International Research Journal of Innovations in Engineering and Technology (IRJIET)

ISSN (online): 2581-3048

Volume 9, Issue 11, pp 1-11, November-2025

https://doi.org/10.47001/IRJIET/2025.911001

Experimental Study of R-32/R-290 Mixture as a Replacement for R-410A with Mixture Variation Optimization Using the Weighted Product Method

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***Abstract* - The primary issue in refrigeration is environmental pollution caused by synthetic HFC refrigerants like R-410A, which has a very high Global Warming Potential (GWP) of 2088. As a more environmentally friendly alternative, this study explores the potential of a mixture of R-32 (GWP = 675) and R-290 (GWP = 3). Blending these two refrigerants aims to find a composition that significantly reduces global warming impact—with a mixture GWP much lower than that of R-410A—while maintaining similar thermodynamic characteristics to conventional refrigerants. This study focuses on retrofitting an R-410A split AC system with an R-32/R-290 mixture in a 68%/32% composition using a drop-in substitute method, without modifying the main system components. The experiment was conducted with four variations of mixture mass charges: 54%, 57%, 60%, and 63% of the standard R-410A charge mass of 340g. System performance was analyzed based on cooling capacity, power consumption, and Coefficient of Performance (COP) using REFPROP software, and the mixture variation was optimized using the Weighted Product (WP) method. The experimental results indicate that the 63% charge variation most closely approximates the performance of R-410A. To achieve optimal performance, further research is recommended, focusing on the optimization of the capillary tube's diameter and length to reduce the pressure drop. This optimization is expected to enhance system efficiency and further reduce the GWP from 2088 (R-410A) to 460 (R-32/R-290 mixture).**

Keywords: Refrigerant, Retrofit, Hydrofluorocarbon (HFC), Hydrocarbon (HC), R-410A, R32/R290.

I. INTRODUCTION

Science and technology must be utilized ethically for the preservation of nature, which is a prerequisite for the continued existence of humanity. This is exemplified by the use of refrigerants in cooling machines, which contribute to comfort and food preservation through cooling or freezing, but may threaten the environment through ozone depletion and global warming [15]. An Air Conditioner (AC) is an electronic machine that functions to regulate temperature, humidity, and air quality within a room, and its system requires a refrigerant, which is a chemical substance used to transfer heat from one place to another in a cooling system. As refrigerants have developed, they now come in various types to meet the needs of every required cooling system; however, selecting a good refrigerant is not easy, as different types of refrigerants produce different cooling performances [7]. Among the types of refrigerants such as R-32, R-290, and R-410a, manufacturers and importers of air conditioning units tend to prefer refrigerants like R-32 and R-410a to be applied in air cooling systems and traded.

The R-410A refrigerant is one of the refrigerants used as a replacement for R-22 in household air conditioners. R-22 refrigerant belongs to the hydrochlorofluorocarbon (HCFC) group, substances which can damage the ozone layer and contribute to global warming, possessing an Ozone Depletion Potential (ODP) of 0.05 and a Global Warming Potential (GWP) of 1810 [10]. The Indonesian government has set a target to reduce carbon emissions by 20% by 2020, where reducing carbon emissions means reducing fossil energy consumption and improving energy efficiency, with one of the steps being taken by the government being to increase the use of new and renewable energy to 17% by 2025 (Perpres No. 5 of 2006 [8]. Therefore, in the field of air conditioning, the HCFC R-22 is being gradually replaced by R-410A refrigerant. However, R410A still has a relatively high Global Warming Potential (GWP) value which will have a negative environmental impact and are facing phase-down challenges in its use, which has become an interesting concern for researchers to conduct studies in finding substitutes for R410A [3].

Refrigerant R-410A has a relatively small temperature glide, it is classified as an azeotropic mixture; the R-410A mixture consists of a blend of 50% R-32 (difluoromethane) and 50% R-125 (pentafluoroethane). Consequently, for the R-32/R-290 mixture refrigerant, its composition must be

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Volume 9, Issue 11, pp 1-11, November-2025
https://doi.org/10.47001/IRJIET/2025.911001

carefully considered so that the resulting temperature glide closely approximates that of the azeotropic R-410A mixture. Using REFPROP software, the dew point and bubble point temperatures of the R-32/R-290 mixture were calculated to achieve a temperature glide near that of R-410A, for which the ratio of 68%/32% by weight of each refrigerant was determined [12].

R-32/R-290 refrigerant mixture has higher values than R-410A in terms of mass flow rate, compressor work, compressor power, compressor efficiency, refrigeration effect, and refrigeration capacity; however, the Coefficient of Performance (COP) for the R-410A refrigerant is higher than that of R-32/R-290, and the performance of the R-290/R-32 mixture with mass variations of 47%, 50%, and 53% under evaporator inlet temperatures of 22°C and 27°C and condenser inlet temperatures of 28°C and 35°C is still insufficient to replace R-410A refrigerant [3].

Overall, the R-32/R-290 mixture for split AC systems has a positive impact on cooling system performance, COP, cooling effect, and compressor work, with the average electrical power consumption for the mixture refrigerant being 12.9% lower compared to R410A, which is caused by the lower density of the mixture refrigerant resulting in lighter compressor work and lower electric current; however, there are still some shortcomings, including higher evaporator temperatures compared to using R410A, therefore, more focus must be placed on determining the mixture composition ratio, because the process of mixing R-32/R-290 is quite difficult to achieve an azeotropic mixture; therefore, a temperature glide still occurs in the evaporator and condenser areas leading to unstable temperature attainment which causes temperature fluctuations [14].

