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Investigation of Heat Recovery Potential According to Flue Gas Field Measurements in Solid Fuel-Fired Buildings with District and Central Heating Systems

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Abstract: In this study, flue gas heat recovery potential was determined by using the flue gas measurements from boilers of buildings with solid fuel-fired district and central heating systems in Balikesir, Turkey. Potential flue gas heat recovery potential in terms of energy savings were examined. The potential of heating the preheated water and combustion air supplied to the boiler was analyzed. Thus, the efficiency of the heating system was increased, and energy savings were achieved by providing fuel savings. In order to reduce the flue gas temperature in solid fuel-fired boilers, the acidification temperature, fuel properties and excess air coefficient should be known. Below the acidification temperature, corrosion and other adverse effects may occur in the flue and in the heat exchanger. In this study, acidification temperature and fuel and combustion characteristics of coal were taken into account. Generally, seven types of coal are used for heating purposes in Balikesir province. Thus, flue gas heat recovery potential was determined for these seven types of coal. In terms of energy savings, the recovery potential in Balikesir province was calculated to be between 287,706 and 152,780 kW.

Keywords: chimney gas temperature; heat recovery; acid dew point temperature; air excess coefficients; lignite coal

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1. Introduction

One source of energy losses in buildings is those that occur during heating. The most widely used method for heating buildings is to obtain heat energy by burning fossil fuels. As a result of losses in boilers, not all of the energy obtained from fossil fuels can be used. Important losses occur in boiler chimneys as a result of fuel combustion. Considering the number of boilers used in various sectors, this loss has increased significantly in recent years [1].

As a result of the reduction in energy resources, waste heat needs to be recovered. The advantages of waste heat recovery can be classified into two categories: direct and indirect. The advantages of direct heat recover are the reduction in consumption and cost, whereas the advantages of indirect heat recovery are the reduction in air pollution and the sizing of equipment, such as fans, chimneys and boiler air ducts [2].

In the design of heat recovery units in boilers, important parameters include the amounts of carbon, hydrogen, oxygen and sulfur contained in the fuel. Van Krevelen graphs classify solid fuels based on the mole ratios of H/C and O/C, determining the quality of solid fuels. The fuel quality is important in chimney heat recovery. Apart from this, the dew point temperatures of the water and sulfuric acid vapor in the chimney are among other important parameters. In addition, outdoor temperature and relative humidity are also effective parameters [3,4].

In flue gas heat recovery applications, sulfur dioxide in the flue gas reacts chemically with water vapor to release sulfuric acid. When the water and sulfuric acid vapor in the flue gas come into contact with the cold surfaces in the heat exchanger and inside the chimney, if the temperature drops below the dew point, the water and sulfuric acid vapors condense, causing corrosion. The dew point temperature of sulfuric acid is higher than that of water vapor [4]. These dew point temperatures, which are important in recovering heat from the boiler flue gas, present the problem of low-temperature corrosion [5].

In coal-fired boilers, 4–8% of the heat content of the fuel is carried by the flue gas and can be converted into thermal energy [6]. Boilers can generally lose 20% of their combustion energy through flue gas and can recover 50% of this lost energy according to operating conditions by using a flue gas heat exchanger [7].

The change in the temperature of the boiler flue gases is a result of the heat exchange between the flue gases and a heated fluid, depending on the type of boiler. The temperature of the flue gases is also affected by the amount of supplied air, which is not involved in combustion and must be heated from ambient temperature to outlet temperature [8].

The most common methods used to reduce the exhaust flue gas temperature and increase the waste heat recovery are preheating of the air supplied to the boiler, preheating of the water supplied to the boiler and obtaining hot water for use. To this end, a heat exchanger is placed in the chimney. Here, the heat transfer surface in the heat exchanger should be well-calculated. Increasing this surface area may not achieve the desired energy savings and may also increase the cost of the heat exchanger [9].

According to a literature review, Jamil et al. [1] et al. investigated the usability of a boiler flue heat recovery system to heat boiler return water and boiler feed air. To this end, they designed a recovery system consisting of an indirect contact condensation unit, a mechanical compression heat pump and a combination of two air preheaters. Thermodynamic analyses of the system were conducted. Sensitivity analysis was carried out to determine effects of different operating parameters on the performance of the chimney heat recovery system and the boiler. Terhan and Comakli [2] conducted energy and exergy analyses for flue gases, which represent the largest heat losses in boilers, in the district heating system of a university comprising natural-gas-fired boilers. The ratio of flue gas energy to exergy losses in the boilers was determined. Engin et al. [3] presented the results of an extensive experimental study on the combustion of low-grade Turkish lignites in a 30 kWh circulating fluidized bed combustor. Terhan [4] analyzed the dew point temperatures of water and sulfuric acid vapors in flue gas by burning fuels such as coal, fuel oil, natural gas, LPG and wood in boilers in multiple cities in Turkey. Jin Y. [5] et al. examined a waste heat recovery system with an organic liquid cycle integrating an organic Rankine cycle in a 660 MW supercritical coal-fired power plant. Wei et al. [6] investigated a new system using the residual heat in sulfur-reduced flue gas using absorption technologies to reduce the waste flue gas temperature in the boiler at the Jinan-Beijiao coal-fired cogeneration power plant in China. The recovered heat was then used to heat the return water. Terhan and Comakli [7] investigated the condensation of water vapor in flue gas to recover the latent heat of the exhaust flue gas of 60 MW natural-gas-fired boilers in a district heating system of a university. The design calculations of a flue gas condenser consisting of reverse-flow U-shaped stainless steel pipe bundles were performed with a computer program using the one-dimensional finite difference method. Bukowska et al. [8] investigated chimney heat recovery proposals in bituminous coal-fired boilers with varying loads in Poland. The thermal losses of the boilers, the overall efficiency of the boiler plant, the exhaust gas temperature and the excess air factor were examined. In chimney heat recovery, a heat exchanger (economizer) was proposed to preheat the hot water supplied to a boiler. Xu et al. [9] proposed a flue gas heat recovery system and an additional economizer system for coal-fired boilers. Direct use of flue gas energy and indirect flue gas heat recovery systems were investigated. Shamsi et al. [10] et al. suggested a new waste heat and water recovery system that produces power in a thermal power plant, both working with the organic Rankine cycle and using a single working fluid consisting of cooling cycles. Kon and Caner [11] investigated the heat recovery potential from flue gases of natural gas-fired boilers in a central heating system for four climatic regions of Turkey. The recovery energy potential of the flue gases was calculated according to the air excess coefficients and flue gas temperatures of the boilers. Men et al. [12] proposed a new flue gas waste heat recovery system in Beijing to improve the thermal efficiency of a steam pump boiler with flue gas recirculation system and reduce oxynitride emissions. In the system, the oxidizing air is preheated and humidified before combustion in the boiler. Zhao et al. [13] analyzed the waste heat potential of flue gas to increase the efficiency of a space heating system with natural gas and identified problems associated with the conventional space heating system. Wei et al. [14] performed detailed calculations of acid condensation in coal-fired boilers. A detailed new calculation model for the acid dew point was proposed. Kon and Caner [15] investigated the potential of flue gas heat recovery in heating installations in buildings due to the increase in the surface area and volume with an increase in the number of buildings to be heated. Xiang et al. [16] developed a thermodynamic formula for acid dew point estimation to reduce the temperature of exhaust flue gas in boilers. Accordingly, a quasi-experimental prediction model was proposed. Blanco and Pena [17] investigated the effects of acid dew point temperature on preheaters in a thermal power plant. The service life and maintenance cost of the equipment were examined in the transition to different fuels. To recover flue gas waste heat, a steam pump system consisting of a gas condenser, an air humidifier and a gas–water heat exchanger was installed by Wei et al. [18]. Then, they investigated the heating and humidification of boiler oxidizing air by means of a condenser and humidifier and investigated flue gas dew point improvement. Lu et al. [19] investigated a new gas-fired absorption heat pump, investigating the sensible and latent heats, i.e., the waste heat of flue gas, their recovery in the solution preheater and an intermediate evaporator. Chakrovorty et al. [20] conducted research to reduce PM, SO_2, NO_x and CO_2 emissions and achieve waste heat recovery from a specially modified chimney for local rice boiling industries. Xiao et al. [21] investigated the use of economizers for flue gas waste heat recovery in a coal-fired 600 MW ultra-supercritical power plant in China. The simulation results were examined to determine the effect of flue gas exhaust temperature on reducing the flue gas acid dew point in the presented economizer system. Kon and Yuksel [22] investigated the flue gas heat recovery potential for a 600,000 kcal/h natural-gas-fired boiler in a seven-story public building in Balıkesir and recorded flue gas measurements. The authors determined that the chimney has the potential for heat recovery by obtaining waste heat for hot water. Xun et al. [23] proposed a new type of low-pressure intermediate plate economizer for flue gas recovery in coal-fired boilers. The performance of this economizer was investigated by numerical simulations, and the results were compared experimentally. Niu et al. [24] examined an absorption heat pump system and investigated its use in flue gas heat recovery with natural gas in northern China, examining the temperature reduction in heat exchangers.

