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Theoretical analysis of a lignite-fired power plant with pre-drying system in terms of energy efficiency and economy

Ön kurutma sistemli linyit yakıtlı bir termik santralin enerji verimliliği ve ekonomiklik açısından teorik analizi

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Theoretical Analysis of a Lignite-Fired Power Plant with Pre-Drying System in Terms of Energy Efficiency and Economy

Highlights

- ❖ Coal Fired Power Plant
- ❖ Power Plant Efficiency Improvement
- ❖ Pre-Drying of Coal
- ❖ Fluidized Bed Dryer
- ❖ Theoretical Analysis

Graphical Abstract

The figure shows the change in net power plant efficiency for coal types according to pre-drying degree.

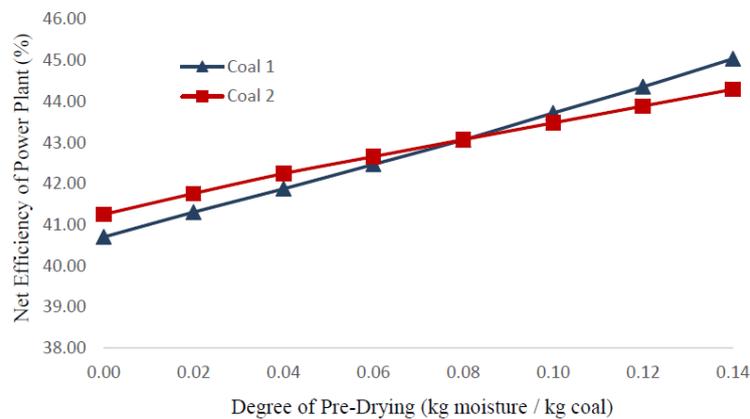


Figure. Net efficiency change of power plant according to the degree of pre-drying

Aim

The aim of this investigation is to design a pre-drying system that uses flue gas waste heat for a thermal power plant firing medium to high moisture coal.

Design & Methodology

In the study, coal pre-drying system was designed. In addition, drying characteristics of the coals were obtained and the coals to be used in the study are analyzed..

Originality

Considering Turkey's coal reserves, the majority of domestic reserves are lignite with high humidity and low thermal value. Moisture content of lignite is one of the significant factors affecting the heat loss in the thermal power plant boiler. Against this backdrop, a theoretical investigation has been performed.

Findings

The energy efficiency increase with coal pre-drying is greater for coal-fired power plants with a higher initial moisture content.

Conclusion

Due to the increase in the lower heating value and in the boiler efficiency, the efficiency of the power plant with pre-drying could increase by 3.04-4.34%. The coal pre-dried power plant had far more economic performance than a power plant without pre-drying system, since more electricity would be obtained thanks to the increase in efficiency of the plant.

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Theoretical Analysis of a Lignite-Fired Power Plant with Pre-Drying System in Terms of Energy Efficiency and Economy

Araştırma Makalesi / Research Article

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ABSTRACT

The coals with different initial moisture content to be used in the theoretical analysis were tested according to the related test standards and the results were used in the analysis. In the designed system, waste heat in the flue gas is used as the heat source. The fresh air is heated for drying in the shell-tube heat exchanger by means of flue gas. In fluidized bed dryers, the moisture of the coal was reduced by contacting the raw coal with the drying air. Due to the high initial moisture of the coals used in the theoretical analysis, the pre-drying degree could be at most 0.14 in order that the boiler feeding rate be the same as in the power plant feeding rate without pre-drying system. The system theoretically does not conform to the design parameters and the boiler feed rate is less than the flow rate of power plant without pre-drying system when the pre-drying degree is greater than 0.14. The pre-drying system had ten small capacity dryers working simultaneously to ensure the continuity of the boiler feed. In the study, the theoretical analysis was performed, and thermal performance of the power plant were formulized and graphically presented according to pre-drying degree. Thanks to the pre-drying system, owing to the decrease in the moisture content of the coal, a reduction in the flue gas flow rate and the amount of energy required to evaporate the moisture are realized. As a result, there was a decrease in the boiler losses and an increase in the efficiency of the boiler. The increase in boiler efficiency was 10.74% when coal 1 had been used and it was 7.92% when coal 2 had been used. Since the coals are dried in the same drying system under the same conditions, the moisture of coal 1 decreases more, thus the losses of the boiler decrease more. Due to the increase in the lower heating value and in the boiler efficiency, the efficiency of the power plant with pre-drying could increase by 3.04-4.34%. The coal pre-dried power plant had far more economic performance than a power plant without pre-drying system, since more electricity would be obtained thanks to the increase in efficiency of the plant. The redemption period of the system was determined as 2 years with coal 1 and it was determined as 3 years with coal 2. After the payback periods, the system makes a net profit and brings in an average of 55 million TL extra income per year. In addition, it was observed that when the degree of pre-drying was decreased, economic efficiency of the system also decreased. It is aimed that the study will provide principles of energy efficiency improvement in coal fired power plants with pre-drying system and will guide people who wants to do similar studies.

Keywords: Coal fired power plant, pre-drying of coal, fluidized bed dryer, power plant efficiency improvement, theoretical analysis.

1. INTRODUCTION

Energy is the foundation of economic development and has a great importance in the development of nations. Energy, which is one of the basic inputs of economic and social development, is become increasingly important in the future of the world and humanity. Therefore, planning and management sizes of energy gain importance. In this regard, effective and rational use of national resources is vital for energy management for every country. In recent years, ignoring domestic resources by focusing on imported resources in the selection of sources for electricity generation of Turkey has created significant risks in terms of energy security. Particularly, the opening of an uncouncted, unplanned natural gas entry to Turkey resulted in the abandonment of electricity generation in thermal power plants using domestic coal.

Examining the domestic installed capacity of coal, which is of great importance for Turkey, it is in evidence that the ratio in the coal based installed capacity is 53.5% while the proportion in the total installed capacity is

12.1% [1]. Turkey has 51 operating power plants using domestic coal. There are 14 lignite, 1 anthracite and 1 asphaltite thermal power plant with installed capacity of over 100 MW [2]. Considering Turkey's coal reserves, the majority of domestic reserves are lignite with high humidity and low thermal value.

Moisture content of lignite is one of the significant factors affecting the heat loss in the thermal power plant boiler. Moisture absorbs the combustion heat in the high exergy released by the combustion, and evaporates which results in increasing fuel consumption, flue gas quantity, energy consumption, maintenance costs, and reduces plant efficiency. In addition, moisture reduces the brittleness of coal, reduces the quality of grinding, and makes separation, classification and blending difficult. If the moisture content of lignite is reduced, the lower heating value and the thermal performance of the power plant will increase, and the flue gas flow rate will decrease. Therefore, drying of lignite before the boiler feed is of great importance.

Studies on pre-drying in thermal power plants are examined and a literature review is conducted. Rotary dryers, rotary tube dryers, pneumatic dryers, fluidized

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bed dryers, vibratory dryers, mill-type dryers, shaft dryers, dryer with moving bed and superheated steam dryers are used for drying of coal [3]. Waste heat recovery systems using the driers mentioned in the literature have been designed. In the studies, boiler flue gas, waste steam from the turbine or condenser cooling water have been used as a heat source. One of these studies designed a system in which the boiler flue gas is used as a waste heat source. In this system, the efficiency of the plant increases by 0.6-0.9% when the raw coal receives 0.1 kg of moisture per kg. As a result of economic analysis, it is found that the plant with pre-drying system is more economical than non-pre-drying plants [4]. In another study, waste steam at 55 °C is used as a heat source. In the designed system, it is concluded that the efficiency of the thermal power plant can be increased from 37.6% to 38.9% by fluidized bed drying [5]. In another system where the absorption heat pump is used as a dryer, solar energy is used with the parabolic collectors to drive the pump. Thanks to the designed system, the consumption of raw coal of 4.6 kg/h in total energy has reduced and the exergy efficiency has increased by 1.2% and 1.8% [6]. In a different system designed using a fluidized bed dryer, steam and feed water are used as a waste heat source. In the system, where different dehumidification scenarios are designed, it is concluded that the plant efficiency will increase by 1.33-2.09% [7]. In an alternative study using solar collectors, the hot water is used to heat the drying air in the fluidized bed. The energy and exergy efficiency of the power plant has increased by 0.5% and 1.6% respectively, and it can produce 29.6 MW more electricity [8]. A further study is designed with different systems using flue gas or steam, and results are compared. In the systems where the flue gas is used as a heat source, the thermal efficiency of the plant is increased most in the fluid bed dryer, and least in the rotary dryer [9]. When low pressure steam is used as a heat source in a lignite fired power plant with a vacuum dryer integrated, the net efficiency of the plant is 2.39%. When the heat pump is used, it is concluded that the net efficiency of the plant increased by 1.88% [10]. In an experimental study, a small-scale fluidized bed dryer set is established. Experimentally, the minimum fluidization velocity for coal is determined. As a result of the experiments, it is concluded that the temperature increases in the drying air entering the fluidized bed has increased the drying rate [11]. In a system using a rotary tube dryer, it is concluded that when the condensate is sent to the deaerator, the plant efficiency can be increased by 1.87%, and when it is sent to the condenser, the efficiency can be increased by 1.72% [12].

