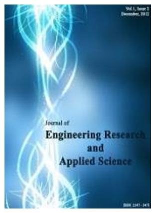
Journal of Engineering Research and Applied Science
Available at www.journaleras.com
Volume 12 (2), December 2023, pp 2360-2368
ISSN 2147-3471 © 2023



Performance of Air Source Heat Pump Using the TRNSYS Simulation Program

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Abstract
The current study introduces a numerical model of the TRNSYS software and MATLAB programming to investigate the efficiency of a heat pump system in the climates of Afghanistan. The simulations incorporate hourly weather data specific to each city and detailed representations of the heat pump systems. The selected heat pump model is an air-source heat pump with specified heating and cooling capacities. A heat pump stands as one of the most widely used devices for converting energy and supplying essential heating and cooling to buildings throughout cold and warm seasons. It is gaining popularity due to its ability to harness clean energy from the environment rather than depending on fossil fuels. This feature makes it more appealing. It can extract heat from the surrounding lower-temperature air and convert it into higher-temperature heat, which can subsequently be utilized for heating structures or generating hot water. However, a significant factor influencing its performance is the combination of high humidity and low outdoor temperatures, which results in a noticeable decrease in the efficiency of the ASHP. This study calculates the heat pumps' performances and energy consumption over a year for each city, considering the dynamic interaction between the systems, the buildings, and the outdoor environments. The results provide insights into the heat pumps' efficiencies, including COP values for heating modes, annual energy consumptions, and indoor temperature profiles. Comparative analyses across the cities allow for the evaluation of the impact of different climates on the heat pumps' performances. The results provide valuable insights for making well-informed decisions regarding energy-efficient heating solutions customized for the unique climates of Afghanistan.

Keywords: *ASHP; Coefficient of Performance (COP); SPF; TRNSYS; MATLAB; Afganistan*

1.. Introduction

Heat pump systems have gained significant attention as energy-efficient solutions for heating and cooling buildings in various climates [1]. In the context of Afghanistan, where energy consumption and cost-effective thermal comfort are critical considerations, understanding the efficiency of heat pump systems in different cities climates is crucial for informed decision-making and sustainable building practices. This study aims to investigate the efficiency of air-source heat pump systems in Afghanistan by using TRNSYS simulation and MATLAB program. Afghanistan experiences diverse climates, ranging from continental and dry in the northern regions to arid and semi-arid climates in the southern and western parts. Each city has distinct weather patterns, including variations in temperature, relative humidity, solar radiation, and wind speed [1-34].

2. Heat Pumps for low-carbon heating and cooling

Air Source Heat Pumps (ASHPs) offer several advantages. Renewable energy sources are used to replace fossil fuels in the production of energy as a result of global warming and the need for sustainable alternatives [1]. A progressively attractive approach to advancing decarbonization efforts involves the adoption of heat pump systems. By transitioning from conventional electric heaters and traditional boilers to HPs, particularly when integrated with photovoltaics and battery storage, it becomes feasible to reduce greenhouse gas emissions from buildings [2]. ASHPs are highly energy-efficient, extracting heat from the outdoor air even in cold temperatures and using less energy compared to traditional heating systems. This efficiency translates into cost savings over the long term, despite the higher upfront cost of ASHP installation. ASHPs are versatile, providing both heating and cooling functions, eliminating the need for separate systems [17].

The disadvantage of ASHPs is the performance limitations in extremely cold climates, requiring supplemental heating or backup systems. They can generate some noise during operation. ASHPs also

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require outdoor space for installation, which can be a constraint in some cases. Finally, their dependence on electricity means they are subject to availability and pricing, potentially leading to higher operational expenses in regions with high electricity costs [22]. Enhanced understanding of the operational performance of ASHPs holds the potential to significantly contribute to climate mitigation endeavors, while improving their efficiency can play a key role in curtailing energy consumption. Moreover, factors such as system configuration, management, installation, user practices related to heating, and diverse meteorological conditions collectively impact the performance of heat pumps [2].

