Research Article

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Reducing surface heat loss in steam boilers

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Abstract: In this study, heat losses occurring on the outer surface of a steam boiler used in the distillation process in a textile company are discussed in detail. All surfaces of the boiler were scanned with a thermal camera to determine the non-insulated or poorly insulated areas. By drawing the schematic image of the boiler, the side surfaces, front cover, back cover, and parts of the smoke pipe were shown in different colors, and the temperature distributions in different parts of the boiler were revealed. Although most of the heat loss occurs on the side surfaces of the boiler, it was observed that these surfaces were already insulated. For this reason, a Pareto diagram was prepared according to the surface temperature to get an idea about where to start the improvement studies. Especially on the front and back cover surfaces, high-temperature values were measured and, it was determined that the heat loss on these surfaces was also at high levels. It was suggested that high-temperature surfaces should be covered with insulating jackets and pads, and sample applications were shown. The energy savings to be achieved and the payback period of the investment was revealed.

Keywords: energy efficiency, boiler efficiency, steam boiler, surface heat loss, Pareto analysis

1 Introduction

Steam systems are a part of almost every major industrial process today. Due to the abundance of water vapor and its ability to store and transport a large amount of energy in a small volume, steam has been used extensively to the present day [1]. Steam has the highest amount of energy that can be conveyed per unit mass (in the form of latent heat), and therefore it is an extremely cost-effective means of heat convection. Steam flows inside the system without assistance from external energy sources such as pumps, so it can be controlled very precisely [2–4].

The vast majority of industrial facilities in our country use steam in process lines. Steam is used extensively, especially in the fields of textiles, garments, food, chemicals, pharmaceuticals, electricity generation, and regional heating [5]. Because of its ubiquitous use and great energy potential, steam can save a significant amount of cost. Therefore, an efficient boiler has also a significant influence on heating-related energy savings. A substantial amount of energy can be saved by adopting energy saving measures and by improving the overall boiler efficiency. In general, reducing losses without requiring substantial investments is rather simple [6,7].

It is possible to reach high efficiency values by applying the technically and financially feasible technological opportunities offered by today's technologies. Steam power plants operating at low efficiency also lead to an increase in environmentally harmful gas emissions, adding environmental costs to the financial cost. For these reasons, the steam system is in the first place in energy recovery studies [8,9,10]. Boiler efficiency is always below 100% in steam systems. However, most of the heat loss can be minimized with proper operation and practical maintenance. Energy losses in the boiler can be mainly studied in three main categories [11]:

1. Stack gas loss
   a. Dry stack gas loss: Discharge of heat from the stack through waste gases.
   b. Combustion loss: Loss due to unburned fuel and incomplete combustion.
   c. Enthalpy loss: Convection of heat out of the chimney by hot water vapor, including both latent and sensible heat.
2. Heat loss from the surface
3. Blow-off loss

One of the works that can be done to achieve a high boiler efficiency is to reduce heat loss from the surface. For this, the outer surface temperatures should be at the lowest possible values. The factors that cause the

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increase in outer wall temperatures can be listed as follows [12,13]:

- Use of insulation materials that are not suitable for the technique
- Insulation material with an insufficient thickness
- An insulating frame that will form a heat bridge
- Design shortcomings/errors

In modern boilers, the outer wall losses are generally less than 1% if the boiler is running at full load. In old boilers, this rate can be up to 10% due to poor insulation [7,11,14]. Radiation and convection losses can be calculated by measuring the ambient and boiler outer surface temperatures [11,15]. To determine the surface losses in the boiler, the entire boiler surface should be scanned with a thermal camera, and poorly insulated areas should be detected [16].

In steam boilers, the pressure and temperature inside the boiler are constant, regardless of the capacity. The outer wall heat loss is expressed as a percentage of the fuel input energy. Due to this, the outer wall heat loss (%) increases as the boiler load decreases [2,13]. For example, for a steam boiler with a capacity of 1,000 kW, the temperature of saturated water vapor at the pressure of 6 bar is 165°C. If the capacity is 500 kW, there will be an increase in outer wall heat loss because the desired pressure and temperature values will not change. For a boiler with a capacity of 1,000 kW, the loss of outer wall heat loss is 10 kW, while increasing to 2% when the capacity decreases to 500 kW. In this regard, as the boiler capacity decreases, the loss of outer wall heat loss increases proportionally [16]. For most well-maintained boilers, the wall heat loss at full load is expected to be about 0.1–2% of the total fuel input energy [2].

