

Evaluation of Energy Saving and Environmental Protection Effect of Heat Pump for Heating Make-up water for Industrial Boilers

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ABSTRACT

This paper investigates the integration of heat pumps for heating boiler feedwater and evaluates the impacts of feedwater temperature and condensate recovery rates on fuel consumption, energy efficiency, and CO₂ emissions. The results show that using heat pumps significantly reduces boiler fuel consumption, especially when the feedwater temperature increases and the condensate recovery rate is high. In terms of energy, the cost of heat pumps for water heating is significantly lower than that of fuel combustion. With a boiler without condensate recovery, the maximum cost of heat pumps is only about 50% of that of fuel combustion. Economically, heat pumps provide substantial benefits, with maximum cost savings achieved at a water temperature of 75°C. On average, a 10% reduction in the condensate recovery rate, the cost saved in 1 hour is 2000 VND/ton of steam. Additionally, integrating heat pumps reduces CO₂ emissions, particularly in boilers without condensate recovery, with the highest emission reduction reaching 17.8 kgCO₂/ton of steam. These findings demonstrate that using heat pumps is not only energy-efficient and cost-effective but also contributes to environmental protection by reducing greenhouse gas emissions.

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1. Introduction

Boilers are crucial devices in the industry, with the primary function of generating high-pressure steam for heating in various technological processes through fuel combustion. The fuel used for boilers includes sources derived from fossil fuels and biomass.

Boilers are high-power energy conversion devices, so improving conversion efficiency to save energy and protect the environment is a matter of significant concern. Enhancing boiler thermal efficiency involves waste heat recovery and combustion process optimization, two feasible solutions that have long been applied in practice. The primary heat loss from boilers, emitted exhaust gas, is widely utilized in heating feed water, heating air, or preheating fuel. Combustion process optimization has also been explored by improving furnace design, grates, combustion methods, and air supply.

Condensate recovery is also an energy-saving solution. Depending on the technological characteristics, the condensate recovery rate varies. Higher recovery rates of high-temperature condensate lead to lower fuel consumption for the boiler. Conversely, lower recovery rates mean that more fuel is needed to preheat the make-up water.

Thus, it can be seen that improving boiler efficiency has been extensively studied. The remaining issue with modern boilers is the environmental impact. Fuel combustion in boilers can cause environmental issues if not properly controlled. When fuel is burned, emissions such as CO₂, SO₂, NO_x, and fine particulate matter may be released into the air, contributing to air pollution and climate change. Therefore, environmental protection in boiler use is of utmost importance. Environmental measures include using cleaner fuels like natural gas or biomass, advancing combustion technology to minimize emissions, and implementing modern dust filtration and exhaust treatment systems.

In recent years, considerable research has focused on co-firing biomass with fossil fuels in fossil fuel boilers to reduce greenhouse gas emissions. However, the practical application of this technology has been limited due to some unresolved technical issues.

Heat pumps are commonly used heating devices, often utilized in applications such as space heating and hot water supply. The energy efficiency of heat pumps is significantly higher compared to electric resistance methods. According to manufacturers' specifications, the Coefficient of Performance (COP) of heat pumps ranges from 4 to 8, depending on condensation temperature and ambient temperature. However, a disadvantage of heat pumps is that they only operate efficiently within a low-temperature range. Compared to primary energy sources like fuel, heat pumps still offer better energy efficiency, even though they are powered by electricity. Given that the average efficiency of power plants is around 40%, approximately 2.5 kW of heat is required to produce 1 kW of electricity. When using 1 kW of electricity to operate a heat pump, it can generate between 4 to 8 kW of heat. From these comparisons, a preliminary conclusion can be drawn that heating water with heat pumps is the most efficient method.

Make-up water for boilers is at a low temperature; thus, using a heat pump to preheat make-up water for the boiler will help reduce fuel consumption. The COP of a heat pump is significantly influenced by ambient temperature: the higher the ambient temperature, the higher the COP. Since the air around the boiler house receives heat radiated from the boiler, the relatively high air temperature will contribute to increasing the heat pump's COP.