The impact of climatic conditions on the system's functionality prompted engineers to investigate the most pivotal variables. Notably, temperature and atmospheric humidity stand out as the most crucial climatic parameters affecting the performance of heat pumps [1],[4]. On the other hand, ambient temperature plays a vital role in heat pump operation. Heat pumps extract heat from a low-temperature source (outdoor air, ground, or water) and transfer it to a higher-temperature destination (indoor space) [17]. The performance of a heat pump is affected by the temperature difference between the source and destination. In colder climates, lower outdoor temperatures significantly impact the heat pump's efficiency and capacity. As outdoor temperatures decrease, the heat pump's ability to extract heat diminishes, and it may consume more energy to meet heating requirements. Extremely low temperatures can even lead to operational issues, reduced efficiency, or system malfunctions if the heat pump isn't designed or equipped to handle such conditions [19].

The TRNSYS simulation tool provides a reliable platform for simulating heat pump performance, accounting for the dynamic interaction between the heat pump, the building, and the external environment [23-34]. By integrating hourly weather data, building thermal modeling, and detailed representations of the heat pump systems, this study aims to assess the efficiency of heat pumps under varying climatic conditions. The selected heat pump models have specified heating and cooling capacities, and the simulations incorporate control strategies to optimize their performance. Parameters such as temperature setpoints, and operating schedules are adjusted to suit the specific climate conditions of each city [23].

Consequently, researchers have turned to a diverse range of simulation techniques to explore and investigate ASHP systems. For instance, Safa et al [11]. employed TRNSYS to simulate and evaluate the performance of a two-stage variable speed ASHP system in Canada. Their assessment encompassed both heating and cooling capabilities, with variations in the coefficient of performance (COP) confined within specific ranges. Similarly, Le et al [13]. performed a techno-economic evaluation of ASHPs in residential structures across various UK locations, drawing on validated TRNSYS simulations to underpin their analysis. Kropas et al. [14] investigate the heat pump efficacy in the Baltic States using TRANSYS simulation tools. They investigate the effect of climate conditions on heat pump performance using TRANSYS simulation tools [30-34].

The benefits and drawbacks of ASHPs have been discussed in research. A comparison of air-to-air and air-to-water HP heating systems was done in research by Xiao et al. [5] under a range of ambient temperatures, from 7°C to -20°C. While the air-to-air HP system demonstrated higher performance and thermal comfort, the air-to-water HP system produced a more uniform distribution of indoor air temperature and velocity [1-8].

Kelly and Cockroft [6] conducted yearly simulations of the ASHP in the UK, noting that the system was more expensive but produced less carbon dioxide than a condensing gas boiler system. In their study, Ma et al. [7] employed numerical simulations to examine how various air supply parameters of the ASHP air conditioner affect local thermal comfort. Their findings demonstrated that integrating the ASHP with local electronic equipment resulted in improved indoor heating. [8] gives a thorough overview of the many software programs available for studying the integration of renewable energy systems, including HP. Numerous studies have examined the effectiveness of HP systems using the computational tool TRNSYS [9,12, 23, 31].

3. Research Methodology

The methodology utilized in this investigation involved creating and employing a numerical model using both TRNSYS simulation software and MATLAB. This model was used to evaluate how well an ASHP performs in different ambient air temperatures. The process of constructing the model and the fundamental assumptions made during its development were explained. To validate the model's accuracy, calibration was carried out by contrasting its predictions with operational parameters presented by other researchers. Given the significant impact of the operational environment on ASHP performance, the modelling analysis was conducted in various cities in Afghanistan. The climatic conditions in these regions hold a vital role in understanding the behaviour of the ASHP system. Additionally, the method for assessing the efficiency of the ASHP system was explained, providing a means to measure its overall performance [28-34].

Through the use of this all-encompassing approach, the research aimed to provide a deeper understanding of how ASHPs perform when faced with shifts in ambient air factors. The integration of modeling techniques, calibration, validation, examination of climatic conditions, and efficiency evaluation collectively contributed to conducting a comprehensive analysis of the investigated ASHP system.