2 Heat loss from the boiler surface

According to EN 12953, the production standard of a fire tube boiler, the outer wall heat losses of a boiler should be limited to 1% of the total boiler capacity. These losses are depending on the boiler's outer wall temperatures. Heat losses on the outer surface of the boiler occur in two different ways in the form of radiation and convection. The heat loss caused by convection is directly proportional to the wall temperatures, and the heat loss by radiation is directly proportional to the fourth force of these temperatures [8,17]. Heat loss by convection from the surfaces is shown in Equation (1), where F is the total surface area, k is the total convective heat transfer coefficient, T_y is the surface temperature, and T_0 is the ambient temperature. To find the total heat lost by convection, the equation is exerted separately for the surfaces at different temperatures, and the results are summed [8].

The amount of heat lost by convection:

$$Q_{\text{convection}} = F.\ k.\ (T_y - T_0)\ \text{(W)} \tag{1}$$

The amount of heat lost by radiation can be calculated using equation (2), where ε denotes the black-body coefficient and σ denotes the Planck coefficient:

$$Q_{\text{radiation}} = F.\ \varepsilon.\ \sigma(T_y^4 - T_0^4)\ \text{(W)} \tag{2}$$

The total outer wall heat loss is obtained by summing the convection and radiation losses [11]:

$$Q_{\text{total loss}} = Q_{\text{convection}} + Q_{\text{radiation}}\ \text{(W)} \tag{3}$$

3 Application of insulation to reduce heat loss from the boiler surface

Thermal insulation is one of the energy-saving methods that can be applied to hot and cold pipelines, facilities, and buildings with heat loss or gain; although it does not require much investment cost, it can save significant amounts of energy and repay itself in a short time with the savings it provides [18]. The most important purpose of boiler outer surface insulation is to reduce the heat loss from the system to the environment and ensure that the properties of the hot flow are kept at the desired level and reduce heat losses from the surface [7,19].

Thermal insulation materials and compositions can be defined as protection equipment or materials against "heat loss" and provide resistance to it. The greater the temperature differences between the system and the environment, the greater the heat transfer rate. The heat flow that may occur between the two environments can be slowed down by placing barriers on the path where the flow occurs. For these reasons, thermal insulations play an important role in the design of the system and are taken into account in the production of all energy-efficient systems and equipment. In addition, insulation is one of the important parameters generally used in energy-saving studies [15].

Insulation of boilers is normally carried out by the manufacturing companies either at the manufacturing site or at the place where the boilers will be mounted at the plant establishment stage [7,19]. Steam boilers are insulated with mineral wool insulation material with a thickness of 80–120 mm. The insulation is protected by a thick steel or aluminum sheet of 1 mm thickness. Boiler parts exposed to high-temperature gases such as the burner connection entry, front fume cupboard, and back cleanout cover without water cooling are coated with refractory material to avoid damage to the steel material. The most commonly used refractory material is fireproof concrete. Some manufacturers also use special materials that are lighter and have a lower heat convection coefficient instead of these heavy materials which do have not very strong thermal insulation properties [19].

Different temperature distributions are available on the outer surfaces of a steam boiler. The boiler body, which is insulated with a thick mineral-based material, is in the range of 35–50°C. The outer surfaces of metal parts that are in contact with boiler water or steam that are not suitable for isolation, such as manholes and hand-holes, ringbolts, and safety valves, are at steam temperature. In the parts that are in contact with the smoke gas such as burner connection flange, boiler doors, fume cupboard, and explosion cover, they are at surface temperatures of 120–200°C [8]. The temperatures of the open surfaces will vary according to the saturation temperature of the steam produced by the steam boiler [11]. During design and installation, boilers with the lowest possible outer wall heat loss rate should be preferred.

