OPTIMIZATION OF ENERGY EFFICIENCY IN BOILER OPERATIONS FOR SODIUM BICARBONATE PRODUCTION

ORIGINAL SCIENTIFIC ARTICLE

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DOI: 10.51558/2232-7568.2025.18.1-2.17

RECEIVED 2025-06-11
ACCEPTED 2025-08-25

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ABSTRACT:
Soda is a key raw material widely used in various industries, including food, pharmaceuticals, detergents, and glass production. At the "Sisecam Soda Lukavac" plant, soda is produced using the Solvay process, which relies on an aqueous solution of sodium chloride (NaCl) and calcium carbonate ($CaCO_3$). Due to the limited availability of global soda sources, efforts are being made to increase production capacity. However, higher production requires greater amounts of industrial water, resulting in increased consumption of fresh water from the Modrac reservoir. To reduce this consumption and minimize environmental impact, this study investigates the reuse of the waste condensate stream from the slaking drums as the aqueous solution of calcium hydroxide (lime milk) through the installation of a barometric condenser operating on the principle of direct contact between the cooling medium and steam. A barometric condenser was proposed for recovering approximately 8339.3 kg/h of steam, which would reduce water consumption by 7.58% and thermal energy losses by 29.3 %, with a payback period of less than six years. Reusing this waste condensate stream is expected to achieve significant operational, ecological, and economic improvements.

KEYWORDS: soda production, waste stream, condensate, water, reuse

INTRODUCTION

One of the most widely used sodium salts in daily life - both as a food additive and in personal care products, as well as across numerous sectors of the chemical industry - is sodium bicarbonate. Industrial-scale soda production began in the late 18th and early 19th centuries via the Le Blanc process. However, due to its technical and economic limitations, the Le Blanc method was gradually replaced during the second half of the 19th century by the more efficient Solvay process, developed by Ernest Solvay. The last factory using the Le Blanc process ceased operation in 1923 [7],[13].

Modern facilities, such as the Sisecam Soda Lukavac plant, employ the Solvay process to produce various grades of soda, including both light and dense soda ash, as well as technical, food-grade, and feed-grade sodium bicarbonate [1]. The primary raw materials used in the process are sodium chloride (NaCl) and calcium carbonate ($CaCO_3$). The overall chemical reaction that governs soda production is:

$$CaCO_3 \text{ (limestone)} + 2NaCl \text{ (brine)} \rightarrow Na_2CO_3 + CaCl_2$$

The reaction proceeds through intermediate compounds such as ammonium bicarbonate (NH_4HCO_3) and sodium bicarbonate ($NaHCO_3$), with ammonia serving as a recyclable auxiliary component in a closed-loop system. Similar findings on the conversion of trona to sodium bicarbonate have been reported by Cho [3], confirming the efficiency of intermediate bicarbonate reactions in soda production. Light soda produced by this method has a bulk density of approximately 470–600 kg/m³ and is primarily used in the manufacture of detergents and related chemical products [2]. The process involves saturating a concentrated NaCl solution with ammonia, followed by carbonation with CO_2 generated from the calcination of calcium carbonate. The resulting calcium oxide (CaO) is primarily used to prepare calcium hydroxide ($Ca(OH)_2$), a key reagent for regenerating ammonia.

The preparation of calcium hydroxide is a highly exothermic reaction, which produces large amounts of steam typically released into the atmosphere. In the interest of reducing fresh water usage and minimizing environmental emissions, industrial practice is increasingly focused on process optimization and waste stream recovery [4],[13].

This study aims to evaluate the feasibility and environmental benefits of reusing condensate generated in the slaking drums for calcium hydroxide preparation. This recovery can be achieved by installing a barometric condenser that operates on the principle of direct contact between secondary steam and a cooling medium (water). The integration of such a system could lead to significant cost savings, reduction in wastewater discharge, and overall improvements in the environmental performance of the plant.

