

Enhancing Energy Efficiency through the Redesign of a Steam Condensate Recovery System in a Manufacturing Plant

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Abstract

Steam boilers are essential for heating in many manufacturing industries. In the plant studied, steam transfers heat to equipment such as blenders, additive tanks, and hot water systems during operation. This process produces condensate, which is nearly equal in volume to the steam supplied. Recovering and re-using this condensate is highly beneficial because it retains heat and reduces water consumption. However, most condensate is discharged directly into drains. This not only wastes the energy originally used to heat the boiler water but also harms the environment by releasing hot water into the drainage system. To address this issue, a condensate recovery system was designed and tested through simulations using Pipe Flow Expert and Festo Fluidsim software. The final system was implemented in a blending plant and featured optimized return pipelines from seven blenders and automated pump control. The recovered hot condensate is collected in a tank and returned to the deaerator for boiler feedwater. Validation through simulation and plant trials showed fuel savings of 15% and overall energy reductions of 30%. These results demonstrate that condensate recovery conserves energy, lowers emissions, and supports sustainable operations in line with UN Sustainable Development Goal 12.

Keywords

Steam Condensate Recovery System, Energy Efficiency, Heat Recovery, Industrial Sustainability, Boiler Fuel Savings

1. Introduction

Condensate recovery is an important practice in steam-based heating systems. In many plants, condensate is discharged to drains, resulting in significant energy and water losses. Recovering this condensate reduces waste, improves boiler efficiency, and lowers operational costs. This study focuses on a real case at a manufacturing plant with a blending facility. The plant uses steam boilers to heat blenders, additive tanks, and hot water systems. During heating, steam transfers latent heat to the equipment and condenses into hot water, known as condensate. The volume of condensate produced is almost equal to the steam supplied, making it valuable to recycle instead of discarding. The existing recovery system in the plant is manually operated and has several limitations. Only condensate from the additive tanks and hot water system is returned to the collection tank, while condensate from the blenders is drained away.

The aim of this study is to redesign and develop a more efficient condensate recovery system. Currently, several technologies are employed for steam condensate recovery. **Table 1** summarizes their strengths, limitations, and potential improvements. Mechanical recovery uses steam traps and pumps, which are simple and reliable but can fail under fluctuating loads [1] [2]. Flash steam recovery captures excess steam from hot condensate, improving efficiency but requiring precise control [2] [3]. Vacuum-based systems enhance condensate return in low-pressure areas but are costly to maintain [4] [5]. Automated systems with sensors and PLCs improve efficiency but require technical expertise [4]. Based on this review, the proposed design combines mechanical recovery with automated pump control using sensors and a PLC, providing a balance between efficiency, reliability, and cost-effectiveness.

Table 1. Technologies for steam condensate recovery.

Technology type	Comparative analysis				Ref.
	Description	Strength	Limitations	Potential improvements	
Mechanical recovery	Uses steam traps and pumps	Simple and reliable	Trap failure risk; less efficient under variable loads	Improved trap design; adaptive load control	[1]
Flash steam recovery	Captures flash steam from hot condensate	High energy recovery	Requires precise control; less effective in fluctuating conditions	Advanced control integration	[2]
Vacuum-based systems	Uses vacuum pumps in low-pressure areas	Effective in complex systems	High initial cost; complex maintenance	Simplified maintenance; lower cost	[4]
Automated control systems	Integrates sensors and PLCs	High efficiency; fast response	Expensive; requires skilled operation	Cost-effective, user-friendly design	[5]
Energy recovery systems	Focuses on recovering thermal energy	Very efficient; reduces operating costs	Integration challenges; limited scalability	Modular, scalable solutions	[3]

Recent studies highlight a wide range of technologies developed for condensate recovery in industrial systems. Commercial solutions such as the Power Trap,

TACTS, and Wolfram recovery systems have been applied across manufacturing and cogeneration plants to improve efficiency and reduce water losses. Noor *et al.* [3] (2020) demonstrated the use of membrane distillation for flue gas condensate treatment in municipal solid waste plants. It achieved separation efficiencies comparable to or better than reverse osmosis while utilizing available heat sources. In the building sector, Algarni *et al.* [6] (2018) reviewed HVAC condensate recovery. It emphasizing its role in water sustainability and energy management. Similarly, Kurniawan [7] (2017) investigated recovery methods for steam turbine surface condensers, showing that proper treatment can restore condensate quality to meet boiler feed-water requirements. Patented approaches such as Gluntz [8] (1996) also illustrate innovative strategies for water inventory management in condenser pools of boiling water reactors.