Using heat pumps to provide hot water is regarded as a more energy-efficient solution compared to electric or hot water boilers. Recently, numerous studies have aimed to enhance the energy efficiency of heat pumps.

Xu et al. [1] conducted a simulation study on combining a heat pump with a boiler that utilizes exhaust gases to supply hot water to the boiler on a cruise ship. The results showed that combining a heat pump for water heating saved 77.1% in energy and 66.9% in operating costs.

Xu et al. [2] also conducted an economic evaluation of a solar heating plant combined with an air-to-water heat pump. The study found that system efficiency improved, with the system's COP increasing from 1.22 to 2.62, and CO₂ emissions reduced from 192 kg/MWh to 74 kg/MWh.

Yingjie et al. [3] conducted a study on enhancing heat pump efficiency in water heating using a cascade heat pump system. The results indicated that within an ambient temperature range of -30 to 50°C, the new system's average and maximum performance improvement factors reached 34.8% and 107.7%, respectively, compared to cascade heat pumps. When compared with single-stage heat pumps, the new system showed average and maximum performance improvements of up to 25.8% and 55.6%.

Zhan et al. [4] carried out an experimental study on high-temperature heating using a heat pump that recovers energy from compressed air. The experimental results showed that when the ambient temperature varied from 10°C to -20°C, heating capacity and the temperature difference between water inlet and outlet decreased by only 4.82% and 4.99%, respectively, indicating minimal impact. However, when water flow rate changed from 4m³/h to 10m³/h, heating capacity increased slightly by 3.35%, while the water temperature difference between inlet and outlet significantly decreased by 141.95%.

Choi et al. [5] conducted an experimental study on combining a heat pump with a PV/T solar panel. Their results showed that the PV/T collector achieved a higher output than the PV module, with additional thermal energy of approximately 30.28%. The overall efficiency of the PV/T collector reached 46.89%, 2.99 times higher than the PV module. The average and maximum COP increases for the PV/T-assisted heat pump were 3.12% and 8.57%, respectively, compared to a standalone heat pump.

Wang et al. [6] also conducted a technical-economic assessment of a PV/T system combined with a heat pump for heating. The results showed that the combined system achieved a seasonal performance factor of 2.3, reducing energy consumption by 56% and operating costs by 27.7% compared to a conventional gas boiler system.

Li et al. [7] conducted a study comparing the performance of an air heat pump combined with a vacuum tube solar water heater and a micro PV/T heat pipe. Results showed that the heat pump heating system combined with a PV/T heat pipe performed better than the heat pump heating system with a

vacuum tube water heater. Solar energy utilization increased by 19%, system energy efficiency by 2.2%, primary energy savings by 12.3%, payback period was 0.9 years shorter, and CO₂ emissions reduced by 494.7 kg during winter.

Overall, studies on combining heat pumps with other thermal devices to improve energy efficiency have yielded positive results. However, there has been no research on using a heat pump for preheating boiler feedwater.

To improve energy efficiency and environmental protection for industrial boilers, this paper will study the use of a heat pump to preheat make-up boiler feedwater.

