

REDUCING DEAERATOR-RELATED ENERGY LOSSES IN STEAM BOILERS

*Ahmet Fevzi SAVAŞ^{*1}, Ceyda KOCABAŞ²*

¹Alternative Energy Resources Technology - Bilecik Şeyh Edebali University Vocational School, Bilecik, Turkey

²Quality Control in Manufacturing - Bilecik Şeyh Edebali University Vocational School, Bilecik, Turkey

* Corresponding author; E-mail: ahmetfevzi.savas@bilecik.edu.tr

Improving energy efficiency helps to achieve a more reliable energy supply and a sustainable environment. In the current study, some observations were made in a textile factory to improve the energy efficiency of the industrial steam boiler. Deaerator is one of the main points of energy loss in the boiler. It is possible to reduce energy loss in the deaerator by using today's scientific and technological possibilities. The Failure Mode and Effects Analysis (FMEA) method was used in determining and ranking the factors causing energy loss in the deaerator. Some improvements were suggested based on the data of the FMEA study. The amount of energy loss in the deaerator was calculated by establishing mass and energy balances both in the current situation and after the improvements. As a result, when suggestions were applied, the energy loss in the deaerator, which was 373.6 kW before, could be reduced to 40.4 kW. Also, the net steam production capacity of the steam system will increase by approximately 9%. The payback period of the proposed investments was calculated as 2.8 months by performing the economic analysis. The study outcomes revealed that the FMEA technique, which is used as a risk analysis and failure prevention method within the scope of process improvement studies, can also be used to increase boiler energy efficiency.

Key words: Steam boiler, Deaerator, Energy loss, Energy efficiency

1. Introduction

Steam has been one of the most valuable forces in the service of humanity for nearly 250 years. Boiler systems are widely used in industries and power plants to generate steam [1,2]. Steam boilers are devices that produce steam at the desired pressure, temperature, and amount. The heat energy obtained by any means is given to the water in a closed container, and then this water is evaporated [3]. Energy efficiency studies are of great importance in equipment with widespread use and high fuel consumption [4]. A significant part of the world's energy consumption is used in boilers. Many losses cause the boiler energy efficiency to decrease. One of these losses is caused by the deaerator, which is a part of the boiler system.

Free oxygen (O₂) and carbon dioxide (CO₂) may be found in dissolved form in the feedwater pumped into the boiler. These gases must be neutralized. Otherwise, as a result of the reaction of O₂ with metallic iron, cavities are formed on the waterside of the boiler pipes, and this causes the life of

the boiler to decrease [5]. CO_2 gas is transported to the equipment along with the steam. When the steam turns into condensate, CO_2 is dissolved in the condensate, and carbonic acid (CO_3) is formed. CO_3 creates longitudinal slits in the condensate pipes. To be protected from these effects, the gases in the feedwater given to the boiler must be removed very well [3]. TS EN 12953 defines the O_2 limit in the feedwater as 0.05 mg/l in steam boilers with operating pressure of up to 20 bar [6,7]. In addition, the boiler feedwater must be completely free of CO_2 gas [3].

The separation of gases from feedwater can be accomplished by physical and chemical methods [3]. In the chemical method, the amount of O_2 in the feedwater can be reduced by using oxygen-binding chemicals. However, using chemicals to purify the oxygen in the feedwater is a relatively expensive method [7]. The addition of chemicals causes an increase in blow-down frequency, which increases operating costs due to the cost of water replacement and additional energies needed to reheat water that is lost during blow-down [8]. For this reason, the most convenient and widespread method is to separate the gases using a deaerator physically. Devices that separate corrosive gases from feedwater are called deaerators. The deaerator working system used in the boiler is shown schematically in Fig. 1 [5].