4. Employed Model

The TRNSYS model utilized in this study serves as a comprehensive simulation instrument designed to evaluate the performance of heat pump systems under diverse climate conditions. Widely acknowledged in the domains of building energy analysis and renewable energy systems, TRNSYS ncompasses various components that collectively simulate the interactions and behavior of the heat pump system, the building, and the surrounding external climate. The process involves creating a comprehensive model of the heat pump system, including components such as the heat pump unit, heat source, distribution system, and the conditioned space or building. Specific climate data for each city is then integrated into the model, including variables like outdoor temperature and humidity. Once the simulation is configured, the TRNSYS and MATLAB programs execute the model, running simulations over a defined period to capture seasonal variations. The results obtained offer valuable insights into the heat pump's energy consumption, thermal efficiency, and relevant metrics. By comparing these outcomes across different cities, researchers can make informed decisions about heat pump design, control strategies, and energy management, ultimately optimizing performance under varying climatic conditions.

The designed system follows the approach of previous research by Kropas, et al [14], which aimed to assess the system's performance under various climatic conditions. The system is structured using different components referred to as Types. The core elements of the system consist of an air source heat pump known as Type 665-3. This model operates as an air source heat pump, with airflow occurring on both the condenser and evaporator sides of the device. Additionally, the system incorporates a Type 4a storage tank, a simulated heated room model designated as Type 12c, Type 2a controllers, and circulation pumps categorized as Type 110 [14]. The system comprises two primary circuits: the production circuit and the heat consumption circuit, interconnected through the storage tank. The air-source heat pump is responsible for producing hot water. When there is a need for heating, the hot water from the storage tank is utilized for the room heating system. The system operates exclusively during the designated heating season, which is specified by employing Type 14k [14]. According to the assumptions within the model, the heating system begins its operation on the 1st of December and concludes on the last day of February (specifically, during hours 1416 to 8040 within the model). To show the results, a Type 65a printer is utilized, while a Type 10-6 component is integrated for additional data handling. The schematic representation of the system can be observed in Figure 1 [14].

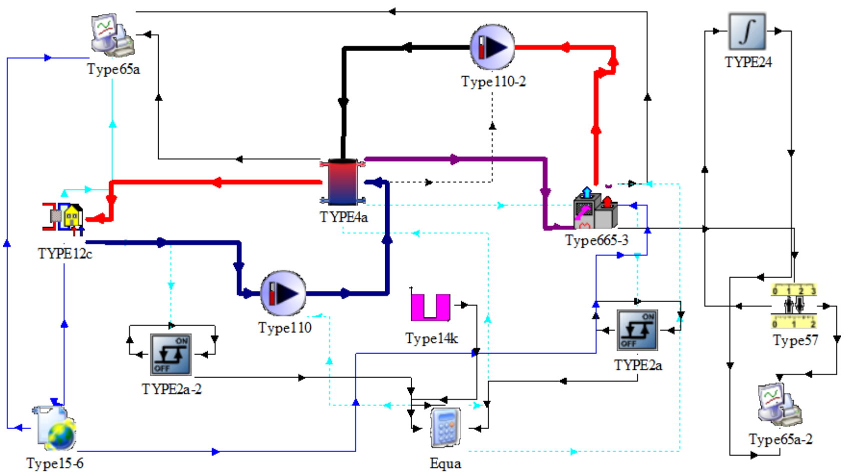


Figure 1. System simulation in TRANSYS

The ASHP Type 665-3 in TRNSYS is adjusted to assess its efficiency even low temperatures by incorporating ambient temperature data. The heat pump model is enhanced with data spanning from -10°C to 27°C, enabling the identification of a system that aligns with real-world experimental data. The temperature and efficiency parameters within this range are extracted from the manufacturer's documentation for the physical heat pump in operation.

5. Validation of the Model

The validation process of the TRNSYS model involved a calibration procedure designed to verify its accuracy. This procedure involved comparing the simulation results with data obtained from both the heat pump manufacturer and previous researchers in the same field. The experimental setup utilized a 7 kW heat pump with a coefficient of performance (COP) of 4.46. This COP value was determined based on environmental temperatures of 7°C and a heat carrier temperature of 35°C, as specified in the experimental data [14].