2. Theoretical Basis

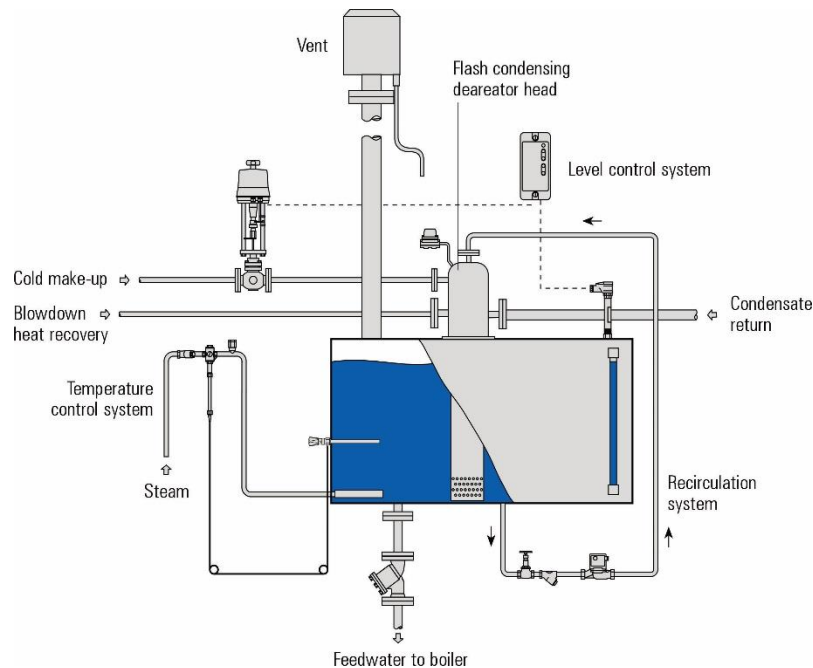


Figure 1. Principle diagram of the deaerator [8].

The schematic diagram of the deaerator tank is shown in Figure 1. Condensate from the technological process, typically at an average temperature of 90°C, is collected and mixed in the deaerator tank with make-up water, which has an ambient temperature of 30°C. In industrial applications, it is not feasible to recover 100% of the condensate, so additional fresh water is needed to compensate for losses along the pipeline and steam used directly. Depending on the condensate recovery rate, the mixed water temperature will vary accordingly.

To prevent boiler corrosion caused by oxidation, the water in the deaerator tank must be heated to 100°C or higher to allow dissolved oxygen to escape. The heat source commonly used to heat the deaerator tank is steam generated from the boiler. If the condensate recovery rate is low, a greater amount of make-up water lowers the mixed water temperature, thus requiring more steam to heat the water in the deaerator tank. This, in turn, reduces boiler efficiency, increases fuel consumption, and raises greenhouse gas emissions.

To heat the water in the deaerator tank while reducing the amount of steam extracted from the boiler, the temperature of the make-up water supplied to the deaerator tank must be increased. The solution chosen in this study for heating the make-up water is to use a heat pump. The schematic diagram of the boiler feedwater system combined with a heat pump is shown in Figure 2.

A heat pump used for water heating is a highly energy-efficient device. However, this efficiency depends on the temperature of the heated water. The higher the outlet water temperature from the heat pump, the lower the COP of the heat pump. Therefore, it is necessary to determine the optimal temperature value to achieve maximum overall energy efficiency for the system.

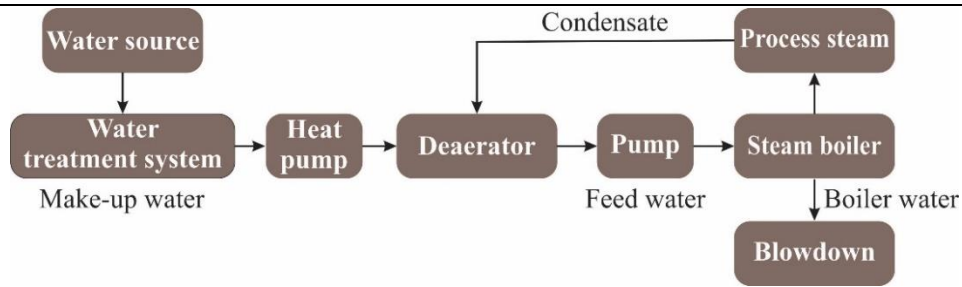


Figure 2. Water system diagram of the boiler.

The research method involves theoretical calculations, using heat and mass balance equations to examine the effects of the outlet water temperature from the heat pump and the condensate recovery rate on steam extraction flow rate, fuel consumption, greenhouse gas emissions, etc. Additionally, the impact of the outlet water temperature on the heat pump's COP is calculated. Based on these analyses, recommendations on the application range of heat pumps for water heating in various types of boilers are proposed.

Apart from the operating temperature, the type of refrigerant also affects the COP of the heat pump. Currently, three types of refrigerants are used for heat pumps on the market: R134a, R410a, and R717 (NH_3). Depending on the specific application and requirements related to safety, economy, and the environment, a suitable refrigerant is selected. Among the commonly used refrigerants, only R717 is suitable for high-temperature water heating applications. Therefore, in this study, R717 is selected as the refrigerant for the heat pump used for preheating boiler feedwater.

