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Research Article

Parametric and Predictive Analysis of Window AC System Based on VCRS

Deshdeep Gambhir [1,*] and Ashish Raj [2]
[1] Assistant Professor, Department of Mechanical Engineering, Maharaja Agrasen Institute of Technology, PSP Area, Plot No. 1, Sector 22, Rohini, Delhi - 110086, India.
[2] Student, Department of Mechanical Engineering, Maharaja Agrasen Institute of Technology, PSP Area, Plot No. 1, Sector 22, Rohini, Delhi - 110086, India
*Corresponding Author Email Address: deshdeep31@gmail.com
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ABSTRACT
This research examines the performance of a modified window air conditioning system. The setup allows independent control of the condenser fan and blower. Experiments were conducted to study the effects of condenser and evaporator pressures on system efficiency. The Coefficient of Performance (COP) was the key performance metric. Data collected from the experiments were used to train machine learning models.
Ridge regression techniques were applied to predict system performance. Results show a strong link between pressure parameters and COP. The study highlights how combining experimental insights with computational tools can improve HVAC system efficiency. Future work may explore real-time optimization methods to enhance cooling performance further.

1. Introduction

Window air conditioners (ACs) are widely used in residential and commercial spaces for their affordability and effective cooling. These systems are ideal for localized cooling, making them popular in regions with hot and humid climates. Typically, they are effective in cooling single rooms and are often preferred in residential and small commercial settings. These systems operate on well-established principles of refrigeration, where heat is achieved using a combination of compressors, heat exchangers, capillaries and fans. While these components are typically optimized for standard conditions, detailed parametric studies are often limited in real-world systems. Such studies can provide deeper insights into how specific parameters influence system performance, including the Coefficient of Performance (COP) and related energy dynamics [1].

The performance of a window AC system is influenced by several factors, such as the design of key components and operating conditions. In conventional systems, the condenser fan and blower are mounted on a single shaft, rotating at the same speed. This limits the ability to optimize their individual performance, as user control is often restricted to predefined speed settings, such as low, medium, and high. Furthermore, the static design of conventional systems does not allow real- time adjustments to adapt to varying cooling demands, leading to suboptimal energy usage. This restriction limits opportunities for efficiency improvements and customization [2]. Additionally, conventional performance analyses rely heavily on experimental data, leaving room for computational tools to offer better predictions.

Several studies have investigated methods to improve the efficiency of air conditioning systems. Researchers have explored the effects of operational parameters like condenser and evaporator pressures on the overall system performance. For example, studies have shown that reducing condenser pressure can improve the Coefficient of Performance (COP) For example, studies have shown that reducing condenser pressure can improve the Coefficient of Performance (COP) by lowering the compressor's workload. Conversely, optimizing evaporator pressure allows the refrigerant to absorb more heat, enhancing cooling capacity [3]. However, there is often a trade-off between these parameters, requiring careful calibration to achieve the best results.

Past work has also highlighted the importance of advanced control mechanisms and the use of predictive models for system optimization. Traditional systems rely heavily on static designs and fixed algorithms, which can fail to account for dynamic factors such as fluctuating ambient conditions or varying load requirements. Machine learning techniques, such as regression models, have shown promise in bridging this gap by analyzing large datasets to predict performance metrics accurately [4]. For instance, Ridge and Lasso regression are effective in reducing overfitting while identifying key predictors, making them suitable for air conditioning systems with limited datasets.

This study modifies a window air conditioning unit to enable more flexible control of its key components. The modified system was used to conduct experiments analyzing the effects of condenser and evaporator pressures on the Coefficient of Performance (COP). The present study builds on these insights by integrating experimental and computational methods to optimize a window AC system [5]. A test rig was designed to allow independent control of the condenser fan and blower, providing the flexibility to study their effects on system performance. In conventional systems, the condenser fan and blower are mounted on a single shaft, rotating at the same speed. The primary modification involved separating the condenser fan and blower, which were previously mounted on opposite sides of a single motor shaft and operated at the same speed. This was achieved by installing individual motors for each fan, allowing independent operation. Additionally, speed control was enabled for both fans through the integration of separate regulators, providing precise adjustments tailored to experimental requirements.