Thiyagu et al. [25] examined an economizer to heat the feed water supplied to the boiler and a heat exchanger to heat the air supplied to the boiler in order to recover flue gas heat. The heat exchanger was analyzed using ANSYS 14.5 software. Lepiksaar et al. [26] investigated heat recovery through a flue gas condenser and the decrease in the return water temperature in a district heating system, estimating the amount of energy savings. A calculation model was developed for various return water temperatures in the district heating system. Abdullah B. [27] B. Abdullah examined the precautions to be taken in boilers and burners and the factors causing internal cooling of the boiler by conducting a flue gas analysis. Fialko et al. [28] studied a heat recovery system in which the exhaust gas is cooled below the dew point of water vapor and investigated a protection technology to prevent the formation of condensation in the exhaust gas ducts of boiler plants for high recovery of exhaust gas heat. Liu and Sun [29] experimentally investigated a flue gas waste heat recovery system was experimentally, considering the acid corrosion of the exhaust gas of boilers in coal-fired power plants. They researched the exhaust gas temperature with varying flue gas flows, flue gas temperatures and ambient air temperatures. Suggestions were made for economizer and air heater properties in chimney heat recovery. Cui et al. [30] analyzed an absorption heat pump for flue heat recovery of natural-gas-fired boilers. A two-stage waste heat recovery system was optimized, and the dew effect on chimney heat recovery was investigated. Terhan [31] conducted a combustion analysis of coal fuels for multiple provinces in Turkey with the aim of preventing the risk of corrosion on the surfaces of a heat exchanger designed for the application of latent heat recovery from waste flue gas in boilers. The author determined in which regions of the designed heat exchanger the flue gas temperature reached the dew point temperatures of sulfuric acid and water vapor. The heat exchanger used for the designed air preheating consists of a reverse-flow, U-shaped stainless steel tube bundle. Zhao et al. [32] examined the problems of district heating systems with natural gas boilers and analyzed the waste heat recovery potential of the chimney. They developed a new process to reduce the outlet temperature of the flue gas to about 20 °C and analyzed the economic performance of the proposed process. Yalçın [33] calculated the cost of hot water or saturated steam for different air excess coefficients in boilers using natural gas and coal. Thermodynamic calculations were performed for the highest combustion temperature in the boiler in a continuous flow open system; the fuel, air and feed water entering the boiler; and the mass flow rate of the flue gases coming out of the boiler. Kon and Yuksel [34] determined CO_2 emissions, water vapor and dew point temperature values of the combustion gases released by natural-gas-fired boilers in a heat center in a public building consisting of a seven-story main building and a single-story printing house in Balikesir province. To this end, the flue gases in heating boilers were measured. Differences between theoretical values and measured values were investigated. Kon and Caner [35] examined the energy properties of new slurry fuels according to their Van Krevelen diagrams. The required stoichiometric air–fuel ratio in the burner was calculated during the combustion process.

The aim of the present study is to determine the flue gas heat recovery potential and its evaluation possibilities for and entire city using the flue gas measurements from boilers of buildings with district and central heating systems containing an average of 41 flats with a central heating system in the city center using coal provided by the Balikesir Municipality Environmental Protection and Control Department of Turkey. Measurements were conducted in February and March 2019. In the city center of Balikesir, the measurements were taken in the district and central heating systems in 12 neighborhoods with central and district heating systems fueled by coal. Because Balikesir has a generally mild climate, it was assumed that the heating system works 14 h a day. In the study, Kütahya Tunçbilek (washed), Kütahya Ömerler (washed), Kütahya Seyitomer-Höyükaltı, Manisa Imbat (washed), Bursa Orhaneli, Bursa Keles and Çanakkale Çan lignite coals from the surrounding cities for heating purposes were used as fuel. We determined the flue gas heat recovery potential of the boilers of these seven types of coal-fired buildings with district and central heating. To determine the flue gas heat recovery potential in lignite coal-burning boilers, we considered the acidification temperature and the amounts of carbon, hydrogen, oxygen and sulfur with respect to the fuel and combustion characteristics of the lignite coal, as well as their ratios to one another. For the flue gas heat recovery evaluation of the boilers, energy savings were achieved by using heat exchangers placed in the flue to heat the feed water supplied to the boiler and to heat the combustion air supplied to the boiler. We determined energy-saving potential for the whole city based on these investigations and research. Buildings with central and district heating systems can benefit from flue gas heat, which has the potential to be used and wasted, therefore achieving energy savings. In solid fuel boilers, the properties and content of solid fuel are important parameters for flue gas recovery. In this study we investigated the flue gas heat recovery potential and usage possibilities in buildings using lignite coal in central and district heating systems.

2. Methodology

In the literature, industrial flue heat recovery potentials are generally determined. Flue heat recovery potential studies for residences with central and district heating systems include theoretical investigations. In this study, the flue heat recovery potential of coal-fired boilers was determined for a whole city according to the values measured in the flue. In addition, changes in flue heat recovery potential due to different lignite quality and properties were investigated. The highest and lowest flue heat recovery potentials of these coals were determined. The results of this study will contribute to the literature with respect to these features. Schematic representations of flue gas measurement analyzers are presented in Figure 1. Figure 2, shows a schematic representation of the proposed flue heat recovery system for the boilers.

