IRSTI 50.43.31 https://doi.org/10.26577/jpcsit2024-02b02

B. Amangeldy[1,2], N. Tasmurzayev[1,2,*], Sh. Shinassylov[2]

[1]Joldasbekov Institute of Mechanics and Engineering, Almaty, Kazakhstan.
[2]Al-Farabi Kazakh National University, Almaty, Kazakhstan.
*e-mail: tasmurzayev.n@gmail.com

INTEGRATION OF REAL-TIME DATA MONITORING IN VAPOR COMPRESSION DISTILLATION: A SCADA-BASED APPROACH

This study delves into the enhanced integration of Supervisory Control and Data Acquisition (SCADA) systems into Vapor Compression Distillation (VCD) processes for water treatment and desalination. Recognizing the limitations of current VCD systems—such as inefficient real-time data utilization, a predominant focus on theoretical models, and insufficient attention to maintenance and reliability in challenging environments—this research presents a comprehensive SCADA-based VCD system designed to overcome these challenges. Our system significantly improves real-time monitoring and dynamic operational adjustment capabilities, thereby optimizing system responsiveness and operational efficiency. By incorporating advanced sensor technologies and predictive maintenance algorithms, the study ensures heightened reliability and reduced downtime, marking a substantial improvement over traditional VCD systems. The practical implementation of these enhancements is validated in a live operational setting, demonstrating their effectiveness in real-world applications. The findings underscore the potential of integrating SCADA systems to revolutionize VCD processes, making significant strides towards more sustainable and efficient water treatment solutions.

Keywords: Vapor Compression Distillation, SCADA, Water Treatment, Desalination, Real-time Data Monitoring, Predictive Maintenance, System Reliability, Operational Efficiency.

1. Introduction

Vapor Compression Distillation (VCD) is a pivotal technology for water treatment and desalination, known for its operational efficiency and adaptability in various environments. Recent advancements have focused on the integration of Supervisory Control and Data Acquisition (SCADA) systems to enhance the responsiveness and efficiency of VCD processes. This integration enables comprehensive monitoring and control, crucial for optimizing performance and managing resources effectively. Our study advances this integration by demonstrating a practical SCADA-based framework in a fully operational VCD system, leveraging real-time data to enhance system responsiveness and manage resources effectively.

While recent studies have significantly advanced the energy efficiency and operational reliability of VCD systems, many still exhibit limitations in their integration of real-time data analytics. Such limitations often lead to suboptimal decision-making and delayed responses to system deviations, which can adversely affect overall system performance [1]. Moreover, much of the existing research tends to prioritize theoretical or simulation-based studies over extensive practical validation, resulting in a disconnect between expected and actual performance under real-world conditions [2] [11]. Furthermore, ongoing maintenance and reliability in harsh or variable operational environments such as space applications or industrial settings are not adequately addressed, which can lead to increased downtime and maintenance costs [3]. Ameri et al. [4] and Bin Amer [5] [12] explored optimizing multi-effect distillation systems using thermal vapor compression, focusing on design parameters and system specifications. While these studies provide a solid theoretical foundation, our research extends this by implementing these theoretical optimizations in practical, real-world settings, thus bridging the gap between theoretical expectations and actual system performance. This practical implementation ensures that the optimizations are not only theoretically sound but also effective under real operational conditions.

Hamed et al. [6] and the analysis in the Water journal focus on the thermal performance and economic aspects of VCD systems [13]. Building on these studies, our work integrates SCADA systems that allow for dynamic adjustments in operational parameters, thereby enhancing energy efficiency and reducing operational costs more effectively than previous models. This integration provides a direct translation of theoretical energy savings into tangible cost reductions and performance improvements.

The readiness assessment of VCD for spacecraft wastewater processing by Noble et al. [7] and [14] highlights its suitability for space applications. Our system not only incorporates similar reliability and maintainability features but significantly enhances them with modern SCADA capabilities, ensuring superior performance in microgravity environments and extending the technology's applicability to more demanding settings.

Schubert [8] and Schmidt [9] compared various water recovery techniques, underlining the advantages of VCD over other distillation processes. Our research leverages these inherent advantages while further reducing operational complexities through automated controls and predictive maintenance algorithms. This not only simplifies the operational process but also reduces the frequency and impact of maintenance issues, enhancing system longevity and reliability.

Finally, the review by Processes journal on commercial thermal technologies for desalination provides an overview of the state of the art [10] [15], emphasizing the potential for integration of renewable energies. Our study not only acknowledges these developments but also operationalizes them by optimizing our SCADA-based system to utilize renewable energy sources effectively. This approach not only addresses the current energy efficiency issues but also positions our system as a more sustainable solution compared to those reviewed in the Processes journal.

Our work directly addresses these challenges by enhancing real-time data integration through a sophisticated SCADA-based approach. This not only improves the responsiveness and adaptability of the VCD system but also ensures that operational parameters are dynamically adjusted in response to environmental changes, thus maintaining optimal performance and reducing downtime. Unlike many theoretical studies, our research includes detailed practical implementation and extensive on-site validation, ensuring that our models are not only theoretically sound but also robust and reliable in practical applications. Additionally, our system design incorporates predictive maintenance tools and fault detection algorithms, significantly enhancing the reliability and longevity of the system. This predictive approach helps in anticipating potential failures before they occur, thus minimizing unplanned downtime and extending the system's operational life.

