



SMART WASTE HEAT RECOVERY IN TEXTILE DYEHOUSE

Professional paper
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ABSTRACT: Textile dyehouses are among the most energy-intensive manufacturing facilities due to their high steam and hot water demand. A considerable amount of thermal energy is lost through flash steam generated in condensate return systems, which is often discharged directly to the atmosphere. This study presents an automation-assisted flash steam recovery system developed for a textile dyehouse to improve waste heat utilization and reduce steam consumption. In the proposed configuration, flash steam is recovered through a plate heat exchanger and utilized for hot water production. A PLC-based control strategy dynamically manages the recovered energy according to process requirements by switching between cold water heating and hot water boosting modes. The hot water tank is additionally utilized as a thermal energy storage unit, enabling continuous utilization of recovered energy under varying operating conditions. The results demonstrate that the proposed approach effectively reduces steam demand and carbon emissions while improving overall energy efficiency. The study highlights the potential of combining flash steam recovery, thermal energy storage and intelligent control for sustainable energy management in textile dyehouses.

Keywords: Flash steam recovery, Waste heat recovery, Thermal energy storage, Energy efficiency, Textile dyehouse.

PAMETNO ISKORIŠĆENJE OTPADNE TOPLOTE U BOJADŽINICI TEKSTILA

APSTRAKT: Tekstilne bojadžinice spadaju među industrijske pogone sa najvećom potrošnjom energije zbog visokih zahteva za parom i toplom vodom. Značajna količina toplotne energije gubi se kroz fleš paru nastalu u sistemima povrata kondenzata, koja se u većini slučajeva ispušta direktno u atmosferu. U ovom radu predstavljen je automatizovani sistem za povraćaj energije iz fleš pare razvijen za tekstilnu bojadžinicu sa ciljem povećanja energetske efikasnosti i smanjenja potrošnje pare. Predloženi sistem koristi pločasti izmenjivač toplote za proizvodnju tople vode, dok PLC zasnovana upravljačka



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strategija dinamički upravlja povraćenom energijom u skladu sa potrebama procesa. Sistem automatski prelazi između režima zagrevanja hladne vode i povećanja temperature postojeće tople vode, pri čemu rezervoar tople vode istovremeno funkcioniše kao jedinica za skladištenje toplotne energije. Rezultati pokazuju da kombinacija povraćaja energije iz fleš pare, skladištenja toplotne energije i inteligentnog upravljanja predstavlja efikasno rešenje za smanjenje potrošnje energije i emisija ugljen-dioksida u tekstilnim bojadžinicama.

Ključne reči: *Povraćaj fleš pare, Povraćaj otpadne toplote, Skladištenje toplotne energije, Energetska efikasnost, Inteligentni upravljački*

1. INTRODUCTION

The textile industry is recognized as one of the most energy-intensive manufacturing sectors due to the substantial thermal energy required during wet processing operations such as dyeing, washing, rinsing and finishing. Particularly in textile dyehouses, large quantities of steam and hot water are continuously consumed to maintain process temperatures and ensure product quality. As a result, textile wet processing accounts for a significant portion of industrial energy consumption, water usage and greenhouse gas emissions [1]. In recent years, increasing energy costs and sustainability-driven production policies have intensified the need for efficient waste heat recovery strategies capable of reducing both operational expenses and environmental impacts.

A considerable amount of thermal energy supplied to textile dyehouses is discharged through wastewater streams, condensate return systems and vented steam losses. Consequently, numerous studies have investigated heat recovery opportunities in textile processes. Early studies mainly focused on recovering sensible heat from hot wastewater through process modifications and heat exchanger integration. Kiran-Ciliz [2] demonstrated that wastewater-based heat recovery systems can significantly reduce resource consumption and annual energy costs in textile wet processing applications.

Recent studies have further improved these approaches by integrating thermal energy storage, pinch analysis and heat exchanger network optimization into textile heat recovery systems. Seo et al. [3] proposed a heated water storage-supported recovery system for textile dyeing processes, while Zuberi et al. [4] emphasized the importance of thermal energy storage for batch-operated textile systems with fluctuating thermal demand. Similarly, Kim et al. [5,6] applied pinch analysis and heat pump-assisted heat exchanger networks to optimize wastewater heat recovery systems and reported substantial reductions in energy consumption and operational costs. Although these studies provide valuable contributions regarding process integration and energy optimization, the majority of existing textile literature primarily focuses on wastewater-based heat recovery systems. Compared with wastewater recovery applications, flash steam recovery from condensate systems has received relatively limited attention in textile-related studies. Flash steam is generated when high-pressure condensate is exposed to lower pressure conditions, causing



part of the condensate to re-evaporate. This secondary steam contains a considerable amount of recoverable thermal energy; however, in many industrial facilities it is either partially utilized or directly vented to the atmosphere due to the absence of continuous low-pressure steam demand [7,8]. Conventional flash steam recovery systems generally operate efficiently only when steam generation and process demand occur simultaneously. In batch-operated textile dyehouses, however, hot water demand varies continuously depending on production schedules, machine loading and process sequencing. Consequently, mismatches between fluctuating flash steam availability and intermittent process demand reduce overall recovery efficiency and limit the effective utilization of recovered energy.