Overall, the literature demonstrates that condensate recovery systems provide multiple benefits, including improved boiler efficiency, reduced energy costs, and mitigation of environmental impacts [9]–[15]. These findings support the importance of the present study, which integrates mechanical recovery with automated pump control to offer a cost-effective and sustainable solution for medium-scale industrial applications.

2. Methodology

The methodology for this study was structured to systematically evaluate, redesign, and validate the steam condensate recovery system at the manufacturing blending plant. It began with a feasibility study of the existing system to identify inefficiencies and quantify the potential for energy and cost savings. The assessment included both process flow analysis and direct measurements of condensate characteristics such as temperature and pH.

Based on the findings, a new system layout was proposed to maximize condensate recovery from all seven blenders, incorporating improvements in piping, pumping, and control design. The proposed system was then subjected to detailed simulation and validation using two specialized software tools. Pipe Flow Expert was employed to model hydraulic performance, including flow rates, pressure drops, and pump operation under various scenarios, while Festo Fluidsim was used to simulate the control strategy for automated condensate transfer.

This combined approach ensured that the redesigned system was not only technically feasible but also optimized for energy efficiency, operational reliability, and sustainability before full-scale implementation.

2.1. Feasibility Study of the Existing System

The study began with a feasibility assessment of the current condensate recovery system. The goal was to understand how the boiler, deaerator, and seven blenders are connected, and to evaluate whether the condensate produced could be effectively recovered and reused. In the existing setup, steam generated at 110°C and 2.5 bar is supplied to seven blenders, additive tanks, and a hot water system. The

flow process for the current condensate recovery system is illustrated in **Figure 1**.

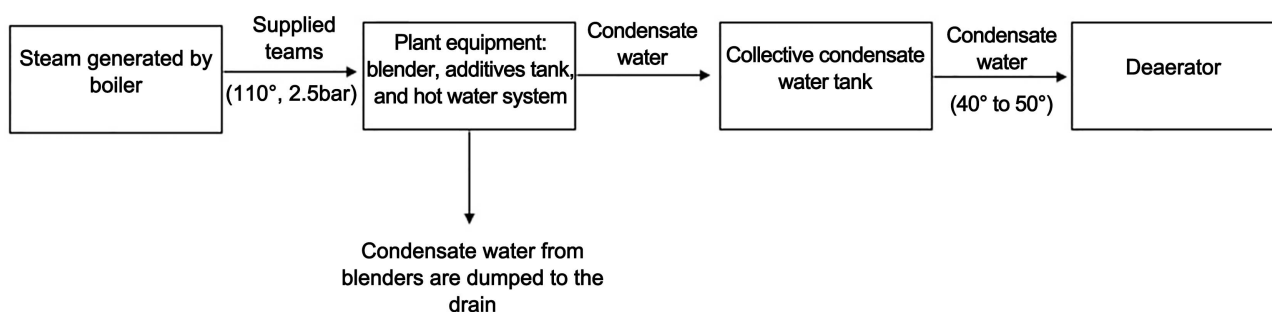


Figure 1. The flowchart for the current condensate water recovery system at the studied plant.

During heating, the steam condensed into hot water. Most of the condensate from the blenders is discharged directly into drains, while only condensate from the additive tanks and hot water system is collected and returned to the deaerator. The returned condensate typically reaches the deaerator at 40°C - 50°C, but large amounts of hot condensate are wasted. To assess recovery potential, samples of condensate discharged from the blenders were manually collected in 18 L pails. Field measurements were conducted using calibrated digital thermometers with an accuracy of $\pm 0.5^\circ\text{C}$ and portable pH meters with a precision of ± 0.05 . Data were recorded at 30-minute intervals during peak operation to capture representative system performance. Each sample was tested for temperature and pH, as illustrated in **Figure 2**. Results showed that condensate temperatures reached as high as 95°C, demonstrating significant potential for energy recovery.