MATERIALS AND METHODS

Raw Materials and Process Description

Calcium oxide (CaO), used as the main reactant for the preparation of calcium hydroxide ($Ca(OH)_2$) suspension (commonly known as lime milk), was sourced directly from on-site lime kilns. The CaO was transported to the slaking unit via enclosed belt conveyors to prevent moisture absorption and contamination. The chemical purity of calcium oxide used in the process was not less than 90%, with magnesium oxide (MgO) present in quantities below 2%. Given its low concentration, the influence of MgO on the process was considered negligible.

The slaking process was carried out in horizontal rotary slaking drums constructed from carbon steel with thermal insulation to minimize heat losses. Each drum operated at a rotation speed of 2–3 rpm and was equipped with spirally arranged internal paddles to ensure homogeneous mixing and horizontal material transport. Water was preheated to a temperature range of 50–65°C and was introduced together with CaO through a centrally positioned pipe at the front end of the drum. The slaking reaction is exothermic, raising the slurry temperature to between 95–98°C.

The following chemical reactions occurred during the process:

$$CaO + H_2O \rightarrow Ca(OH)_2 \ (+Q)$$
$$MgO + H_2O \rightarrow Mg(OH)_2 \ (+Q)$$

The secondary reaction involving MgO was excluded from further energy and mass balance calculations due to its minor contribution.

Equipment and Separation Method

At the discharge end of each slaking drum, a separation drum was installed, composed of a concentric cylindrical screen (mesh size 2–3 mm) for separating coarse residues. The process yielded three distinct fractions: residual stones, fine sand, and a calcium hydroxide slurry. Solid fractions were mechanically transported to the separator using internal paddles, while the lime slurry overflowed from the drum and was directed to a storage tank before further use in the ammonia recovery section.

The separated stones were recycled and mixed with fresh calcium carbonate for re-calcination, whereas the sand, classified as waste, was directed to waste grinding units. To minimize the presence of abrasive particles in the final slurry which could damage downstream equipment - vibrating screens were employed for additional purification of the lime milk. Moist steam released from the upper section of the slaking drum was captured and occasionally condensed using simple water-injection spray condensers positioned above the separation unit. The warm condensate-enriched water could then be reused as slaking water.

Mathematical Process Description and System Definition

Based on the technical configuration described above, a process flow diagram was developed, including all relevant components: the rotary slaking drum, feed tanks for CaO and water, and output reservoirs for the final $Ca(OH)_2$ product. An informational schematic was also constructed to support the formulation of mass and energy balance equations. This diagram defines key process variables (e.g., mass flows, temperatures, enthalpies) required to simulate the system and to calculate operational efficiency (Figure 1).

