International Journal of Heat and Technology
Vol. 43, No. 1, February, 2025, pp. 19-28
Journal homepage: http://iieta.org/journals/ijht

Optimization and Intelligent Control of Municipal Wastewater Treatment Process Based on Heat Recovery

Ding Ding[1*], Chunyu Zhao[1], Yinjie Guo[1], Tianyi Du[2]

[1] Department of Architectural Engineering, North China Institute of Aerospace Engineering, Langfang 065000, China
[2] Library, North China Institute of Aerospace Engineering, Langfang 065000, China

Corresponding Author Email: jane860523@nciae.edu.cn

https://doi.org/10.18280/ijht.430103

Received: 20 August 2024
Revised: 30 November 2024
Accepted: 17 December 2024
Available online: 28 February 2025

Keywords:
municipal wastewater treatment, heat recovery, thermodynamic simulation, system optimization, intelligent control

ABSTRACT

With the continuous progress of urbanization, municipal wastewater treatment has become a core issue in urban environmental management. However, traditional wastewater treatment processes often face challenges of high energy consumption and low efficiency, resulting in significant negative environmental impacts. To enhance the sustainability and energy efficiency of wastewater treatment, heat recovery technology has emerged as a promising solution. By recovering and utilizing waste heat during the treatment process, it is possible to effectively reduce energy consumption and improve overall system efficiency. Therefore, heat recovery-based municipal wastewater treatment technology has become a focal point of current research. Although existing studies have explored the application of heat recovery in wastewater treatment, there are still some limitations, particularly in thermodynamic analysis and system optimization for practical applications. Most current studies focus primarily on the analysis of individual heat recovery effects, lacking comprehensive system simulation and intelligent control methods. As such, further in-depth research into the thermodynamic characteristics of heat recovery systems and intelligent optimization control strategies is of great theoretical significance and practical value. This paper primarily investigates the thermodynamic simulation and analysis of heat recovery-based municipal wastewater treatment systems, conducts a systematic analysis of energy flows within the heat recovery process, and explores the application of intelligent control technologies for system optimization. The research includes: first, thermodynamic simulation and analysis of municipal wastewater treatment systems, exploring the efficiency and influencing factors of heat recovery; secondly, proposing an intelligent control-based optimization method for heat recovery to improve system operational efficiency and energy-saving performance. This research not only provides new insights for energy-efficient optimization in wastewater treatment technologies but also offers theoretical support for intelligent control research in related fields.

1. INTRODUCTION

With the acceleration of urbanization and the increase in population, municipal wastewater treatment has become an important issue in modern urban environmental management [1-3]. Traditional municipal wastewater treatment processes not only require significant energy consumption but also generate large amounts of greenhouse gas emissions, putting pressure on the ecological environment [4, 5]. Therefore, how to achieve efficient recovery and utilization of energy during the wastewater treatment process has become an important research direction to improve treatment efficiency, reduce energy consumption, and minimize environmental impact. Heat recovery, as an effective energy-saving technology, has gradually been applied to the field of municipal wastewater treatment. By utilizing the heat generated during the wastewater treatment process, it can not only reduce the system's energy consumption but also improve the sustainability of the wastewater treatment process [6-8].

At present, research on heat recovery-based municipal wastewater treatment systems has made some progress, but most studies remain at the level of thermodynamic analysis and optimization of heat recovery efficiency, lacking systematic and comprehensive research. Especially in practical applications, the complex thermodynamic variations within the wastewater treatment system and the issue of how to effectively integrate heat recovery with intelligent control strategies have not been sufficiently discussed [9-14]. Through in-depth research on the thermodynamic analysis and energy flow of wastewater treatment systems, combined with advanced intelligent control technologies, it is possible not only to optimize the heat recovery efficiency in the wastewater treatment process but also to improve the overall operational performance and stability of the system, thus promoting the development of wastewater treatment technology towards higher efficiency and intelligence [15-19].

Although previous research has conducted preliminary investigations on heat recovery in municipal wastewater treatment systems, the current research methods still have certain limitations [20-23]. Existing thermodynamic simulation studies often focus on the establishment of theoretical models, lacking sufficient consideration of actual operating conditions and multiple variables, resulting in significant discrepancies between simulation results and the actual system's operation. Furthermore, traditional control strategies often rely on preset rules and experience, making it difficult to achieve real-time and intelligent adjustments to the dynamic changes in the wastewater treatment process. Therefore, how to establish a more accurate thermodynamic model and optimize the system using intelligent control algorithms is an issue that needs to be addressed.

This paper focuses on two main areas of research:

Heat recovery optimization: By conducting thermodynamic simulations and analyses of heat recovery in municipal wastewater treatment systems, the study explores its potential and influencing factors. A thermodynamic model tailored to real operating conditions is established to optimize heat recovery efficiency. Intelligent control optimization: Using real-time monitoring and feedback mechanisms, the study applies intelligent control theory to optimize the control strategies of wastewater treatment systems, enhancing response speed and stability under varying conditions.

Overall, the research aims to provide efficient and intelligent solutions for heat recovery in municipal wastewater treatment, promoting energy savings, emission reduction, and resource recovery with both theoretical and practical significance.

2. THERMODYNAMIC SIMULATION AND ANALYSIS OF HEAT RECOVERY-BASED MUNICIPAL WASTEWATER TREATMENT SYSTEM

2.1 Physical model

In order to optimize the heat recovery-based municipal wastewater treatment process, it is essential to accurately define the physical model of the system, particularly with a detailed analysis of the key components and working principles involved in heat recovery during the wastewater treatment process. The core components of the system constructed in this paper include the evaporator, compressor, condenser, and expansion valve. These components work together to form a cyclic thermodynamic process. The working fluid, which is a low-boiling-point medium such as ammonia or R134a, flows within the system and undergoes a phase change to achieve heat transfer and conversion. Specifically, the working fluid absorbs low-temperature heat from the municipal wastewater in the evaporator, evaporates into vapor, and then is compressed by the compressor, converting the low-temperature, low-pressure vapor into high-temperature, high-pressure vapor. The vapor then enters the condenser, releases heat to heat the high-temperature heat source, and ultimately condenses back into liquid form. Afterward, it passes through the expansion valve and returns to the evaporator to continue absorbing heat and cycle repeatedly. Figure 1 illustrates the system architecture.