When other studies are examined, unlike other flue gas drying systems, flue gas was not used as direct drying air. The reasons for that is specified as follows. If flue gas is directly used as drying air, the SO_3 that is in the flue gas cause H_2SO_4 to be formed by reacting with water vapor in the flue gas and humid coal which results in corrosion. Besides, since the water vapor in the flue gas will slow

down the evaporation rate of moisture content of coal during drying, it will increase residence time of coal in the fluidized bed. Also, using flue gas in the drying system would cause pressure drop, and regulating the flow rate and speed of flue gas could lead to similar issues as well. Therefore, even if there are heat losses, flue gas will be used by heating up with fresh air and then used as a heat source due to the foregoing reasons. Moreover, exit temperature of flue gas is 160 °C. Flue gas exits from desulphurization plant at 70 °C in the reference power plant. However, that temperature is not suitable for drying, so the flue gas is sent to the heat-exchanger which is planned to be manufactured from corrosion-resistant material. Eventually, flue gas exits the heat-exchanger at 100 °C and enters the desulphurization plant. Yet another difference of the designed system is instead of using one large capacity fluidized bed dryer, lower capacity parallel working dryers are designed. Thus, system efficiency is aimed to be increased by contacting drying air and moist coal more homogeneously.

In studies in the literature, theoretical results of the efficiency of the power plant were investigated and discussed based on the difference between the lower heating values of coal at two different moisture contents. Moreover, it is stated that one fluidized bed dryer was used in the theoretical analysis. In this study, the residence time and the mass transfer between the dry air coming from the heat exchanger and the high moisture coal were calculated in the fluidized bed dryer design. In the theoretical study, it was concluded that when a single large capacity fluidized bed dryer for lignite-fired thermal power plants was designed to provide continuity in boiler feed, the amount of the moisture absorbed from the coal was very low. In addition, if the capacity of the dryer system is large, the cost of system components increases and maintenance problems arise. Therefore, instead of a single large capacity dryer, a system consisting of small capacity dryers that works simultaneously to ensure the continuity of the boiler feed has been selected and designed. The system has been designed with a pre-drying degree of 0.14. It has been concluded that 10 small capacity dryers are needed to avoid interruption of boiler feed in mass transfer and residence time calculations. In the designed system, the system works with reducing the residence time for smaller pre-drying degrees. In this way, both the continuity of the boiler feed will be ensured and the power plant efficiency will be increased more. Furthermore, despite the increase in initial costs, maintenance costs will be reduced and the risk of failure of the pre-drying system will be eliminated with possible failures in the designed system. In other words, the system will be disabled during any maintenance or failure in the system consisting of a single dryer, while the system will be able to operate continuously even if maintenance and malfunctions occur in the designed system.

Against this backdrop, a theoretical investigation has been performed. The aim of this investigation is to design

a pre-drying system that uses flue gas waste heat for a thermal power plant firing medium to high moisture coal. In the study, the shell-tube heat exchanger will be designed by using the flue gas values of an existing thermal power plant and the air to be used in the fluidized bed dryer will be heated with the help of this heat exchanger. By using this design of the fluidized bed dryer, the effects of coal with different initial humidity and contents on the power plant efficiency will be examined as a result of pre-drying and economic analyzes of the designed systems will be performed.

2. SYSTEM DESCRIPTION

Waste heat is used as the heat source for pre-drying in order to increase the plant efficiency. Flue gas, cooling water in condenser or waste steam in turbine outlet can be used as a heat source to achieve efficiency improvement of power plant. The temperature of the flue gas, which is approximately 50 °C higher than the temperature of the cooling water in the condenser, is about 150-170 °C. It is also easier to heat the drying air with flue gas in terms of system design. On the contrary, it is more difficult to design the system that works with waste steam due to the challenges of thermodynamic calculation. Therefore, the system using flue gas waste heat is designed.

loss of the boiler is slightly reduced. Therefore, there is an increase in the efficiency of the boiler.

As shown in Fig. 1, the flue gases generated by combustion in the boiler enter the heat exchanger by means of the bypass system, and then the flue gases entering the heat exchanger heat the fresh air and return to the flue system with the help of the bypass system. At that moment, the fresh air heated in the heat exchanger goes to the dryers. The temperature of the air rises and the humidity of the air decreases in the heat exchanger. Temperature and flow rate of air, which is required for drying process, are arranged with the help of heat exchanger fans and flow regulating valves.

Raw coal coming into the fluidized bed dryers is exposed to heated air. In the fluidized bed dryers, the powdered coal and the drying air are contacted for predetermined period. The purpose of the heat-exchanger in the designed system is to supply 100 °C drying air. Besides, pre-drying degree of coal can be regulated by changing residence time of coal in the dryer. The longer the residence time, the more moisture the drying air can absorb. In addition, using air in the drying process will provide thermodynamic convenience. While humid air is released into the atmosphere by passing through the electro filters, pre-drying coal is fed to the boiler.

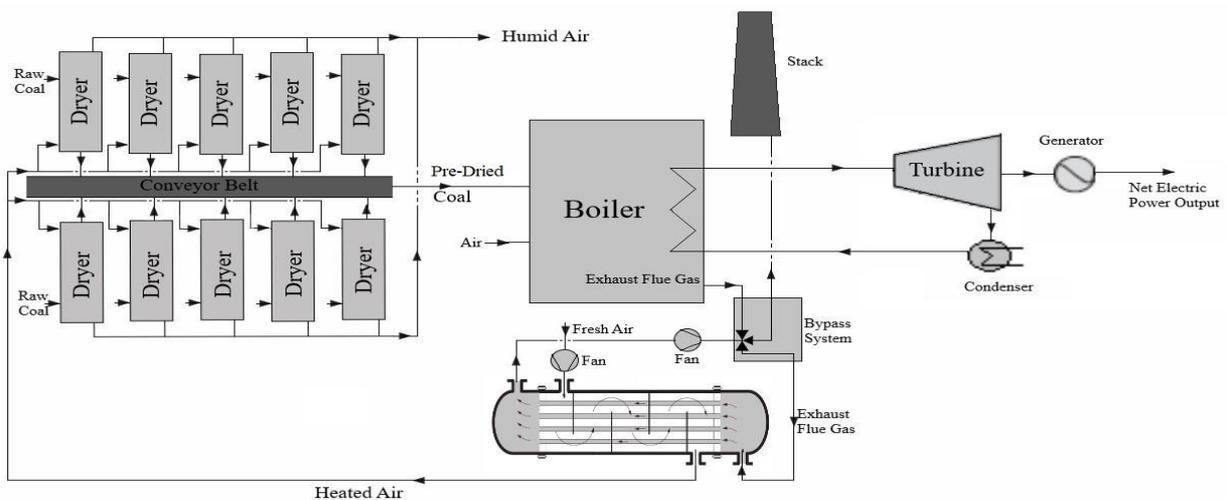


Figure 1. Schematic view of pre-drying power plant using waste heat of flue gas

The schematic view of the system is shown in Fig. 1. In the systems designed for comparison with the thermal power plant taken as a reference, the design is made according to the same boiler feed flow rate of reference power plant. Therefore, a system consisting of dryers that are synchronized with each other is designed. In other words, there is a certain time between discharging coal from the 1st dryer and discharging the coal from the 2nd dryer to the conveyor belt. There is a certain time between each dryer. This will ensure continuity in boiler feed. In addition, it is assumed that the efficiency of the turbine and generator is not changed for comparison. However, as the losses in the flue gas decrease, the total

The boiler generates heat owing to coal burning. Using this heat, the feed water entering the boiler is heated to produce steam. The steam from the boiler enters the turbine to generate work. Generator produce electric power. Thanks to the designed system, the lower heating value of the pre-drying coal increases because the moisture content of the coal decreases. When compared to the reference power plant, the amount of heat generated by the combustion increases. As the amount of live steam and the enthalpy of the steam increase, the work produced in the turbine also increases. Therefore, the net amount of electricity power increase.