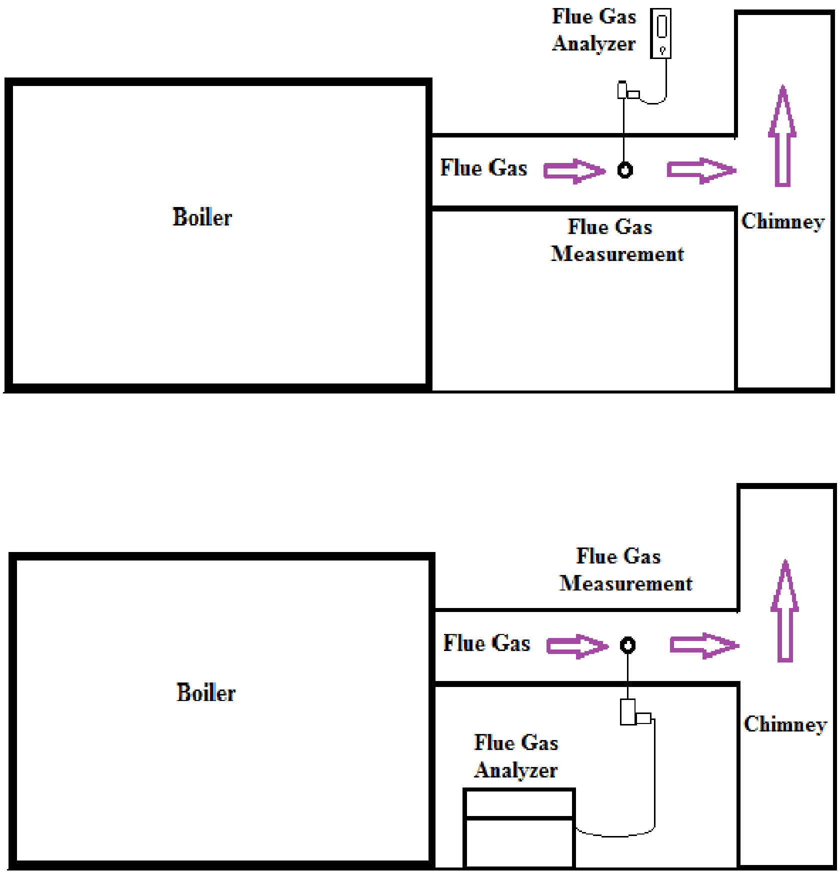
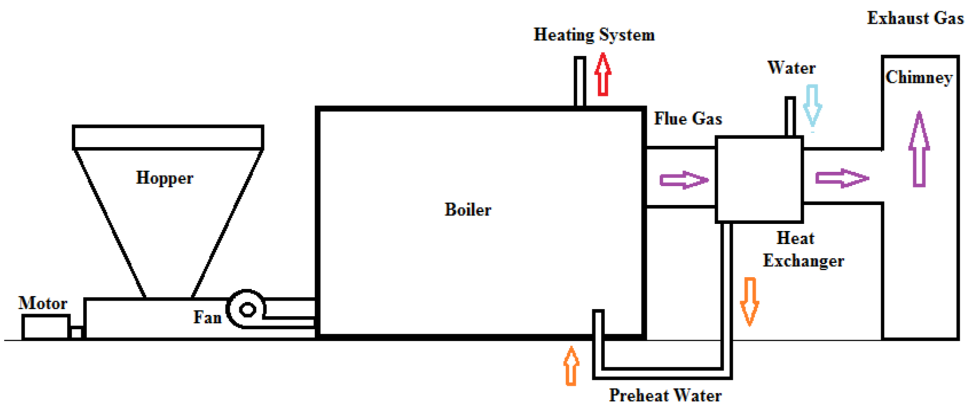
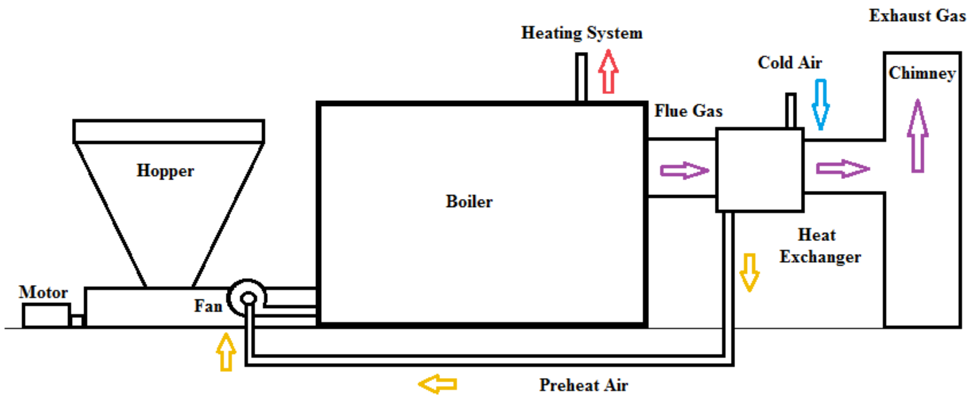


Figure 1. Flue gas measurement analyzers.



(**a**)

Figure 2. *Cont*.



(**b**)

Figure 2. Schematic representation of flue gas heat recovery systems: (**a**) preheated water; (**b**) preheated combustion air.

2.1. Combustion Equation

Combustion of fuel with moist air can be calculated according to the following equation:

$$C_eH_dO_cS_kN_f + (a_{min})\lambda(O_2 + 3.76\ N_2 + 0.00145\,CO_2 + bH_2O) \rightarrow xN_2 + yO_2 + zCO_2 + kSO_2 + (t + a_{min}\lambda b)\ H_2O \quad (1)$$

where a_{min} is the minimum amount of oxygen required for fuel to burn, and λ is the excess air coefficient [33,34].

$$a_{min} = (e + \frac{d}{4} + k - \frac{c}{2}) \quad (2)$$

The molecular weight of fuel is calculated according to the following equation:

$$M_f = 12e + d + 16c + 32k + 14f \quad (3)$$

2.2. Climate Characteristics of Balikesir Province

Balikesir is a city in the northwest of Turkey bordering the Marmara and Aegean Seas, with a population of 1,228,620. Its area is 14,299 km^2, and it is located between 39°40′ N and 26°28′ E [36]. As it is in the 2nd climate zone according to the Turkish insulation standard TS 825, it has a temperate climate [37].

2.3. Total Fuel Consumption Calculation

The heating period in Balikesir province is approximately 210 days. The heating system operates for an average of 14 h a day as the second operation according to the Turkish heating system standard TS 2164 [37,38]. The city center of Balıkesir is reported to required 232,353.5 MWh of heating in an average year [37]. The total annual coal consumption equation for the city is expressed as:

$$F = \frac{QP}{\eta\ LHV\ n} \quad (4)$$

where Q is the heating need of dwelling, P represents the total population of the city (in the present study, the population of the city center is 364,370 people), η is the fuel thermal efficiency, LHV is the lower calorific value of the fuel and n is the number of people living in a dwelling (4 people per dwelling was assumed in the present study) [39]. In Balikesir, 65.8% of the houses are heated with coal [36,40].

2.4. Flue Gas Energy-Saving Potential

The total flue gas amount is calculated as [2,7,41]:

$$V_{FGA} = x + y + z + k + (t + a_{min} \lambda b) \quad (5)$$

Carbon dioxide ratio of flue gases:

$$x_{CO_2} = \frac{z}{V_{FGA}} \quad (6)$$

Water vapor rate:

$$x_{H_2O} = \frac{t + a_{min} \lambda b}{V_{FGA}} \quad (7)$$

Nitrogen ratio:

$$x_{N_2} = \frac{x}{V_{FGA}} \quad (8)$$

Oxygen ratio:

$$x_{O_2} = \frac{y}{V_{FGA}} \quad (9)$$

Sulfur dioxide ratio:

$$x_{SO_2} = \frac{k}{V_{FGA}} \quad (10)$$

The molar specific heats of each of the components that make up the flue gas are calculated as follows:

$$\overline{C_{pCO_2}} = 22.26 + 5.981\ 10^{-2} T_{Flue} - 3.501\ 10^{-5} T_{Flue}^2 + 7.469\ 10^{-9} T_{Flue}^3 \quad (11)$$

$$\overline{C_{pH_2O}} = 32.24 + 0.1923\ 10^{-2} T_{Flue} + 1.055\ 10^{-5} T_{Flue}^2 - 3.595\ 10^{-9} T_{Flue}^3 \quad (12)$$

$$\overline{C_{pO_2}} = 25.48 + 1.520\ 10^{-2} T_{Flue} - 0.7155\ 10^{-5} T_{Flue}^2 + 1.312\ 10^{-9} T_{Flue}^3 \quad (13)$$

$$\overline{C_{pN_2}} = 28.90 - 0.1571\ 10^{-2} T_{Flue} + 0.8081\ 10^{-5} T_{Flue}^2 - 2.873\ 10^{-9} T_{Flue}^3 \quad (14)$$

$$\overline{C_{pSO_2}} = 25.78 + 5.785\ 10^{-2} T_{Flue} - 3.812\ 10^{-5} T_{Flue}^2 + 8.612\ 10^{-9} T_{Flue}^3 \quad (15)$$

where T_{Flue} is the temperature of the flue gas (K).