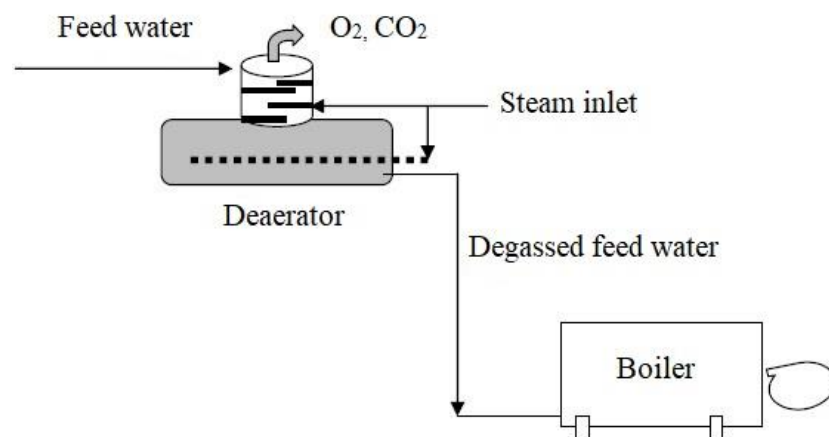


Figure 1. Deaerator working system

The fundamental function of the deaerator is the removal of dissolved gases from the water [9]. At 60 °C, CO_2 is separated from the water, and at 85 °C, the dissolved O_2 components in the water decrease to the levels that will not cause corrosion, and the separation process is completely realized at 102 °C [3]. In this way, the feedwater is increased to 102 °C. At this temperature, the dissolved CO_2 in the feedwater is completely eliminated, and the O_2 concentration decreases below 0.05 mg/l [7]. The deaerator, which performs many functions in an industrial steam system, also provides preheating of the feedwater [9]. In addition, by giving feedwater to the boiler at a temperature close to the steam temperature, thermal stresses and thermal shocks that may occur in the boiler are minimized [3]. To reduce the energy losses related to the deaerator in the boilers, the factors that cause and increase this loss should be determined first. In analyzing these factors, the Failure Mode and Effect Analysis (FMEA) method which is a systematic study method, can be used. FMEA is a frequently used method for assessing product quality risks in production or equipment failures in maintenance. This method can also be used to identify, evaluate and prioritize risks that lead to reduced boiler energy efficiency.

The question of how energy loss experienced in the deaerator can be reduced has been underexplored so far. One of the studies focusing on that question finds that by adding a heat

exchanger to the deaerator gas discharge line, pre-heating of the fresh feedwater is ensured before being sent to the condensing economizer. In addition, two flash steam devices were included in the system, and they provided flash steam from both blowdown water and condensate to the deaerator [7]. Another research shows that most of the heat in boilers using a blowdown system can be recovered by passing the water through a two-stage system consisting of a flash steam tank and a heat exchanger before being discharged to the sewer. It needs to use this flash steam directly in the process or the deaerator [10]. The amount of heat recovered by passing the blowdown through flash steam and the heat exchanger is calculated and the energy transferred to the deaerator via flash steam is determined [11]. In a more recent research project, the amount of steam required to be sent to the deaerator was reduced from 1128 kg/h to 725 kg/h by utilizing the flash steam of the surface blowdown [6].

Some authors propose alternative sources to steam for use as desorbing agents in deaerators. One of the methods is to degas the make-up water by utilizing boiler exhaust gases as the desorption agent. In this research, feedwater deaeration is ensured at a relatively low temperature [12]. In some other research, it is suggested to use flue gases for water degassing [13]. It is proved the suitability of this new technology by calculations based on the equations of heat and material balance [14]. A second way to ensure the low-temperature deaeration of the make-up water is to use natural gas as a desorbing medium [15]. The necessary and actual costs of using natural gas show that this method promises much more energy efficiency compared to other alternatives [16]. Another way is to use flash steam as the desorbing agent and to develop an excess-pressure deaeration unit. This unit implements the deaeration process control involving flash-steam flowrate regulation to attain the specified efficiency of the process [17]. The proposed technologies make it possible to increase the energy efficiency of the boiler by eliminating the consumption of steam for the deaeration process.

In previous studies, improvement suggestions to prevent energy loss in the deaerator have been presented in detail. But no study has been encountered in which risk analysis techniques such as FMEA are used to reduce energy loss. Unlike them in the current study, the FMEA technique was used to assess the energy loss during the boiler degassing process. This study is valuable because, to our knowledge, no systematic and risk-based study presents the deaerator loss in the boiler. As a novelty, FMEA, which is one of the quality improvement tools, was used by adapting it to the energy field. For energy risks with high-risk priorities, improvement suggestions were proposed to the extent of today's technological possibilities. The energy losses before and after the improvements were analyzed in detail.