The higher the evaporation temperature, the higher the COP of the heat pump. Since the primary goal is water heating, the heat pump's cold source is the surrounding air. A distinctive feature of boilers is that the air around the boiler room is warmer than the outside ambient temperature due to heat radiating from the boiler, making the use of a heat pump even more efficient. Besides heating water, the heat pump also reduces the air temperature in the boiler room, creating better working conditions for boiler operators.

The maximum hot water temperature achievable with a heat pump using R717 refrigerant is 90–95°C, and with a boiler room ambient temperature of 35–40°C, the maximum temperature lift between the two heat sources is 55–60°C. For a single-stage compression heat pump, the average temperature lift is 35–40°C; beyond this range, a two-stage compression cycle is used.

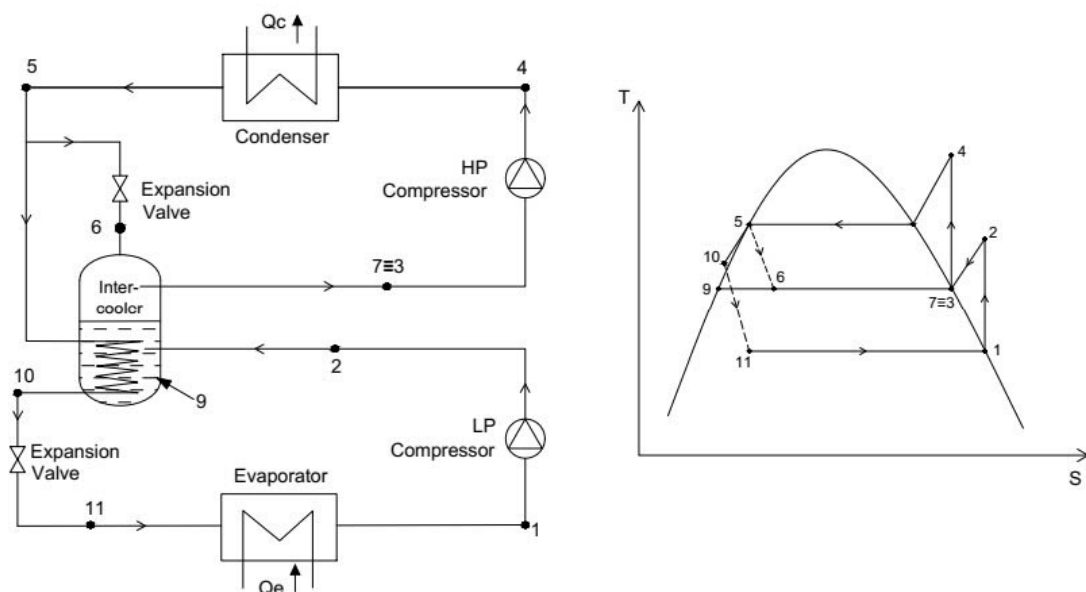


Figure 3. Schematic diagram and cycle of a two-stage heat pump.

Several parameters in the boiler affect its efficiency. To study the effect of a heat pump on the energy-saving potential of the boiler, the following assumptions are made in this research:

The specific heat of water is constant.

The boiler efficiency is 85%.

The condensate temperature returning to the deaerator tank is 90°C.

Combustion is complete.

The boiler fuel is bituminous coal with the following composition: C = 53.13%, H = 3.62%, N = 1.24%, S = 0.62%, O = 11.22%, Ash = 10.17%, Moisture = 20%.

Coal price is 150 USD/ton.

The temperature of the feedwater to the deaerator tank is at its boiling point at atmospheric pressure.

The ambient temperature of the boiler room is 35°C.

The temperature difference between the evaporation temperature and the ambient temperature is 10°C.

The boiler does not use an indirect economizer.

The deaerator tank is heated solely by steam extracted from the boiler.

The efficiency of the single-stage compressor in the heat pump is 90%.

