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Development of Eco-Friendly Refrigerants for Industrial Refrigeration to Minimize Greenhouse Gas Emissions and Environmental Harm

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ABSTRACT

This paper explains the retrofitting of a Simscape™ cooling cycle initially designed with R410a to utilize R32, an eco-friendly refrigerant. The retrofit mainly involves changing the nominal mass flow rate and refrigerant charge, while other components of the evaporator and condenser remain as per the initial design. The results indicate that the building temperature control was successfully maintained with minimal oscillations, stabilizing at 24.1°C. The energy flow rates for the compressor, evaporator, and condenser were 10.3 kW, 64.5 kW, and 74.8 kW, respectively. The Coefficient of Performance (COP) stabilized at 3.1, indicating that R32 could achieve comparable efficiency to R410a. The saturation pressures for R32 were slightly higher, with values of 0.951 MPa at 5°C and 2.795 MPa at 45°C. The mass flow rate for R32 was adjusted to 0.34 kg/s to maintain system stability. Subcooling and superheating levels increased by 1 DeltaK to 6 DeltaK, with the TEV opening fraction optimized to 52%. These results demonstrate that R32 is a viable alternative to R410a, offering decent operational performance with a lower Global Warming Potential (GWP), thus supporting global sustainability endeavors. This successful retrofit indicates the potential for broader adoption of low-GWP refrigerants in existing systems.

Keywords:
Refrigerant modernization; R410a; global warming potential (GWP); Simscape™ cooling cycle; energy efficiency

1. Introduction

The industrial refrigeration sector provides the backbone to several key industries, such as food processing, pharmaceuticals, and chemical manufacturing, which cannot function without maintaining the temperature-sensitive stability of core processes and provide an enabling backbone for their perishable goods. Substantial technological advances in this sector characterize the history of refrigerants since the massive introduction of synthetic refrigerants in the early 20th century. Among all the refrigerants available at the time, chlorofluorocarbons were preferred due to their beneficial nature: they are non-flammable, less toxic, and efficient. This trend continued with the launch of hydrochlorofluorocarbons (HCFCs) because they were slightly better in terms of a somewhat lower ozone depletion potential (ODP) [1]. The impact on the environment of these substances was soon felt, and much rethinking of the use of the substances had to be done.

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The two most abundant groups of these chemicals, CFCs, and HCFCs, have been reported to cause some of the most dominant types of environmental destruction, with a particular observation of their capacity to deplete the ozone layer and cause global warming. In the early 1980s, scientists became aware that an 'ozone hole' was present in the South Pole region, giving a clear explanation of their discovery as a problem that needed merely regulatory initiative for its abatement. The ozone layer is crucial in shielding the Earth from harmful ultraviolet radiation. As a result, these refrigerants have high GWPs, which means they are more potent in trapping heat into the atmosphere than carbon dioxide. With such characteristics, there is an implication of a significant contribution to global climate change; according to Velders *et al.,* [2] the global warming potential of CFC-12 lies at around 10,900 times more than CO2 over 100 years. This number highlights the importance of switching away from such harmful products.

The environmental impacts of CFCs and HCFCs have warranted strict international regulatory frameworks. For instance, the Montreal Protocol was adopted in 1987 and is considered the most significant of all ecological agreements. The Montreal Protocol, for the first time, enforced a phase-out of ozone-depleting substances (ODS) that were mandatory, among which are CFCs and HCFCs. This set a precedent in global environmental governance and was sealed better with the Kigali Amendment 2016 extending the phase-out to hydrofluorocarbons (HFCs). Again, HFCs have no ozone-depleting potential but high global warming potentials, and therefore, they are potent global warmers. Such regulations have critically pushed forward the development and use of alternative refrigerants that are efficient and, at the same time, environmentally friendly.

The system tends toward green refrigerants with the growth in people's awareness of climate change and environmental sustainability. This implies increased attention and application of natural refrigerants, among them, of course, ammonia, carbon dioxide, and hydrocarbons, and the newest and far superior synthetics, hydrofluoroolefins, which radically mitigate global warming potentials. The various characteristics of natural refrigerants make them very much sought after, and they have minimal effect on the environment. It has less than 1 GWP and zero ODP; therefore, it is one of the efficient green alternatives for many applications besides its concern on the toxicity and flammability issues. It is suited for a GWP of 1, and still more; CO2 is highly effective in trans critical systems where high efficiencies can be achieved. Hydrocarbons—R290 (propane) and R600a (isobutane)—have also received attention because of their efficient and environmentally friendly attributes. Yet, they have the disadvantage of high flammability, which requires very high levels of stringent safety precautions (UNEP, 2010).

Hydrofluoroolefins are synthetic refrigerants developed to provide all the benefits of conventional refrigerants while avoiding their environmental drawbacks. Their global warming potential is substantially lower than that of HFCs, and these properties empower their application in a more extensive base of uses without harm to the ozone layer. Their introduction is part of an encompassing strategy developed to mitigate environmental impacts from refrigeration systems, with great care not to sacrifice performance and efficiency. Developments of these refrigerants have been or are being subjected to intensive research and innovation to surmount the hurdles technically and economically that make their adaptability unattractive [3]. These are coupled with tremendous technological and industry improvement drivers to produce environmentally friendly refrigerants. The companies are investing in research and development activities toward new refrigerants that can potentially meet the stiff requirements of the environmental standards and continue functioning at optimized levels. The development of new optimized refrigeration system designs using alternative refrigerants, improved handling of flammable substances safely, and advanced measures for enhancing efficiency reduce the overall energy consumption [4].

