Düzce University Journal of Science and Technology
Düzce Üniversitesi Bilim ve Teknoloji Dergisi

14 (2), 2026, 594-604.
https://doi.org/10.29130/dubited.1702319

e-ISSN: 2148-2446
https://dergipark.org.tr/en/pub/dubited

Research Article

Monitoring the Performance of a Transcritical Heat Pump Using an IoT System

Arif Emre Özgür[1], Özdemir Deniz[2], Ümit Murat Gül[3]*

[1] Isparta University of Applied Sciences, Faculty of Technology, Isparta, Türkiye.
ror.org/02hmy9x20

[2] Isparta University of Applied Sciences, Isparta OSB Vocational School, Isparta, Türkiye.
ror.org/02hmy9x20

[3] Isparta University of Applied Sciences, Graduate Education Institute, Department of Mechanical Engineering, Isparta, Türkiye.
ror.org/02hmy9x20

*Corresponding author:
umg@umg.gen.tr

Received: 22.05.2025
Revision: 09.03.2026
Accepted: 09.03.2026
Online: 19.04.2026

Abstract: The growing energy demand and environmental concerns have increased the orientation towards energy- efficient and environmentally friendly technologies. In this context, transcritical heat pumps using natural refrigerant R744 (CO_2) stand out. However, real-time monitoring is critical for operating and managing these systems at optimum performance. This study aimed to develop a unique system to monitor and analyze the performance of a transcritical CO_2 heat pump using Internet of Things (IoT) technologies. The system is based on Raspberry Pi and Arduino microcontrollers, various sensors (temperature, pressure, flow, power), a MySQL database, and a dual interface (Lazarus-based local and PHP/JavaScript/HTML-based web). While Arduino collected and processed sensor data using C language, the object-oriented software developed with Lazarus on Raspberry Pi received, processed, stored the data, and presented it on the local interface. Simultaneously, the web interface provided remote access and visualization of the data. The developed system successfully monitored the critical performance parameters of the heat pump (temperature, pressure, flow, power consumption, data required for COP calculation). The results indicate that the proposed IoT-based monitoring system has the potential to increase the energy efficiency of transcritical heat pumps, facilitate operational management, and enable early detection of potential failures.

Keywords: *Transcritical heat pump, IoT, R744 (CO_2), Performance monitoring, Energy efficiency*

I. INTRODUCTION

The growing energy demand and environmental awareness regarding the impacts of fossil fuels have increased the need for sustainable and efficient energy solutions (Llopis et al., 2015; Nekså, 2002; Song et al., 2022). Heating, ventilation, and air conditioning (HVAC) systems account for a significant portion of total energy consumption. In this field, heat pumps stand out as efficient technologies that provide heating and cooling by transferring energy from one environment to another. In particular, transcritical heat pumps using natural refrigerant carbon dioxide (R744 or CO_2) offer an environmentally friendly alternative with low global warming potential (GWP=1) and ozone depletion potential (ODP=0) (Kim et al., 2004; Lorentzen & Pettersen, 1993). A transcritical cycle is a thermodynamic process in which the fluid operates at temperatures and pressures above the critical point, where heat transfer occurs without a distinct phase change (Deniz, 2024; Gao et al., 2022; Mostofa & Islam, 2023). These cycles can provide high efficiency with fluids having low critical temperatures, such as CO_2. However, the performance of transcritical systems is highly sensitive to operating conditions (pressure, temperature, etc.) and requires precise control and continuous monitoring for optimal efficiency (Alam, 2021).

Conventional monitoring methods are generally limited in real-time data collection and remote access. Internet of Things (IoT) technologies offer a powerful potential to overcome these limitations by combining sensors, microcontrollers, internet connectivity, and data analysis platforms. IoT enables real-time monitoring of system parameters, storage and analysis of data locally or in the cloud, and presentation through user-friendly interfaces. This helps optimize energy consumption, detect performance degradation or malfunctions early, and simplify system management.

The purpose of this paper is to present a unique IoT-based system designed, developed, and tested to monitor the performance of a transcritical R744 heat pump. The system was developed using low-cost and widely used hardware (Raspberry Pi, Arduino) and software tools (Lazarus, Python, PHP, MySQL). The study covers the entire process from collecting sensor data to processing, storing, and visualizing it through both local (desktop) and web-based interfaces.

II. LITERATURE REVIEW

Studies on transcritical CO_2 heat pump and refrigeration systems emphasize the environmental advantages and efficiency potential of these technologies. Song et al. (2022) noted that CO_2's low GWP and ODP values, along with the potential for increased efficiency with advanced components like ejectors, and highlighted the importance of IoT

This is an open access paper distributed under the terms and conditions of the Creative Commons Attribution-NonCommercial 4.0 International License.

integration. Nekså (2002) established fundamental principles of CO_2 heat pump systems that continue to influence modern designs. Llopis et al. (2015) examined the effects of mechanical subcooling on performance, demonstrating significant energy improvements in transcritical CO_2 systems. Kim et al. (2004) provided comprehensive analysis of fundamental process and system design considerations in CO_2 vapor compression systems, while Lorentzen and Pettersen (1993) pioneered environmentally benign CO_2 systems for mobile applications.