Data collected from these experiments were used to train machine learning models, which were then applied to predict the COP under various conditions [6-8]. By combining experimental analysis with machine learning, this research aims to provide a framework for designing more efficient and adaptable cooling systems.

The goal of this project was not to directly enhance energy efficiency but to investigate the relationship between COP and energy consumption through meticulous parameter adjustments. By systematically altering condenser and evaporator pressures, the experimental setup created a controlled environment to examine their impact on system performance [9-11]. This process facilitated the generation of a high- quality, experimentally-derived dataset, which stands as a notable advancement over the synthetic or randomly generated datasets frequently employed in similar research. Such robust datasets hold significant value for predictive modeling and offer a reliable basis for future advancements in the field.

2. Description of the VCR System

Figure 1 shows the schematic diagram of the proposed VCRS along with its P-h (Pressure- enthalpy) and T-s (Temperature-entropy) diagram. The Vapor Compression Refrigeration System (VCRS) is one of the most widely used cooling technologies in air conditioning and refrigeration. It operates based on a closed-loop thermodynamic cycle that transfers heat from a lower-temperature region to a higher-temperature region [12-14]. This system relies on the phase change of a refrigerant, alternating between liquid and vapor states, to facilitate heat transfer efficiently. A VCRS consists of four primary components: the compressor, condenser, capillary, and evaporator. Each of these components plays a vital role in the cycle. In a Vapor Compression Refrigeration System (VCRS), the refrigerant undergoes a continuous cycle of phase changes, transferring heat from the cooled space to the surroundings [15]. The cycle is divided into four main processes:

Compression (Process 1-2)

- The refrigerant enters the compressor as a low-pressure, low-temperature vapor.
- The compressor raises the refrigerant to a high-pressure, high-temperature superheated vapor.
- This process is represented as an isentropic compression on the P-h diagram and a vertical line on the T-s diagram.

Heat Rejection in Condenser (Process 2-3)

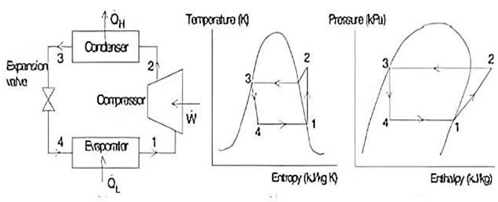
- The high-pressure, high-temperature vapor flows into the condenser, where it releases the latent heat to the surroundings.
- As the refrigerant loses heat, it condenses into a high- pressure liquid.
- On the P-h diagram, this is shown as a constant pressure heat rejection, while on the T-s diagram, it moves horizontally to the left.

Expansion through Expansion Valve (Process 3-4)

- The high-pressure liquid refrigerant passes through the expansion valve, where its pressure drops significantly.
- This pressure drop causes a part of the refrigerant to evaporate, resulting in a low-pressure, low-temperature mixture of liquid and vapor.
- On the T-s diagram, the expansion process is nearly isenthalpic (constant enthalpy), and on the P-h diagram, it is a vertical downward line.

Heat Absorption in Evaporator (Process 4-1)

- The low-pressure refrigerant enters the evaporator, where it absorbs heat from the surrounding space.
- As it absorbs heat, the refrigerant completely evaporates into a low pressure-vapor, completing the cycle.
- On the T-s diagram, this is shown as constant pressure heat absorption, while on the P-h diagram, it moves horizontally to the right.



$$COP = \frac{h_1 - h_4}{h_2 - h_1}$$

Figure 1. Schematic diagram of VCRS cycle

3. Procedure Of Modification Of AC System

The modification of a conventional window air conditioner (AC) into a test rig was a critical step to enable detailed parametric and predictive analysis. The process involved careful planning and execution to ensure the system could operate under controlled conditions and provide reliable data. Below is a step-by-step outline of the modification procedure:

Dismantling the Original Setup

- The window AC unit was carefully dismantled to access its internal components, particularly the condenser fan and blower.
- The condenser fan and blower, which were originally mounted on opposite sides of a single motor shaft, were separated to allow independent operation.