3. METHODOLOGY

In the designed system, heat exchanger, dryer, and boiler units are examined. Hot air is required to dry the coal in the fluidized bed dryer. In order to heat the air, heat exchanger utilizes waste heat from the flue gas. In the first stage, the heat transfer in the designed heat exchanger is examined to determine the properties of the drying air. In the second stage, fluidized bed dryer is theoretically designed while heat and mass transfer mechanisms are examined. Then, the increase in the lower thermal value of the coal is examined and the efficiency increase in the boiler is calculated. In the fourth stage, the change in net electrical power output is examined. Finally, the economic analysis of the designed system is done.

In order to compare the designed system, coals with different initial moisture and content are required. These coals are tested to obtain heating values according to standards.

3.1. Analysis of Coal Samples

Coal tests are conducted on two different samples, and type of coals are selected based on the most common coal reserves in Turkey. Supplied coals are conserved by preventing change in their moisture content before the experiments are performed.

The coal samples are tested with the devices given in Table 1. The coals are dried in the drying oven at 70 °C for 48 hours before the test. First of all, the elemental analysis of the coals is made. The determination of sulfur is carried out at 1350 °C [13]. In the other element analyzer, carbon hydrogen and nitrogen quantities are determined at 900 °C [14]. Then, thermogravimetric analyzer obtains moisture content, volatile matter, ash and fixed carbon content of the coals [15]. Finally, the coal samples are tested in the calorimeter and the higher heating value is obtained on a dry basis [16,17].

After experimentally obtaining the higher heating value on the dry basis, the other heating values are calculated by the transition formulas between the bases using the elemental contents according to ISO 1928 and ASTM

Table 1. Sensitivity and uncertainty of measuring/test devices

Name of Measuring/Test Devices	Mark and Model	Sensitivity	Uncertainty
Digital Scale	Sartorius BP110S	± 0.0001 g	± 0.0002 g
Drying Oven	Nüve KD200	± 0.1 °C	± 1.13 °C
Elemental Analyzer (For determination of sulfur)	Leco 628S	± 0.0001 g	± 0.0005 g
Elemental Analyzer (For determination of hydrogen, oxygen and nitrogen)	Leco CHN 628	± 0.0001 g	± 0.052 g
Thermogravimetric Analyzer	Eltra Thermostep	± 0.0001 g	± 0.018 g
Calorimeter	IKA C5000	± 1 J	± 0.002 J

D5865 standards. The lower and higher heating value of the original basis are calculated using the moisture and elemental contents of the coal as follows:

$$LHV_{dry} = HHV_{dry} - 212w_H - 0.8(w_O + w_N) \text{ (J)} \quad (1)$$

$$LHV_{Mar} = LHV_{dry} \frac{100-M_{AR}}{100} - Q_{mar} \text{ (kCal)} \quad (2)$$

$$Q_{mar} = \frac{0.01H_{vap} \frac{M_{AR}}{18.0154}}{4.1868} \text{ (kCal)} \quad (3)$$

$$HHV_{Mar} = HHV_{dry} \frac{100-M_{AR}}{100} \text{ (kCal)} \quad (4)$$

3.2. Analysis of Measurement Uncertainty

Non-negative numerical parameters that define the distribution of the magnitude values attributed to the measurements based on the information obtained are called measurement uncertainty [18]. The accuracy of the measurement results is important in the experiments. Therefore, calibration and measurement uncertainties are important. The measurement devices used in the experiment have deviations from the correct measurement and measurement uncertainties. Therefore, uncertainties arising from the measurement accuracy of the devices should be calculated. The size to be measured in the system is R, and the n independent variables that affect this size are $x_1, x_2, x_3, \dots, x_n$. In this case, the size to be measured can be written with the help of Eq. 5. The error rates of each independent variable $U_{x_1}, U_{x_2}, U_{x_3}, \dots, U_{x_n}$ and if the error rate of Y is U_Y the uncertainty analysis equation is calculated as follow [19]:

$$Y = Y (x_1, x_2, x_3, \dots, x_n) \quad (5)$$

$$U_Y = \left[\left(\frac{\partial Y}{\partial x_1} U_{x_1} \cdot DC_{x_1} \right)^2 + \left(\frac{\partial Y}{\partial x_2} U_{x_2} \cdot DC_{x_2} \right)^2 + \dots + \left(\frac{\partial Y}{\partial x_n} U_{x_n} \cdot DC_{x_n} \right)^2 \right]^{1/2} \quad (6)$$

where U_Y is uncertainty (absolute value) of the measurand Y and U_{x_i} is uncertainty (absolute value) of the input quantity x_i . Moreover, DC_x is distribution coefficient.

In industrial applications, a higher level of reliability is needed. In those cases, expanded uncertainty is used to define uncertainty in the measurements. Expanded uncertainty of measurement is obtained by multiplying the standard uncertainty $u(y)$ of the output estimate y by a coverage factor k [19]:

$$U = kU_Y \quad (7)$$

The value of the scope factor is selected based on the targeted reliability level. Most commonly, the overall uncertainty by using the coverage factor $k = 2$ gives a level of confidence of approximately 95%.

In the thermal value analysis, the extended uncertainty of the model function is approximately 11 kCal. That is, the uncertainty of the function at the 95% confidence level is 0.17%.

3.3. Heat Exchanger

Heat exchangers are devices that provide the transfer of thermal energy between two or more fluids at different temperatures [20]. The shell-tube heat exchanger is chosen to heat the fresh air at designed system. Shell-tube heat exchanger with a plurality of pipes arranged parallel to the body axis is designed. In order to improve the heat transfer and maintain the uniform spacing between the pipes, the baffles are fitted in the body. Combustion gases at 160 °C and the fresh air at 20 °C enters the heat exchanger. As a result of the heat transfer, temperatures of the flue gas and air are 100 °C, when they leave the heat exchanger.

The heat transfer mechanism in the heat exchanger is continuous flow. In continuous flow systems, changes in kinetic and potential energy can be neglected, if there is no work. The energy balance is as follows:

$$\dot{Q} = \dot{m} \cdot c_p \cdot \Delta T \tag{8}$$

If there is no heat generation in the system and thermal energy change of the system, the inlet energy is equal to the outlet energy. Because the temperature difference between hot and cold fluids varies throughout the heat exchanger, the log mean temperature difference method is calculated as follows [21]:

$$\dot{Q} = U \cdot A_s \cdot \Delta T_{lm} \tag{9}$$

$$\frac{1}{U} = \frac{1}{h_o} + \frac{r_o}{r_i} \frac{1}{h_i} + R_{ft} \frac{r_o}{r_i} + R_{ft} + r_o \frac{\ln(\frac{r_o}{r_i})}{k} \tag{10}$$

$$A_s = N_t \cdot \pi \cdot D_o \cdot L \tag{11}$$

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln(\frac{\Delta T_1}{\Delta T_2})} \tag{12}$$

where ΔT_1 is the temperature difference between the inlet flue gas and the heated air. ΔT_2 is the temperature difference between the outlet flue gas and the fresh air.

The flue gas passes through the inside of the tubes. Since the mass flow rate of the flue gas is very high, turbulent flow occurs. Therefore, the friction coefficient in the smooth pipes in the flow is obtained by Gnielinski correlation [22]. The internal convection coefficient depending on Reynolds number calculated as follows:

$$f = (1.58 \ln(Re) - 3.28)^{-2} \tag{13}$$

$$\frac{h_i \cdot D_i}{k} = \frac{(\frac{f}{2})(Re-1000)Pr}{1+12.7(\frac{f}{2})^{0.5}(Pr^{\frac{2}{3}}-1)} \tag{14}$$

The fresh air passes through the outside of the tube bundles. As shown in Fig. 2, baffles are used for the shell side. The use of baffles in shell-tube heat exchanger has two advantages when designing. The first of these advantages is that baffles support the tubes in terms of structural rigidity and prevent the vibration or sagging of the tubes. The other increases the heat transfer coefficient

and directs the flow through the shell. The following correlations for the shell-side heat transfer coefficient are used [23]:

$$\frac{h_o \cdot D_e}{k} = 0.36 \cdot (\frac{D_e \cdot G_s}{\mu})^{0.55} \cdot (\frac{c_p \cdot \mu}{k})^{1/3} \cdot (\frac{\mu_b}{\mu_w})^{0.14} \tag{15}$$

where D_e is the equivalent diameter, calculated according to the sequence of the tube bundles of the flow. It is calculated as follows for the square layout:

$$D_e = \frac{4(P_T^2 - \frac{\pi d_o^2}{4})}{\pi d_o} \tag{16}$$

The bundle crossflow area, A_s , at the center of the shell is calculated as follows:

$$A_s = \frac{D_s \cdot C \cdot B}{P_T} \tag{17}$$

Then, the shell-side mass velocity is found with

$$G_s = \frac{\dot{m}}{A_s} \tag{18}$$

Waste heat in flues gas is used as the heat source. Heat exchanger is designed for pre-drying degree of 0.14. The heat exchanger takes the fresh air at the ambient temperature and heats it up to 100 °C. Then it transmits the flue gas back to the bypass system.