The use of IoT technologies in CO_2 refrigeration systems is covered extensively in recent literature. Gao et al. (2022) integrated PLC/HMI systems with IoT modules to provide remote monitoring and control in CO_2 refrigeration systems, demonstrating both the potential for energy savings and the operational benefits of connected monitoring architectures. Deniz (2024) examined the effect of PID control in variable frequency compressor control on reducing energy consumption. Mostofa and Islam (2023) demonstrated IoT benefits in solar energy facilities, while Alam (2021) explored broader applications in smart cities.

There are also more specialized studies on transcritical CO_2 systems with various performance enhancement approaches. Casi et al. (2022) examined the effects of subcoolers and internal heat exchangers on performance in an experimental platform, demonstrating improved efficiency. Vieren et al. (2023) investigated the thermodynamic potential of transcritical cycles for high temperature differences in industrial processes and their role in waste heat recovery.

IoT monitoring applications in various fields provide valuable insights for CO_2 refrigeration systems. Bhardwaj et al. (2022) applied IoT in the healthcare sector, Sridharan et al. (2019) in heat exchangers, and Koo et al. (2015) in water management systems. Syafrudin et al. (2018) showed benefits of IoT and big data processing in manufacturing processes.

Recent advancements in transcritical CO_2 systems with IoT integration show promising results. Chen et al. (2023) emphasized the importance of IoT monitoring for detecting sensor failures in electric bus heat pump applications.

While these studies demonstrate the potential of transcritical CO_2 systems and the capabilities of IoT in monitoring/control areas, studies that combine these two technologies, particularly those that offer both local and web-based user interfaces based on widespread and low-cost hardware/software platforms, are limited. The study presented in this paper aims to fill this gap by presenting the design, implementation, and test results of a unique IoT monitoring system built on accessible platforms like Raspberry Pi and Arduino, using Lazarus and web technologies with a dual interface.

III. MATERIAL AND METHOD

A. *Hardware Components*

The hardware infrastructure of the system consists of components selected considering reliability, cost- effectiveness, and flexibility.

A.1. Central Processing Unit

Raspberry Pi 400 model was used as the brain of the system. It provides a suitable platform for sensor integration and software operation with its low power consumption, sufficient processing power, integrated keyboard, and GPIO pins. This model is equipped with a quad-core ARM Cortex-A72 processor running at 1.8 GHz, 4GB LPDDR4-3200 RAM, and an integrated Wi-Fi module, making it ideal for system integration with its compact structure.



Figure 1. Raspberry Pi 400 model used as the central processing unit

A.2. Data Collection Unit

Arduino Uno microcontroller board was chosen to read and pre-process analog and digital signals from sensors. It was programmed with C language to communicate serially with the Raspberry Pi. Arduino Uno, with its ATmega328P

microcontroller, 6 analog inputs, and 14 digital input/output pins, allows connection of various sensors. Its 16 MHz operating frequency and protocol supports such as UART, I2C, and SPI provide sufficient capacity for data collection operations.