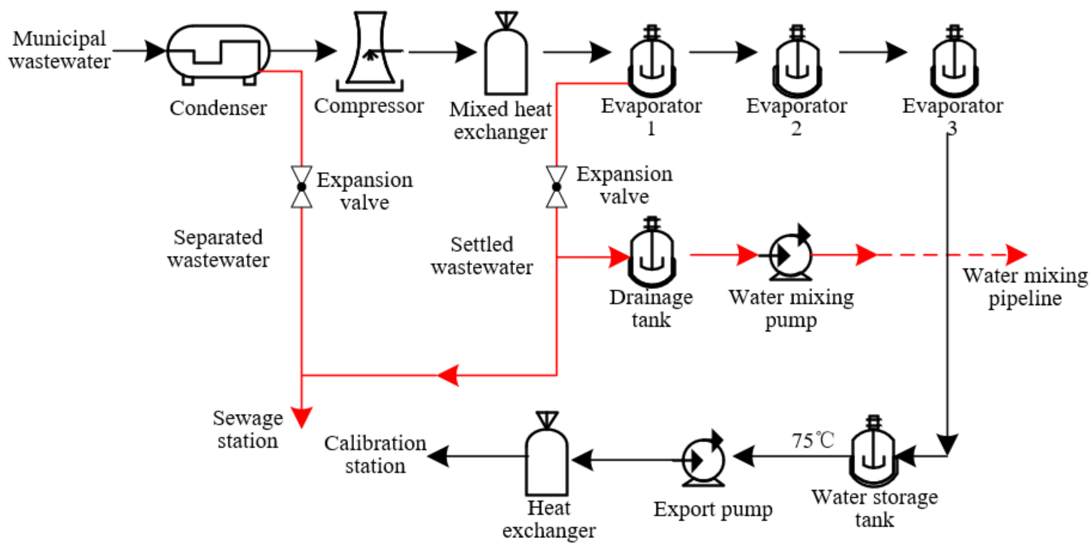

Figure 1. Heat recovery-based municipal wastewater treatment system architecture

Based on the thermodynamic model, the proposed heat recovery system not only achieves efficient recovery of heat from the wastewater treatment process but also optimizes the overall process design of wastewater treatment. The wastewater treatment process itself involves various chemical and physical reactions, and traditional wastewater treatment methods typically consume large amounts of external energy, leading to low energy efficiency. By introducing a heat recovery mechanism, the system can effectively recover waste heat from the treatment process, reducing dependence on external energy and optimizing the energy utilization structure. On this basis, by integrating the thermodynamic model, the various stages of the working fluid cycle are precisely calculated and optimized, providing thermal energy support for each stage of wastewater treatment, thereby achieving energy saving, emission reduction, and improved treatment efficiency.

In addition to the optimization of thermodynamic simulation, the research in this paper further proposes an optimization scheme for the wastewater treatment process based on intelligent control technology. Traditional municipal wastewater treatment processes mostly rely on fixed control strategies or experience-based rules, lacking flexible dynamic adjustment mechanisms. To adapt to environmental changes and system load fluctuations during the wastewater treatment process, intelligent control strategies can monitor the operation status of the wastewater treatment system in real-time and automatically adjust the operation of the heat recovery system according to changes. Through real-time data collection and feedback, the intelligent control system can coordinate the operation of key components, such as the compressor, evaporator, and condenser, to achieve the synergistic optimization of heat recovery and the wastewater treatment process.

2.2 Thermodynamic calculation of the system

(1) Determination of design operating conditions

To effectively recover the waste heat from the jet pump outlet to provide heating for the multi-stage evaporation system, thus optimizing the wastewater treatment process and achieving energy-saving effects, it is necessary to conduct a reasonable design of the operating conditions in the system. In the specific design, it is essential to fully understand the waste heat parameters and thermal energy requirements in the municipal wastewater treatment process. These parameters include the wastewater temperature, wastewater flow rate, outlet water temperature of the jet pump, the thermal energy required for wastewater treatment, and the operating conditions of the heat recovery system. These factors directly influence the design and optimization of the heat recovery system.

In the design, the selection of the working fluid is crucial to the system’s efficiency and stability. Common low-boiling-point working fluids, such as ammonia and R134a, have low evaporation temperatures and high heat transfer capabilities. These properties enable them to effectively absorb heat in the low-temperature environment of municipal wastewater and enhance heat recovery efficiency. During this process, the temperature of the evaporator must match the temperature of the municipal wastewater to ensure maximum heat recovery while avoiding excessive energy loss. Therefore, determining the design operating conditions not only requires an accurate assessment of the wastewater’s waste heat but also needs to adjust the evaporator's working temperature reasonably according to the thermodynamic properties of the circulating working fluid to ensure optimal heat recovery in all stages of the system.

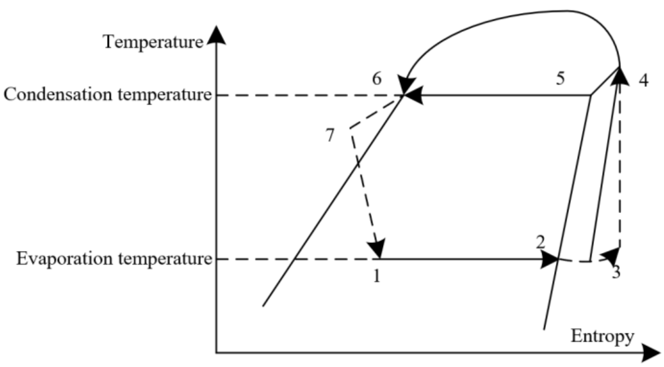

Figure 2. Temperature-entropy diagram of heat pump working fluid

In the thermodynamic cycle, simplified assumptions are made in this paper to facilitate the calculation and optimization process. Figure 2 presents the temperature-entropy diagram of the heat pump working fluid. The phase change process of the working fluid in the evaporator and condenser is assumed to be an isobaric process, which simplifies the thermodynamic analysis of the system, making the design of the heat recovery system more intuitive and practical. At the same time, the expansion valve is assumed to be an isenthalpic process to simplify the model and make optimization during practical operations easier. Based on these assumptions, the enthalpy-entropy diagram of the working fluid can effectively demonstrate the working process of the heat recovery system. Specifically, the isobaric heat absorption process of the working fluid in the evaporator causes it to change from liquid to vapor, after which it enters the condenser via the compressor, releasing heat during this process, and ultimately undergoes pressure adjustment through the expansion valve.