By addressing the noted gaps in the existing literature and demonstrating substantial improvements in system design and functionality, our research marks a significant advancement in the field of vapor compression distillation. The integration of SCADA systems in our VCD process not only enhances operational efficiency but also contributes meaningfully to the broader goals of improving global water treatment technologies. Our approach clearly delineates the practical and technological advancements over existing methods, providing a more reliable, efficient, and adaptable system.

2. Methodology

This section outlines the systematic approach and technical methodologies employed to evaluate the functionality and efficiency of the advanced Vapor Compression Distillation (VCD) system. It delineates the strategies and technologies integrated to optimize the distillation cycle, detailing the pivotal roles of various system components, their interconnections, and the operational protocols that ensure the VCD process runs at peak performance.

2.1. Overview of System Components

The Vapor Compression Distillation (VCD) system is designed following the ISA 95 standard architecture, which is instrumental in bridging the gap between corporate and control systems. This standard provides a framework for integrating enterprise and control systems, facilitating better data exchange and streamlined operations across different levels of the organization.

The ISA 95 standard enhances the system's efficiency by structuring data and operations into defined categories and levels, from direct control systems up to enterprise management layers. This architectural approach ensures that each component in the VCD system is optimized for its specific role while maintaining seamless interaction with other system components. It allows for scalable, modular system expansions and updates without compromising system integrity and operability.

Figure 1 presents a detailed architecture of our advanced Vapor Compression Distillation system, illustrating how integrated sensor data and automated controls optimize the entire distillation cycle. In the VC process, precision in temperature and pressure control is paramount, as it directly affects the efficiency and output quality of the distillation.

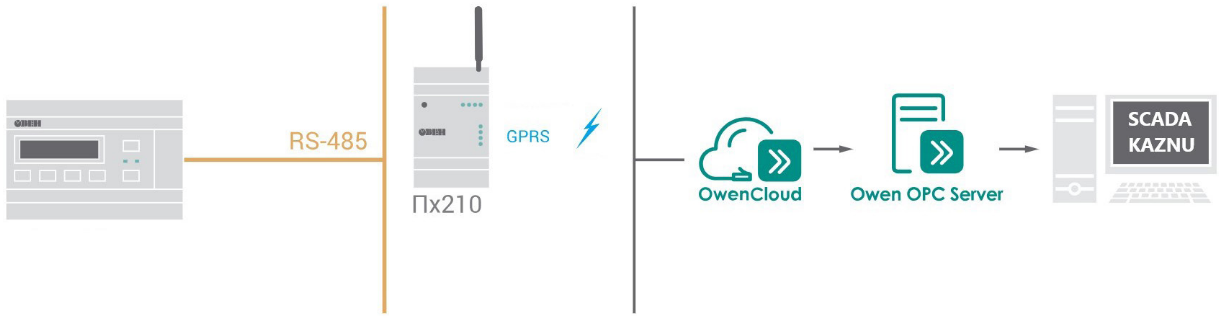

Figure 1 – General view of the architecture

At the outset, PT100 sensors, known for their high accuracy and stability, are strategically positioned near critical components such as compressors, condensers, and evaporators. These sensors are connected via a 4-20mA current loop to the MSD200 module, which ensures robust transmission of analog signals over distances without degradation, critical in the noisy environment of industrial facilities. The MSD200 collects this temperature data, which reflects the operational conditions of the compressor and the condenser units.

This temperature data is vital because the compressor in the VC system plays a crucial role by mechanically compressing steam to a higher pressure, significantly increasing its temperature. The compressor's performance directly influences the thermal energy available for heating the incoming seawater in the evaporator. As the MSD200 transmits these real-time data to the PM210 via an RS-485 connection using the Modbus RTU protocol, it ensures rapid and reliable digital communication, essential for timely adjustments.

The PM210 module aggregates this data and utilizes GSM technology to transmit it to a cloud-based system. This enables remote monitoring and facilitates data-driven decisions from a centralized location. In the cloud, data is further processed and relayed to the SCADA system through an OPC server. This step is critical as the SCADA system uses this data to provide operators with real-time visualization of key parameters like steam pressure, temperature at various stages, and condensation rates.

The real-time data fed into the SCADA system allows for continuous monitoring and dynamic adjustment of the compressor speeds and cooling system settings. These adjustments are crucial for maintaining optimal conditions within the VC cycle, ensuring that the compressed steam is at the ideal temperature and pressure to efficiently evaporate the seawater. The condenser's role is equally vital, as it must effectively condense the steam back into liquid water after it has transferred its thermal energy to the feedwater, all of which relies heavily on accurate data from the PT100 sensors.

Figure 2 provides a detailed view of the interface between a PT100 resistance temperature detector (RTD) and the MSD200 control module. The PT100 sensor, which utilizes a two-wire configuration, is connected via a shielded twisted pair (SFTP) cable that helps mitigate electromagnetic interference, ensuring accuracy and reliability in temperature readings. This connection includes a 250 Ohm precision resistor at the analog input module, which is critical for converting the resistance changes of the PT100 into a proportional current signal ranging from 4-20mA.