Installing Individual Motors

- Separate motors were procured for the condenser fan and the blower.
- Each motor was securely mounted in positions that ensured proper alignment with the existing components.

- The connections were checked for stability to avoid vibration or misalignment during operation.

Integrating Speed Control Mechanisms

- Regulator circuits were installed for both the condenser fan motor and the blower motor.
- These regulators allowed precise speed adjustments, enabling the variation of the convective heat transfer coefficient (h), which directly impacts the overall heat transfer coefficient (U) and heat exchanger effectiveness.

Installing Measurement Instruments

- Pressure gauges were fitted to monitor condenser and evaporator pressures accurately.
- Thermocouples were placed at strategic locations to measure temperatures at the condenser and evaporator inlets and outlets.
- A data acquisition system (DAQ) was connected to collect and store the measured parameters for subsequent analysis.

Reassembling the Unit

- The modified components, including the independent motors and regulators, were integrated into the original housing of the window AC unit.
- Care was taken to ensure all electrical connections were insulated and secure.
- The reassembled unit was tested for operational stability before proceeding to the experimental phase.

Calibrating the Setup

- The regulators were calibrated to ensure accurate speed control for both the condenser fan and blower.
- All measurement instruments, including the pressure gauges and thermocouples, were tested and calibrated for accuracy.

Testing the Modified System

- The modified unit was operated under standard conditions to verify its functionality.
- Initial test runs were conducted to ensure the system responded correctly to variations in fan speeds and other parameters.

Preparing the Test Rig for Experiments

- The modified unit was set up in a controlled environment to simulate varying ambient conditions.
- A detailed checklist was created to ensure all components were functioning correctly before beginning the experiments.

4. Data Collection & Dataset Prepration

The data collection process was a critical component of this study, as the quality of the dataset significantly impacts the accuracy and reliability of predictive modeling. Unlike prior research that often relied on synthetic or simulated data, this project focused on generating a high-quality, experimentally- derived dataset to bridge the gap in existing literature.

4.1 Data Collection Process

The data collection procedure was very crucial part of this study, and this involves:

Experimental Setup

- A modified window air conditioning (AC) system served as the test rig for data collection.
- The system was equipped with independent motors for the condenser fan and blower, each with adjustable speed controls.
- Precision instruments, including pressure gauges and thermocouples, were installed to measure key parameters such as condenser pressure, evaporator pressure, and temperature at multiple points.

Parameter Tuning

- The condenser fan and blower speeds were systematically varied to alter the convective heat transfer coefficient (h), which directly influences the overall heat transfer coefficient (U) and the effectiveness of the heat exchangers.
- For each set of fan speeds, the resulting pressures in the condenser and evaporator coils were recorded.
- The Coefficient of Performance (COP) was calculated for each configuration based on the recorded data.

4.2 Dataset Preparation

The dataset preparation was another very crucial step of this study, as the quality of the dataset significantly impacts the accuracy and reliability of predictive modeling. This steps involves:

Data Formatting

- Each data point included input variables such as condenser pressure, evaporator pressure, along with the corresponding COP as the output variable.

Dataset Organization

- Table 1 showing the final dataset was structured as follows:
  - **Independent Variables**: Condenser pressure and evaporator pressure.
  - **Dependent Variable**: Coefficient of Performance (COP).
- The dataset was saved in a machine-readable format (e.g., CSV or Excel) for use in predictive modeling

Table 1. A snapshot of dataset prepared for machine learning implementation.