2. Material and Method

Failure Mode and Effects Analysis (FMEA) is a powerful technique for predicting and preventing failures that may occur in products or equipment. This method can also be used to investigate and fix problems in an existing system by incorporating team experience, especially in situations where it is difficult to obtain data [18]. In this method, the risk priority numbers of all failures are calculated, and the necessary precautions are determined for all risks, starting from the potential failure with the highest risk priority number. After the implementation of the measures, the risk priority numbers are recalculated, and the progress achieved is revealed.

FMEA was first developed by the American army to detect system and hardware errors and prevent them before they occur. In 1998, it was accepted as a general standard and started to be used in three leading automotive companies (Chrysler, Ford, and General Motors) operating in the USA

[19]. Today, the use of FMEA in ISO/TS 16949, ISO 9001, and other management systems has become mandatory [20, 21]. FMEA has found a wide area of use in many sectors such as chemistry, space, automotive, and electricity [22]. In addition, it is also used in the examination of defects and malfunctions that may occur in various plant equipment and their harmful effects on the system [23]. Three indicators are considered when examining failures with FMEA:

Occurrence: Frequency of failure

Severity: Impact level of failure

Detection: Detectability of failure

There is no standard for the size of the range of numbers used to assign numerical values to severity, probability, and detectability indicators. The commonly used range is 1–10. Each of the three factors is scored on a scale of 1 (Best) to 10 (Worst). The combined effect of these three factors is the Risk Priority Number (RPN). RPN is obtained by multiplying three factors.

$$\text{Risk Priority Number (RPN)} = \text{Occurrence} \times \text{Severity} \times \text{Detection}$$

FMEA technique is also used in determining which failure will be prioritized in process improvement studies and thus saving resources [20]. This method can play a significant role in determining which energy-saving area should be the starting point for improvement. To apply the FMEA method, product and maintenance-oriented FMEA rating tables were adapted according to the energy field, and accordingly, Tab. 1 was created as a rating table. In this table, occurrence, severity, and detection indicators were scored between 1 (Best) and 10 (Worst) [24].

Table 1. Energy FMEA rating table (adapted from [25])

Occurrence	Score	Severity	Score	Detection	Score
Extremely high occurrence (\geq in 2)	10	Hazardous, very high energy loss without warning	10	No chance to detect energy loss	10
Very high occurrence (1 in 3)	9	Critical effect, very high energy loss with warning	9	Very remote chance to detect energy loss	9
High occurrence (1 in 8)	8	Extreme effect, very high energy loss	8	Remote chance to detect energy loss	8
Frequent occurrence (1 in 20)	7	Major effect, high energy loss	7	Slight chance to detect energy loss	7
Moderate occurrence (1 in 80)	6	Significant effect, moderate energy loss	6	Low chance to detect energy loss	6
Occasional occurrence (1 in 400)	5	Moderate effect, low energy loss	5	Moderate chance to detect energy loss	5
Slight chance of occurrence (1 in 2000)	4	Slight effect, very low energy loss	4	Moderately high chance to detect energy loss	4
Very slight chance of occurrence (1 in 15.000)	3	Slight effect, minor energy loss	3	High chance to detect energy loss	3
Remote (1 in 150.000)	2	Very slight effect, very minor energy loss	2	Very high chance to detect energy loss	2
Extremely remote (\leq 1 in 1.500.000)	1	Unnoticeable effect, no energy lost	1	Almost certain to detect energy loss	1

While creating an energy FMEA table, possible failure types that reduce energy efficiency should be determined. In determining possible types of failure, company energy audit reports, failure-maintenance reports, and test and analysis results can be used. In addition, the experience and knowledge of technical personnel can be utilized. To determine the occurrence, severity, and detection indicators of failures, the grading approach in Table 1 is employed. According to this table, numerical values of "1" can be given to the minimum occurrence degree and "10" to the maximum. The degree of "occurrence" indicates how often the predicted energy loss failure is encountered for a certain period of time. In assigning a value to the failure severity, "1" indicates the minimum and "10" the maximum importance. The degree of "severity" changes depending on the increase in energy consumption, deterioration of the process, and whether life safety is in danger or not. The "Detectable" value represents a measure of the success of detecting the energy loss failure. The failure detection value will be "1" for easily noticed and "10" for undetectable risk [24].

The RPN is used to decide which risks need improvement. Corrective action is recommended for all risks, starting from the highest risk priority number. The aim is to develop various preventive activities to bring the RPN closer to 1 [23]. The evaluation scale regarding the number of risk priorities is given in Tab. 2. [26]. According to this table, precautions must be taken for risks with an RPN value above 100.

