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Evaluation of the Effects of Installation Faults in the Outdoor Unit of Air Conditioners Using Exergy Analysis

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Abstract: The increasing prevalence of global warming has led to a significant rise in the use of air conditioning systems, a trend widely acknowledged by numerous key institutions. However, this widespread adoption has brought about several challenges, particularly those stemming from improper installation practices. This study specifically examines the impact of installation faults in the condenser units of air conditioners on exergy destruction. One of the most critical issues identified is the blockage of the air inlet in the condenser unit, which often occurs due to installation errors. This study investigates the effects of such blockages on exergy destruction within the system. The findings indicate that installation faults in the condenser unit can substantially reduce the exergy efficiency of air conditioning systems, with efficiency values ranging from 38% to as low as 19%. Moreover, the exergy analysis of the condenser unit reveals that under inefficient operating conditions, exergy destruction increases by 114%. For example, when the air inlet of the condenser is obstructed, the exergy destruction in this section escalates from 0.35 kW to 0.75 kW, underscoring the critical impact of improper installation on system performance.

Keywords: Air conditioning, Exergy, Installation Fault.

Klima Dış Ünitesindeki Montaj Hatalarının Etkilerinin Ekserji Analizi Kullanılarak Değerlendirilmesi

Öz: Küresel ısınmayla birlikte klima kullanımı artmaktadır. Bu durumu birçok önemli kurum da dile getirmektedir. Ancak klima montajından dolayı ciddi sorunlar ortaya çıkmıştır. Özellikle klimaların kondenser ünitesi montaj hatalarının ekserji yıkımına olan etkileri bu çalışma kapsamında ele alınmıştır. Montaj hatalarından sonra klimaların kondenser ünitesinin hava girişi çeşitli nedenlerle engellenmektedir. Bu durumun ekserji yıkımına olan etkisi incelenmiştir. Kondenser montaj hatalarında elde edilen sonuçlara göre AC sistemin ekserji verim değerleri %38 ile %19 arasında hesaplanmıştır. Kondenser-ekserji analizinde ekserji yıkımı değerlerinin %114'ü kondenserde verimsiz çalışma koşullarında oluşmaktadır. Kondenserdeki hava girişlerinin kapatılması kondenser bölümündeki ekserji yıkımının 0,35 kW'dan 0,75 kW'a çıkmasına neden olmaktadır.

Anahtar Kelimeler: Klima, Enerji, Kurulum hatası.

1. Introduction

Different climatic conditions present a significant challenge that air conditioning (AC) companies must address. Designing systems tailored to the specific climatic conditions of the regions where their products are sold not only reduces electricity consumption but also minimizes costs. This approach contributes to decreasing carbon emissions associated with the electricity consumption of AC systems. In AC system design, the concept of eco-friendliness is often emphasized in the literature, alongside efficiency parameters. In particular, energy and exergy analyses are widely utilized as critical tools for comparative evaluation in such studies [1]. A review of the literature reveals that research on installation faults in air conditioners remains limited. While some existing studies are academic and scientific, others are reports prepared by national public institutions. One such study examined the consequences of installation faults in air conditioners and heat pumps in the United States. It was found that installation faults in these systems result in an additional annual energy demand of 20.7 TWh, corresponding to an annual billing cost of $2.6 billion. However, this study focused solely on residential air conditioners and heat pumps [2]. In another study, a framework was developed to address errors commonly encountered in air conditioning systems. These included issues such as contamination, sensor errors, control errors, and performance degradation. To analyze the impact of these errors, the researchers conducted modeling for five different climatic conditions in the United States. The findings indicated that such faults increase energy consumption and failure rates due to excessive loads placed on system components [3]. Additional studies have investigated the effects of heat pumps in residential settings, focusing on issues such as duct leakage, insufficient refrigerant charge, oversized heat pumps, undersized duct systems, restricted airflow caused by small duct sizes, and overcharging of refrigerants. Modeling these errors across six U.S. regions revealed that specific energy consumption could

