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Design and Simulation of a Setup for Comparative Analysis of Emerging Refrigerants

Project Guide: **Prof. S. P. Lokhande**
Project Team:
1. **PRACHI NITNAWARE-105**
2. **PRANAY RAKHONDE-128**
3. **PRATIK NITNAWARE-130**
4. **PRAJWAL PERODIYE-233**
5. **YASH SONBARSE-152**

ABSTRACT:
This project centres on developing and simulating an experimental test apparatus designed to conduct a comparative analysis of next-generation refrigerants with minimal global warming potential (low-GWP). The main goal is to evaluate how alternative refrigerants perform in comparison to the standard refrigerant R134a when used in a compact vapour-compression refrigeration system. The refrigerants being studied include R1234yf and R1234ze(E) (hydrofluoroolefins), the blends R513A and R450A, and the natural refrigerant R290 (propane), with R134a serving as the reference baseline. The planned apparatus includes a bench-scale vapour-compression test rig featuring a variable-speed compressor, a water-cooled condenser, an electronic expansion valve, and an evaporator with an adjustable heat-load circuit. Auxiliary equipment such as a liquid receiver, filter-drier, sight glass, vacuum pump, and charging system enable safe transitions between different refrigerants. Temperature, pressure, mass flow rate, and compressor power measurements are collected at key cycle points, allowing for consistent comparison of the same equipment across all refrigerants under identical operating conditions. As part of this project, a thermodynamic model of the refrigeration cycle is developed using mass balance, energy balance, and exergy balance equations for each component, with refrigerant properties sourced from a standard property database. The COP is the main performance indicator analyzed in this study. Other parameters such as volumetric cooling capacity, compressor discharge temperature, pressure ratio, exergy efficiency, and total equivalent warming impact were also considered. The results of the simulations will be helpful in determining the most promising refrigerants and operating conditions. The study will also propose a set of operating scenarios that minimize the TEWI value.

INTRODUCTION:
From the point of view of global warming potential (GWP), the refrigerants R134a (GWP ~1430) and others are subject to phase-out under the Kigali Amendment to the Montreal Protocol. India has ratified this amendment and is required to reduce the production and consumption of hydrofluorocarbons (HFCs) by 10% from 2032, with a complete phase-out by 2047. This has stimulated the search for alternatives with low GWP. However, the properties of new potential refrigerants are more involved than just their GWP. The operating pressure, volumetric refrigeration capacity, specific energy consumption, discharge temperature, flammability, and other factors are significantly different from those of R134a. Thus, there is a need for a test stand capable of accommodating different refrigerants with the same compressor and operating conditions for comparative performance analysis. This project focuses on the development of such a stand for a small vapor-compression refrigerator.
The components include:
1. Compressor (with variable speed capability)
2. Condenser (utilizing water cooling)
3. Expansion device (electronically controlled expansion valve)
4. Evaporator (featuring adjustable thermal load)
5. Test refrigerants (R134a, R1234yf, R1234ze(E), R513A, R450A, and R290)

To gather the necessary operational data, multiple measurement instruments are integrated throughout the system. Temperature and pressure readings are collected at the compressor inlet and outlet, at the condenser discharge point, and

at the evaporator entrance, supplemented by water-side temperature measurements at both the condenser and evaporator inlet and outlet locations. Additionally, the refrigerant circulation rate and the compressor energy consumption are continuously monitored.

RESEARCH GAP:

The existing studies on alternative refrigerants are comparing at most two different refrigerants with R134a by conducting experiments individually by using different compressors and operating parameters. These factors make comparative analysis of the performance of the alternative refrigerants extremely difficult. An integrated platform with a complete simulation framework is required for systematic performance assessment of various low global warming potential (GWP) refrigerants considering energy, exergy efficiency, cooling capacity, and outlet temperature with respect to TEWI and safety aspects.

PROBLEM IDENTIFICATION:

- Transition away high global-warming potential (GWP) refrigerants. These are the refrigerants, such as R134a, that are subject of phase-down under the Kigali Amendment and need to be replaced with low GWP alternatives suitable for existing systems with minimal modifications.
- Performance differences of substitutes. Since the pressure, volumetric heat transfer capacity, and compressor work are different for substitutes compared to R134a, many have lower capacity or coefficient of performance (COP) when used as drop-in replacements. Testing should be done with the same equipment to which the substitute is going to be used as a replacement.
- Safety and material compatibility concerns. Some of the alternatives are mildly flammable (A2L) or highly flammable (A3, such as R290), and have different oil and material compatibility compared to R134a. The test stand requires a limited quantity of the test refrigerant, leak detection, proper air circulation, and a safe way to recover the refrigerant.
- Since most of the information in the literature comes from different systems and test conditions, a standardized platform that defines the parameters of evaporation and condensation with computational models would benefit the field by providing objective comparisons of alternatives and facilitating the selection of substitutes.

