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Original Article

Optimization of Refrigeration Systems Using Eco-Friendly Refrigerants

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ABSTRACT

Refrigeration and air-conditioning are essential for food preservation, medicine storage, industrial processing, and thermal comfort. However, conventional refrigeration systems rely heavily on synthetic refrigerants such as chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and hydrofluorocarbons (HFCs), which contribute to ozone depletion and global warming. With increasing environmental concerns and international regulations, there is a growing need for eco-friendly refrigerants with low global warming potential (GWP) and zero ozone depletion potential (ODP). This study focuses on optimizing refrigeration systems using environmentally friendly refrigerants such as carbon dioxide (CO_2), hydrocarbons (HCs), ammonia (NH_3), and hydrofluoroolefins (HFOs). System performance is evaluated through thermodynamic analysis, mathematical modeling, and computer-based optimization under various operating conditions. Key performance indicators include coefficient of performance (COP), exergy efficiency, cooling capacity, and total equivalent warming impact (TEWI). The results show that optimized systems using eco-friendly refrigerants can achieve performance comparable to or better than traditional systems while significantly reducing environmental impact. This research contributes to the development of sustainable refrigeration technologies aligned with global environmental goals.

KEYWORDS

Eco-Friendly Refrigerants, Refrigeration Optimization, Energy Efficiency, Natural Refrigerants, Global Warming Potential, Sustainable Cooling.

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1. INTRODUCTION

1.1. Background

Refrigeration systems are critical to the contemporary society according to the way they assist vital areas of the society like food preservation and transportation, pharmaceutical storage, data centres cooling, air conditioning and manufacturing in industries. Out of the testable refrigeration technologies, the most widely used are vapor compression which possess the qualities of reliability, simplicity and capacity to cool a lot of material. Nevertheless, the advanced development of refrigeration and air-conditioning systems in the world has resulted in a remarkable rise in the world energy consumption and related greenhouse gas emissions. These systems consume a significant amount of electricity in residential, commercial, and industrial systems hence contributing indirectly to climate change by the generation of emission through power. Moreover, the wide use of conventional refrigerants, especially the chlorofluorocarbons (CFCs) and hydrofluorocarbons (HFCs), have caused some serious concerns to the environment. Although CFCs had the leading role in the depletion of the ozone layer, several HFCs have very high values of global warming potential (GWP) and this means that in case they are emitted into the atmosphere, they contribute significantly to global warming. To address these environmental pressures, the international treaties like Montreal Protocol and Kigali Amendment have required the gradual phase-out and cut down of high-GWP refrigerants. These laws have speeded up the research and development project aimed at relying on more environmentally friendly options. This has led to the increased interest in eco-friendly refrigerants based on natural substances like carbon dioxide, ammonia, and hydrocarbons, and also new lower GWP synthetic compounds. Despite these substitutes being potentially very beneficial to the environment, there are multiple technical obstacles associated with their implementation in the current refrigeration systems. Problems concerning flammability, toxicity, high operating pressures, and material compatibility should be taken seriously so that operation can be safe and efficient. Moreover, fluctuations in thermodynamic parameters tend to demand redesigning of systems and optimization of performance. Thus, they must be analyzed systematically and optimised so as to be able to effectively integrate the use of eco-friendly refrigerant without compromising on the aspect of high energy efficiency, high pertinacity and observing safety standards in its operation.

1.2. Environmental Impact of Conventional Refrigerants

The intensive application of traditional refrigerants in refrigeration systems and the air-conditioning systems has resulted in severe environmental issues during the last several decades. These refrigerants especially the chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs) were originally created to offer safe, stable and efficient cooling. Scientific studies however have brought forth the reality that their excessive emission into the atmosphere bears grave implications to the ozone layer as well as the planetary global climate mechanism. The environmental effects of the conventional refrigerants can be categorized in large groups of ozone depletion, global warming, atmospheric persistence and indirect effects via energy use.

