within the mechanical system. Furthermore, an extra temperature probe was placed within the evaporator chamber to accurately gauge the water temperature. This probe was interfaced with an Arduino, programmed in its specific coding language, as indicated in Figure 4b. The temperature within the refrigeration chamber was systematically recorded at 10-minute intervals over a total runtime of 180 minutes, providing detailed insights into the cooling performance of the system throughout the experiment.

2.4 Operating Procedure

The procedure for evaluating the LPG refrigeration system is designed to ensure the accurate assessment of the system's functionality, safety, and performance efficiency. This methodology unfolds through a series of carefully structured steps, beginning with a thorough examination of all system components. This preliminary step is crucial, especially given the flammable nature of LPG, and involves comprehensive safety and functionality checks to confirm the system is leak-free and all components are operational. Personnel are required to wear appropriate protective gear to safeguard against potential hazards. Leak testing is meticulously performed at all connection points using the soap solution method, ensuring the safety and integrity of the system. Following the initial safety checks, the procedure advances to the setup of system components. This phase involves filling the evaporator container with approximately 2 liters of water and positioning the temperature sensor inside the evaporator. The water is then allowed to stabilize at room temperature, setting the stage for accurate data collection. Data acquisition devices are activated, and the LPG cylinder is carefully placed on a digital scale to facilitate precise mass measurement. The cylinder is then inverted to enable the controlled flow of liquid LPG into the system, with valve adjustments made to maintain a consistent exit pressure of 15 psi. The next critical step involves the determination of raw data using specialized measurement tools, including a pressure gauge for monitoring LPG pressure at both the inlet and outlet points, a temperature sensor for recording water temperature, and a scale for measuring the mass flow rate of LPG. The mass flow rate is calculated by tracking the decrease in LPG mass over a specified time period. Data gathering extends over a three-hour period, with interval measurements of intake and outlet pressures, water temperature, and the mass of the LPG cylinder recorded every ten minutes. Additional measurements of water temperature are taken at five-minute intervals during subsequent one-hour sessions to ensure comprehensive data collection. The subsequent phase involves calculating the enthalpies and heat loss of LPG based on the raw data gathered. Enthalpy calculations leverage the measured pressures and the known composition of Philippine LPG, which consists of 60% butane and 40% propane. By referring to LPG property tables and applying the respective percentages, accurate enthalpy values are derived. Finally, the work of the system is calculated by incorporating the determined enthalpies and mass flow rate to ascertain the system's work output in kilowatts. Heat loss calculations utilize a formula that includes the specific heat capacity of water, the mass of water, and the observed temperature change, allowing for the computation of heat loss within the system. The system's Coefficient of Performance (COP) is then calculated by dividing the heat loss by the system's work output, providing a quantitative measure of the system's efficiency. This detailed experimental procedure is essential for the reliable evaluation of the LPG refrigeration system's performance. By adhering to a methodical approach that emphasizes safety, precision, and thorough data collection, researchers ensure that the findings are credible and valuable for furthering the understanding and application of LPG refrigeration technology.

2.5 Mathematical Modeling of Refrigeration Performance

During the experimentation, the researchers collected raw data relevant to the operation of the LPG refrigeration system, focusing on variables such as Pressure Drop, Mass Flow Rate, and Temperature Change, using the designated data-gathering instruments. Following the initial data collection phase, the researchers evaluated the system's efficiency by analyzing the gathered information. The performance analysis entailed calculating various thermodynamic properties and operational metrics, including Enthalpies, Water Heat Loss, Work, and the system's Coefficient of Performance (COP). Considering that LPG cylinders typically contain a mix of 80% liquid and 20% vapor (ES Systems, 2021) and leveraging the known properties of propane and butane, the researchers were able to determine the enthalpies based on the LPG's composition ratio of 60% butane and 40% propane. Work calculations were carried out using the unsteady state formula, which involves determining the internal energies and enthalpies relative to temperature changes between the start and end of the experiment. The heat loss of water was calculated using the specific heat capacity of water, the mass of the water, and the observed temperature differential, embodying the conservation of energy principle in an unsteady-state system. The COP was then calculated by dividing the quantified heat loss of water (Q) by the work (W) conducted by the system. Understanding the distinction between steady and unsteady flow process is crucial for comprehending the system's dynamics. In steady flow, mass and energy within the system remain constant over time, while in unsteady flow processes, these quantities can vary, reflecting the continual movement of fluid into and out of the control volume (Avinash, 2018). Equation 1 by Cengel and Boles (2006) outlines the basic relationship that explains the conservation of energy in unsteady systems. This equation was used in this study to calculate the performance of this LPG refrigeration system.