Average specific heat of flue gases:

$$\overline{C_{PORT}} = x_{CO_2} \overline{C_{PCO_2}} + x_{O_2} \overline{C_{PO_2}} + x_{H_2O} \overline{C_{PH_2O}} + x_{N_2} \overline{C_{PN_2}} + x_{SO_2} \overline{C_{PSO_2}} \quad (16)$$

Molar mass of fuel:

$$MM_{Fuel} = e\, MM_C + d\, MM_H + c\, MM_O + k\, MM_N + f\, MM_S \quad (17)$$

where MM_{Fuel} is the molar mass of the fuel, MM_C is the molar mass of carbon, MM_H is the molar mass of hydrogen, MM_O is the molar mass of oxygen, MM_N is the molar mass of nitrogen and MM_S is the molar mass of sulfur (kg/kmol).

The molar mass of air:

$$MM_{Air} = MM_{O_2}\, x_{O_2} + MM_{N_2}\, x_{N_2} + MM_{CO_2} x_{CO_2} + MM_{H_2O}\, x_{H_2O} \quad (18)$$

where MMAir is the molar mass of air, MM_{O_2} is the molar mass of oxygen, MM_{N_2} is the molar mass of nitrogen, MM_{CO_2} is the molar mass of carbon dioxide and MM_{H_2O} is the molar mass of water (kg/kmol) [2,7,41].

Molar mass of flue gases:

$$MM_{FG} = x_{CO_2}\, MM_{CO_2} + x_{H_2O}\, MM_{H_2O} + x_{O_2}\, MM_{O_2} + x_{N_2}\, MM_{N_2} + x_{SO_2}\, MM_{SO_2} \quad (19)$$

where MM_{FG} is the molar mass of flue gases, MM_{CO_2} is the molar mass of carbon dioxide, MM_{H_2O} is the molar mass of water vapor, MM_{O_2} is the molar mass of oxygen, MM_{N_2} is the molar mass of nitrogen and MM_{SO_2} is the molar mass of sulfur dioxide (kg/kmol).

The mass of the flue gases per unit time is the sum of the masses of the fuel and air per unit time.

$$m_{Fuel} + m_{Air} = m_{FG} \quad (20)$$

where were m_{Fuel} is the mass of fuel per unit time, m_{Air} is the mass of air per unit time and m_{FG} is the mass of flue gases per unit time and units (kg/s).

Fuel energy obtained by the combustion of fuel:

$$E_{Fuel} = m_{Fuel}\, LHV \quad (21)$$

where E_{Fuel} is the energy obtained by the combustion of the fuel (kJ/s), m_{Fuel} is the fuel consumption per unit time (kg for solid fuels and m^3 for gas and liquid fuels), LHV is the lower heating value (kJ/kg for solid fuels), λ is the excess air coefficient.

The mass of air per unit time (kg):

$$m_{Air} = \frac{m_{Fuel}\ (4.76145 + b)\ \lambda\ MM_{Air}}{MM_{Fuel}} \quad (22)$$

Mass of flue gases per unit time (kg):

$$m_{FG} = m_{Fuel} + \frac{m_{Fuel}\ (4.76145 + b)\ \lambda\ MM_{Air}}{MM_{Fuel}} \quad (23)$$

The mole amount of flue gases per unit time is calculated as follows:

$$n_{FG} = \frac{m_{FG}}{MM_{FG}} \quad (24)$$

where n_{FG} is the flue gases per unit time (kmol).

Some of the fuel energy obtained by combustion of the fuel is lost through flue gases. The energy carried by the flue gases are sensible energy arising from the flue gas temperature and the latent energy carried by the water vapor in the flue gases. The heat energy that can be recovered by cooling the flue gases in the heat exchanger to a temperature (T) above the dew point [2,7,41]:

$$E_R = n_{FG}\ \overline{C_{PORT}}\ (T_{FG} - T) \quad (25)$$

$$\%\text{Flue Loss} = \frac{E_R}{E_{Fuel}} 100 \quad (26)$$

The amount of energy that can be obtained to preheat the water or air to be supplied to the boiler:

$$E_R = m\ C_p\ (T_x - T) \quad (27)$$

where m is the amount of water or air to be preheated, C_p is specific heat of the air or water, T is the temperature of the water or air before preheating and T_x is the desired temperature of the water or air after preheating [41].

2.5. Sulphuric Acid and Water Vapour Dew Point Temperatures

Average meteorological values are presented for the days and hours of measurement; relative humidity is 78.6%, atmospheric pressure is 1007 mb and outdoor temperature is 4.5 °C [42]. The sulfuric acid and water vapor dew point temperatures in the flue can be determined according to the following formulae [31,41].

Water vapor pressure:

$$P_{H_2O} = \frac{n_{H_2O}}{n_{FG}} P_{atm} \quad (28)$$

where n_{H_2O} is the mole amount of moisture in the flue gas.

Sulfur oxide pressure:

$$P_{SO_3} = \frac{n_{SO_3}}{n_{FG}} P_{atm} \tag{29}$$

where n_{SO_3} is the mole amount of sulfur trioxide in the flue gas.

$$(SO_2 + 1/2\ O_2 \rightarrow SO_3)$$

Water vapor dew point temperatures:

$$T_{WDT} = 0.001173333\ (P_{H_2o})^3 - 0.0942\ (P_{H_2O})^2 + 3.429666667\ (P_{H_2O}) + 19.8 \tag{30}$$

Sulfuric acid vapor dew point temperatures:

$$T_{ADT} = 203.25 + \log\ (P_{H_2O}) + 10.83\ \log\ (P_{SO_3}) + 1.06\ (\log\ (P_{SO_3}) + 8)^{2.19} \tag{31}$$

2.6. Properties of Coals

The we determined the seven most used lignite coals in Balikesir province. The lignite coal extraction fields in the province of Balikesir are listed Figure 3. The chemical compositions of these lignite coal types are presented in Table 1. Th lower heat values of different types of lignite coal shown in Table 2. The H/C, O/C, S/C and S/O ratios for these seven types of lignite coal are shown in Table 3. The thermal efficiency of lignite coals is assumed to be 60% [38].