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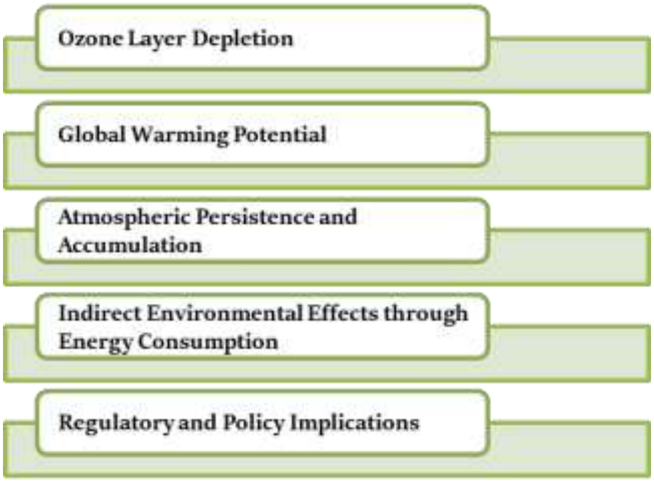

Fig 1 - Environmental Impact of Conventional Refrigerants

1.2.1. Ozone Layer Depletion

The chlorine atoms found in chlorofluorocarbons and hydrochlorofluorocarbons are known to cause significant destruction of the ozone layer in the earth. After these releases into the atmosphere, the acetone ultimately accumulate in the stratosphere where they are split apart by the ultraviolet radiation, releasing chlorine radicals. These radicals react with own molecules of ozone, which are depleted. As a result of the destruction of the ozone layer, harmful ultraviolet radiation has access to the Earth surface exposing the planet to the threat of skin cancer, cataracts and environmental destruction. The extreme environmental impacts of the depletion of the ozone envisioned the introduction of international treaties, including the Montreal Protocol, to limit and gradually eliminate compounds that depleted the ozone.

1.2.2. Global Warming Potential

Hydrofluorocarbons with values of global warming (GWP) are very high ozone friendly, and thus, they contribute heavily to climate change. GWP is a ratio that determines the capability of a material to trap heat in the air compared to carbon dioxide. GWP of a number of popular HFCs is between hundreds and several thousands, including R134a and R404A. These refrigerants tend to take a long duration in the atmosphere once they escape to the environment under leakage, inappropriate disposal or accidents and increase the greenhouse effect in the environment. Due to this, refrigeration and air-conditioning systems with high-GWP refrigerants add to global warming to a large extent.

1.2.3. Atmospheric Persistence and Accumulation

Traditional refrigerants are not easily broken down in atmosphere as they constitute chemically stable mixtures of chemical substances. In its favour is this high stability that gives such systems high atmospheric lifetime, which is not years in duration, but can be several decades. These substances have a cumulative effect on the environment as a result of the fact that, these substances persist and hence become accumulated in the air over a long period of time. Even minimal leakages per year may lead to a substantial emissions of the impact in the long run, and refrigerant handling and recovery all become highly important to the environment.

1.2.4. Indirect Environmental Effects through Energy Consumption

Among the direct emissions, a conventional refrigerant also causes environmental degradation indirectly because of the energy used. Most traditional refrigeration systems that have traditional refrigerants have lower efficiencies which result in an increase of the power consumption. A significant part of the world electricity continues to be produced through fossil fuels and thus the higher the demand of energy, the greater the carbon dioxide production. These indirect emissions tend to surpass direct refrigerant emissions during the life of the system adding even more weight to the environmental footprint of traditional refrigeration technologies.

1.2.5. Regulatory and Policy Implications

The increasing realization of the environmental effects of the traditional type of refrigerants has promoted the enforcement of stringent laws by the governments and international bodies. Policies like the Montreal protocol, Kyoto protocol and Kigali Amendment are aimed at reducing the production and use of chemicals that deplete the ozone and substances with the high GWT. These standards promote the use of greener refrigerants, the use of efficient technologies and the development of sustainable cooling systems. Adherence to such policies has emerged as one of the determinants of innovation in refrigeration world.