$$m_2(u_2+KE_2+PE_2)-m_1(u_1+KE_1+PE_1)$$
$$= m_{in}\sum(h_{in}+KE_{in}+PE_{in})-m_{out}\sum(h_{out}+KE_{out}+PE_{out})+Q-W \quad (1)$$

Hence, kinetic energy and potential energy components are outlined in Equation 2.

$$m_2\left(u_2+\frac{1}{2}V_2{}^2+gZ_2\right)-m_1\left(u_1+\frac{1}{2}V_1{}^2+gZ_1\right)$$
$$= m_{in}\sum(h_{in}+\tfrac{1}{2}V_{in}^2+gZ_{in})m_{out}\sum(h_{out}+\tfrac{1}{2}V_{out}^2+gZ_{out})+Q-W \quad (2)$$

The LPG refrigeration system as depicted in Figure 5 is uniquely characterized by having a single exit pathway with a complete absence of any mass inflow mechanism.

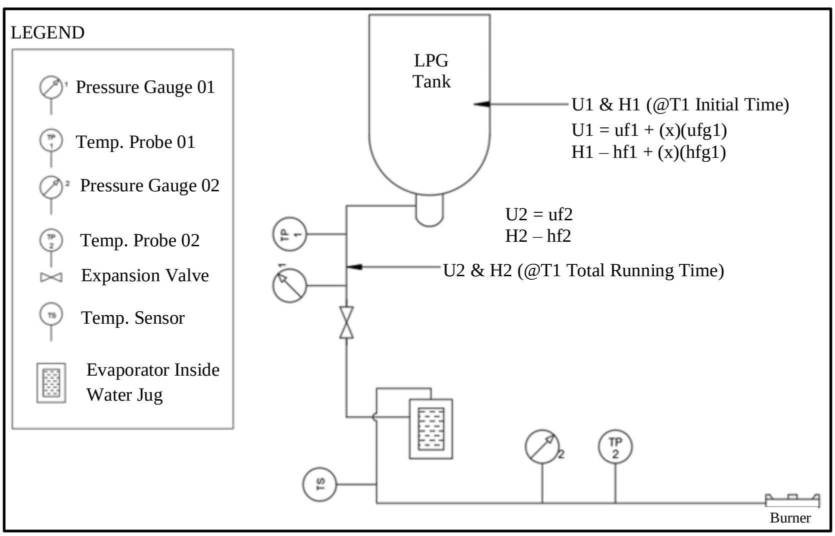

Figure 5. Schematic Diagram of LPG Refrigeration System

To minimize thermal losses, insulation was applied around the system, ensuring that heat transfer to the environment via conduction, convection, or radiation was negligible. Furthermore, changes in kinetic and potential energy within the evaporator were considered insignificant. By excluding heat transfer (Q), as well as kinetic and potential energy terms from Equation 2, Equation 3 is derived.

$$m_2u_2\text{-}m_1u_1\text{=-}m_{out}h_{out}\text{-}W \tag{3}$$

Rearranging the equation gives the formula for work shown in Equation 4.

$$W = m_1u_1 - m_2u_2 - m_{out}h_{out} \tag{4}$$

In this equation, the system's inlet temperature is considered equivalent to the LPG's temperature within the tank. Here, u_1 represents the internal energy for a two-phase mixture at the inlet temperature at the initial time, calculated as $\boldsymbol{u_1 = u_f + xu_{fg}}$. Similarly, u_2 is the internal energy at the saturated liquid state, at the inlet temperature but at the final time, expressed as $\boldsymbol{u_2 = u_f}$. The terms h_1 and h_2 denote the enthalpies at the two-phase mixture and the saturated liquid state, respectively, both at the inlet temperature at the initial and final times, where $\boldsymbol{h_1=h_f + x_{hfg}}$ and $\boldsymbol{h_2=h_f}$. The average enthalpy, h_{out}, is calculated as the mean of h_1 and h_2, while m_{out} is the difference between m_1 and m_2, representing the mass flow out of the system.

Heat transfer to the system is equal to the energy increase of the system (Cengel and Boles, 2006). According to Sta. Maria (2001), when a product is placed into storage and its initial temperature is higher than the temperature of the storage environment, the product begins to emit heat to its surroundings. This process continues until the temperature of the product adjusts and becomes equal to the temperature of the storage space. The calculation of the heat emitted during this adjustment period can be performed using specific thermodynamic equations. These equations account for various factors, including the initial and final temperatures, the thermal properties of the product, and the duration of time over which the temperature equalization occurs.