The challenges associated with variable operating conditions have recently attracted increasing attention in industrial waste heat recovery research. Studies on dynamic waste heat recovery systems indicate that designs based solely on steady-state assumptions are insufficient for processes characterized by variable thermal loads [9]. Under such conditions, real-time monitoring, adaptive control strategies and short-term thermal energy storage become essential for improving operational stability and maximizing heat recovery performance.

Within this context, the present study proposes an automation-assisted dynamic flash steam recovery system specifically designed for textile dyehouses. In the proposed system, flash steam discharged from the condensate tank vent is separated and utilized through a plate heat exchanger for hot water production. Operational parameters such as temperature, flow rate and storage tank level are continuously monitored and controlled using temperature sensors, flowmeters and modulating control valves.

Unlike conventional flash steam recovery applications, the proposed system operates under two adaptive operating scenarios according to real-time process requirements. When hot water demand exists, cold make-up water is heated using recovered flash steam and supplied directly to the process. During periods of low or no demand, the recovered thermal energy is utilized to increase the temperature of the water already stored in the hot water tank. In this way, the storage tank functions not only as a passive reservoir but also as an active thermal energy storage unit capable of absorbing excess recovered energy.

The originality of this study lies in the integration of flash steam recovery, demand-responsive control and active thermal energy storage within a single textile dyehouse application. While previous textile studies have mainly focused on wastewater heat recovery systems and general industrial studies have investigated flash steam recovery separately [10,11], the combined implementation of condensate vent flash steam recovery with real-time automation and storage-supported energy management remains limited in the literature. Therefore, the proposed approach aims to address an important research gap by providing a flexible and scalable energy management solution capable of improving waste heat utilization, reducing steam consumption and supporting sustainable textile manufacturing practices.

2. METHOD

2.1. Conventional Condensate Handling System

The study was conducted in a textile dyehouse with an average steam consumption of approximately 2,200 tons per month. The steam system operates at a pressure of 7 bar, and condensate generated in the dyeing and washing processes is returned to the boiler house through a condensate collection network. Measurements showed that the condensate return flow rate was approximately 4 t/h, with an average condensate temperature of 90°C. Before the implementation of the proposed system, the condensate return line discharged directly into an atmospheric condensate tank. The pressure drop between the process equipment and the condensate tank caused a portion of the condensate to flash into steam. This flash steam was continuously vented to the atmosphere through the tank vent without any heat recovery.

As a result, a significant amount of thermal energy contained in the flash steam was lost. Figures 1(a), 1(b) and 1(c) show the condensate tank vent line and the flash steam released to the atmosphere under conventional operating conditions.

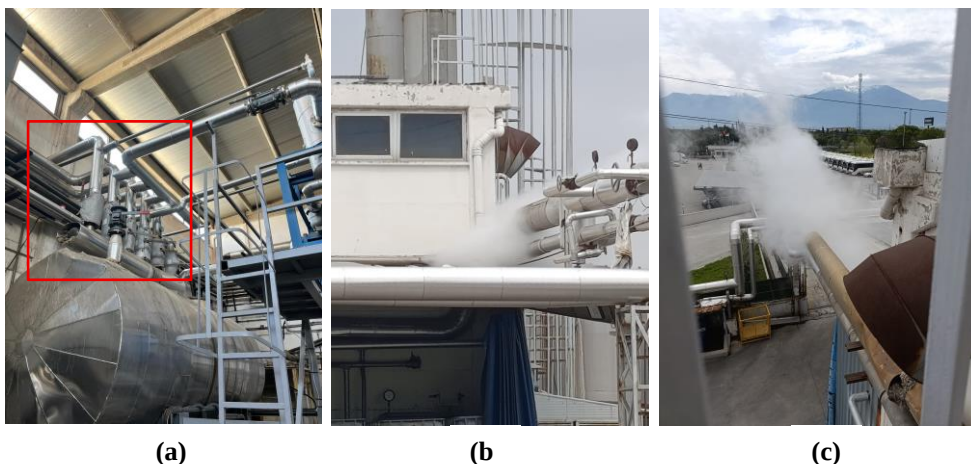


Figure 1: (a) Condensate tank vent line and (b), (c) flash steam discharged to the atmosphere before implementation of the recovery system.

