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# EXPERIMENTAL INVESTIGATION OF A FOOD PLANT USING WASTE HEAT RECOVERY SYSTEMS TO DETERMINE THE POTENTIAL FOR FUEL SAVINGS

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**Abstract**: Nowadays, energy efficiency is the crucial element in industry in terms of improving operating conditions steam boilers. Generally, feed-water economizers and air preheaters are used for this aim in steam boilers to recover heat from the flue gases. The measurements of volumetric percentages O2 (5.7%) and CO (0%) in flue gas, temperatures of flue gas (100, 150, 168, 218 °C), ambient (23.8 °C), surface (38.3, 40.8, 65.5, 132.5, 166.65 oC), feed-water (108°C) preheated feed water (133 °C) and steam (166.65 °C), consumption of natural gas (149.4 $Nm^3$/15 mins) and steam (2000 kg/15 mins), conductivity of feed-water (134.25 ppm) and boiler water (3500 ppm), operating pressures (6.3 bar), absolute pressure (7.3 bar) are performed experimentally. Various case studies such as steam boiler operation without the use of economizer or air preheater, economizer addition to the steam boiler, addition of air preheater to steam boiler, addition of both economizer and air preheater to steam boiler are carried out to discuss the effects of the use of either feed-water economizer or air preheater separately and together. Consequently, total heat loss and efficiency values, fuel consumption and saving amounts, investment and operation-maintenance costs, some economic analyses using the methods of net present value and internal rate of ratio are calculated using measured values for each case study separately and compared with each other considering the case studies. It is expected from this study that investors will benefit from the calculation process used for an example application of steam boiler in a food plant to establish heat recovery systems in plants. As a result of experimental analyses, the heat recovery method from flue gas is found to be one of the effective processes to save energy in a boiler as expectedly.
**Keywords**: Heat recovery, Industrial processes, Energy Efficiency, Fuel saving, Boiler, Economizer, Air preheater, Method of Net Present Value (NPV), Method of Internal Rate of Return

# ISI GERİ KAZANIM SİSTEMLERİ KULLANILAN BİR GIDA FABRİKASININ YAKIT TASARRUF POTANSİYELİNİN DENEYSEL OLARAK ARAŞTIRILMASI

**Özet**: Günümüzde, buhar kazanlarının işletme şartlarını iyileştirme açısından bakıldığında enerji verimliliği endüstrideki en önemli unsurdur. Bu amaçla buhar kazanlarında baca gazından ısı geri kazanımı için genellikle besleme suyu ekonomayzerleri ve hava ısıtıcıları kullanılır. Baca gazı içindeki $O_2$ (5.7%) ve CO (0%) hacimsel yüzdesi, baca gazı sıcaklıkları (100, 150, 168, 218 °C),ortam sıcaklığı (23.8 °C), yüzey sıcaklıkları (38.3, 40.8, 65.5, 132.5, 166.65 °C), besleme suyu sıcaklığı (108°C),ön ısıtılmış besleme suyu sıcaklığı (133 °C) ve buhar sıcaklığı (166.65 °C),doğal gaz tüketim miktarı (149.4 $Nm^3$/15 dakika) , buhar tüketimi (2000 kg/15 dakika), besleme suyu iletkenliği (134.25 ppm), kazan suyu iletkenliği (3500 ppm), işletme koşulları (6.3 bar), mutlak basınç (7.3 bar) ölçümleri yapılmıştır. Sistem ekonomayzer veya hava ısıtıcı kullanılmadan, ekonomayzer kullanılarak, hava ısıtıcısı kullanılarak, hem ekonomayzer hem hava ısıtıcısı kullanılarak farklı şekillerde çalıştırılarak değerlendirilmiş, hem besi suyu ısıtıcısının ve ekonomayzerin ayrı ayrı ve birlikte kullanılmasının etkileri incelenmiştir. Bu nedenle, ölçüm sonuçları kullanılarak her durum için ayrı ayrı toplam ısı kaybı ve verim değerleri, yakıt tüketimi ve tasarruf miktarı, yatırım ve işletme-bakım maliyetleri hesaplanmış ve Net Bugünkü Değer ile İç Karlılık Oranı metodları kullanılarak ekonomik analizleri yapılmış, farklı uygulamalar birbirleriyle karşılaştırılmıştır. Bir gıda tesisindeki buhar kazanı için yapılan bu örnek çalışmanın tesislerinde ısı geri kazanım sistemi kuracak yatırımcılar için faydalı olacağı düşünülmektedir. Deneysel analizlerin sonucu olarak, baca gazından ısı geri kazanım metodunun bir kazanda enerji tasarrufu yapmak için en etkili metodlardan biri olduğu görülmüştür.
**Anahtar Kelimeler**: Isı geri kazanımı, Endüstriyel prosesler, Enerji verimliliği, Yakıt tasarrufu, Kazan, Ekonomizer, Hava ısıtıcısı, Net bugünkü değer yöntemi, İç verimlilik yöntemi