Heat loss (Q) can be calculated using the formula by multiplying the mass, the temperature differential between the inside and outside surfaces, and the material's specific heat capacity, as shown in Equation 5.

$$Q=\frac{mC_p\Delta T}{t} \tag{5}$$

The total heat load (Q_{TOT}) is the sum of the heat required to cool the product from its entrance temperature to the freezing temperature (Q_1), the heat required to freeze the product (Q_2), and the heat required to cool the product from the freezing temperature to the final storage temperature (Q_3), as described in Equation 6.

$$Q_{TOT}=Q_1+Q_2+Q_3 \tag{6}$$

By rearranging the terms, Equation 7 provides a comprehensive expression for calculating the total heat load, incorporating the specific heat capacities of water and ice, the temperature changes, and the latent heat of water.

$$Q_{TOT}=\dot{m}[\left(Cp_w\Delta T\right)+Ls+Cp_i\Delta T] \tag{7}$$

where m is the mass of water (kg); C_{pw} is the specific heat capacity of water (4.187 kJ/kg-K); C_{pi} is the specific heat capacity of ice (2.0935 kJ/lg-K); ΔT is the change of temperature; Ls is the latent heat of water (kJ/kg); t is the running time.

According to Cengel and Boles (2006), the COP measures the effectiveness of a refrigerator's operation by evaluating its efficiency in extracting or removing a certain amount of thermal energy, denoted as Q_A, from the cooling space, which requires the input of work, represented by W. The formula for calculating the COP, provided in Equation 8, is crucial for assessing the effectiveness with which a refrigerator can move thermal energy out of the space it is designed to cool, compared to the amount of energy it expends during the operation. Connor (2019) notes that the COP is significantly influenced by the outdoor temperature and the targeted indoor temperature. For a temperature difference of around 25°C, the COP might be close to 2.5. However, when the temperature gap narrows to about 8°C, the COP can rise to approximately 3.5.

$$COP=\frac{Q_A}{W} \tag{8}$$

where W is the Work Input and Q_A is the Refrigerating Capacity.

To measure the correctness of the model, percentage error was calculated using the formula of Serway and Jewett (2018) as can be seen in Equation 9.

$$Percentage\ Error=\frac{Y\text{-}R}{Y}x100\% \tag{9}$$

Where Y represents the experimentally measured COP values, and R represents the predicted COP values.

2.6 Calculation of System's COP

The COP of the LPG refrigeration system during Test 1 was calculated over a running time of 3 hours (10,800 seconds), during which the temperature decreased from an initial 22.2°C (state 1) to a final 8.5°C (state 2). The mass of LPG consumed was 3.987 kg, determined by subtracting the final mass (7.013 kg) from the initial mass (11 kg). Internal energies (U) and enthalpies (h) for butane and propane were obtained from thermodynamic tables at the respective temperatures, as shown in Table 2.

Table 2. Internal Energy (U) and Enthalpy (h) of Butane and Propane

Substance	Temperature (°C)	Phase	U (kJ/kg)	h (kJ/kg)
Butane	22.2	Saturated Liquid	$U_f = -346.10$	$h_f = -345.50$
Butane	22.2	Saturated Vapor	$U_g = -51.03$	$h_g = -12.71$
Propane	22.2	Saturated Liquid	$U_f = -43.32$	$h_f = -41.54$
Propane	22.2	Saturated Vapor	$U_g = 252.40$	$h_g = 298.60$
Butane	8.5	Saturated Liquid	$U_f = -378.80$	$h_f = -378.40$
Propane	8.5	Saturated Liquid	$U_f = -78.97$	$h_f = -77.79$

At 22.2°C, the weighted average internal energy of saturated liquid LPG (U_f) was calculated using Equation 10,

$$U_f = (0.6)(-346.10) + (0.4)(-43.32) = -224.988\ kJ/kg \tag{10}$$

and the enthalpy (h_f) using the LPG composition of 60% butane and 40% propane is shown in Equation 11.