Table 2. Design values of the heat exchanger

Feature	Explanation	Quantity / Dimension
D_s	Shell inside diameter	3.16 m
L	HEX Length	12.6 m
d_o	Tube outer diameter	60.33 mm
d_i	Tube inner diameter	49.25 mm
N_t	Total number of tubes	1000
N_p	Number of tube passes	1
N_B	Number of baffles	45
B	Baffle spacing	0.25 m
B_C	Baffle cutting ratio	%25
C	Clearance between tubes	0.025 m
CL	Tube layout constant	1
CTP	Tube count calculation constant	0.93
R_{ft}	Total fouling	0.000176 m ² K/W
k	Thermal conductivity of tube wall	60 W/m.K

The design of the heat exchanger is made according to the pre-drying degree of 0.14 as the maximum drying size of the system. Flow rate and speed of the drying air can be regulated by using fans and valves. When more drying is desired at the same drying temperature, either coal must be kept in the bed for extended period of time or more air must be supplied for the same duration. Therefore, heat exchanger does not have to be changed in

order to change the drying degree. The parameters that are used while designing the heat-exchanger and the design outcomes are listed below in Table 2.

3.4. Fluidized Bed Dryer

The heated air is transported to the dryers through ducts. In fluidized bed dryers, heat and mass transfers occur. A fluidized state is achieved when air with suitable velocity passes through the coal layer. The air flow velocity at which the packed bed is converted into a fluidized bed is known as the minimum fluidization velocity. The Archimedes number used to calculate the minimum fluidization velocity is calculated as follows [24]:

$$Ar = \frac{\rho_f D_p^3 (\rho_s - \rho_f) g}{\mu_f^2} \quad (19)$$

The minimum fluidization velocity is calculated as follows [25]:

$$u_m = \frac{\mu_f}{\rho_f D_p} [(42.81^2 + 0.061 Ar)^{0.5} - 42.81] \quad (20)$$

In fluidized bed design, some features must be taken into account besides the minimum fluidization velocity. One of these features is porosity, defined by [3]

$$\psi = 1 - \frac{V_m}{V_z} \quad (21)$$

where V_m is volume of coal particle in the bed, V_z is total volume of the bed. The porosity of a fluidized bed dryer can vary in a wide range since it depends on the air velocity. Furthermore, industrial fluidized bed dryers operate in the range of 0.55 to 0.75 porosity [3].

The temperature of air decreases and the amount of moisture it carries increases. Heat transfer increases the temperature of the coal to be fed to the boiler. The heat transfer for turbulent flow in the dryer is calculated as follows [21]:

$$Nu = 0.023 Re^{0.8} Pr^{0.3} \quad (22)$$

In the drying process, the mass transfer mechanism is realized by diffusion. The main mechanism of diffusion is molecular propagation as a result of the concentration gradient. In drying applications, the mass transferred is generally water vapor. The presence of the gradient between the dry air and the water vapor causes mass transfer. Due to irregular molecular motions, water vapor is emitted into the mixture of moist air in the direction where the concentration decreases. The diffusion coefficient required to calculate the mass transfer is calculated as follows [21]:

$$D = 1.87 \times 10^{-10} \frac{T^{2.072}}{P} \quad (23)$$

When calculating the mass transfer, Sherwood number is used instead of the Nusselt number. Also, the Schmidt number is used instead of the Prandtl number. The Sherwood number and mass transfer coefficient are calculated as follows [21]:

$$Sh = \frac{h_m D_h}{D} = 0.023 Re^{0.8} Sc^{0.3} \quad (24)$$

The total mass transferred is calculated by the difference in concentration. It is assumed that air and water vapor

behave as ideal gas. The total amount of moisture taken from coal is calculated as follows [21]:

$$\dot{m}_d = \frac{h_m A_d}{R_v} \left(\frac{P_{v,s}}{T_s} - \frac{P_{v,\infty}}{T_\infty} \right) \quad (25)$$

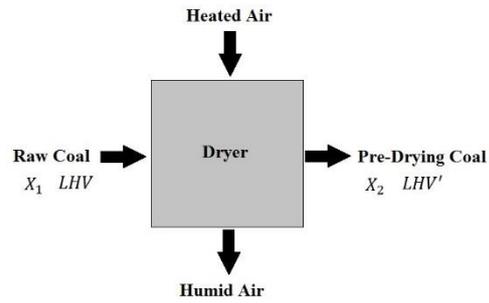


Figure 2. Coal pre-drying process

Moisture content and the lower heating value of the coal entering the dryer change as shown in Fig. 2. The mean residence time of coal in the fluidized bed dryer is determined empirically and calculated by

$$\tau = \frac{\rho_s A_d H (1 - \psi) (Mar_1 - \frac{(1 - Mar_1) Mar_2}{1 - Mar_2})}{\dot{m}_d} \quad (26)$$

After the coal enters the dryer, it is exposed to hot air. As a result, mass transfer results in reduced moisture content of the coal. The degree of pre-drying that represents the mass flow rate of removed moisture from raw coal is defined as:

$$\mu = \frac{Mar_1 - Mar_2}{M} \quad (27)$$

3.5. Boiler

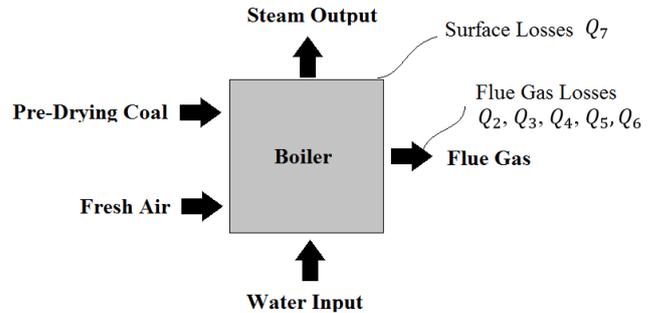


Figure 3. Boiler energy balance

Boiler energy balance is shown in Fig. 3. Pre-drying coal and fresh air enters the combustion chamber. Because of the combustion, a part of the heat converts the boiler feed water into steam. Moreover, the remaining part of the heat is the heat loss. Boiler efficiency is calculated as follows with indirect method [26]:

$$\dot{Q}_{in} = \dot{Q}_1 + \dot{Q}_2 + \dot{Q}_3 + \dot{Q}_4 + \dot{Q}_5 + \dot{Q}_6 + \dot{Q}_7 \quad (28)$$

where \dot{Q}_{in} is the heat input of the boiler. \dot{Q}_1 is the heat output of the boiler. \dot{Q}_2 is the heat loss due to dry flue gas. While \dot{Q}_3 is the heat loss due to moisture in fuel, \dot{Q}_4 is the heat loss due to water from combustion of hydrogen

in fuel. \dot{Q}_5 is the heat loss due to incomplete combustion. \dot{Q}_6 is the heat loss due to moisture in combustion air. \dot{Q}_7 is the heat loss due to surface radiation, convection and other miscellaneous losses.