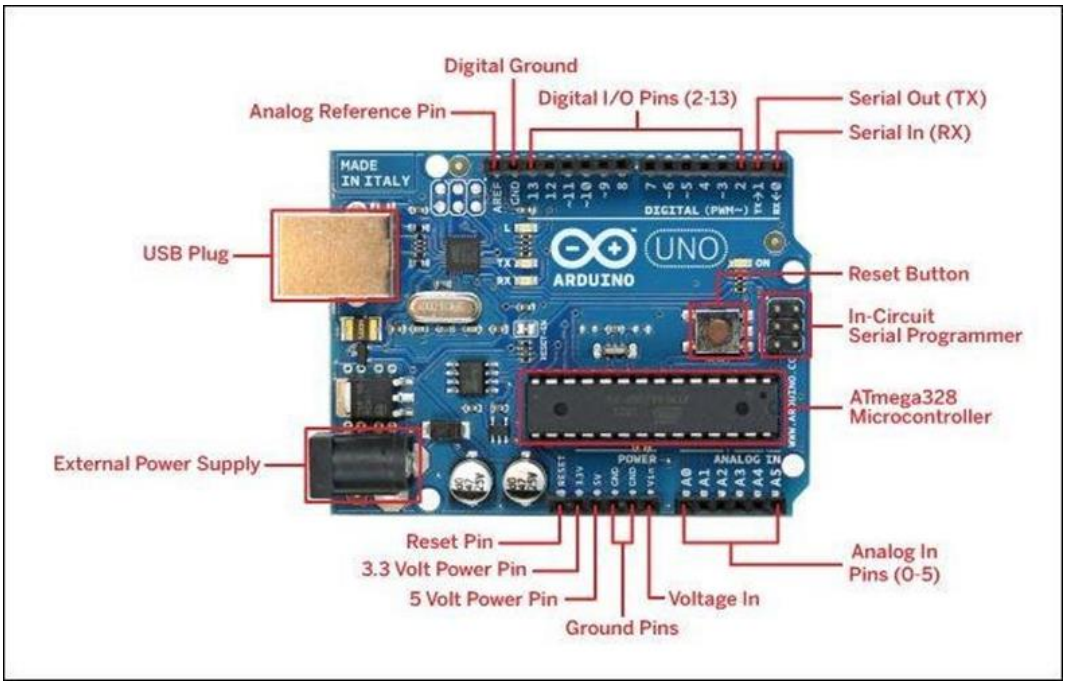


Figure 2. Arduino Uno microcontroller board used for data collection

A.2.1 Sensors

Various sensors were used to measure the critical performance parameters of the heat pump:

Temperature Sensors (PT100 RTD) with Class A precision (-200°C ~ 850°C operating range, ±0.15°C accuracy) were used to measure temperatures at different points in the system. These sensors were connected to Arduino via MAX31865 RTD-to-Digital converter modules. Temperature calculation was performed using the Callendar-Van Dusen equation (Eq.1).

$$T = \frac{-A + \sqrt{A^2 - 4b\left(1 - {}^{R}/_{R_0}\right)}}{2B} \quad (1)$$

Pressure Sensors with 0.5-4.5V output range were used to measure critical pressure values in the system. These sensors have measurement ranges of 0.3585 ~ 4048 kPa for gas line pressure, 200 ~ 600 kPa for water line pressure, and 210 ~ 900 kPa for airline pressure. Voltage values obtained from the sensors were converted to pressure values using a conversion factor (Eq.2).

$$P = V_{measurement} \times \text{ conversion coefficient} \quad (2)$$

Flow Sensors (YF-S201 for water flow and AWM3300V for air flow) with digital pulse output were used. The YF-S201 sensor has a measurement range of 10-200 L/s, while the AWM3300V sensor has a range of 10-1000 L/s. Pulse signals from the sensors were connected to Arduino's digital input pins, and flow rate was calculated using pulse frequency (Eq.3).

$$Q = \frac{Pulses}{10} x \text{ conversion coefficient} \quad (3)$$



Figure 3. Temperature and pressure sensors installation on the heat pump system

B. Software Components and Architecture

The system has a dual-layer software architecture designed for optimal performance and usability.

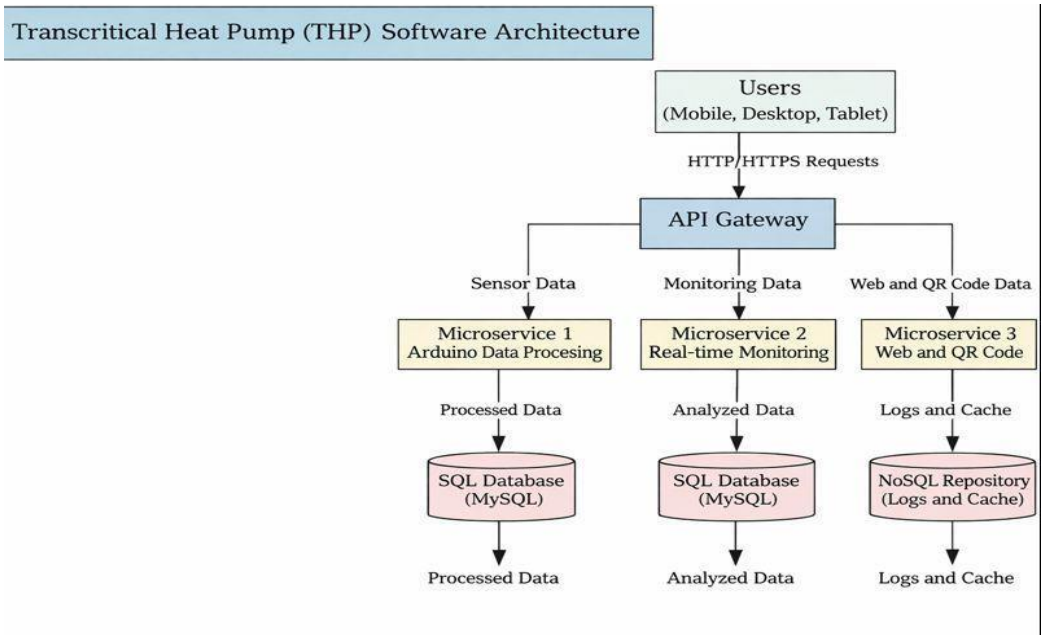


Figure 4. System software architecture diagram

B.1. Operating System and Database

Debian-based Raspberry Pi OS operating system was used on the Raspberry Pi. Web server functionality was provided by Nginx with PHP-FPM for processing PHP code. For data storage and management, MariaDB database management system was implemented. The database structure was optimized for time-series data storage with timestamps, allowing efficient query performance for both real-time and historical data access