2.2. Proposed Flash Steam Recovery System

To recover the thermal energy contained in the flash steam, a flash steam recovery system was installed between the condensate return line and the condensate collection tank. The proposed system consists of a flash tank, a plate heat exchanger, hot and process water storage tanks, temperature sensors, flowmeters, and PLC-controlled proportional valves. As shown in Figure 2, condensate returning from the production processes at approximately 90°C is first directed to a flash tank with a capacity of 6 t/h. Due to the pressure reduction inside the flash tank, a portion of the condensate is separated as flash

steam. The generated flash steam is then transferred to a plate heat exchanger, where its thermal energy is utilized for water heating.

The recovery system was designed to operate under two different heating scenarios according to process requirements. In the first scenario, cold make-up water supplied from the process water tank is heated from approximately 20°C to 65°C before being transferred to the hot water tank. In the second scenario, water already stored in the hot water tank is recirculated through the heat exchanger and heated from approximately 40°C to 85°C before being returned to the tank.

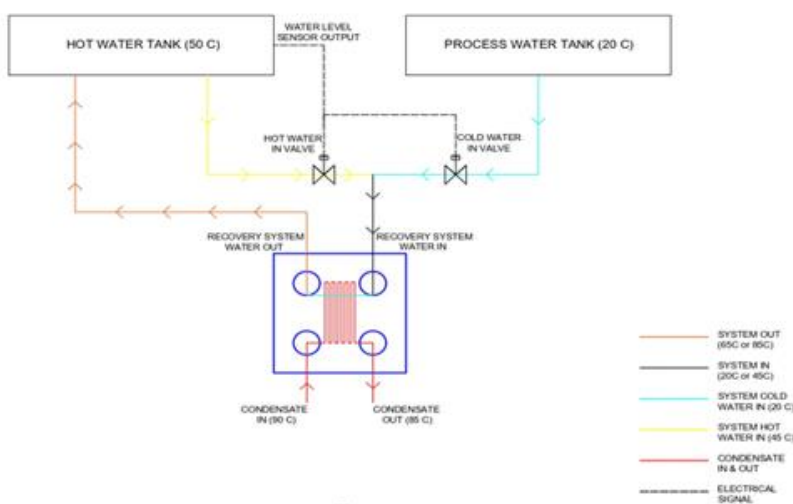


Figure 2: Schematic diagram of the proposed flash steam recovery system.

By enabling both operating modes, the system allows continuous utilization of recovered flash steam energy regardless of instantaneous hot water demand. In this configuration, the hot water tank functions not only as a storage unit but also as a thermal energy storage component capable of absorbing excess recovered energy.

2.3. Dynamic Control and Energy Management Strategy

Unlike conventional flash steam recovery systems, the proposed system was designed to operate dynamically according to real-time process conditions. A PLC-based control architecture was implemented to continuously monitor the hot water tank level, water temperatures and flow rates, and to automatically select the most appropriate operating mode.

The control strategy is based on the hot water tank level. When the tank level falls below 50%, the system operates in cold water heating mode. In this mode, make-up water



supplied from the process water tank is directed to the plate heat exchanger and heated from approximately 20°C to 65°C before being transferred to the hot water tank.

When the hot water tank level exceeds 80%, the system switches to hot water boosting mode. In this operating mode, water from the hot water tank is recirculated through the heat exchanger and heated from approximately 40°C to 85°C before being returned to the tank. This operating strategy enables the hot water tank to function as a thermal energy storage unit, allowing excess recovered energy to be stored for future process demands.

The outlet water temperature is continuously regulated through PLC-controlled proportional valves. Temperature measurements obtained from PT100 sensors are used as feedback signals to maintain the desired outlet temperature setpoint. Variations in flash steam generation caused by changes in condensate flow rate or production conditions are automatically compensated through valve modulation, ensuring stable system operation without operator intervention.

As a result, the developed control strategy enables continuous utilization of flash steam energy under varying production conditions while maximizing energy recovery efficiency and minimizing thermal energy losses.

2.4. Energy Recovery Calculation

The recovered thermal energy was calculated based on the measured water flow rates and temperature differences across the heat exchanger. The amount of recovered heat was determined using Equation (1):

$$Q = m \cdot c_p \cdot \Delta T \quad (1)$$

where Q is the recovered thermal energy (kJ), m is the mass of heated water (kg), c_p is the specific heat capacity of water (4.18 kJ/kg·°C), and ΔT is the temperature increase across the heat exchanger (°C).

The total recovered energy was calculated separately for the cold water heating mode and the hot water boosting mode and subsequently combined to determine the overall system performance. The equivalent steam savings were calculated by dividing the recovered thermal energy by the latent heat of saturated steam at the operating pressure of 7 bar, which was taken as 2050 kJ/kg [12].

