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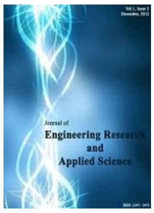

Air Source Heat Pumps for Decarbonizing of Space Heating and Cooling: Performance Simulation with TRNSYS

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Abstract
Heat pumps can play an important role in meeting global targets for energy savings and low carbon emissions. Air source heat pump is an energy-efficient technology that allows heating at different ambient temperatures. ASHPs can be used in different climates, from -25°C to +50°C. It presents the ASHP applications all over the world and highlights the measures to be taken to accelerate the use of ASHPs in buildings. 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. 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: *Air Source Heat Pump (ASHP); TRNSYS Simulation; Space heating and cooling*

1. Introduction

The global climate is undergoing major changes due to high concentrations of carbon dioxide in the atmosphere [1]; this is already evident from the occurrence of more extreme weather events around the world [2]. Energy consumption also induces climate change, but at the same time, climate change impacts the energy sector, both in terms of supply capacity and changes in energy demand [3]. The building sector, one of the most energy-intensive, will be strongly affected by this change. Buildings are recognized as the largest contributors to global warming [4] and are responsible for a large proportion of total energy consumption [5], followed by transportation, industry, and agriculture. Governments have begun revising their energy strategies and policies to mitigate these problems, and are working to achieve zero net greenhouse gas emissions by 2050. One answer to mitigating or rather reducing this trend is the different types of renewable energies that are increasingly widespread [6],[7],[8]. There is a growing interest in energy-efficient environmental systems that guarantee an adequate indoor climate for years to come. By increasing building energy efficiency, significant economic, social, and environmental benefits can be achieved [9].

Reducing building energy demand requires a broad awareness of how the climate will change to direct effective building energy efficiency actions [10]. This applies both to the design of new buildings and in the retrofit phase. It is unthinkable that actions taken today will be ineffective, due to climate change, in the next 50 years, when the investment costs have not yet been amortized. A large part of primary energy is used for heating and cooling buildings [11], [12]. It is expected that in the future cooling energy demand will prevail over heating [13]. An increase in outdoor temperatures can lead to a significant worsening of indoor comfort in buildings. This results in the need for air conditioning systems, leading to increased energy consumption and operating costs. This is especially true for buildings constructed in today's warm climates where a correct choice of air conditioning systems can contribute to climate change mitigation [14], although it is a very complex

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assessment, as many variables must be considered [15].

In this context, air-source heat pumps (ASHPs) have captured growing interest due to their high energy efficiency. The ASHP is a technology that can significantly contribute to the reduction of energy consumption in buildings. Among all types of heat pump systems, the ASHP has many advantages [16], it is an efficient and environmentally-friendly system that can provide an adequate indoor climate [17], and it is a viable alternative to traditional air conditioning systems, both in terms of energy and cost. Although these systems are widely adopted, their performances are strongly affected by external conditions, especially in cold areas [18]. Specifically, the performance of ASHP systems is significantly reduced below low temperatures [19].

2. Heat pumps for decarbonizing building air conditioning

2.1. Introduction

Since the energy crisis in the 1970s, energy conservation has always been a hot topic for policymakers and practitioners worldwide. Currently, energy consumption in buildings accounts for about 30% of total energy consumption [20]. Owing to the increasing demand for improved thermal comfort in the building environment, the energy use of heating, ventilation and air conditioning (HVAC) systems accounts for almost half of the energy consumption of buildings. Therefore, it is important to increase the energy efficiency of HVAC systems in order to meet energy saving and low carbon emission targets [21-24].

Traditionally, both a chiller and a boiler are used in a building for cooling and heating, respectively. However, boilers, such as coal-fired and gas-fired boilers, are not environmentally friendly because of the emissions of greenhouse gases and particles during combustion. The electric boiler, or direct electric heating, is not energy-efficient due to low primary energy efficiency. Thus, as one of the promising technologies for efficient heating and cooling with a single device, the heat pump has been widely developed and used all over the world. Depending on the type of heat source/sink, the heat pump can generally be classified as an air-source heat pump (ASHP), ground-source heat pump (GSHP), water-source heat pump (WSHP) [25-28].