The heat balance equation for the deaerator tank:

$$G_n \cdot i_n + G_{bs} \cdot i_{bs} + G_h \cdot i_h = G_c \cdot i_c \quad (1)$$

Mass balance equation for the deaerator tank:

$$G_n + G_{bs} + G_h = G_c \quad (2)$$

Lower heating value of solid and liquid fuels:

$$Q_t = 339 \cdot C + 1030 \cdot H - 109 \cdot (O - S) - 25 \cdot W \quad (3)$$

Useful heat energy for generating steam:

$$Q_1 = \eta \cdot Q_t \quad (4)$$

Fuel consumption of the boiler:

$$B = \frac{D}{Q_1} (i'' - i_c) + \frac{D_x}{Q_1} (i' - i_c) \quad (5)$$

CO₂ emissions corresponding to the carbon content of the fuel:

$$\begin{array}{rcc} C & + & O_2 & = & CO_2 \\ 12\text{kg} & & 32\text{kg} & & 44\text{kg} \\ 1\text{kg} & & 2,67\text{kg} & & 3,67\text{kg} \end{array} \quad (6)$$

Energy balance equation at the intercooler tank of the two-stage heat pump:

$$m_1 \cdot h_5 + (m_3 - m_1)h_6 + m_1 \cdot h_2 = m_3 \cdot h_3 + m_1 \cdot h_9 \quad (7)$$

Flow rate ratio of NH₃ through the high-pressure compressor to the low-pressure compressor:

$$k = \frac{m_3}{m_1} = \frac{h_5 + h_2 - h_6 - h_9}{h_3 - h_6} \quad (8)$$

COP of 1-stage heat pump:

$$COP = \eta_i \cdot \frac{h_2 - h_9}{h_2 - h_1} \quad (9)$$

COP of 2-stage heat pump:

$$COP = \eta_i \cdot \frac{m_3(h_4 - h_5)}{m_1(h_2 - h_1) + m_3(h_4 - h_3)} = \eta_i \cdot \frac{k(h_4 - h_5)}{(h_2 - h_1) + k(h_4 - h_3)} \quad (10)$$

3. Results and Discussion

3.1. Effect of the condensate recovery ratio and the temperature of the make-up water on fuel consumption.

The calculation results in Figure 4 show that the impact of the make-up water temperature and the condensate recovery ratio on fuel consumption is quite significant. Fuel consumption has a linear relationship with the make-up water temperature. The higher the make-up water temperature and the condensate recovery ratio, the lower the fuel consumption. For the boiler fuel being bituminous coal, the fuel consumption to produce 1 ton of steam with a condensate recovery of 90% is 142 kg, while without condensate recovery, it is 158 kg. In this case, the additional fuel consumption without condensate recovery is quite large, up to 11.2%. The condensate recovery ratio is a passive parameter since it depends on the characteristics of the technological process. If the make-up water is heated from another thermal source, the fuel consumption for the boiler will decrease significantly. For a boiler without condensate recovery, an increase of 10°C in the make-up water temperature results in an average reduction in fuel consumption of about 2%.

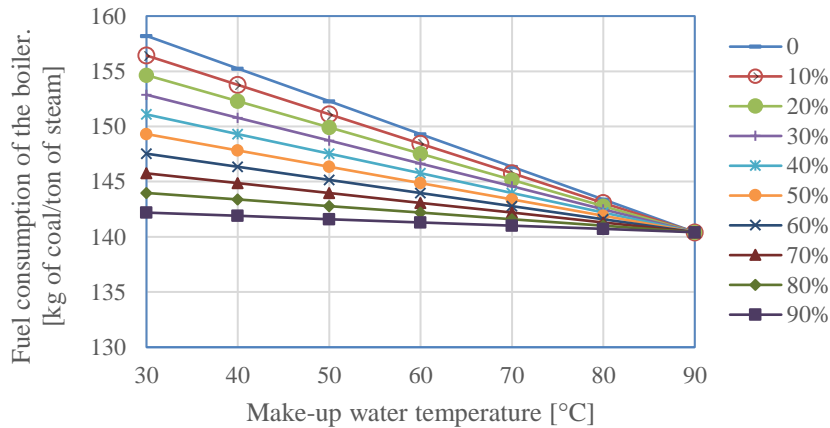


Figure 4. The impact of make-up water temperature and heat recovery rate on the fuel consumption of the boiler.