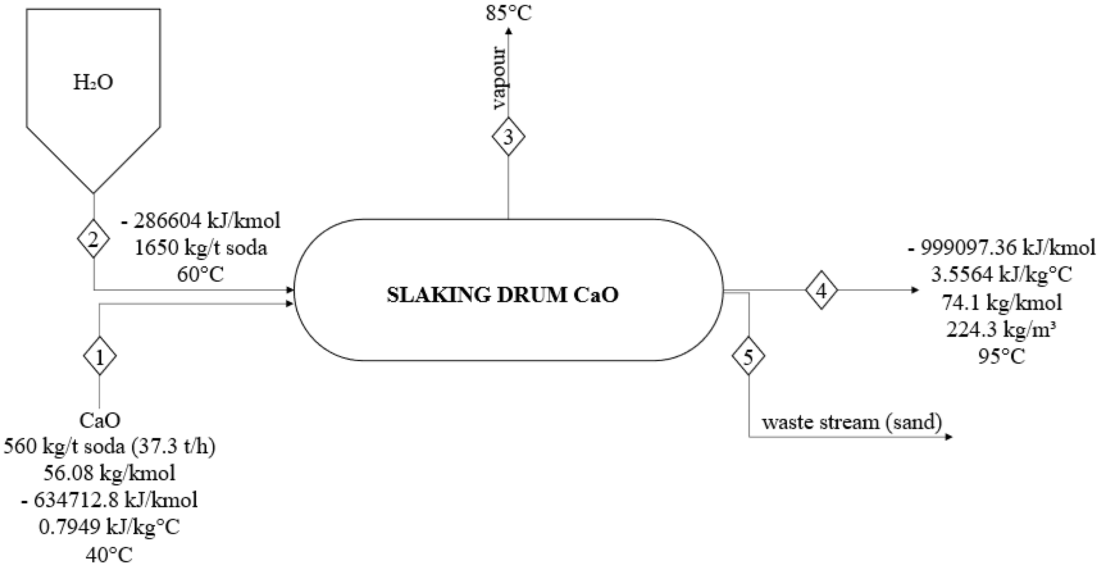

Figure 1. Process (information) diagram of calcium hydroxide aqueous solution production

The accuracy of the mathematical model relies on experimentally measured input parameters, including: feed rate of CaO (kg/h), water consumption rate (m^3/h), slurry temperature at exit (°C), condensate temperature, steam generation rate. Standard approaches to heat and mass balance in chemical engineering processes are described in detail by Jaćimović & Genić [5], which provided the theoretical foundation for the applied methodology.“

RESULTS AND DISCUSSION

Mass and Energy Balance for Lime Milk Production

To quantitatively evaluate the efficiency of the lime milk production process, a complete material and energy balance was performed based on a daily soda ash production of 1600 tons. The total mass balance equation was formulated as follows (Equation 1):

$m_{CaO}+m_{H_2O}=m_{Ca(OH)_2}+m_{pp}$ .... (1)

where: m_{CaO} – mass of calcium oxide, m_{H_2O} – mass of water, $m_{Ca(OH)_2}$ – mass of calcium hydroxide, m_{pp} – mass of generated steam.

The heat balance equation:

$$m_{CaO}\cdot h_{CaO}+m_{H_2O}\cdot h_{H_2O}+Q_R=m_{Ca(OH)_2}\cdot h_{Ca(OH)_2}+m_{pp}\cdot H_k, \qquad (2)$$

where: h_{CaO}, h_{H_2O}, $h_{Ca(OH)_2}$ – standard enthalpies of the respective substances, H_k – is the enthalpy of steam condensation and Q_R – heat released by the reaction. Thermodynamic data for enthalpies and reaction heat were taken from Ražnjević [8].

Based on raw material inputs, approximately 110 m^3/h of water is required for lime slaking, equivalent to 1650 kg per ton of soda produced. From the input of 1850 tons of $CaCO_3$ daily, the derived mass of CaO is calculated to meet the stoichiometric need for 1600 tons of Na_2CO_3 production, or approximately 560 kg CaO per ton of soda (Equation 3).

$m_{(CaO)}=\frac{1850}{2.067}=895.01$ t/d .... (3)

The concentration of the lime milk produced was determined to be 224.3 kg_{CaO}/m^3. Accordingly, the required volume of lime milk per ton of soda is approximately 2.49 m^3 (Equation 4).

$v=\frac{m_{CaO}}{\rho_{CaO}}=\frac{560}{224.3}=2.49\ m^3$ .... 4)

The residual content of $CaCO_3$ in the lime milk, obtained from lab analysis, was 37.29 kg_{CaO}/m^3, which influences the overall purity of the slurry (Equation 5).

m_{CaCO_3}=37.29 kg/m^3· 2.49 m^3= 92.85 93.25 kg, ... (5)

To solve for $m_{Ca(OH)2}$ system of equations combining the mass and energy balances was constructed. The amount of generated steam, essential for assessing potential for heat recovery, was derived through Equation 6–9, based on the reaction enthalpy (Equation 7) and molar conversion data (Equation 8).