Hence, the boiler efficiency can be expressed as:

$$\eta_b = [1 - (\dot{q}_2 + \dot{q}_3 + \dot{q}_4 + \dot{q}_5 + \dot{q}_6 + \dot{q}_7)] \times 100 \quad (29)$$

After pre-drying process, $\dot{q}_5, \dot{q}_6, \dot{q}_7$ are nearly unchanged. Due to the mass ratio of dry flue gases, the lower heating value of coal and the mass ratio of the hydrogen in fuel will increase as moisture content of coal decreases, \dot{q}_2 and \dot{q}_4 will decrease slightly. Similarly, \dot{q}_3 decreases because the moisture content of the coal is reduced. Heat loss due to dry flue gas can be calculated as [27]:

$$\dot{q}_2 = \frac{m_{fg} c_{p_{fg}} (T_g - T_a)}{LHV} \quad (30)$$

In the designed system, it is proposed that the coal flow rate of the systems is chosen as constant parameter to make comparison. Therefore, the mass ratio of dry flue gases will increase as the mass weight of the moisture decreases. The lower heating value of coal will also increase. As a result, the heat loss due to dry flue gas will be reduced slightly. The heat loss due to moisture in fuel and water from combustion of hydrogen in fuel are calculated as follows [26]:

$$\dot{q}_3 = \frac{M_{ar}[c_{pw}(100-T_a) + c_{pv}(T_g-100) + h_{fg}]}{LHV} \quad (31)$$

$$\dot{q}_4 = \frac{9w_H[c_{pw}(100-T_a) + c_{pv}(T_g-100) + h_{fg}]}{LHV} \quad (32)$$

The heat loss due to moisture in fuel will decrease as the moisture content of coal decreases. Moreover, the mass ratio of hydrogen and the lower heating value of coal will increase as the mass weight of the moisture decreases. In addition, the temperature of the flue gas decreases, so the heat loss due to water from combustion of hydrogen in fuel will slightly decrease.

Consequently, the net improvement of the boiler efficiency can be obtained by:

$$\Delta\eta_b = (\dot{q}_2 - \dot{q}_2') + (\dot{q}_3 - \dot{q}_3') + (\dot{q}_4 - \dot{q}_4') \quad (33)$$

3.6. Steam Turbine and Generator

The steam produced in the boiler is sent to the turbine. Turbine efficiency does not change because the pressure and temperature of the steam are the same. Therefore, the specific heat consumption rate of the steam cycle is unaltered. Nonetheless, the total energy input of the boiler will increase, so the steam flow rate will increase under the same coal feed rate. The steam mass flow rates with coal pre-drying and without coal pre-drying are calculated as:

$$M_S = \frac{M.LHV.\eta_b}{d_0} \quad (34)$$

$$M_S' = \frac{M.LHV'.(\eta_b + \Delta\eta_b)}{d_0} \quad (35)$$

3.7. Self-Consumption of Power Plant

In the designed system, there is no change in the energy consumption of the pulverizer since the boiler feed rate

is the same. Two radial fans are used in the system. One of them is used in the by-pass system and the other is used to send the heated air to the dryer. Moreover, the electric consumption of the pump will increase since the steam mass flow rate increases. The power consumption of the fan is calculated as follows [28]:

$$P_{fan} = \frac{V.\Delta P_t}{1000.\eta_f} \quad (36)$$

The increase of the electric consumption of the pumps can be expressed as [4]:

$$\Delta P_{pumps} = \left(\frac{M_S'}{M_S} - 1\right) \cdot \alpha \cdot P_0 \quad (37)$$

Finally, the change of the self-consumption is calculated as:

$$\Delta P_0 = P_{fan_1} + P_{fan_2} + \Delta P_{pumps} + P_{dryers} \quad (38)$$

3.8. Net Change in Energy Output of Power Plant

The energy efficiency of power plant without coal pre-drying is calculated by energy equilibrium. The input energy of the power plant depends on the mass flow rate of the coal fed to the boiler and the lower heating value. Some of the input energy is converted to electrical energy. The energy output of power plant without coal pre-drying is calculated as follows:

$$P_e = M.LHV.\eta_b.\eta_i \quad (39)$$

The efficiency of the pre-drying power plant will increase as the efficiency of the boiler and the lower heating value of coal will also increase. The energy output of pre-drying power plant is obtained by:

$$P_e' = M.LHV'.(\eta_b + \Delta\eta_b).\eta_i \quad (40)$$

Finally, net change in energy output and net efficiency of the power plant with coal pre-drying is obtained by:

$$P_{net} = (M.LHV.\eta_b.\eta_i) - P_0 \quad (41)$$

$$\Delta P_{net} = \{[M.LHV'.(\eta_b + \Delta\eta_b).\eta_i] - M.LHV.\eta_b.\eta_i\} - \Delta P_0 \quad (42)$$

$$\eta_{PP} = \frac{P_{net}}{M.LHV} \quad (43)$$

3.9. Economic Analysis of the System

The net present value method is used to make an economic analysis of the system. The difference between the present value of the cash benefit that will be provided during the life of the system and the present value of the expenses such as investment and maintenance of the system is called the net present value method. By using this method, the combined interest rate is used to make the economic analysis of the system [29].

$$i_e = (1 + i) * (1 + d) - 1 \quad (44)$$

To carry out the analysis with the help of the calculated combined interest rate, the current value method is calculated by means of the benefits and costs Eq. 41 and

the difference between the total benefits and the total costs is calculated with the help of Eq. 42 [29].

$$NPV = Benefit - Cost \tag{45}$$

$$NPV = \sum_0^N \frac{R_{in}}{(1+i_e)^n} - \sum_0^N \frac{R_{on}}{(1+i_e)^n} \tag{46}$$

In the designed system, income from additional annual electricity sales is considered as benefit. On the other hand, investment and annual maintenance costs of the system is considered as the cost. The income from additional annual electricity sales is calculated as follows [4]:

$$\Delta I_e = P_{net} \cdot \Delta \eta_{net} \cdot N \cdot w \cdot p_e \tag{47}$$

$$\sum_0^N \frac{R_{in}}{(1+i_e)^n} = \sum_0^N \frac{R_{on}}{(1+i_e)^n} \tag{48}$$

As seen in Eq. 48, where the benefit and cost are equalized, n represents the period of redemption. In the designed system, after the redemption period, the system will provide economic benefits within the lifetime of the system.

4. RESULTS AND DISCUSSIONS

The air heated by the flue gas is used for drying. Due to drying, the moisture of the coal is reduced, and the lower heating value is increased. As a result of the humidification process, the temperature of the air decreases and the relative humidity increases. Besides, the boiler losses will decrease, and the thermal efficiency of the power plant will increase. Thus, more electricity can be produced with the same coal feed rate.

After coal 1 is fired, while flow rate of flue gas at 160 °C is 493 kg/s, it decreases to 477 kg/s for a pre-drying degree of 0.14. The same situation is observed when coal 2 is fired by a decrease of coal flow rate from 530 kg/s to 511 kg/s with the identical pre-drying degree. All of the flue gas enters the desulphurization plant after entering the heat exchanger with the bypass system.

In order to compare the operational performance of the power plant with coal pre-drying, two different coal samples with different moisture content and characteristics are used. By performing the experiments, heating values and contents of coal are obtained. The

Table 3. The analysis of the coals

Type	M _{AR} (%)	Ash (%)	V (%)	C (%)	S (%)	H (%)	LHV (kCal/kg) (Received Basis)	LHV (kCal/kg) (Dry Basis)	HHV (kCal/kg) (Received Basis)	HHV (kCal/kg) (Dry Basis)
Coal 1	50.46	19.76	20.28	9.5	1.61	1.34	988	2587	1315	2655
Coal 2	38.4	30.16	21.73	9.71	1.93	1.96	1765	3228	2050	3327

analysis of the coals is shown in Table 3. Coal 1 is used in the reference power plant. Performance parameters of the reference power plant used in theoretical analysis are given in Table 4. The reference values obtained from the operation of coal 2 in the reference power plant are given in Fig. 7c.

Table 4. Reference power plant parameters

Parameter	Unit	Value
Coal mass flow rate	kg/s	192.3
LHV of Coal	kCal/kg	988
Total energy input	MW	795.5
Total electrical output	MW	338.8
Self-consumption of the plant	MW	15.1
Net electrical output	MW	323.8
Net efficiency	%	40.7

In the designed system, the coal must be dried in the fluidized bed dryer for approximately 104 seconds, for a pre-drying degree of 0.14. Therefore, 10 dryers with 15 meters height and 0.5 m edge square section are required to dry the coal as well as the same boiler feed flow rate of the power plant without pre-drying system. The dryers have small dimensions and working simultaneously with each other. In this way, dehumidification takes places under maximum operating conditions. Some of the dryers will be shut down by the system when the amount of moisture to be removed is reduced. As a result, drying process can be carried out without changing the boiler feed rate.