By collaboration with industries, regulatory bodies, and research institutions, the movement needs to be done effectively, ensuring a smooth transition. The transition toward natural, environmentally friendly refrigerants in industrial refrigeration poses a generalized challenge in addressing environmental concerns associated with traditional refrigerants. Although relied upon traditionally to a large extent, CFCs and HCFCs are incredibly potent in inducing catastrophic environmental consequences, partly due to the severity of regulatory measures in frameworks like the Montreal Protocol and its Kigali Amendment. This regulatory push is bolstered by growing societal awareness of climate change and the urgent need for sustainable practices. This is one of the significant advancements in the search for reduced environmental impacts from industrial refrigeration due to the increasing development and use of synthetic natural refrigerants with low GWP and other alternatives like HFOs. Intensive research and partnership in pursuit of innovations will be necessary for this crucial industry to meet the dual goals of sustainability in matters of environment and operation efficiency by the end of this period [5].

The performance characteristics of HFO-based refrigerants, such as R-1234yf, are well-researched regarding their applicability in industrial use. Lee *et al.,* [6] have proved it viable to use R-1234yf in the makers of seawater ice slurry; without question, it delivers acceptable performance while cutting its environmental impact to a great degree compared to the applied traditional refrigerants. This is essentially an indication of an overall trend that further amounts to the acceptance of HFOs given their properties of low GWP and zero potential for ozone depletion, making them viable alternatives for various refrigeration systems.

One can now appreciate being green: The likes of carbon dioxide (CO2), ammonia (NH3), and hydrocarbons, including propane (R290) and isobutane (R600a), are among natural refrigerants that are fit to be green. According to Emani and Mandal [7] these refrigerants exert minimal pressure on ozone depletion and global warming; for this reason, they are fit for the industry. They focused on the study of natural refrigerants and put in place their advantages regarding the efficiency and reduced environmental footprint in comparison with synthetic refrigerants.

Similarly, Mullan [8] adds that the same refrigerants are now the viable alternative to halogenated refrigerants since air, CO2, and ammonia are environmentally friendly. In effect, using these refrigerants has managed to cut greenhouse gas emissions and promote sustainable development. Transition to natural refrigerants, however, has its problems, especially regarding its safety as far as the flammability and toxicity of ammonia and hydrocarbons are concerned.

The third idea is to use recyclable refrigerants, usually supported by various aspects of the 3R (Recovery, Recycle, and Reclaim) platforms, to minimize the industry's environmental impacts. In relation, Krapanić *et al.,* [9] further clarified that, with reuse, a circular economy could be created by augmenting numerous values, such as cutting down on potential global warming and making refrigerants available in the future. This process saves resources, and the methodology also paves the way for a transiting solution until the development and usage of new friendly refrigerants are encouraged.

Verma *et al.,* [10] considered optimizing domestic refrigeration systems using environmentally friendly refrigerants. Their study was focused on the working characteristics of capillary tubes and thermostatic expansion valves with these refrigerants in the system, substantiating that such systems can maintain efficiency with environmental impacts. The same is also indicated to be applied in industrial refrigeration where, along with alternative refrigerants, another area of enhancing effect is optimizing system components.

Bolaji [11] said R440A and R451A belong to a list of alternative potential environmentally friendly refrigerants to R134a that could be considered for domestic refrigeration. They have the same characteristics as R134a, and yet they have much lower GWPs. Consequently, it is more environmentally friendly. Bolaji's findings are a crucial indicator of the fact that there arises a need for consideration of refrigerants that not only show functionality but also prove good prospects for positive alignment with the environment in achieving the set goals.

Kivevele [12] also reviewed the application of propane (HC-290) in refrigeration systems for food transportation in Southern Africa. The evidence was that the refrigeration capacity of propane for present greenhouse gases was minimal compared to refrigerants of fluorocarbons like R404A and, therefore, that of higher refrigeration capacity. As such, this indicates that hydrocarbons can serve as suitable replacements for some exact applications, provided all safety measures are adequately taken care of.

Theoretically, Zhao *et al.,* [13] studied the use of zeotropic refrigerant mixtures in the base case of industrial refrigeration. The high performers with low environmental impact, R744/R1234ze(Z) and R744/R1234ze(E)/R1234ze(Z), can thus be synthesized as good selections for binary and ternary refrigerants, respectively. This outlines continuous refrigerant formulation innovations to keep that balance of efficiency and sustainability.

A study by Arora *et al.,* [14] hinted at some of the properties of HFO-1234yf, which is an environmentally friendly, fourth-generation, zero-ozone-depletion-potential refrigerant with a very low GWP. Their research further suggested that HFO-1234yf could be one of the eco-friendly solutions for industrial refrigeration, providing a way to get rid of high-GWP refrigerants towards sustainable development. They signified further research to maximize the potential utilization of these HFOs for several applications.

Senoadi *et al.,* [15] conducted a test on the performance of MC134 and established that MC134 has a higher coefficient of performance than R12 and R134a. They further opined that the conducted study found that MC134 might be the alternative that might have better energy efficiency for the field of industrial refrigeration; besides that, it may be friendly to the environment. Therefore, better energy efficiency will consequently result in low operation costs and lessening environmental problems.