Based on the above description, this study examines the performance of the R-32/R-290 refrigerant mixture with a blend ratio of 68/32% using 4 different refrigerant charge variations (54%, 57%, 60%, 63%), with the variation optimization conducted using the weighted product method.

The novelty of this research lies in its comprehensive experimental evaluation its comprehensive experimental evaluation of R-32/R-290 refrigerant mixtures as a direct drop-in replacement for R-410A in household air-conditioning systems, combined with optimization of mixture charge variation using the Weighted Product (WP) multi-criteria method. Unlike previous studies that only examined thermodynamic characteristics or fixed mixture ratios, this study introduces four optimized charge variations (54%, 57%, 60%, and 63% of the R-410A mass) to identify the best operating condition based on both performance and environmental metrics. The integration of experimental data with REFPROP-based simulation and WP decision analysis provides a new quantitative framework for selecting eco-friendly refrigerant blends with reduced GWP while maintaining comparable system performance to R-410A. The optimized composition achieves a significant GWP reduction (from 2088 to 460) with minimal efficiency loss, demonstrating practical feasibility for retrofit applications without component modification.

II. LITERATURE REVIEW

A refrigerant is the most crucial component in a refrigeration machine, as it absorbs heat from one location and discharges it to another through the mechanisms of evaporation and condensation [1]. In the refrigeration cycle, the refrigerant functions as a working fluid that undergoes phase changes from liquid to vapor and then back from vapor to liquid, thus forming a closed flow cycle, except for refrigeration cycles that use air as the refrigerant, where the refrigerant remains in the gas phase [4]. The requirements for selecting a refrigerant for a refrigeration unit are that the evaporation pressure must be sufficiently high, the condensation pressure should not be too high, it must have a sufficiently small specific volume, a high coefficient of performance, sufficiently high thermal conductivity, low viscosity in both liquid and vapor phases, it must be non-flammable, non-corrosive to metals, non-toxic, colorless and odorless, have a stable chemical structure, have a low boiling point that must be lower than the designed evaporator temperature, and have a high latent heat of vaporization so that the amount of heat absorbed in the evaporator is large.

The price of CFC (chlorofluorocarbon) refrigerants remains lower compared to its replacement refrigerant (HFC), and the presence of illegal CFC entering Indonesia causes the price of this refrigerant to be lower than it should be; since CFC production is banned, many new CFC factories have switched to producing HFC, consequently CFC production is abundant and its price is relatively cheaper compared to HFC (hydrofluorocarbon) refrigerant [14].

An Air Conditioner (AC) is a machine that functions to cool the air around it, which is the general definition of an AC (Air Conditioner). Because refrigerant is volatile and can change form, from liquid to gas, is the reason it is chosen as the circulated material; refrigerant gas compressed by the compressor can become hot in the condenser pipe, and the circulation of refrigerant gas is restricted in the expansion valve section, causing its pressure to increase further and leading to a temperature drop in the evaporator pipe [11]. Throughout the circulation system, the refrigerant mass remains constant unless leakage occurs in the system, and the refrigerant gas will undergo changes in phase, temperature,

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and pressure, with the circulation of refrigerant gas in an AC unit being called a vapor compression refrigeration cycle [11].

2.1 Refrigerant

A refrigerant is a working fluid that circulates in the refrigeration cycle, utilizing the cooling and heating effects in refrigeration machinery by absorbing heat from one location and discharging it to another through the mechanisms of evaporation and condensation. In refrigeration systems, several refrigerants to be used must be considered, such as chlorofluorocarbons (CFCs), ammonia, hydrocarbons (propane, ethane, ethylene), carbon dioxide, air, and even water (in applications above the freezing point). A thermal system involves the determination of thermodynamic properties, where a property is any characteristic or feature of a substance that can be quantitatively assessed, such as temperature, pressure, and density [1]. And each refrigerant has different characteristic properties that affect the resulting refrigeration effect and COP (Coefficient of Performance) [9]. With the R-32/R-290 refrigerant composition of 68%/32% closely approximating the characteristics of R-410A.

Table 1: Characteristics R-410A & R-32/R-290

Refrigerant	R-410A	R-32/R-290
Composition	50% R32 50% R125	68% R-32 32% R-290
Characteristics		
Molecular Weight (g/mol)	72.585	49.194
Normal boiling point (°C)	-51.44	-
Critical temperature (°C)	71.35	62.105
Critical pressure (bar)	47.539	62.105
Latent heat in 7.2 °C (kJ/kg)	212.22	269.77
Latent heat in 54 °C (kJ/kg)	123.69	123.18

Source: (Tian et al., 2015)

Table 1 shows that at a latent heat of 7.2°C, R32/R290 is 27.1% greater than R410A, and since latent heat constitutes the majority of the cooling capacity, a larger latent heat is beneficial for increasing the cooling capacity.

2.1.1 Flammability Comparison

Refrigerant flammability is classified by ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers), and Table 2 shows the flammability comparison for refrigerant types R-32, R-290, and R-410A.