To further optimize the municipal wastewater treatment process and achieve intelligent control, the determination of design operating conditions must also consider the dynamic changes of the system under different operating conditions. For example, during the municipal wastewater treatment process, the flow rate and temperature of the wastewater may change due to seasonal variations, fluctuations in water usage, and other factors. Therefore, during the design process, this paper sets up a flexible adjustment mechanism for the heat recovery system, enabling it to monitor the operation status of the wastewater treatment system in real-time and automatically adjust key parameters such as the evaporator temperature and compressor load based on real-time data. In addition, the introduction of intelligent control strategies will enable the heat recovery system not only to optimize energy saving but also to work in coordination with other stages of the municipal wastewater treatment process. Through the feedback mechanism of the intelligent control system, the working states of each component can be dynamically adjusted based on the treatment needs of the wastewater and process conditions, thereby optimizing the energy efficiency and stability of the entire wastewater treatment process while maintaining efficient heat recovery.

(2) Determination of system operating parameters

In the heat recovery-based municipal wastewater treatment system, the main operating parameters involved include the evaporation temperature s_{EV}, condensation temperature s_{co}, compressor suction temperature s_3, evaporator heat load W_2, and the evaporator steam flow rate l_0, among others. The rational selection and setting of these parameters directly affect the efficiency of the heat recovery system, the optimization of the wastewater treatment process, and the effectiveness of the intelligent control system.

a) Evaporation temperature s_{EV}

The evaporation temperature s_{EV} refers to the temperature at which the working fluid absorbs heat and undergoes phase change in the evaporator. In the heat recovery system, the role of the evaporator is to recover heat from the municipal wastewater, typically evaporating the working fluid within the temperature range of the wastewater. The selection of the evaporation temperature must match the temperature of the municipal wastewater to ensure that heat is effectively transferred from the wastewater to the working fluid. If the evaporation temperature is too high, the working fluid may not be able to absorb enough heat from the low-temperature wastewater, while if it is too low, the thermodynamic properties of the working fluid may be affected. Therefore, rationally selecting the evaporation temperature is key to optimizing heat recovery. It is assumed that the temperature difference between the evaporator and the low-temperature heat source is Δs_{EV}=10°C.

b) Condensation temperature s_{co}

The condensation temperature s_{co} refers to the temperature at which the working fluid releases heat and condenses into liquid form in the condenser. This temperature is typically closely related to the temperature of the high-temperature heat source. The setting of the condensation temperature determines how much heat the working fluid can transfer to the heat source, so its selection not only affects the efficiency of heat recovery but also the overall energy efficiency of the system. If the condensation temperature is too low, the system will be unable to transfer sufficient heat to the heat source, while if it is too high, the condensation process may be incomplete, affecting the system's stable operation.

c) Compressor suction temperature s_3

The compressor suction temperature s_3 refers to the temperature of the working fluid before entering the compressor. This parameter directly impacts the compressor's workload and efficiency, which in turn affects the overall efficiency of the heat recovery system. If the suction temperature is too high, the compressor will require more energy to compress the working fluid, reducing the system's overall thermal efficiency. Conversely, if the suction temperature is too low, the compressor's working efficiency may decrease. Therefore, it is crucial to control the suction temperature rationally to improve the system's efficiency and reduce energy consumption. In practical applications, the suction temperature is often related to the evaporation temperature s_{EV}, and the two should be reasonably matched based on the thermodynamic properties of the working fluid. This paper selects an overheating degree of 5°C, which gives the following equation:

$$s_3 = s_{EV} + 5 \tag{1}$$

d) Evaporator heat load W_2

The evaporator heat load W_2 refers to the amount of heat absorbed by the working fluid in the evaporator. This parameter reflects the amount of heat extracted from the wastewater in the heat recovery system and directly impacts the overall performance of the system. The larger the evaporator heat load, the more heat the system can recover from the wastewater, thereby improving the system's energy utilization. During the design, the evaporator heat load should be matched with the heat supply capacity of the municipal wastewater to ensure that the system can operate stably under different operating conditions. By adjusting the design parameters of the evaporator, such as evaporation temperature and water flow rate, the heat load can be effectively optimized, thereby improving recovery efficiency. Assuming that the enthalpy at the evaporator outlet is denoted as g_3, and the enthalpy at the evaporator inlet is denoted as g_1, the following calculation formula applies:

$$W_2 = H\left(g_3 - g_1\right) \tag{2}$$

e) Evaporator steam flow rate l_0

The evaporator steam flow rate l_0 refers to the mass flow rate of the working fluid that transitions into steam in the evaporator. This parameter is one of the key indicators for evaluating the thermal energy transfer efficiency of the heat recovery system. The size of the evaporator steam flow rate determines how much heat the working fluid can absorb in the evaporator, which in turn affects the system's heat recovery capability. If the steam flow rate is too large, excessive heat may be absorbed, but the excessively high flow speed may reduce the evaporation efficiency and lead to poor heat recovery. On the other hand, if the flow rate is too small, it may not meet the system's heat demand. Therefore, during the design, it is necessary to adjust the steam flow rate based on the wastewater temperature, flow rate, and required heat load to achieve the optimal heat recovery effect. Assuming the specific enthalpy of the steam entering the evaporator is denoted as g''_0, and the specific enthalpy of the saturated water exiting the evaporator is denoted as g'_0, the following calculation formula applies:

$$l_0 = \frac{W_2}{g''_0 - g'_0} \tag{3}$$

3. EXERGY ANALYSIS OF THE MUNICIPAL WASTEWATER TREATMENT SYSTEM BASED ON HEAT RECOVERY

3.1 Exergy analysis of major components

In the municipal wastewater treatment system based on heat recovery, the system's thermal efficiency and overall energy performance are closely related to the performance of its key components. The compressor, condenser, expansion valve, and evaporator are the four critical components, and their operating efficiency directly determines the system's heat recovery effect and economic viability. Therefore, analyzing the energy losses of these components is essential for improving system performance and optimizing design.