Table 2. RPN evaluation scale

RPN	Decision
RPN < 40	No need to take action
$40 \leq \text{RPN} \leq 100$	Precaution can be taken
RPN > 100	Precaution must be taken strictly

3. Results and Discussions

This study was carried out in the boiler workshop of one of Turkey's leading textile factories. The company has a steam boiler with a capacity of 5 t/h that produces steam for use in the distillation process. In the current system, there is a deaerator to separate the gases in the fresh feedwater coming from the softening system. The deaerator is operated under a vapor pressure of 0.2 bar to ensure the degassing temperature.

3.1. Energy FMEA for Deaerator

The FMEA study was carried out to reduce the energy losses caused by the deaerator in the boiler. The risks leading to energy loss were determined by taking the opinions of the technical personnel and evaluating the literature on this subject. The cause and possible effects of each risk were identified. The severity, probability of occurrence, and detectability of each risk were scored using a 1-10 scale. The FMEA Table (Tab. 3) was obtained by calculating the risk priority numbers for each risk. According to Tab. 3, "the use of fresh steam in the deaerator" and "the steam loss in the deaerator" is the risks with a high-risk priority score. The RPN scores of these risks should be reduced by taking necessary precautions.

Table 3. Energy FMEA Study for Energy Loss in Deaerator (Current situation)

Energy Failure Mode and Effects Analysis (FMEA)								
Process	Potential Failure mode for Energy	Potential Failure Causes	Potential Failure Effects	Precaution, Current controls	Severity	Occurrence	Detection	RPN
Steam Production	Loss of energy in the deaerator due to waste steam	Loss of steam with corrosive gases separated from the feedwater	Boiler efficiency decreases, and energy loss occurs.		6	4	5	120
	Energy loss due to the use of fresh steam in the deaerator	Using the fresh steam produced in the system to separate the gases from the feedwater			7	6	5	210

3.2. The Deaerator Energy Loss in the Boiler System

It is observed from Tab. 3 that there are two types of energy loss in the deaerator. The first of the losses in the deaerator is the loss of some steam through the extracted corrosive gases. Corrosive gases extracted from the feedwater in the deaerator are discharged through the gas relief valve located at the top of the deaerator dome. During this process, some steam leaves the system with these gases. In practice, the amount of steam lost is calculated as 0.5% of the total steam production capacity of the system [6]. In the current system, the amount of steam lost with the gases evacuated in the deaerator was calculated as 0.5% of the boiler capacity and was found to be 25 kg/h.

$$\begin{aligned} \text{Boiler Steam Capacity} &= 5000 \text{ kg/h} \\ \dot{m}_{ws} &= 5000 \times 0.005 = 25 \text{ kg/h} \end{aligned}$$

The energy released with 25 kg/h steam discharged with the waste gas was calculated using Eq. (1) and found to be 18.6 kW.

$$\begin{aligned} Q_{\text{energy lost with } ws} &= \dot{m}_{ws} \times h_{s, 0.2\text{bar}} \quad (1) \\ Q_{\text{energy lost with } ws} &= 25 \times 2683 = 67\,085 \text{ kJ/h} = 18.6 \text{ kW} \end{aligned}$$

Another type of energy loss in the deaerator is fresh steam loss. In the deaerator, fresh steam produced in the system is used in degassing the gases from the feedwater. This situation causes some of the steam produced to be spent here, resulting in efficiency loss [24]. The mass and energy balance equations can be used simultaneously to analyze complex systems when solving multiple equations with multiple unknowns [10]. By establishing the mass and energy balances of the deaerator, the amount of fresh steam required for the deaerator can be calculated. Also, fresh steam losses can be found. The steam boiler in the facility produces steam at a pressure of 5 t/h and 10 bar. However, some of the steam produced is used in degassing gases in the deaerator. To determine the net steam

production, it is necessary to know the amount of steam sent to the deaerator. The amount of fresh steam used in the system can be calculated by the mass and energy balance chart for the deaerator given in Fig. 2.