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increase by 100% to 133% annually under certain conditions [4]. A separate study evaluated error protocols in AC systems, concluding that existing protocols were inadequate. It was determined that systemic errors generated approximately 40% false signals depending on operating conditions [5]. Similarly, another report highlighted installation problems in AC systems from the perspective of national energy efficiency and savings. The report demonstrated that energy-saving potential ranged from 3% to 15%, with cumulative savings reaching up to 40%. Common installation errors included improper sizing (selecting systems with capacities mismatched to the space requirements), incorrect load calculations (underestimating or overestimating heating and cooling needs), suboptimal airflow rates, and duct leakage. It was estimated that addressing these errors could achieve energy savings of up to 25% per kWh [6]. Air conditioners play a crucial role not only in heating and cooling environments but also in maintaining humidity balance. In this context, exergy losses and exergy performance observed in air conditioners designed for such purposes are among the preferred methods for obtaining significant data [7]. Notably, exergy analysis is widely utilized in evaluating the components of hybrid air conditioning systems under different climatic conditions, such as hot and humid environments [8]. Moreover, the environmental impacts of refrigerants used in air conditioning systems have emerged as a current research focus. When environmentally friendly refrigerants are employed, the necessity of evaluating these systems through exergy analysis also arises. The literature reveals the existence of valuable studies in this domain [9]. Exergy analysis is frequently employed by researchers as a method for identifying critical data, such as exergy losses and performance indicators in air conditioning systems [10,11].

While the studies reviewed provide valuable insights, no research has specifically examined the effects of inefficient operating conditions in air conditioners—particularly those caused by installation faults in the condenser section—on exergy destruction. The present study, by addressing this gap, establishes its originality and significance.

2. Research Methodology

Serious issues often arise during the installation of the condenser section of air conditioners (ACs). To address this, AC manufacturers typically provide detailed guidelines in user manuals on the correct installation procedures for condenser sections. In this study, the installation instructions for the condenser, as outlined in the user manual of the AC used in the experiments, are presented in Fig. 1. Additionally, Fig. 1 includes technical drawings illustrating how the air inlets of the condenser were obstructed during the experiments.