Condenser_Pr	Evaporator_Pr	COP
15.0	5.6	3.3
19.6	3.0	2.8
17.9	2.6	3.1
16.8	4.0	3.1
13.2	5.9	3.2
12.5	3.0	3.2
18.9	4.7	3.3

5. Machine Learning Implementation

To analyze the relationship between system parameters and the Coefficient of Performance (COP), machine learning (ML) algorithm were applied to the experimentally-derived dataset. These algorithms were chosen for their ability to

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handle structured data and their performance in predictive modeling tasks.

In this study, we have selected the Linear Regression algorithm shown in fig 2 to implement the machine learning model for the prepared dataset Linear regression is a widely used supervised machine learning technique that establishes a linear relationship between a dependent variable (target) and one or more independent features (inputs). This is achieved by fitting a linear equation to the observed data.

The primary goal of the linear regression algorithm is to determine the best-fit line or equation that minimizes error and accurately predicts target values based on input variables.

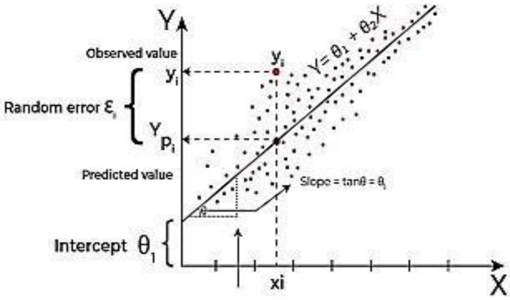


Figure 2. Graph of linear regression model

6. Methods Used To Improve Predictability

To improve the accuracy and reliability of the machine learning model, regularization techniques were employed. Regularization is a critical step in machine learning to reduce errors and prevent overfitting. Overfitting occurs when the model becomes too complex, learning unnecessary patterns or noise from the training data, which compromises its performance on new data

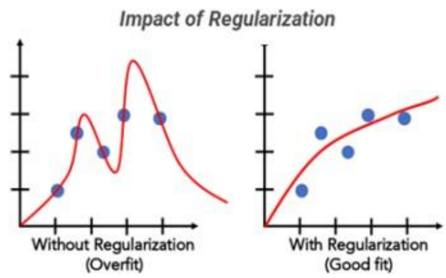
Regularization techniques address this by adding a penalty term to the model, which helps control complexity and ensures better generalization.

In our case we used L2 Regularization technique (Ridge regression), Ridge regression adds a penalty term to the loss function based on the squared values of the model coefficients.

$$SSE_{ridge} = \sum (y_i - \hat{y}_i)^2 + \lambda \sum \beta_j^2$$

7. Ridge Regression Model

Ridge Regression is an enhanced version of the classical regression model that incorporates a correction term to address overfitting and improve prediction accuracy. This correction is achieved by introducing a penalty to the regression coefficients, helping the model generalize better to unseen data. The Ridge Regression formula is an extension of the Sum of Squared Errors (SSE) used in classical regression. It introduces a regularization term to shrink the coefficients (Beta values) toward zero shown in fig 3.



Notes: 1. The graph is clearly showing how the regularization technique helps in avoiding overfitting.

Figure 3. Impact of regularization

8. Procedure for Predictive Analysis

The predictive analysis our study involves following steps as stated below:

Data Collection and Preprocessing

- The first step involved collecting real-time data from the experimental setup of the modified Window AC test rig.
- Splitting the dataset into training and testing subsets, typically in an 80:20 ratio for model training and evaluation.

Selection of Machine Learning Algorithm

- Linear Regression was selected as the primary machine learning algorithm to predict COP based on input parameters.
- To improve the model's generalizability and prevent overfitting, Regularization technique i.e. L2 (Ridge) were applied

Model Training

- The preprocessed training dataset was fed into the linear regression model to establish relationships between input features and the COP.
- The algorithm computed the optimal coefficients for the independentvariables to minimize the error between Actual and predicted values.

Model Validation and Evaluation

- The trained model was validated using the testing dataset to assess its performance and accuracy.
- Evaluation metrics were used to analyze the prediction quality, including: Mean Absolute Error (MAE), Mean Squared Error (MSE)& R-squared (R^2), which indicates the model's ability to explain the variability in COP.