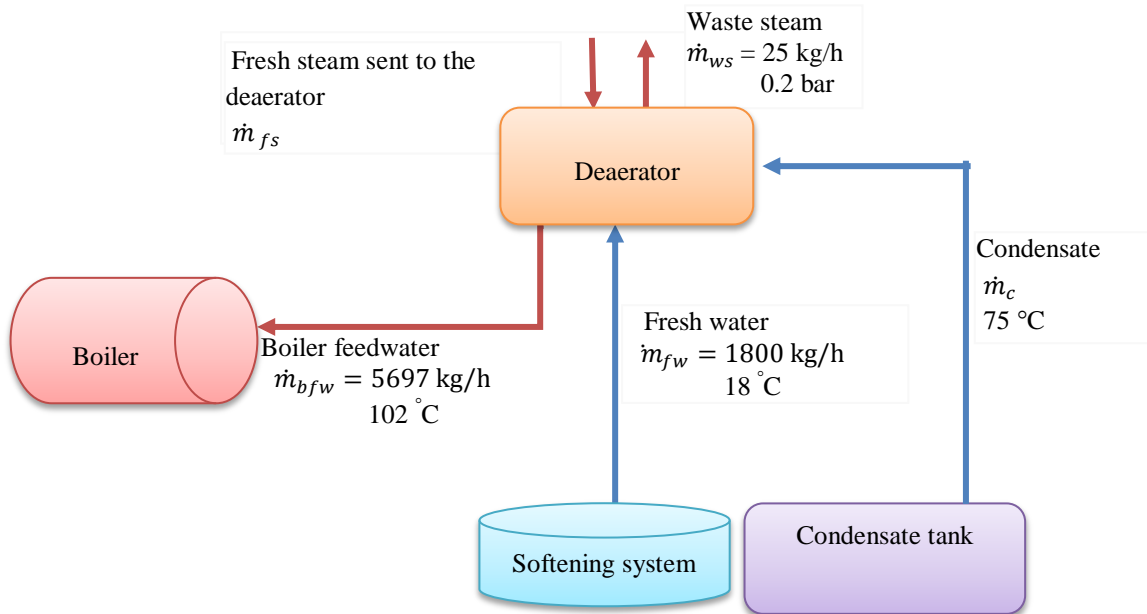


Figure 2. Deaerator mass and energy balance diagram for the current situation

Using the Eq. (2) and (3), which shows the mass and energy balance for the deaerator, respectively, the amount of condensate entering the deaerator was found to be 3463 kg/h, and the amount of fresh steam sent to the deaerator was 460 kg/h. In this case, the net steam production of the boiler was 4540 kg/h. The energy loss due to the use of fresh steam in the deaerator was calculated as 355 kW.

Mass balance

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \quad (2)$$

$$\dot{m}_{fs} + \dot{m}_{fw} + \dot{m}_c = \dot{m}_{bfw} + \dot{m}_{ws}$$

$$\dot{m}_{fs} + 1800 + \dot{m}_c = 5697 + 25$$

$$\dot{m}_{fs} + \dot{m}_c = 3922$$

$$\dot{m}_{fs} = 3922 - \dot{m}_c$$

Energy balance

$$\sum Q_{in} = \sum Q_{out} \quad (3)$$

$$\dot{m}_{fs} \times h_{fs \ 10bar} + \dot{m}_{fw} \times h_{fw \ 18^\circ C} + \dot{m}_c \times h_c \ 75^\circ C = \dot{m}_{bfw} \times h_{bfw \ 102^\circ C} + \dot{m}_{ws} \times h_{ws \ 0.2bar}$$

$$\dot{m}_{fs} \times 2779,7 + 1800 \times 75,7 + \dot{m}_c \times 314 = 5697 \times 427 + 25 \times 2683$$

$$(3922 - \dot{m}_c) \times 2779,7 + 1800 \times 75,7 + \dot{m}_c \times 314 = 5697 \times 427 + 25 \times 2683$$

$$\dot{m}_c = 3463 \text{ kg/h}$$

$$\dot{m}_{fs} = 460 \text{ kg/h}$$

$$\dot{m}_{ns} = 5000 - 460 = 4540 \text{ kg/h}$$

$$Q_{\text{energy lost by } fs} = \dot{m}_{fs} x h_{s \text{ 10bar}}$$

$$Q_{\text{energy lost by } fs} = 460 \times 2779,7 = 1\,278\,662 \text{ kJ/h} = 355 \text{ kW}$$

$$Q_{\text{total energy lost from the deaerator}} = Q_{\text{energy lost by } ws} + Q_{\text{energy lost by } fs}$$

$$Q_{\text{total energy lost from the deaerator}} = 18.6 + 355 = 373.6 \text{ kW}$$