The insulation of old boilers may have worn out over time depending on the usage. The temperature increase that occurs on the outer surface of the insulation alarms us that the effectiveness of the insulation is decreasing. A decrease in the amount of heat provided by boilers under the same conditions and a decrease in the operating temperatures of process equipment are also denotations that there is a problem with the isolation of the system [7]. Due to environmental conditions or damage during operation, periodic repairs may be required for outer surfaces. In addition, during annual inspections, the refractory should be checked for troubleshooting or cracks and fractures. The thermal cycle or direct strike to the hot material may have led to a fracture of the refractory. This opportunity is included under predictive and preventive maintenance best practices for reliable steam system operations. Facility personnel is required to use a thermal camera, search for hot spots (temperatures >70°C), and compare these images from time to time to see if any repairs are entailed. There are several reasons for damaged or missing insulation. Some of them are as follows [2]:

- Lack of insulation due to maintenance activities
- Loss/damaged insulation due to misuse
- Damaged insulation due to accidents
- Wear and tearing of insulation due to ambient conditions
- Non-insulated valves and other components as no insulation is made in their design

The insulation status of the boiler and its equipment should be checked from time to time and, if necessary, the insulation should be changed. Instead of renovating by using a material of the same thickness as the old during the replacement, an economic assessment should be made on the basis of the energy and plant costs at the time of replacement and the insulation to be implemented should be re-determined accordingly [7,20]. The critical question here is whether the insulation will be made over the existing insulation when it is damaged or is decided to replace, or whether the old one will be dismantled and replaced. If space permits, it is recommended to make a second layer over the existing insulation, but in a good shape and form. However, in inadequate areas, especially in worn and damaged points, the old one must be dismantled and replaced with a new one [15]. Insulation is constructed in such a way as to bring the boiler surface temperature to a value approximately 30°C above the ambient temperature and is sufficient to minimize the heat losses [7,11,14].

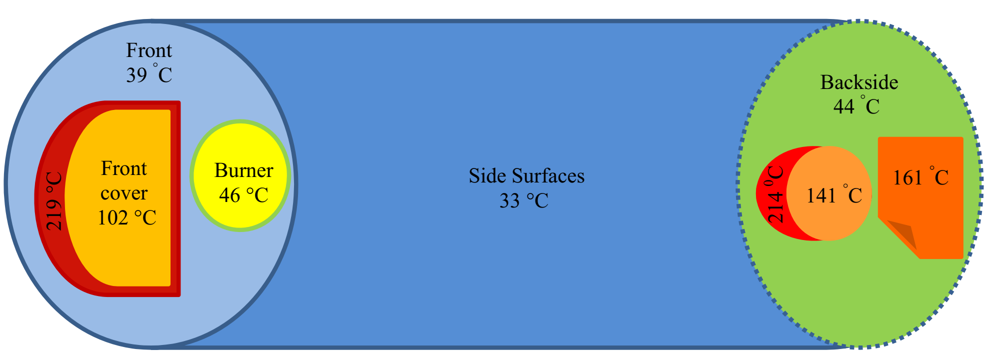

Figure 1: Schematic representation of heat losses in steam boilers.

The economic benefits of insulation applications vary from application to application. The economic advantage of insulation applications is not limited to fuel or energy savings. At the same time, due to the decrease in the capacity of the equipment used in energy production, smaller areas will be needed and due to the reduction in the size of auxiliary enterprises, it will also provide an economic gain during the first investment. In addition, with the insulation applications, there will be a reduction in the establishment investment of the convection distribution system and in the operating costs of the convection-distribution system, such as condensation losses and the operation of pump systems. Investments in an existing enterprise may not have all of these advantages. However, when the load of the facility increases due to insulation applications in case of capacity increase, it will save on additional investment costs in energy production systems, as well as less energy will be consumed, and a significant amount of fuel savings will also be achieved depending on the current situation [6]. Fuel saving will also contribute to the reduction of greenhouse gas emissions. Thus, it will be possible to ensure sustainable, effective, and efficient production conditions.

4 Heat losses from the boiler surface in the current situation

For a steam boiler installed 17 years ago with a steam capacity of 5 t/h and working at a pressure of 10 bar at a plant operating in Bilecik city, outer wall heat losses were calculated. The boiler works about 5,760 h a year and produces steam at a temperature of about 240°C. Outer wall heat losses were tried to be detected by using a thermal camera and an infrared thermometer. The representative scheme of the boiler was drawn and the parts such as the front cover, and fume cupboard were shown in different colors, and the changing temperature distributions in different parts of the boiler are presented in Figure 1.