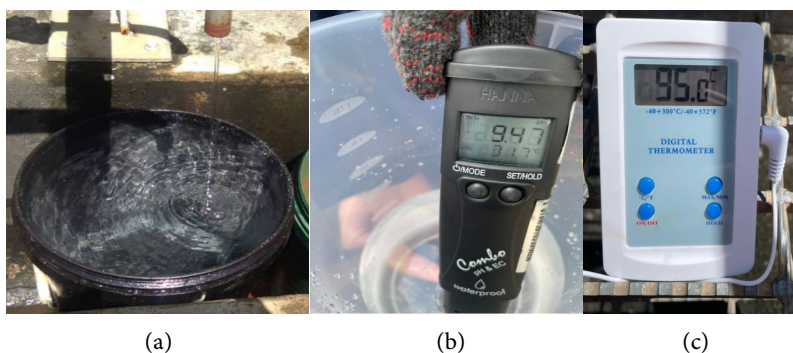


Figure 2. The feasible study on the steam condensate (a) the steam condensate discharged from each individual blenders are collected manually using 18 L pail, (b) PH tested on the water sample collected, (c) temperature for the sample water, shows 95 degree.

2.2. New Design Layout for The Condensate Recovery System

Based on the feasibility study, a new system layout was designed to recover condensate from all seven blenders as illustrated in **Figure 3**. The design includes three design considerations:

1) Condensate Header Integration

A 6-inch condensate header connects all blenders, directing condensate effi-

ciently to a central line instead of discharging it into drains. This ensures balanced flow and reduces localized pressure losses.

2) Automated Pumping and Control

A new pumping system with automatic control is integrated through a PLC. The pump is designed to manage both steam and hot water return while maintaining safe suction head ($NPSH_a > NPSH_r$). This minimizes cavitation risks and ensures reliable operation.

3) Condensate Conditioning and Return

The collected condensate, typically at 60°C - 100°C, is routed to the deaerator. There, it is mixed with treated water and preheated before returning to the boiler. Mechanical steam traps are installed at each blender outlet to prevent steam loss and maintain system pressure.

This design captures condensate from all blenders, retains heat quality, and reduces both water and fuel consumption. In addition, it standardizes the recovery process across all units, which simplifies maintenance and monitoring. The centralized header and automated control system also provide flexibility to handle varying production loads without compromising efficiency.

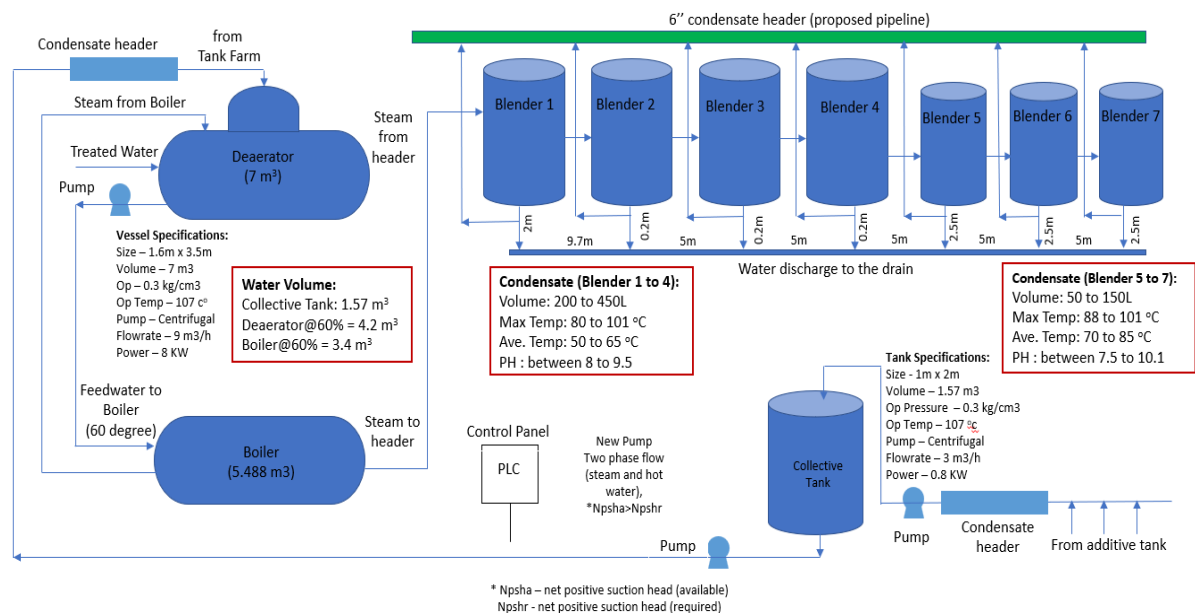


Figure 3. The new system layout that is designed to recover condensate from all seven blenders.