$$h_f = (0.6)(-345.50) + (0.4)(-41.54) = -223.916\ kJ/kg \tag{11}$$

The internal energy and enthalpy of state 1 and 2 are calculated as shown in Equations 12-15. With a vapor quality (x) of 0.20, indicating 20% vapor and 80% liquid, the internal energy at state 1 was:

$$U_1 = -224.988 + (0.20)((70.342 - (-224.988)) = -165.92\ kJ/kg \tag{12}$$

and the enthalpy was:

$$h_1 = -223.916 + (0.20)((111.81 - (-223.916)) = -156.77\ kJ/kg \tag{13}$$

At 8.5°C (state 2), the internal energy of saturated liquid LPG was:

$$U_f = (0.6)\,(-378.8) + (0.4)\,(-78.97) = -258.87\ kJ/kg \tag{14}$$

and the enthalpy as:

$$h_f = (0.6)\,(-378.4) + (0.4)\,(-77.79) = -258.16\ kJ/kg \tag{15}$$

The average enthalpy (h_{out}) used in the work calculation was obtained by averaging h_1 and h_2, shown in Equation 16.

$$\frac{h_1 + h_2}{2} = \frac{-156.77 + (-258.16)}{2} = -207.47\ kJ/kg \tag{16}$$

The work done by the system is 75.69 Watts which was calculated using Equation 4, as follows:

$$W = (11\ kg)\left(-165.92\ \frac{kJ}{kg}\right) - (7.013\ kg)\left(-258.87\ \frac{kJ}{kg}\right) - (3.987\ kg)\left(-207.47\ \frac{kJ}{kg}\right)$$

$$W = 817.52\ kW\ x\ \left(\frac{1{,}000W}{1\ kW}\right) x \left(\frac{1}{10{,}800} sec\right) = 75.69\ Watts$$

The refrigeration effect (RE) is 17.74 Watts which was calculated using Equation 5, as shown below:

$$RE = \frac{mC_p\Delta T}{t} = \frac{(2kg)(4187\frac{J}{kg-K})(23.44 - 0.56)}{10800} = 17.74\ Watts$$

where $m=2\ kg$ of water cooled.

Finally, using Equation 8, the COP for Test 1 was calculated as 0.23:

$$COP = \frac{17.74\ W}{75.69\ W} = 0.23$$

Illustrated above is the COP result for Test 1, but the maximum COP achieved by the system after five tests is 1.78. For Test 1 and all subsequent tests, the COP was calculated using the same process, applying the standard formula of COP (Equation 8). However, the values used in the calculation vary between tests. These variations include the refrigeration effect, which depends on the heat absorbed by the refrigerant and can change due to differences in system conditions such as inlet and outlet temperatures. Additionally, the work input differs based on the power consumed, influenced by operational parameters like pressure levels and refrigerant flow rates. Each test represents a unique combination of these parameters, resulting in different COP values, with 1.78 being the highest value recorded.

3. Results and Discussion

3.1 Component Integration and Experimental Evaluation

The movement of the refrigerant through various components in the refrigerant cycle results in changes in its pressure and temperature. This cycle is essential for operation and includes three key phases: mass consumption, pressure reduction, and temperature variation. Mass consumption is critical for calculating the system's work. Across five experimental trials, an average mass consumption of 0.218 kg was observed as can be seen in Table 3. This outcome is associated with an initial pressure of 30 psi and a variable outlet pressure between 28 psi and 10 psi. It was found that mass consumption of the system escalates with an increase in outlet pressure and diminishes when the outlet pressure falls, indicating a direct relationship between mass consumption and outlet pressure. The system experienced an average pressure decline of 15 psi as the LPG refrigerant passed through the expansion valve. According to Blackwell (2015), to achieve cooling in the refrigeration chamber, the refrigerant is forced through the expansion valve, which lowers its pressure by restricting the flow. This limitation results in a reduced volume of refrigerant in the subsequent section, allowing the refrigerant to expand slightly. Shah and Gupta (2014) corroborated this by documenting an average pressure reduction of 20 psi from an initial pressure of 80 psi, noting that the use of a low-pressure regulator would lead to different pressure adjustments. Following the expansion valve, the LPG refrigerant enters the evaporator coil within the refrigeration chamber, lowering the water temperature. Blackwell (2015) explains that the refrigerant enters the evaporator as a low-pressure, low-temperature liquid and begins to boil and evaporate, generating a cooling effect. The refrigerant exits the evaporator as a saturated, low-pressure gas, proceeding to the burner for combustion. The unique LPG-elevated configuration was found to be more efficient in reducing cooling time compared to standard set-ups. Utilizing a 3/16-inch diameter copper tube with

18 coils, the coldest temperature reached was -3.50 degrees Celsius within three hours, while a water temperature of 11.19 degrees Celsius was achieved in 50 minutes. In comparison, Manohar *et al.* (2020) reported a water temperature of 23.4 degrees Celsius after 50 minutes using a 1/12" diameter copper tube, suggesting that the tube size in this experiment facilitates quicker cooling than that used in the previous study. However, it is important to note that continuous operation of the LPG system is limited to only 10 hours.