In the current case, the heat losses in different parts of the boiler were calculated separately and presented in Table 1, and the total heat loss was calculated as 18.5 kW. In Table 2, the coefficients used to calculate heat loss from the surface by convection and radiation are given.

When Figure 1 and Table 1 are examined, it is seen that the boiler side surfaces and the front and back surfaces are insulated. However, serious temperature values were measured on the front cover and back cover surfaces, and

Table 1: Heat losses on the surface of the steam boiler before the improvement works

Surfaces	The side surface of the front cover	The side surface of the back cover	Smoke pipe	The back surface of the back cover	The front surface of the front cover	Burner	The back surface of the boiler	The front surface of the boiler	The side surface of the boiler
Average temperature (°C)	219	214	161	141	102	46	44	39	33
Area (m^2)	0.96	0.33	0.42	0.19	1.19	0.64	3.3	2.32	36.13
Heat loss by convection (W)	1,571	526	489	190	814	146	698	397	4,411
Heat loss by radiation (W)	2,659	872	640	227	808	110	520	288	3,108
Loss (%)	29.7	9.8	7.9	2.9	11.4	1.8	8.6	4.8	52.8

Table 2: Values and coefficients used in calculations

Boiler room temperature (°C)	Heat transfer coefficient (W/m^2 K)	Emissivity	Planck coefficient (W/m^2 K^4)
18	8.14	0.95	5.67×10^{-8}

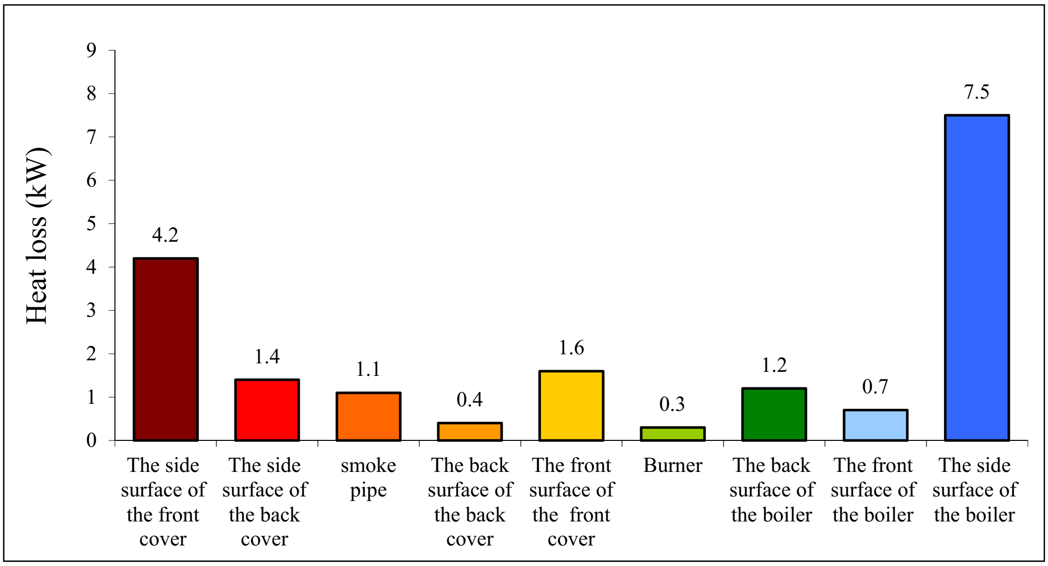

Figure 2: Distribution graph of steam boiler heat losses before improvement works.

it was found that the heat losses caused by these temperature values were also at high levels. The heat loss distribution graph prepared to have an idea of where to start the work on reducing surface heat loss in the boiler is given in Figure 2.