2.3. Simulation with Pipe Flow Expert

To validate the proposed design, simulations were carried out using Pipe Flow Expert software. This software models pipe networks, calculates flow rates, pressure drops, and pump performance, and helps identify system inefficiencies. Two blender groups were considered:

- **Blenders 1 - 4:** Capacity 200 - 450 L, condensate temperature 50°C - 65°C.
- **Blenders 5 - 7:** Capacity 50 - 150 L, condensate temperature 70°C - 85°C.

Simulation inputs included pipe specifications (diameter, roughness, length,

loss coefficients), flow data (mass flow, velocity, volume), and pressure conditions at each node. Energy losses from friction, fittings, and pumps were also analyzed. The results confirmed that the new layout could handle variable loads, maintain safe operating pressures, and minimize energy loss before implementation at full scale.

2.4. Control Design with Festo Fluidsim

The control system for transferring condensate from the collection tank to the deaerator was simulated using Festo Fluidsim. Circuit diagrams were developed to include pumps, valves, and sensors. The simulation tested two main operating states:

- For collection mode, the tank fills with condensate until it reaches a set level.
- For release mode, once the level is reached, valves open, and the pump transfers the condensate to the deaerator.

This simulation confirmed the functionality of automatic level control and reliable water transfer, reducing dependence on manual operation. It also demonstrated reliable water transfer, as the condensate was discharged to the deaerator at the correct timing and flow rate. This prevented overflow, dry running, and unnecessary interruptions. Through sensor-based actuation, the system reduced dependence on manual monitoring, minimized human error, and improved both safety and efficiency.

3. Results, Analysis and Discussion

3.1. Temperature and Water Quality Profiles

In the feasibility study, data collection was carried out to evaluate the operation and performance of the existing condensate recovery system. Key parameters recorded included the date, blender ID, blender size, blender capacity, condensate volume, pH, and temperature.

Measurements were taken over seven days across different blenders. On the first day, Blender 1 (15,000 - 43,000 L capacity) recorded a working volume of 29,648 L. It produced 289 L of condensate per blend, with a pH of 8.01. The maximum condensate temperature was 90.2°C, with an average of 55.2°C. On the second day, Blender 3 (9000 - 30,000 L) had a capacity of 10,068 L. It produced 207 L of condensate, with a pH of 9.78 and a temperature reaching 101°C, averaging 91°C.

In addition to temperature and pH, condensate quality parameters were analyzed to ensure suitability for boiler reuse. The measured values were as follows: total dissolved solids (TDS) < 50 ppm, hardness < 1 ppm, and final pH in the range of 8.0 - 9.8. These results comply with standard boiler feed-water specifications, which typically require TDS < 200 ppm, hardness < 2 ppm, and pH between 7.5 - 10 [2]. Compliance with these limits ensures that the recovered condensate can be safely returned to the deaerator without risk of corrosion or scaling.

Overall, these results revealed clear variations in blender capacity, condensate output, temperature and compliance parameter to provide a comprehensive over-

view of the system's operational characteristics. It gave valuable insights into daily conditions and confirmed the potential for performance improvements. Overall, the feasibility study established a solid foundation for redesigning the condensate recovery system to improve efficiency and effectiveness.

3.2. Pipe Flow Expert Simulation

The simulation results demonstrated clear improvements in the system's performance. The optimized design significantly reduced pressure drops across the network, which translates to lower pumping energy requirements. Flow rates were more evenly balanced, ensuring all sections of the system received adequate supply without overloading any individual component.

Data collected from the simulations confirmed that the redesigned system would operate more efficiently than the current configuration. Key improvements include:

- Reduced friction losses are noticeable indicating lower friction within the pipes. It leads to decreased energy consumption.
- Balance flow distribution with even flow rates across the system, preventing bottlenecks and enabling smooth operation.
- Stable pressure levels within optimal ranges, enhancing both reliability and component longevity.