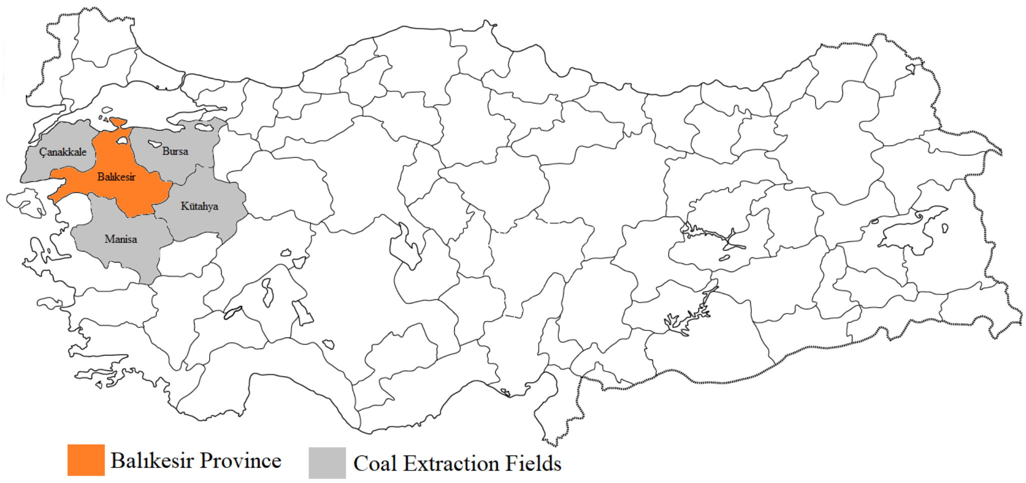


Figure 3. Balikesir province and Lignite coal extraction fields used in the study in Turkey.

Table 1. Chemical compositions of different types of lignite coal [3].

Lignite Coal Type	C	H	N	O	S	Ash
Kütahya Tunçbilek (washed)	70.58	4.12	2.19	6.23	2.29	14.59
Kütahya Ömerler (washed)	69.30	4.31	2.44	5.48	1.49	16.98
Kütahya Seyitomer-Höyükaltı	56.35	3.24	1.18	12.63	2.19	24.41
Manisa Imbat (washed)	66.54	4.11	1.98	11.71	1.01	14.76
Bursa Orhaneli	69.26	4.74	0.97	13.50	2.18	9.35
Bursa Keles	51.03	4.02	1.17	11.54	1.97	30.27
Çanakkale Çan	39.21	2.86	0.96	7.67	5.69	43.60

Table 2. Lower heat values of different types of lignite coal [3].

Lignite Coal Type	Lower Heat Value (LHV) (kWh/kg)
Kütahya Tunçbilek (washed)	6.025
Kütahya Ömerler (washed)	5.956
Kütahya Seyitomer-Höyükaltı	3.536
Manisa Imbat (washed)	5.697
Bursa Orhaneli	4.519
Bursa Keles	2.972
Çanakkale Çan	3.219

Table 3. Composition ratios for different types of lignite coal.

Lignite Coal Type	H/C	O/C	S/C	S/O
Kütahya Tunçbilek (washed)	0.700	0.066	0.012	0.185
Kütahya Ömerler (washed)	0.746	0.059	0.008	0.137
Kütahya Seyitomer-Höyükaltı	0.690	0.168	0.014	0.086
Manisa Imbat (washed)	0.741	0.132	0.006	0.044
Bursa Orhaneli	0.821	0.146	0.012	0.081
Bursa Keles	0.945	0.170	0.015	0.086
Çanakkale Çan	0.875	0.147	0.054	0.372

2.7. Excess Air Coefficient and Flue Gas Temperature Measurements

The highest flue gas temperature measured by the Environmental Protection and Control Unit of Balikesir Metropolitan Municipality in the boilers of twelve apartments with coal-fired district and central heating systems in the city center was determined as 246 °C; the lowest measured temperature was 154 °C, and the average was 199 °C [43]. Measurements were performed between 9 February 2019 and 9 March 2019. These values and others are presented in Figure 4. The highest measured excess air coefficient was 7.1, the lowest was 2.41 and the average was 4.65 [36,43]. These values and others are shown in Figure 5. Measurements were conducted in boilers of apartment building with coal-fired district and central heating systems with an average of 41 flats [43]. A flow chart of the study is shown in Figure 6. The necessary parameters for both the emissions released from the flue to the environment and the heat recovery potential of the flue gas were determined according to flue gas measurements. In addition, the combustion efficiency of the boiler and the potential to reduce fuel consumption can be examined. According to the measurements, the boiler is expected to become steady first. Then, the probe of the flue analyzer is placed in a small channel opened in the flue for flue gas measurement in the boilers, and measurements are conducted at three or more intervals, depending on the diameter and thickness of the flue. The measurement is completed with the flue gas analyzer by taking the average of three or more measurements. The 12 measurements recorded in the present study were conducted in buildings with central and district heating systems burning lignite coal at different locations in the city.

Flue gas temperature, excess air coefficient, flue gas flow and pressure for combustion efficiency, fuel consumption and recoverable heat energy potential can be measured from flue gas in the boilers. Various compounds related to the fuel (solid, liquid or gas) used in the boiler are measured to determine the gas released into the atmosphere. In the present study, flue gas measurements were conducted taking into consideration the higher use of coal fuel in February and March. Buildings using central heating consist of between 8 and 56 flats, whereas flats using district heating contain between 96 and 150 flats, with an overall average of 41 flats per building.

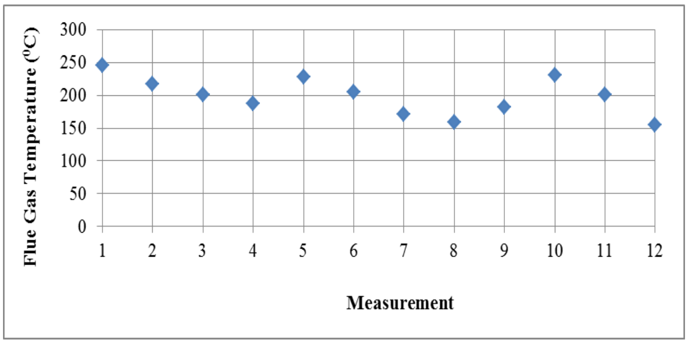


Figure 4. Flue gas temperature measurements [43].

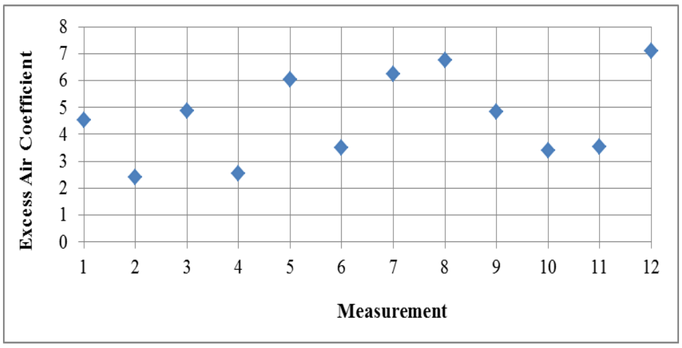


Figure 5. Excess air coefficient measurements [43].