The system is powered by a stable 24 VDC source, which is essential for maintaining consistent sensor performance and signal integrity across the measurement range. The PT100 is deployed to monitor temperature fluctuations within key components of the VCD process, specifically around the compressor and associated heat exchange equipment. This real-time temperature data is vital for controlling the operational parameters of the heating and cooling cycles, which are pivotal to the efficiency and effectiveness of the VCD system.

Accurate temperature measurement allows the system to dynamically adjust process variables in response to changes in thermal load, thereby optimizing the energy consumption and prolonging the lifespan of critical components through better thermal management. This figure not only illustrates the physical setup but also underscores the integration of sensor input into the broader process control framework managed via the MSD200 module.

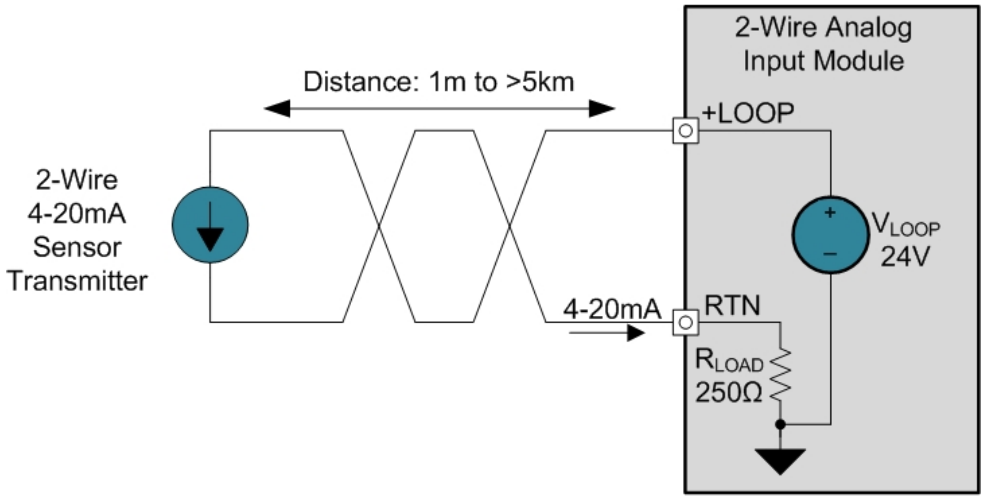

Figure 2 – PT100 4-20mA to analog input of the MSD200

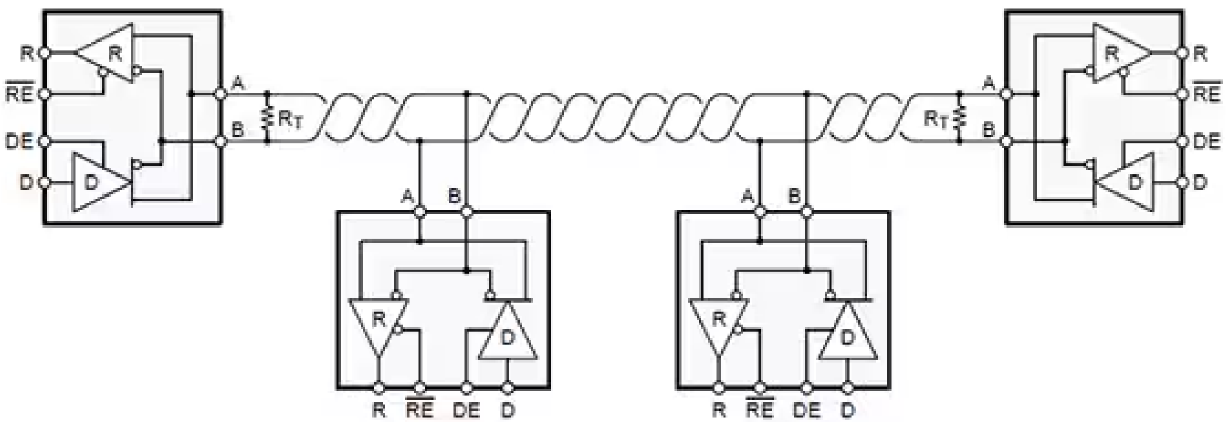

Figure 3 – MSD200 and PM210 connection by RS-485 ModBus RTU

Figure 3 illustrates the RS-485 network topology used in our Vapor Compression Distillation system, showcasing how the MSD200, PM210, and multiple MV210 units (totaling four devices) are interconnected. In this setup, the A and B pins of the RS-485 interface are used for differential communication, serving as the receive (RX) and transmit (TX) lines, respectively. This configuration enhances data integrity and noise immunity in the industrial environment, which is crucial for maintaining the accuracy of transmitted signals over long distances.

The devices are daisy-chained in a linear bus topology, a method that facilitates the connection of multiple devices along a single communication line without the need for a home-run cable to each device. This efficient wiring scheme minimizes installation costs and complexity. Each device, including the PM210 and MSD200, is sequentially connected, allowing for streamlined communication across the network.

A terminator resistor (Rt) is strategically placed at each end of the bus to prevent signal reflections, which are a common issue in longer bus configurations. These terminators are essential for ensuring the stability and reliability of the RS-485 network, especially when operating at high baud rates or over longer distances.