B.2. Application Software

Two complementary interfaces were developed to provide comprehensive access to the system:

B.2.1. Local Interface

An object-oriented desktop application was developed using Lazarus IDE and Free Pascal programming language. This application provides the following functionalities:

• Real-time sensor data acquisition via serial communication with Arduino

- Data processing and calculation of derived parameters
- Database storage with configurable recording frequency
- Graphical presentation with charts and indicators
- System diagnostics and configuration options



Figure 5. Lazarus-based local interface showing real-time monitoring data

B.2.2. Web Interface

A responsive web application was created using PHP, JavaScript, and HTML to enable remote monitoring. Key features include:

- Real-time data visualization through colored indicator panels
- Historical data browsing with filtering and pagination
- P-h diagram visualization for thermodynamic analysis
- JSON data export for third-party applications
- Mobile-friendly responsive design



Figure 6. Web-based interface for remote monitoring Access

C. Test Device: Transcritical Heat Pump

The developed IoT monitoring system was tested on a specially designed R744 (CO_2) transcritical heat pump. The test device consists of the following main components:

Semi-hermetic compressor compatible with R744
Custom-designed spiral tube heat exchanger (gas cooler)
Flash gas separator for liquid-gas phase separation
Electronic expansion valve (EEV) for flow control
Micro-channel evaporator

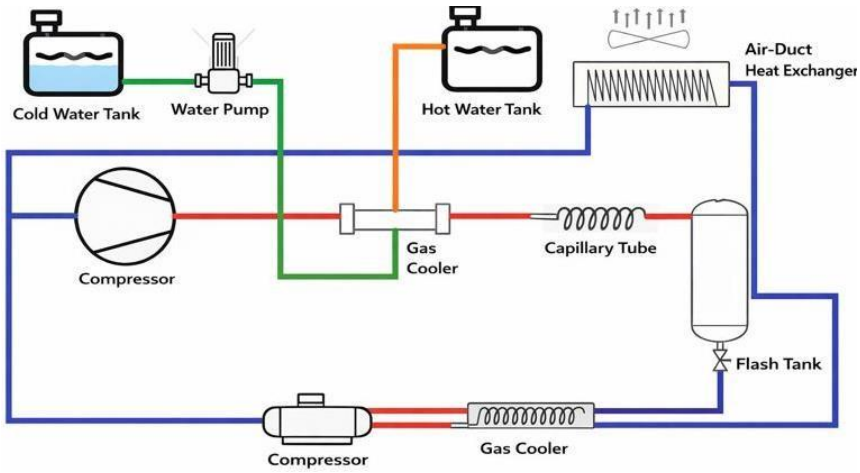


Figure 7. Block diagram of the transcritical heat pump test system



Figure 8. Views of the assembled transcritical heat pump system from two different angles

The transcritical heat pump system consists of several key components that work together to achieve efficient heat transfer. The main components include:

1. Compressor: A semi-hermetic compressor compatible with R744 that pressurizes and circulates the refrigerant. The compressor increases the pressure and temperature of the refrigerant, initiating the thermodynamic cycle.
2. Gas Cooler: A custom-designed spiral tube heat exchanger where the high-pressure, high- temperature refrigerant from the compressor releases heat to the water flow. This component was specifically designed and manufactured for this application to optimize heat transfer efficiency with counter-flow arrangement.
3. Flash Gas Separator: This component separates the liquid and gas phases of the refrigerant after expansion. The

liquid phase is directed to the evaporator, while the gas phase returns directly to the compressor.

4. Electronic Expansion Valve (EEV): Controls the refrigerant flow rate and creates the pressure differential necessary for the cycle. The opening degree of this valve was varied during tests to optimize system performance.

5. Evaporator: A micro-channel heat exchanger where the liquid refrigerant absorbs heat from the ambient air and evaporates.

System performance was tested at various EEV openings (0%, 2%, 4%, and 6%), with temperature, pressure, flow rate, and power consumption data collected at each setting.

IV. RESULTS AND DISCUSSION

The data obtained during tests with the developed IoT system on the transcritical heat pump provided detailed insights into the operational behavior of the system. Tests were conducted at different Electronic Expansion Valve (EEV) opening values to assess system performance under various operating conditions.