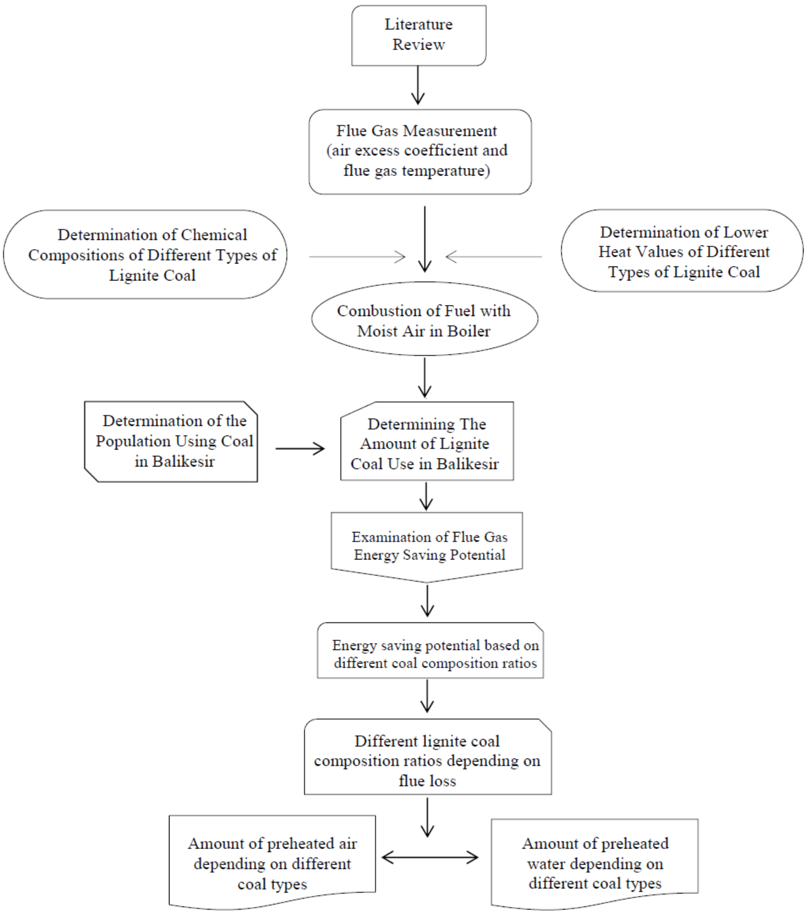


Figure 6. Flow chart of the study.

3. Results and Discussions

We examined the chemical compositions for flue gas heat recovery of seven most used types of lignite coal in Balikesir, which are burned in boilers in central and district heating systems. The highest C ratio of 70.58% is associated with Kütahya Tunçbilek (washed) coal, and the lowest C ratio is 39.21%, corresponding to Çanakkale Çan coal. The highest H ratio is associated with Bursa Orhaneli coal (4.74%) and the lowest H ratio corresponds to Çanakkale Çan coal (2.86%). The highest O rate is associated with Bursa Orhaneli coal (13.50%), and the lowest O rate corresponds to Kütahya Ömerler (washed) coal (5.48%). The highest S ratio is associated with Çanakkale Çan coal (5.69%), and the lowest S ratio corresponds to Manisa Imbat (washed) coal (1.01%). In terms of the compositions of the seven investigated coal types, Kütahya Tunçbilek (washed) coal contains the most C (5.882), and Çanakkale Çan coal contains the least C (3.268). When the H ratio is considered, the highest ratio is associated with Bursa Orhaneli coal (4.740), with the lowest H ratio corresponding to Çanakkale Çan coal (2.860). The highest O rate is associated with Bursa Orhaneli coal (0.844), and the lowest O rate corresponds to Kütahya Ömerler (washed) coal (0.343). The highest S ratio was found in Çanakkale Çan coal (0.178), and the lowest S ratio corresponds to Manisa Imbat (washed) coal (0.032). The highest H/C ratio is associated with Bursa Keles coal (0.945), and the lowest H/C ratio corresponds to was Kütahya Tunçbilek (washed) coal (0.700). The highest O/C ratio was calculated in Bursa Keles coal (0.170), and the lowest O/C ratio corresponds to Kütahya Ömerler (washed) coal (0.059). H/C and O/C are the ratios used to determine the quality of coal as fuel. According to the literature, the fuels with the highest H/C and O/C ratios are those that produce the most heat when burned. The highest water vapor dew point temperature was determined at 19.842 °C in Bursa Keles coal, and the lowest at 19.829 °C in Kütahya Tunçbilek (washed) coal. The water vapor dew point temperature is directly proportional to the H/C and O/C ratios. The water vapor dew point increased with increased carbon content. Carbon is the most important burning element in fuels. Sulfur causes acidification, which damages the flue. Therefore, the acidification temperature of coal-fired boilers is an important factor in the flue. When the temperature drops below this threshold, corrosion and other negative effects are caused in the flue. In the present study, flue gas heat recovery was calculated by reducing the flue gas temperature to the acidification temperature. In the absence of sulfur content in fuels such as natural gas, the flue temperature can be increased to the dew point temperature, which is much lower. Thus, a much higher rate of flue gas heat recovery can be achieved in natural-gas-fired boilers. The highest S/C ratio was calculated in Çanakkale Çan coal (0.054), and the lowest S/C ratio corresponded to Manisa Imbat (washed) (0.006). The highest S/O ratio was found in Çanakkale Çan coal (0.372), and the lowest S/O ratio corresponded to Manisa Imbat (washed) coal (0.044). Therefore, the highest acid dew point temperature was detected in Çanakkale Çan coal (169.713 °C) and the lowest in Manisa Imbat (washed) coal (143.526 °C). The acid dew point temperature of coal with high S/C and S/O ratios is directly proportional. Values related to water vapor dew point temperature and H/C and O/C ratios, as well as acid dew point temperature and S/H and S/O ratios are presented in Figure 7.

The results of this study can serve as a basis for future studies to determine both the emission and heat recovery potential of the flue gas of boilers, depending on the characteristics of the solid fuel used for central and district heating systems. The recovery potential from flue gases of boilers used in industry has been investigated in the literature. This preliminary study can be extended to settlements that burn solid fuel through central and district heating systems. In the present study, we demonstrated that energy saving can be achieved not only in big cities but also in buildings with a smaller central heating systems. The use of natural gas is increasing in buildings with central and district heating systems, such as in the city of Balikesir. Therefore, in future studies, the flue gas heat recovery potential for systems using natural gas can be investigated. The use of solid, liquid and gas fuels can be compared in terms of flue gas recovery. For settlements such as smaller towns, the potential of flue gas recovery can be investigated for different fuel types.

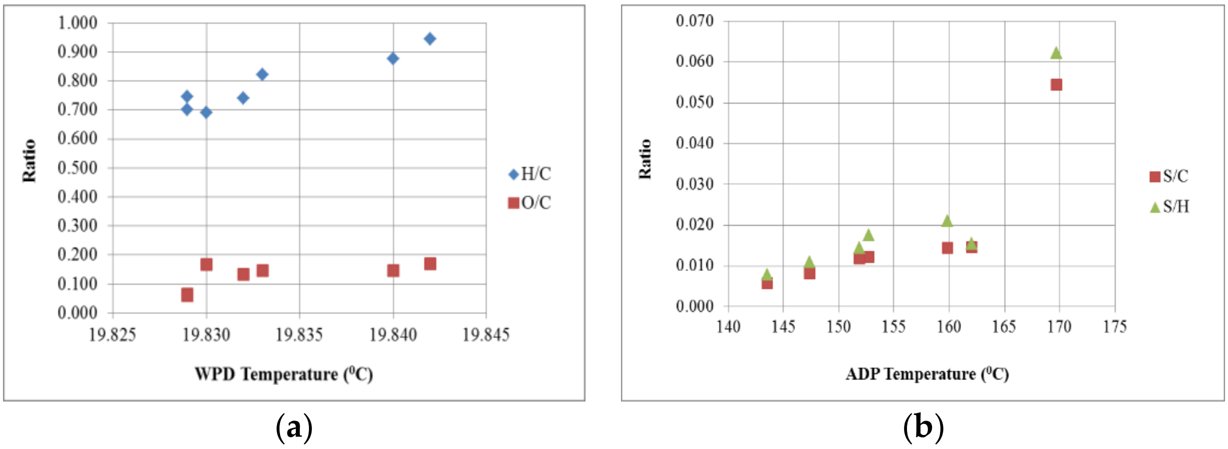


Figure 7. (**a**) Water vapor dew point temperature and (**b**) acid dew point temperature based on varying ratios.