3.2 Performance of LPG

In this investigation, a series of five experimental assessments were conducted, with each experiment spanning a total of 180 minutes and observation made at 10-minute intervals as presented in Table 3. The data outline the consumption patterns of Liquefied Petroleum Gas (LPG) by the refrigeration system over the course of a three-hour period, with measurements taken at each interval. During the initial half of the observed period, a noticeable rate of LPG utilization was recorded, amounting to approximately 1.8 kg. This equates to an average LPG consumption rate of 0.218 kg per 10-minute interval. The relationship between the absolute pressure at the exit point from the evaporator and elapsed time was graphically represented in Figure 6. Analysis of this graph reveals a linear correlation between these variables. The term "pressure drop" is defined as the variance observed between the inlet and outlet pressures, which was noted to increase from 4.8 psi to 17 psi at each successive 10-minute interval, indicating a direct relationship with the passage of time.

Table 3. Average consumption of mass from experiment.

TEST	Average Consumption Every 10 mins
1	0.222 kg
2	0.203 kg
3	0.184 kg
4	0.258 kg
5	0.221 kg
Average	0.218 kg

Furthermore, Figure 7 explains the temporal behavior of water temperature within the system. A significant reduction in temperature was observed within an 80-minute timeframe, where temperatures dropped from 25°C to 2°C. Beyond this point, the decrease in temperature proceeded at a more gradual pace as the system neared and subsequently surpassed the freezing threshold, ultimately achieving a minimum temperature of -3.5 °C after a total duration of three hours.

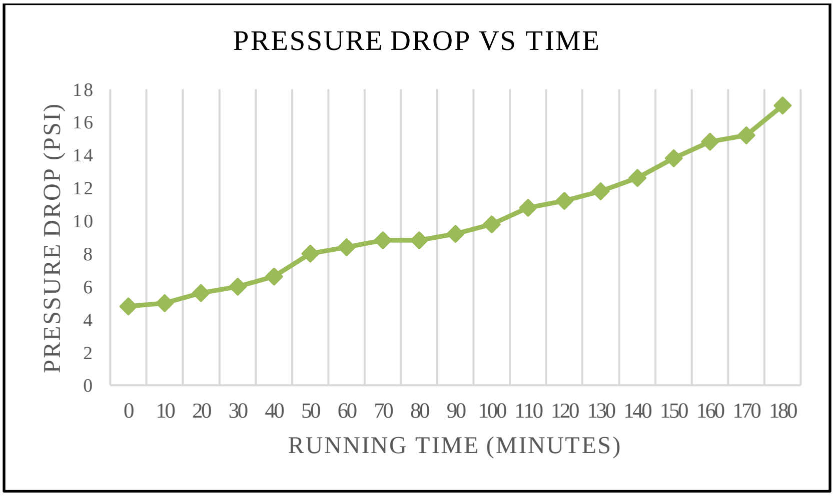

Figure 6. Pressure Drop vs Time graph of experimental result.

3.3 Coefficient of Performance

The system's COP was determined through analysis of the empirical data accumulated over a span of three hours, with observations recorded at 10-minute intervals. The calculated COP values, as determined using Equation 8 in Section 2, exhibited a range from 0.023 to 1.78, indicating a progressive increase in system efficiency over time. This upward trend in COP is graphically depicted in Figure 8, illustrating a direct correlation between the passage of time and the improvement in system performance. This observation supports the assertion that the system's efficiency, as measured by COP, increases with the duration of operation.

The effectiveness of a refrigeration system is quantitatively assessed through its COP, where higher COP values indicate greater system efficiency, as outlined by Connor (2019). In the present study, which examined the system under transient state conditions, the maximum COP achieved was approximately 1.78. This value is notably lower compared with the COP of 5.08 obtained in the investigations of Shah and Gupta (2014) and the study conducted by Manohar *et al*. (2020) with a COP of 6.3. The higher COP in their study can be attributed to the assumption that the input work was equivalent to the energy needed to fill a single cylinder of the tank. This assumption resulted in a significant increase in the COP calculation, yielding values that exceed the typical COP of around 2.95 for standard domestic refrigerators.