Table 2: Refrigerant Flammability Level

Refrigerant	Safety class
R-32	A2L
R-290	A3
R-410A	A1

Source:(Kennoy *et al.*, 2016)

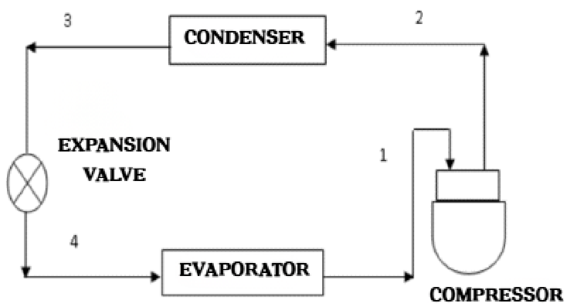
The safety class description is as follows:

1. A1 : Non-flammable.
2. A2L : Low flammability.
3. A3 : Highly flammable.

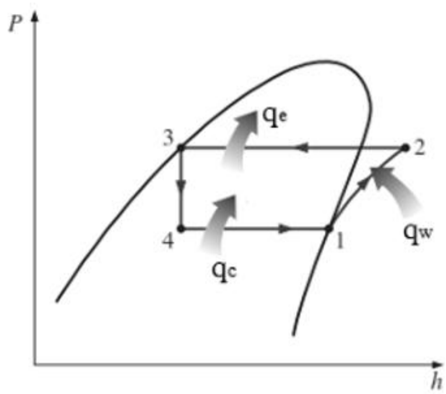
Refrigerants R290 and R32 have flammable properties classified under categories A3/A2L with a Lower Explosive Limit (LEL) of 0.038 kg/m³/0.0306 kg/m³ and an Upper Explosive Limit (UEL) of 0.171 kg/m³/0.710 kg/m³ respectively, along with a practical limit of 0.008 kg/m³/0.061 kg/m³ [12], where the LEL or Lower Explosive Limit represents the minimum concentration of gas or vapor in air that can ignite when exposed to an ignition source, meaning if the concentration of R-290 in air is below 0.038 kg/m³ it will not burn even in the presence of a flame, while the UEL or Upper Explosive Limit indicates that if the gas concentration of R-290 exceeds 0.171 kg/m³ it will not burn due to excessive gas and insufficient oxygen.

2.2 Vapor Compression System

Vapor compression consists of a compressor, condenser, expansion valve, and evaporator, as shown in Figure 1.



(a)



(a)

Figure 1: (a) Schematic Diagram (b) P-h Diagram of vapor compression system

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The following is an explanation of the vapor compression process shown in Figure 1:

1. **Compression Process (1-2)**
   This process is carried out by the compressor and occurs isentropically. The initial condition of the refrigerant upon entering the compressor is saturated vapor at low pressure; after compression, the refrigerant becomes high-pressure vapor. Since this process occurs isentropically, the temperature at the compressor outlet also increases.

2. **Condensation Process (2-3)**
   This process takes place in the condenser. The high-pressure and high-temperature refrigerant from the compressor releases heat, causing its phase to change to liquid. This means that heat exchange occurs in the condenser between the refrigerant and its environment (air), causing heat to transfer from the refrigerant to the cooling air, which makes the refrigerant vapor condense into liquid.

3. **Expansion Process (3-4)**
   This expansion process occurs isenthalpically. This means there is no change in enthalpy but there is a pressure drop and temperature decrease; the pressure reduction process occurs in the expansion valve, which is in the form of a capillary tube that functions to regulate the refrigerant flow rate and reduce pressure.

4. **Evaporation Process (4-1)**
   This process occurs isobarically and isothermally (constant pressure, constant temperature) in the evaporator. Heat from the room will be absorbed by the low-pressure liquid refrigerant, causing the refrigerant to change phase into low-pressure vapor. The condition of the refrigerant upon entering the evaporator is actually a mixture of liquid and vapor.[6]

2.3 Formulation of Vapor Compression System

Cooling load calculation is a primary aspect in designing an air conditioning system, as the results of this calculation determine the required refrigeration capacity to condition the air in a room for optimal comfort [9].

a) Refrigeration Effect

$$Q_{in} = (h_1 - h_4)$$

Source: (Amrullah *et al.*, 2017)

Explanation:
Q_{in} =Refrigerationefect (kJ/kg)
h_1 = Enthalpy entering the compressor (kj/kg)
h_4 = Expansion enthalpy(kj/kg)

b) Compressor Work

$$Q_w = (h_2 - h_1)$$

Source: (Amrullah *et al.*, 2017)

Explanation:
Q_w = Compresor work (kJ/kg)
h_2 = Enthalpy of refrigerant out compressor(kJ/kg)
h_1 = Enthalpy of refrigerant in compressor(kJ/kg)

c) Refrigation Capacity

$$Q_{evap} = \dot{m}\,(h_1 - h_4)$$

Source: (Widodo, 2024)

Explanation:
Q_{evap} = Refrigeration capacity (W)
$\dot{m}$ = Mass flow rate (kg/s)
h_1 = Enthalpy of refrigerant in compressor(kJ/Kg)
h_4 = Enthalpy of refrigerant outexpansion (kJ/Kg)

d) Superheating Temperature

$$\Delta T_{SH} = T_{aktual} - T_{saturasi}$$

Source: (Bunganaen, 2022)

Explanation:
ΔT_{SH} = Superheating temperature(°C)
T_{aktual} = Actual suction line temperature (°C)
$T_{saturasi}$ = Boiling point at a given pressure (°C)

e) Subcooling Temperature

$$\Delta T_{SH} = T_{saturasi} - T_{aktual}$$

Source: (Bunganaen, 2022)

Explanation:
ΔT_{SC} = Subcoolingtemperature (°C)
$T_{saturasi}$ = Saturation temperature at a given pressure (°C)
T_{aktual} = Actual liquid line temperature (°C)

f) Coefficient of Performance

$$COP = \frac{Qin}{Qw}$$

Source: (Fajar *et al.*, 2022)