To reduce the energy loss in the deaerator due to waste steam, a copper tube heat exchanger, which cannot be affected by oxygen corrosion, can be added to the system to recover the energy carried by the corrosive gas and waste steam. The energy balance diagram of the heat exchanger is given in Fig. 3. With the copper tube heat exchanger connected to the deaerator gas discharge line, 25 kg/h of waste steam is condensed and discharged to the drain as water at 60 °C. Simultaneously, fresh feedwater at 18 °C can be passed through this heat exchanger. With the energy balance, it was determined that the fresh feedwater can be increased to approximately 26 °C. In the new case, the amount of energy to be lost with the wastewater was calculated using Eq. (4) and found to be 1.8 kW. Thus, the energy loss due to waste steam will be 1.8 kW instead of 18.6 kW.

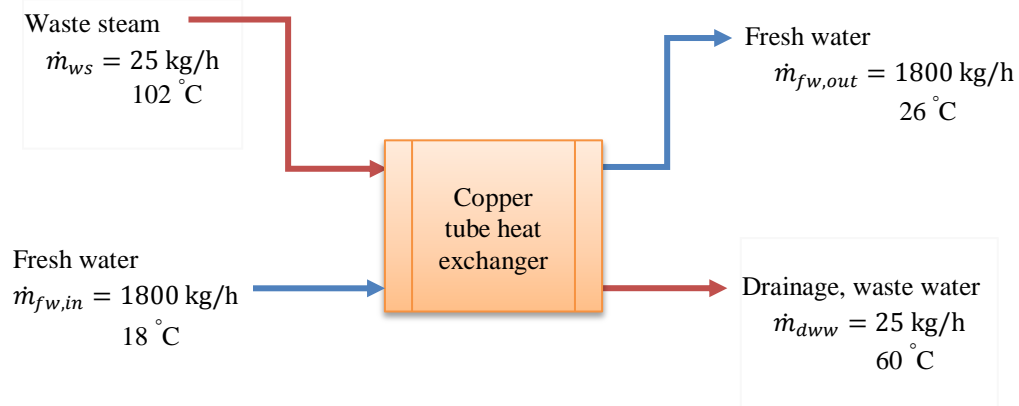


Figure 3. Energy balance for copper tube heat exchanger

$$\sum Q_{in} = \sum Q_{out}$$

$$\dot{m}_{ws} \times h_{ws \text{ 102}^\circ\text{C}} + \dot{m}_{fw,in} \times h_{fw \text{ 18}^\circ\text{C}} = \dot{m}_{fw,out} \times h_{fw \text{ 26}^\circ\text{C}} + \dot{m}_{dww} \times h_{dww \text{ 60}^\circ\text{C}}$$

$$25 \times 2683 + 1800 \times 75.7 = 1800 \times h_{fs} + 25 \times 251.4$$

$$h_{fw} = 109.4 \text{ (26}^\circ\text{C)}$$

$$Q_{\text{energy lost by } ws} = \dot{m}_{ww} x h_{ws \text{ 60}^\circ\text{C}} \quad (4)$$

$$Q_{energy\ lost\ by\ ws} = 25 \times 251,4 = 6\ 285\ \text{kJ/h} = 1,8\ \text{kW}$$

Energy loss due to the use of fresh steam in the deaerator, another risk in the FMEA table, should also be reduced. For this purpose, a flash steam device can be added to the condensate return so that some of the condensates that expand from 5 bar to 0.2 bar can be recovered as flash steam. The resulting flash steam can be used by feeding into the deaerator. In the new condition, the steam required for the deaerator can be provided with flash steam instead of fresh steam.

In case the selected improvements are implemented, the energy and mass balance in the deaerator is expected to be as in Fig. 4. The amount of fresh steam that should be sent to the deaerator in the new condition was investigated using mass and energy equations. The flash steam obtained from the condensate was found to be 401 kg/h [34]. The fresh steam to be sent to the deaerator was calculated as 50 kg/h. While the net steam production was 4540 kg/h in the previous case, it will be 4950 kg/h in the new condition.