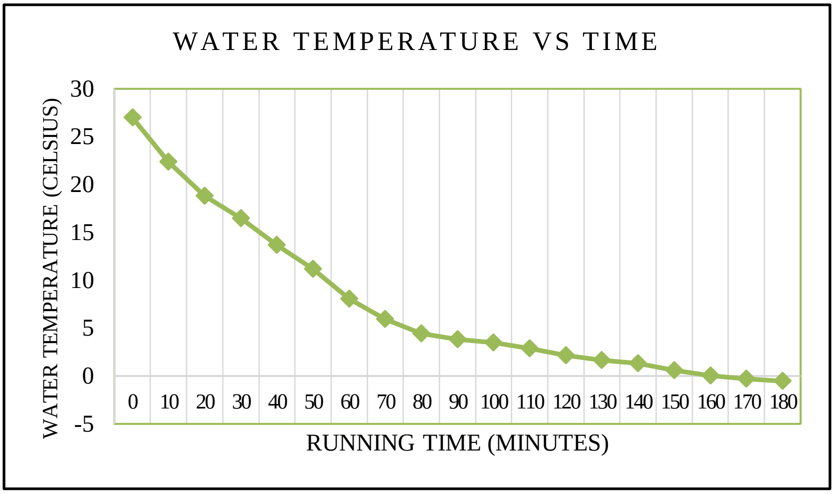

Figure 7. Water Temperature vs Time graph of experimental result

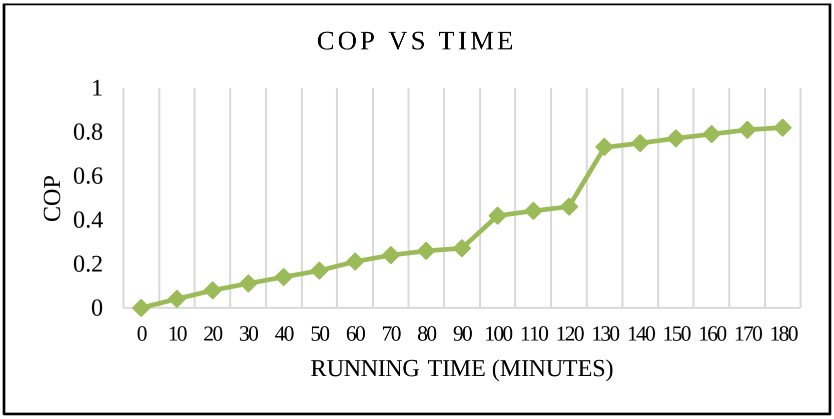

Figure 8. COP vs Time graph of experimental result

Specific properties of butane and propane, the primary constituents of LPG in the Philippines, were used in the calculation of work. This approach facilitates a more comprehensive and accurate determination of COP, enhancing the understanding of LPG's efficacy as a refrigerant. Despite the COP not reaching the standards typically associated with conventional domestic refrigerators, the system under investigation still manifested a tangible refrigeration effect.

3.4 Percent difference

Comparing predicted values (*R*) with experimentally measured values (*Y*) provides an assessment of the accuracy of the model. An average percentage error was first calculated for each data point, and then the errors were averaged to obtain an overall average percentage error. The mean average percentage error was determined to be 22.12%, which indicates that, on average, the predicted COP value deviates from the actual measured value by almost 22%.

4. Conclusion and Recommendation

The evaporator of the LPG refrigeration system achieved a significant cooling effect, reaching temperatures as low as -3.5 °C and culminating in ice formation within the chamber. Operating with an average LPG mass flow rate of 0.363 g/s, the system demonstrated consistent performance and operational stability. The open-loop and unsteady-state nature of this refrigeration system results in pressure and mass changes over time, leading to a decrease in work as the mass of LPG diminishes. The significance of this reduction in work in the calculation of the Coefficient of Performance (COP) lies in its inverse relationship with COP, as the amount of input work decreases, there is a corresponding increase in the COP, which explains why the COP improves over time. An average percent difference of 22.12% suggests that the mathematical model has a reasonable degree of accuracy but also indicates that there is still room for improvement. This level of deviation implies that other factors influencing the COP may not yet captured by the current model. Additionally, inaccuracies can arise from operational environmental changes during the experiment or from assumptions made in the mathematical calculations. An enhanced version of the COP calculation model might involve introducing more input variables or employing advanced modeling techniques with thorough data testing to better explain and predict results. While the current mathematical model provides an approximate estimate of the COP in LPG refrigeration systems, ongoing research should focus on reducing this error by incorporating additional variables and refining the model for increased accuracy and applicability.