$$\mathrm{m_{CaO}} \cdot \mathrm{h_{CaO}} + \mathrm{m}_{H_2O} \cdot \mathrm{h}_{H_2O} + \mathrm{Q_R} = \mathrm{m}_{Ca(OH)_2} \cdot \mathrm{h}_{Ca(OH)_2} + (\mathrm{m_{CaO}} + \mathrm{m_{H2O}} - \mathrm{m}_{Ca(OH)_2}) \cdot \mathrm{H_k} \quad (6)$$

$$\Delta H_{reaction} = \sum H_{products} - \sum H_{reactants} = -\ 77832.6\ \mathrm{kJ/kmol} \quad (7)$$

$$\mathrm{n} = \frac{\mathrm{m}_{Ca(OH)_2}}{\mathrm{Mr}_{Ca(OH)_2}} = 10.698\ \mathrm{kmol} \ldots\ldots\ldots\ldots (8)$$

$$\mathrm{Q_R} = 77832.6\ \mathrm{kJ/kmol} \cdot 10.698\ \mathrm{kmol} = 832653.1\ \mathrm{kJ}\ (9)$$

By solving the system of balance equations, the obtained mass of Ca(OH)$_2$ is: $m_{Ca(OH)_2}$ = 2542 kg/t$_{\mathrm{soda}}$.

From these calculations, the heat released during the slaking process and the thermal content of both CaO and water (Equations 10–13) were incorporated to yield a total incoming heat value of approximately1264676.2 kJ. The heat content of the produced lime milk was computed at 370690.7 kJ (Equations 14–16). At 98°C, the resulting amount of steam per ton of soda was determined to be 138.5 kg (Equation 17).

Furthermore, the heat contained in CaO is calculated according to the following equation:

$$\mathrm{Q_{CaO}} = \mathrm{m} \cdot \mathrm{C_p} \cdot \Delta\mathrm{T}, \ \ldots\ldots\ldots\ldots \quad (10)$$

$$\mathrm{Q_{CaO}} = 560\ \mathrm{kg} \cdot 0.7949\ \mathrm{kJ/kg°C} \cdot 40°\mathrm{C} = 17807.1\ \mathrm{kJ} \quad (11)$$

$$\mathrm{Q}_{H_2O} = 1650\ \mathrm{kg} \cdot 4.184\ \mathrm{kJ/kg°C} \cdot 60°\mathrm{C} = 414216\ \mathrm{kJ} \quad (12)$$

$$\mathrm{Q_{uk}} = \mathrm{Q_R} + \mathrm{Q_{CaO}} + \mathrm{Q}_{H_2O} = 1264676 \ldots\ldots\ldots\ \mathrm{kJ} \quad (13)$$

$$\mathrm{Q}_{Ca(OH)_2} = 2542\ \mathrm{kg} \cdot 3.5564\ \mathrm{kJ/kg°C} \cdot 98°\mathrm{C} = 885956.1\ \mathrm{kJ} \quad (14)$$

$$\mathrm{Q}_{CaCO_3} = 93.25\ \mathrm{kg} \cdot 0.8786\ \mathrm{kJ/kg°C} \cdot 98°\mathrm{C} = 8029.4\ \mathrm{kJ} \quad (15)$$

$$\mathrm{Q_{steam}} = \mathrm{Q_{uk}} - \mathrm{Q}_{Ca(OH)_2} - \mathrm{Q}_{CaCO_3} = 370690.7\ \mathrm{kJ} \ldots\ldots \quad (16)$$

$$\mathrm{m_{steam}} = \frac{\mathrm{Q_{steam}}}{\Delta\mathrm{H_{cond}}} = \frac{370690.7}{2666.33} = 139.02\ \mathrm{kg_{steam}/t_{soda}} \ldots\ldots\ldots \quad (17)$$

When scaled to a daily production of 1600 tons, this corresponds to 222.4 t/d or 9266.6 kg/h of steam without losses. Assuming a 10% loss factor, the effective amount of recoverable steam is 8339.9 kg/h (Equations 18–19).

$$m_{losses} = 9266.6 \cdot 0.1 = 926.66\ \mathrm{kg/h} \ldots\ldots\ldots\ldots (18)$$

$$m_{steam} = 9266.6 - 926.66 = 8339.9\ \mathrm{kg/h} \ \ldots\ldots\ldots (19)$$

Design and Thermal Performance of the Barometric Condenser

To utilize the steam waste stream, a barometric condenser was evaluated for its ability to condense steam via direct contact with cooling water. Key input parameters are listed in Table 1, including steam flow rate, water inlet/outlet temperatures, pressures, and specific enthalpies.