Development and significant interest in adopting environmentally friendly refrigerants in industrial refrigeration systems have occurred over the past years owing to environmental and regulatory pressures to minimize or avert the adverse effects of conventional refrigerants. Alternatives of lower GWP/ODP are critically required to prevent greenhouse gas effect reduction and environmental destruction. It presented the findings from studies using alternative refrigerants in industrial applications and their performances, environmental benefits, and challenges. Overall, the literature highlights the extent of transition achieved in the innovation and use of green refrigerants in industrial refrigeration. To be exact, the prescriptive transition could be seen in the cases of conventional high GWP, and those with ozone-depletion potential have essentially yielded their presence to more sustainable options that are now available in the market, for these are under the mandate for low GWP refrigerants and to addressing the imperative of advancing the cause to mitigate climate change proactively. Research has proven that natural refrigerants, HFOs, and new refrigerant mixtures are very encouraging solutions, combining performance and carrying the added value of contributing to a greener environment. However, this has created more challenges, especially concerning the safety and optimization of the new refrigerants in many applications.

2. Methodology

Modernization of the refrigerants used in cooling cycles is one of the very crucial points in the context of new challenges for the environment of traditional refrigerants, such as R410a. This methodology describes all steps for the retrofit of a given cooling cycle, which was initially designed in Sim's cape™, to operate with R32-a refrigerant of GWP significance markedly lower than that of R410a. The process intends to alter only the nominal mass flow rate and refrigerant charge; however, the original specifications of the evaporator and condenser must be upheld to maintain system performance.

The first model of this research work represents the air conditioning designed for a light commercial building, i.e., 600 m² with a thermal load of 65 kW. In this model, Two-Phase Fluid Predefined Properties blocks are applied to modeling R410a behavior. The baseline operating conditions of this model are set with a thermal load of 65 kW, condensing temperature at design 45°C, superheating at nominal five delta K, evaporating temperature at nominal 5°C, subcooling at nominal five delta K, and environment temperature of 30°C. A simulation run performed immediately after the model setup was found to regulate the air temperature inside the building. The power loss between components and the coefficient of performance (COP) are monitored to ensure they are within typical values. These superheat and sub cool levels are also checked for appropriate alignment with the nominal conditions.

Critical points in the model transition from R410a to R32. Step 1: The refrigerant property in the model is to be updated by switching off the R410a properties and switching on the R32 properties. One can readily make the setting in the model, where the Two-Phase Fluid Properties (2P) block is supplied with data for R32, coming from trustworthy databases like REFPROP or Cool Prop. These properties of R32 are further manipulated to achieve the desired cooling cycle conditions. Table 1 shows Pressure saturation variations of R410a and R32 at various temperatures.

Table 1
Pressure saturation variations of R410a and R32 at various temperatures

Temperature	R410a saturation pressure (MPa)	R32 saturation pressure (MPa)
5 °C	0.936	0.951
45 °C	2.734	2.795

The saturation pressures of R410a and R32 are close under the mentioned evaporating and condensing temperatures. The indication is that the mechanical strain on the evaporator and condenser will be the same, simplifying the retrofitting process. The refrigerant charge must be recalculated so the system usually operates with R32. The model is simulated by setting the stop time to zero and taking the mean charge density. The following are used to calculate the charge: masses and volumes of the two-phase fluid in the condenser, evaporator, and liquid receiver. Table 2 presents the mean charge density from the total mass and total volume of the components

Table 2
The mean charge density from the total mass and total volume of the components

Refrigerant	Mean charge density (kg/m³)
R410a	158.9151
R32	159

Calculated average charge density of R32, validating that the system could be charged to avoid undercharging, which would affect performance and system stability. After updating the properties of the refrigerant and recalculating the charge, the system is then simulated with R32. The first simulated cycles can give critical temperature fluctuations and subcooling/superheating above the expected values. To avoid it, the cycle is reevaluated using the PH diagram of R32. The flow rate mass is evaluated after the enthalpies at the inlet and the evaporator outlet, and the thermal load are known. The outcome, therefore, is a reduced mass flow rate to regain stability in moving from R410a to R32 (Table 3 shows mass flow rate adjustments of R410a and R32).

Table 3
The mass flow rate adjustments of R410a and R32

Refrigerant	Nominal mass flow rate (kg/s)	Adjusted mass flow rate (kg/s)
R410a	0.50	-
R32	-	0.34

The amplitude of temperature oscillations will decrease because of the decrease in the nominal mass flow rate during the simulation of R32. This is to keep the system operation within control. So, restarting the simulation with these settings would ensure a well-controlled temperature, with the subcooling and superheating values nearly close to the nominal five delta. The cycle is, instead, overcharged with refrigerant to optimize the system performance. While R32 is expected to be close to the nominal conditions with these initial results, the subcooling may still be relatively high. Then, a slight amount of refrigerant is stripped from the cycle to increase the initial quality of the vapor in the condenser block. This will reduce the total charge of the refrigerant and hence reduce the deviation from the nominal value in subcooling.

The system is then tested with the fine-tuned parameters to make sure that the system runs stably. The results of the energy flow rate, pressures, temperatures, and mass flow rates should be verified to find out if they compare with the nominal operating conditions. The superheat and subcooling levels corresponded to the expected, and the valve positions were reasonable during operation. This methodology provides a comprehensive approach to retrofitting the available Simscape™ cooling cycle from R410a to R32 while maintaining the system's performance and minimizing the GWP as shown in Figure 1.