(1) Exergy loss analysis of the compressor

The compressor plays a vital role in the heat pump system, primarily functioning to compress the low-temperature, low-pressure refrigerant to a high-temperature, high-pressure state, thus providing power for the system. However, the operation of the compressor is not ideal, and its efficiency is affected by various factors, leading to energy losses. The first factor is the adiabatic efficiency of the compressor. The ideal compression process is adiabatic, meaning no heat exchange occurs during compression. In practice, however, compressors typically experience some heat exchange and mechanical losses, leading to energy loss. In the system design, the adiabatic efficiency for both low-pressure and high-pressure compression processes is usually set at 0.85, indicating that approximately 15% of the energy is converted into heat loss during the compression process. Additionally, the superheat of the compressor's outlet also affects its efficiency. To prevent damage to the compressor from liquid refrigerant, the refrigerant is typically superheated to a certain degree. An increase in superheat causes the compressor to consume more work, reducing efficiency. According to the analysis in this paper, the effect of superheating on the Coefficient of Performance (COP) is small but still represents a significant loss factor. Specifically, assuming the specific exergy value of the refrigerant entering the compressor is represented by r_1, and the specific exergy value leaving the compressor is represented by r_2, the compression work-specific exergy is denoted as q, and the compressor's exergy loss is denoted as τ, with the ambient temperature represented by S_0, the exergy balance equation is:

$$r_1 + q = r_2 + \tau_{12} \tag{4}$$

where,

$$r_1 = g_1 - S_0 t_1 \tag{5}$$

$$r_2 = g_2 - S_0 t_2 \tag{6}$$

$$q = g_2 - g_1 \tag{7}$$

(2) Exergy loss analysis of the condenser

The main function of the condenser is to transfer the heat of the high-temperature, high-pressure refrigerant discharged by the compressor to the cooling medium, causing it to condense into liquid form during the cooling process. However, the heat exchange efficiency of the condenser is influenced by various factors, leading to energy losses. The insulation performance of the condenser is an important factor affecting its efficiency. Poor insulation, high ambient temperature, or high temperature of the cooling medium will reduce the heat exchange effect. According to the analysis in this paper, the insulation coefficient of the condenser is typically set at 0.93, meaning that about 7% of the heat is lost due to insufficient insulation, resulting in energy loss. Furthermore, the heat exchange efficiency of the condenser is closely related to its surface area, fluid flow method, and the temperature of the cooling medium. In practical operation, the condenser's heat exchange efficiency may decrease due to issues such as fouling, corrosion, or uneven flow, which increases energy losses. Optimizing the design, materials, and maintenance of the condenser can effectively reduce these losses. Specifically, assuming the specific exergy value of the refrigerant entering the condenser is r_2, and the specific exergy value leaving the condenser is r_3, the specific exergy value of the cooling water entering the condenser is r_y, and the specific entropy value leaving the condenser is r_x, the internal loss of the condenser is τ_{23}, and the heat released is denoted as w, with the condensation temperature represented by S_G, the exergy balance equation is:

$$r_2 + r_y = r_3 + r_x + \tau_{23} \tag{8}$$

where,

$$r_2 = g_2 - S_0 t_2 \tag{9}$$

$$r_3 = g_3 - S_0 t_3 \tag{10}$$

$$r_y = g_y - S_0 t_y \tag{11}$$

$$r_x = g_x - S_0 t_x \tag{12}$$

$$w = g_2 - g_3 \tag{13}$$

3.2 Exergy loss analysis of the expansion valve

The expansion valve is a critical component in controlling the flow and pressure of the refrigerant in the refrigeration system. During the throttling process, the refrigerant experiences a sharp pressure drop, and its temperature decreases as well, resulting in certain energy losses. The efficiency of the expansion valve is typically not very high because the throttling process is inherently irreversible and involves unavoidable pressure losses during the flow of the refrigerant. The efficiency of the expansion valve is generally set at 0.95, meaning about 5% of the energy is lost during the throttling process. The losses of the expansion valve are closely related to its design and operating conditions. If the valve's adjustment is improper or it malfunctions, greater energy losses may occur. Additionally, the precision of the flow control of the expansion valve is another factor that affects the losses. In practical operation, if the expansion valve cannot precisely control the flow, it may result in uneven refrigerant flow, pressure fluctuations, and system instability, thereby increasing the losses. Optimizing the design of the expansion valve, improving its control accuracy, and ensuring proper maintenance and management can reduce these losses. Specifically, assuming the specific exergy value of the refrigerant entering the expansion valve is r_3, and the specific exergy value leaving the expansion valve is r_4, the expansion valve's exergy loss is denoted as τ_{34}, with the ambient temperature represented by S_0, the exergy balance equation can be expressed as:

$$r_3 = r_4 + \tau_{34} \tag{14}$$

where,

$$r_3 = g_3 - S_0 t_3 \tag{15}$$

$$r_4 = g_4 + S_0 t_4 \tag{16}$$

$$g_3 = g_4 \tag{17}$$

3.3 Exergy loss analysis of the evaporator

The main function of the evaporator is to absorb heat from the low-temperature, low-pressure liquid refrigerant and transform it into a gaseous state, thereby recovering heat in the system. The performance of the evaporator directly impacts the system's heat recovery efficiency. The heat exchange efficiency of the evaporator is the primary factor affecting its energy losses. The ideal evaporation process should be a highly efficient heat exchange process, where the refrigerant rapidly absorbs heat from the surrounding medium and undergoes phase change. However, the heat exchange efficiency of the evaporator is influenced by multiple factors, such as the temperature of the wastewater, contamination of the evaporator's surface, and uneven fluid flow. According to this study, the heat exchange efficiency of the evaporator is typically limited, meaning some heat is not effectively recovered. Additionally, the insulation performance of the evaporator may also affect its efficiency. If the insulation is poor, heat may be lost during the heat transfer process, reducing heat recovery efficiency. Improving the insulation design of the evaporator and minimizing heat losses can help enhance the overall system performance. Specifically, assuming the specific exergy value of the refrigerant entering the evaporator is r_4, and the specific exergy value leaving the evaporator is r_1, the specific exergy value of the refrigerant's heat absorption during evaporation is r_0, and the specific exergy value of the cooling water entering the condenser is r_y, and leaving the condenser is r_x, the evaporator's exergy loss is denoted as τ_{41}, with the heat absorption amount denoted as w_0, and the evaporation temperature represented by S_M, the exergy balance equation is:

$$r_4 + r_y = r_1 + r_x + \tau_{41} \tag{18}$$

where,

$$r_4 = g_4 - S_0 t_4 \tag{19}$$

$$r_x = g_x - S_0 t_x \tag{20}$$

$$r_y = g_y - S_0 t_y \tag{21}$$

$$r_1 = g_1 - S_0 t_1 \tag{22}$$

$$w_0 = g_1 - g_4 \tag{23}$$

4. EXPERIMENTAL RESULTS AND ANALYSIS

This paper uses R134a and R410A as refrigerants, and based on the high-temperature heat recovery process driven by wastewater waste heat, calculates various performance indicators of the system, such as the corrected COP, and analyzes the effects of different parameters on system performance.