Table 1. Basic data for the calculation of the barometric condenser (BK)

Parameter	Symbol	Value	Unit
Mass of steam condensed in the barometric condenser	M_{sup}	8339.9	kg/h
Steam temperature	t_{sup}"	85	ºC
Cooling water temperature – inlet to the condenser	t_{ul}	25	ºC
Cooling water temperature – outlet from the condenser	t_{iz}	35	ºC
Ambient pressure	p	1	bar
Steam pressure	p_{sup}	0.085	bar
Specific enthalpy of steam	i"	2640.1	kJ/kg
Specific heat capacity of cooling water	c	4.184	kJ/kg
Cooling water density – inlet to the condenser	ρ	996.23	kg/m^3

Using Equations 20–21, the required cooling water mass and volumetric flow rates were computed. For the assumed steam velocity w_{sup}= 15 m/s, the condenser diameter was optimized to 1900 mm (Equation 22), and plate spacing parameters were derived accordingly (Equation 23).

$$M_w = \frac{M_{sup} \cdot \left(i'' \text{-} c \cdot t_{iz}\right)}{c \cdot \left(t_{iz} \text{-} t_{ul}\right)} = \frac{8339.9 \cdot (2640.1 \text{-}\ 4.184 \cdot 35)}{4.184 \cdot (35\text{-}25)} = 497057.2 \text{ kg/h} \quad (20)$$

$$V_w = \frac{M_w}{\rho} = \frac{493964.8}{996.23} = 498.9 \ \ \text{m}^3\text{/h} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (21)$$

$$d_{BK} = \sqrt{\frac{4 \cdot M_{sup} \cdot v''_{sup}}{3600 \cdot \pi \cdot w_{sup}}} = \sqrt{\frac{4 \cdot 8339.9 \cdot 17}{3600 \cdot \pi \cdot 15}} = 1.8288 \text{ m} \quad \ldots\ldots\ldots \quad (22)$$

$$l_{BK} = \frac{d_{BK}}{2} + 50 = \frac{1900}{2} + 50 = 1000 \text{ mm} \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (23)$$

Equations 24 - 28 were used to determine the water layer height, flow velocities, overflow thickness, and equivalent diameter, which are critical to efficient heat exchange. Thermal calculations (Equations 29–32) established the outlet water temperature and heat exchange at each plate.

$$h = \left(\frac{M_w}{0.42 \cdot d_{BK} \cdot \sqrt{2 \cdot g}}\right)^{2/3} = \left(\frac{0.13807}{0.42 \cdot 1.9 \cdot \sqrt{2 \cdot 9.81}}\right)^{2/3} = 0.1151 \text{ m} \ldots \quad (24)$$

$$w_o = \frac{V_w}{3600 \cdot d_{BK} \cdot \text{h}} = \frac{498.9}{3600 \cdot 1.9 \cdot 0.1151} = 0.6385 \text{ m/s} \ldots\ldots\ldots\ldots\ldots\ldots \quad (25)$$

$$w_{sr} = \frac{w_o + \sqrt{w_0^2 + 2 \cdot g \cdot H}}{2} = \frac{0.6385 + \sqrt{0.6385^2 + 2 \cdot 9.81 \cdot 0{,}6}}{2} = 2.238 \ \ \text{m/s}. \quad (26)$$

$$\delta = \frac{V_w}{3600 \cdot w_{sr} \cdot d_{BK}} = \frac{498.9}{3600 \cdot 2.238 \cdot 1.8288} = 0.0388 \ \ \text{m} \ \ldots\ldots\ldots\ldots\ldots \quad (27)$$

$$\mathrm{d}_{\mathrm{ek}} = \frac{2 \cdot \mathrm{d}_{\mathrm{BK}} \cdot \delta}{\mathrm{d}_{\mathrm{BK}} + \delta} = \frac{2 \cdot 1.8288 \cdot 0.0388}{1.8288 + 0.0388} = 0.0759 \ \ \text{m} \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (28)$$