When the graph given in Figure 2 is examined in detail, it is seen that the side surfaces of the boiler, where heat loss is the highest, have a temperature of 33°C and are already insulated. Therefore, it would be a more correct approach to concentrate on the insulation of regions

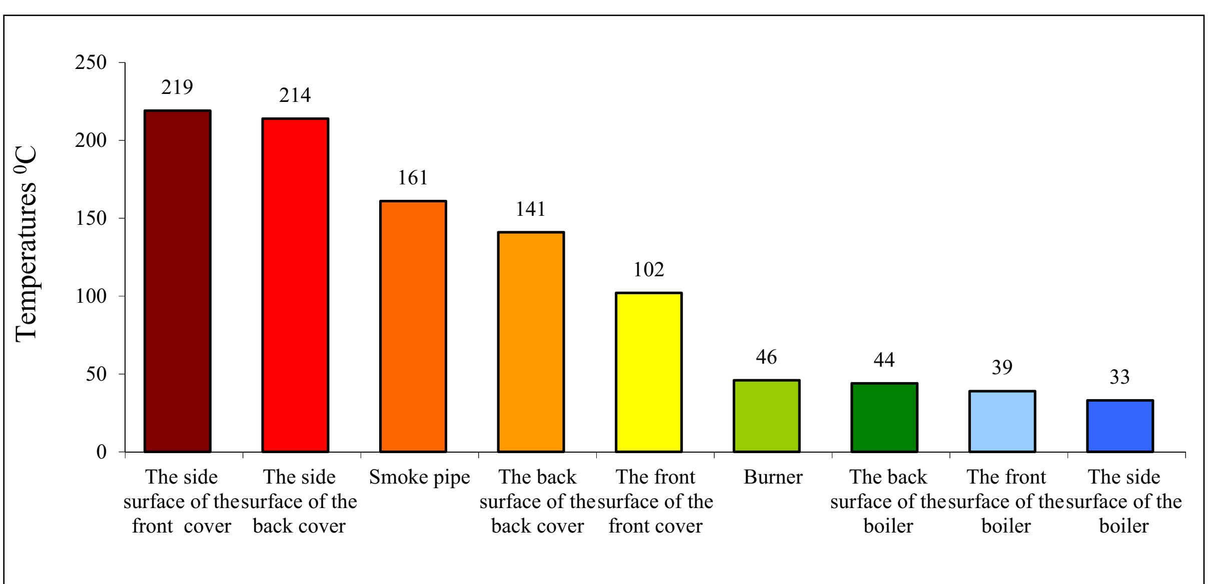

Figure 3: Pareto diagram of surface temperature before improvement works.

with high temperatures. The Pareto diagram prepared for this purpose, which reflects the change of boiler outer wall temperatures according to the regions, is presented in Figure 3. The temperature values specified in the Pareto diagram were obtained by taking the average of at least four measurements for each region and when the boiler room temperature was 18°C. When this figure was analyzed, it was found that the temperature was very high, especially on the front and back covers. At the same time, a significant amount of heat is lost on these surfaces.

5 Improvement proposal

Boiler covers are usually left uninsulated by the boiler manufacturers or insufficient insulation is applied. Boiler cover jackets provide an excellent solution in these cases. To prevent heat loss from the boiler covers, the boiler covers can be covered with insulation jackets suitable for the desired surface so that there is no open part, by taking the necessary measurements with the right insulation materials and fabrics. These products, which are manufactured in the workshop or on-site, are dressed on the machine or equipment according to the place of application in such a way as to prevent heat loss from the surface. A machine isolated in this way becomes ready for repair, thanks to the easy removal of the jackets during periodic maintenance or repair. After the necessary repairs are made, the jackets and pads are put back in their old places and the machine becomes ready to work in a very short time. These applications continue to save energy in enterprises for many years without losing their properties. Thus, by keeping the surface temperatures at the desired levels, personal protection in terms of occupational health and