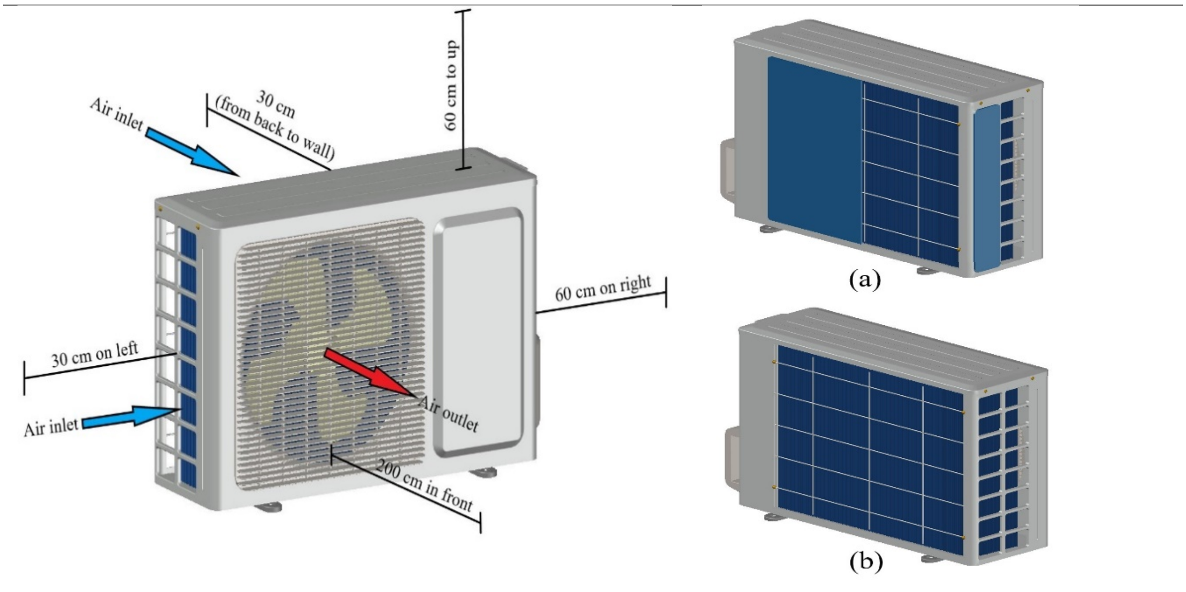
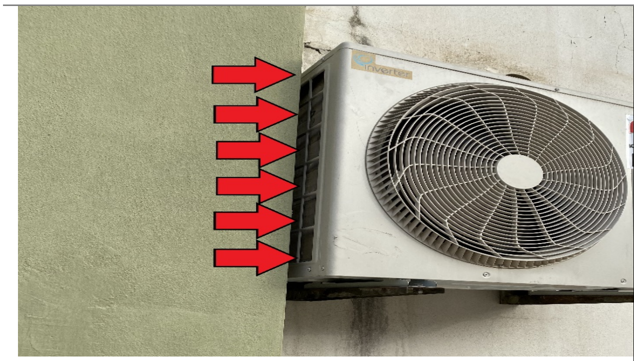
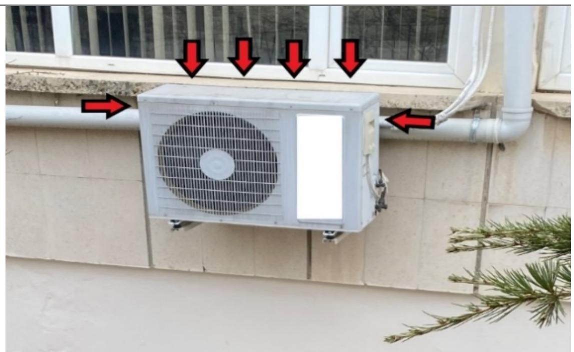


Figure 1. (Left) Illustration of the condenser section installation in the AC system. (Right) Technical depiction of how the air inlets were obstructed during the experiments ((a)- airflow blocked state, (b)- airflow open state).

In Fig. 1 (left), the air inlets and outlets of the condenser section are illustrated. The condenser section features air inlets located on the back and left sides. Heat absorbed by the evaporator section is transferred to the condenser via the refrigerant and compressor. The surrounding air is drawn through the condenser's heat exchanger with the aid of a fan, enabling the heat extracted from the evaporator to be discharged into the environment. However, as obstructions increase and the airflow entering the condenser decreases, the compressor unit consumes more electricity to transfer this heat effectively. A split type AC system was used in the experiments. The working fluid used in the cycle of the system is R32. While the cooling capacity of the system is 12000 BTU/h, the seasonal efficiency value is 6.1 in the AC system cooling mode. The experimental process consists of two parts. In the first part, the AC was installed in accordance with the installation procedure of the authorized service and then the system was operated. The energy consumption values of the AC, which was installed in accordance with the installation procedure of the authorized service, were calculated. The values obtained from this analysis are for reference or comparison parameters. In the second part, installation faults was created. Barriers are placed in the air inlets of the condenser section. The air inlets utilized during the experiments are shown in Fig. 1 (right). In Fig. 1 (right-a and b), the air inlets on the back and left sides of the condenser are partially obstructed, with a blockage of 50%. During the experiments, the air inlets were closed to varying degrees: back inlets at 25%, 50%, 75%, and 100%, and left-side inlets at 25%, 50%, and 75%. Notably, when the back and left air inlets were completely (100%) blocked, the automation system automatically shut down to protect the AC system components. As a result, the maximum closure of the left-side air inlet was limited to 75%. The closed areas were calculated as percentages of the total air inlet area, which measures 0.346 m². A more detailed explanation of these calculations is provided in the Results and Discussion section. The experiments were also conducted at different fan speeds in the evaporator section. Specifically, fan speeds were set at 20%, 40%, 60%, 80%, and 100%. This approach allowed for a clearer assessment of how varying operating conditions of the AC system influence the effects of installation faults in the condenser section on the system's performance parameters. Finally, Fig. 2 provides visual evidence of incorrect outdoor unit installation in the air conditioning system.