$$c_o = 0.029 \cdot \left(\frac{d_{ek} \cdot g}{w_{sr}^2}\right)^{0.2} \cdot \left(\frac{H}{d_{ek}}\right)^{0.7} = 0.029 \cdot \left(\frac{1.8288 \cdot 9.81}{2.238}\right)^{0.2} \cdot \left(\frac{0.6}{0.0759}\right)^{0.7} = 0.1868 \quad (29)$$

$$c_o = \log\left(\frac{t_{sup} \text{-} t_{ul}}{t_{sup} \text{-} t_2}\right) = 0.1973 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (30)$$

$$\mathrm{c} = 10^{\mathrm{c_o}} = 10^{0.1973} = 1.575 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (31)$$

$$t_I = \frac{c \cdot t_{sup} - \left(t_{sup} - t_{ul}\right)}{c} = \frac{1.575 \cdot 85 - (85 - 25)}{1.575} = 46.9°\text{C} \ldots\ldots \quad (32)$$

$$Q_I = \frac{M_w \cdot c \cdot \left(t_I \text{-} t_{ul}\right)}{3600} = \frac{497057.24 \cdot 4.184 \cdot (46.9\text{-}25)}{3600} = 12651.43 \ \ \text{kW} \quad (33)$$

$$M_{kond} = \frac{Q_I}{i'' \text{-} c \cdot t_{II}} = \frac{12651.43}{2640\text{-}4.1863 \cdot 46.9} = 5.176 \text{ kg/s} \ \ldots\ldots\ldots\ldots\ldots \quad (34)$$

$$M_I = \frac{M_w}{3600} + M_{kond} = \frac{497057.24}{3600} + 5.176 = 143.24 \text{ kg/s} \ \ldots\ldots \quad (35)$$

Based on the calculations (Equations 20–35), a cooling water flow rate was sized to support condensation of 8339.9 kg/h of steam with only one contact plate. This simplicity contributes to ease of installation and reduced maintenance. Previous studies support the use of barometric condensers in similar exothermic processes where waste steam is present at low pressures [13].

The condenser design indicated that one contact plate was sufficient (Equation 36), with a required 4958 nozzles (Equation 37) to ensure complete vapor-liquid contact. The barometric downpipe design, based on Equations 38–40, confirmed feasibility using a 609.4 mm internal diameter pipe.

$$n_r = \frac{log\left(\frac{t_{sup} \text{-} t_{ul}}{t_{sup} \text{-} t_{iz}}\right)}{log\left(\frac{t_{sup} \text{-} t_{ul}}{t_{sup} \text{-} t_{II}}\right)} = \frac{\log\left(\frac{85\text{-}25}{85\text{-}35}\right)}{\log\left(\frac{85\text{-}25}{85\text{-}46.9}\right)} = 0.401 \quad (36)$$

$$n_{otv} = \frac{W}{0.1} = \frac{498.9}{0.1} = 4989 \quad (37)$$

$$d_{cr} = \sqrt{\frac{4 \cdot \left(M_w + M_{sup}\right)}{3600 \cdot \pi \cdot w_{cij} \cdot \rho}} = \sqrt{\frac{4 \cdot (497057.24 + 8339.9)}{3600 \cdot \pi \cdot 0.6 \cdot 996.23}} = 0.546 \text{ m} \quad (38)$$

$$\mathrm{w}_{\mathrm{cr}} = \frac{4 \cdot \left(M_w + M_{sup}\right)}{3600 \cdot d_{cr}^2 \cdot \pi \cdot \rho} = \frac{4 \cdot (497057.24 + 8339.9)}{3600 \cdot \left(\frac{609.4\text{-}20}{1000}\right)^2 \cdot \pi \cdot 996.23} = 0.51 \text{ m/s} \quad (39)$$

$$H_I = 10.36 \cdot \left(p \text{ -} p_{sup}\right) = 10.33\text{-}(1 \text{ - } 0.085) = 9.445 \text{ m} \quad (40)$$

Design parameters such as nozzle count, water film thickness, and pipe dimensions were optimized to ensure stable flow, effective condensation, and temperature control of the outgoing water. This aligns with findings reported by Posavec [6], who demonstrated that similar condensers can recover over 90% of latent heat from low-pressure process steam. Also such design considerations are consistent with process design methodologies reported by Šef & Olujić [9].