4.1. Change in Lower Heating Value of Coals

Because of the dehumidification process in the designed system, the amount of change in the lower heating value, which is obtained using Eqs. 1, 2, 3 and 4, according to the changing moisture content is shown in Fig. 4. Since the coals has different initial moisture content, the comparison is made according to the degree of pre-drying. Furthermore, as the lower heating values of the coals are different, the amount of change in the lower heating value is examined. As shown in Fig. 4, a linear increase in the lower heating value is observed as the degree of pre-drying increases. When the initial moisture content of Coal 1 is reduced from 50.46% to 42.34%, the lower heating value rises from 988 kCal / kg to 1245 kCal / kg. Similarly, the initial moisture of Coal 2 is reduced from 38.4% to 28.37%, while the lower thermal value rises from 1756 kCal / kg to 2136 kCal / kg. Consequently, the higher the initial moisture content, the higher the increase in the lower heating value.

4.2. Boiler Efficiency Improvement

Reducing the moisture content of the coal and the flue gas temperature is an important factor that increases the efficiency of the boiler. Since the flue gas temperature of the boiler decreases, the losses due to the moisture

content and hydrogen content will be reduced. This also affects the increase in the higher heating value. Similarly, as the moisture content of the coal decreases, the mass ratios of dry gases in the flue gas increase. Consequently, the losses due to dry flue gas, moisture and hydrogen content of coal decreases. Eqs. 29, 30, 31, 32 and 33 present the efficiency improvement of the boiler. Fig. 5 shows the increase in the efficiency of the boiler depending on the degree of pre-drying. As seen in Fig. 5, the drying of the coal with high moisture content increases the efficiency of the boiler more than the coal with lower moisture content.

When coal 1 is examined, a linear increase in the efficiency of the boiler is observed. While the degree of pre-drying is 0.02, the efficiency increase in the boiler is 4.92%. Moreover, when the pre-drying degree is 0.14, an increase of 10.74% is observed in the efficiency of the boiler. On the contrary, when coal 2 is examined, a lower efficiency increase is observed at the same pre-drying degree. While the degree of pre-drying is 0.02, the efficiency increases in the boiler according to drying coal 2 is 4.37%. When coal 1 is used at the 0.02 degree of pre-drying, the increase in boiler efficiency is 12% higher than the increase in coal 2. However, when the pre-drying degree is 0.14, the difference of increase in boiler efficiency between coal 1 and coal2 is 35%. As a result, as the initial moisture content of coal decreases, the increase in boiler efficiency decreases according to the pre-drying degree. As a consequence of the analysis, the efficiency of the boiler increases from 75% to 83-86%.

4.3. Net Efficiency Change of Power Plant

As a result of the analyzes, the lower thermal value of the coal feeding the boiler increases. Moreover, because of the designed system, the loss of the boiler decreases and its efficiency increases. Thus, the amount of steam produced increases. Although the consumption of self-consumption of power plant and drying system increases, the amount of net electricity generated increases. The increase in the efficiency of the power plant is shown in Fig. 6. with the help of Eqs. 41, 42 and 43

As seen in the Fig. 6, the net efficiency of power plant without pre-drying system is 40.70% when coal 1 is used and 41.25% when coal 2 is used. When the pre-drying degree is 0.14 in the pre-drying system, the net efficiency of the power plant is increased to 45.04% when coal 1 is used. In the same case, when coal 2 is used, net efficiency rises to 44.29%. While the same rate of moisture is taken in both coals, the efficiency increase is higher in the plant when coal 1 is used. This is due to the fact that the moisture content is higher, the rate of increase in the lower heating value is higher although the same amount of moisture is taken. The increase in boiler efficiency is also higher. Therefore, the net efficiency of the pre-dried power plant used in coal 1 is higher than coal 2, although it is higher than the net efficiency of the power plant without pre-drying system used in coal 2.

4.4. Economic Analysis

The net electricity production increase in the power plant is calculated by the help of the designed system and the theoretical analysis. With the help of Eq. 47, additional annual income is calculated. The redemption periods of the systems are calculated by the investment costs and the annual extra income with the help of Eq. 48. Price offers are received from the companies that are working on heat recovery projects, and the average of those values are used. The values and parameters used in economic analysis are given in Table 5.

Table 5. Economic analysis parameters of power plant

Parameter	Unit	Value
Installed capital cost of dryers	Million TL	19.8
Installed capital cost of HEX	Million TL	2.1
Installed capital cost of fans	Million TL	0.95
Installed capital cost of ducts and auxiliary equipment	Million TL	1.13
Additional yearly operating and maintenance cost	Million TL	0.5
Annual operation hours	Hour/year	3365
Annual capacity factor	%	80
Grid feed-in tariff	TL/kWh	0.26
Interest rate	%	15
Inflation rate	%	10
System life	Year	25

The redemption periods calculated with the help of Eqs. 47 and 48 are shown in Fig.8. As a result of the economic analysis, when the pre-drying degree is 0.02 and 0.04, the designed system is not applicable. Therefore, the redemption periods of these values are not shown in Fig. 7. As shown in the figure, the redemption period decreases as the degree of pre-drying increases. Besides, the more the initial humidity of coal, the shorter the depreciation period when the redemption periods of coals with different moisture content are compared. In the years after the calculated redemption period, the designed systems will provide extra income during their lifetime. Components of the system on which the economic analysis is conducted is chosen for a pre-drying degree of 0.14. Pre-drying degree can be increased or decreased by arranging the flow rate and speed of the drying air. Since the system can be arranged with only domestic equipment, no need to change the main components. Therefore, the economic analysis is conducted based on system component costs.