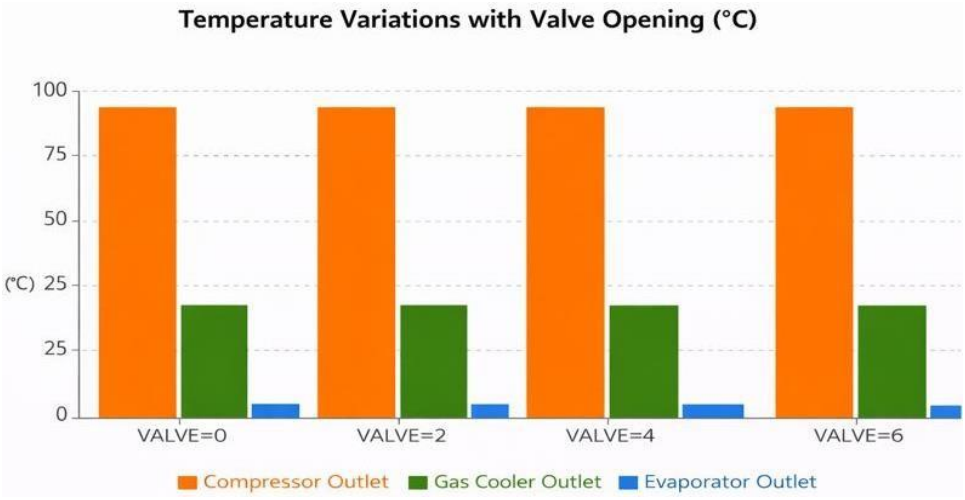


Figure 9. Temperature variations with different valve openings

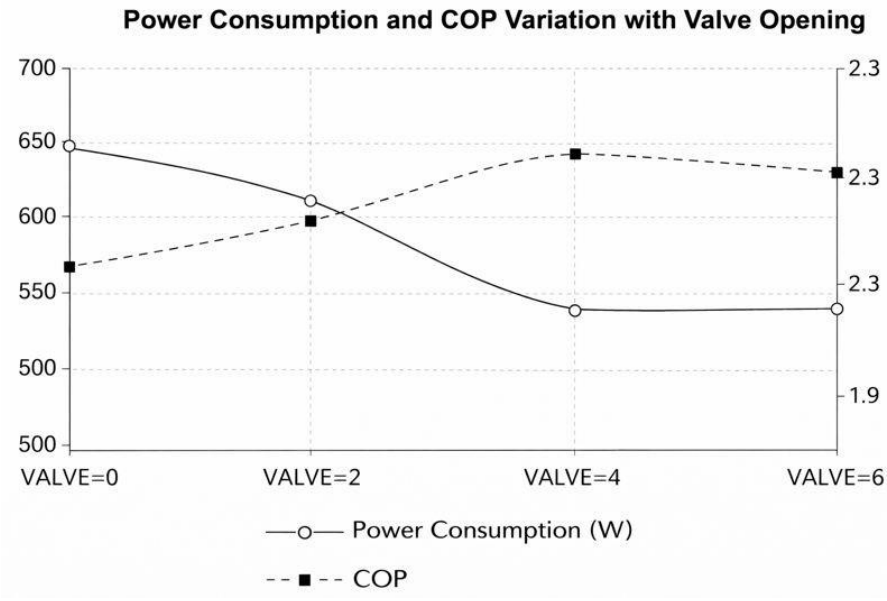


Figure 10. Power consumption and COP variations with different valve openings

Figures 9 and 10 show the effects of valve opening on system performance parameters. As seen in Figure 9, the compressor outlet temperature decreases from 94.2°C at VALVE =0 position to 88.8°C at VALVE =4% position, while the gas cooler outlet temperature remains relatively stable between 33-34°C across all valve positions. Figure 10 demonstrates that power consumption decreases significantly with valve opening adjustment, reaching its minimum (542W) at VALVE =4% position.

The relationship between key system parameters and valve openings is further detailed in Table 1, which presents the average operating values recorded during steady-state conditions.

Table 1. Key performance parameters at different valve openings

Parameter	Unit	VALVE=0	VALVE =2%	VALVE =4%	VALVE =6%
T_Compressor_Outlet	°C	94.2	92.0	88.8	89.2
T_GasCooler_Outlet	°C	34.0	33.6	33.3	33.6
T_Evaporator_Outlet (R744)	°C	6.3	5.6	4.5	4.9
T_Water_Inlet	°C	28.3	28.1	27.8	28.1
T_Water_Outlet	°C	35.5	35.2	35.1	35.2
Power Consumption	W	650	614	542	545
Water Flow Rate	L/min	0.9	0.7	0.2	0.2
T_Air_Inlet	°C	29.8	30.0	30.4	30.4
T_Air_Outlet	°C	27.1	27.6	28.5	28.6
COP		2.20	2.25	2.30	2.28

Table 1 reveals several significant relationships. Most notably, power consumption is lowest at VALVE=4% position (542W), representing a 16.6% reduction compared to VALVE =0% position (650W). Despite this significant energy saving, the water outlet temperature remains nearly constant (35.1- 35.5°C across all settings), indicating that heating capacity is maintained even with reduced power consumption.