1.3. Refrigeration Systems Using Eco-Friendly Refrigerants

Refrigeration The past few years have seen a keen interest in the implementation of refrigeration systems that utilize environmentally friendly refrigerant, due to the increasing environmental awareness and the severe limitations on the use of Substances with high-global-warming-potential (GWP). These natural gases which cause no harm to the environment are carbon dioxide (CO_2), ammonia (NH_3), the hydrocarbon types which are propane (R290) and isobutane (R600a), and the newly invented low-GWP synthetic substances. Due to a low potential of causing ozone depletion and with low contribution to global warming, the alternatives are also becoming a popular choice as domestic, commercial, and industrial refrigeration choices. Natural refrigerants specifically have very good thermodynamic characteristics, which may translate to high system efficiency provided that the right design and operating strategy is adopted. The transcripticall ref systems have applied the use of carbon dioxide in refrigeration systems particularly in the supermarket and heat pump systems because it is not toxic, inflammable and has lesser environmental effect. Its high operation pressure however calls upon special components and solid system design. Ammonia is still used as one of the most effective refrigerants when used in large-scale industrial refrigeration due to its excellent heat transfer properties and low energy use, though its toxicity restricts its use in the home refrigeration industry. Hydrocarbon refrigerants are characterized by high performance and high coefficients of performance although, they are flammable and thus demand strict safety complete measures. In the meantime, there is the development of low-GWP synthetic refrigerants that would integrate safety to the environment as well as desirable characteristics in their operations. Keeping eco-friendly refrigerants in refrigeration systems is successfully integrated through considering the compatibility of the system, its safety and performance optimization. The thermophysical relative to conventional refrigerants differences often require compressor design, size of heat exchanger, and control measures. Modern system modeling, simulation and optimization methods would be crucial to attaining a high degree of reliability and efficiency of operation. As the world continues to undergo technological evolution and favorable government policies, eco-friendly refrigeration systems based on the environmentally-friendly refrigerant will be instrumental in enhancing sustainable refrigeration systems and lowering the environmental impact of the refrigeration industry.

2. *LITERATURE SURVEY*

2.1. Evolution of Refrigerants

The natural refrigerants used in the first generation refrigeration system were mainly ammonia (NH_3), carbon dioxide (CO_2) and sulfur dioxide because these were suitable and accessible because of their good thermodynamic properties. They were efficient in heat transfer and energy efficiency but with difficulties with regard to toxicity, flammability and operating high pressures. New synthetic refrigerants like chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs) were subsequently developed in response to these constraints with the development of chemical engineering in the mid-20th century. Such refrigerants were better in terms of stability, non-toxicity as well as the ease of handling and hence enjoyed a wide usage in home and industrial refrigeration systems. Their negative effect on the ozone layer was however discovered and their potential of global warming was very high so there were international regulations like Montreal Protocol, and the Kigali Amendment. Consequently, the trend in recent research and industrial applications has returned to the more sustainable natural refrigerants and low-GWP-based approach with a focus on sustainability and submission to the regulatory standards.

2.2. Studies on Natural Refrigerants

A large number of studies have been aimed at testing the performance of natural refrigerants, including carbon dioxide (CO_2), ammonia (NH_3), and hydrocarbons like propane (R 2 90) and isobutane (R 6 00a). The new type of transcritical refrigeration system utilizing CO_2 has also received interest because of the minimal ozone depletion potential and low global warming potential as well as the capacity to operate at low temperatures. They have however sensitive performance to ambient conditions and must operate at high pressures and hence a strong system design is required. Ammonia-type systems are used in the field of industrial refrigeration due to their better heat transfer properties and high level of energy-efficiency, but toxicity is an issue that constrains their use in domestic applications. Hydrocarbon refrigerants have a large thermodynamic efficiency and minimal environmental impact, but are limited by flammability. In general, current studies illustrate the fact that natural refrigerants are able to operate in a manner that results in high efficiency and low foot拥ferences to the environment in case the appropriate safety considerations and design of the system are put in place.

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2.3. Optimization Techniques in Refrigeration

Optimization methods have been used more to improve the performance and energy efficiency of refrigeration systems. Genetic algorithms, particle swarm optimization, artificial neural networks, and response surface methodology are some of the methods used by researchers to establish optimum operating parameters and system configurations. Imported variables are optimized using these techniques and some of them include compressor speed, refrigerant charge, evaporator and condenser temperatures and heat exchanger dimensions. These methods of optimization have one major goal, i.e., the reduction of energy use and the maximization of coefficient of performance (COP) and reliability of the system. There is also the growing popularity of multi-objective optimization which enables to consider the energy efficiency, economic cost, and the environmental impact simultaneously. The combination of computational modalities and optimization algorithms has contributed tremendously to the enhancement of operational as well as design of modern day refrigeration systems.

