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# Investigating Internal Heat Exchanger Performance in a VCR System with a $CO_2$ and LPG Refrigerant Mixture

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***Abstract:*** *In this study, an attempt was made to develop a cooling system with an internal heat exchanger using a mixture of carbon dioxide ($CO_2$) and liquefied petroleum gas (LPG) as refrigerants to help eliminate the global warming potential and other harmful environmental effects caused by conventional refrigerants'. The $CO_2$ and LPG refrigeration experimental setup was constructed with varying sizes of capillary tubes, a pressure controller, an evaporator, and a gas hob. The working ranges were initially confirmed through exploratory experiments with low-pressure and high-pressure flow circuits, using and without an internal heat exchanger (IHE). The evaporator temperature helped to determine the proportional changes in the coefficient of performance (COP). The REFPROP software design was used to conduct experiments and determine the important process parameters. A confirmation test was performed to validate the expected results of the REFPROP software technique. The results showed that the experiments conducted using IHE had a COP with greater performance levels as follows: mean of 1.398 and SD of 0.367 which is greater than the value of the experiments undertaken without IHE which had a COP performance levels as follows: mean of 0.67 and SD of 0.19. The Paired Samples T-test found these differences to be significant, at p-value < 0.033. The null hypothesis was rejected, hence there is evidence to suggest that the COP of the experiment with IHE is statistically greater than the COP of the experiment without IHE, with a 95% confidence interval of -1.357 and -0.099.*

***Keywords:*** *Carbon dioxide, Coefficient of Performance, Liquefied Petroleum Gas, Pressure, Refrigeration, Temperature*

## 1. INTRODUCTION

The IHE transfers heat between the low-pressure and high-pressure flow circuits [1]. IHE helps improve system performance by sub-cooling the refrigerant supplied to the evaporator through the refrigerant control device. IHE has long been used in the refrigeration and air conditioning industries because it can improve the efficiency of refrigeration cycles for many commonly used and potential replacement refrigerants, including R134a, R744, and R1234yf, [2]. IHE increases the quality of the liquid refrigerant that enters the evaporator, potentially boosting system capacity and coefficient of performance (COP). It also allows for greater heat transmission between the condenser's high-temperature liquid and the evaporator's temperature vapour. IHEs are often used in residential systems. Heat exchangers transfer heat between two or more liquids, vapours, or gases of different temperatures [3]. Depending on the types of heat exchanger used, heat can be transported through direct fluid contact or a solid separator that keeps fluids from touching. A liquid-to-liquid, liquid-to-gas, or gas-to-liquid procedure is also an option.

The types and materials of components used in heat exchangers can vary widely. Depending on the type of heat exchanger and how it is meant to be utilised, different parts and materials are employed. Heat exchangers commonly consist of shells, tubes, spiral tubes (coils), plates, fins, and adiabatic wheels. Although metals like copper, titanium, and stainless steel are highly suitable and often used for heat exchanger construction due to their high thermal conductivity, other materials like graphite, ceramics, composites, or plastics may offer greater benefits depending on the needs of the heat transfer application.

There are merits and limits for the three different types of heat exchangers: parallel, cross, and counter flow. Although the counter flow exchanger design is the most efficient in terms of heat transfer rate per unit surface area among the three types of heat exchangers [4]. The other two types are also very effective. Heat exchangers are classified into two categories: recuperative and regenerative. The fluids circulate at the same time through a recuperative heat exchanger, which contains individual flow channels for each fluid as well as a wall between the flow paths that transfer heat. A regenerative heat exchanger has a single flow route that alternately circulates hot and cold fluids according to [5]. Heat can be transported between fluids via recuperative heat exchangers, either directly or indirectly. Heat is transferred directly from one fluid to another in direct contact with heat exchangers because the fluids are not separated inside the device. However, in indirect heat exchangers, the fluids are kept apart by thermally conductive parts like tubes or plates. The two basic brands of regenerative heat exchangers are static and dynamic. In static regenerators, also known as fixed bed regenerators, the heat exchanger material and components remain stationary as fluids pass through the device, but in dynamic regenerators, the material and components move as heat is conveyed [6]. Heat exchangers come in a variety of various designs. In Industry, condensers, evaporators, boilers, twin conduit heat exchangers, plate heat exchangers, shell and tube heat exchangers, and other types are commonly used.