## NOMENCLATURE

| | |
|---|---|
| A | heat transfer surface area, [$m^2$] |
| BF | amount of fuel, [kg $h^{-1}$] |
| BM | blow down proportion, [%] |
| Bt | cash inflows, [$] |
| CF | carbon mass amount in fuel, [%] |
| Ct | cash outflows, [$] |
| Dh | steam generated by boiler, [kg $h^{-1}$] |
| g | inflation rate, [%] |
| I | conductivity, [ppm] |
| IRR | Method of Internal Rate of Return |
| L | loss, [%] |
| LHV | low heating value of fuel, [kJ $m^{-3}$] |
| HF | hydrogen mass amount in fuel, [%] |
| HHV | high heating value of fuel, [kJ $m^{-3}$] |
| hFW | enthalpy of feed-water, [kJ $kg^{-1}$] |
| hg | enthalpy of steam, [kJ $kg^{-1}$] |
| i | interest rate, [%] |
| NPW | Method of Net Present Value |
| PP | payback period |
| r | real interest rate, [%] |
| T | temperature, [°C] |
| Q | energy rate from the fuel, [kW $m^{-3}$] |
| U | total heat transfer coefficient, [W $m^{-2}K^{-1}$] |

**Symbols**

| | |
|---|---|
| η | efficiency |
| ε | emissivity |

**Subscripts**

| | |
|---|---|
| b | boiler |
| BD | blow down |
| Con | convection |
| DFG | dry flue gas |
| FG | flue gas |
| MFG | moist flue gas |
| NG | natural gas |
| Rad | radiation |
| s | surface |
| T | total |
| 0 | ambient |

## INTRODUCTION

In this study, a 7.8 MW Scotch type steam boiler is used as a test component in a food plant to improve the energy efficiency and reduce the natural gas consumption using an economizer and an air preheater. Steam boilers are usually used in many applications and houses, and produce very high amounts of energy. Therefore, they consume quite high amount of fuel. Solutions are about reducing the fuel consumption by means of heat recovery and decrease of energy waste. Energy efficiency of large energy boilers is generally calculated by the indirect method which is related with the determination of flue gas losses and unburned combustible losses. The information on the operating parameters affecting the temperature of flue gases and the substances of combustible particles in the solid combustion products should be known to determine these losses.

Price and Majozi (2009) investigated the traditional steam system consist of a steam boiler and the connected heat exchanger network (HEN). They used a process integration technique considering conceptual and mathematical analysis without compromising boiler efficiency as case studies. It was found that the efficiency can be maintained for a reduced steam flow rate preheating the return flow.

Kuprianov (2005) performed theoretical and experimental studies on development and application of the method aimed at excess air optimization for utility/industrial steam boilers fired with fossil fuels using the cost-based excess air optimization. Experimental and theoretical, firing different fossil fuels in utility and industrial boilers, pursuing distinct goals, etc. are discussed as case studies. As a result of the work, noticeable reduction of the total operational costs, associated with the fuel consumption and environmental impact for the particular boiler is obtained by switching the combustion excess air to the optimized or "compromise" values.