2.4. Exergy and Sustainability Analysis

Exergy analysis has been developed as an effective means of analyzing thermodynamic performance of refrigeration systems with regard to determining the irreversibility and the cause of energy degradation. In contrast to traditional analysis of energy, exergy analysis takes into account not only the amount of energy, but also qualitative aspects of it and gives more comprehensive information about inefficiencies in the system. Exergy researchers have projected the exergy techniques to compressors, condensers, evaporators, and expansion apparatus to assess the role they play in overall destruction of exergy. Simultaneously, life cycle climate performance (LCCP) and Total Equivalent Warming Impact (TEWI) sustainability assessment instruments have been popularly used to measure the environmental impact of refrigeration systems over their lifetime and operational life cycles. These indicators take into consideration both direct emission due to leakage of the refrigerant as well as the indirect emission due to energy demand. Application of exergy analysis as well as sustainability analysis can lead to the thorough analysis of the situation and allow the establishment of the environmentally friendly technologies of the refrigeration type.

2.5. Research Gaps

Although much knowledge is available on the topic of refrigerants and optimization of refrigerator systems, there are still many knowledge gaps in the literature. Most research focuses on single elements, discrete refrigerants, or individual performance characteristics, and does not focus on interactions of various subsystems. In addition, most of the studies place more emphasis on energy efficiency without considering economic viability, safety, and sustainability of the environment in the long term. Coherent system-level optimization systems that take into account in concert thermodynamic performance, costs over life cycle, environmental effects, and operational safety are only partial. Also, many of the suggested optimization models are not experimentally validated especially when operating in real-world conditions. These gaps need to be addressed to come up with comprehensive and viable refrigeration strategy to satisfy future regulatory, economic and sustainability demands.

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3. METHODOLOGY

3.1. System Description

The current research takes into account a traditional one-stage vapor compression refrigeration unit, which is the most common system in refrigerators of domestic, business, and industrial cooling processes. The system has four main components; a compressor, a condenser, an expansion valve and an evaporator, which works in a closed-loop solution including one another in order to attain the required cooling capacity. These elements may operate in a continuous cycle and the refrigerant moves through each part where a change in phases and pressure variations produces the capacity to transfer heat effectively. The refrigeration process starts with the evaporator, in which the mixture of liquid and vapor at low pressure absorbs the heat in the refrigeration cavity, and fully evaporates into a fully saturated or slightly superheated vapor. The cooling effect needed to achieve refrigeration is achieved through this absorption of heat. The vapour refrigerant is then taken to the compressor whereby it is high-pressure and temperature compressed. The compressor provides an essential role in the circulation of refrigerant in the system as well as the provision of necessary pressure difference between the high and low pressure sides of the system. The vapor coming out of the compressor is at high pressure and high temperature and is transferred into the condenser where it rejects heat to the surrounding environment, usually by means of air or water cooling. The removal of heat causes the refrigerant to pass through a change of state to a liquid that rapidly creates high-pressure subcooled or saturated liquid, at the outlet of the condenser. This is a heat rejection that is needed to stabilize and ensure efficiency in the system. The liquid refrigerant then moves through the expansion valve which is a throttling device. Expansion valve causes the refrigerant pressure and temperature to drop suddenly forming a low-pressure combination between liquid and vapor. This solution is then feed to the evaporator and the cycle is complete. The flow rate of the refrigerant also depends on the cooling demand and this is controlled by the expansion device. In general, the single stage vapor compression refrigeration system is a simple, reliable and cost effective cooling system applicable in cooling processes. It has a compact size, simplicity in operation and adapts to different refrigerants thus being suitable to a diverse variety of temperature applications.

3.2. Mathematical Modeling

The mathematical models to assess the performance of the vapor compression refrigeration system are formulated on the principles of the mass, energy, and exergy conservation. The models are used to study how the system would behave under various conditions of operation and predict efficiency of the system. Mass balance is used to guarantee that the flow rate of the refrigerant mass is constant all through the cycle at steady-state. The energy balance equations are modeled on each component to calculate the work input, heat transfer as well as the thermodynamic properties changes. System irreversibilities and losses are analyzed by means of exergy balance equations. A combination of these governing equations allows one to have a more detailed look at analyzing and optimizing the refrigeration system.