Predictive Analysis Results

- The model predicted the COP values based on various combinations of input features such as condenser pressure, evaporator pressure.
- Graphical analysis was conducted to visualize the relationships between parameters and the COP:
- Line Plots shown in fig 4 showing COP variations with condenser and evaporator pressures.
- Scatter Plots illustrating the correlation between pressures and COP.
- Histograms of COP shown in fig 6 values to analyze the frequency distribution and performance trends.

- Predicted Vs actual COP shown in fig 5 Demonstrates the predictive accuracy of the Ridge Regression model

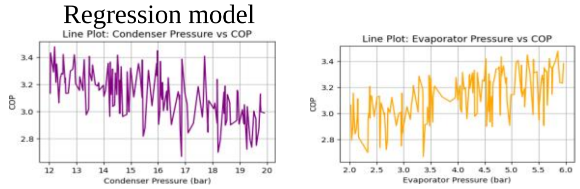


Figure 4. Line Plots diagram

Interpretation and Insights

- The predictive analysis provided insights into how parameter tuning impacts the COP.
- It was observed that:
- On decreasing the condenser pressures while maintaining evaporator pressure constant results in increment of COP of the system and vice versa.
- On increasing the evaporator pressures while maintaining condenser pressure constant results in increment of COP of the system and vice versa
- Fan speed adjustments influence the heat transfer coefficients and, consequently, system performance shown in fig 7.

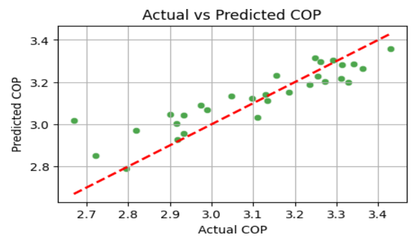


Figure 5. A plot between Predicted Vs actual COP

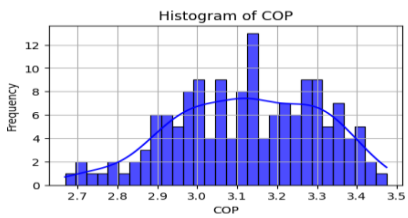


Figure 6. Histograms of COP

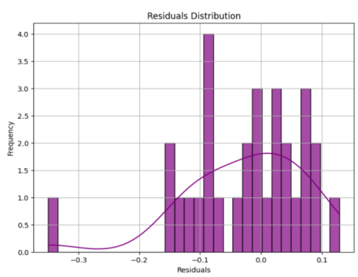


Figure 7. Residual distribution curve

9. Conclusions

The study successfully demonstrated the application of machine learning techniques, specifically Linear Regression with regularization methods, to predict the Coefficient of Performance (COP) of a modified Window Air Conditioning (AC) system. The predictive analysis provided valuable insights into the relationship between system parameters—such as condenser pressure, evaporator pressure, and fan speeds—and system performance, represented by COP.

Through systematic data collection, preprocessing, and modeling, a real-world dataset was generated, offering a reliable foundation for predictive modeling and performance analysis. Unlike synthetic datasets, the experimental data enabled the development of a more accurate and robust model. Key findings include:

Condenser and evaporator pressures significantly impact the COP, with clear trends observed within specific operational ranges. Fan speed adjustments influence heat transfer coefficients, thereby affecting system performance and efficiency.

Regularization techniques, Ridge (L2) regression, effectively reduced model overfitting and improved generalizability.

The developed machine learning model not only predicted COP values with high accuracy but also provided a strong framework for performance optimization. This study highlights the potential of data-driven approaches in analyzing and improving HVAC systems, paving the way for further research into advanced optimization techniques and alternative system designs.

Overall, the findings contribute to a better understanding of parameter interactions in vapor compression refrigeration systems and demonstrate the benefits of integrating experimental data with machine learning for predictive analysis and performance enhancement

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