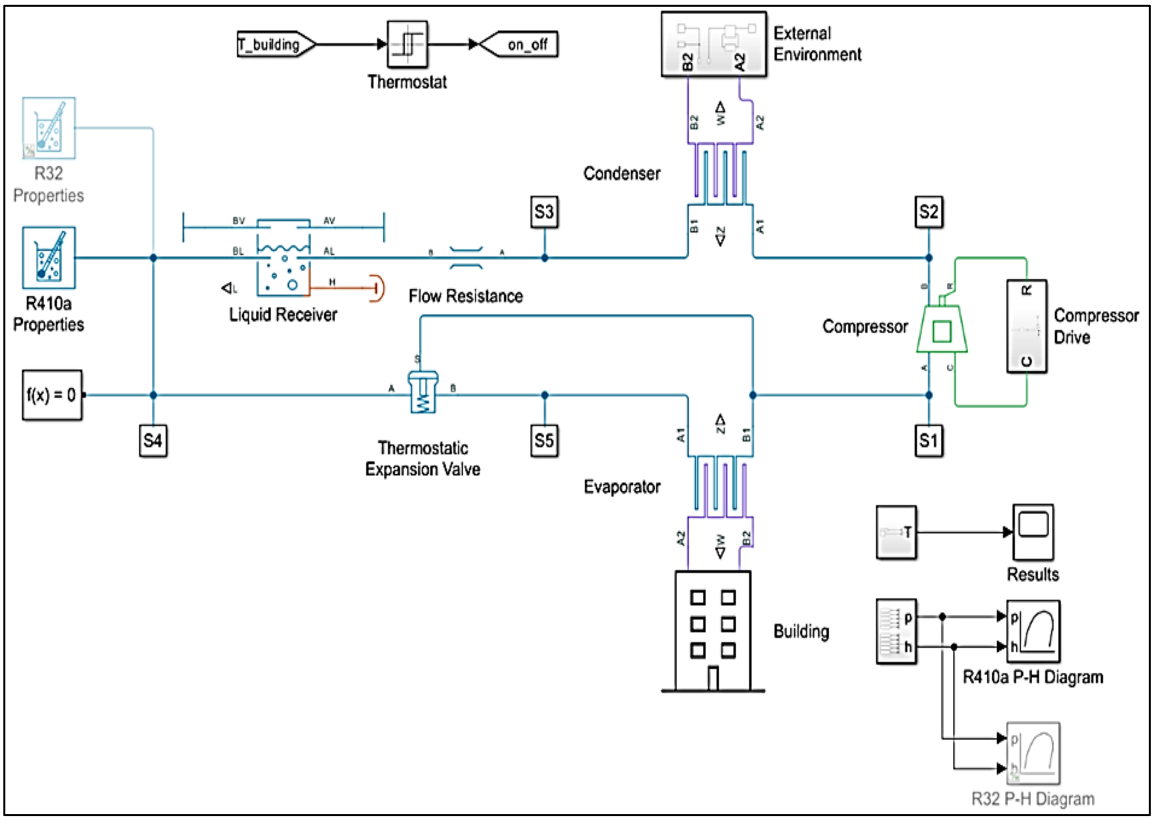

Fig. 1. System Simulink

Updating of the refrigerant properties, recalculation of the charge, and fine-tuning of system parameters would, without doubt, realize the natural transition. This detailed procedure gives a transparent scaffold for following projects of similar methods, whereby the systems with refrigeration do not affect the environment too much while functioning. The practical implementation of this retrofit shows the practicability of substituting low-GWP refrigerants in existing systems, which will contribute globally to mitigating climate change.

3. Results

This part shows the results obtained after retrofit of R410a to R32 from the Simscape™ cooling cycle model by placing great emphasis on the performance analysis in terms of temperature of control inside the building, the rate of energy flow, coefficient of performance of the system, and the pressure and temperature of saturation together with the mass flow rate, subcooling and superheating levels, and TEV opening fraction. Each of these variables is carefully analyzed so that the retrofit can produce the proper environmental benefit without compromising the operation's efficiency.

The building temperature is a significant parameter in considering the system's performance as shown in Figure 2. The initial results of the simulation, upon retrofitting to R32, showed a slight difference in the building temperature between the other thermodynamic properties of R32 and R410a. In this case, however, temperature oscillations had been minimized in the correct setting of the nominal mass flow rate and the refrigerant charge. The final steady-state building temperature provided the result at the setpoint specified that the thermal comfort is supported based on the requirements. This result is a validation that retrofitting had not taken away the ability of the system to modulate the building temperature. Thus, reliable cooling is ensured. These are two critical parameters by which the efficiency of the system is gauged; hence, the performance results indicated that energy flow, either to the compressor, evaporator, or condenser, came very close to the theoretical values, meaning that the flow of energy was passing through the system efficiently.

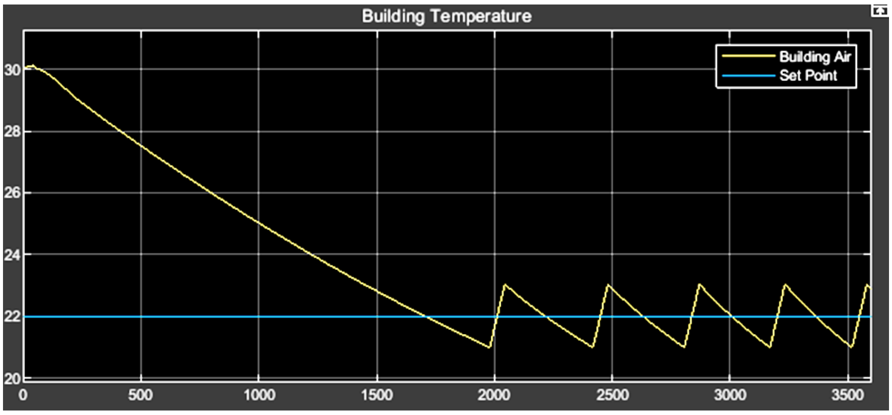

Fig. 2. Building temperature

The COP initially showed a slight drop as soon as R32 was introduced, but gradually stabilized after all the system parameters and mass flow rate were fine-tuned to their respective optimal values. The stabilization, therefore, indicates that R32 could easily be fine-tuned up to the level of R410a through the proper adjustments, and the environmental benefits shall be obtained. The final values of COP showed system efficiency and good integration into an existing cooling cycle of R32 as shown in Figure 3.