Contrary to WSHP and GSHP, ASHP takes/rejects heat from/into the ambient air, which is cheap and can be implemented anywhere. Therefore, ASHP plays an increasingly important role in cases where both heating and cooling are required. In recent years, many efforts have been devoted to extending the application of reversible ASHP in the heating and cooling of buildings. On the other hand, the principles of ASHP, the state of the art of ASHP technologies and their applications all over the world are given. Since the research on ASHP cooling has been well developed in recent years, the current challenge comes from heating. Therefore, this Informatory Note focuses mainly on new developments in the field of heating, and some technologies are also applicable to cooling [29], [30], [31], [32].

2.2. Operational principles

The mechanism of a reversible Air Source Heat Pump (ASHP) is quite similar to the typical vapor compression cycle in which the compressor, condenser, throttling valve and evaporator are connected in series. The only difference is the four-way valve located at the outlet of the compressor, as shown in Figure 1 [8]. When the ASHP is operating in cooling mode, the compressed hot gas is directed through the four-way valve to the outdoor condenser where the refrigerant is condensed to a liquid by discharging heat into the ambient air. Then the liquid refrigerant is throttled into low pressure two-phase state and absorbs heat from the air or water in the evaporator to achieve the cooling effect of air or water [33-36].

The vaporized refrigerant then returns to the compressor and is compressed into hot gas. When the ASHP is operating in heating mode, the four-way valve is switched in its flow direction [8]. The compressed hot gas is directed through the four-way valve to the indoor condenser, where the refrigerant is condensed by discharging heat into the air or water for space heating. Then the liquid refrigerant is throttled into low pressure two-phase state and passes through the outdoor heat exchanger to absorb heat from the ambient air. The ASHP is normally divided into two types based on the heat transfer fluid of space cooling/heating. The air-to-air type mainly refers to split air conditioner, packaged air conditioner, etc. The air-to-water type is used to supply high temperature water or chilled water for heating or cooling indoor air, respectively, by different kinds of indoor terminal units such as air handling unit, fan coil unit, radiator, radiant panel [37-39].

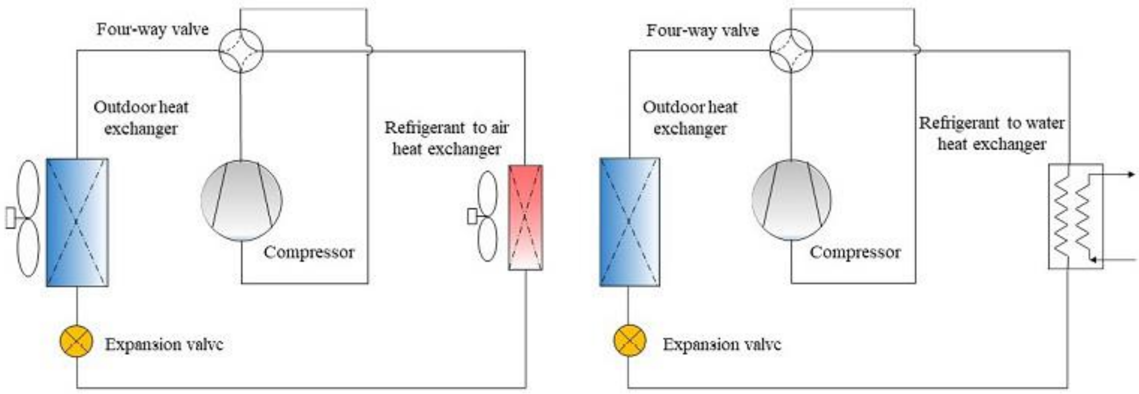

Figure 1. Schematic of the ASHP [8].

Since ASHP extracts heat from the ambient during heating mode, the normal heating efficiency of ASHP is normally 3 to 4 times that of direct electrical heating. However, several factors have a significant impact on the performance of ASHP. Firstly, ASHP performance is significantly reduced at low ambient temperatures. Secondly, the frosting problem heavily affects energy efficiency and reliability during the heating period. To solve the problems, many researchers and engineers have devoted a great deal of effort to improve ASHP technology in recent years [8].