All heat exchangers work agreeing to the Zeroth, First, and Second Laws of Thermodynamics, regardless of their nature or design. The plate exchanger performs best when there is a turbulent flow on both sides. Due to the flow's equal dispersion, a high heat transfer coefficient and turbulence are required. A regenerator for a plate heat exchanger can only handle low viscosities [7]. The double-pipe heat exchanger described in this study is typical in small refrigeration systems. The item is composed of two concentric tubes separated by a gap. Two fluids circulate in the inner tube and the gap between the two tubes. A single-phase-flow heat exchanger may accommodate fluids of the same phase but at different temperatures. Furthermore, two-phase-flow heat exchangers are an option that can handle fluids in many phases [8]. Two-phase flow heat exchangers are widely utilised in refrigeration and air conditioning systems for residential, commercial, and industrial applications. According to [9], they have the greatest potential to transform refrigeration and air conditioning. There is solid evidence that the IHE improves the performance of refrigerators and air conditioners.

The optimal refrigerant ratio blend of liquefied petroleum gas (LPG) and carbon dioxide ($CO_2$) was determined using theoretical simulation using the REFPROP 9.0 programme. As it is exceptionally low critical point temperature of 30.97° C and extremely high critical point pressure of 7.38 MN/$m^2$ [10], which are undesired in a refrigeration system, the use of $CO_2$ necessitates the inclusion of IHE into the system. Because IHE utilisation provides comparatively large performance benefits when compared to traditional refrigerants, the emergence of alternative, more environmentally friendly refrigerants such as R744 ($CO_2$) has raised interest in IHE development [11]. $CO_2$ is a natural working fluid and has long been seen as a feasible replacement for produced refrigerants due to its numerous advantages, including outstanding thermophysical properties, low cost, uninflammability, and lack of toxicity. However, the transcritical $CO_2$ refrigeration cycle is appropriate since the critical temperature of $CO_2$ is frequently lower than the average heat rejection temperature of air conditioning systems [12]. Numerous devices have been proposed to address the issues associated with $CO_2$ as a refrigerant, including expanders, internal heat exchangers, two-stage compressors, and two-phase ejectors. The most significant boost in cycle efficiency is expected when an expander is utilised in place of the throttle valve. This would result in less net compression work and improvement in the evaporator's cooling effect. Using parametric analysis, [13] revealed that the cycle COP increase might reach 25% when an expander with an isentropic efficiency of 60% is employed. [14] reported that the cycle's COP and energy efficiency increased by 33% and 30%, respectively when an expander was replaced in the throttling valve. [15], installing an 80% isentropic efficiency expander in place of the throttling valve resulted in an 18% rise in COP and a 2.5% decrease in the ideal heat rejection pressure. [16] integrating a three-stage expander with two-stage compression and intercooler in a $CO_2$ refrigeration system can increase the system's $CO_2$ efficiency by at least 40%. [17] developed a prototype reciprocating piston expander and found that it enhanced COP by 7% to 10.5% and increased cooling capacity by 3.5% to 5.7%. [18] reported that an expander-compressor enhanced cycle COP by 23.5% and boosted cooling capacity by 8.6% when they studied its performance using numerical simulation. It was observed that when compared to a throttling valve it was found that a double-acting rotary vane expander prototype boosts COP by 27.2% according to [15,19], evaporator temperature of 0°C and a gas cooler outlet temperature of 60°C, IHE offered a 15% increase in cycle COP and a 13% decrease in optimum heat rejection pressure in comparison to those of the regular transcritical cycle. [19] explained that addition of IHE the refrigerating system may raise the cooling capacity and COP in the transcritical $CO_2$ cycle by 6.2%–11.9% and 7.1%–9.1%, respectively. Through their experimental research, [20] discovered that the use of IHE can increase COP in residential applications by 10%. The addition of IHE to a transcritical $CO_2$ refrigeration system can increase cooling capacity by up to 12%, cycle COP by up to 12%, and discharge temperature by up to 15% at evaporating temperature, according to experimental results [21]. It was found by [22] through both theoretical and practical study that the IHE addition increases cycle COP by over 20% at a gas cooler outlet temperature of 35 °C. [23] found that an IHE only slightly lowers the COP in a $CO_2$ subcritical refrigeration cycle. Regarding a booster system, [24] arrived at basically identical conclusions. R744 ($CO_2$) exhibits an intriguing behaviour in that, in a system lacking an IHE, it provides relatively tiny cooling capabilities. It is not even possible to achieve positive cooling capacity when the evaporation temperature is too high.