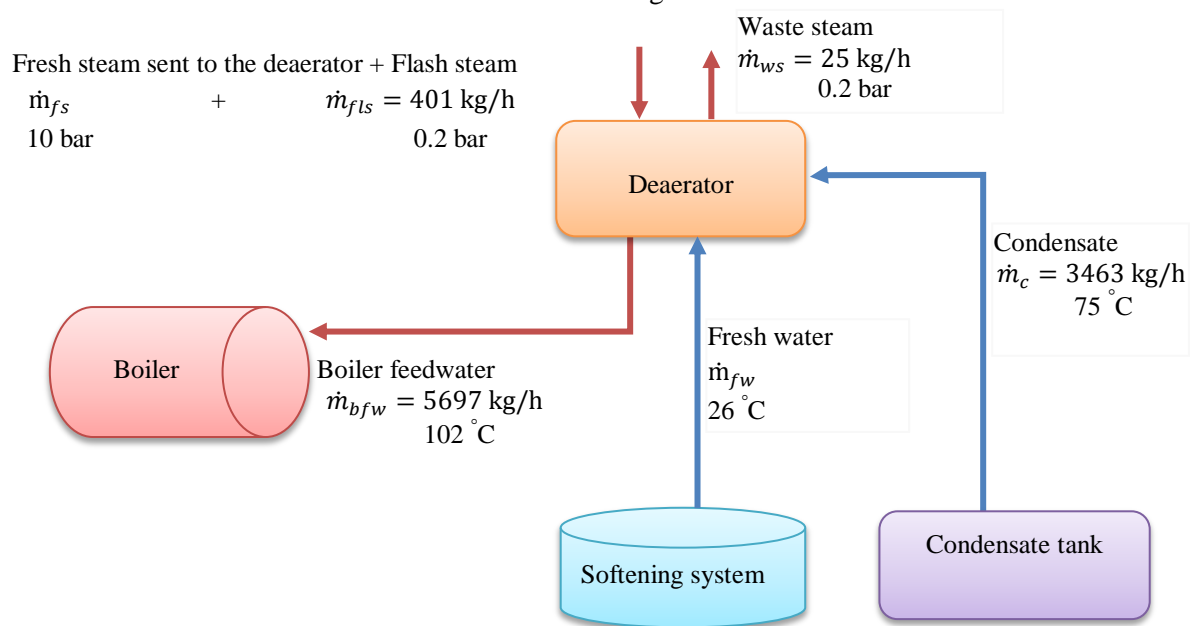


Figure 4. Deaerator mass and energy balance after improvements

Mass balance:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out}$$

$$\dot{m}_{fs} + \dot{m}_{fls} + \dot{m}_{fw} + \dot{m}_c = \dot{m}_{bfw} + \dot{m}_{ws}$$

$$\dot{m}_{fs} + 401 + \dot{m}_{fw} + 3463 = 5697 + 25$$

$$\dot{m}_{fs} + \dot{m}_{fw} = 1858$$

$$\dot{m}_{fw} = 1858 - \dot{m}_{fs}$$

Energy balance:

$$\sum Q_{in} = \sum Q_{out}$$

$$\dot{m}_{fs} \times h_{fs\ 10bar} + \dot{m}_{fls} \times h_{fls\ 0.2\ bar} + \dot{m}_{fw} \times h_{fw\ 26^\circ C} + \dot{m}_c \times h_{c\ 75^\circ C} = \dot{m}_{bfw} \times h_{bfw\ 102^\circ C} + \dot{m}_{ws} \times h_{ws\ 0.2bar}$$

$$\dot{m}_{fs} \times 2779,7 + 401 \times 2683 + (1858 - \dot{m}_s) \times 109,4 + 3463 \times 314 = 5697 \times 427 + 25 \times 2683$$

$$\dot{m}_{fs} = 50\ \text{kg/h}$$

$$\dot{m}_{fw} = 1858 - 50 = 1808\ \text{kg/h}$$

If a flash steam unit is placed at the condensate outlet and a copper tube heat exchanger is added to the deaerator outlet, the amount of energy lost due to the use of fresh steam in the deaerator will be 38.6 kW.

$$Q_{energy\ lost\ by\ fs} = \dot{m}_{fs} \times h_{s\ 10bar}$$

$$Q_{energy\ lost\ by\ fs} = 50 \times 2779,7 = 138\ 985\ \text{kJ/h} = 38.6\ \text{kW}$$

The amount of energy lost by waste steam was calculated as 1.8 kW. In this case, the total energy loss in the deaerator will be 40.4 kW.