3. State of the art of technologies

3.1. Low-temperature ASHP

The poor performance of ASHP at low temperatures results in insufficient heating capacity and low coefficient of performance (COP). The low heating capacity can be attributed to the largely reduced refrigerant density at the suction port and the lower volumetric efficiency of the compressor. The poor COP is due to the high-pressure ratio, the low isentropic efficiency of the compressor and the high throttling loss. To improve the performance of the compressor, several kinds of new technologies have been developed. Variable frequency compressor technique is an effective method for increasing the heating capacity of the ASHP [2]. By speeding up the compressor in low temperature conditions, it is possible to rapidly increase the displacement of the compressor and thus the heating capacity of the ASHP [8].

However, inverter technique cannot contribute to the improvement of the COP. To simultaneously improve the heating capacity and COP at low ambient temperatures, multistage compression technologies have been developed and implemented. According to the number of compression stages and the cycle configuration, the multi-stage compression ASHP can be classified into cascade type and two-stage compression type [8]. In particular, to improve the heating capacity of single-stage compression system at low ambient temperature, a refrigerant can be injected directly into the compressor during the compression process is known as quasi two-stage compression. Since the quasi two-stage compression type has the characteristics of two-stage compression type, it can be classified as a two-stage compression type [8].

3.1.1. Cascade ASHP

The low ambient temperature leads to a high-pressure ratio in the system, which results in high compression work and high throttling loss, and eventually to low energy efficiency of the ASHP. A simple idea to reduce loss and enhance efficiency to use two vapor compression cycles in series to replace the single vapor compression cycle. This is the cascade ASHP system. As shown in Fig. 2, the cascade compression system consists of two independent vapor compression cycles [8]. One cycle is the low temperature cycle and the other is the high temperature cycle. These two cycles are connected by the shared cascade heat exchanger, which serves the low-temperature cycle as a condenser and the high-temperature cycle as an evaporator. In winter, the low temperature cycle absorbs heat from the environment through the air source evaporator [8]. Through the low-temperature cycle, the heat is raised to a higher temperature and supplied to the high-temperature cycle as a heat source. In the high-temperature cycle, the heat is again brought to the temperature required for space heating [14-18].

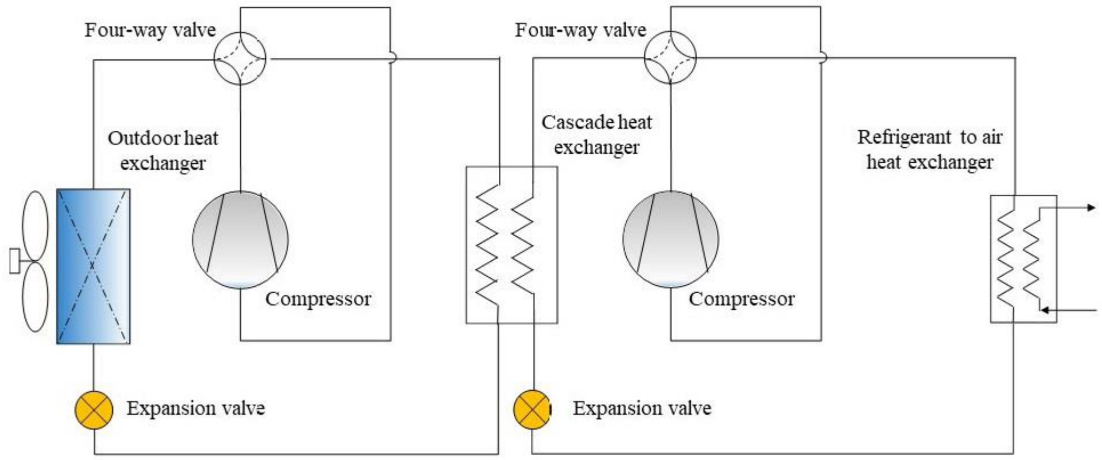

Figure 2. Schematic of the cascade ASHP [8]