Economic and Environmental Impact

The integration of a barometric condenser into the lime milk production section offers both technical and economic benefits. The recovery of low-pressure process steam, which otherwise escapes into the atmosphere, enables significant thermal savings and reduces fresh water demand. According to recent studies, direct-contact condensers operating under optimized conditions can achieve more than 95% efficiency in steam condensation and heat recovery, particularly in industries with high water usage such as soda ash, pulp, and textile manufacturing [10],[11]. By redirecting the condensate into the process — either for reuse in lime slaking or as boiler feedwater — the system reduces the operational need for raw water intake, which directly impacts water sourcing costs and aligns with sustainable water use goals. In addition, minimizing heat losses through steam recondensation supports the broader industrial objective of reducing the carbon footprint of energy-intensive operations. Nguyen and Kim showed that integration of condensate recovery in industrial steam networks can reduce fuel consumption by up to 18% and water demand by up to 25% [12].

In the context of the Sisecam Soda Lukavac facility, the calculated amount of condensable steam from the slaking drums (approximately 8339.9 kg/h after losses) represents a valuable energy stream. Using barometric condensation technology, this energy can be recovered in a compact system that requires minimal mechanical components and maintenance. The reuse of the resulting warm condensate has additional benefits — particularly when used as preheated slaking water, which improves process thermal stability and reaction kinetics.

Furthermore, the environmental impact of steam emissions is not negligible. Released steam can carry trace contaminants, contribute to local humidity fluctuations, and generate visible plumes that may be subject to regulatory constraints. Closed-loop condensation not only prevents such releases but also reduces thermal pollution, helping meet environmental compliance standards [12].

From a financial perspective, the initial investment in the barometric condenser system (estimated at 41 000 KM) is offset by annual savings in water procurement and operational efficiency. Given an estimated savings of over 10 000 KM/year, the system achieves a return on investment in less than six years, which is consistent with findings in similar implementations in the chemical sector [10]. When broader environmental and resource conservation benefits are included, the long-term value of such integration becomes even more significant.

Ultimately, the adoption of such heat and water recovery systems reflects a shift toward circular process design and industrial symbiosis, where waste streams are re-evaluated as resources. This philosophy is increasingly supported by sustainability frameworks and ISO standards for energy and water management in process industries.

CONCLUSION

The results of this study demonstrate that integrating a barometric condenser into the lime milk production process in soda ash manufacturing can lead to significant improvements in energy efficiency, water conservation, and environmental performance. The condensation and reuse of steam generated during the slaking of calcium oxide not only reduce the demand for fresh industrial water - which is both costly and ecologically sensitive - but also recover valuable thermal energy that would otherwise be lost to the atmosphere.

Quantitative analysis confirmed that more than 220 tons of steam are produced daily during lime slaking, of which approximately 8.3 tons per hour can be recovered even after accounting for process losses. Reusing this condensate as preheated slaking water or boiler feedwater contributes to lower energy input requirements and enhances process stability.

Economically, the estimated payback period of 5.7 years makes the proposed condenser system a viable investment, particularly in light of rising energy and water costs. From an environmental standpoint, the closed-loop operation minimizes steam emissions and aligns with sustainable industrial practices and circular economy principles.

Moreover, the analysis reflects current trends in modern chemical engineering that emphasize integrated resource recovery and system-wide efficiency improvements. By adopting this approach, soda production facilities can not only reduce their ecological footprint but also enhance operational resilience and cost-effectiveness.

Therefore, the implementation of a barometric condenser in this context represents a technically sound, economically feasible, and environmentally responsible solution for modernizing the soda ash production process.

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