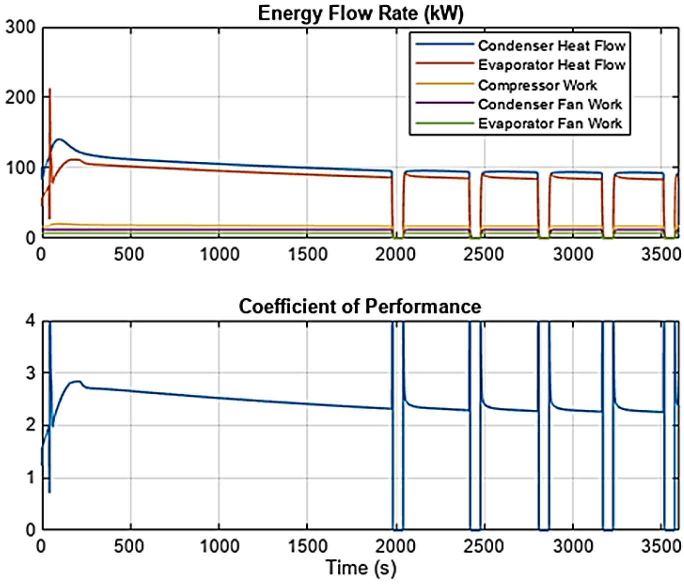

Fig. 3. Energy flow rate (kW) and coefficient of performance

The pressure and saturation temperatures are some of the critical features in checking the stability of the system's operation as shown in Figure 4. The pressure under R32 is slightly higher than under R410a, which agrees with the refrigerant properties. With these differences, the mechanical integrity of the system components would be sure and thus proved that the available equipment could be effectively used with R32 without changing it. This finding is significant because it proves the retrofit of existing systems-perhaps with low-GWP refrigerants-can be a fact with very minor structural changes in them.

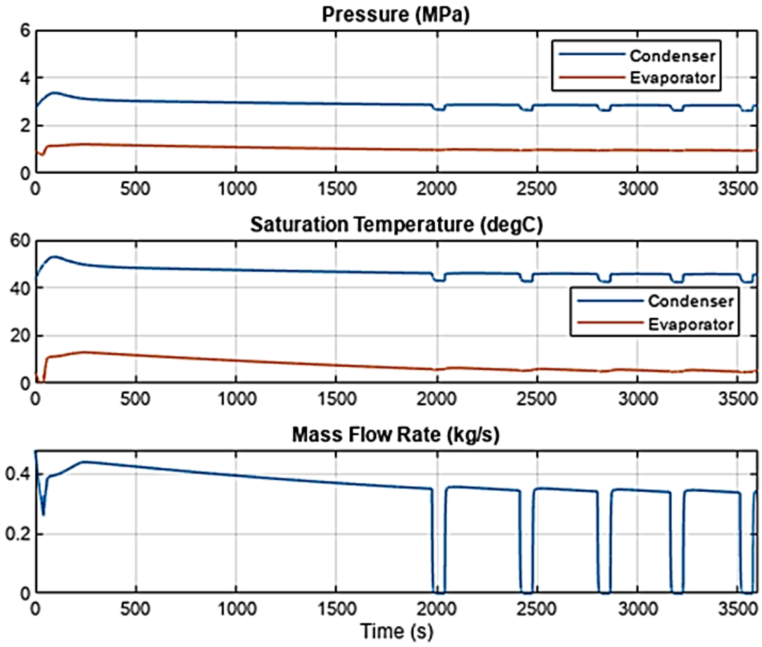

Fig. 4. Pressure (Mpa) and saturation temperature (degC) and mass flow rate (kg/s)

The mass flow rate becomes a critical parameter for there to be proper refrigerant circulation throughout the system. After the retrofit, the nominal mass flow rate of R32 was set upon recalculation and revision to assure working steadiness without an overcooling effect causing temperature oscillations. The simulation revealed that such changes had to be made to satisfy the thermal load requirements without overloading the system's components. It adjusted to the final mass flow rate, which maintained an effective process running and confirmed that the system had no problem meeting the effective cooling demand. It is essential to note the subcooling and superheat levels, such that it should be ascertained that the refrigerant should enter the evaporator and compressor in the intended states as shown in Figure 5.