With the cascade ASHP, the pressure ratio of each cycle is greatly reduced. Total compression loss and throttling loss are reduced. As a result, the COP of the ASHP can be enhanced. In addition, it is remarkable that different refrigerants can be used in two cycles depending on the working conditions. However, the intermediate heat exchanger imposes a temperature difference that inevitably leads to some loss of efficiency. As the cascade system can be achieved with two well-known single-stage systems, some applications for space or water heating have been available for some years [3, 4]. Unfortunately, this cycle requires the use of two compressors and an extra heat exchanger, which increases the cost compared to the single cycle [8].

3.1.2. Two-stage compression ASHP

The two-stage compression ASHP can be considered as a simplification of cascade compression, which connects two refrigerant cycles together. As shown in Fig. 3, the two-stage compression ASHP can be divided into two groups according to the type of economizer, the type of flash tank (FT) [5] and the type of intermediate heat exchanger (IHX) [6].

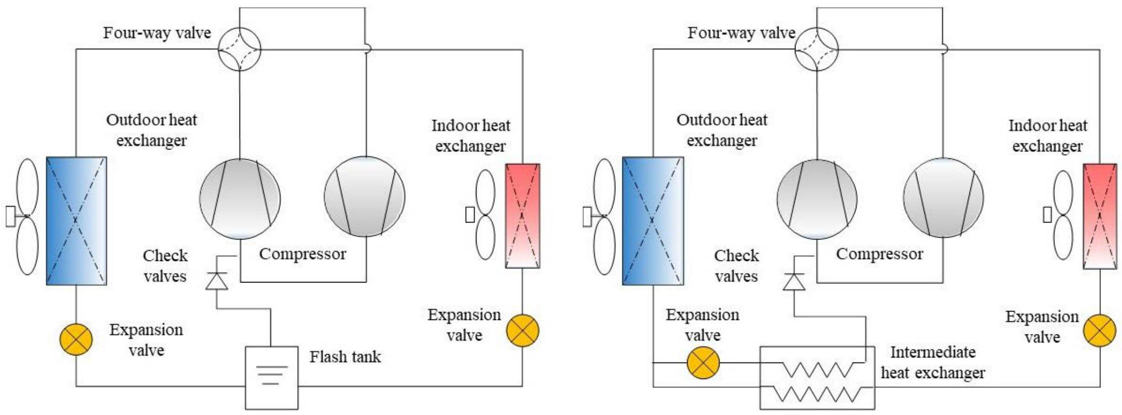

Figure 3. Schematic of the two-stage compression ASHP [8].

In the FT-type two-stage ASHP, the liquid refrigerant leaving the indoor condenser is throttled in two phases and sent into the FT. In the FT, the two-phase refrigerant is separated into saturated gas and saturated liquid [8]. The saturated gas refrigerant is mixed with the refrigerant discharged from the lower-stage compressor and then recompressed by the upper-stage compressor. The saturated liquid flows into the outdoor evaporator after leaving the second expansion valve. After evaporating in the evaporator, the gas refrigerant is compressed by the lower-stage compressor and mixed with the intermediate pressure gas from the FT.

For the IHX-type two-stage ASHP, the liquid refrigerant at the condenser outlet is directly separated into two paths. The secondary refrigerant is throttled into intermediate pressure. The low-temperature refrigerant cools the mainstream refrigerant to subcooling state in the IHX. Then, the secondary refrigerant becomes saturated or superheated and is mixed with the refrigerant from the lower-stage compressor. The mixture is sucked in by the upper-stage compressor for further compression. The subcooling mainstream refrigerant at the IHX outlet is throttled, then passes through the evaporator, and finally reaches the lower-stage compressor. It is then compressed to an intermediate pressure to mix with the secondary refrigerant [8].