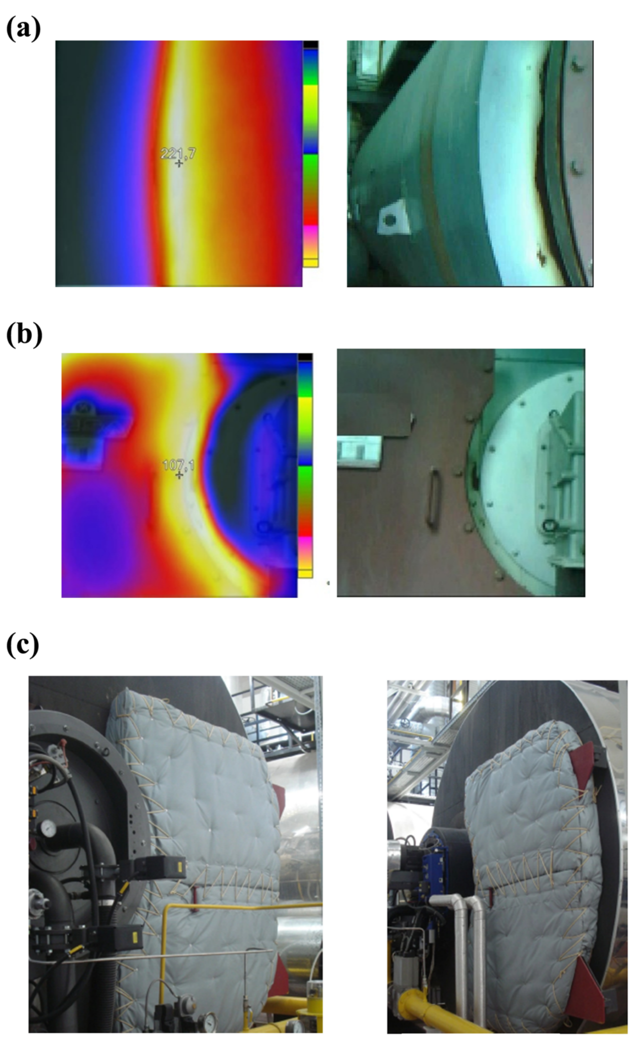

Figure 4: (a) Side surface of the front cover (219°C), (b) front surface of the front cover (102°C), and (c) recommended insulation jacket for the front cover.

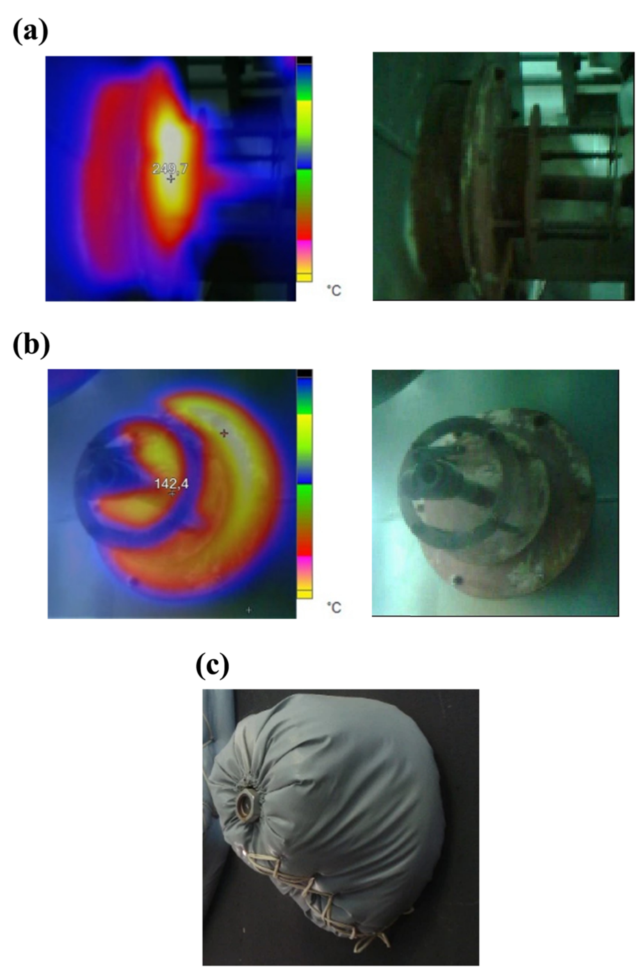

Figure 5: (a) Side surface of the back cover (214°C), (b) front surface of the back cover (141°C), and (c) recommended insulation pad for the back cover.

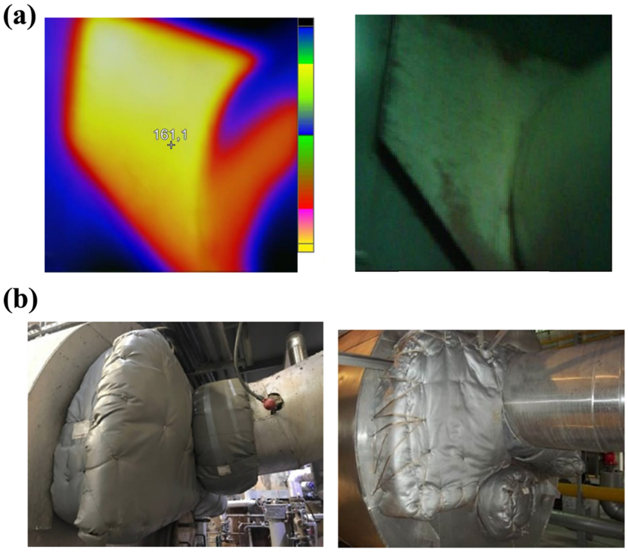

Figure 6: (a) Smoke pipe (161°C) and (b) recommended insulation jacket and pad for the smoke pipe.