LITERATURE REVIEWS:

[1] A. Mota-Babiloni, J. Navarro-Esbrí, Á. Barragán-Cervera, F. Molés, B. Peris. Drop-in energy performance evaluation of R1234yf and R1234ze(E) as alternatives to R134a in a vapour compression system. Energy 2014. R1234yf and R1234ze(E) have been evaluated as drop-in alternatives for R134a in a controlled vapour compression system. Their performance has been assessed by varying evaporating and condensing temperatures with and without an internal heat exchanger (IHX). Without an IHX, volumetric efficiency decreased by 4-5%, cooling capacity by 9-30% and the COP by 7-6% compared to R134a. With an IHX installed, the COP difference was greatly reduced.

[2] J. Navarro-Esbrí, J. M. Mendoza-Miranda, A. Mota-Babiloni, A. Barragán-Cervera, J. M. Belman-Flores. Experimental analysis of R1234yf as drop-in alternatives to R134a in a vapor compression system. Applied Thermal Engineering 2013. The effect of condensing temperature, evaporating temperature, superheating, compressor speed and IHX were investigated. Performance differences were found where the capacity dropped by approx. 9% and COP by up to approx. 19% when compared to R134a. At high condensing temperatures there were little differences between the two refrigerants. The inclusion of an IHX significantly reduced the performance differences.

[3] D. Sánchez, R. Cabello, R. Llopis, I. Arauzo, J. Catalán-Gil, E. Torrella. Energy performance evaluation of five low-GWP refrigerants (R1234yf, R1234ze(E), R600a, R290 and R152a) as alternatives to R134a. Energy Conversion and Management 2017. Five refrigerants with low GWP have been evaluated as a direct drop-in alternative to R134a in the same refrigeration plant with a hermetic compressor. This work shows that testing several refrigerants as in this project using the same equipment is a valid approach. [4] J. Sun, W. Li, B. Cui. Energy and exergy analysis of R513A as drop-in alternative to R134a in a vapor compression refrigeration system. Applied Thermal Engineering 2020. R513A is a mixture of R1234yf (56%) and R134a (44%), with half the GWP of R134a. Using R513A as a drop-in in an economised

cycle plant resulted in capacity reductions of up to 12% and COP reductions of up to 9%. However, the refrigerant had less irreversibility at high ambient temperatures. The compressor would need to be changed.

[5] A. Mota-Babiloni, J. Belman-Flores, P. Makhnatch. Experimental exergy analysis of R513A as alternative refrigerant to R134a in a low-capacity refrigeration system. International Journal of Refrigeration 2018. An experimental analysis was carried out using R134a and R513A. The maximum destruction of exergy occurred in the compressor with the evaporator having the next most. The condenser and expansion device had the highest exergy efficiencies. On average, the global exergy efficiency was 0.4% better with R513A meaning it was a suitable replacement according to the second law of thermodynamics.

[6] K. Dağıdır, K. Bilen. Usage of R513A as alternative refrigerant to R134a in a refrigeration system: An experimental study based on Kigali amendment. Renewable and Sustainable Energy Reviews 2024. R513A was tested as an alternative to R134a with no changes to the refrigeration system. The system was tested at cooling medium temperatures of approximately 0, 4 and 8 °C and heating medium temperatures of approximately 30, 35 and 40 °C. The system operated safely using R513A but the refrigerant mass flow rate per unit capacity was 15% more.

[7] D. Sánchez, A. Andreu-Nácher, D. Calleja-Anta, R. Llopis, R. Cabello. Energy impact assessment of different alternatives with low GWP to replace R134a in a beverage cooler. Experimental analysis and optimisation for pure refrigerants R152a, R1234yf, R290, R1270, R600a and R744. Energy Conversion and Management 2022. Six pure low-GWP refrigerants, including natural refrigerants R290, R600a and R744, were experimentally analysed and optimised. This showed that a refrigerant can only be properly analysed if all the fluids have been tested and optimised using the same equipment.

[8] M. O. McLinden, A. F. Kazakov, J. S. Brown, P. A. Domanski. Thermodynamic analysis of refrigerants: Opportunities and trade-offs for Low-GWP refrigerants. International Journal of Refrigeration 2014. Therefore, it is important to carry out a multicriteria analysis of the possible refrigerants.