The heat pump model was formulated to address two primary objectives: replenishing a storage tank and producing domestic hot water (DHW) at a temperature of 50°C. The circulation pump, referred to as Type 110-2, was set with a flow rate of 0.38 kg/s. Conversely, the storage tank, designated as Type 4a, was tailored to closely resemble the characteristics observed in the practical trial. This storage tank possessed specific features, including a volume of 0.47 m³, a height of 1.961 m, and a heat loss coefficient of 0.76 W/(m²·K). These thoughtfully selected parameters aimed to accurately mimic the conditions of the practical demonstration. [14].

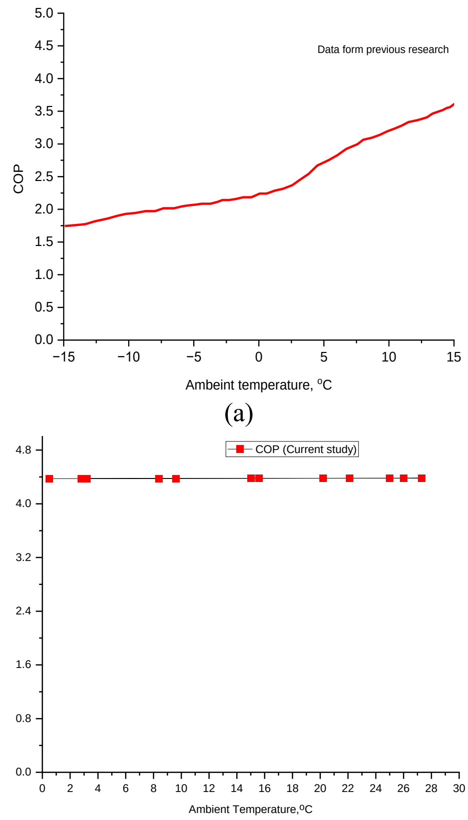
The calibration procedure entailed a comprehensive evaluation, involving a thorough comparison between the simulation outcomes utilizing climate data from Afghanistan and the results obtained by other researchers, alongside the experimental data. This exhaustive analysis was undertaken to establish the trustworthiness of the TRNSYS model. In this context, the heated room was depicted in the model using Type 12c, with an assigned loss coefficient of 80 W/K and a room temperature set at 20°C [14]. The coefficient of performance (COP) is a fundamental factor in evaluating heat pump efficiency. It is computed by dividing the heat produced (Q) in (kWh) by the electricity consumed (Pel) in kWh [21]:

$$COP = \frac{Q}{P_{el}} \quad (1)$$

A higher COP indicates better efficiency, as the heat pump is producing more heat for each unit of electricity consumed. In addition to COP, the seasonal performance factor (SPF) is utilized to assess the efficiency of an air source heat pump (ASHP) over an entire season. SPF is calculated by dividing the total seasonal heat energy generated (Q_{season}) by the total seasonal electricity consumed ($P_{el.seasonal}$) [21]:

$$SPF = \frac{Q_{seasonal}}{P_{el.seasonal}} \quad (2)$$

Both Coefficient of Performance (COP) and Seasonal Performance Factor (SPF) are pivotal metrics that offer valuable insights into the operational efficiency of a heat pump. They assess the ratio of heat energy output to the corresponding electricity input. A higher SPF value signifies a more efficient heat pump, capable of generating a greater amount of heat energy for a given quantity of electricity consumed. These parameters hold a critical role in appraising the effectiveness of heat pump systems in real-world scenarios.



(a)

(b)

Figure 2. Provides a condensed depiction of the findings from prior research (a) alongside the outcomes derived from current study (b).