[25] worked on the efficiency of the Joule-Thomson refrigeration system with a heat exchanger placed between the condenser and the expansion device. The exergy efficiency, exergy destruction ratio, and coefficient of performance of the Joule-Thomson refrigeration system with a heat exchanger were measured. For the experimental investigation, the study employed a combination of R290/R600a (40/60, 50/50, 60/40, and 70/30 by weight) as an environmentally friendly refrigerant. The findings showed that the coefficient of performance increased by 10.45% and the energy efficiency increased by 4.25%.

It is known that various authors have investigated and implemented IHE to increase the efficiency of heat pumps, air conditioning, and refrigeration systems. This work addresses the 'experimental performance of internal heat exchangers in vapour compression refrigeration systems using a mixture of $CO_2$ and LPG as refrigerant'. Several studies have been done on IHE between the low-pressure and high-pressure flow circuits to improve system performance by further sub-cooling the refrigerant supplied to the evaporator through the refrigerant control device. However, there is no adequate literature on $CO_2$ and LPG Refrigerant mixture investigation on IHE performance in VCR systems. In this work, the mixture of $CO_2$ and LPG Refrigerant mixture impacts on the IHE performance of VCR shall be investigated.

## 2. MATERIALS AND METHOD

The materials used in carrying out this experiment are a locally developed refrigerator, developed tube-in-tube type IHE, refrigerants (carbon dioxide $CO_2$, liquefied petroleum gas LPG), digital weighing balance, pressure gauge, and digital multimeter. Figure 1, shows the pictorial view of the tube-in-tube type developed IHE.

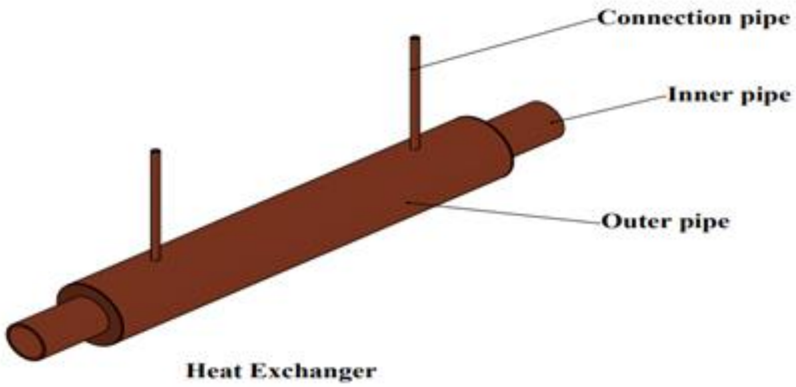


Figure 1: Sectional view of the internal heat exchanger

The refrigerants, $CO_2$ and LPG were charged into the refrigerator compressor suction using the pressure gauge set; the gas container sensibly stood on the digital weighing balance to display the mass flow of each of the refrigerants as it was charged into the compressor. The refrigerator was connected to electricity. The setup is shown in Figure 2.

The experiment was set up first without the IHE as shown in Figure 3. Readings were taken across the major components of the refrigeration. Likewise, the setup with IHE is shown in Figure 4. Readings were also recorded. The readings which include $Tcomp_{out}$, $Tcond_{in}$, $Tcond_{out}$, $Tdrier_{out}$, $Tevap_{in}$, $Tevap_{out}$, $Tcom_{in}$; the refrigerant pressure $Pcomp_{suc}$, $Pcomp_{dis}$,; the mass flow rate $\dot{m}_{LPG}$, and $\dot{m}_{CO2}$. Second, the system, with the internal heat exchanger was test-run and readings were taken too; $Tcomp_{out}$, $Tcond_{in}$, $Tcond_{out}$, $TIHE_{in}$, $TIHE_{out}$, $Tdrier_{out}$, $Tevap_{in}$, $Tevap_{out}$, $Tcomp_{in}$; the refrigerant pressure $Pcomp_{suc}$, $Pcomp_{dis}$, the enthalpies were calculated for and the COP for the two experiments were obtained. Figures 3 and 4 show the two experimental ranges.