Explanation:
COP = Coefficient of Performance

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Q_{in} = Refrigeration Effect (kJ/kg)
Q_w = Compressor Work (kJ/kg)

2.3.1 Multi-Criteria Decision Making (MCDM) Method

The MCDM (Multi-Criteria Decision Making) method is used for decision-making with multiple criteria. One of these methods is Weighted Product (WP), which has been applied in thermal system optimization due to its:

- Ability to handle criteria with different units
- Consideration of preference weights for each criterion
- Superiority in generating objective rankings

The following equation is used:

$$Pi = \prod_{j=1}^{n} (aij)^{wj}$$

Source: (Triantaphyllou, 2000)

Explanation:

Pi = Preference value.
aij = xij for benefit criteria.
aij = $\frac{1}{xij}$ for cost criteria..
wj = normalized weight for criterion -j.
xij = value of criterion-j for alternative - i.

There are two criteria: benefit and cost, both yielding different reference values (Pi). A higher Pi value indicates that the alternative is better at fulfilling all criteria, and the weights.

III. EXPERIMENTAL METHOD

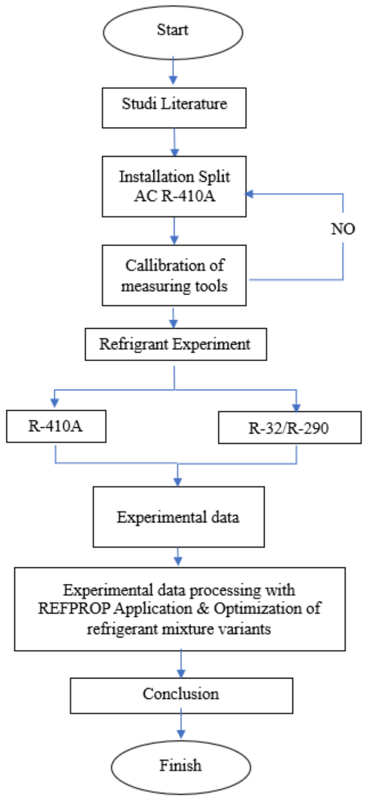
This experimental used Split AC Haier HSU-05GTO03 that was originally designed to operate with R410A, used in the experiment; its designed refrigerating capacity was 5000 BTUH (1.46 kW). Its condenser and evaporator were placed in a polyurethane duct with size of 0.52 x 0.75 m. The air temperatures in the condenser and evaporator were set by placing a heater and a cooler in front of them, respectively, and was controlled using an electronic thermostat.

3.1 Experimental Procedure

In the refrigerant testing stage, the split air conditioner was charged with 340gram of R410A according to system specifications. There are four charged variations in the R-32/R-290 refrigerant mixture, namely 54%, 57%, 60%, and 63%.

The experiment was conducted with an air temperature passing through the evaporator of 27 °C and an air temperature passing through the condenser of 35 °C.

In the data processing stage, the experimental data was simulated using REFPROP software. The values entered into the simulation were based on temperature (°C) and pressure (psia), thereby obtaining the enthalpy value.



'**Figure 2 : Flow Chart**

In the variation optimization stage, we used the weighted product method based on 9 calculation parameters, the weights, and 2 criteria specified in the table 3.

Table 3 : Parameters of Calculation Performance Refrigerant

No	Parameters	Weight	Criteria
1	Evaporator Temperature	5	Cost
2	Cooling Capacity	5	Benefit
3	Coefficient of Performance	4	Benefit
4	Compressor Power	3	Cost
5	Compressor temperature	3	Cost
6	Superheating Temperature	2	Cost
7	Subcooling Temperature	2	Benefit
8	Refrigeration Effect	1	Benefit
9	Compressor Work	1	Cost
	Weights Total	**26**	

- Benefit = The higher the value, the better the outcome.
- Cost =The lower the value, the better the outcome.

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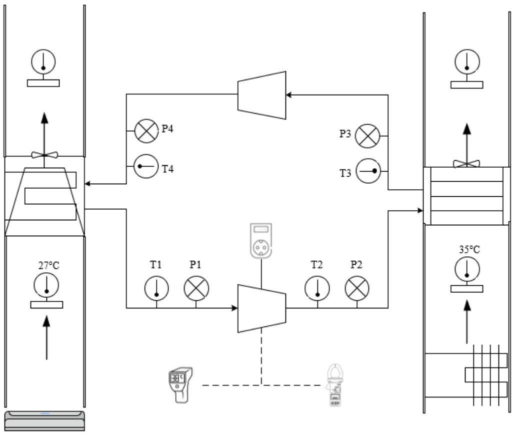
3.2 Experimental apparatus

(a)



(b)

Figure 3: (a) Split AC Haier HSU-05GTO03 (b) Schematic Diagram of Experimental Equipment

The following are the testing steps for R-410A and the R-32/R-290 mixture:

1. After the air conditioner has been running for 1 hour, stabilize the evaporator inlet air temperature by turning on an additional split air conditioner to 27°C, and set the condenser inlet air temperature by turning on the heater to 35°C.
2. Note that the evaporator inlet air temperature thermometer and condenser thermometer have been set to 27°C and 35°C, respectively.
3. Data collection is performed using pressure, temperature, and power measuring instruments for 20 minutes at 2-minute intervals.

IV. RESULTS AND DISCUSSIONS

4.1 Performance Analysis

Based on the experimental data obtained, the following are the results of testing the R-410A and R-32/R-290 refrigeration systems with four refrigerant variations. Figure 4, 5 shows plot diagram P-h, and T-s from the software REFPROP.