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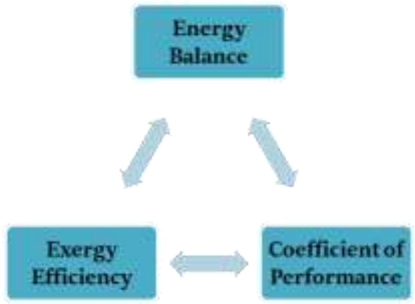

Fig 2 - Mathematical Modeling

3.2.1. Energy Balance

The energy balance equations are employed in determining the energy interactions that take place in the various parts of the refrigeration system. Rarely are the work input and the change in enthalpy of refrigerant equated in energy balance, as is the case with the compressor. The compressor work is assigned to

$$\mathbf{Wc = m(h_2 - h_1),}$$

Wc represents the power input to the compressor and m is the mass flow rate of the refrigerant and h 1 is the specific enthalpy at the compressor inlet and h 2 is the specific enthalpy at the compressor outlet. This equation implies that the effort that is necessary by the compressor is determined by the extent to which the enthalpy of the refrigerant increases in the compression. In the case of the evaporator, the energy balance is the amount of heat that was taken in the refrigerated space. The cooling capacity is provided by.

$$\mathbf{Qe = m(h_1 - h_4),}$$

Qe is heat absorbed in the evaporator and h 4 the specific enthalpy at evaporator entrance and h 1 the specific enthalpy at exit. This equation proves that the refrigeration effect is dependent on the enthalpy difference between the evaporator.

3.2.2. Coefficient of Performance

Coefficient of performance (COP) is a good parameter that is utilized to measure the cooler system efficiency. It is described as a ratio of beneficial cooling received and the amount of work input given to the compressor. It can be mathematically represented as.

$$\mathbf{COP = Qe / Wc,}$$

Qe is the refrigeration effect and W c is the compressor work. The higher is the COP, the higher is the performance of the system, the higher is the amount of cooling generated with the same amount of energy put into the system. Operating temperatures, the properties of the refrigerant, and efficiencies of its components affect the COP.

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3.2.3. Exergy Efficiency

The efficiency in using exergy is employed to indicate the success with which it uses the available energy and to determine the losses caused by irreversibilities. It is characterized as the relative output of useful exergy to the exergy input. In the case of a refrigeration system, an exergy efficiency can be typically given by the following expression:

$$\eta_{ex} = \text{Useful exergy output} / \text{Exergy input},$$

And useful exergy output is proportional to the cooling effect generated in a specific temperature, and the exergy input is proportional to the electrical work input into the compressor. Exergy analysis aids in the identification of the things that have the highest forms of energy degradation e.g. the compressor and expansion valve. With this, system performance can be increased and energy consumption decreased and environmental impact decreased by increasing the exergy efficiency.

3.3. Optimization Framework

This research incorporates a multi-objective optimization model in the simultaneous global maximization of the coefficient of performance (COP), and minimization of the total equivalent warming impact (TEWI) of the refrigeration system. These are two aims which depict energy efficiency and environmental sustainability, respectively.

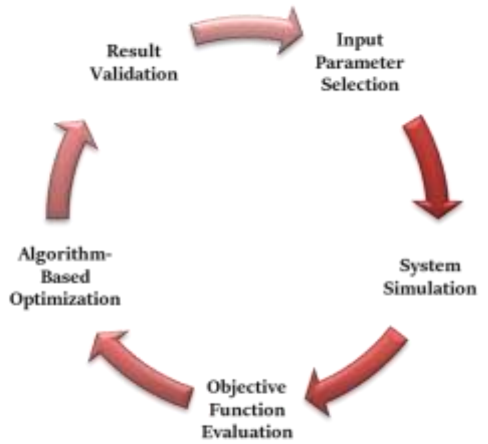

Fig 3 - Optimization Framework

3.3.1. Input Parameter Selection

The initial phase of optimization process is the choice of suitable input parameters which have great contribution to the performance of the system. These parameters are compressor speed, evaporator temperature, condenser temperature, mass flow rate of the refrigerant, degree of superheating and subcooling. The components of the selected parameters are selected on the basis of the influence on the energy consumption, cooling capacity, and environmental performance. These input variables should be selected and ranged properly in order to achieve realistic and meaningful output of optimization.

3.3.2. System Simulation

Once the choice of the input parameters is made, elaborate system simulation model is created to reflect the realistic operating behavior of the refrigeration cycle. The principle underlying this type of simulation is thermodynamic equations, refrigerant property data, and component performance characteristics. The model computes system outputs including cooling capacity, compressor power, COP and TEWI of the various combinations of the input variables. With system simulation, it is possible to evaluate the performance of the system in different operating conditions without fully experimental testing.