3.1.3. Quasi two-stage compression ASHP

As illustrated in Fig. 4, the quasi two-stage compression ASHP, also called a gas injection system, is quite-similar to the two-stage compression ASHP. The only difference is that a compressor with an intermediate injection port is used to replace two tandem compressors in a two-stage system. In case of a quasi-two-stage ASHP, the saturated gas refrigerant from the FT or the secondary refrigerant from the IHX is injected into the compression chamber of the compressor, instead of in the middle of the two compressors [36-39].

The quasi two-stage ASHP is a simplification of two-stage system. It uses a specifically designed gas-injected compressor to replace both compressors, thus avoiding the problem of oil balance between two compressors and reducing the cost of the ASHP. More importantly, by closing the valve on the injection line, the quasi two-stage system can be easily transferred to the single-stage mode, optimizing the performance of the quasi two-stage ASHP not only in summer but also in winter. For this reason, quasi two-stage compression technology has been widely adopted in recent years in ASHPs for low ambient temperature [7].

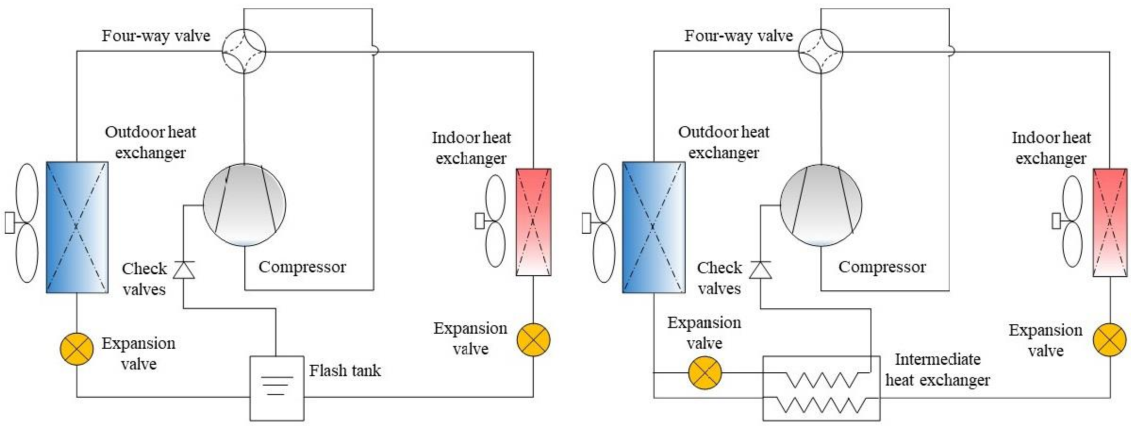

Figure 4. Schematic of the quasi two-stage compression ASHP [8].

4. Research Methodology

4.1. Introduction

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 [13]. 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 behavior 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 [14-18]. 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 [13-18].

4. 2. 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 [18].

The designed system follows the approach of previous research by Kropas, et al [24], 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 5 [24].