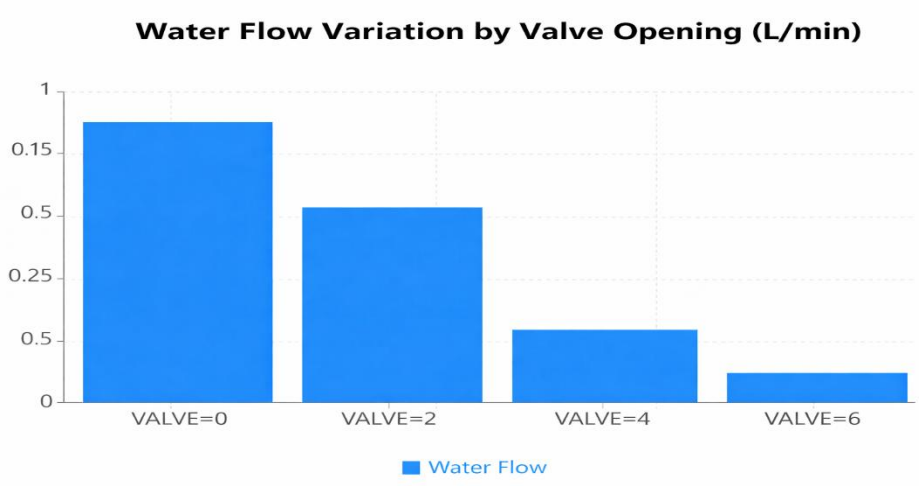


Figure 11. Water flow rate variations with different valve openings

As shown in Figure 11, water flow rate decreases significantly as valve opening increases, from 0.9 L/min at VALVE =0% position to 0.2 L/min at VALVE =4% and VALVE =6% positions.

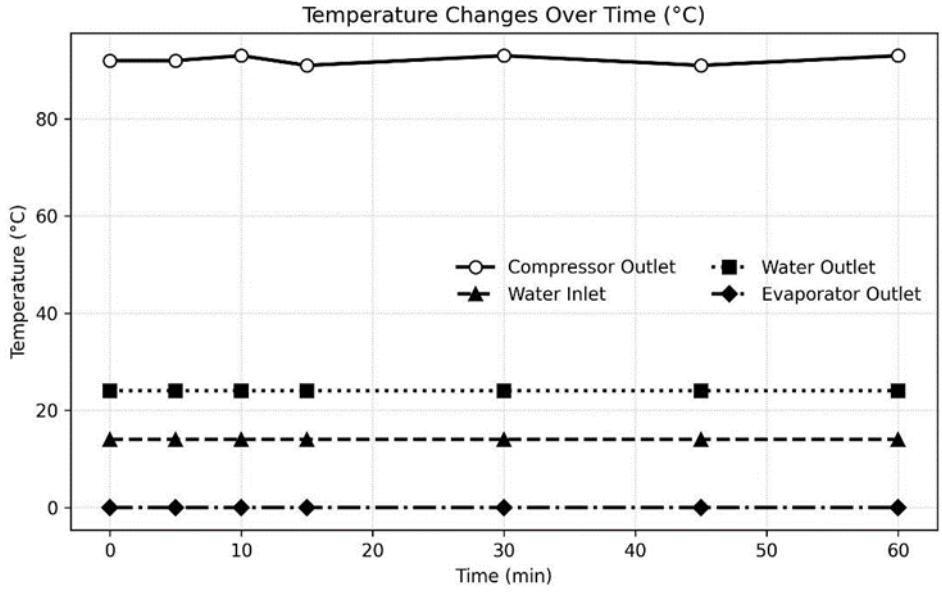


Figure 12. Temperature profiles over time during system operation

Figure 12 shows the dynamic behavior of the system through temperature profiles recorded over time. The compressor outlet temperature exhibits some oscillation while the water outlet temperature remains relatively stable, demonstrating the system's ability to maintain consistent heating performance despite variations in operating conditions.