Overall, the use of Pipe Flow Expert software proved invaluable in optimizing the condensate water recovery system. **Figure 4** shows the simulations of the new layout design, that verifies the proposed modifications would deliver a more efficient, reliable, and cost-effective solution. It supports the project's goal of improving system performance and reducing operational costs.

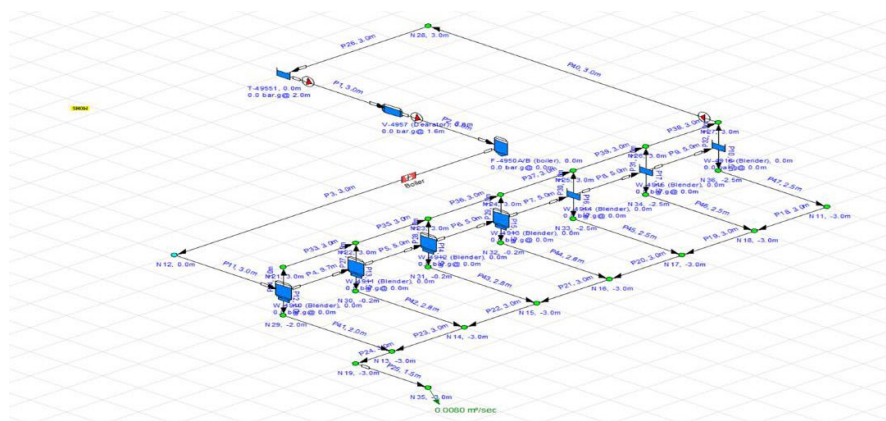


Figure 4. New layout design in pipe flow expert software.

In addition, multiple operating scenarios were tested to evaluate system performance. These simulations identified potential issues and improvement areas, ensuring the design is both robust and efficient prior to implementation. The design principles are as follows:

- Utilizes gravitational pressure flow from higher to lower elevations.

- Relies on pressure differences caused by height variations.

This approach ensures that the new design is fully evaluated and optimized before actual deployment, thereby increasing the reliability and efficiency of the condensate water recovery system. The sample of simulations results are as illustrated in **Figure 5**.

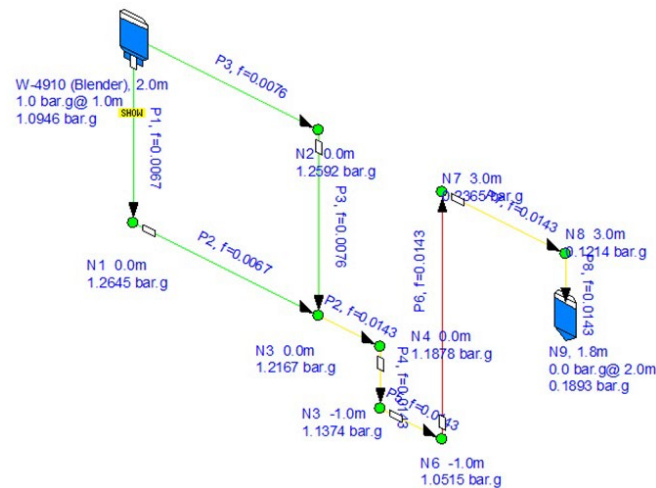


Figure 5. Simulation sample of the redesigned pipeline for Blender 4.

The simulation provided a detailed analysis of the redesigned system, covering flow rates, pressure profiles, pressure drops, friction losses, velocities, and overall efficiency. For example:

- Node N1: Entry pressure of 1.2645 bar (g) and exit pressure of 1.2167 bar (g).
- Pipe P2: Mass flow of 6.5005 kg/s, volumetric flow of 0.0067 m³/s, head loss of 0.208 m, and velocity of 2.127 m/s.
- Pipe P1: Pressure drop of 0.0478 bar.

The analysis confirmed that pressure drops remained within acceptable limits, with no adverse impact on system performance. Flow rates and velocities aligned with design specifications, ensuring effective fluid transport. Furthermore, the low friction losses demonstrated that the redesigned network successfully minimized energy wastage, improving overall system efficiency. The simulation results validated that the redesigned condensate water recovery system meets performance targets. The new layout improves efficiency, reduces energy losses, and maintains stable operating conditions, while also highlighting potential areas for refinement before implementation.