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6. References

Abbood, M.H., Hashim, H.T., & Amin, A.S. (2020). Investigation of environmentally-friendly alternative refrigerants for automotive air conditioning systems. In IOP Conference Series: Materials Science and Engineering (Vol. 671, No. 1, p. 012139). IOP Publishing. https://doi.org/10.1088/1757-899X/671/1/012139

ACRIB. Air Conditioning and Refrigeration Industry Board, (2001). Guidelines for the use of Hydrocarbon Refrigerants in Static Refrigeration and Air Conditioning Systems. Carshalton, Surrey, UK.

Adhav, A.S., Dudhe, S.S., Jadhav, V.D., Pagar, S.A., & Salunke, G.B. (2017). Electricity Free Refrigeration using LPG. Retrieved from https://www.academia.edu/31673800/Electricity_Free_Refrigeration_using_LPG

Ahmad, R.H., Bhuiyan, A.A., Xu, F., Sujon, A.S., Karim, M.R., Moin, E.H., & Sadrul Islam, A.K.M. (2020). Comparative analysis of refrigerant performance between LPG and R134a under subtropical climate. Journal of Thermal Analysis and Calorimetry, 139, 2925-2935. https://doi.org/10.1007/s10973-019-09126-3

AIRAH. (2013). Australian Institute of Refrigeration, Air-Conditioning and Heating Incorporated. Flammable refrigerants safety guide. Retrieved from https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=308694f4fef24df206277b9061aeb322695d4541

Blackwell, W. (2015). Sustainable Retail Refrigeration. John Wiley & Sons Ltd. The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK. pp 351.

Cengel, Y.A. & Boles, M.A. Thermodynamics: An Engineering Approach. 5th ed. Boston: McGraw-Hill Higher Education, 2006. Print.

Connor, N. (2019). What is Coefficient of Performance - COP - Refrigerator, Air Conditioner - Definition. Thermal Engineering. Retrieved from https://www.thermal-engineering.org/what-is-coefficient-of-performance-cop-refrigerator-air-conditioner-definition/

Demharter, A. (1998). Polyurethane rigid foam, a proven thermal insulating material for applications between +130°C and −196°C., 38(1), 113–117. https://doi.org/10.1016/s0011-2275(97)00120-3

Elgas (2019). How Much Pressure is in LPG & Propane Gas Cylinder-Bottle. Retrieved from https://www.elgas.com.au/blog/1969-how-much-pressure-is-in-lpg-propane-cylinders-in-what-state/

ES Systems (2021). What is liquefied petroleum gas and how does it work? Retrieved from https://esenssys.com/liquefied-petroleum-gas-guide/#

El-Morsi, M. (2015). Energy and exergy analysis of LPG (liquefied petroleum gas) as a drop in replacement for R134a in domestic refrigerators. Energy, 86, 344-353. https://doi.org/10.1016/j.energy.2015.04.035

Emani, M.S., Roy, R., & Mandal, B.K. (2017). Development of refrigerants: a brief review. Indian J. Sci. Res, 14(2),175-181.

Fernando, J. (2022). Hydrocarbons: Definition, Companies, Types, and Uses. Retrieved from https://www.investopedia.com/terms/h/hydrocarbon.asp.

Heisler, H. (2002). Advanced Vehicle Technology. Elsevier. Linacre House, Jordan Hill, Oxford. 654pp.

Iyer, G.V., Mastorakis, N.E., & Theologou, A.I. (2006). Experimental investigations on eco-friendly refrigeration and air conditioning systems. Proceedings of 4th WSEAS International Conference Fluid Mechanics Aerodynamics (Vol. 2017, pp. 445-450).

Jadyar, A. (2021). Highly Secured LPG Refrigeration System. International Journal for Research in Applied Science and Engineering Technology, 9(5), 677–679. https://doi.org/10.22214/ijraset.2021.34200

Liu, B.Y., Tomasek, M.L., & Radermacher, R. (1995). Experimental results with hydrocarbon mixtures in domestic refrigerator/freezers (No. CONF-950104-). American Society of Heating,

Manohar, M., Sahu, P.K., Sahu, P.K., Singh, D., & Chandra, A. (2020). Design Analysis and Performance of Low Cost Refrigeration System using LPG. Retrieved from https://www.ijesc.org/upload/1c58ceee9a810532dab0c45ce2b82687.Design%20Analysis%20and%20Performance%20of%20Low%20Cost%20Refrigeration%20System%20using%20LPG.pdf