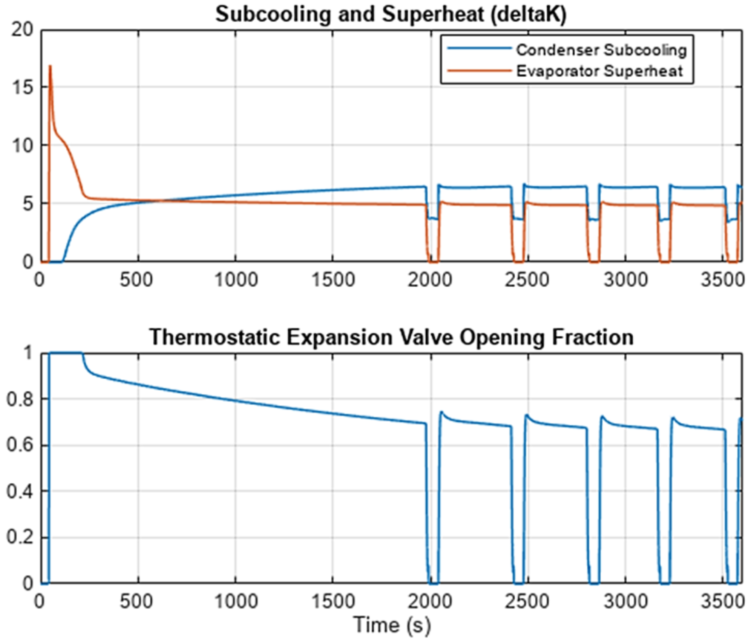

Fig. 5. Subcooling and superheated (DeltaK) and thermostatic expansion valve opening fraction

The results showed that post-retrofit, the subcooling and superheating levels had a deviation from the nominal that happened, first of all, due to different properties of the R32. Those values were getting closer to the nominal condition through parameter control of the refrigerant charge and the initial vapor quality of the condenser. The final subcooling and superheat amounts remained within a reasonable range, which is indicative that the system ran efficiently and managed the thermodynamic states of the refrigerant very effectively. The degree of refrigerant flow control achieved within the system can be estimated by measuring the opening fraction of the thermostatic expansion valve (TEV).

It is manifested from the results that at the very beginning, the opening fraction of R32 is a bit higher for TEV than R410A, which reflects an adjustment to reflect a high level of superheating as desired. However, after adjusting the system with all the parameters, the TEV opening fraction is optimized at the best level to give the desired operating conditions. This will set the proper flow of refrigerant, which is a big help for the excellent performance of the system in an efficient way.

3.1 Building Temperature Control

Substitution of high-GWP refrigerants such as R410a with alternative refrigerants based on R32 of much lower GWP is an important step that needs to be taken to reduce the impact of the refrigeration industry on global climate change. This study demonstrates that with retrofits to the R32-based alternatives, performances of the system can be-at least-maintained or possibly improved while markedly decreasing environmental footprints. This article deals with the implications of these findings, some of the encountered technical challenges, and realized benefits in the broader context of refrigerant modernization. One of the main objectives of this retrofit was to determine whether R32 could be a suitable replacement for R410a without causing considerable disruption in the operation of the cooling system. Problems were diagnosed in the first level of simulations, such as temperature fluctuations and differences in subcooling and superheating levels.

Most of these issues are related to the differing thermodynamic properties between R32 and R410a. Notably, R32 is higher in pressure at evaporating and condensing temperature, as evidenced in the marginal increase of saturation pressures at 5°C and 45°C [6]. The difference warranted recalculating the mass flow rate and refrigerant charge entering the system. This change in the nominal mass flow rate adjusted the system for stable operation. For the refrigerant R32, this mass flow was reduced from 0.50 kg/s to 0.34 kg/s, as it is more efficient and provides a better cooling capacity. This would offset the cooling capacity of the observed relatively large value, which resulted in temperature oscillations. Temperature control with high stability was eventually achieved by mass flow tuning, which means R32 can be applied to the systems if the application was calibrated correctly. This coincides with the results from a recent study, which showed that R32 works efficiently when the system is set right for better operation [11].

Table 4 presents the temperature control performance before and after retrofitting the cooling cycle from R410a to R32. The setpoint temperature remained constant at 24.0°C for both refrigerants, ensuring a consistent comparison. Initial temperature oscillations were slightly higher with R32 (±0.6°C) compared to R410a (±0.5°C), indicating minor fluctuations during the transition period. However, the steady-state temperature showed only a marginal increase of 0.1°C with R32, validating that the retrofit did not compromise the system's ability to maintain thermal comfort. These results demonstrate that R32 can effectively regulate building temperature, making it a viable alternative to R410a with minimal impact on temperature stability.

Table 4
Temperature control performance before and after retrofitting the cooling cycle from R410a to R32

Parameter	Initial R410a	Retrofitted R32	Difference
Setpoint temperature (°C)	24.0	24.0	0.0
Initial temperature oscillations (°C)	±0.5	±0.6	+0.1
Steady-state temperature (°C)	24.0	24.1	+0.1

3.2 Energy Flow Rate and Coefficient of Performance (COP)

In this research, the study was directed to evaluate the performance of the retrofitted system on energy efficiency. It first went down upon transitioning to R32 and eventually stabilized after the adjustment of the parameters of the system. The final COP values under R32 are in the same range as under R410a, and it can be said that there was no deterioration in the efficiency of the system during a refrigerant change. This is very important since it would mean the possibility of R32 providing an energy-efficient solution like or even better than R410a in the search to reduce operating costs and lower environmental impact. R32 systems have a high COP, with this value measured as like that from the findings of Arora *et al.,* [14] in some other applications.

Table 5 compares the energy flow rates of key components and the COP before and after retrofitting to R32. The compressor's energy flow rate decreased slightly from 10.5 kW to 10.3 kW with R32, while the evaporator and condenser maintained similar energy flow rates, indicating efficient energy transfer. The COP showed a minor initial drop from 3.2 to 3.1 with R32, which stabilized after system parameters were optimized. This stability signifies that R32 can achieve comparable efficiency to R410a, reinforcing its suitability as an eco-friendly alternative. The results highlight that R32 can sustain system efficiency while reducing the environmental impact.