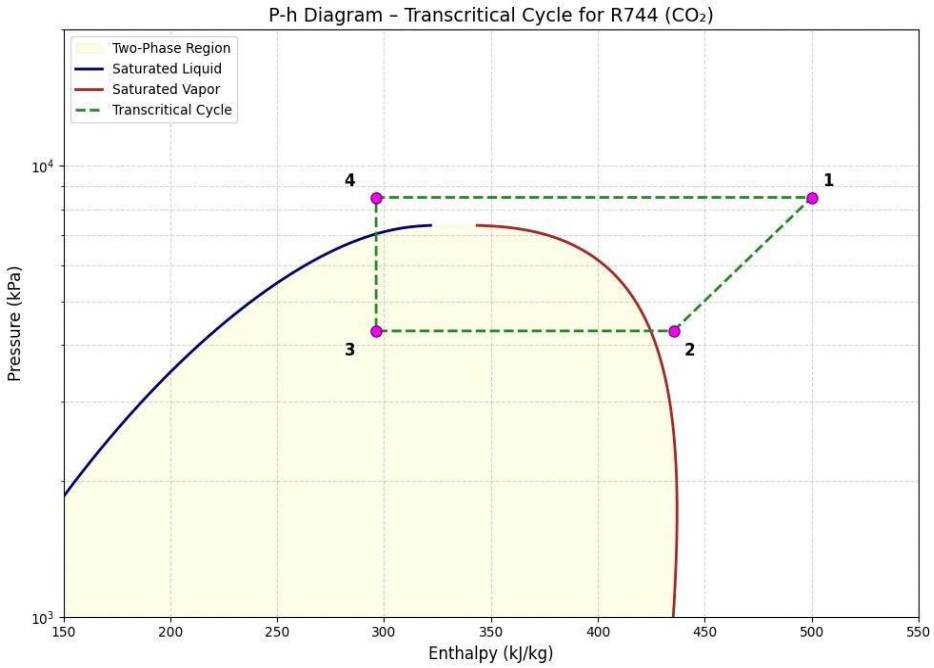


Figure 13. P-h diagram visualization of the transcritical CO_2 cycle in the IoT system interface

The P-h diagram visualization provided by the IoT system (Figure 13) allows real-time monitoring of the thermodynamic state of the refrigerant throughout the cycle. This visualization is particularly important for transcritical CO_2 systems, as it helps engineers identify the operating conditions and optimize the cycle efficiency. The diagram shows the four main points of the cycle: compressor inlet, compressor outlet (in the supercritical region), gas cooler outlet, and evaporator outlet. The critical point of CO_2 is clearly marked, helping operators ensure that the high-pressure side of the cycle operates in the transcritical region. This real-time visualization capability is one of the key advantages of the developed IoT monitoring system.

The IoT system's performance was also evaluated in terms of data acquisition, processing speed, and interface responsiveness, as shown in Table 2.

Table 2. IoT System Performance Data

Test Phase	Average Time (ms)	Success Rate (%)
Sensor Connection	50	100
Data Processing Speed	120	98
Database Recording Time	35	99
Web Interface Loading Time	200	97

The equation for the Coefficient of Performance (COP) calculation is given by (Eq.4).:

$$COP = \frac{Q_h}{W_{in}} \quad (4)$$

where Q_h is the heat output (calculated from water flow rate and temperature difference) and W_{in} is the power input to the compressor.

Performance calculations showed that at VALVE=4 position, the system achieved the highest COP value, correlating with the lowest power consumption observed at this setting. This optimization was made possible by the real-time monitoring capabilities of the IoT system, which allowed precise adjustment of operating parameters.

V. CONCLUSION

This study successfully developed and implemented an IoT-based monitoring system for a transcritical R744 heat pump using widely available and cost-effective components. The system provided comprehensive real-time monitoring capabilities through both local and web-based interfaces, enabling detailed performance analysis and optimization.

The key findings from this research include:

1. The dual-interface approach (local Lazarus-based and web-based) provides flexible monitoring options suitable for different user requirements and access scenarios.
2. Optimal valve opening settings were identified, with VALVE =4% position yielding the best energy efficiency (16.6% reduction in power consumption compared to baseline).
3. The IoT system demonstrated reliable data acquisition and processing capabilities, with data processing times averaging 120ms and system reliability exceeding 98%.
4. Real-time visualization of the P-h diagram and key performance parameters enabled immediate assessment of system thermodynamic behavior and efficiency.

The developed system offers significant potential for practical applications in energy optimization, predictive maintenance, and performance monitoring of transcritical heat pump systems. Future work could explore the integration of machine learning algorithms for automated optimization, expanded sensor networks for more detailed system analysis, and cloud-based data analytics for long-term performance evaluation.

DECLARATIONS

Acknowledgements: This work was supported by Research Fund of Isparta University of Applied Sciences. Project Number: BAP – 2023-YL1-0210.

Author Contributions: Conceptualization, A.E.Ö. and Ö.D.; Methodology, A.E.Ö. and Ö.D.; Software, Ü.M.G.; Validation, Ö.D. and Ü.M.G.; Formal analysis, Ü.M.G.; Investigation, Ü.M.G.; Resources, A.E.Ö.; Data collection, Ü.M.G.; Data curation, Ü.M.G.; Writing—original draft, Ü.M.G.; Writing—review & editing, A.E.Ö. and Ö.D.; Visualization, Ü.M.G.; Supervision, A.E.Ö. and Ö.D.; Project administration, Ö.D.; Funding acquisition, A.E.Ö. All authors have read and approved the final version of the manuscript.