By taking into account and optimizing these parameters, it becomes feasible to design, install, and operate a heat pump system that delivers optimal efficiency and performance for both heating and cooling applications. Fig. 2 presents the simulation results obtained from two distinct sources: earlier researchers' findings and the outcomes derived from the current research efforts. This visual representation likely illustrates a comparison of various performance metrics or data points between the two sources. The purpose of such a figure could be to showcase how the simulation results from the current research align or deviate from the findings of previous researchers. This comparison aids in assessing the validity and impact of the newly developed model, providing insights into potential advancements or discrepancies in the field of study.

6. Climate Data for Selected Regions

The climate conditions in Afghanistan vary across different regions of the country. The northern regions of Afghanistan, including cities like Kabul and Mazar-i-Sharif, experience a continental climate. Winters are cold with temperatures dropping below freezing, and summers are generally warm to hot. The temperature range between seasons can be significant. The southern and western parts of Afghanistan, such as Kandahar and Herat, have arid and semi-arid climates. These regions are characterized by hot, dry summers and relatively mild winters. Rainfall is limited, and the climate is generally dry throughout the year. Afghanistan has distinct seasons, including spring, summer, autumn, and winter. Each season has its own temperature and weather patterns. Summers can be hot, with temperatures often exceeding 35°C in some areas, while winters can be cold, with temperatures dropping below freezing, especially in the higher altitude regions. Understanding the specific climate conditions of different cities in Afghanistan, such as Kabul, Herat, Mazar-i-Sharif, Kandahar, Jalalabad, and Helmand,is crucial for analyzing the performance and efficiency of heat pump systems. This knowledge allows for the accurate simulation and optimization of heat pump designs to suit the local climate and maximize energy efficiency in buildings.

Table1. Six different cities weather data.

City	Latitude [°]	Longitude [°]	Altitude [m]	T avg, °C	RH avg, %
Kabul	34.516	69.195	1800	14.6	36
Mazar-i-Sharif	36.700	67.200	378	16.7	47
Kandahar	31.600	65.780	1021	20.7	31
Jalalabad	30.612	74.292	184	24.7	58
Herat	34.217	62.217	964	16.5	38
Helmand	31.550	64.367	780	21.1	31

T_{avg} and RH_{avg} are the annual average temperature and relative humidity of air [15].

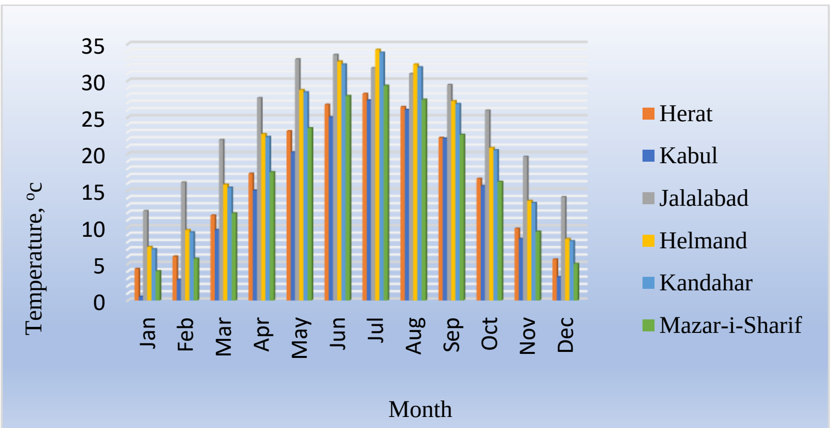


Figure 3. Monthly average air temperature of six cities.

Despite the overall similarity in climatic conditions among Kabul, Balkh, Kandahar, Herat, Helmand and Jalalabad. The analysis of climatic data, as shown in Figure 3, reveals certain distinctions.

Further examination of the ambient air temperature and its duration in the chosen cities (depicted in Figure 4) uncovers that same portion of the year is characterized by temperatures falling within the range of -8 °C to +10 °C. This temperature bracket occupies a larger portion of time when compared to the warmer seasons in the same cities. To be specific, the timeframe spanning from -10 °C to +10 °C constitutes approximately 43.78% of the annual duration in Kabul.