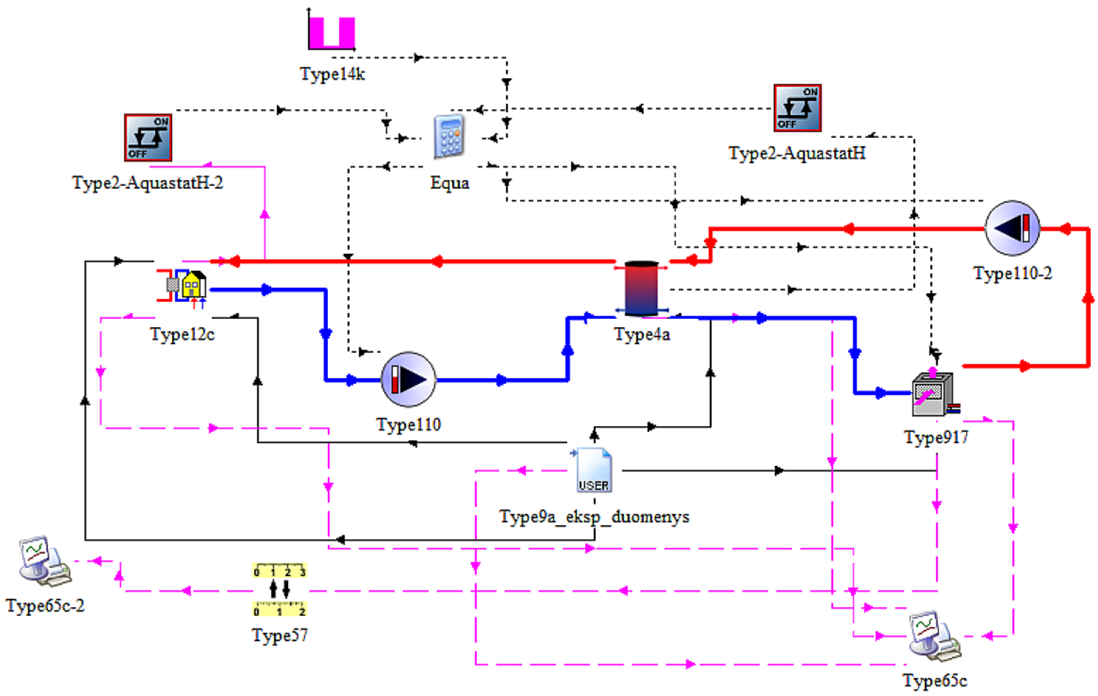

Figure 5. TRNSYS model of the system with air source heat pump.

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 [18].

4.3. 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 [18]. 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 [24].

The heat pump model was formulated to address two primary objectives: replenishing a storage tank and producing domestic hot water at a temperature of 50°C [18]. 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 m^3, a height of 1.961 m, and a heat loss coefficient of 0.76 W/(m^2·K). These thoughtfully selected parameters aimed to accurately mimic the conditions of the practical demonstration [24].

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]:

$$COP = (Q/P_{elec}) \quad (1)$$

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 ($P_{elec\text{-}seasonal}$) [21]:

$$SPF = (Q_{seasonal} / P_{elec\text{-}seasonal}) \quad (2)$$

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 [18].

5. Results and discussions

In this section, we reveal the results obtained from modeling the operational characteristics of a building's heating system utilizing an 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. In this study, we have considered for modeling in Afghanistan is Kabul. 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. Figures 6 visually elucidate the variability of the heat pump COP obtained through simulation in relation to ambient air temperatures for each month of the year.

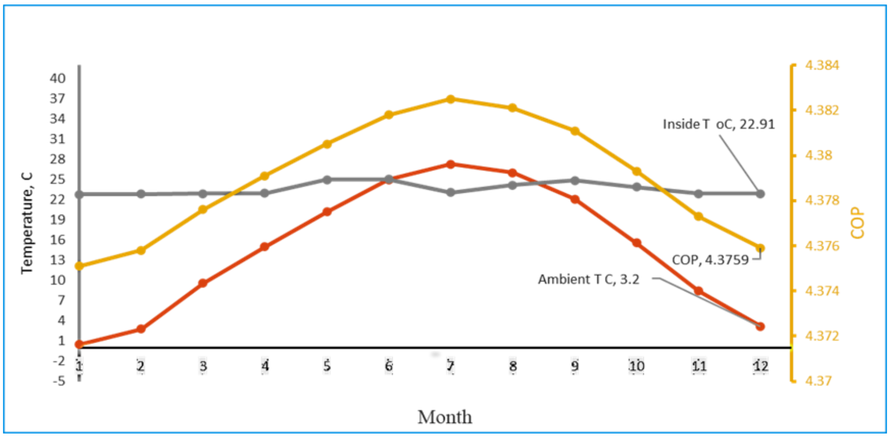

Fig. 6. Relationship between the heat pump COP and the ambient air temperature in Kabul.

The information gleaned from Figure 6 illustrates that the heat pump 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. In the context of Kabul, the highest COP value documented is 4.4, while the lowest stands at 4.4. 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 in these areas. It is important to note that, for assessment purposes, the storage tank is not considered; the focus is solely on evaluating the heat pump's performance.

6. 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 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 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 heating season attributed to its distance from the sea, provides an advantage for ASHP usage, contributing to higher COP and SPF values.

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