3.3. Fluidsim Control Simulation

The Festo Fluidsim model verified the reliability of the automated control system, as shown in **Figure 6** and **Figure 7** respectively. The simulation showed two clear operating states:

- 1) The condensate tank filled until a set water level was reached.
- 2) Once the threshold was met, valves opened, and the pump transferred con-

densate to the deaerator.

This control strategy proved effective in ensuring continuous operation without manual intervention. It also prevented risks such as overflow or underfeeding of the deaerator.

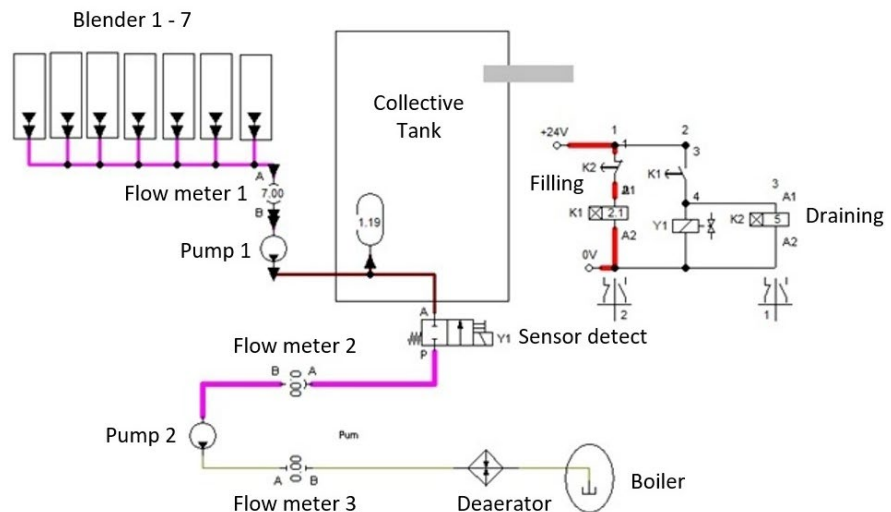


Figure 6. Fluidsim control simulation when collective tank collecting the condensate water condition.

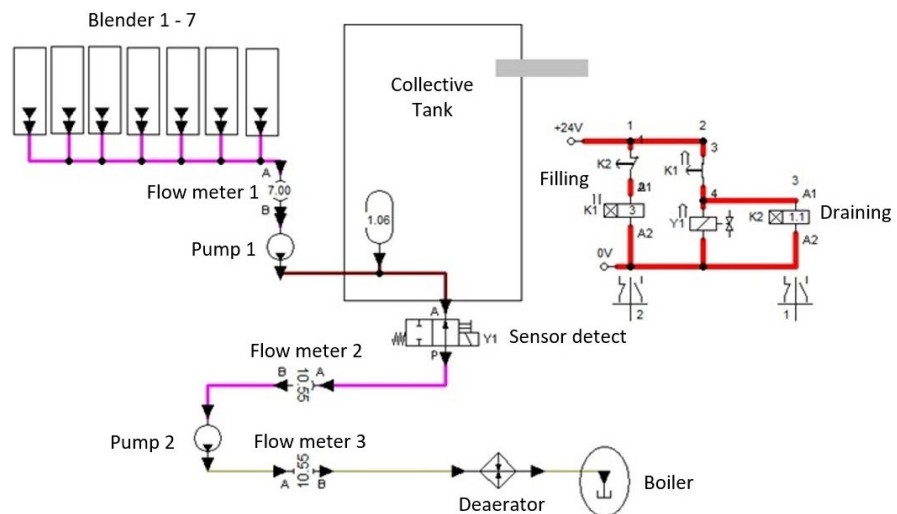


Figure 7. Fluidsim control simulation when collective tank releases the condensate water condition.

3.4. Cost and Energy Savings

The energy savings due to recovered heat were calculated using the following relationship:

$$\text{Energy saving} = Q_{\text{recovered}} \times (1/\eta_{\text{boiler}}) \quad (1)$$

where $Q_{\text{recovered}}$ is the amount of heat recovered and η_{boiler} is the boiler efficiency. This expression quantifies the reduction in additional energy required by

the boiler to generate steam. It highlights the efficiency improvement achieved through condensate recovery.