Moghari *vd* (2012) performed both numerical and experimental investigations on determining temperature distribution of water and flue gas flows in its different heat exchange equipment using a D-type water-cooled natural gas-fired boiler. Heat transfer characteristics were analyzed with the zonal method. They have agreed results between the numerical and experimental values about the distribution of heat flux on different furnace walls and that of flue gas and water/steam temperature in different convective stages including superheater, evaporating risers and downcomers modules, and economizer.

Aljundi (2009) presented the energy and exergy analysis of a power plant aiming to analyze the system components separately. As a result, largest energy and exergy losses were identified by a component wise modeling and their sites were determined. The condenser has the maximum energy losses with 134MW while only 13 MW was lost from the boiler system. It is also found that preheating the combustion air and reducing the air–fuel ratio can reduce the exergy destruction in a boiler system.

Tanetsakunvatana and Kuprianov (2007) investigated the boiler heat losses and thermal efficiency experimentally. They also discussed the effects of operating conditions and fuel quality in their study. They concluded that the excess air ratio, unit load and fuel lower heating value affect the boiler thermal efficiency weakly. The determination of the emission rates and specific emissions for $NO_x$, $SO_2$ and CO were performed while they benefitted from the fuel consumption boiler to determine the emission characteristics for $CO_2$ with the use of fuel-C.

Kljajic *vd* (2012) presented a method for modeling, assessing, and calculating the efficiency of boilers using measured operating performance of 54 randomly selected boilers. Their method was developed based on a neural network approach and they estimated the boiler efficiency and analyzed the possibilities for enhancing efficiency.

Rusinowski and Stanek (2010) developed a hybrid model of a boiler using both analytical modelling and artificial intelligence. The balance equations were included in their analytical sort of the model whereas the dependence of the flue gas temperature and the mass fraction of the unburnt combustibles in solid combustion products on the operating parameters of a boiler were included in their empirical model.

Bujak (2008) proposed a mathematical model belonging to a boiler room to investigate its thermal efficiency. An open thermodynamic system exchanging mass, energy, and heat with the atmosphere was used in the model. The experimental study took 18 months and the results were validated by a real steam boiler of a hospital.

Bujak (2008) developed a mathematical model to determine the optimized energy losses for a group of liquid- or gas-fired shell boilers providing a common load. According to their model, differences in the energy losses between the standard and optimized conditions were found as a maximum value of 79 kJ/s when the heat load increased from 0 to 30%. They proposed their optimization system to the existing and proposed plants. They found that less than half a year for the optimization controller is necessary to the payback period on investment.

Chen *vd*, (2012) investigated to obtain large amount of low grade heat available from a flue gas condensing system through industrial condensing boilers and their feasibility in a large scale district heating system as a case study. They reviewed the technology and application of industrial condensing boilers in several heating systems. Their study indicated that the tested system could achieve importantly higher efficiency values than conventional boilers by recovering the latent heat of water vapor in the flue gas through condensing boilers. They also benefitted from Net Present Value (NPV) calculations and these calculations show that the use of carbon steel condenser instead of a stainless steel condenser ensured cash return in a relatively shorter period of time.

Yang and Dixon (2012) prepared some case studies on assessing and investing in boiler steam systems. They proposed methodologies and approaches for data collection and performed some analyses for their countries specifically. They checked if investing in energy efficiency in industrial boiler steam system in China and Vietnam are cost effective as a result of their analyses.

Saidur *vd*, (2010) analyzed the useful concept of energy and exergy utilization and benefitted from the boiler system. They calculated energy and exergy efficiencies in a boiler as 72.46% and 24.89%, respectively. The combustion chamber is found as the main provider for exergy destruction followed by heat exchanger of a boiler system. Moreover, they also used variable speed drive in boiler's fan energy savings and heat recovery from flue gas to reduce the boiler's energy use. As a result of their analyses, the payback period is found almost 1 year for heat recovery from a boiler flue gas.