The highest flue efficiency loss was calculated in Bursa Keles coal (1.734%), and the lowest fuel efficiency loss corresponded to Kütahya Tunçbilek (washed) coal (0.921%). The flue efficiency loss depends on the H/C and O/C ratios of the coal. Coals with high H/C and O/C ratios exhibit high flue efficiency loss. The heating value is inversely proportional to the flue loss. Bursa Keles coal has the lowest heating value of 2.972 kWh, and Kütahya Tunçbilek (washed) coal has the highest heating value of 6.025 kWh. The heating values of the coals depend on the amount of coal consumption in kilograms per second in the central and district heating system, as well as the flue loss values in the boilers after the coal is burned (Figure 8).

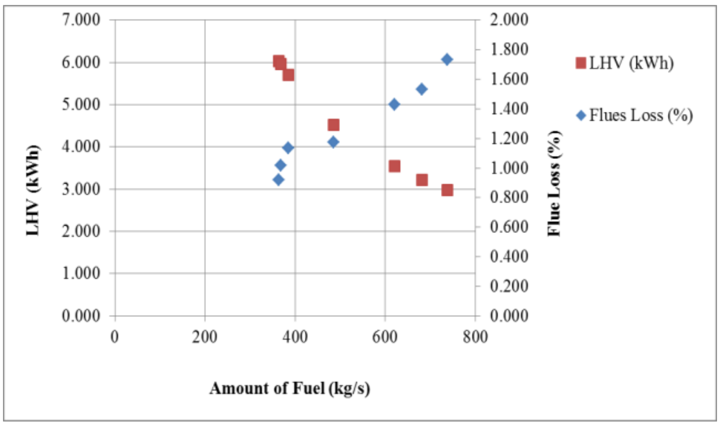


Figure 8. Amount of fuel required according to the coal lower heating value and flue loss.

The most fuel is required when burning Bursa Keles coal (739 kg/h), and the least among of fuel is required when burning Kütahya Tunçbilek (washed) coal. Bursa Keles coal has the highest flue gas heat recovery potential of 4,027,889 kWh, with lowest flue gas heat recovery potential corresponding to Kütahya Tunçbilek (washed) coal (2,138,920 kWh). More flue loss occurs in coals with lower heating values and high H/C and O/C ratios, but with more flue gas heat recovery potential. In coals with lower heating values and low H/C and O/C ratios, a large portion of the coal is converted into heat energy via burning in boilers in central and district heating systems. On the other hand, in coals with lower heating values and high H/C and O/C ratios, some of the heat energy is lost as flue loss as a result of combustion, as not all of the coal is burned in the boilers, and smooth combustion does not occur. Changes in H/C, O/C, S/C and S/H ratios in terms of flue gas recovery energy-saving potential of the seven investigates lignite coal types are shown in Figure 9. Changes in H/C, O/C, S/C and S/H ratios of lignite coals due to flue loss in boilers in apartment buildings with coal-fired district and central heating systems are shown in Figure 10. The changes in the S/H ratio depending on the S/C ratio and changes in the O/C ratio depending on the H/C ratio of different lignite coal types are shown in Figure 11.

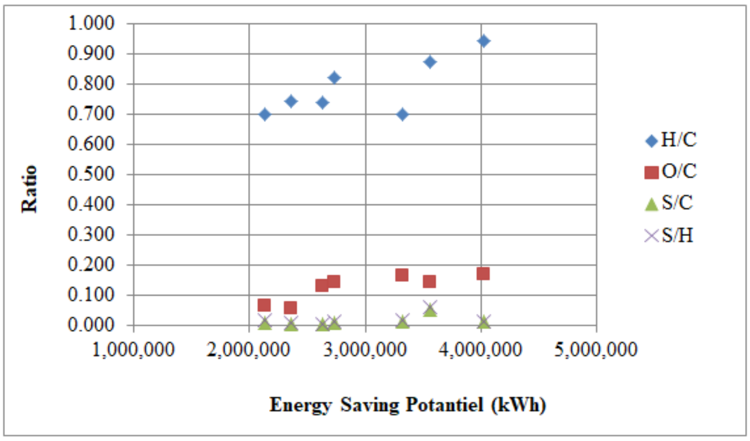


Figure 9. Energy-saving potential based on different lignite coal composition ratios.

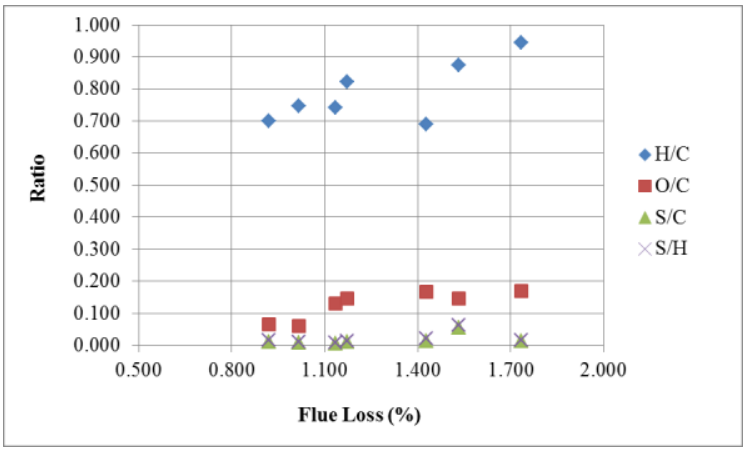


Figure 10. Different lignite coal composition ratios depending on flue loss.

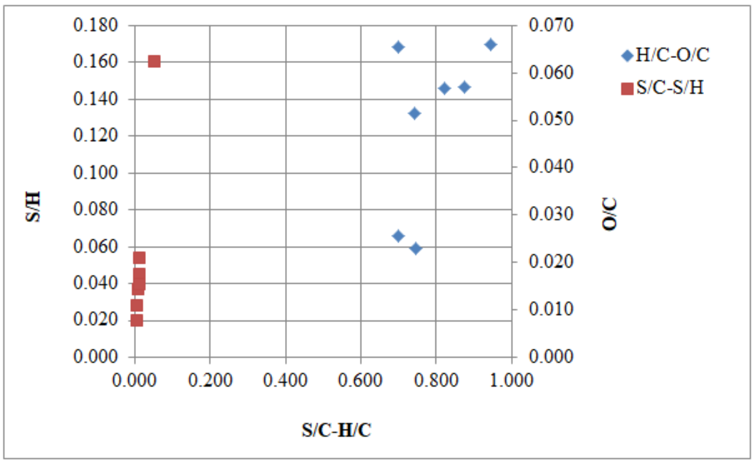


Figure 11. Different lignite coal composition ratios.

In order to increase the efficiency of central and district heating systems in apartment buildings by 1%, it is necessary to increase (preheated air) the temperature of the combustion air supplied to the boiler by 20 °C. The efficiency of the heating system will increase by 1% with every 20 °C increase in the temperature of the combustion air supplied to the boiler. Thus, if the combustion air temperature is increased by 40 °C, the efficiency will be increased by 2%, and with an increase of 60 °C, the efficiency will be increased by 3% [44]. The most preheated air can be generated using (14,307 kg/h), with the least amount of preheated air generated using Kütahya Tunçbilek (washed) coal (7597 kg/h) if the temperature of the combustion air is increased by 20 °C. The highest (7153 kg/s) and lowest (3799 kg/s) air volume can be generated using Bursa Keles coal and Kütahya Tunçbilek (washed) coal, respectively, if the combustion air is increased by 40 °C. The highest (4769 kg/s) and lowest (2533 kg/s) air volume can be generated using Bursa Keles coal and Kütahya Tunçbilek (washed) coal, respectively, if the temperature of the combustion air is increased by 60 °C. These values are presented in Figure 12.