To demonstrate this effect, a simple enthalpy balance was performed. Heating 1 kg of condensate at 95°C to the boiler operating condition of 110°C requires approximately 62 kJ. In contrast, heating 1 kg of fresh make-up water from 30°C to 110°C requires about 293 kJ, based on standard steam table properties. This comparison shows that using recovered condensate reduces the heating energy demand by nearly 80%. When scaled to the plant's daily condensate flow, the saving translates into an overall ~30% reduction in energy consumption, consistent with industry-reported values.

The corresponding monetary savings can be expressed as:

$$C_{\text{recovered}} = \text{Energy saving} \times C_{\text{energy}} \quad (2)$$

where C_{energy} is the cost of energy per unit. By applying this relation, the energy savings are directly translated into economic terms. This confirms that recovered condensate not only improves thermal efficiency but also yields substantial reductions in operating costs.

The system's performance was evaluated based on actual plant data and cost analysis. **Table 2** summarizes the savings achieved.

Table 2. Cost saving summary based on the proposed design that are installed in the studied plant.

Table head	Actual plant data and cost analysis			
	Monthly		Annually	
	Volume	Cost (RM)	Volume	Cost (RM)
Water (m ³)	249.15	608.67	2989.82	7304.07
Diesel (L)	2085.88	7926.34	25030.55	95116.08
CO ₂ emission	5590.16	Not define	67081.87	Not define
Total saving (RM)	8535.01		102420.15	

These results confirm that condensate recovery reduces fuel use, improves boiler efficiency, and lowers operating costs. The environmental benefits are also significant, with reduced emissions of CO₂, NO_x, and SO_x, contributing to improved workplace safety and sustainability.

3.5. Overall System Performance

The combined experimental and simulation results highlight several important benefits of the redesigned condensate recovery system. One of the most significant improvements is efficiency: by returning condensate at higher temperatures, the energy required for reheating in the boiler is reduced. This directly translates into lower fuel and water consumption, making the system more cost-effective and allowing for a short payback period. Reliability is also enhanced through automated control, which minimizes the need for manual intervention and ensures

stable, consistent operation. In addition, the system contributes to sustainability goals by reducing both emissions and water wastage, aligning with broader environmental targets across the industry. Overall, the redesigned condensate recovery system effectively addresses the limitations of the previous configuration and delivers measurable gains in efficiency, cost savings, and environmental performance.

4. Conclusions and Future Work

This study successfully redesigned and implemented a steam condensate recovery system for a manufacturing blending plant, with results showing clear improvements in efficiency, cost savings, and sustainability. The new pipeline layout minimized frictional and pressure losses while maintaining condensate temperature, which reduced the energy required for reheating in the boiler. These efficiency gains translated directly into financial benefits, with estimated annual savings of about RM 100,000 achieved through lower water and diesel consumption. At the same time, the environmental impact was significantly reduced, as CO₂ emissions decreased, alongside reductions in NO_x and SO_x, contributing to cleaner and safer plant operations. System reliability also improved with the introduction of automated pumping and control, which eliminated reliance on manual operation and ensured consistent and safe condensate recovery.

Overall, the new design proved to be technically feasible, economically viable, and environmentally beneficial. It not only addressed the shortcomings of the previous setup but also demonstrated how optimized condensate recovery can enhance industrial efficiency while supporting broader sustainability goals.

While the redesigned condensate recovery system demonstrated significant improvements in efficiency and cost savings, certain limitations remain. The current design has been validated for medium-scale plant operations. To scale it to larger facilities may require additional measures such as enhanced pipe insulation, modular pumping systems, or advanced flow balancing. Furthermore, performance under highly fluctuating production loads may be affected by transient variations in condensate flow, potentially reducing recovery efficiency.

Looking ahead, several opportunities exist to further improve and expand the system. Full-scale validation across wider plant operations, combined with long-term monitoring under real industrial conditions, would strengthen performance assessment. Temperature retention could be enhanced by exploring the use of insulation and heat exchangers to minimize heat loss during storage and transfer. The integration of IoT-based smart monitoring would allow real-time tracking of condensate flow, temperature, and overall efficiency, while scalability studies could assess the adaptability of the design for larger facilities and other industrial applications. Finally, a full life-cycle sustainability assessment would provide a comprehensive evaluation of the long-term environmental and financial impacts.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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