NASA. National Aeronautics and Space Administration (2015). NASA Study Shows That Common Coolants Contribute to Ozone Depletion. Retrieved from https://www.nasa.gov/press-release/goddard/nasa-study-shows-that-common-coolants-contribute-to-ozone-depletion

Nasution, D.M., Idris, M., Pambudi, N.A., & Weriono. (2019). Room air conditioning performance using liquid-suction heat exchanger retrofitted with R290. Case Studies in Thermal Engineering, 13, 100350. https://doi.org/10.1016/j.csite.2018.11.001

Nithiyanand, P., Krishnan, A., Baby, B., Baby, D., & Sufaid, M. (2020). Design of LPG used refrigeration system using Nozzle expansion. International Research Journal on Advanced Science Hub, 2(04), 46-53.

Oyelami, S. & Bolaji, B.O. (2016). Design and construction of a vapour compression refrigeration system as test rig to investigate the performance of Liquefied Petroleum Gas (LPG) as refrigerant. Retrieved from http://repository.fuoye.edu.ng/handle/123456789/2308

Quraishi, M.A.N.A. & Wankhede, U.S. (2013). Use of hydrocarbons and other blends as refrigerant. International Journal of Modern Engineering Research, 3(1), 250-253. https://www.ijmer.com/papers/Vol3_Issue1/BP31250253.pdf

Rehman, H.U., Awan, A., Khan, N., Naseer, F., & Ali, K. (2023). Using Liquefied Petroleum Gas (LPG) as an Environmentally Friendly Alternative Refrigerant. Retrieved from https://www.xisdxjxsu.asia/V19I03-60.pdf

Raiyan, M.F. & Rehman, O.A. (2017). Effects of Chlorine-based refrigerants on atmosphere and search for alternative refrigerants-A review. Retrieved from https://www.researchgate.net/publication/324830749_Effects_of_Chlorine_based_refrigerants_on_atmosphere_and_search_for_alternative_refrigerants-A_review

Rayos, A.H. (2017). LPG Industry Regulatory Framework (Household LPG) and Gasoline Station Training and Loan Fund. Department of Energy. Retrieved from https://www.doe.gov.ph/sites/default/files/pdf/announcements/epower_fontana_04_04_lpg_industry_regulatory_framework.pdf?withshield=1

Sathayan, S., Gopakumar, M.G., Krishnan, S.J., Gopan, N., & Nithin, S. (2018). Design of Lpg Refrigeration System. International Journal of Innovative Research in Science, Engineering and Technology, 7(6), 2319-8753. https://doi.org/10.15680/IJIRSET.2018.0705054

Satwik, N., Kumar, B.S., Krishna, T.G., Ravinda, M., & Kumar, B.K. (2016). Refrigeration System by using LPG (Liquefied Petroleum Gas). International Journal and Magazine of Engineering, Technology, Management and Research, 3(5), 226-235.

Serway, R.A. & Jewett, J.W. (2007). Physics for scientists and engineers with modern physics (7th ed.). Thomson Brooks/Cole.

Shah, I.H. & Gupta, K. (2014). Design of LPG refrigeration system and comparative energy analysis with domestic refrigerator. International journal of engineering sciences & research technology, 3(7), 206-213.

Shahare, U., Yadav, K., Dongre, V., Umre, A., Gajbhiye, K., & Bhaisare, Y. (2021). Fabrication of low-cost refrigeration system by using LPG. International Journal of Advanced Research in Science, Communication and Technology, 6(8), 282–286. https://doi.org/10.48175/ijarsct-1846

Siddegowda, P., Mundur Sannappagowda, G., Jain, V., & Javare Gowda, S. (2019). Hydrocarbons as Alternate Refrigerants to Replace R134a in Domestic Refrigerators. Journal of Composite & Advanced Materials/Revue des Composites et des Matériaux Avancés, 29(2).

Srinivas, P., Chandra, R.P., Kumar, M.R., & Reddy, N. (2014). Experimental investigation of LPG as refrigerant in a domestic refrigerator. J. Mechan. Eng. Res.

Technol.2(1),470-476.

Sta. Maria, H.B. (2001). Refrigeration and air conditioning (3rd ed.). National Book Store.

United Nations. (2015). Transforming our world: The 2030 Agenda for Sustainable Development. United Nations. https://sdgs.un.org/2030agenda