Table 5
Comparison the energy flow rates of key components and the COP before and after retrofitting to R32

Component	Energy flow rate with R410a (kW)	Energy flow rate with R32 (kW)	COP with R410a	COP with R32
Compressor	10.5	10.3	3.2	3.1
Evaporator	65.0	64.5	-	-
Condenser	75.0	74.8	-	-

3.3 Pressure and Saturation Temperature

The profiles of the pressure and saturation temperature of the system were additional inputs for the success of the retrofit. Similarly, pressures at all points within the system were slightly higher with R32 than with R410a, which can be explained in terms of the properties of the two refrigerants. However, these pressure increases were not so high as to impact system mechanical integrity adversely, implying that existing equipment will handle the slight variations without much modification. Such adaptability is very crucial, as it will allow a wide spread of adoption because it requires retrofitting existing systems with just a few hardware changes [7].

Table 6 shows the details the pressure and saturation temperature comparisons between R410a and R32. The saturation pressure for R32 was slightly higher at both 5°C and 45°C compared to R410a, with differences of +0.015 MPa and +0.061 MPa, respectively. Despite these increases, the evaporator and condenser temperatures remained unchanged, ensuring the system's operational integrity. The slight pressure increase confirms that R32 can be used without significant mechanical modifications to exist components, simplifying the retrofit process. These findings validate that R32 can function effectively within the same temperature range as R410a, supporting its adoption in existing systems.

Table 6
Details the pressure and saturation temperature comparisons between R410a and R32

Parameter	R410a	R32	Difference
Saturation pressure at 5°C (MPa)	0.936	0.951	+0.015
Saturation pressure at 45°C (MPa)	2.734	2.795	+0.061
Condenser temperature (°C)	45.0	45.0	0.0
Evaporator temperature (°C)	5.0	5.0	0.0

3.4 Mass Flow Rate

Table 7 presents the outlines the adjustments in mass flow rates required for the transition from R410a to R32. The nominal mass flow rate for R410a was 0.50 kg/s, which needed to be reduced to 0.34 kg/s for R32. This adjustment ensures stable operation and prevents overcooling effects that could lead to temperature oscillations. The recalibration of mass flow rates is crucial for maintaining system performance and efficiency. By setting the adjusted mass flow rate correctly, the system can meet the cooling demands effectively without overloading the components. This adjustment showcases the adaptability of the cooling cycle to accommodate different refrigerants while maintaining operational efficiency.

Table 7
Outlines the adjustments in mass flow rates required for the transition from R410a to R32

Refrigerant	Nominal Mass Flow Rate (kg/s)	Adjusted Mass Flow Rate (kg/s)
R410a	0.50	-
R32	-	0.34

3.5 Subcooling and Superheating Levels

It is subcooling and superheating that ensure the refrigerant in the correct state goes into the evaporator and the compressor. Concerning subcooling and superheating, after retrofitting, the trend lines moved further away from the nominal five delta K of the subcooling and superheating levels. However, this was effectively achieved near the nominal condition by changing the refrigerant charge and initial quality of the vapor of the condenser. The final subcooling and superheating levels are way within the acceptable range, and this portrays the system to be effective. This appears to impose quite fine-tuned adjustments for the system to be at the optimal level of performance using R32, a reflection of some findings for other low-GWP refrigerants [10].

The opening fraction of a thermostatic expansion valve is an essential measure of how effective the control over refrigerant flow in a system is. With R32, this TEV opening fraction was slightly higher, which is to be expected, since it is needed to tune the valve finer to arrive at the same superheating level. With a system finetuned, the TEV opening fraction will be set to the operating conditions. This adaptation allowed the flow of refrigerant to flow accordingly so that proper control was carried out, allowing the system to run constantly and at a good enough level. The possibility of adjusting the TEV opening fraction fine-tunes the system for the new refrigerant, possibly one of the most essential features that make a successful retrofit following [12].

The overall success of this retrofit project demonstrates how all other such projects worldwide can fit into a global vision of reducing the environmental impacts of refrigeration systems. The conclusions can point to other low-GWP refrigerants that may be similarly introduced into current systems with proper adjustments that allow for appropriate success in the primary objective: to drive the industry's roadmap into a more sustainable future. This is especially critical in light of international agreements, for example, the Kigali Amendment to the Montreal Protocol, that aims to phase down the high-GWP refrigerants globally [16].

This further suggests that regulatory backing is required, and a cooperative approach from the industry needs to be taken on board so this transition towards environment-friendly refrigerants is successfully made without many hiccups. Whenever a new refrigerant is adopted, generally, the industry requires changes in the standards and regulations to ensure safety and performance. As such, it will require the collaboration of the manufacturers, policymakers, and researchers to rise to the technical challenges that are fostered by the new refrigerants and disseminate the best retrofitting practices to the already existing installations. This will be of paramount importance toward realizing and ensuring the environment receives the full benefits of low-GWP refrigerants [3].

The economic dimensions are also critical when retrofitting low-GWP refrigerant systems. Retrofit setup charges might be higher initially, considering system re-commissioning and, most likely, some part replacements. However, in the long term, enhanced energy efficiency savings, along with no regulatory penalties for using high-GWP refrigerants, will more than compensate for the investment not to mention the environmental benefits, specifically the reduction of greenhouse gases, which are applied to the sustainability goals on a micro and macro level for the organizations and the nations. Furthermore, economic incentives such as tax breaks or subsidies offer yet another way to improve the range of choice in eco-friendly refrigerants, making retrofits more affordable [9].