4.1 Thermodynamic calculation results with R134a as the working fluid

When R134a is selected as the working fluid, based on the process node parameters of the system driven by wastewater waste heat, the initial calculated COP is 3.5. However, considering the actual operating efficiency of the system, the corrected COP is 2.11. The correction process includes considering factors such as the overheating of the compressor outlet fluid, the adiabatic efficiency of low-pressure and high-pressure compression, the insulation coefficients of the evaporator and condenser, and the efficiency of the expansion valve. These factors' corrections effectively reflect the performance degradation caused by equipment efficiency losses, incomplete energy transfer, and other reasons in actual operation.

According to the data in Table 1, the temperature, enthalpy, and entropy values of R134a as the working fluid in the municipal wastewater treatment system at various process nodes can provide important foundations for thermodynamic simulation and analysis. Specifically, the initial temperature of the system is 34.62°C, with an enthalpy of 16.25 kJ/kg, but the entropy value is not given. As the working fluid moves through the system, the temperature remains around 34°C, but the enthalpy and entropy values fluctuate, reflecting energy changes during the heat exchange process. For example, at node 3, the enthalpy reaches 22.31 kJ/kg, and the entropy increases to 1.6584 kJ/(kg·K), while at node 4, the enthalpy further increases to 27.62 kJ/kg. Between nodes 5 and 7, the fluctuation in enthalpy decreases to 54.26 kJ/kg, 41.32 kJ/kg, and 36.26 kJ/kg, respectively, while the entropy remains relatively stable between nodes 6 and 7, indicating that the thermodynamic process of the system tends toward stability, which may result in higher energy recovery efficiency.

Table 1. Process node parameters of the municipal wastewater treatment system with R134a as the working fluid

Name	Temperature (°C)	Enthalpy (kJ/kg)	Entropy (kJ/(kg·K))
1	-	34.62	-
2	34	16.25	-
3	34	22.31	-
4	104	54.26	1.658
5	91	24.26	-
6	91	41.32	-
7	88	36.26	-

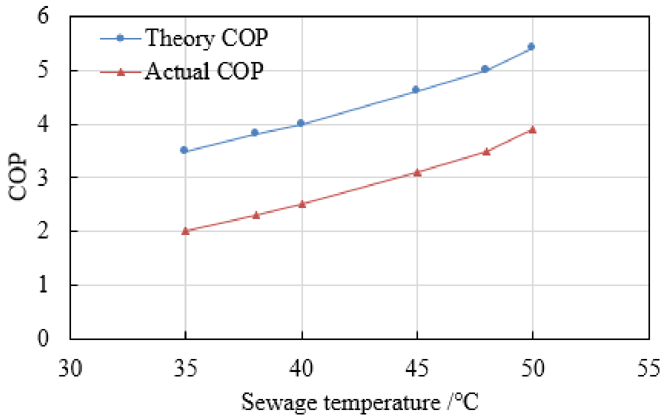

Figure 3. COP of the municipal wastewater treatment system as a function of wastewater temperature

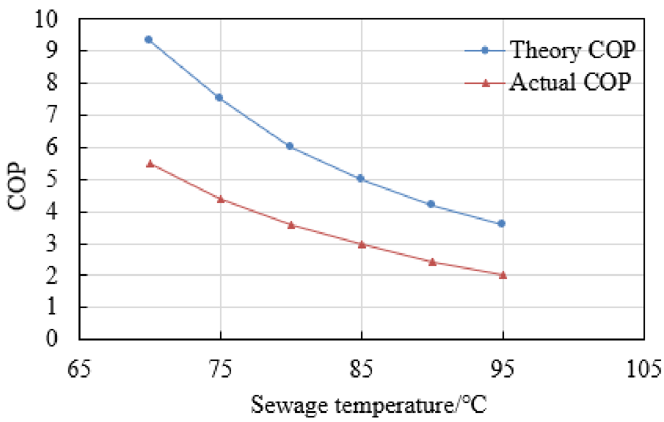

Figure 4. COP of the municipal wastewater treatment system as a function of high-temperature water temperature

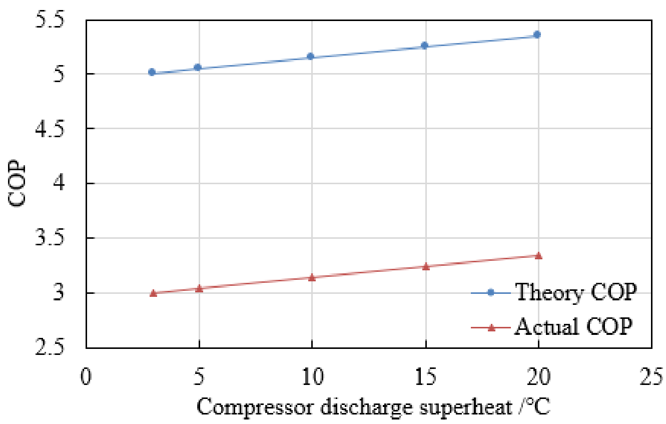

Figure 5. COP of the municipal wastewater treatment system as a function of compressor discharge overheating

Figures 3-5 show the variation of COP with wastewater temperature, high-temperature water temperature, and compressor discharge overheating, respectively. From these graphs, it can be observed that the high-temperature water temperature has the greatest impact on COP. The increase in high-temperature water temperature significantly reduces the system's COP, mainly because higher high-temperature water temperatures increase the pressure and temperature requirements during the condensation of the refrigerant, thereby increasing the compressor's workload and reducing heat recovery efficiency. On the other hand, the impact of compressor outlet overheating on COP is relatively small. Although an increase in overheating slightly increases compressor power consumption, its effect on the overall system performance is relatively limited.