Conflict of Interest: The authors declare no conflict of interest.

Supporting Institutions: This research was funded by the Research Fund of Isparta University of Applied Sciences (Project Number: BAP – 2023-YL1-0210).

Ethical Approval: This study does not involve human or animal participants. All procedures followed scientific and ethical principles, and all referenced studies are appropriately cited.

Plagiarism Statement: This article has been evaluated for plagiarism and no instances of plagiarism were detected.

Use of AI Tools: The authors declare that no Artificial Intelligence (AI) tools were used in the creation of this article.

REFERENCES

Alam, T. (2021). Cloud-based IoT applications and their roles in smart cities. *Smart Cities, 4*(3), 1196–1219. https://doi.org/10.3390/smartcities4030064

Bhardwaj, V., Joshi, R., & Gaur, A. M. (2022). IoT-based smart health monitoring system for COVID-19. *SN Computer Science, 3*(1), Article 137. https://doi.org/10.1007/s42979-022-01015-1

Casi, Á., Aranguren, P., Araiz, M., Sánchez, D., Cabello, R., & Astrain, D. (2022). Performance assessment of an experimental CO_2 transcritical refrigeration plant working with a thermoelectric subcooler in combination with an internal heat exchanger. *Energy Conversion and Management, 268*, Article 115963. https://doi.org/10.1016/j.enconman.2022.115963

Chen, S., Yang, W., Wu, H., Deng, R., Li, T., Guo, Y., & Jin, Z. (2023). Experimental study on the heating performance of transcritical CO_2 heat pump for electric buses. *Science and Technology for the Built Environment, 29*(1), 65–74. https://doi.org/10.1080/23744731.2022.2133855

Deniz, Ö. (2024). Control of a heat pump compressor with variable frequency device driven by PID. *International Journal of Engineering and Innovative Research, 6*(1), 1–14. https://doi.org/10.47933/ijeir.1380664

Gao, J., Wang, J., & Xie, J. (2022). Application of PLC and HMI in the CO_2 transcritical refrigeration experimental platform. *Scientific Reports, 12*(1), Article 15199. https://doi.org/10.1038/s41598-022-19602-w

Kim, M. H., Pettersen, J., & Bullard, C. W. (2004). Fundamental process and system design issues in CO_2 vapor compression systems. *Progress in Energy and Combustion Science, 30*(2), 119–174.

https://doi.org/10.1016/j.pecs.2003.09.002
Koo, D., Piratla, K., & Matthews, C. J. (2015). Towards sustainable water supply: Schematic development of big data collection using internet of things (IoT). *Procedia Engineering, 118*, 489–497. https://doi.org/10.1016/j.proeng.2015.08.465
Llopis, R., Cabello, R., Sánchez, D., & Torrella, E. (2015). Energy improvements of CO_2 transcritical refrigeration cycles using dedicated mechanical subcooling. *International Journal of Refrigeration, 55*, 129–141. https://doi.org/10.1016/j.ijrefrig.2015.03.016
Lorentzen, G., & Pettersen, J. (1993). A new, efficient and environmentally benign system for car air-conditioning. *International Journal of Refrigeration, 16*(1), 4–12. https://doi.org/10.1016/0140-7007(93)90014-Y
Mostofa, K. Z., & Islam, M. A. (2023). Creation of an Internet of Things (IoT) system for the live and remote monitoring of solar photovoltaic facilities. *Energy Reports, 9*, 422–427. https://doi.org/10.1016/j.egyr.2023.09.060
Nekså, P. (2002). CO_2 heat pump systems. *International Journal of Refrigeration, 25*(4), 421–427. https://doi.org/10.1016/S0140-7007(01)00033-0
Song, Y., Cui, C., Yin, X., & Cao, F. (2022). Advanced development and application of transcritical CO_2 refrigeration and heat pump technology—A review. *Energy Reports, 8*, 7840–7869. https://doi.org/10.1016/j.egyr.2022.05.233
Sridharan, M., Devi, R., Dharshini, C. S., & Bhavadarani, M. (2019). IoT based performance monitoring and control in counter flow double pipe heat exchanger. *Internet of Things, 5*, 34-40. https://doi.org/10.1016/j.iot.2018.11.002
Syafrudin, M., Alfian, G., Fitriyani, N. L., & Rhee, J. (2018). Performance analysis of IoT-based sensor, big data processing, and machine learning model for real-time monitoring system in automotive manufacturing. *Sensors, 18*(9), Article 2946. https://doi.org/10.3390/s18092946
Vieren, E., Demeester, T., Beyne, W., Arteconi, A., De Paepe, M., & Lecompte, S. (2023). The thermodynamic potential of high-temperature transcritical heat pump cycles for industrial processes with large temperature glides. *Applied Thermal Engineering, 234*, Article 121197. https://doi.org/10.1016/j.applthermaleng.2023.121197