Figure 2: Experimental setup

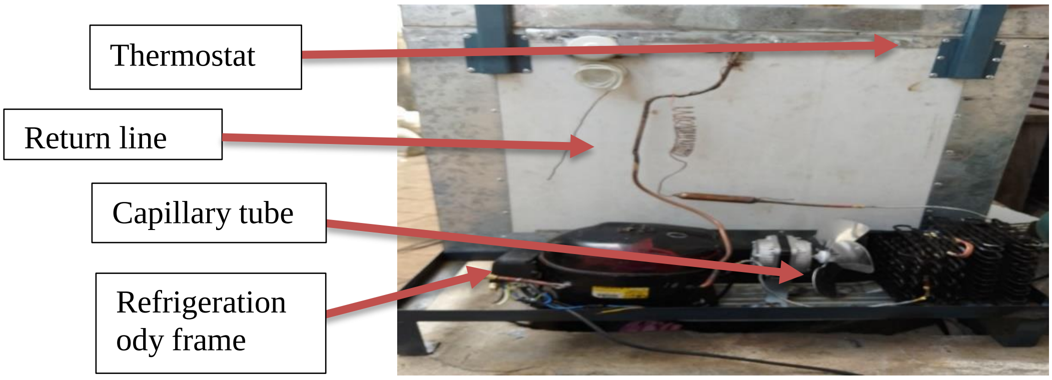


Figure 3: The pictorial setup of the cooling system without internal heat exchanger

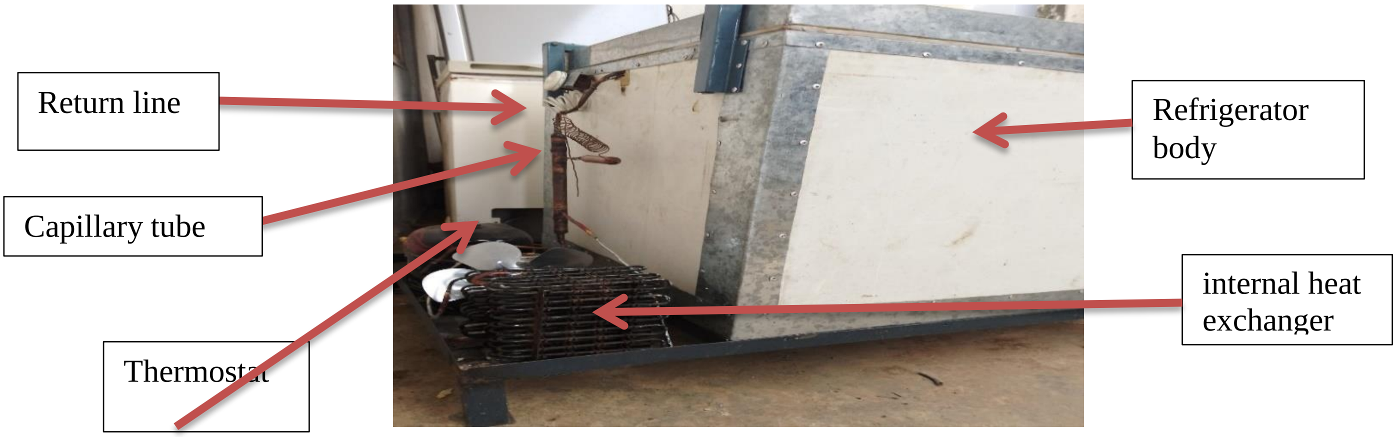


Figure 4: The pictorial setup of the cooling system with internal heat exchanger

## 3. RESULTS AND DISCUSSION

Readings were taken after the setup of the cooling system, without IHE and with IHE.