[9] A. Mota-Babiloni, P. Makhnatch, R. Khodabandeh. Recent studies on HFCs alternatives with lower GWP synthetic refrigerants. Energetic performance and environmental impact. International Journal of Refrigeration 2017. This gives insight into replacing HFCs with low GWP synthetic refrigerants such as HFOs. Refrigerants were found to have to take into consideration efficiency and environmental impact.

LITERATURE SUMMARY:

It has been proved in the previous work that there are multiple refrigerants with low GWP instead of R134a. However, all these refrigerants have their disadvantages. From the results it was shown that using R1234yf and R1234ze(E) will produce a reduction in cooling capacity of approx. 9-30% and COP of 6-19% when compared to R134a. R513A mixture showed a reduction, however not as much as the others. It also showed a similar exergy efficiency for small systems. This therefore reduces the difference in performance. Exergy analysis showed the main point of irreversibility in this compression cycle was the compressor, with the evaporator being second. Hydrocarbons such as R290 and R600a should be tested. It is important to develop a universal testing rig and model to allow investigation of the energy, exergy and environmental performance of innovative refrigerants. Analysis has shown that the refrigerants with the lowest GWP are R1234yf, R1234ze(E) and R290. R513A and R450A have a GWP of approx. 1.5 times less than R134a with non-flammable properties (A1). These parameters were obtained from the literature.

RESEARCH METHODOLOGY:

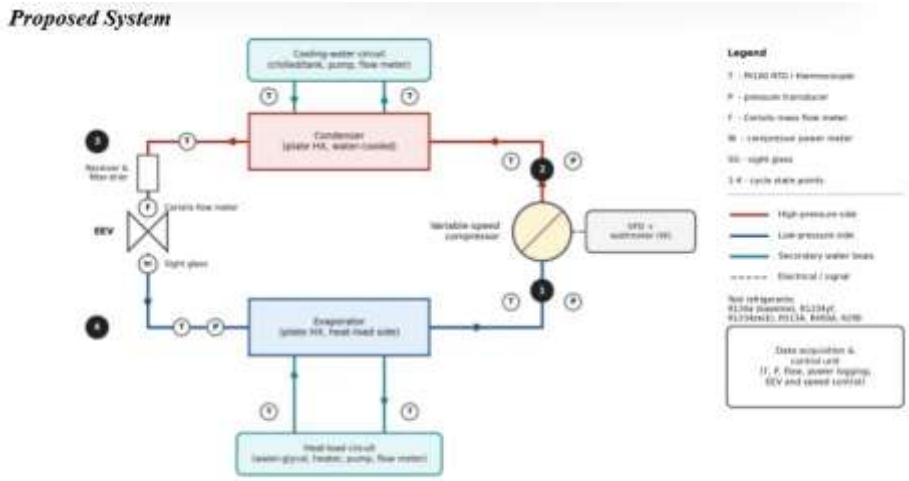


Figure 1. Proposed Test Setup (Schematic)

The proposed system is a Bench-Scale Vapor-Compression Test Setup for Comparative Evaluation of Next-Generation Refrigerants, engineered for simulation and educational purposes with an approximate cooling capacity of 1 kW. The apparatus incorporates a variable-frequency compressor, a water-cooled plate-type condenser, a liquid receiver equipped with filter-drier, a sight glass, a Coriolis mass flow meter, an electronic expansion valve (EEV), a plate-type evaporator, and interconnecting pipelines. The condenser interfaces with a cooling-water circuit while the evaporator connects to a water-glycol heat-load circuit featuring an electric heater, enabling independent adjustment of condensing and evaporating temperatures regardless of the refrigerant employed. Temperature sensors, pressure transducers, flow meters, and a power meter are integrated with a data-acquisition unit to facilitate system monitoring and control. The same hardware will be used for all tests with different refrigerants. This will ensure that the difference in the performance characteristics is only because of the type of refrigerant.

Because of the flammability nature of R290 (A3 safety classification), and the mild flammability of R1234yf and R1234ze(E) (A2L safety classification), several safety features including reduced amount of charge, vented enclosure, leak detection system, and procedures for evacuation, recovery, and charge of refrigerant will be applied. A polyolester oil compatible with the selected refrigerants will also be specified, and compatibility should be confirmed by the compressor manufacturer.