3.3.3. Objective Function Evaluation

The objective functions are developed to measure the performance objectives of the optimization process. In the given study, COP and TEWI have been taken as their main objective functions. The COP is derived by dividing the refrigeration effect by the compressor work and TEWI by the direct emissions of carbon refrigerants as well as indirect emissions of energy. At every simulated operating condition setting, evaluation of the objective functions is done to evaluate the effectiveness of the system in meeting desired performance specifications. It is based on these values on which optimization is made.

3.3.4. Algorithm-Based Optimization

Complex optimization procedures, genetic algorithms or particle swarm optimization are used to find the best solution on the space of parameters. These algorithms apply iterative procedures based on natural or social phenomena to investigate a set of possible solutions at the same time. They can be used in the handling of non-linear and multi dimensional optimization problems. The algorithms use trial and error, but with repeated trials this method will produce a number of optimal solutions or near optimal solutions.

3.3.5. Result Validation

The last phase of the optimization framework is the validation of the obtained results to provide its accuracy and practical use. Optimized results are also checked against the baseline system performance, experimental data, or studies already done by comparing the results. Sensitivity measurement can also be done to observe the soundness of the optimized parameters in different operating situations. This experiment ensures that the proposed optimization approach can give credible contributions to the efficiency and environmental performance of the system and could be implemented in the real-life refrigerating systems.

3.4. Simulation and Experimental Setup

In the current research, both computer simulation analysis and experimental research are conducted to analyze the effectiveness of the vapor compression refrigeration system and to verify the suggested optimization framework. The studies on simulation are carried out with the help of the MATLAB package along with the REFPROP that provides the accurate thermal-physical properties of refrigerants. MATLAB is utilized in creating mathematical models depending on the equations of mass, energy, and exergy balances, whereas REFPROP is intertwined with getting more accurate

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values of enthalpy, entropy, density, and specific heat at various operating conditions. These integrated systems allow the close examination of the system behavior with the different evaporator and condenser temperatures, compressor speeds, and rates of refrigerant flow. The simulated techniques are used to selectively determine key performance parameters of cooling capacity, power consumption of compressor, coefficient of performance (COP), and total equivalent warming impact (TEWI) of various refrigerants, including CO 2, R290 and R134a. In order to confirm the results of the simulations, experimental studies are conducted based on the vapor compression refrigeration test rig which is of the laboratory scale. The experimental apparatus is a hermetic compressor, air-cooled condenser, thermostatic expansion valve as well as finned-tube evaporator designed to perform at varying refrigerant operating conditions. Safety The test rig will be designed to permit the use of both natural and synthetic refrigerants safely with the help of the use of the suitable safety equipment, including the pressure relief valves, leakage detection systems, and the ventilation. The temperature sensors, pressure transducers, flow meters, and power analyzers are placed at the important points to measure the operating parameters more precisely. Real time measurements are recorded using data acquisition systems which are analyzed later. There is a large variety of operating conditions in which experiments are conducted in order to recreate reflective operating conditions. With each refrigerant, steady-state performance data will be obtained and compared with the simulation data. This comparison assists in the evaluation of the accuracy of the model developed and the potential grounds of deviation. A combination of simulation and experimental research contributes to the enhancement of reliability of the study and guarantees that the proposed optimization framework can be applied to the real-life refrigeration systems.

4. RESULTS AND DISCUSSION

4.1. Performance Comparison

Fluctuation on the coefficient of performance (COP) with the evaporator temperature using the various refrigerant types is examined to compare and evaluate their energy efficiency with varying operating conditions. The evaporator temperature is an important factor that will impact the refrigeration effect and compressor workload and thus will largely affect the system performance. Overall, high temperature of the evaporator raises the COP of the refrigerator system with all refrigerants. This trend is possible due to the fact that an increase in the temperature of the evaporator results in the fact that the temperature difference between the evaporator and the condenser decreases resulting in a lower compression ratio and less power is used by the compressor. The system thus consumes less energy to operate in order to achieve the cooling effect leading to better efficiency. In the case of natural cooling gases like CO 2 and R290, the COP is clearly dependent on operating conditions. COP is very susceptible to temperature of evaporator and gas cooler pressure in the instance of CO 2 based systems, particularly those in transcritical region. CO 2 systems also have rather low COP, especially in the lower evaporator temperatures (high operating pressures and more compressor work). Nevertheless, with increase in evaporator temperature, there is evident enhancement in COP, which renders CO 2 competitive with the traditional refrigerants in favorable circumstances. The high COP values of R290, with its positive thermodynamic characteristics, usually show relatively high values across a large operating evaporator temperature