Table 1: Temperatures of the major components without internal heat exchanger

| Compression Temp ($^0$C) | | Condenser Temp ($^0$C) | | Drier Temp ($^0$C) | | Evaporation Temp ($^0$C) | |
|---|---|---|---|---|---|---|---|
| In | Out | In | Out | In | Out | In | Out |
| 26 | 38 | 42 | 32 | 31 | 33 | 21 | 17 |
| 25 | 33 | 33 | 25 | 25 | 22 | 19 | 21 |
| 23 | 36 | 39 | 31 | 29 | 31 | 16 | 14 |
| 27 | 39 | 51 | 31 | 31 | 31 | 16 | 16 |
| 23 | 41 | 41 | 30 | 30 | 33 | 17 | 26 |
| 23 | 41 | 35 | 29 | 29 | 30 | 16 | -4 |
| 26 | 37 | 39 | 32 | 33 | 34 | 15 | -1 |
| 25 | 46 | 48 | 34 | 34 | 35 | 14 | -3 |
| 21 | 47 | 52 | 33 | 33 | 33 | 14 | 25 |
| 30 | 44 | 46 | 35 | 35 | 36 | 20 | 25 |

The readings were taken after the inflow of the two refrigerants; the LPG mass inflow was 25.48 g, while that of $CO_2$ was 2.52 g, it was noticed that the return flow into the compressor shows frozen along the line at the inflow of $CO_2$ as shown in Figure 2. This demonstrates the true properties of high pressure linked with $CO_2$ gas. Table 1 shows that the input of the refrigerant phase into the compressor and the outflow into the evaporator via the drier out were not regulated, as they were in the cooling system with an internal heat exchanger. The suction pressure was low (1.4710 Mpa), but the discharged pressure was a little high (5.0995 MPa); this was connected with the behaviour of $CO_2$ gas without regulation; little wonder the compressor was quite hot after working for three hours, which was not the case with IHE.

Table 2: Temperatures of the major components with internal heat exchanger

| Compression Temp ($^0$C) | | Condenser Temp ($^0$C) | | Heat Exchanger Temp ($^0$C) | | Drier Temp ($^0$C) | Evaporation Temp ($^0$C) | |
|---|---|---|---|---|---|---|---|---|
| In | Out | In | Out | In | Out | Out | In | Out |
| 29 | 39 | 34 | 31 | 31 | 29 | 29 | 11 | 14 |
| 29 | 40 | 45 | 31 | 32 | 30 | 31 | 10 | 11 |
| 31 | 48 | 51 | 34 | 34 | 30 | 30 | 09 | 10 |
| 31 | 49 | 50 | 33 | 32 | 30 | 30 | 10 | 14 |
| 29 | 50 | 48 | 32 | 31 | 29 | 29 | 11 | 10 |
| 29 | 51 | 59 | 31 | 31 | 29 | 30 | 11 | 09 |
| 29 | 42 | 59 | 31 | 31 | 29 | 30 | 13 | 13 |
| 29 | 40 | 49 | 31 | 31 | 29 | 30 | 13 | 09 |
| 29 | 39 | 49 | 30 | 31 | 29 | 29 | 09 | 07 |
| 29 | 39 | 51 | 30 | 31 | 29 | 29 | 06 | 05 |
| 31 | 51 | 57 | 37 | 34 | 31 | 32 | 09 | 11 |
| 31 | 49 | 38 | 34 | 34 | 31 | 32 | 10 | 11 |
| 31 | 35 | 41 | 34 | 34 | 31 | 31 | 11 | 08 |
| 30 | 35 | 44 | 34 | 34 | 30 | 31 | 08 | 07 |

The readings of the cooling system with the internal heat exchanger Table 2 show the orderliness in the reading, which is associated with the incorporation of the IHE device. The readings from the return line i.e. from the internal heat exchanger to the compressor aligned with the flow of the refrigerant from the IHE into the evaporator via the capillary tube (compressor in and heat exchanger out). Unlike the readings on the cooling system without this device which was not steady. This shows the function of the IHE device as there was an exchange of heat within the device between the inflow from the condenser and the return from the evaporator. The phase of the refrigerant inflow into the compressor was maintained at regulated temperature by the IHE