In addition, the reduction in carbon emissions was estimated based on the annual steam savings achieved by the proposed recovery system. The calculated energy recovery, steam savings and emission reduction values were used to evaluate the technical performance of the developed flash steam recovery and energy management system.

3. RESULTS

3.1. Energy Recovery Performance

The proposed flash steam recovery system successfully utilized the thermal energy contained in the flash steam generated from the condensate return system. The recovered energy was used in two different operating modes: cold water heating and hot water boosting.



During the monitoring period, approximately 2,398 m³ of cold make-up water was heated from 20°C to 65°C, while 4,552 m³ of water from the hot water tank was heated from 40°C to 85°C. The corresponding energy recovery values are presented in Table 1.

Table 1: Energy recovery performance of the proposed system

Parameter	Value
Cold water heated (m ³ /month)	2,398
Hot water heated (m ³ /month)	4,552
Cold water heating energy recovery (kJ/month)	451,063,800
Hot water boosting energy recovery (kJ/month)	856,231,200
Total recovered energy (kJ/month)	1,307,295,000

The results indicate that the proposed system recovered approximately 1.31×10^9 kJ of thermal energy per month. Furthermore, approximately 65.5% of the total recovered energy was obtained during the hot water boosting mode. This finding highlights the importance of utilizing the hot water tank as a thermal energy storage unit. Without the storage-assisted operating mode, a significant portion of the recovered flash steam energy would remain unused during periods of low hot water demand.

3.2. Steam Saving Potential

To evaluate the impact of the recovered energy on boiler operation, the total recovered energy was converted into equivalent steam savings using the latent heat of saturated steam at 7 bar operating pressure (2050 kJ/kg).

The results are summarized in Table 2.

Table 2: Equivalent steam savings achieved by the proposed system

Parameter	Value
Latent heat of steam at 7 bar (kJ/kg)	2,050
Equivalent steam saving (ton/month)	638
Equivalent steam saving (ton/year)	7,652

The recovered thermal energy corresponds to approximately 638 tons of steam savings per month, equivalent to 7,652 tons annually. Considering that the facility consumes approximately 2,200 tons of steam per month, the proposed system reduced steam demand by nearly 29%.

This result demonstrates that flash steam discharged from condensate systems represents a substantial energy recovery opportunity in textile dyehouses. The achieved steam savings are particularly significant because they were obtained without modifications to the production process itself and solely through the recovery and intelligent management of waste thermal energy.

3.3. Environmental Impact and System Evaluation

The reduction in steam generation requirements directly decreased fuel consumption and associated greenhouse gas emissions. Based on the annual steam savings, the proposed system achieved an estimated reduction of 2,437 tons of CO₂ emissions per year.

Table 3: Environmental benefits of the proposed system

Parameter	Value
Annual steam saving (ton/year)	7,652
Annual CO ₂ reduction (ton/year)	2,437

Beyond the energy and environmental benefits, the developed system demonstrated stable operation under varying production conditions. The PLC-based control architecture continuously adjusted the operating mode according to hot water tank level and process requirements, ensuring that recovered flash steam energy was continuously utilized. The use of proportional control valves and temperature feedback from PT100 sensors enabled automatic compensation for fluctuations in flash steam generation without operator intervention.

Compared with conventional flash steam recovery applications, which typically depend on simultaneous heat demand, the proposed approach increased energy utilization by integrating dynamic control with thermal energy storage. This configuration minimized energy losses during low-demand periods and enabled continuous recovery of flash steam energy throughout plant operation.

4. CONCLUSION

This study demonstrated the feasibility of recovering flash steam energy from condensate tank vents in textile dyehouses through an automation-assisted energy management system. The proposed configuration combined flash steam recovery, thermal energy storage and dynamic process control within a single integrated framework.

The system recovered approximately 1.31×10^9 kJ of thermal energy per month, corresponding to an equivalent steam saving of 638 tons per month or 7,652 tons annually. Considering the facility's average monthly steam consumption of 2,200 tons, the recovered energy reduced steam demand by approximately 29%.

The results also showed that a significant portion of the recovered energy was utilized during the hot water boosting mode, demonstrating the effectiveness of using the hot water tank as a thermal energy storage unit. This approach enabled continuous utilization of flash steam energy even during periods of low process demand, thereby minimizing energy losses.

In addition to the energy savings, the proposed system achieved an estimated annual reduction of 2,437 tons of CO₂ emissions, contributing to the sustainability objectives of textile manufacturing. The PLC-based control architecture ensured fully automatic



operation and maintained stable performance under varying process conditions without requiring operator intervention.

Overall, the proposed approach offers a practical and scalable solution for improving energy efficiency in textile dyehouses by transforming an often-vented waste energy stream into a continuously usable thermal energy source through intelligent energy management.

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