safety is provided, and serious energy savings are achieved [19,20].

Serious heat losses were detected in the fume cupboard on the front and back covers of the steam boiler used in the enterprise. The heat lost from the boiler's outer walls can be minimized by using boiler jackets and pads. Boiler covers can be covered with insulation jackets using the right insulation material in the required dimensions so that there will be no open part suitable for the cover surface [21]. In Figures 4–6, thermal images of boiler parts with high surface temperatures are given and examples of insulation jackets and pads that can be applied for these regions are shown. The proposed boiler insulation jackets and pads are manufactured using high-temperature resistant and low-thermal conductivity materials.

6 Heat losses from the surface after improvement

To determine the amount of savings to be provided by insulation, the heat losses occurring in the hot surfaces in the previous state and after insulation were calculated. If the surface temperatures are brought to 38°C using insulation jackets and pads for high-temperature areas of the boiler, the total heat loss will decrease from 18.5 to 10.5 kW. The total heat loss that will occur in the proposed case is shown in Table 3.

It was calculated that 8 kW of heat savings per hour can be achieved if the proposed insulation investments

Table 3: Heat losses on the surface of the steam boiler after improvement works

Surfaces	The side surface of the front cover	The side surface of the back cover	Smoke pipe	The back surface of the back cover	The front surface of the front cover	Burner	The back surface of the boiler	The front surface of the boiler	The side surface of the boiler	
Average temperature (°C)	38	38	38	38	38	46	44	39	33	
Area (m^2)	0.96	0.33	0.42	0.19	1.19	0.64	3.3	2.32	36.13	
Heat loss by convection (W)	156	54	68	31	194	146	698	397	4,411	
Heat loss by radiation (W)	113	39	49	22	140	110	520	288	3,108	
Total heat loss (kW)	0.3	1.4	1.1	0.4	1.6	0.3	1.2	0.7	7.5	10.5
Loss (%)	2.6	0.9	1.1	0.5	3.2	2.4	11.6	6.5	71.3	

are made, and the payback period of the investment was found to be 3 months.

Insulation cost = 3,600 TL
Natural gas unit price = 0.3075 TL/kW
Boiler annual operating time = 5,760 h
Natural gas saving = 8 kW × 5,760 = 45,080 kW/year
Annual saving = 14,171 TL/year
Payback period = 3,600/14,171 = 3 months

7 Conclusion

In this study, the surface heat losses of a steam boiler used for 17 years in the distillation process in a company operating in the textile sector were scrutinized. Temperatures in different parts of the boiler were measured using a thermal camera and an infrared thermometer, and areas with insufficient and incomplete insulation were tried to be detected. In this direction, a heat loss graph was created and a Pareto diagram was used to determine the primary region for improvement. According to the Pareto diagram, it was seen that serious temperature values were reached on the front and back covers. For improvement, it was proposed to cover surfaces with high temperatures by insulating jackets and pads. By calculating the heat losses before and after the improvement, it was envisaged that 8 kW of heat can be saved per hour, thanks to the insulation. It was calculated that the investment required for insulation will repay itself in as little as 3 months.

Insulation of non-insulated areas in the boiler and renewal of insulation in places with poor insulation will prevent heat energy loss and provide an efficiency-enhancing effect. Insulation is one of the issues that are primarily and widely discussed in energy recovery studies because it can be easily applied, saves serious amounts of energy, and can repay itself in a short time. Insulation saves fuel and money, as it reduces the amount of heat loss. If we look at it from a broader perspective, it can be easily stated that insulation not only reduces energy consumption but also protects the environment.

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Data availability statement: All data generated or analyzed during this study are included in this published article (and its supplementary information files).

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