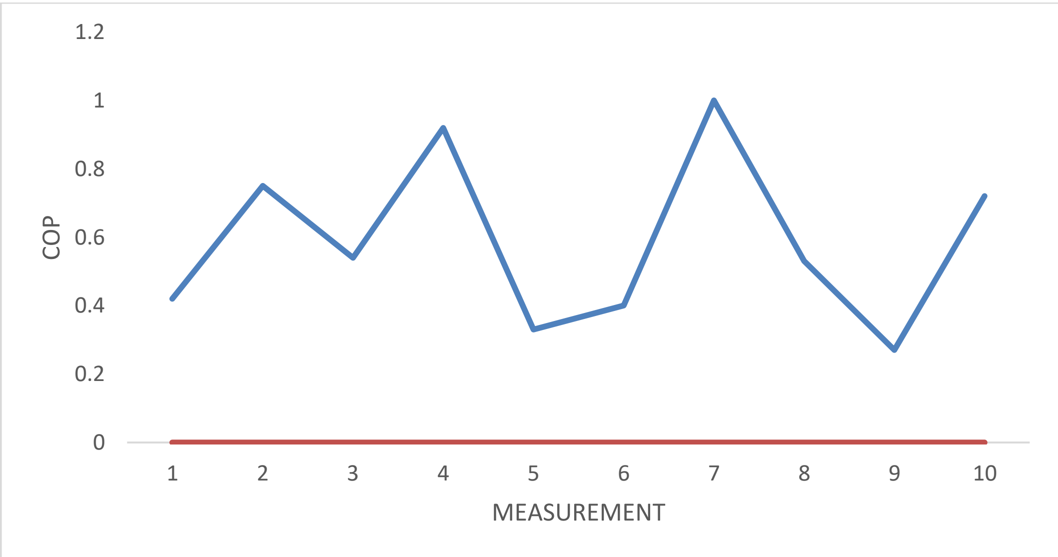


Figure 5: the effect of the blend of $CO_2$ and LPG on COP without IHE

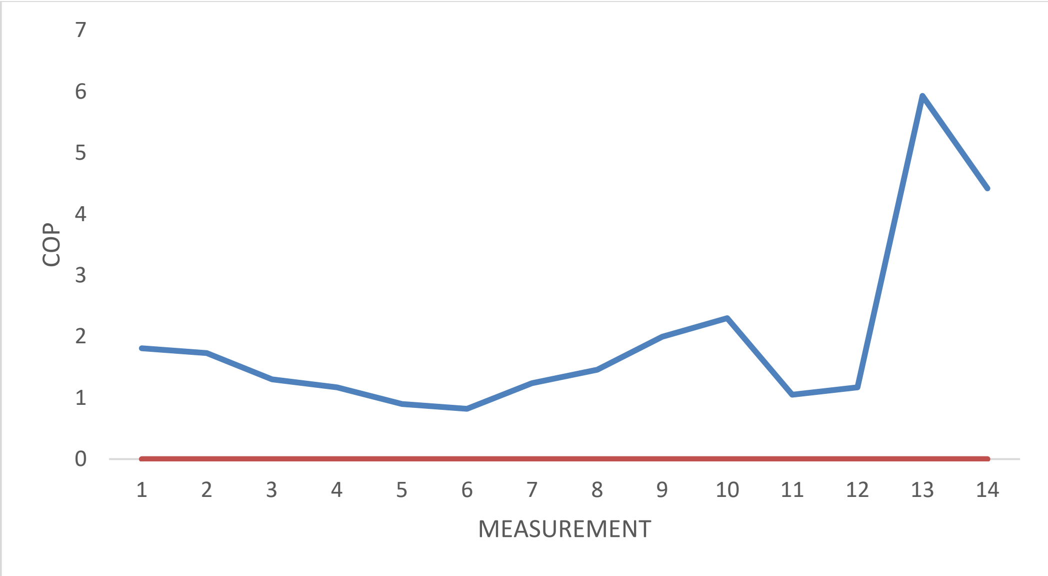


Figure 6: The effect of the blend of $CO_2$ and LPG on COP with IHE

Figure 5 and Figure 6 show the effect of the blend of $CO_2$ and LPG on the COP without and with IHE. The effect of the blend on COP in Figure 5 was wavelike i.e. the maximum it attained was 1; but in Figure 6 the COP rose steadily down the slope and picked up again, and got to around 6.

The paired T-test was used to compare the experiment results without IHE COP with the experiment with IHE COP. The test helps to determine whether there is statistical evidence that the mean difference between the observations is significantly different. Table 3 shows the experimental readings having similar evaporating temperatures.