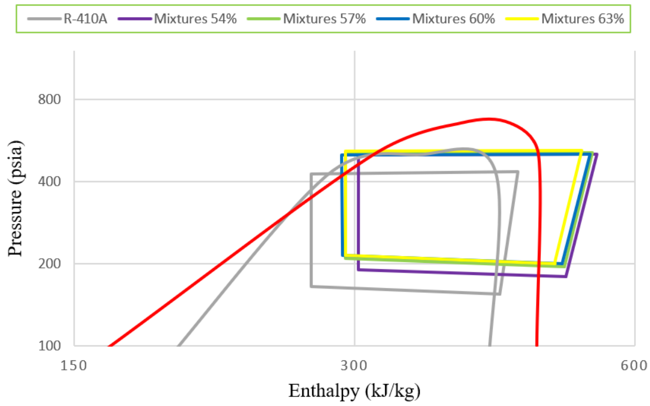


Figure 4 : P–h diagram of R-410A and R-32/R-290 mixtures (54–63%)

As shown on the vertical axis of the Figure 4 P-h diagram, compared with R-410A, the R32/R290 blends operate at higher suction and discharge pressures and show higher liquid enthalpy after condensation. The blends deliver larger specific refrigeration effect (h1–h4 ≈ 200–210 kJ/kg versus ~160 kJ/kg for R-410A), so mass flow required for the same cooling is lower. However, compressor specific work (h2–h1) rises markedly (~33–41 vs ~20 kJ/kg), increasing discharge temperature, power, and condenser heat rejection. Among blends, 60–63% present the best compromise—retaining the higher qL (specific refrigerantion effect) while limiting work relative to 54–57%. Overall, the dataset indicates lower COP than R-410A despite higher capacity per kilogram, requiring valve sizing and condenser checks.

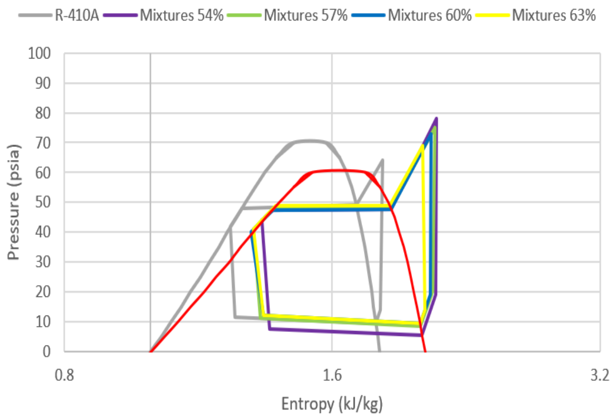


Figure 5 : T–s diagram of R-410A, and R-32/R-290 (54% - 63%)

As shown of the Figure 5, based on the T–s data at four state points (1: compressor inlet, 2: condenser inlet, 3: condenser outlet, 4: evaporator inlet), the R32/R290 mixtures exhibit distinct behavior compared to R-410A. At state 2, discharge temperatures for the mixtures are higher at lower fractions (78 °C for 54%) and gradually decrease with higher

International Research Journal of Innovations in Engineering and Technology (IRJIET)

ISSN (online): 2581-3048

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R290 content (75–73–69 °C for 57–60–63%), making the 60–63% blends more favorable regarding compressor outlet temperature. At state 3, condenser outlet temperatures are similar or slightly lower (≈44→41–40–41 °C), implying comparable heat rejection loads. At state 4, representing the evaporator inlet, R32/R290 54% shows a lower temperature (≈7.5 °C) than R-410A (≈11.5 °C), indicating stronger cooling and dehumidification potential, while 60–63% mixtures are slightly warmer (≈12 °C), suggesting reduced latent performance. The higher entropy rise between points 1–2 for the mixtures reflects increased compressor work, requiring optimization of expansion and mass flow.

Figure 6 – 14 shows the performance R-410A, R-32/R-290 54%,57%,60%,63%.

1. Evaporator Outlet Temperature

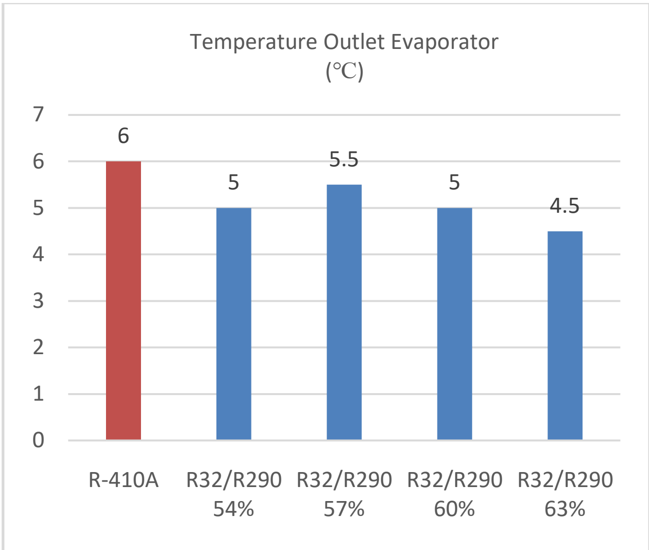

Figure 6 : Temperature Outlet Evaporator

Based on Figure 6, all tested R-32/R-290 mixtures achieved lower evaporator outlet temperatures (4.5–5.5°C) than R-410A (6°C). Among these, the 63% mixture demonstrated the best performance, reaching the lowest outlet temperature of 4.5°C. This is attributed to an optimal synergy between the high operating pressure of R-32 and the high latent heat of vaporization of R-290, which together facilitate highly effective heat absorption. It should be noted, however, that this lower temperature increases the potential for evaporator frosting, which could adversely affect system performance.