3.2. Effect of hot water temperature on the COP and equivalent fuel consumption of the heat pump.

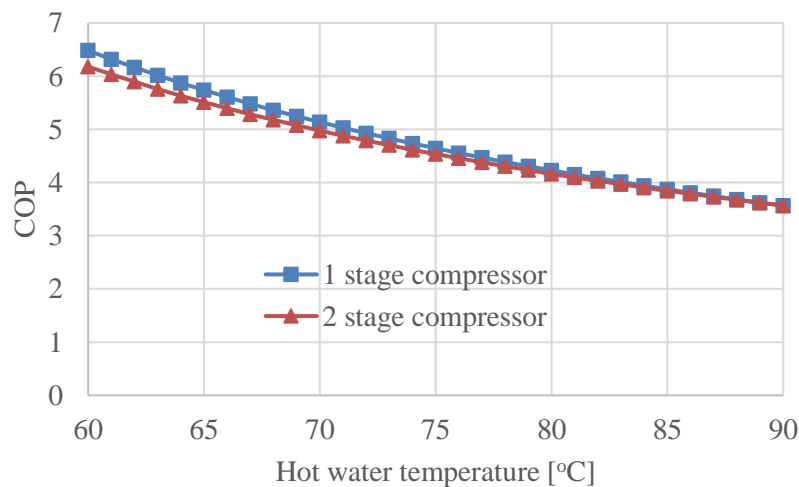


Figure 5. The impact of hot water temperature on the COP of the heat pump.

The calculation results shown in Figure 5 indicate that the COP of the heat pump decreases as the hot water temperature increases. The shape of the COP curve suggests that the rate of decrease in COP with respect to hot water temperature slows down. According to theoretical results, the COP of the single-stage cycle is higher than that of the two-stage cycle. However, in practice, if the single-stage heat pump operates at high temperature ranges, it will have lower compression efficiency and reduced compressor durability. According to the manufacturer's recommendations, the single-stage cycle should be used at temperatures below 75°C, while the two-stage cycle is recommended for temperatures above 75°C. The COP at a hot water temperature of 90°C is 3.57. With this COP value, heating water using a heat pump remains more energy-efficient compared to heating through fuel combustion. Thus, heating water at lower temperatures will result in a higher COP, leading to greater economic efficiency.

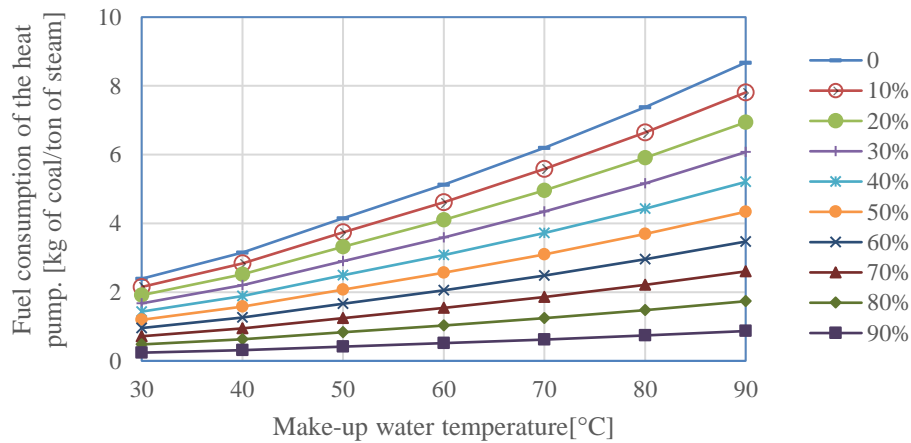


Figure 6. The impact of hot water temperature and the condensate recovery ratio on the equivalent fuel consumption of the heat pump.