Table 3: The experimental readings for statistical authentication

| Evaporating Temperature ($^oC$) | COP Without IHE | COP With IHE |
|---|---|---|
| 4 | .72 | 1.17 |
| 2 | .75 | 1.11 |
| 0 | .92 | 1.24 |
| -2 | .54 | 2.01 |
| -4 | .42 | 1.46 |

To investigate this, we express the hypotheses thus;

$H_0$: $\mu_1 = \mu_2$ (There is no difference in the coefficient of performance between the experiment without IHE and the experiment with IHE)

$H_1$: $\mu_1 \neq \mu_2$ (There is a difference in the coefficient of performance between the experiment without IHE and the experiment with IHE)

A. The paired sample statistics

Table 4 depicts descriptive statistics for the two coefficients. We are mainly interested in the mean and the standard deviation. We can see from the two means that the experiment with IHE COP has a greater coefficient of performance (mean = 1.398, SD = 0.367) than the experiment without IHE COP samples (mean = 0.67, SD = 0.194). We can also see from the standard deviations that the ones with IHE COP levels are dispersed.

Table 4: Paired samples statistics

| | | Mean | N | Std. Deviation | Std. Error Mean |
|---|---|---|---|---|---|
| Pair 1 | Experiment without IHE COP | .6700 | 5 | .19416 | .08683 |
| | Experiment with IHE COP | 1.3980 | 5 | .36684 | .16405 |

Source: Authors' computation

B. The paired sample test

Table 5 explains the inferential T-test statistics. This table will help us decide whether there is a statistically significant difference between the performance levels and whether our null hypothesis can be rejected in favour of our research hypothesis. There are many columns included in this table, but the most important ones are the three on the right-hand side. These important sections are described below:

Table 5: The aired samples test

| | | Paired Differences | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Mean | Std. Deviation | Std. Error Mean | 95% Confidence Interval of the Difference Lower | Upper | T | df | Sig. (2-tailed) |
| Pair 1 | Experiment without IHE COP - Experiment with IHE COP | -0.72800 | 0.50672 | 0.22661 | -1.35718 | -0.09882 | -3.213 | 4 | 0.033 |

Source: Authors' computation

- The t-test statistic is (-3.213). This is the determined t-value, which expresses the difference in scores across our two coefficients of performance. When the t value increases, the higher the gap between the values.
- df = (4). It is an important statistic that needs to be reported, as its value directly impacts the significance of the t-statistic.
- Sig. (2-tailed) = (0.033): Sig. represents significance level. It calculates the likelihood that the results occurred by random (assuming the null hypothesis was true). For t to be significant, the p-value must be less than or equal to 0.05, according to convention. If this is significant, we can reject the null hypothesis. If it is greater, there is a need to maintain the null hypothesis that there are no differences across levels.

In conclusion, the data demonstrated that the experiment with IHE COP performed better (mean = 1.398, SD = 0.367) than the trial without IHE COP. The T-test revealed a significant difference ($p < 0.033$). The null hypothesis was rejected, hence there is evidence to imply that the experiment with IHE COP has a statistically significant higher coefficient of performance than the experiment without IHE COP, with a 95% confidence interval of -1.357 and -0.099.

## 4. CONCLUSION

The combination of $CO_2$ and LPG refrigerants was utilised in the experimental analysis using the REFPROP software design of experiments to determine the COP of the refrigerator with or without IHE. The impact of $C0_2$ and LPG refrigerant blends has been studied. The capillary tube offers large decreases in temperature due to sufficient pressure drop and reduced frictional losses.

Whereas, increasing the entire system operating time, the evaporator cooling rate was improved by increasing the consumption of fluid. The consumption rate is also proportional to the operating time (top) of the system. the results showed that the experimental analysis with IHE COP showed greater performance levels (mean = 1.398, SD = 0.367) than the experiment without IHE COP (mean = 0.67, SD = 0.194). The Samples T-test found the difference to be significant, $p < 0.033$. Consequently, results from this study can be used to select the optimum process parameters for providing better cooling in the evaporator. While expanding the system's running time, the evaporator cooling rate will be improved by increasing fluid consumption. The consumption rate is proportional to the system's running time. The results revealed that the experimental analysis with IHE COP performed better (mean = 1.398, SD = 0.367) than the experiment without IHE COP. T-test revealed a significant difference ($p < 0.033$). Hence, this study results can be used to determine the best process parameters for delivering greater cooling in the evaporator. Introduction of Artificial Intelligent (AI) application software shall be of great benefit in the future study of COP refrigerator with or without IHE.

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