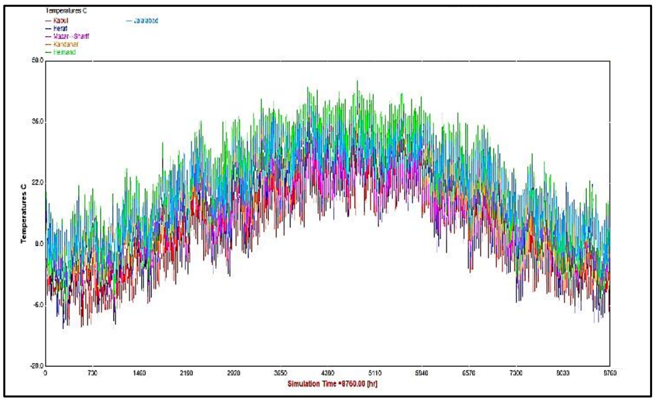


Figure 4. Hourly distribution of air temperature.

This highlights the fact that, during the winter time of the year, these cities experience temperatures suitable for indoor heating requirements. Within this timeframe, the heat pump would be actively employed to supply heat for indoor spaces. This analysis underscores the importance of the heating season and the significance of effective heating systems, such as the examined heat pump, in guaranteeing both comfort and energy efficiency within these specific climatic conditions.

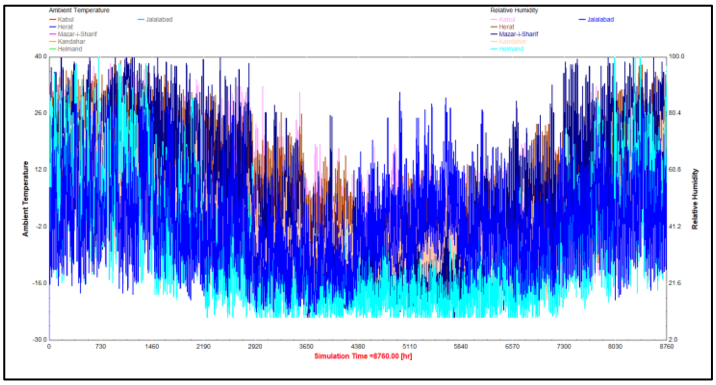


Figure 5. Hourly relative humidity (RH).

The assessment of relative humidity (RH) in the selected cities indicates that during certain periods, RH levels tend to be quite high. For instance, in Kabul, RH levels of 50% or more are present for approximately 14% of the time, which translates to about 1221 hours. Similarly, in Herat, this elevated RH situation occurs for roughly 15.2% of the time, corresponding to around 1326 hours (Figure 5). These findings suggest that the climate conditions in these cities generally exhibit moderate humidity levels, which can have advantages in preventing frost. Therefore, it becomes crucial to investigate the performance of air source heat pumps (ASHP) in environments characterized by both low temperatures and relative humidity levels.

7. Results

In this section, we reveal the results obtained from modeling the operational characteristics of a building's heating system utilizing an Air Source Heat Pump (ASHP) in several selected cities within the country. We illustrate these outcomes through graphical representations and subsequently provide a comprehensive comparison and analysis of these graphical results.

7.1. Kabul Province

The first city we have considered for modeling in Afghanistan is Kabul, the capital. Kabul's climate falls under the continental category, featuring warm summers and cold winters. During the winter months spanning from December to February, temperatures range between – 5 °C and 8°C. The average temperature in Kabul during the heating season varies from around 3°C to 10°C during the day, with nighttime temperatures dropping to approximately -2°C to -6°C. The winter period in Kabul is characterized by cold weather, shows the importance of heating systems to maintain a comfortable indoor environment. Notably, Figures 6 visually elucidate the variability of the heat pump coefficient of performance (COP) obtained through simulation in relation to ambient air temperatures for each month of the year.