This RS-485 network is vital for the VCD system as it enables the central SCADA system to monitor and control multiple devices efficiently. Through the Modbus RTU protocol, the SCADA system can retrieve compressor status, temperature readings, and other critical operational data from the MSD200 and

PM210, and also send control commands to adjust operational parameters. This level of integration and communication is fundamental for optimizing the VCD process, enhancing system responsiveness, and ensuring energy-efficient operation.

2.2. Experimental Setup

The experimental setup is meticulously designed to evaluate the efficacy and robustness of our Vapor Compression Distillation system. This section details the configuration of the experimental apparatus, the step-by-step procedures conducted during testing, and the specific performance metrics that are assessed.

Figure 4 offers a comprehensive view of the actual implementation of our Vapor Compression Distillation system, as installed in laboratory 103 of the Faculty of Information Technology at Al-Farabi KazNU. This image captures the critical elements of the system's architecture, providing a real-world perspective on how the theoretical designs are applied practically.

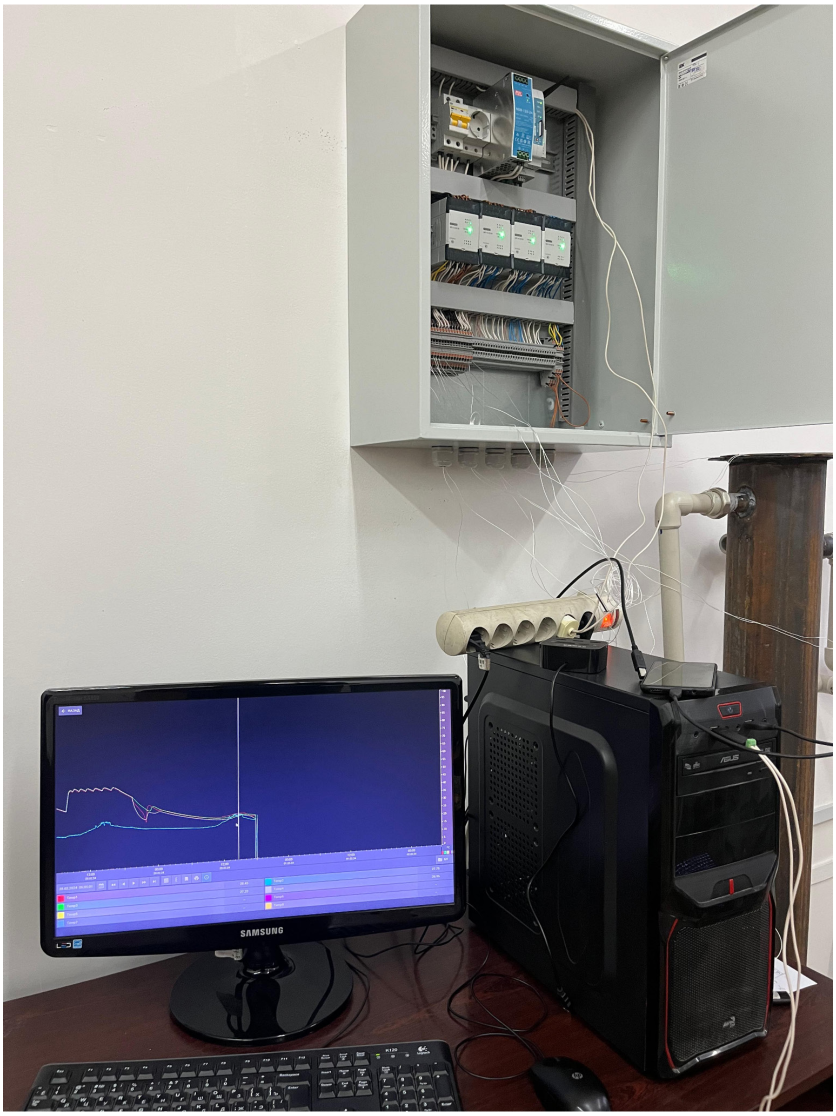

Figure 4 – General view of the system

The figure prominently features the data collection layer, which is the foundational aspect of our system's operational intelligence. This layer consists of numerous sensors and data acquisition devices that continuously monitor various process parameters such as temperature, pressure, and flow rates throughout the VCD process. These devices are crucial for gathering the real-time data necessary for precise control and monitoring.

Central to the figure is the server equipped with an OPC (OLE for Process Control) server and SCADA (Supervisory Control and Data Acquisition) system. This server acts as the hub for all data communication, processing, and management. The OPC server standardizes the communication between hardware and software components, ensuring seamless data flow from the field devices to the SCADA system. The SCADA system, in turn, provides a robust platform for real-time process visualization and control. It displays critical information through an intuitive interface that includes trends and graphical representations of the operational data.

Additionally, the real-time interface for monitoring highlighted in the figure is crucial for operational oversight. It allows operators and researchers to observe immediate system responses and adjust parameters dynamically, enhancing the VCD process's efficiency and responsiveness. This interface not only displays trends and real-time data graphs but also includes controls for manipulating process variables directly, thereby facilitating immediate adjustments to optimize performance and energy usage.