Barroso *vd*, (2003) carried out an experimental work in order to increase the efficiency of the RETAL-type boiler. They paid attention on the importance of the stoichiometric ratio and steam power on the overall efficiency during their test evaluation. They determined the optimum waste heat recovery scheme from both, thermal and economical viewpoints and thus they performed an optimum boiler design. They calculated the total cost and decided the most efficient low-temperature heat recovery system as the combination of an economizer followed, in the direction of the exhaust gas flow, by an air heater.

Energy efficiency is a concept that should be applied and become widespread all over the world. The increase in the energy efficiency of boilers is one of the fundamental responsibilities in plants. Today, there are many methods employed in order to increase the efficiency of steam boilers. In the present study, the effects of the use of economizer and air preheater with various case studies, most commonly used in steam boilers, on boiler efficiency and fuel consumption were examined and the economic analyses of these case studies were conducted using real experimental data taken from a Scotch type steam boiler in a plant. The calculation procedure is given as a methodology regarding with the determination of Scotch type steam boiler's heat losses, efficiency and the economic analysis of the system considering investment costs in this paper. The significance of use of heat recovery method from flue gas is also emphasized as an effective process to save energy in a boiler.

## EXPERIMENTAL SETUP

Fig. 1 shows the schematic view of the examined Scotch type steam boiler with feed water economizer and air preheater in a food plant in Turkey. It has got 7.8 MW power, 8 ton/h installed capacity, 300 $m^2$ area, 7.3 bar operating pressure (saturated vapor) and it is a natural gas-fired one.

It is possible to heat boiler feed water with the flue gasses within heat exchangers called economizer. With this method, fuel consumption is reduced because the feed water conveyed to the boiler has a higher temperature. A feed water economizer reduces steam boiler fuel requirements by transferring heat from the flue gas to incoming feed water. Generally, boiler efficiency can be increased by 1% for every 5°C reduction in flue gas temperature. By recovering waste heat, an economizer can often reduce fuel requirements by 5% to 10%. The minimum level of flue gas temperature that can be achieved with a flue gas heat recovery system depends on the type of the fuel used.

Generally, economizer gas output temperature can be reduced down to 180°C in boilers using fuel oil, 150°C in boilers using diesel oil and 110°C in boilers using natural gas. In this study, the flue gas temperature was reduced from 218°C to 150°C in the economizer as shown in Table 1. Approximately, it should be noted that each case of heating the air for more than 50°C brings along a 2% saving.

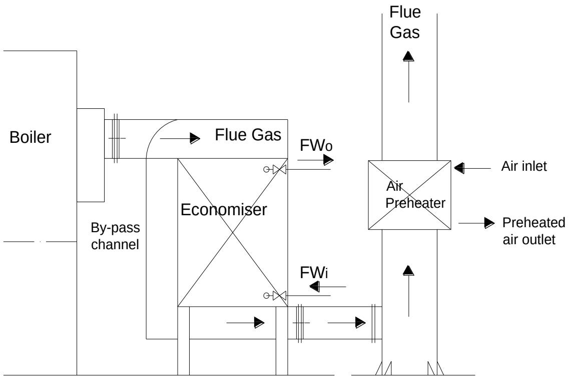


**Figure 1.** Schematic view of used Scotch type steam boiler with feed water economizer and air preheater

The measurements and calculations necessary for the purpose of determining the effects of economizer and/or air preheater applications in the boiler house of a food plant on the boiler efficiency were conducted. Economic feasibility of the heat recovery systems planned to be implemented in consequence of these measurements and calculations were scrutinized. In order to monitor economizer and air preheater performance and their contribution to fuel saving, 4 different applications were planned and 4 respective efficiencies were calculated. The case studies performed in the food plant's Scotch type steam boiler are shown separately as follows:

Case 1: Steam boiler operation without the use of economizer or air preheater
Case 2: Economizer addition to the steam boiler
Case 3: Addition of air preheater to steam boiler
Case 4: Addition of both economizer and air preheater to steam boiler

Table 1 shows the measured values from the system illustrated in Fig. 1 according to the investigated case studies above. It should be noted that flow rates, pressures and thermal conductivity values were measured by existing equipment on the system, temperatures and flue gas emissions were measured by a thermal camera and a flue gas analyzer respectively.