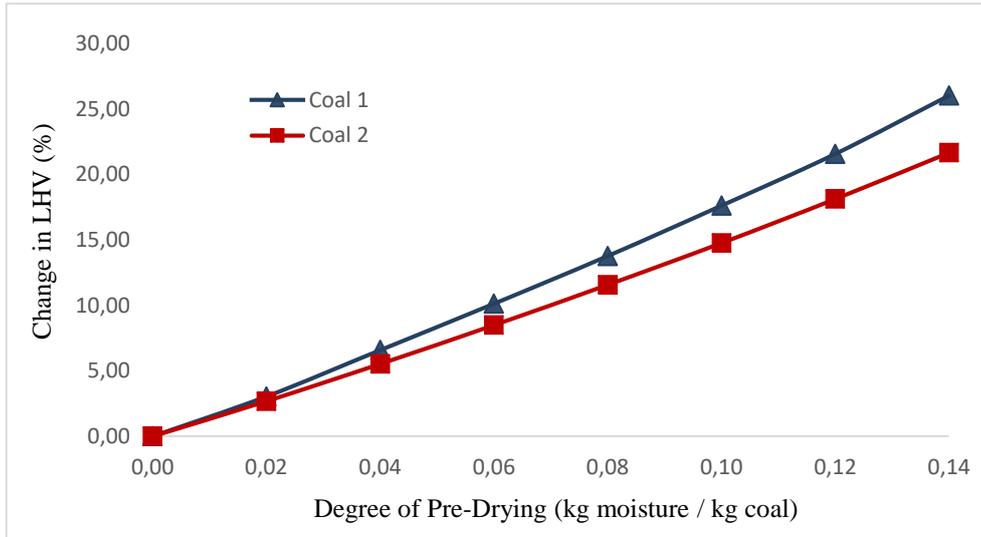


Figure 4. Change in LHV of coals according to the degree of pre-drying

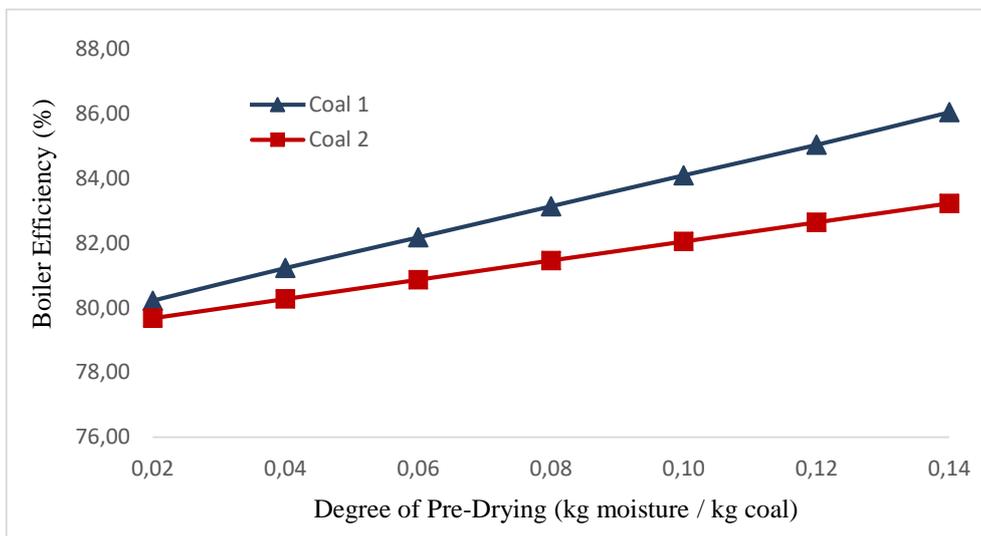


Figure 5. Boiler efficiency improvement according to the degree of pre-drying

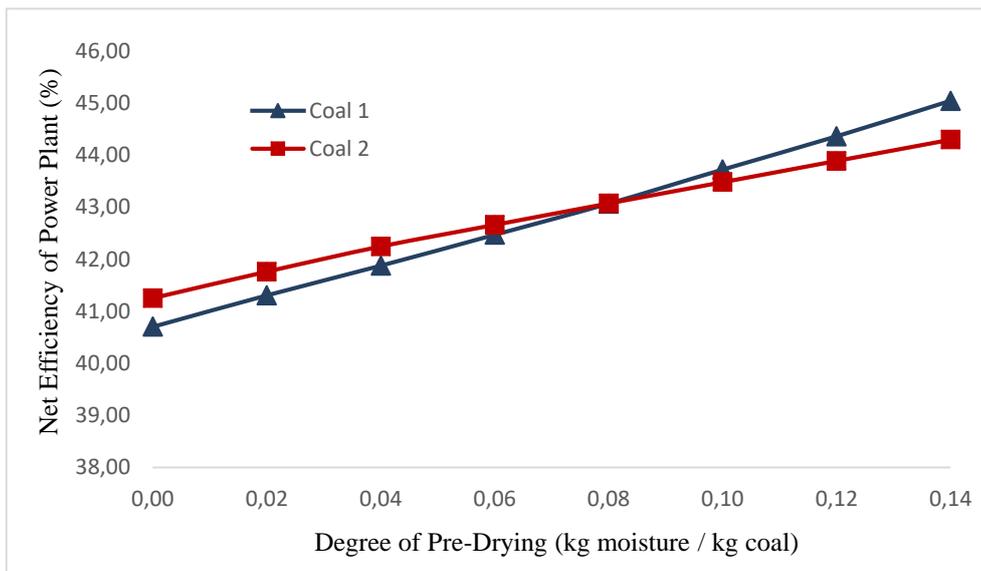


Figure 6. Net efficiency change of power plant according to the degree of pre-drying

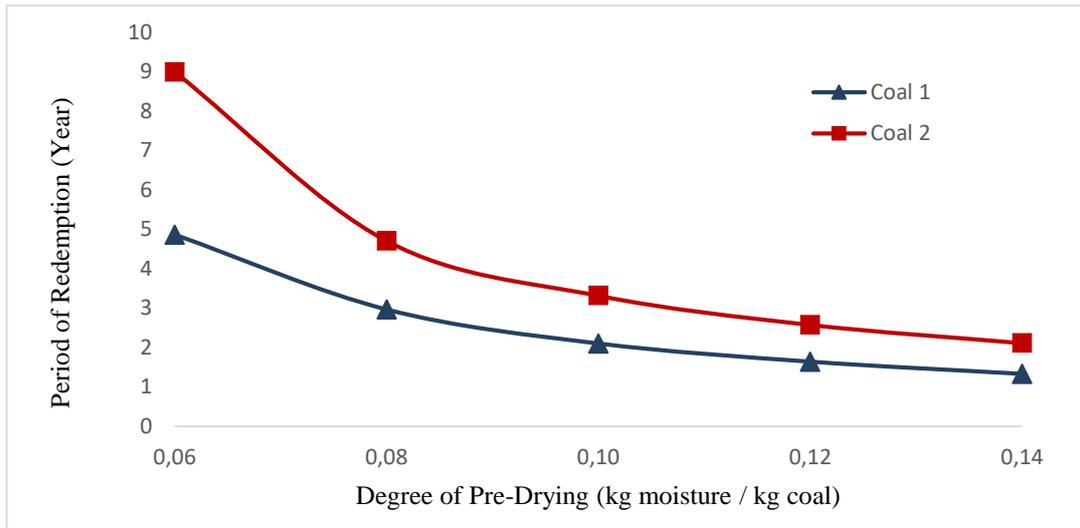


Figure 7. Period of redemption according to the degree of pre-drying

5. CONCLUSIONS

The coals to be used in the theoretical analysis were tested according to the related experiment standards, and experiment results were used in the analysis. In the designed system, waste heat in the flue gas was used. The flue gas entering the heat exchanger was used to heat the fresh air to be used in the dryer. Then the raw coal coming into the fluid bed dryer system, which operates in parallel, was fed to the boiler after being subjected to pre-drying process. The theoretical analysis was performed, and thermal performance of the power plant were formulized and graphically presented according to pre-drying degree.

In order to achieve higher pre-drying degree at the same feed rate, a system with ten fluidized bed dryers operating in parallel was designed. In other studies related coal pre-drying by waste heat of flue-gas, when the pre-drying degree was 0.10, an increase of the net efficiency of the plant is 0.9% [4]. In the designed system, when the coal with approximately the same moisture content was used, the pre-drying degree was 0.10 and the increase in the net efficiency of power plant was 3.02%. In a system where a fluidized bed dryer was used, an increase of 1.3% was observed in the net efficiency of the plant [5], while an increase of 4.34% in the efficiency can be improved thanks to the parallel working dryers in this study. In another study using fluidized bed driers, where waste steam was used as waste heat, an increase of 2.09% in net efficiency of power plant was observed [7].

The followings conclusions can be drawn:

- The moisture content of coal adversely affects the efficiency of coal-fired power plant. When more moisture is removed, a further increase in the lower heating value is observed. Accordingly, an increase of 3.04-4.34% will be observed in the power plant efficiency.
- As a result of pre-drying and decreasing the flue-gas outlet temperature, improvement in the boiler efficiency is observed. The higher initial moisture

content in the pre-drying process, the greater the increase in boiler efficiency. In the pre-drying degree of 0.14, the increase in boiler efficiency when coal 1 is used is 2.82%, which is higher than coal 2.

- The energy efficiency increase with coal pre-drying is greater for coal-fired power plants with a higher initial moisture content.
- As the number of fluidized bed dryer with lower capacity is increased, the removed moisture is higher than the single-dryer systems with large capacity.
- As a result of the economic evaluation, the coal pre-dried power plant has far more economic performance than power plant without pre-drying. In addition, when the degree of pre-drying is increased, the economic efficiency of the system also increases.
- Pre-drying ensures the reduction of flue gas flow, the amount of water vapor in the system and the flue gas, thus preventing system failures and reducing system maintenance costs.
- When foreign source dependence in energy and unit energy costs are considered, it is important to put the designed system into practice.
- The study conducted can be considered as a guide for the similar studies regarding the utilization of waste heat.

NOMENCLATURE

Abbreviations

LHV	lower heating value (kCal/kg)
HHV	higher heating value (kCal/kg)
NPV	net present value

Symbols

α	percentage of power consumption pf pumps (%)
A_d	diffusion area (m ²)
A_o	heat transfer area based on the outside surface area of tubes (m ²)
A_s	crossflow area at or near shell centerline (m ²)
Ar	archimedes number