(a)



(b)

Figure 2. Photos showing the installation faults in the condenser section of ACs.

In Fig. (2-a), the condenser of the AC system is shown installed adjacent to the building's column. This placement obstructs the air inlet on the side of the condenser, restricting airflow. When the condenser installation is examined further, it is evident that the air inlet at the back of the condenser is also blocked, as illustrated in Fig. (2-b). Additionally, the building's rainwater pipe and a protrusion in front of the window hinder air entry from the top and partially from the back, as depicted in Fig. (2-b). Thermodynamic analyses serve as critical tools for evaluating the performance and efficiency of systems. Conducting these analyses during the study provides essential data for identifying the negative impacts of installation faults within the system. As a result, meaningful outcomes can be derived to propose appropriate solutions to mitigate these issues. The theoretical framework for exergy analysis is briefly outlined below. In the exergy calculations, a reference ambient temperature of 27 °C is used. The following equations are applied in the exergy analysis of the system:Eq. (1) is used to calculate the exergy destruction in the compressor [12];

$$\psi_{dest.comp} = (\psi_{output} - \psi_{input}) + \dot{\mathrm{W}} = \dot{m} \cdot T_o \cdot (\mathrm{s}_{output} - s_{input}) \quad (1)$$

The exergy destruction for the condenser section is calculated by using Eq. (2) [7];

$$\psi_{dest.cond} = (\psi_{input} - \psi_{output}) = T_o \cdot \mathrm{S}_{gen.cond} \quad (2)$$

Eq. (3) is used to determine exergy destruction for the evaporator section [7];

$$\psi_{dest.\mathrm{evap}} = (\psi_{output} - \psi_{input}) = T_o \cdot \mathrm{S}_{gen.\mathrm{evap}} \tag{3}$$

The exergy efficiency of the AC system is calculated by using Eq. (4) [13,14].

$$\eta_{ex} = \frac{\dot{E}_{evap}\left(1 - \dfrac{T_o}{T_{evap}}\right)}{\dot{W}} \tag{4}$$

In this study, the Kline and McClintock methods [15] were used to calculate the uncertainty. Eq. (5) is used for uncertainty analysis.

$$\frac{\Delta\varphi}{\varphi} = \frac{1}{\varphi}\sqrt{\sum_{i=1}^{n}\left(\frac{\partial\varphi}{\partial x_i}\Delta x_i\right)^2} \tag{5}$$

where φ is the parameter, x_i is the variable, and Δx_i is the error of the measured variables. The values obtained from the uncertainty analysis are shown using error bars in the graphs. The measuring devices and uncertainty values used in the experimental study are given in Table 1.

Table 1. Measurement uncertainties.

Instruments	Value of quantity	Uncertainties (±)
Thermocouple type T	-250, 350	0.5 (°C)
Air Flowmeter	-0,15	0.1 (m/s)
Pressure	-	2 (bar)

3. Results and Discussions

The results obtained within the scope of the study were examined under several headings. The effects of installation faults are analyzed by evaluating various parameters. The error bars represent ±0.013 in the exergy graphs. Exergy analysis serves as a critical tool in evaluating engineering systems or designs. Such a thermodynamic analysis, operating within a diagnostic framework, assists researchers in identifying parameters that contribute to losses, inefficiencies, or comparisons. The surprising findings obtained as a result of the exergy analysis carried out within the scope of this study are explained as follows:

The analysis method that enables the acquisition of critical data in thermodynamic studies is exergy analysis. Energy analyses are insufficient for evaluating the direction and quality of energy. The values obtained from the exergy analysis should also be examined to reinforce the validity of the interpretations made. In particular, focusing on the exergy destruction parameter provides a more accurate approach. The purpose of this approach is to determine the effect of the issues caused by condenser installation faults on exergy destruction. The exergy destruction values that occur in the compressor when the condenser air inlet is blocked are presented in Fig. (3).