2. Cooling Capacity

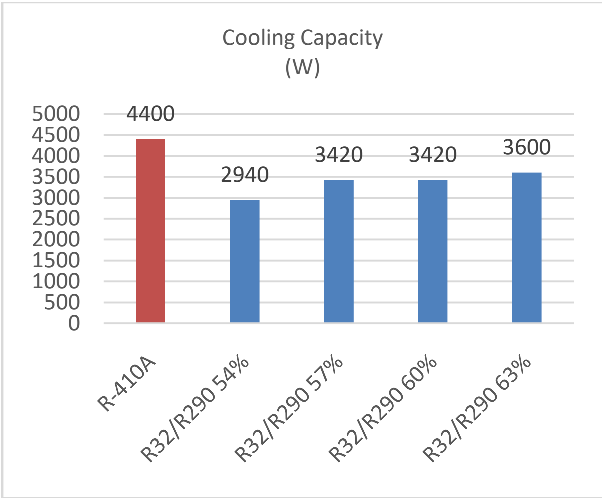

Figure 7 : Cooling Capacity

Based on Figure 7, the comparison of cooling capacity shows that although the R-32/R-290 mixture has a better refrigeration effect per kilogram, R-410A achieves a higher total capacity (4400 W). All mixture variations result in lower capacities, with an increasing trend along with mass addition: the 54% variation only reaches 2940 W (the lowest, a 33.18% decrease), the 57% and 60% variations both achieve 3420 W (a 22.27% decrease), and the 63% variation reaches 3600 W (the highest among the mixtures, an 18.18% decrease). This phenomenon is caused by a combination of factors including mass flow rate, vapor density, and physical system limitations such as the size of the capillary tube and evaporator. Although the 63% variation demonstrates the best heat transfer capability among the mixtures, the overall thermodynamic characteristics of the mixtures still result in a lower total cooling capacity compared to the near-azeotropic refrigerant R-410A.

3. Coefficient of Performance

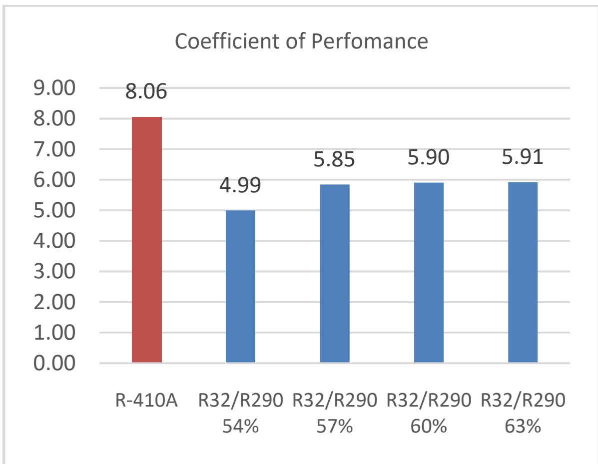

Figure 8 : Coefficient of Perfomance

ISSN (online): 2581-3048
Volume 9, Issue 11, pp 1-11, November-2025
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Figure 8 shows that R-410A achieves the highest COP value of 8.06, attributable to its combination of high refrigerating capacity (4400 W) and low compressor power consumption (548.83 W). In contrast, all R-32/R-290 mixture variations exhibit lower COP values ranging from 4.99 to 5.91. Among these mixtures, the 63% variation demonstrates the best performance, resulting from its optimal balance between increased refrigerating capacity (3600 W) and higher compressor power consumption (599.31 W). Overall, the higher compression ratio and limited cooling capacity of the mixtures prevent the system efficiency from matching that of R-410A, although the 60% and 63% variations show the closest approximation to its performance.

4. Compressor Power

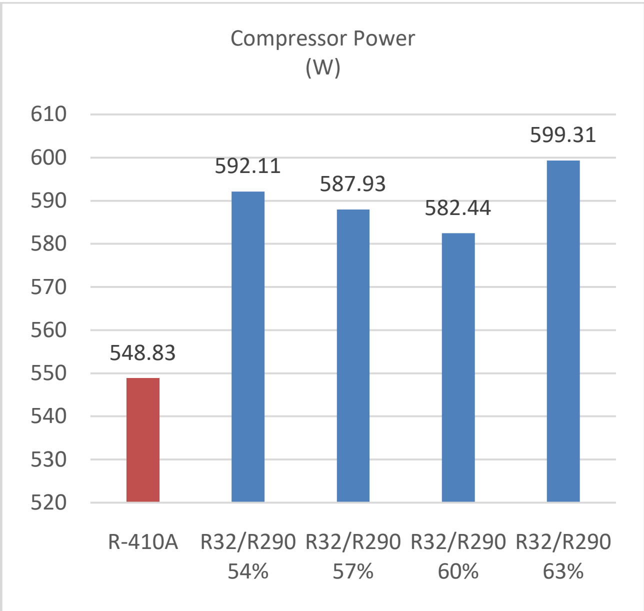

Figure 9 : Compressor Power

Figure 9 shows that R-410A demonstrates the lowest compressor power consumption at 548.83 W, while all R-32/R-290 mixture variations require higher power input. The highest power consumption was recorded for the 63% variation (599.31 W) and the lowest for the 60% variation (582.44 W), with the 57% and 54% variations consuming 587.93 W and 592.11 W respectively. This compressor power level is directly proportional to the compressor work, where R-410A shows the lowest value (19.83 kJ/kg), while the R-32/R-290 mixtures exhibit higher values ranging between 32.93-40.65 kJ/kg.