## CALCULATION PROCEDURE FOR ENERGY EFFICIENCY

Thermal efficiency of a boiler is an indicator of the extent with which the energy of the fuel burned in the boiler can be utilized. In order to achieve a high level of efficiency, the measures that can be taken during the design and manufacture phases, on the basis of all of the known losses, have to be determined and implemented.

While energy efficiency in boilers is based on the perfection of combustion and the rate with which the heat energy generated with combustion is transferred to the fluid in the boiler, flue gas emissions depend on a number of factors including, again the quality of combustion, furnace and burner design and also the pollutants present in the fuel used.

Thermal efficiency of boilers is ascertained by means of the determination of losses. The general losses in boilers are presented in this section. The total heat amount obtained from per unit mass of fuel is calculated as follows:

$$q = LHV\ \eta_b \tag{1}$$

where LHV is the low heating value of fuel.

Boiler efficiency can be determined on the basis of the measurements carried out in the facilities. In order to do this, it is necessary to accurately determine the amount of steam generated by the boiler in a unit of time. The heat obtained from the fuel is transferred to the feed water in steam boiler. The heat obtained in the boiler, in other words, the amount of steam can be calculated with the aid of the below equation.

$$D_h\ .\ (h_g - h_{FW}) = BF\ .\ LHV\ .\ \eta_b \tag{2}$$

where $D_h$ and BF are the steam generated by boiler and amount of fuel, respectively

Heat loss percentages of certain types were calculated pursuant to the Turkish Standard 4041, on the basis of the measurements. This standard contains testing and efficiency requirements for hot water, super-heated water and steam boilers and heat losses are calculated as percentiles considering low heating value of fuel.

Percentage of heat loss due to dry flue gas outlet is calculated using as:

$$L_{DFG} = \frac{K.(T_{FG} - T_0)}{CO_2} . \frac{HHV}{LHV} \tag{3}$$

where HHV is the high heating value of fuel, the 'K' value is calculated on the basis of the characteristic of the fuel and obtained as:

$$K = \frac{69.7 C_F LHV^2}{HHV^3} \tag{4}$$

Carbon dioxide amount in the flue gas is obtained as:

$$CO_2 = 1 - \frac{O_2}{21} . CO_{2,max} \tag{5}$$

Percentage of heat loss due to moisture (sensible heat of $H_2O$) in the flue gas is determined as:

$$L_{MFG} = \frac{9.H_F.(50 - T_0 + 0.5.T_{FG})}{HHV} . \frac{HHV}{LHV} \tag{6}$$

**Table 1.** Measured values from Scotch type steam boiler according to the investigated case studies.

| $O_2$ (%) | CO (%) | $T_{FG}$ (°C) | $T_o$ (°C) | $T_{FW}$ (°C) | $I_{FW}$ (ppm) | $B_{NG}$ ($Nm^3$/15 mins) | $D_h$ (kg/15 mins) | $P_{op}$ (bar) | $P_{abs}$ (bar) | $T_{sat}$ (°C) | $T_{s,f}$ (°C) | $T_{s,r}$ (°C) | $T_{s,rt}$ (°C) | $T_{s,l}$ (°C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Case 1: Steam boiler operation without the use of economizer or air preheater | | | | | | | | | | | | | | |
| 5.7 | 0 | 218 | 23.8 | 108 | 134.25 | 149.4 | 2000 | 6.3 | 7.3 | 166.65 | 65.5 | 132.5 | 38.3 | 40.8 |
| Case 2: Economizer addition to the steam boiler | | | | | | | | | | | | | | |
| 5.7 | 0 | 150 | 23.8 | 133 | 134.25 | 149.4 | 2000 | 6.3 | 7.3 | 166.65 | 65.5 | 132.5 | 38.3 | 40.8 |
| Case 3: Addition of air preheater to steam boiler | | | | | | | | | | | | | | |
| 5.7 | 0 | 168 | 23.8 | 108 | 134.25 | 149.4 | 2000 | 6.3 | 7.3 | 166.65 | 65.5 | 132.5 | 38.3 | 40.8 |
| Case 4: Addition of both economizer and air preheater to steam boiler | | | | | | | | | | | | | | |
| 5.7 | 0 | 100 | 23.8 | 133 | 134.25 | 149.4 | 2000 | 6.3 | 7.3 | 166.65 | 65.5 | 132.5 | 38.3 | 40.8 |