Through these calculations and analyses, it is concluded that the actual COP of the system is usually lower than the theoretical value. Within the typical range of oilfield wastewater temperatures, the theoretical COP is higher than the actual COP, indicating that even with a two-stage compression and intermediate cooling high-temperature heat recovery system, the actual operating energy efficiency is still limited by several factors, especially high-temperature water temperature and compressor load.

4.2 Thermodynamic calculation results with R410A as the working fluid

To further improve the system's performance, this paper also studies the thermodynamic calculation results with R410A as the working fluid. Compared to R134a, R410A has better high-temperature heating performance. When R410A is used as the working fluid, the thermodynamic calculation of the wastewater waste heat-driven heat recovery system gives an initial COP of 3.9, and the corrected COP is 2.34. This indicates that when R410A is used as the working fluid, the system's thermodynamic performance is superior to that of R134a. The main reason is that R410A has a lower working temperature and higher heat transfer efficiency, allowing for effective heat recovery at higher temperatures, thereby improving the overall economic performance of the system.

Table 2. R410A as working fluid node parameters

Name	Temperature (℃)	Enthalpy (kJ/kg)	Entropy (kJ/(kg·K))
1	-	356.25	-
2	34	518.26	-
3	34	526.36	-
4	121	578.62	2.215
5	91	536.21	-
6	91	369.25	-
7	88	256.32	-

Based on the data in Table 2, the thermodynamic states of R410A as the working fluid in the municipal wastewater treatment system show changes in temperature, enthalpy, and entropy. The initial enthalpy is 356.25 kJ/kg, with the temperature not given. As the fluid progresses through the system, the temperature stays at 34℃, with enthalpies of 518.26 kJ/kg and 526.36 kJ/kg, respectively. As the system operates, the temperature rises significantly to 121℃, and the enthalpy increases to 578.62 kJ/kg, with the entropy reaching 2.2155 kJ/(kg·K). In subsequent nodes 5 and 6, the enthalpy decreases to 536.21 kJ/kg and 369.25 kJ/kg, respectively, though still within a relatively high range. Finally, at node 7, the enthalpy drops to 256.32 kJ/kg, indicating a significant reduction in energy as the system moves towards the cooling stage. The increase in entropy and changes in enthalpy reflect the irreversible losses and the complexity of energy conversion during the heat recovery process.

From this calculation analysis, it is evident that selecting an appropriate high-temperature compression fluid is crucial for improving the economic viability of high-temperature heat recovery systems. Different fluids exhibit distinct thermodynamic characteristics under the same working conditions, which determines their performance in heat recovery systems. R410A, with its lower boiling point and higher evaporation enthalpy, has a significant advantage in the municipal wastewater treatment process, especially in high-temperature heat recovery. Particularly, when hot water temperatures of 80-90℃ are required, R410A can provide a higher COP, which helps reduce energy consumption and improve the system's economic efficiency.

From the thermodynamic calculation results, although the municipal wastewater treatment system based on heat recovery theoretically has a high potential for heat recovery, the actual COP values are lower in practice. This phenomenon indicates that there are still some efficiency losses during the system design and operation. Therefore, further optimization of system operating parameters, selection of appropriate working fluids, and improving the efficiency of components will be future research directions.

4.3 System exergy analysis

In the municipal wastewater treatment system based on heat recovery, exergy analysis is a crucial step. By evaluating the energy losses at various components, it helps identify the root causes of inefficiencies in the system and propose optimization solutions. This paper calculates the exergy losses at each node of the system, combining actual design results to explore ways to improve system efficiency, reduce irreversible losses, and optimize overall system performance. Based on the design results and the data shown in Table 3, the total exergy efficiency of the heat recovery-based municipal wastewater treatment system is calculated to be 61.3%. This result indicates that energy losses account for 39.7% of the system's total energy. While energy losses are inevitable and represent irreversible processes in the system—such as temperature differences during heat exchange, mechanical friction, and flow resistance—this analysis provides insight into how each component affects the system's energy efficiency, helping us find directions for optimization. From the exergy loss calculations in Table 4, the compressor and evaporator are the main sources of exergy loss, with their losses accounting for a large proportion of the total system loss. Specifically, the losses in the compressor mainly arise from mechanical efficiency and heat losses, while the evaporator's losses are closely related to heat exchange efficiency and fluid dynamics.

From the theoretical and experimental results, it is clear that the evaporator is a key component in the heat recovery-based municipal wastewater treatment system. Its primary task is to absorb heat from wastewater or other heat sources and evaporate the low-temperature, low-pressure liquid refrigerant into a gas. The heat exchange efficiency of the evaporator determines whether the system can effectively recover heat from the wastewater. Based on the exergy analysis results, the evaporator's heat loss is significant, primarily due to the following reasons: First, the heat exchange surface area and flow conditions of the evaporator may not be optimal, especially when the wastewater quality is complex or the flow fluctuates, which can reduce heat exchange efficiency; second, if the evaporator's design temperature is set too low, the temperature difference during the heat transfer process may be too small, leading to increased heat loss. To reduce the evaporator's exergy loss, improving heat exchange efficiency by appropriately raising the evaporation temperature could help. Higher evaporation temperatures increase the vapor pressure of the refrigerant, improving heat exchange effectiveness. Additionally, higher evaporation temperatures also reduce the temperature difference between the evaporator and compressor, thereby reducing compressor energy loss. However, it is important to note that excessively high evaporation temperatures could require stronger pipeline materials, increase system costs, and may pose a risk of freezing. Therefore, the evaporation temperature should be set within a reasonable range to balance cost-effectiveness and system reliability.