Figure 5 – Data acquisition layer

Figure 5 displays implementation of the actual data acquisition components implemented in our Vapor Compression Distillation system. Key elements shown include the circuit breaker, which ensures electrical safety and system protection; the PM210, which acts as a pivotal data processing unit; the MV210, crucial for monitoring and verifying data integrity; and the MSD200, the main controller that orchestrates data collection from various sensors. This setup forms the backbone of our system's ability to gather, analyze, and transmit critical operational data, ensuring the VCD process is continuously optimized for efficiency and safety.

3. Real Time Monitoring and Data Storage

This section elaborates on the mechanisms and infrastructure in place for real-time monitoring and data storage within our Vapor Compression Distillation system. This crucial aspect of the system not only allows for the continual assessment of process efficiency and system health but also ensures that historical data is securely archived for future analysis and regulatory compliance.

3.1. Database Management and Data Integrity

Effective database management is critical for maintaining the integrity and accessibility of the data collected from the Vapor Compression Distillation process. Our system utilizes a robust SQL database architecture that is designed to handle large volumes of data with high transaction rates, ensuring data integrity through redundancy and regular backups. This setup supports a wide range of queries from simple data retrieval to complex analytics, facilitating real-time decision-making and long-term strategic planning.

The database is configured to perform regular integrity checks, verifying data consistency and correctness across all nodes in the system. This proactive approach to data management helps prevent data corruption and loss, which is essential for operational continuity and reliability. Additionally, security measures such as encryption and access controls are implemented to protect sensitive information from unauthorized access and to comply with industry-standard data protection regulations.

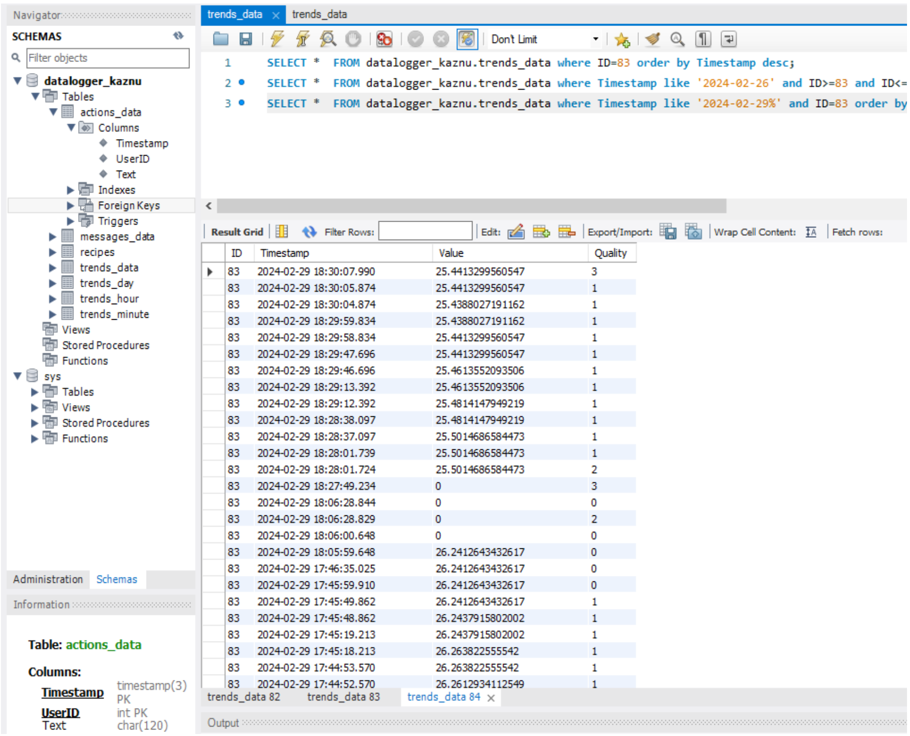

Figure 6 – Collected data from the L1

Figure 6 showcases the sophisticated data management utilized in our Vapor Compression Distillation system, depicted here as a snapshot of the SQL database from the L1 layer. This database holds a substantial number of records, totaling 21,644, which detail critical operational data collected during the distillation process. Each record in the database table is organized with fields for value and timestamp, ensuring that each data point is recorded with its measurement value and the precise time of acquisition.

Notable features of this data storage system include the capability to export data to CSV format, enhancing data analysis and sharing processes. This functionality is essential for effective data saving and retrieval, which are crucial for continuous monitoring and optimization of the VCD process. The database, identified as 'DB kaznu,' primarily stores temperature values, which are critical for monitoring the performance of the system. These records play a pivotal role in analyzing the system's operational efficiency, helping to identify trends, detect potential issues, and ensure optimal system performance.