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range. It has low molecular weight and high latent factor of vaporization thus making it efficient in heat transfer and consuming less energy. The COP values of the synthetic refrigerant R134a are moderate and the results in this temperature range are observed to be fairly constant. It is also true that even though R134a has good efficiency and reliable work, it is not always performed better by R290 at the higher temperatures of the evaporator. The comparative analysis has revealed that R290 has the greatest COP in most operating conditions with that of R134a coming next and when operating at low temperatures, $CO2$ has a relatively low COP but with increase in the temperatures in the evaporator, it improves extensively. These findings demonstrate that an appropriate choice of refrigerants and working conditions should be made to ensure the optimum system performance and energy efficiency.

4.2. Energy and Exergy Analysis

Both energy and exergy analyses are conducted to assess the thermodynamic efficiency of the refrigeration system and to define the key areas of inefficiency. Whereas the energy analysis measures the amount of energy exchanged in the system, exergy analysis measures the quality and utility of energy. Exergy destruction comes about as a result of the irreversibilities in the form of friction, heat exchange existence of finite temperature differences, pressure drops, throttling processes among others. Exergy losses in every component can therefore be examined, which can be used to identify the area where performance is required most, and to improve the efficiency of the entire system.

Table 1: Energy and Exergy Analysis

Component	Percentage
Compressor	35
Condenser	25
Evaporator	20
Valve	20

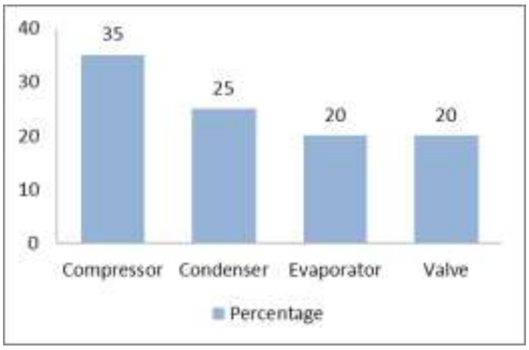

Fig 4 - Graph Representing Energy and Exergy Analysis

4.2.1. Compressor

The compressor is the main element of tools that destroys the greatest exergy, since it is a component that generates about 35 percent of the total losses. This is largely as a result of mechanical friction, electrical losses and irreversible compression processes. Furthermore, imperfect compression and heat exchange between the surroundings due to deviation to ideal assumes additive exergy destruction. Because the compressor is the most energy-sensitive element, there are minimal gains in this efficiency of which a large proportion of total system circulating energy can be saved. Exergy destruction in this component can be reduced by the use of high efficiency motors, enhanced lubrication and optimization of compression ratios.

4.2.2. Condenser

Approximately a quarter of exergy destruction in the system is contributed by the condenser. These losses mainly take place as a result of heat exchange between the refrigerant and the cooling medium through a finite temperature dissimilarity. Irreversibility is also increased by inefficient heat exchange, fouling and drop in pressure within the condenser tubes. These losses are further worsened by higher ambient temperature which decreases the rejection of heat. Survey Increasing surface area in the heat transfer, airflow/water circulation, and keeping heat exchange surfaces clean can greatly decrease the exergy destruction in the condenser.

4.2.3. Evaporator

Close to one-fifth of the exergy destruction is due to the evaporator. Such loss is largely related to heat exchange between refrigerant and the refrigerated compartment at other temperatures. The other irreversibilities are the pressure drops, uneven distribution of refrigerant and partial evapses. Substandard insulation and thermal leakage brought by the environment can also be a cause of poor performance. The reduction of these losses and the maximization of cooling performance can be achieved through optimization of evaporator design, proper distribution of refrigerant and better insulation.

4.2.4. Valve

The expansion valve further adds about 20 percent of the total exergy destruction in the system. This could be largely attributed to throttling process process through which an irreversible reduction of pressure without any useful work production is involved. Entropy generation causes a lot of the energy available to be lost in the course of expansion. The throttling losses inherent in the traditional expansion devices as can be mitigated by applying modern technologies in development of electronic expansion valves or two phase ejectors. These options contribute to the partial recovery of the losses in expansion as well as enhance the efficiency of the whole system.