Table 3. Municipal wastewater treatment system node parameters

Node No.	Temperature (K)	Enthalpy (kJ/kg)	Entropy (kJ/(kg·K))	Flow (kg/s)	Exergy (kJ/kg)
1	14	412.2	1.689	7.8	-88.9
2	73	435.1	1.756	7.8	-58.6
3	57	278.6	1.265	7.8	-82.1
3	52	265.3	1.258	7.8	-82.3
4	16	263.2	1.247	7.8	-85.6
5	37	158.9	0.532	11.6	3.4
6	17	73.2	0.256	11.9	-0.7
7	54	223.5	0.754	31.5	11.2

Table 4. Exergy loss in various components of the municipal wastewater treatment system

Component	Exergy Loss (kW)	Share (%)
Condenser	33.6	13.5
Evaporator	62.5	24.6
Compressor	121.5	42.8
Expansion Valve	32.8	12.3

The compressor, as the core component of the heat recovery system, is responsible for compressing the low-temperature, low-pressure refrigerant into a high-temperature, high-pressure gas, driving the heat recovery process. However, energy losses in the compressor mainly come from mechanical friction, heat losses during the gas compression process, and additional energy consumption due to overly high compression ratios. The energy loss in the compressor is not only related to its design but also to its operating conditions, workload, and external environment. According to the exergy analysis, the compressor's exergy loss accounts for a large proportion of the system's total loss. To reduce compressor energy losses, optimizing the selection and operating conditions of the compressor is essential. First, the compressor should be selected with an appropriate compression ratio based on the operating conditions to avoid excessive workload caused by a high compression ratio. Secondly, attention should be paid to the compressor's heat dissipation issues. Proper thermal isolation and cooling measures can reduce additional energy losses due to heat dissipation. Moreover, ensuring good sealing performance and the optimal condition of mechanical components in the compressor will help improve efficiency and reduce friction losses.

The expansion valve in the thermal energy recovery system controls the flow and pressure of the working fluid. It achieves the refrigeration or heating process by reducing the pressure of the working fluid. However, the throttling process is an irreversible process, and energy losses in this process mainly arise from pressure differences and flow instability. During the throttling process, the pressure of the working fluid suddenly decreases, and the temperature drops sharply, leading to corresponding thermal losses. According to the analysis based on exergy analysis, the energy loss in the throttling process is also significant. To reduce losses in the throttling process, the design and operating parameters of the expansion valve can be adjusted to reduce the pressure difference before and after the valve and maintain the stability of the fluid flow. Additionally, reducing the condensation pressure and increasing the evaporation temperature are important methods to minimize throttling losses. By optimizing the throttling process, the condensation temperature and evaporation pressure can be effectively reduced, which in turn reduces the compression ratio and the overall system energy loss.

The pipeline system, as an important component of the thermal energy recovery system, directly affects the heat transfer efficiency. The thermal conductivity, insulation performance, and flow resistance of the pipes all impact the system's energy efficiency. According to exergy analysis, to reduce thermal losses in the pipeline, materials with low thermal conductivity should be selected, and good insulation should be ensured. In pipeline design, besides selecting materials and ensuring good insulation, attention should also be paid to the layout and diameter design of the pipes, avoiding excessive bends and flow resistance to reduce flow losses.

The exergy analysis of the thermal energy recovery-based municipal wastewater treatment system shows that the compressor and evaporator are the main sources of energy loss. To improve the system's efficiency, optimizing the design of the evaporator should be a priority, appropriately increasing the evaporation temperature, and optimizing the compressor's operating state under the premise of ensuring economy and reliability. By properly selecting the expansion valve and designing the pipeline system, further reduction of throttling and heat transfer losses can effectively improve the overall thermal energy recovery efficiency of the system, thus reducing costs and energy consumption.

5. CONCLUSION

The research in this paper mainly focuses on two aspects: firstly, exploring the thermal energy recovery potential in municipal wastewater treatment systems based on thermal energy recovery through thermal simulations and analysis, and building a thermodynamic model that adapts to actual operating conditions to further optimize the energy recovery efficiency; secondly, introducing intelligent control theory to optimize the control strategy of the wastewater treatment system, using real-time monitoring data and feedback mechanisms to enhance the system's responsiveness and stability under different operating conditions. Through these two aspects, this paper successfully proposes an efficient and intelligent optimization plan aimed at improving the overall performance of municipal wastewater treatment systems, reducing energy consumption, and improving thermal energy recovery efficiency. Experimental data analysis shows that the system can achieve varying degrees of thermal energy recovery using R134s and R410A as working fluids, especially in areas where the state changes of the working fluids are more significant, the system's thermal recovery efficiency and irreversible losses are clearly demonstrated.

This study provides important theoretical and practical guidance for optimizing thermal energy recovery and control strategies in municipal wastewater treatment systems. Based on the thermodynamic model, this paper deeply explores the state changes and efficiency improvements of different working fluids (R134s and R410A) during the energy recovery process, with a particular focus on changes in enthalpy and entropy values of the fluids, revealing the irreversible losses in the energy conversion process and potential efficiency improvement space. Furthermore, through the application of intelligent control theory, the proposed optimization plan not only enhances the system's thermal energy recovery efficiency but also improves the system's responsiveness and stability in dynamic operating states, demonstrating strong practical application potential. These research results have significant theoretical value and practical significance in energy conservation, emission reduction, and resource recovery, especially providing new ideas for energy-saving technology innovation in the wastewater treatment field.

This study has some limitations. First, the experimental data and thermodynamic models are limited to specific operating conditions. Future research should expand the scope to include more wastewater treatment processes and different working fluids. Second, while the intelligent control strategy shows promise, its effectiveness needs validation and optimization in larger-scale systems. Future work could explore multivariable, multi-objective control optimization and adaptive AI-based strategies for more complex systems. Additionally, long-term stability, environmental adaptability, and industrial feasibility are important areas for further research.

ACKNOWLEDGEMENT

This paper was supported by Guidance Project of the Education Department of Hebei Province (Grant No.: ZC2023139) and Science and Technology Research Project of the Housing and Urban-Rural Development Department of Hebei Province (Grant No.: 172).