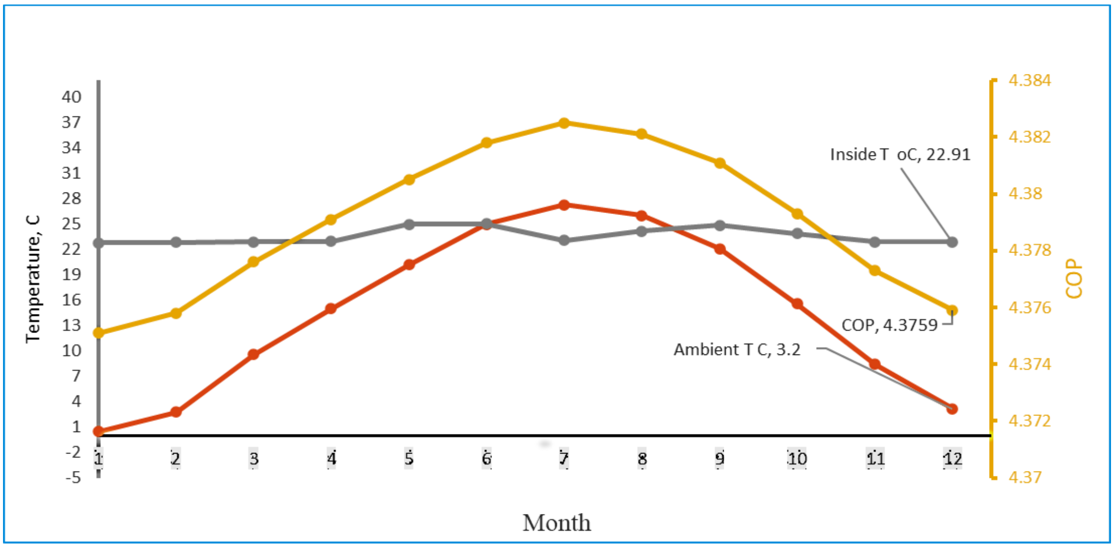


Figure 6. Illustrates the relationship between the coefficient of performance (COP) and the ambient air temperature in Kabul.

The information gleaned from Figure 6 illustrates that the coefficient of performance (COP) experiences variations across different months of the years. When outdoor temperatures are elevated, the COP also tends to be higher, and conversely, lower temperatures correlate with lower COP values. This trend persists within Kabul city as well. In the context of Kabul, the highest COP value documented is 4.382, while the lowest stands at 4.37. On average, a COP of 4.3 is achieved during the heating season. This is attributed to Kabul's higher ambient air temperature, allowing the heat pump to function with increased efficiency over extended periods. This scenario emphasizes the need for additional heat sources or a heat pumps in these areas. It's important to note that, for assessment purposes, the integrated heating element in the storage tank is not considered; the focus is solely on evaluating the heat pump's performance [14].

8. Conclusions

The investigation into heat pump efficiency across various cities of Afghanistan, carried out through TRNSYS simulation and the MATLAB program, yields several notable findings. The outcomes emphasize the substantial impact of climate conditions on heat pump performance. Cities with milder climates, such as Kabul and Mazar-i-Sharif, demonstrate a greater need for heat pump systems compared to cities with hotter or more extreme climates, like Helmand, Kandahar, or Jalalabad. The COP values and energy consumption show significant variations across these cities due to fluctuations in outdoor temperature and other climatic factors.

Modifications were made to the Heat Pump Type 665-3 in the TRNSYS program, aligning it with the manufacturer's data and previous research. This adaptation rendered the model appropriate for simulating the system in Kabul. The correlation observed between the results confirmed the model's validity for subsequent analysis. The performance parameters declared by the manufacturer for the ASHP and the simulated system, the primary factor that influences COP is the ambient air temperature and the temperature of the prepared heat carrier. However, relative humidity also plays a significant role, particularly in cold climate countries characterized by low temperatures and high humidity during the heating season. Coastal cities or those located near bays are particularly vulnerable to such conditions, which can result in freezing within the heat pump evaporator, thereby affecting both system efficiency and operation. Afghanistan, due to its relatively low relative humidity in heatin season attributed to its distance from the sea, provides an advantage for

ASHP usage, contributing to higher COP and SPF values.

Acknowledgment.
The authors acknowledged to Turkish Academy of Sciences for financial support of this study.

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