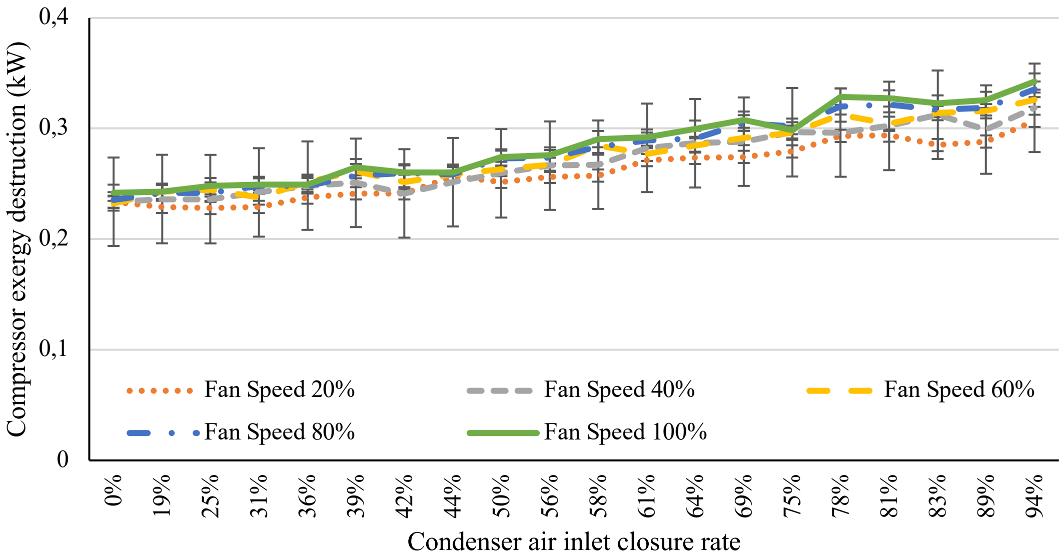


Figure 3. Exergy destruction in the compressor section.

The exergy destruction increased by 41.66% when the condenser air inlet was blocked. Error bars in the graph range between ±0.04. The exergy destruction reference value is 0.24 kW. The compressor power increased incrementally as the air inlet was gradually closed. As expected, the exergy destruction increases with higher power consumption. The values in Fig. (3) confirm this observation. The extra power consumption increases the exergy destruction value to as much as 0.34 kW due to the closure of the air inlet. It has been calculated that the exergy destruction reaches 0.247 kW, 0.27 kW, and 0.29 kW if the evaporator fan speed is 100% and the condenser air inlets are closed by 25%, 50%, and 75%, respectively. Notably, exergy refers to the quality of energy as well as its quantity. In this context, it can be predicted that closing the air inlets of the condenser section may result in a significant increase in exergy destruction, particularly within this system component. Fig. (4) visually represents this prediction.