4.3. Environmental Impact Assessment

The greenhouse effect of the refrigeration system is assessed by Total Equivalent Warming Impact (TEWI) method because the method offers a holistic assessment of the greenhouse gasses emission throughout the operation durability of the system. TEWI considers direct emissions caused by leakage of refrigerant and disposal of the same and indirect emissions caused by the consumption of electricity in the system. The combination of these two methods allows a more realistic approach to the problem of the total contribution of the refrigeration systems to global warming. TEWI analysis is used in the current research to make comparisons between standard refrigerants like R134a with environmentally friendly ones, like natural refrigerants and low-global-warming-potential (GWP) fluids. According to the results, the environmentally friendly refrigerant (CO 2 and R 290) is

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significantly effective to lower the lifetime greenhouse gas emission than R134a. This saving is between 40 and 60 percent depending on the operating conditions, system performance and leakage rates. The low GWP of natural refrigerants is one of the primary factors that caused this improvement. The GWP of CO 2 is 1 and that of R290 is less than 5 when compared to R134a which has a GWP of about 1430. Consequently, the immediate contribution of gases emitted as a result of spillage of refrigerants is greatly reduced under the adoption of green refrigerant types. Besides direct emission reduction, there is also an increase in efficiency of a system that reduces indirect emissions. The systems operating with natural refrigerants are often optimized and have a higher COP value which reduces electricity used in the service life. Given that most of the indirect sources of emission are due to power generation, increased energy efficiency is significant towards reduction of environmental impacts. In addition, more modern designs of systems, enhanced technologies of sealing and enhanced maintenance methods also contribute to decreased refrigerant leakage and even bring down TEWI values. Comprehensively, the TEWI analysis shows that switching towards the use of eco-friendly refrigerants is significant in terms of environmental impact without affecting the system performance. The dramatic decrease in the lifetime emissions shows that natural refrigerants can be important means to topple the global climate change and make it satisfy the global environmental regulations. Such results motivate the need to shift to sustainable refrigeration systems in an attempt to realize both environmental and energy targets in the long run.

5. CONCLUSION

This paper has introduced an overall, and a holistic optimization package to enhance performance, efficiency and environmental sustainability of vapor compression refrigeration system using environmentally friendly refrigerants. A unified method was established by integrating mathematical modeling, numerical simulation, and experimental validation taking into consideration to investigate and improve the behavior of the system in different operating conditions. The use of the mass, energy, and exergy balance equations offered a good theoretical support to the assessment of system performance, and MATLAB and REFPROP allowed the proper prediction of thermodynamic properties and operative characteristics. Experimental studies also enhanced the credibility of the suggested methodology as it verified the results of the simulations in natural laboratory conditions.

The evidence presented in this paper is a clear indication that even natural refrigerants and low-global-warming-potential (GWP) alternatives, including CO 2 and R 290 can reach extremely high levels of energy efficiency with the help of suitable system design and optimization strategies. Optimization of the performance was relative to the analysis of performance that showed that the optimized systems would have had a better coefficient of performance (COP) at a large range of evaporator temperatures and hence, reduced the total consumed energy. Besides that, exergy analysis found significant sources of irreversibility in system components, especially the compressor and condenser. By means of optimization, the total exergy losses decreased up to 15% which means increased thermodynamic efficiency and a better use of the available energy.

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The benefits of using environmentally friendly refrigerants were further validated by a study of the growth of environment using the Total Equivalent Warming Impact (TEWI) method. The findings were high lifetime greenhouse gas reductions between 40 and 60 percent compared to R134a conventional refrigerants. These cuts were made both possible by low direct emissions since the GWP values are low and indirect emissions lowered by increasing energy efficiency. This outcome indicates the possibility of natural refrigerants contributing to climate change in the world and meeting new environmental standards.

The above optimization framework can be very useful in its practical applications by system designers, manufacturers and policymakers in choosing the appropriate refrigerants and operating conditions of refrigeration systems to ensure sustainability. The methodology is balanced in system development and decision-making because it provides the performance, environmental, and thermodynamic analyses. Further studies will be targeted at the practice of advanced control measures, exploration of combinations of hybrid and blended refrigerants, and field testing at large scale, and in actual operating conditions. Such cases will also increase the reliability of the system, its adaptability, and viability in terms of business and will help popularize sustainable refrigeration technologies.

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