The power of the heat pump is determined from the COP, the flow rate of water, and the temperature difference of the hot water leaving the heat pump. The energy used by the heat pump is electrical energy; with a coal-fired power plant efficiency of 40%, the fuel consumption equivalent of the heat pump will be calculated. The results shown in Figure 6 indicate that the variation of fuel consumption equivalent of the heat pump with respect to the hot water temperature is nonlinear, and the rate of increase in fuel consumption with respect to hot water temperature accelerates. The results also show that the fuel consumption equivalent of the heat pump for providing hot water to a boiler without condensate recovery using natural water and a boiler with 90% condensate recovery is 7.8 kg/ton of steam. This value is 50% lower than the case of heating through fuel combustion, which is 16 kg/ton of steam. This demonstrates that using a heat pump to supply hot water to the boiler is very beneficial in terms of economics, energy, and the environment.

3.3. The influence of the condensate recovery rate and the temperature of the make-up water on operating costs.

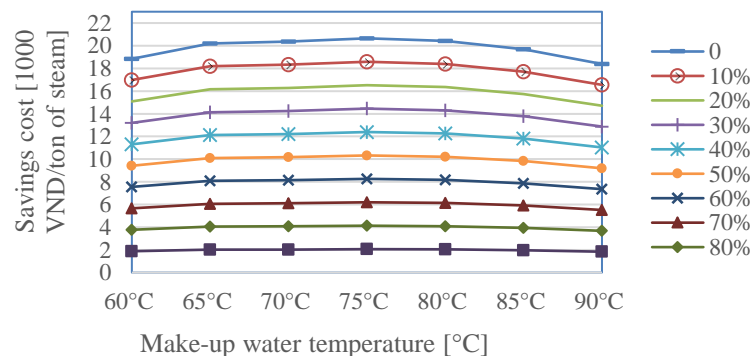


Figure 7. The impact of hot water temperature and the condensate recovery ratio on economic benefits.

The higher the temperature of the hot water coming out of the heat pump, the more energy-efficient it is compared to burning fuel for water heating. However, as the hot water temperature increases, the COP of the heat pump decreases, meaning the energy costs for heating the water increase, and vice versa. A higher hot water temperature from the heat pump results in lower make-up heating costs for the boiler. Conversely, if the hot water temperature from the heat pump is low, the make-up heating costs for the boiler increase. The calculation results shown in Figure 7 indicate that with varying condensate recovery rates, the cost savings achieved by using the heat pump to heat the make-up water for the boiler reach their maximum value at a hot water temperature of 75°C. The savings in cost for producing 1 ton of steam in one hour is 20,600 VND for the boiler without condensate recovery. On average, for every 10% decrease in the condensate recovery rate, the savings in cost increase in 1 hour is 2,000 VND/ton of steam.

3.4. The impact of the condensate recovery rate and the temperature of the make-up water on CO₂ emissions.

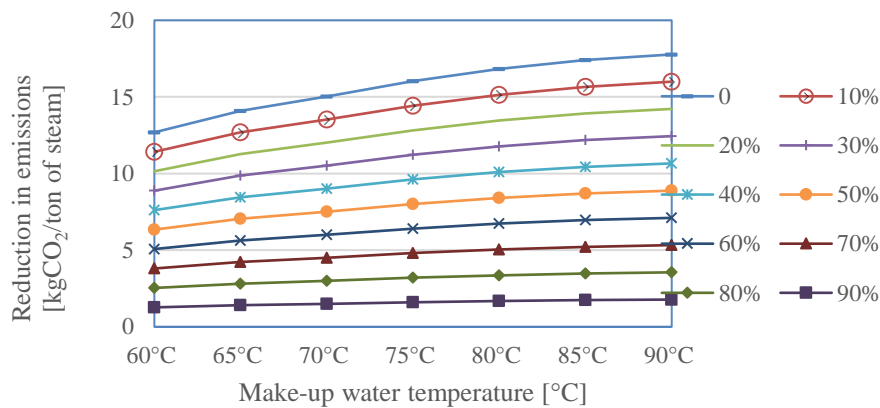


Figure 8. The impact of hot water temperature and the condensate recovery ratio on CO₂ emissions.