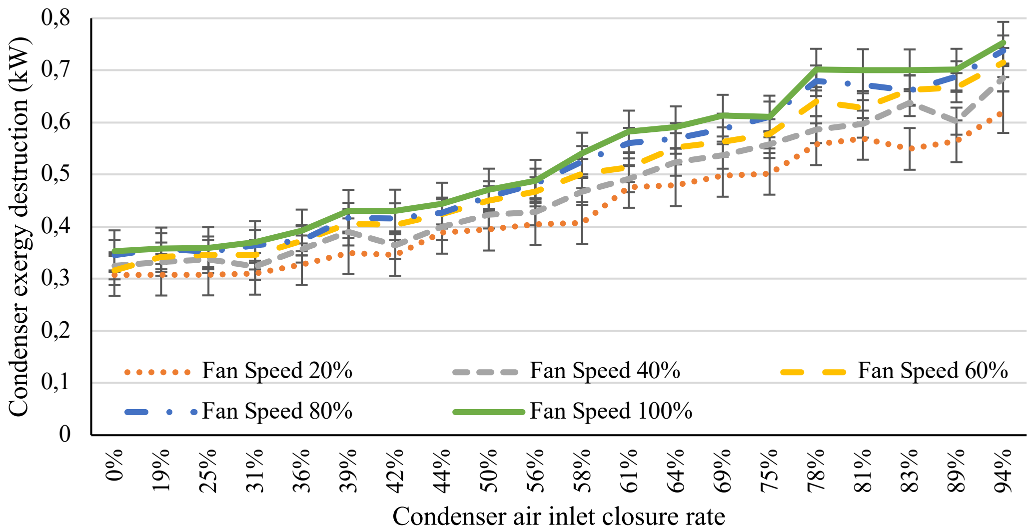


Figure 4. Exergy destruction in the condenser section.

In the condenser-exergy analysis, 114% of the exergy destruction values occur under inefficient operating conditions within the condenser. Closing the air inlets in the condenser increases the exergy destruction in the condenser section from 0.35 kW to 0.75 kW. This significant rise demonstrates serious inefficiency in the condenser. However, the same interpretation cannot be directly applied to the data obtained from the exergy analysis of the evaporator. The exergy destruction values in the evaporator are presented in Fig. (5).

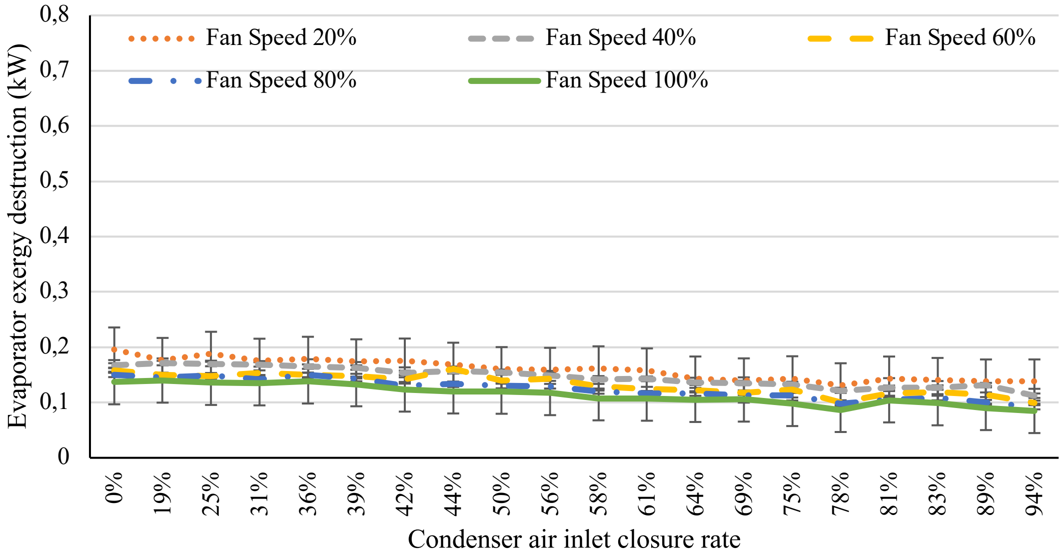


Figure 5. Exergy destruction in the evaporator section.

Error bars in the graph range between ±0.04. The gradual closure of the condenser air inlets does not significantly affect the exergy destruction in the evaporator. Variability in the evaporator remains limited as the system increases the capacity of electricity-consuming components such as the compressor and fan. Another important parameter in exergy analysis is exergy efficiency. The effects of air inlet closure and the variability in the ηex value under different operating conditions are illustrated in Fig. (6).