If the selected improvements are implemented, the energy loss of the deaerator will decrease from 373.6 kW to 40.4 kW, saving 333.2 kW per hour and resulting in a reduction of 89% in energy loss. Total annual saving was calculated as 31.859 \$/year and shown in Tab. 4. The payback period of the investments was found to be approximately 2.8 months.

Table 4. Energy savings in case of implementation of selected improvements

Boiler's Annual Working Hours	5760	h/ year
Unit Price of Natural Gas (February 2022)	0,0166	\$/kWh
Boiler's Natural Gas Saving (Hourly)	333,2	kW/h
Boiler's Natural Gas Saving (Annual)	1919,232	kW/year
Boiler's Natural Gas Saving (\$)	31.859	\$/year
CO ₂ Emission Reduction	324	tons/year
Investment Cost	7.354	\$
Payback Period	2.8	month

If the selected improvements are implemented, the RPN numbers of the risks specified in the FMEA table may decrease as indicated in Tab. 5.

Table 5. Energy Loss in Deaerator Energy FMEA Study (Status after improvements)

Energy Failure Mode and Effects Analysis (FMEA)								
Process	Potential Failure mode for Energy	Potential Failure Causes	Potential Failure Effects	Precaution, Current controls	Severity	Occurrence	Detection	RPN
Steam Production	Loss of energy in the deaerator due to waste steam	Loss of steam with corrosive gases separated from the feedwater	Boiler efficiency decreases, and energy loss occurs.	Recovery of waste heat using a copper tube heat exchanger	6	1	5	30
	Energy loss due to the use of fresh steam in the deaerator	Using the fresh steam produced in the system to separate the gases from the feedwater		Use of flash steam from condensate instead of fresh steam	7	1	5	35

4. Conclusions

In the current study, the energy loss caused by the deaerator of the steam boiler in a company operating in the textile sector was investigated. FMEA technique was used to identify potential risks and prioritize them. Recommendations were proposed for each risk to reduce energy losses in the deaerator.

The results suggested adding a flash steam unit to the condensate outlet and a copper tube heat exchanger to the gas discharge outlet of the deaerator. In this way, heat recovery can be achieved from flash steam and the extracted gases. Thus, the energy loss in the deaerator, which was previously 373.6 kW, could be reduced to 40.4 kW. In other words, the energy loss caused by the deaerator will be reduced by 89%. Thus, the net steam production of the system will increase and become 4950 kg instead of 4540 kg. The investment payback period is calculated as 2.8 months. After the amortization period, the company will save approximately 31.859 \$ every year, depending on the currency rate.

In this study, the energy loss of the deaerator was systematically examined. The reasons for the energy loss were determined by using the FMEA technique. It was demonstrated that the FMEA technique can be used for reducing energy loss in the deaerator. FMEA is a never-ending work, and as existing technologies and opportunities evolve, they should be included in the system, and then the FMEA work should be updated accordingly. In future studies, other energy losses in the boiler can be

investigated by the FMEA technique too. In addition, the research method described here can be extended by applying it to other energy-using processes and equipment in the plant.

Acknowledgments

This study was derived from the Doctorate Thesis of Ceyda KOCABAŞ titled “Use of Process Improvement Techniques in Increasing Energy Efficiency and Practical Applications in Industry” conducted at Energy Systems Engineering Department, Institute of Science, Bilecik Şeyh Edebali University.

Funding

This work was supported by the Scientific Research Projects (BAP) Commission of Bilecik Şeyh Edebali University (Project No: 2019-01. BŞEÜ.07-01, 2019). <https://bapoto.bilecik.edu.tr/index.php?act=guest&act2=projeler&durum=tamam>

Nomenclature

h	enthalpy, [kJ/kg]
\dot{m}	mass-flow rate, [kg/s]
Q	heat-transfer rate, [kW]

Abbreviations

FMEA	Failure Mode and Effects Analysis
RPN	Risk Priority Number
TS EN12953	Turkish standard institute, steam boilers standard

Subscripts

bfw	boiler feedwater
c	condensate
dww	drainage waste water
fls	flash steam
fs	fresh steam
fw	fresh water
in	inlet
ns	net steam
out	outlet
s	steam
w	water
ws	waste steam

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Submitted: 29.04.2022.

Revised: 25.06.2022.

Accepted: 28.06.2022.