Percentage of heat loss due to unburned carbon monoxide at flue outlet;

$$L_{CO,FG} = \frac{K.CO}{CO_2 + CO}.\frac{HHV}{LHV} \quad (7)$$

where the value K is taken as 32 for natural gas in Eq. (7).

Percentage of heat loss from furnace surface via radiation and convection is calculated as:

$$L_{Rad,Con} = \frac{L''_{Rad,Con}}{Q}.100 \quad (8)$$

where the heat provided by the fuel is calculated as:

$$Q_F = B_F.LHV \quad (9)$$

where the total percentage of heat loss from walls is determined as:

$$L''_{Rad,Con} = (U_{Rad} + U_{Con}).A.(T_s - T_0) \quad (10)$$

where the total heat transfer coefficient of radiation is calculated from the heat balance as:

$$U_{Rad} = \frac{\varepsilon 5.67.10^{-8}}{T_s - T_0}.\left[\left(\frac{T_s}{100}\right)^4 - \left(\frac{T_0}{100}\right)^4\right] \quad (11)$$

where the emissivity (ε) is taken as 0.98 and the total heat transfer coefficient of convection is calculated as:

$$U_{Con} = B.(T_s - T_0)^{0.25} \quad (12)$$

where the coefficient of B in Eq. (12) is taken from Table 2.

**Table 2** B coefficients according to the surfaces [14].

| Surface specification | B |
|---|---|
| Horizontal surfaces (upcast) | 1.7 |
| Vertical surfaces and wide cylinders | 1.45 |
| Horizontal cylinders | 1.2 |

It should be noted that Eq. (10) is calculated for the surfaces at the front, rear, right and left, separately.

Eq. (13) is calculated by summing up the heat loss percentages calculated above:

$$L = L_{DFG} + L_{MFG} + L_{CO,FG} + L_{Rad,Con} \quad (13)$$

Percentage of heat loss due to blow down is expressed as:

$$L_{BD} = \frac{(T_{BD} - T_{FW}).BM.(100 - L)}{((T_{BD} - T_{FW}).BM) + (100 - BM).(660 - T_{FW})}.\frac{HHV}{LHV} \quad (14)$$

where BM is determined as follows:

$$BM = \frac{I_{BD}}{I_{FW}} \quad (15)$$

where $I_{BD}$ and $I_{FW}$ are the conductivity of blow down and feed-water, respectively.

Total heat loss values are obtained from Eq. (16) as:

$$L_T = L + L_{BD} \quad (16)$$

Finally, boiler efficiency can be ascertained by calculating waste heat percentages on the basis of the measurements done pursuant to Turkish Standard 4041 and it is calculated as follows:

$$\eta_b = 100 - L_T \quad (17)$$

## CALCULATION PROCEDURE FOR ECONOMIC ANALYSES

While carrying out the economic analysis of the applications, Net Present Value (NPV) and Internal Rate of Return (IRR) Methods, which take the time value of money into consideration, were employed.

Considering that the economic life of the project is 10 years, interest rate (i) is 20% and inflation rate (g) is 11.14%, real interest rate (r) was calculated as 7.97% with the aid of the Eq. (18) presented below, and these values were used in economic analysis calculations.

$$r = \frac{i - g}{1 + g} \quad (18)$$

Net Present Value (NPV) is the difference amount between the sums of cash inflows ($B_t$) and cash outflows ($C_t$). The present value of money today to the present value of money in future is compared by means of this method considering inflation and returns and it is expressed as:

$$NPV = \sum_{t=0}^{n} \frac{B_t}{(1+r)^t} - \sum_{t=0}^{n} \frac{C_t}{(1+r)^t} \quad (19)$$

Internal Rate of Return (IRR) is the process of applying a discount rate that results in the present value of future net cash flows equal to zero.