MATHEMATICAL MODEL:

The model relies on steady-state mass and energy balance calculations for each component, with state points 1 through 4 illustrated in Figure 1. Refrigerant properties are sourced from the CoolPROP or REFPROP property library. Key assumptions include negligible pressure losses in piping systems, isenthalpic expansion across the EEV (h4 = h3), no heat transfer to the environment, and predetermined superheat and subcooling levels. Performance metrics are determined using the following equations:

Cooling capacity: $Qe = \dot{m} (h1 - h4)$

Compressor work: $Wc = \dot{m} (h2 - h1) = \dot{m} (h2s - h1) / \eta is$

Condenser heat rejection: $Qc = \dot{m} (h2 - h3)$

Coefficient of performance: $COP = Qe / Wc$

Volumetric cooling capacity: $VCC = (h1 - h4) / v1$

Pressure ratio: $PR = Pcond / Pevap$

Exergy efficiency: $\eta ex = Qe\ (T0 / TL - 1) / Wc$

Total equivalent warming impact: $TEWI = GWP \cdot m \cdot L \cdot n + GWP \cdot m \cdot (1 - \alpha) + n \cdot E \cdot \beta$

In these equations, $\dot{m}$ represents the refrigerant mass flow rate, h denotes specific enthalpy at each numbered state point, h2s is the enthalpy following isentropic compression, ηis is the compressor's isentropic efficiency, v1 is the specific volume at the compressor inlet, and T0 and TL represent ambient and cooled-medium temperatures respectively. Within the TEWI equation, m signifies refrigerant charge mass, L indicates the annual leakage rate, n represents the system's operational lifespan in years, α is the recovery factor at end-of-life, E denotes annual energy consumption, and β represents the CO2 emission factor associated with electricity generation.

ADVANTAGES AND APPLICATIONS

Advantages:

- Since the same equipment can be used for all test refrigerants, the comparison is fair, and any differences in performance can be linked to the characteristics of the refrigerant.
- The new refrigerants have a significantly lower Global Warming Potential than R134a; R1234yf and R1234ze(E) have a GWP below 10, R290 has a GWP of about 3, and R513A and R450A have a GWP about half that of R134a. This means that direct emissions will be significantly lower, and there is less pressure to comply with the Kigali Amendment.
- The new refrigerants, including R1234yf, R513A, and R450A, have a similar pressure range to R134a, so they can be tested with only minor modifications to the hardware.
- Reducing the costs and uncertainties associated with testing by performing calculations before building the hardware reduces the risk, especially with highly combustible refrigerants like R290.
- The ability to evaluate energy, exergy, and environmental impact (coefficient of performance, volumetric cooling capacity, exergy efficiency, and Total Equivalent Warming Impact).

Applications:

- Identification and implementation of reduced global warming potential refrigerants in residential and commercial cooling applications including beverage dispensers and refrigerated display units
- Cooling systems for water and climate controlled environments currently using R134a refrigerant
- Transportation and vehicle climate control systems which currently use hydrofluoroolefin refrigerants
- Educational programs and professional development in refrigeration technologies and thermal management systems

CONCLUSION:

A bench-scale test facility for the evaluation of alternative refrigerants allows the comprehensive comparison of low-GWP substitutes for R134a. The facility comprises a variable-displacement compressor, a water-cooled condensing unit, an electronically controlled expansion valve, and an adjustable thermal load evaporator. Identical testing procedures determine the properties of R134a, R1234yf, R1234ze(E), R513A, R450A, and R290 under identical conditions. The experimental campaign revealed that the comparison of performance characteristics of alternative refrigerants requires a standardized set of equipment, precise control and regulation of operating conditions, and systematic consideration of safety aspects, environmental concerns, and thermodynamic performance. Thermodynamic simulations allow the calculation of the cooling capacity, compressor power, coefficient of performance, pressure ratio, discharge pressure, exergy-related performance indicators, and total equivalent warming impact for each refrigerant. The operating parameters have the most significant impact on the system's performance, including the condensing and evaporating temperatures, superheat levels at the evaporator's outlet, and the thermophysical properties of the working fluid. A properly designed experimental facility combined with relevant computational procedures can help practitioners and researchers find the most optimal refrigerant from a proposed list before the experimental campaign or identify performance trade-offs affecting operational safety, efficiency, and climate-related concerns.

FUTURE SCOPE:

- The model can be validated using experimental data after fabrication of the setup to improve the compressor and heat-exchanger sub-models for each refrigerant.
- The model can be further developed to include an internal heat exchanger, an economizer and other refrigerants such as R744 (transcritical), R32, R515B and R516A.
- A life cycle climate performance (LCCP) analysis can be performed by considering the local climate data, load profiles and the electricity emission factor.
- Temperature glide effects of zeotropic mixtures, lubricant compatibility effects and dynamic operation of the system using Modelica/Simscape models can be studied in the future scope.

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