REFERENCES

[1] Chen, X., Xu, Z., Yao, L., Ma, N. (2018). Processing technology selection for municipal sewage treatment based on a multi-objective decision model under uncertainty. International Journal of Environmental Research and Public Health, 15(3): 448. https://doi.org/10.3390/ijerph15030448

[2] Khudair, M.Y., Ethaib, S., Jasim, F.M., Kamel, A.H. (2024). Developing sustainable wastewater treatment systems using biofiltration process. International Journal of Environmental Impacts, 7(4): 781-790. https://doi.org/10.18280/ijei.070418

[3] Mudofir, M., Taufik, M., Rusdan, I.H., Silviani, W.D., Purwono, P. (2023). Physicochemical and microbial characteristics and social perception of treated ablution wastewater reuse in Solo, Indonesia. International Journal of Sustainable Development and Planning, 18(2): 573-582. https://doi.org/10.18280/ijsdp.180227

[4] Rajczyk, R., Bień, J., Palka, H., Pogodziński, A., Smorąg, H. (2014). Co-combustion of municipal sewage sludge and hard coal on fluidized bed boiler WF-6. Archives of Environmental Protection, 40(3): 101-113. https://doi.org/10.2478/aep-2014-0027

[5] Ortega-Quispe, K., Ccopi-Trucios, D., Lozano-Povis, A., Llanos-del-Pino, A., Gabriel-Campos, E., Cordova-Buiza, F. (2024). Sustainable Management of Wastewater Sludge Through Composting with Effective Microorganisms: Enhancing the Growth of Tecoma stans. Organic Farming, 10(2): 108-119. https://doi.org/10.56578/of100202

[6] Aleksić, N., Šušteršič, V., Jurišević, N., Kowalik, R., Ludynia, A. (2023). Reduction of wastewater pollution using the technologies for heat recovery from wastewater in buildings–A review of available cases. Desalination and Water Treatment, 301: 242-255. https://doi.org/10.5004/dwt.2023.29405

[7] Wallin, J. (2021). Case studies of four installed wastewater heat recovery systems in Sweden. Case Studies in Thermal Engineering, 26: 101108. https://doi.org/10.1016/j.csite.2021.101108

[8] Wärff, C., Arnell, M., Sehlén, R., Jeppsson, U. (2020). Modelling heat recovery potential from household wastewater. Water Science and Technology, 81(8): 1597-1605. https://doi.org/10.2166/wst.2020.103

[9] Handayani, T., Priyanto, F.E., Sulistia, S., Oktaviani, A.N., Sopiah, N., Santoso, A.D., Putra, A.S., Djarot, I.N., Widyastuti, N., Tjokrokusumo, D., Apriyanto, H., Rifai, A., Aziz, A., Wijayanti, S.P., Bahua, H., Nuha, N., Isharyadi, F., Paminto, A.K., Ariyani, N.R. (2023). Integrated microalgae cultivation for sustainable wastewater treatment and carbon dioxide bio-fixation in milk factories. International Journal of Sustainable Development and Planning, 18(9): 2941-2952. https://doi.org/10.18280/ijsdp.180932

[10] Smith, N.R., Henze, G.P. (2021). Modelling of wastewater heat recovery heat pump systems. Journal of Sustainable Development of Energy, Water and Environment Systems, 9(1): 1080330. https://doi.org/10.13044/j.sdewes.d8.0330

[11] Janabi, A.S.K., Abdul-Hameed, H.M. (2025). Revolutionizing water hyacinth flash graphene technology to remove Cu(II) from wastewater: Equilibrium isotherm, kinetics and thermodynamic studies. International Journal of Design & Nature and Ecodynamics, 20(2): 275-288. https://doi.org/10.18280/ijdne.200206

[12] Kretschmer, F., Simperler, L., Ertl, T. (2016). Analysing wastewater temperature development in a sewer system as a basis for the evaluation of wastewater heat recovery potentials. Energy and Buildings, 128: 639-648.

https://doi.org/10.1016/j.enbuild.2016.07.024
[13] De Paepe, M., Theuns, E., Lenaers, S., Van Loon, J. (2003). Heat recovery system for dishwashers. Applied Thermal Engineering, 23(6): 743-756. https://doi.org/10.1016/S1359-4311(03)00016-4
[14] Mahdi, M.M., Ebrahim, S.E. (2024). A review of BiOBr-based photocatalysts for wastewater treatment. International Journal of Heat and Technology, 42(1): 219-237. https://doi.org/10.18280/ijht.420123
[15] Cecconet, D., Raček, J., Callegari, A., Hlavínek, P. (2019). Energy recovery from wastewater: A study on heating and cooling of a multipurpose building with sewage-reclaimed heat energy. Sustainability, 12(1): 116. https://doi.org/10.3390/su12010116
[16] Wehbi, Z., Taher, R., Faraj, J., Ramadan, M., Castelain, C., Khaled, M. (2022). A short review of recent studies on wastewater heat recovery systems: Types and applications. Energy Reports, 8: 896-907. https://doi.org/10.1016/j.egyr.2022.07.104
[17] Culha, O., Gunerhan, H., Biyik, E., Ekren, O., Hepbasli, A. (2015). Heat exchanger applications in wastewater source heat pumps for buildings: A key review. Energy and Buildings, 104: 215-232. https://doi.org/10.1016/j.enbuild.2015.07.013
[18] Bartnicki, G., Ziembicki, P., Klimczak, M., Kalitka, A. (2022). The potential of heat recovery from wastewater considering the protection of wastewater treatment plant technology. Energies, 16(1): 227. https://doi.org/10.3390/en16010227
[19] Fiore, S., Genon, G. (2014). Heat recovery from municipal wastewater: Evaluation and proposals. Environmental Engineering & Management Journal, 13(7): 1595-1604. https://doi.org/10.30638/eemj.2014.177
[20] Nourozi, B., Wang, Q., Ploskić, A. (2019). Maximizing thermal performance of building ventilation using geothermal and wastewater heat. Resources, Conservation and Recycling, 143: 90-98. https://doi.org/10.1016/j.resconrec.2018.12.025
[21] Abdel-Aal, M., Schellart, A., Kroll, S., Mohamed, M., Tait, S. (2018). Modelling the potential for multi-location in-sewer heat recovery at a city scale under different seasonal scenarios. Water Research, 145: 618-630. https://doi.org/10.1016/j.watres.2018.08.073
[22] Berariu, R., Butnaru, R., Condurache, G., Bertea, A.F. (2013). Studies on heat recovery from cellulosic textiles finishing wastewater. Environmental Engineering and Management Journal, 12(6): 1295-1300.
[23] Saagi, R., Arnell, M., Wärff, C., Ahlström, M., Jeppsson, U. (2022). City-wide model-based analysis of heat recovery from wastewater using an uncertainty-based approach. Science of the Total Environment, 820: 153273. https://doi.org/10.1016/j.scitotenv.2022.153273