Simple payback period (PP) is calculated for all cases as follows:

$$PP = \frac{investment}{annual\ net\ saving} \quad (20)$$

## RESULTS AND DISCUSSION

There are limitations on the lowest temperature of flue gases to prevent from condensation and possible corrosion in the chimney. It is approximately 120°C for natural gas, 150°C for coal and low sulphur content fuel oils, and 175°C for high sulphur fuel oils. A feed-water economizer is used in case there is insufficient heat transfer surface within the boiler to remove heat of combustion. Boilers, which have more than 1 MW power and operating at pressures exceeding 6 bar or above, are considerably loaded during all year and they are suitable candidates for heat recovery applications. It should be noted that the investigated Scotch type steam boiler has an appropriate one for the pre-heating and economizer improvements on the efficiency with its 7.8 MW power and 7.8 bar operating conditions.

There are several efficiency terms defined by boiler suppliers such as thermal efficiency, combustion efficiency, boiler efficiency and fuel to steam efficiency. The verification of these efficiencies is performed by either test processes costly or basic boiler design data economically. There are common elements on the estimation of efficiencies such as boiler stack temperature, heat content of boiler, fuel specification, excess air levels, ambient air temperature and relative humidity. Boiler efficiency is evaluated with two methods: Input - output or direct method, and heat loss or indirect method. The energy gain of the working fluid to the energy source of the fuel is compared by direct method which may not be as accurate due to errors in measuring devices for fuel and steam flows. Indirect method calculates the efficiency by adding the losses and comparing with the heat input. This method is used in this study due to its high predictability of efficiency.

There are 4 experimental case studies, performed in a food plant, in this investigation. All possible variations on the use of economizer and preheater applications as heat recovery systems are done using a steam boiler to determine energy efficiency, fuel consumption and the payback period of the investment. A beneficial experimental data in Table 1 and other results from Table 3 to 6 are given for other researchers' usage in detail.

**Table 3.** Total heat transfer coefficients by Radiation ($U_{Rad}$) and Convection ($U_{Conv}$) from the steam boiler.

| Heat losses | Case 1-2-3-4 |
|---|---|
| $U_{Rad,f}$ (W/m$^2$K) | 7.155 |
| $U_{Rad,r}$ (W/m$^2$K) | 9.857 |
| $U_{Rad,rt}$ (W/m$^2$K) | 6.253 |
| $U_{Rad,l}$ (W/m$^2$K) | 6.332 |
| $B_f$ | 1.45 |
| $U_{Con,f}$ (W/m$^2$K) | 3.685 |
| $B_r$ | 1.45 |
| $U_{Con,r}$ (W/m$^2$K) | 4.683 |
| $B_{rt}$ | 1.7 |
| $U_{Con,rt}$ (W/m$^2$K) | 3.321 |
| $B_l$ | 1.45 |
| $U_{Con,l}$ (W/m$^2$K) | 3.321 |
| $L''_{Rad,Con,f}$ (W) | 676.057 |
| $L''_{Rad,Con,r}$ (W) | 1788.605 |
| $L''_{Rad,Con,l}$ (W) | 686.562 |
| $L''_{Rad,Con,rt}$ (W) | 604.637 |
| $L''_{Rad,Con}$ (W) | 3230.041 |
| $B_F$ (Nm$^3$/h) | 597.6 |
| LHV (Nm$^3$/h) | 8250 |
| $Q_F$ (kW) | 5724.51 |
| $L_{Rad,Con}$ (%) | 0.07 |