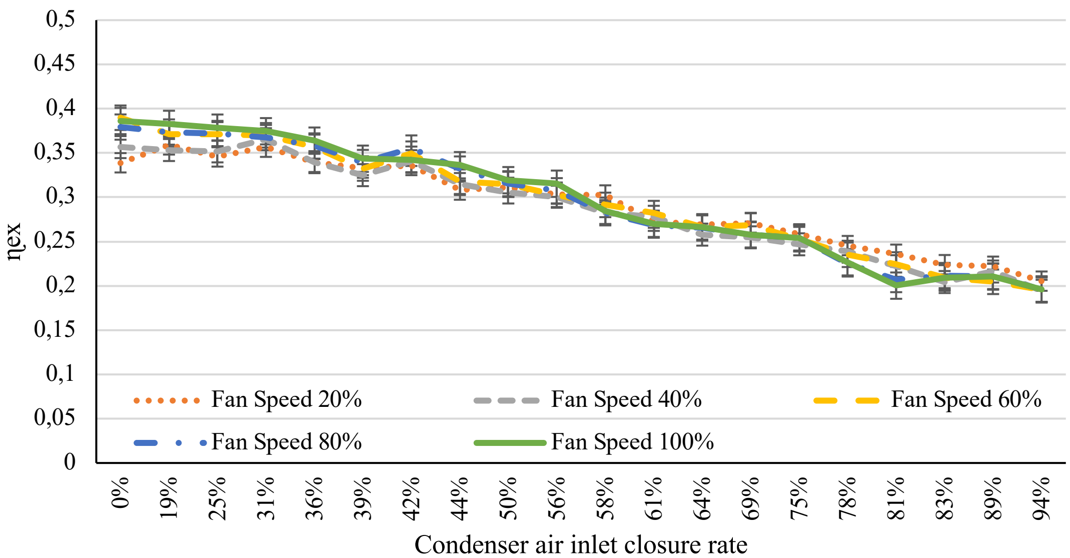


Figure 6. Change in the exergy efficiency of the AC system.

Fig. (6) illustrates the variation in the exergy efficiency of the AC system under different operating conditions. The reference exergy efficiency ranged from 33% to 38%, values consistent with those reported in the literature. While the exergy efficiency of the system varies between 33% and 38% at different cooling capacities, this value has been calculated as approximately 34% in studies from the literature [14]. When the values in the graph are examined overall, the maximum exergy efficiency was calculated to be 38%, while the minimum was 19%. In this study, a case study was carried out to install ACs in buildings. Developing this architectural design lies beyond the expertise of the authors. However, expert architects were asked to design a location on the building's outer wall that adheres to proper installation rules and avoids an unattractive appearance. In the design, it is possible to position the AC in locations distant from living areas, such as bedrooms, ensuring that the sound factor does not disturb either the user or those living on other floors. The design was carried out with many such factors in mind. Since this architectural design falls outside the scope of the study, a detailed explanation is not included. Many regulations must be considered during the construction process of buildings. These regulations typically address factors such as building insulation, fire extinguishing systems for structures with certain room and floor heights, and compliance with earthquake safety standards established by governments and international bodies. Only a few topics are referred to in the above sentence. In reality, construction regulations are far more extensive. In this study, a situation that should be added to these regulations is proposed based on exergy analysis. The necessity of designing suitable buildings for the installation of ACs has become apparent. For example, expert architects were asked to design condenser sections of ACs on the exterior of buildings. These designs aim to avoid any obstruction to air inlets entering the condenser. The design is presented in Fig. (7).

Figure 7. Precreated location in the building for the condenser of the AC ((a)-layout plan, (b)-exterior view).