Table 8 displays comparison the subcooling and superheating levels between R410a and R32. For R32, both subcooling and superheating levels increased by 1 DeltaK, from 5 to 6 DeltaK, compared to R410a. These changes are attributed to the different thermodynamic properties of R32. The adjustments ensure that the refrigerant enters the evaporator and compressor in the intended states, optimizing the system's performance. Maintaining appropriate subcooling and superheating levels is critical for efficient refrigerant flow and heat exchange. The results demonstrate that with proper parameter control, R32 can achieve comparable performance to R410a, ensuring efficient and effective operation. Table 9 displays Comparative Analysis of Results with Literature.

Table 8
Comparison the subcooling and superheating levels between R410a and R32

Parameter	R410a (DeltaK)	R32 (DeltaK)	Difference
Subcooling	5	6	+1
Superheating	5	6	+1

Table 9
Comparative analysis of results with literature

Criteria	Current Study (R32)	Arora *et al.,* [14] - HFO 1234yf	Bolaji [11] - Low GWP Mixtures	Pearson [17] - Ammonia	Emani & Mandal [7] - Natural Refrigerants	Jesus *et al.,* [4] - Sustainable Refrigerants	Mullan [8] - Natural Refrigerants	Kivevele [12] - Propane (HC-290)	Krapanić *et al.,* [9] - Recycled Refrigerants	Sawalha [18] - CO_2 Systems
Temperature Control	Steady-state achieved with minimal oscillations (±0.6°C)	Stable temperatures maintained	Effective temperature regulation noted	Efficient temperature control	Stable operation observed	Effective temperature management	Temperature control efficiency maintained	Stable operation with propane	Effective temperature control observed	Stable temperature control
Energy Flow Rate (kW)	Compressor: 10.3, Evaporator: 64.5, Condenser: 74.8	Comparable energy efficiency observed	Energy flow rates consistent with low-GWP mixtures	High energy efficiency	High energy efficiency observed	Effective energy management	Energy flow rates maintained	Effective energy management	Energy-efficient operation	Efficient energy flow rates
COP	Stabilized at 3.1	Similar COP levels noted	High COP with low-GWP mixtures	High COP, efficient operation	Comparable COP levels	Sustainable refrigerants maintained high COP	Comparable COP	High COP observed with propane	Efficient COP maintained	High COP in transcritical systems
Pressure (MPa)	5°C: 0.951, 45°C: 2.795	Pressures within operational range	Suitable pressures for mixtures	High operating pressures	Efficient pressure management	Pressures suitable for sustainable refrigerants	Pressures maintained within operational limits	Comparable pressures	Suitable pressures observed	Effective pressure management in CO2 systems
Saturation Temperature (°C)	Consistent with R410a	Consistent saturation temperatures	Suitable saturation temperatures	Suitable for various temperatures	Efficient management of saturation temperatures	Effective saturation temperature control	Comparable saturation temperatures	Stable saturation temperatures	Effective saturation temperature control	Suitable saturation temperatures
Mass Flow Rate (kg/s)	Adjusted to 0.34 for R32	Adjusted to suitable levels	Suitable mass flow rates observed	Effective mass flow management	Suitable for various applications	Sustainable refrigerants managed mass flow effectively	Comparable mass flow rates	Effective mass flow rates observed	Efficient mass flow rate management	Suitable mass flow rates
Subcooling (DeltaK)	Increased by 1 (to 6 DeltaK)	Effective subcooling levels	Suitable subcooling levels	Effective subcooling management	Comparable subcooling levels	Effective subcooling control	Comparable subcooling levels	Effective subcooling with propane	Effective subcooling management	Effective subcooling control

Superheating (DeltaK)	Increased by 1 (to 6 DeltaK)	Effective superheating levels	Suitable superheating levels	Effective superheating management	Comparable superheating levels	Effective superheating control	Comparable superheating levels	Effective superheating with propane	Effective superheating management	Effective superheating control
TEV Opening Fraction (%)	Adjusted to 52%	Suitable TEV adjustments	Effective TEV control	Effective TEV adjustments	Comparable TEV control	Effective TEV management	Comparable TEV adjustments	Effective TEV control	Effective TEV management	Effective TEV control

4. Conclusions

This study demonstrates the feasibility and benefits of retrofitting an existing Simscape™ cooling cycle from R410a to R32. The primary challenge was to maintain the system's operational efficiency while significantly reducing its environmental impact. The results confirmed that, with proper adjustments to the nominal mass flow rate and refrigerant charge, the system could achieve stable operation using R32. The building temperature remained effectively controlled, and the energy flow rates and COP indicated efficient performance comparable to the original setup with R410a. The retrofit process involved addressing the initial temperature oscillations and deviations in subcooling and superheating levels due to the different thermodynamic properties of R32. By recalibrating the system's parameters and fine-tuning the refrigerant charge, these issues were resolved, ensuring that the system operated within the desired performance range. The slightly higher pressures associated with R32 were managed without compromising the mechanical integrity of the existing equipment, demonstrating the robustness of the retrofit process. The successful transition to R32 highlights its potential as a sustainable alternative to R410a, aligning with global regulatory efforts such as the Kigali Amendment to the Montreal Protocol, which aims to phase down the use of high-GWP refrigerants. The findings suggest that similar retrofitting projects could be implemented across the industry, facilitating the widespread adoption of low-GWP refrigerants and significantly reducing the refrigeration sector's environmental footprint.

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