5. Compressor Temperature

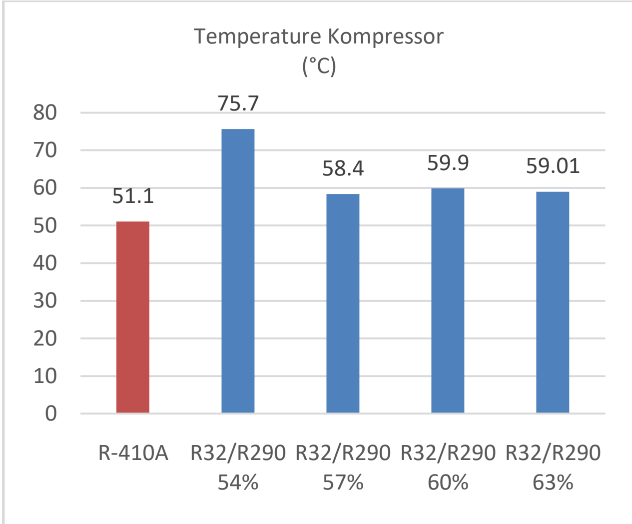

Figure 10 : Compressor Temperature

Based on Figure 10, the compressor temperature of R-410A was recorded as the lowest (51.1°C), while all R-32/R-290 mixture variations exhibited higher temperatures. The 54% variation reached the highest peak (75.7°C) due to its highest compression ratio and compressor work per unit mass. In contrast, the 57%-63% variations stabilized within the range of 58-60°C, corresponding to a decrease in compressor work. Although higher than that of R-410A, these three variations (57%-63%) are more recommended from an operational perspective, as their controlled temperatures can minimize the risk of lubricant degradation and component wear compared to the 54% variation.

6. Superheating Temperature

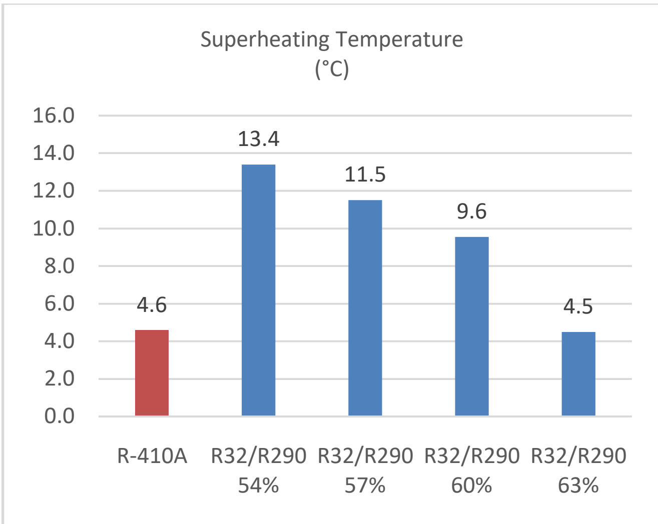

Figure 11 : Superheating Temperature

Based on Figure 11, all R-32/R-290 mixture variations yield higher superheating values compared to R-410A (4.6°C),

International Research Journal of Innovations in Engineering and Technology (IRJIET)

ISSN (online): 2581-3048

Volume 9, Issue 11, pp 1-11, November-2025

https://doi.org/10.47001/IRJIET/2025.911001

with a decreasing trend observed as the refrigerant charge mass increases. The 54% variation recorded the highest value (13.4°C) due to insufficient liquid refrigerant in the evaporator, while the 63% variation achieved the lowest value (4.5°C), equivalent to that of R-410A. These results confirm that the 63% variation represents the optimal composition, exhibiting superheating characteristics that most closely align with the normal operational conditions of standard refrigeration systems.

7. Subcooling Temperature

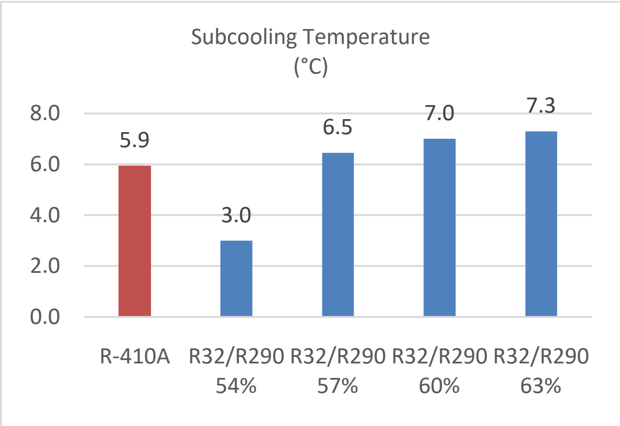

Figure 12 : Subcooling Temperature

Based on Figure 12, the R-32/R-290 mixtures demonstrate significant performance variations compared to R-410A (5.9°C). The 54% variation recorded the lowest value (3.0°C), indicating suboptimal cooling in the condenser, while the 57%-63% variations showed a gradual improvement up to 7.3°C, reflecting better heat transfer effectiveness. With the highest and most stable subcooling values, the 60% and 63% variations prove superior in maintaining expansion process stability and overall system performance consistency.