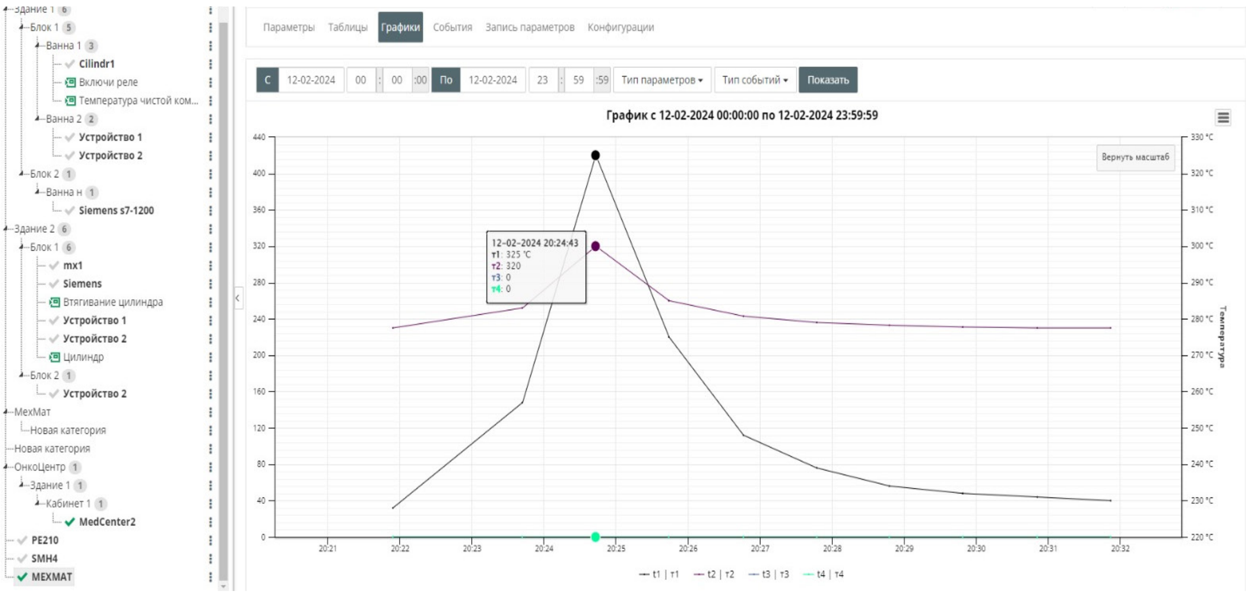

Figure 7 – Remote data monitoring

Figure 7 provides an in-depth look at the remote data monitoring interface utilized in our Vapor Compression Distillation system. This interface displays real-time graphs and trends, accessible both via web and mobile platforms, ensuring critical operational data can be monitored anytime, anywhere. The interface features a dynamic graph that continuously updates with temperature values, reflecting the current conditions of the VCD process.

This monitoring tool is designed to alert operators through notifications if the temperature deviates from predetermined ranges, enabling immediate corrective actions to maintain system efficiency and safety. The interface includes various modes that can be selected to view different aspects of system performance or to adjust monitoring parameters according to specific operational needs.

A specialized tab, labeled 'Mehmat' is included in the interface to provide tailored views or functions designed for specific user requirements or system analysis tasks. This feature enhances the usability of the monitoring system, allowing operators or engineers to quickly access the most pertinent data for making informed decisions about system operations.

3.2. Monitoring Tools for System Management

The monitoring tools integrated into our SCADA system are designed to provide comprehensive management capabilities over the entire Vapor Compression Distillation process. These tools include advanced diagnostic and analytics features that allow system operators and engineers to detect potential issues before they lead to system downtime.

Features such as predictive maintenance algorithms use historical and real-time data to forecast equipment failures, enabling proactive repairs and replacements. Performance benchmarks are continuously updated based on operational data, allowing the system to dynamically adjust operational parameters for optimized performance. Additionally, the SCADA system includes user-configurable alarms and notifications that alert personnel to critical changes or anomalies in system performance.

These monitoring tools are integral to ensuring that the Vapor Compression Distillation system operates within its optimal parameters, providing a high level of control and insight that enhances the overall efficiency and safety of the process.