c	annual capacity factor of power plant	Sh	sherwood number
c_p	specific heat at constant pressure (J/kg.K)	Sc	schmidt number
d	inflation rate (%)	T	temperature (K)
d_0	specific heat consumption rate of steam cycle (kJ / kg-setam)	u_m	minimum fluidization velocity (m/s)
D	diffusion coefficient (m ² /s)	U_{eu}	expanded uncertainty
D_p	diameter of coal particles (m)	U_f	heat transfer coefficient for fouled surface (W/m ² K)
D_e	equivalent diameter (m)	U_x	error rates of each independent variable x
D_h	hydraulic diameter (m)	U_Y	uncertainty analysis equation
DC	distribution coefficient	V	volumetric flow rate of fan (m ³ /s)
f	friction coefficient	V_m	volume of coal particle in the bed (m ³)
g	acceleration of gravity (m/s ²)	V_z	total volume of the bed (m ³)
G_s	shell side mass velocity (kg/m ² s)	w	mass % of the content (%)
h	heat transfer coefficient (W/m ² K)	x	input quantities used for uncertainty of measurement
h_{fg}	latent heat of evaporation of water (kJ/kg)	Y	output quantity depends on input quantities
h_m	mass transfer coefficient (m/s)	μ	degree of pre-drying (kg moisture / kg coal)
H	height of fluidized bed (m)	μ_b	shell side dynamic viscosity at average temperature (kg/m.s)
H_{vap}	constant pressure heat of vaporization of water at 25 °C (kCal)	μ_f	dynamic viscosity of drying air (kg/m.s)
i	interest rate (%)	μ_w	dynamic viscosity at wall temperature (kg/m.s)
i_e	combined interest rate (%)	ρ_f	density of air (kg/m ³)
k	coverage factor	ρ_s	density of coal (kg/m ³)
\dot{m}	mass flow rate (kg/s)	ψ	porosity of fluidized bed dryer
m_{fg}	mass of dry flue gas per kg of coal as-fired (kg flue gas / kg coal)	η_b	boiler efficiency (%)
M	mass of coal in fluidized bed dryer (kg)	η_f	fan efficiency (%)
M_{ar}	as-received moisture value (kg)	η_{PP}	net energy efficiency of power plant (%)
M_s	steam mass flow rate (kg/s)	τ	mean residence time (s)
n	redemption period (year)	ΔT_{lm}	log mean temperature difference (K)
N	project life (year)	ΔI_e	electricity sales income increase (TL)
N_{PP}	annual operation hours of power plant (hour/year)	$\Delta \eta_{net}$	change in net efficiency of power plant
Nu	nusselt number	Subscripts	
p_e	grid feed-in tariff (TL/kWh)	a	ambient
P	power (W)	dry	dry basis
P_e	energy output of power plant	fg	flue gas
P_{net}	net energy output of power plant	g	product combustion
P_0	self-consumption of power plant (W)	H	hydrogen
P_t	pressure drop (Pa)	i	inner
P_T	pitch size (m)	N	nitrogen
P_v	pressure of vapor (kPa)	o	outer
Pr	prandtl number	O	oxygen
Q_{mar}	heat of vaporization of water that originates from as-received moisture value (kCal)	s	liquid-gas interface
\dot{Q}_{in}	heat input of the boiler (W)	w	water
\dot{Q}_1	heat output of the boiler (W)	v	vapor
\dot{Q}_2	heat loss due to dry flue gas (W)	∞	away from surface
\dot{Q}_3	heat loss due to moisture in fuel (W)	DECLARATION OF ETHICAL STANDARDS	
\dot{Q}_4	heat loss due to water from combustion of hydrogen in fuel (W)	The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.	
\dot{Q}_5	heat loss due to incomplete combustion (W)	REFERENCES	
\dot{Q}_6	heat loss due to moisture in combustion air (W)	[1]	Turkish Coal Enterprises, “Annual Report 2018”, Ankara, Turkey, (2019).
\dot{Q}_7	heat loss due to surface radiation, convection and other miscellaneous losses (W)	[2]	Turkish Coal Enterprises, “Coal Sector Report (Lignite) 2016”, Ankara, Turkey, (2017).
R_i	benefit (TL)	[3]	Pikon J., Mujumdar A.S., “Drying of coal, in: Handbook
R_o	cost (TL)		
R_v	gas constant of vapor (kPa.m ³ /kg.K)		
Re	reynolds number		

- of Industrial Drying*", third ed., CRC Press, Boca Raton, FL, (2006).
- [4] Xu, C., Xu, G., Zhao, S., Dong, W., Zhou, L., Yang, Y., "A theoretical investigation of energy efficiency improvement by coal pre-drying in coal fired power plants", *Energy Conversion and Management*, 122: 580-588, (2016).
- [5] Xu, C., Xu, G., Yang, Y., Zhao, S., Zhang, K., Zhang, D., "An improved configuration of low-temperature pre-drying using waste heat integrated in an air-cooled lignite fired power plant", *Applied Thermal Engineering*, 90: 312-321, (2015).
- [6] Xu, C., Bai, P., Xin, T., Hu, Y., Xu, G., Yang, Y., "A novel solar energy integrated low-rank coal fired power generation using coal pre-drying and an absorption heat pump", *Applied Energy*, 200: 170-179, (2017).
- [7] Atsonios, K., Violidakis, I., Agraniotis, M., Grammelis, P., Nikolopoulos, N., Kakaras, E., "Thermodynamic analysis and comparison of retrofitting pre-drying concepts at existing lignite power plants", *Applied Thermal Engineering*, 74: 165-173, (2015).
- [8] Xu, C., Li, X., Xu, G., Xin, T., Yang, Y., Liu, W., Wang, M., "Energy, exergy and economic analyses of a novel solar-lignite hybrid power generation process using lignite pre-drying", *Energy Conversion and Management*, 170: 19-38, (2018).
- [9] Liu, M., Yan, J., Chong, D., Liu, J., Wang, J., "Thermodynamic analysis of pre-drying methods for pre-dried lignite-fired power plant" *Energy*, 49, 107-118, (2013).
- [10] Liu, M., Wu, D., Xiao, F., Yan, J., "A novel lignite-fired power plant integrated with a vacuum dryer: System design and thermodynamic analysis", *Energy*, 82: 968-975, (2015).
- [11] Kızıl, H., "Experimental Analysis of Coal Drying in Fluidized Bed Dryer", Post Graduate Thesis, Zonguldak Karaelmas University Institute of Science and Technology, Zonguldak, Turkey, 43-66, (2011).
- [12] Liu, M., Yan, J., Bai, B., Chong, D., Guo, X., Xiao, F., "Theoretical Study and Case Analysis for a Predried Lignite-Fired Power System", *Drying Technology*, 29(10): 1219-1229, (2011).
- [13] ASTM D4239-18, "Standard Test Method for Sulfur in the Analysis Sample of Coal and Coke Using High-Temperature Tube Furnace Combustion", *ASTM International*, West Conshohocken, PA, (2018).
- [14] ASTM D5373-16, "Standard Test Methods for Determination of Carbon, Hydrogen and Nitrogen in Analysis Samples of Coal and Carbon in Analysis Samples of Coal and Coke", *ASTM International*, West Conshohocken, PA, (2016).
- [15] ASTM D7582-15, "Standard Test Methods for Proximate Analysis of Coal and Coke by Macro Thermogravimetric Analysis", *ASTM International*, West Conshohocken, PA, (2015).
- [16] TS ISO 1928, "Solid mineral fuels - Determination of gross calorific value by the bomb calorimetric method and calculation of net calorific value", *Turkish Standards Institution*. Ankara, Turkey, (2014).
- [17] ASTM D5865-13, "Standard Test Method for Gross Calorific Value of Coal and Coke", *ASTM International*, West Conshohocken, PA, (2013).
- [18] TUBITAK. "Metrology", UME, 1st, Istanbul, Turkey, (2013).
- [19] European Co-operation for Accreditation, "Expression of the Uncertainty of Measurement in Calibration", EA 04-2, (1999).
- [20] Kakaç, S., Pramuanjaroenkij, A., Liu, H., "Heat exchangers: Selection, rating, and thermal design", Boca Raton, FL: CRC Press, (2012).
- [21] Çengel, Y. A., Tanyıldızı, V., "Heat and Mass Transfer: A Practical Approach", İzmir: Güven Kitabevi, (2011).
- [22] Gnielinski, V. "New equations for heat and mass transfer in turbulent pipe and channel flow", *Int. Chem. Eng.*, 16: 359, (1976).
- [23] McAdams, W. H., "Heat Transmission", 3rd ed., McGraw-Hill, New York, (1954).
- [24] Kurtuluş, O., "Investigation of fluid bed drying process", Post Graduate Thesis, Yıldız Technical University Institute of Science and Technology, Istanbul, Turkey, 31, (2007).
- [25] Agarwal, P.K., Mitchell, W.J., La Nauze, R.D. "Transport phenomena in multiparticle systems-III. Active particle mass transfer in fluidized beds of inert particles", *Chemical Engineering Science*, 43: 2511-2521, (1988).
- [26] Harimi, M., Sapuan, S., Ahmad, M., Abas, F., "Numerical study of heat loss from boiler using different ratios of fibre-to-shell from palm oil wastes", *Journal of Scientific and Industrial Research*, 67: 440-444, (2008).
- [27] TS EN 304, "Heating boilers - Test code for heating boilers for atomizing oil burners", *Turkish Standards Institution*, Ankara, Turkey, (2017).
- [28] General Directorate Of Renewable Energy, "Optimization in Industrial Systems, Fan Systems", Ankara, Turkey, (2017).
- [29] Özdemir, M.B., Yatarkalkmaz, M.M., "Energy, Exergy and Economic Analysis of Different Types of Collectors", *Gazi Journal of Engineering Sciences*, 1(2): 235-251, (2015).