8. Refrigeration Effect

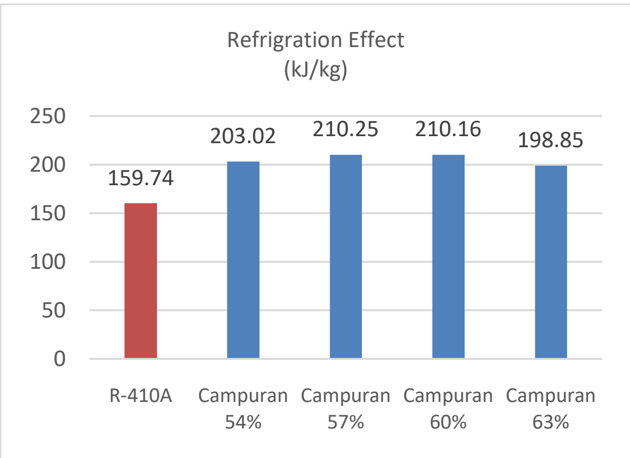

Figure 13 : Refrigeration Effect

Figure 13 shows that the analysis of refrigeration effect reveals all R-32/R-290 mixtures achieve a 24-32% improvement compared to R-410A, with optimal performance at the 57% charge (210.25 kJ/kg) due to its balanced thermodynamic characteristics and flow rate. While the 54% charge is constrained by low flow rate, the 60% and 63% charges experience diminished efficiency resulting from reduced contact time in the evaporator.

9. Compressor Work

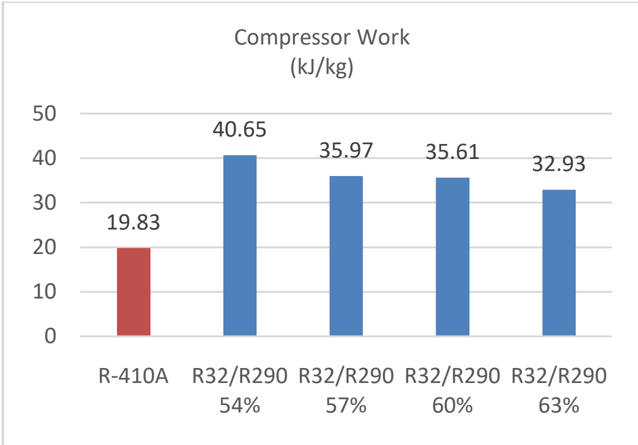

Figure 14 : Compressor Work

Based on Figure 14, the compressor work of R-410A (19.83 kJ/kg) is significantly lower than all R-32/R-290 mixture variations. The highest value was recorded for the 54% variation (40.65 kJ/kg), attributed to its higher compression ratio, while the 63% variation showed the lowest value among the mixtures (32.93 kJ/kg), which remains 66% higher than R-410A. This confirms that zeotropic mixtures require greater compression energy compared to the near-azeotropic refrigerant R-410A.

4.2 Variation Optimization

Table 4: Variation Optimization Result

Refrigerant	Preference Value(*Pi*)	*Ranking*
R-410A	1,614	1
R-32/R-290 63%	1,525	2
R-32/R-290 60%	1,396	3
R-32/R-290 57%	1,321	4
R-32/R-290 54%	1,123	5

V. CONCLUSION

Based on the experimental investigation and performance analysis, the R-32/R-290 mixtures show promising potential as a drop-in substitute for R-410A in residential split air-

ISSN (online): 2581-3048
Volume 9, Issue 11, pp 1-11, November-2025
https://doi.org/10.47001/IRJIET/2025.911001

conditioning systems. All tested mixtures achieved lower evaporator outlet temperatures and higher refrigeration effects than R-410A, confirming their strong cooling capability. However, the mixtures required higher compressor power and exhibited lower overall COP values due to increased compressor work. Among all variations, the **63% charge mixture** demonstrated the best overall performance, achieving the lowest evaporator outlet temperature (4.5 °C), moderate compressor temperature (≈ 58 °C), and COP value closest to R-410A. Optimization using the Weighted Product method ranked the 63% mixture as the most suitable alternative. Furthermore, the R-32/R-290 mixture can significantly reduce the system's Global Warming Potential from 2088 to approximately **460**, offering an environmentally sustainable refrigerant option without requiring system modification.

VI. RECOMMENDATIONS FOR FUTURE RESEARCH

For further study, it is recommended to:

1. Optimize the capillary tube geometry (diameter and length) to reduce pressure drop and improve the energy efficiency ratio (EER).
2. Investigate long-term reliability and safety aspects, including lubricant compatibility and leak behavior, given the mild flammability of the mixture.
3. Analyze charge optimization under different ambient temperatures (e.g., 30 °C, 35 °C, and 40 °C condenser inlets) to validate performance under tropical conditions.
4. Develop numerical and CFD simulations to predict flow and heat-transfer characteristics in evaporator and condenser coils for various R-32/R-290 ratios.
5. Evaluate economic feasibility by comparing lifecycle cost and payback period relative to standard R-410A systems.

ACKNOWLEDGEMENTS

This research is supported by the Training Centre, Diponegoro University and we would like to express our gratitude.

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Citation of this Article:

Gavy Finda Koernia, Rio Rizki Ghifari, & Berkah Fajar TK. (2025). Experimental Study of R-32/R-290 Mixture as a Replacement for R-410A with Mixture Variation Optimization Using the Weighted Product Method. *International Research Journal of Innovations in Engineering and Technology - IRJIET*, 9(11), 1-11. Article DOI https://doi.org/10.47001/IRJIET/2025.911001

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