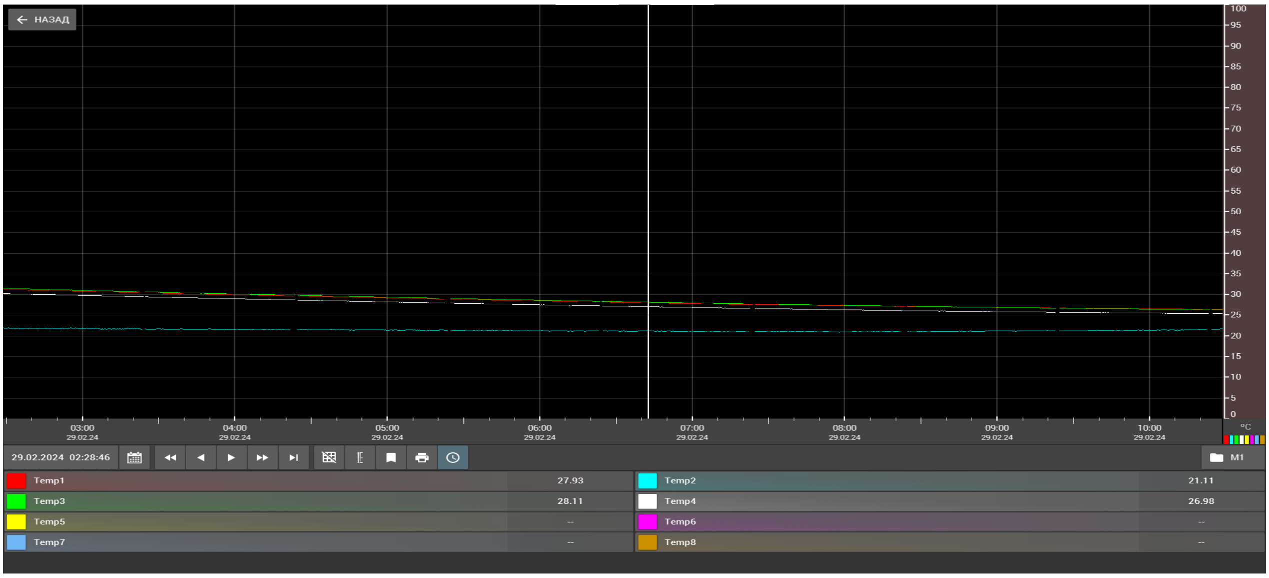

Figure 8 – Real time data analysis in mode M1

Figure 8 illustrates the real-time data analysis capabilities of our Vapor Compression Distillation system in Mode M1. This mode is characterized by a 'calm' setting, where no thresholds are set for triggering alarms or alerts. It showcases a steady, gradual change in data, ideal for monitoring under stable operating conditions. The SCADA interface displays the temperature parameter, labeled 'Temp', reflecting real-time conditions without abrupt fluctuations. This mode is particularly useful for maintaining a steady state in the distillation process, allowing operators to monitor system performance with minimal interference, thus ensuring a consistent output.

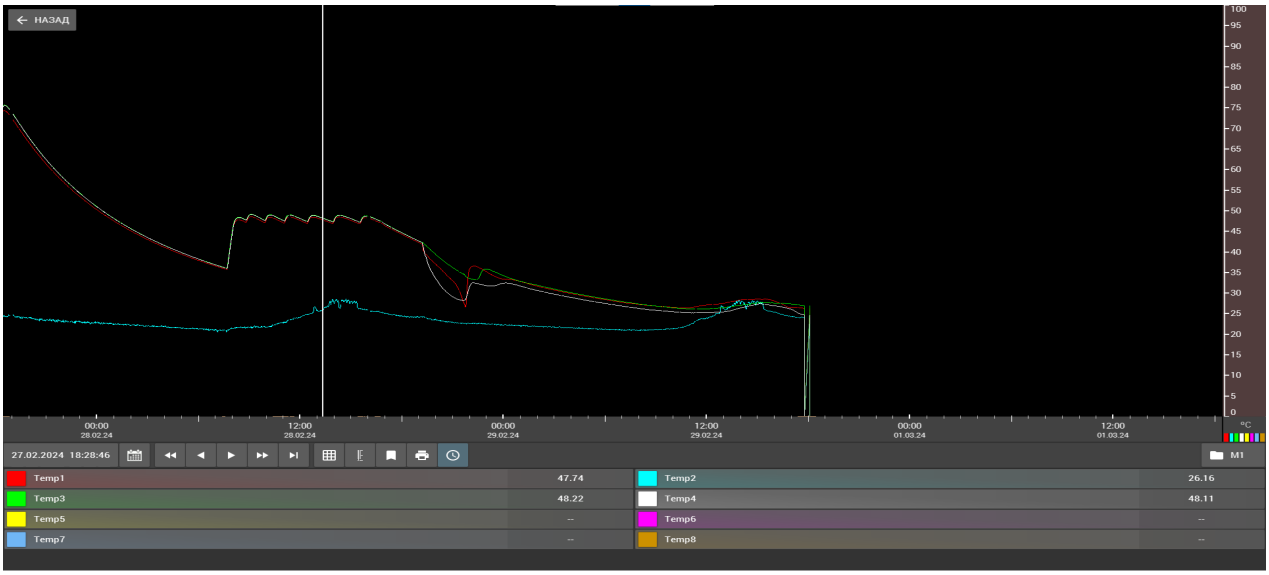

Figure 9 – Real time data analysis in mode M2

Figure 9 depicts the system's real-time data analysis in Mode M2, which is designed for more dynamic operational scenarios. This mode is 'fast' and 'adaptive', capable of handling rapid changes in data, suitable for phases in the distillation process that require quick adjustments to temperature controls. The SCADA system plays a crucial role here, updating the 'Temp' parameter swiftly to reflect the quick-paced changes. This mode enables the system to react immediately to shifts in operational conditions, optimizing the response to sudden thermal variations and ensuring the system's efficiency and safety.

Conclusion

In conclusion, this study has successfully demonstrated a comprehensive analysis of an advanced Vapor Compression Distillation system, designed and implemented following the ISA 95 standard architecture. The integration of sophisticated sensor technology, robust data communication protocols like MODBUS RTU over RS-485, and an efficient cloud-based SCADA system has significantly enhanced the operability and efficiency of the VCD process.

The experimental results confirm that the precise control of temperature and pressure, enabled by the real-time data monitoring and analysis, directly influences the system's efficiency and the quality of the distilled water. The implementation of predictive maintenance tools within the SCADA system has proven essential in minimizing downtime and extending the lifespan of critical components. The use of a robust SQL database for storing and retrieving operational data has supported effective decision-making and process optimization.