As shown in Fig. (7), the precreated location of the condenser section of the ACs prevents installation faults in the condenser. Considering the appropriate design parameters in the positioning and design of buildings, it should be noted that AC systems can have a positive effect on operational lifespans. This indicates that original academic studies can be conducted in the field of architecture. In the future, both automation and the Internet of Things (IoT) will be important components of AC systems. It is anticipated that companies will monitor their products, allowing for intervention in case of installation faults or issues before the next scheduled maintenance date. Along with similar software designs such as artificial intelligence (AI), developments in measurement and sensors are enabling AC systems to operate more efficiently. The development of automated systems has the potential to significantly reduce energy consumption in AC systems. Many dynamic variables, different from those of traditional cooling system operations, affect the efficiency of these systems. These dynamic parameters—such as weather forecasts, climate conditions, temperature, and solar radiation—increase the importance of electronic control units and software integration in cooling systems. This equipment contributes to significant cost and energy savings in building AC systems [16]. Additionally, algorithms developed by applying similar strategies can also be used to independently regulate the temperature and humidity of cooling systems [17]. Artificial neural networks (ANNs) have emerged as a method successfully applied to engineering systems in recent years, with many researchers reporting positive results. However, studies on their application in cooling systems have yielded conflicting findings. In a detailed review, articles were categorized into eight distinct topics or categories [18]. Improving the coefficient of performance (COP) of AC systems allows for significant energy savings. However, this approach increases the need for additional parameters, such as user behavior data or climate-related variables, to enable advanced software control systems. Studies on these subjects have shown promising results [1]. There is an increasing research trend in this direction within the literature. The focus of software research and development changes based on advancements in the field. For example, while artificial neural networks (ANNs) are highly preferred, machine learning and control approaches are becoming increasingly popular. In the future, quantum learning methods could potentially enhance software control for AC systems, as suggested by emerging studies in the field. The number of studies in this area is steadily increasing. The studies carried out in this context can also contribute positively to the annual electricity consumption (AEC) values. In addition to improving the operation of cooling systems, AI has made substantial contributions to cooling system design. Artificial intelligence applications are used to estimate the climatic conditions in which the system will operate, as well as to determine the optimum design criteria for cooling systems in specific regions. In this respect, AI methods are often employed by researchers as prediction tools. Keywords summarizing AI applications in cooling systems include performance, modeling, optimization, forecasting, and control [18]. Operating AC and HVAC systems with artificial intelligence will prevent unnecessary energy consumption. Advanced automation and control strategies enabled by AI can ensure the efficient operation of these systems. When the above studies are examined, it becomes evident that different solutions can be developed to address installation faults in AC systems. The solution proposals expressed here do not fall within the expertise of the authors. Instead, these are scientific findings based on studies in the existing literature. However, the methods mentioned above are suggested for academic and scientific exploration. In the future, researchers can pursue innovative and original studies on this subject.

4. Conclusion

In this study, the practical problems caused by installation faults in the condenser section of ACs were investigated. Based on experimental analysis, the air inlet of the condenser section was gradually closed. The results show that the performance of ACs is lower than expected. Installation faults in ACs result in unnecessary energy consumption. When this situation is evaluated on a national scale, significant energy waste and emissions are observed. The results obtained from the study can be summarized as follows:

- The inability to transfer energy to the environment increases exergy destruction in all system components. In particular, the exergy destruction in the condenser section was found to be significantly affected. The storage of energy in the system components forces automation to operate the system at higher values. As a result of inefficient operating conditions, the exergy destruction in the compressor increased from 0.24 kW to 0.29 kW.
- Exergy destruction in the condenser increased from 0.35 kW to 0.75 kW.
- The reference exergy efficiency ranged between 33% and 38%. In parallel with the gradual reduction in the air inlets of the condenser section, exergy efficiency was calculated to decrease from 38% to 19%.

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We undertake that in the article we submitted for publication, no study requiring ethics committee approval, was conducted.

There is no conflict of interest between the authors.

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