**Table 4.** Total loss and calculated energy efficiency values according to the investigated case studies.

| Total loss / Case | $CO_2$ (%) | K (Eq. 4 ) | BM (%) | $I_{FW}$ (ppm) | $L_{DFG}$ (%) | $L_{MFG}$ (%) | $L_{CO}$ (%) | $L_{Rad,Con}$ (%) | $L_{BD}$ (%) | $L_T$ (%) | $\eta_b$ (%) | Increase in $\eta_b$ (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 8.55 | 0.311 | 3.8 | 3500 | 7.83 | 2.46 | 0.00 | 0.07 | 0.42 | 10.78 | 89.22 | 1 |
| 2 | 8.55 | 0.311 | 3.8 | 3500 | 5.09 | 1.84 | 0.00 | 0.07 | 0.26 | 7.26 | 92.74 | 1.039 |
| 3 | 8.55 | 0.311 | 3.8 | 3500 | 5.82 | 3.07 | 0.00 | 0.07 | 0.43 | 8.32 | 91.68 | 1.027 |
| 4 | 8.55 | 0.311 | 3.8 | 3500 | 3.07 | 1.39 | 0.00 | 0.07 | 0.27 | 4.8 | 95.20 | 1.067 |

Table 3 shows the calculated total heat transfer coefficient values by radiation and convection in the steam boilers numerically. Considering the equations presented in the study and the values obtained from the measurements, total loss values of each case were calculated and the respective efficiency values were obtained in Table 4. Economizer addition to the steam boiler (case 2) are found be more effective with its 3.9% increase in efficiency than the addition of air preheater to steam boiler (case 3) with its 2.7% respected value. Combination of these two cases in the steam boiler (case 4) has the highest efficiency with its 6.7% increase in efficiency as expectedly.

Table 5 shows the fuel consumption and saving amounts according to the investigated case studies. The plant operates for 7200 hours in a year. Unit price of natural gas used as fuel was determined to be 0.45 $\$/m^3$. The hourly and yearly fuel consumption and saving prices calculated on this basis are presented in Table 5.

**Table 5.** Fuel consumption and saving amounts according to the investigated case studies (LHV=8250 $Nm^3/h$, $D_h$=8000 kg/h).

| Fuel consumption and saving / Case | $B_F$ ($m^3/h$) | Fuel Saving ($m^3/h$) | ($m^3/year$) | ($/year) |
|---|---|---|---|---|
| 1 | 600 | - | - | - |
| 2 | 552 | 48 | 345600 | 158020 |
| 3 | 584 | 16 | 115200 | 51475 |
| 4 | 537 | 63 | 453600 | 207546 |

In contrast with Table 4, case 3 has the lowest fuel saving values among all case studies. According to the results of economic analyses in Table 6, payback period is determined by means of the methods of Net Present Value (NPV) and Internal Rate of Return (IRR) for the investigated case studies. Case 2 is found as a better heat recovery application than case 3 with its lower payback period. In addition, the separate application of case 2 does not seem a logical one with its higher payback period than other case studies.

**Table 6.** Results of economic analyses according to the investigated case studies.

| Economic analyses / Case | Investment ($) | O&M ($/year) | Fuel saving ($/year) | NPV | IRR (%) | PP (month) |
|---|---|---|---|---|---|---|
| 2 | 56229 | 1650 | 158020 | 994356 | 250 | 4.32 |
| 3 | 54851 | 1650 | 51475 | 279903 | 77 | 13.21 |
| 4 | 111080 | 2760 | 207546 | 1264792 | 163 | 6.5 |

**CONCLUSION**

The cost-effectiveness of installing a feed water economizer or air preheater in a boiler is given as a methodology regarding with the determination of Scotch type steam boiler's heat losses and efficiency experimentally.

This study was conducted in order to emphasize on the profitability of the system, particularly for the attention of the investors who may abstain from establishing optimum heat recovery systems by solely considering investment costs.

Examining the results of the economic analysis once again manifested how profitable investments heat recovery applications are. In consequence of the economic analysis conducted, it was determined to implement heat recovery systems in the plant in question.

As a result of analyses, the heat recovery method from flue gas is one of the effective processes to save energy in a boiler.

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