The carbon oxidation reaction equation indicates that 1 kg of carbon produces 3.67 kg of CO₂ when burned. From the savings in fuel consumption achieved by using a heat pump to heat the make-up water, combined with the fuel composition, the reduction in greenhouse gas emissions can be determined. The calculation results presented in Figure 8 show that the highest reduction in CO₂ emissions occurs when the boiler does not recover condensate, with a maximum reduction of 17.8 kgCO₂/ton of steam produced. At a condensate recovery rate of 90%, the reduction in emissions is negligible and varies little with the temperature of the hot water. Significant changes in emission reductions occur when the condensate recovery rate drops below 70%. Overall, using a heat pump to preheat the boiler feedwater consistently reduces CO₂ emissions compared to not using a heat pump.

4. Conclusions

This study evaluated the effectiveness of using heat pumps to heat the make-up water for boilers. The results demonstrate that the use of heat pumps offers numerous benefits in terms of economics, energy efficiency, and environmental impact.

Fuel Consumption: Higher temperatures of make-up water and greater rates of condensate recovery lead to reduced fuel consumption. The difference in fuel consumption between a boiler that does not recover condensate and one that recovers 90% of it reaches up to 16 kg/ton of steam, equivalent to an 11.2% increase in fuel consumption when condensate recovery is not practiced.

Heat Pump Efficiency: The COP of the heat pump decreases as the hot water temperature increases and vice versa. However, using a heat pump at higher temperatures still yields energy efficiency. At a hot water temperature of 90°C, the heat pump has a COP of 3.57. With this COP value, utilizing a heat pump for water heating remains more efficient than direct fuel combustion.

Economic Benefits: Heat pumps significantly reduce operating costs. The cost savings achieved with heat pumps peak at a hot water temperature of 75°C, with savings for non-condensate recovering boilers reaching 20,600 VND/ton of steam.

CO₂ Emissions: Incorporating heat pumps in the make-up water heating process significantly reduces CO₂ emissions, especially when the condensate recovery rate is below 70%. The maximum reduction is 17.8 kgCO₂/ton of steam, highlighting the potential of heat pumps to lessen environmental impact.

From these results, it can be concluded that using heat pumps in boiler systems is an effective solution for optimizing energy consumption, reducing costs, and minimizing CO₂ emissions. This contributes to the sustainable development of the industry and environmental protection.

The findings of this study only assess the effectiveness of heat pumps in heating make-up water for coal-fired boilers. Given the diverse fuels used in boilers, further evaluations are needed to fully understand the heat pump's efficacy. Additionally, this study focused solely on using heat pumps for heating make-up water, without assessing energy efficiency when combining heating and cooling functions. For facilities with both boilers and cooling needs, utilizing both heating and cooling capabilities may yield higher efficiencies than operating them separately. There are also significant price differences among heat pump manufacturers, so this study did not evaluate the payback period for using heat pumps for boiler water heating. Overall, preliminary findings indicate the potential for savings through heat pump use. However, accurate results require specific applications for a more detailed evaluation.

List of Symbols

| Symbol | Name | Unit |
|---|--|-------|
| B | Fuel consumption | kg/h |
| D | Steam capacity | kg/h |
| D _x | Mass flow rate of blowdown water | kg/h |
| G _{bs} | Mass flow rate of make-up water | kg/h |
| G _c | Mass flow rate of feed water | kg/h |
| G _h | Mass flow rate of extracted steam | kg/h |
| G _n | Mass flow rate of condensate | kg/h |
| i _{bs} | Enthalpy of make-up water | kJ/kg |
| i _c | Enthalpy of feed water | kJ/kg |
| i _h | Enthalpy of extracted steam | kJ/kg |
| i _n | Enthalpy of condensate | kJ/kg |
| i ^{''} , i ['] | Enthalpy of saturated liquid and saturated steam | kJ/kg |
| Q ₁ | Useful heat for steam generation | kJ/kg |
| Q _t | Lower heating value of fuel | kJ/kg |
| W | Moisture content of fuel | % |
| h ₁ , h ₂ , h ₃ ,...h ₉ | Enthalpy of points in the heat pump cycle | kJ/kg |
| m ₁ , m ₃ | Mass flow rate of low-pressure and high-pressure NH ₃ | kg/s |
| η | Boiler efficiency | % |
| η _i | Adiabatic compression efficiency of compressor | % |

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Conflict of Interest

We declare that there are no conflicts of interest in this paper

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