Future efforts will focus on further integrating renewable energy sources into the system to reduce operational costs and environmental impact. Additionally, exploring advanced data analytics and machine learning techniques could offer predictive insights into system performance and maintenance needs, potentially setting new benchmarks for system efficiency and reliability.

This study not only demonstrates the capabilities of modern Vapor Compression Distillation systems but also underscores the potential for further innovations in this vital area of water purification technology. The continued refinement and advancement of such systems are crucial in addressing the global challenges of water scarcity and sustainability.

References

1. Lawrence D. Noble, Franz H. Schubert, Rex E. Graves, Janie H. Miernik. An Assessment of the Readiness of Vapor Compression Distillation for Spacecraft Wastewater Processing 911454. International Conference On Environmental Systems, ISSN: 0148-7191, e-ISSN: 2688-3627. DOI: https://doi.org/10.4271/911454
2. Robert N. Schmidt. Water Recovery By Vapor Compression Distillation. Intersociety Conference on Environmental Systems, ISSN: 0148-7191, e-ISSN: 2688-3627. DOI: https://doi.org/10.4271/891444
3. F. H. Schubert. Phase Change Water Recovery Techniques: Vapor Compression Distillation and Thermoelectric/Membrane Concepts. Intersociety Conference on Environmental Systems, ISSN: 0148-7191, e-ISSN: 2688-3627. DOI: https://doi.org/10.4271/831122
4. Ameri, M., Mohammadi, S.S., Hosseini, M., & Seifi, M. (2009). Effect of design parameters on multi-effect desalinationsystem specifications. Desalination, 245, 266–283. DOI: 10.1016/j.desal.2008.07.012
5. Hamed, O.A., Zamamiri, A.M., Aly, S., & Lior, N. (1996). Thermal performance and exergy analysis of a thermal vapor compression desalination system. Energy Conversion and Management, 37, 379–387. DOI: 10.1016/0196-8904(95)00194-8
6. Bin Amer, A.O. (2009). Development and optimization of ME-TVC desalination system. Desalination, 249, 1315–1331. DOI: 10.1016/j.desal.2009.06.026
7. Noble, L., Schubert, F., Graves, R., & Miernik, J. (1991). An Assessment of the Readiness of Vapor Compression Distillation for Spacecraft Wastewater Processing. SAE Technical Paper 911454. DOI: 10.4271/911454
8. Schubert, F.H. (1983). Phase Change Water Recovery Techniques: Vapor Compression Distillation and Thermoelectric/Membrane Concepts. SAE Technical Paper 831122. DOI: 10.4271/831122
9. Schmidt, R.N. (1989). Water Recovery By Vapor Compression Distillation. SAE Technical Paper 891444. DOI: 10.4271/891444
10. Commercial Thermal Technologies for Desalination of Water from Renewable Energies: A State of the Art Review. Processes, 2021, 9(2), 262. DOI: 10.3390/pr9020262
11. S. Al-Obaidani, A. Curcio, E. Macedonio, F. Di Profio, G. Alhinai, E. Drioli. "Potential of membrane distillation in seawater desalination: Thermal efficiency, sensitivity study and cost estimation." Journal of Membrane Science, 2008. DOI: https://doi.org/10.1016/j.memsci.2008.04.062.

12. M. Khayet, J.I. Mengual, C. Matsuura. "Novel distillation technique to desalinate seawater using a dual-layer hydrophobic-hydrophilic hollow fiber membrane." Desalination, 2005. DOI: https://doi.org/10.1016/j.desal.2004.11.038.

13. Mirna Rahmah Lubis. Desalination Using Vapor-Compression Distillation: Basics, Notions, and Economics. LAP LAMBERT Academic Publishing.

14. Cong Liu*, Mingshu Bi, Guangrui Cui. Parameter optimization and economic analysis of a single-effect mechanical vapor compression (MVC) distillation system. Desalination and Water Treatment. doi: 10.5004/dwt.2020.26096

15. Abolghasem Kazemi, Mohamadjavad Hosseini, Arjomand Mehrabani-Zeinabad, Vafa Faizi. Evaluation of different vapor recompression distillation configurations based on energy requirements and associated costs. Applied Thermal Engineering, Volume 94, 5 February 2016, Pages 305-313. https://doi.org/10.1016/j.applthermaleng.2015.10.042

Information about authors:

Bibars Amangeldy – Master of technical sciences, Scientific researcher at Joldasbekov Institute of Mechanics and Engineering and scientific researcher at Computer Science labaratory at al-Farabi Kazakh National University (Almaty, Kazakhstan, e-mail: a.s.bibars@gmail.com).

Nurdaulet Tasmurzayev (corresponding author) – Master of technical sciences, Scientific researcher at Joldasbekov Institute of Mechanics and Engineering and scientific researcher at Computer Science labaratory at al-Farabi Kazakh National University (Almaty, Kazakhstan, e-mail: tasmurzayev.n@gmail.com).

Shona Shinassylov – Master of technical sciences, Scientific Computer Science labaratory at al-Farabi Kazakh National University (Almaty, Kazakhstan, e-mail: shona.shinassylov.87@gmail.com).

Submission received: 22 June, 2024.
Revised: 24 June, 2024.
Accepted: 24 June, 2024.