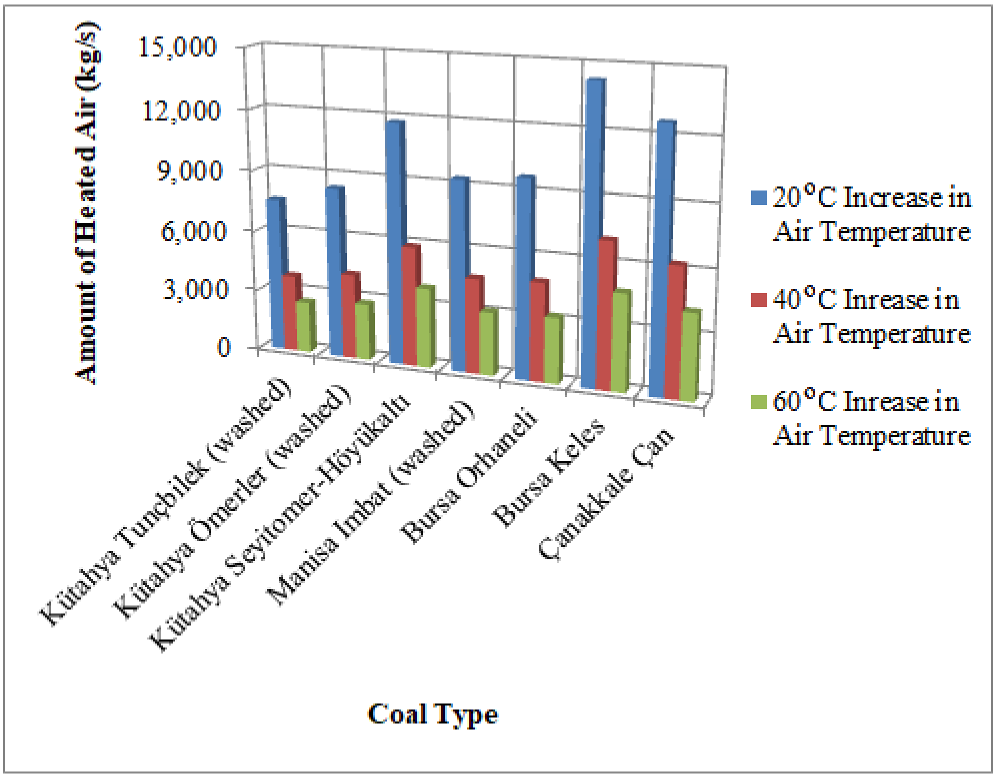


Figure 12. Amount of preheated air depending on the type of coal.

According to measurements of coal-burning district and central heating systems, the temperature of the feed used to supply water to the boiler can be increased by flue gas energy recovery for the whole Balikesir city center. An increase of 6 °C in the preheated water temperature results in a 1% savings in fuel consumption [44]. If the temperature of the preheated water supplied to the boiler is increased by 6 °C, the highest (11,455 kg/h) and lowest (6083 kg/h) air volume can be generated using Bursa Keles coal and Kütahya Tunçbilek (washed) coal, respectively. The highest (5728 kg/s) and lowest (3042 kg/s) air volume can be generated using the same coal types if the temperature of the combustion air is increased by 12 °C. The highest (3818 kg/s) and lowest (2028 kg/s) air volume can be generated using same coal types if the temperature of the combustion air is increased by 18 °C. These values are shown in Figure 13.

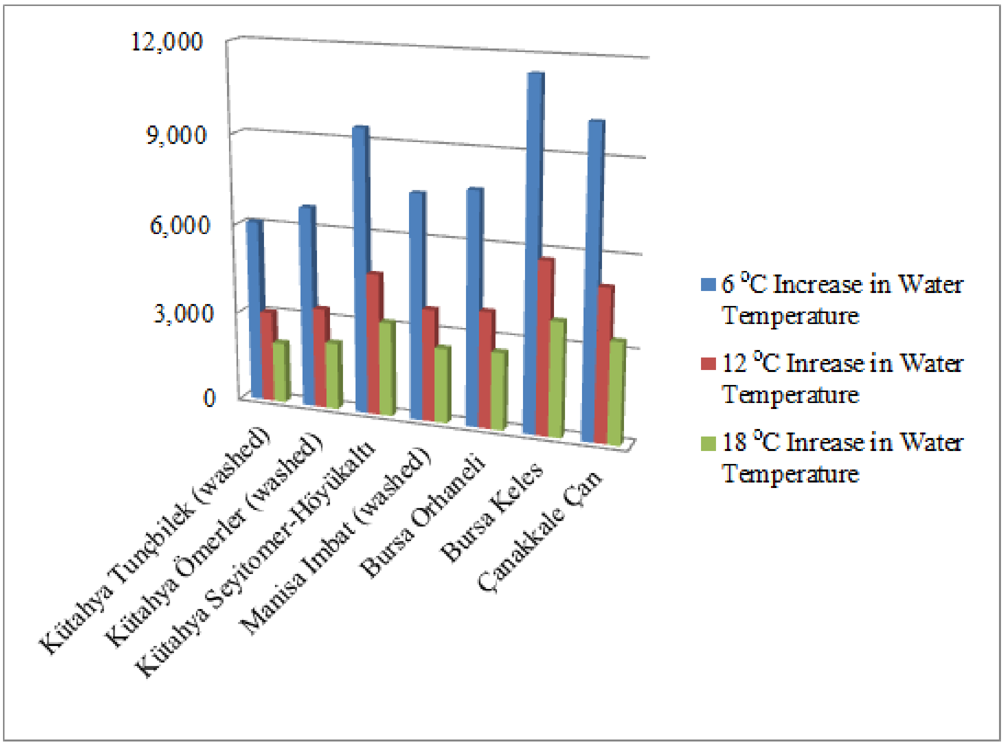


Figure 13. Amount of heated water depending on the type of lignite coal.

4. Conclusions

In the present study, we investigated the flue gas heat recovery potential for Balikesir city center by considering apartment building with central and district heating systems comprising coal-burning boilers. This flue gas heat recovery potential can be used to increase the temperature (preheated air) of the combustion air supplied to the boiler and to increase the temperature of the preheated water supplied to the boiler and taken from the main lines. With heat recovery from flue, the amount of pollutants and emissions released into the atmosphere can be reduced. In this respect, the proposed flue heat recovery system is an environmentally friendly and energy-saving alternative. The following results were obtained in the present study.

As the amount of coal used in boilers in central and district heating system increases, heat loss from the flue gas increases. As the H/C and O/C ratios increase, the percentage of flue loss also increases. As the lower heating value increases, the flue loss decreases. As the H/C and O/C ratios increase, the flue gas heat recovery potential increases. As the lower heating value increases, the flue gas heat recovery potential decreases. S/C and S/H ratios were found to have an indirect effect on flue gas heat recovery without a potential direct effect. The highest flue gas heat recovery potential was calculated in Bursa Keles coal (287,706 kW) and the lowest in Kütahya Tunçbilek (washed) coal (152,780 kW). Bursa Keles coal has the lowest calorific value, whereas Kütahya Tunçbilek (washed) coal has the highest calorific value. The lower heating value of coal is inversely proportional to the flue gas heat recovery potential.

According to measurements conducted by Balikesir Municipality Environmental Protection and Control Department in February and March 2019, the excess air coefficient was much higher than normal, increasing the chimney temperature, indicating that the proposed flue heat recovery system should be used. The proposed system is important in terms of energy saving.

In future studies, we will determine the most suitable design parameters for heat exchangers to be placed in chimneys for flue gas heat recovery. Then, we will examine the tube number, tube diameter, tube shape, tube material, etc., of the heat exchanger.

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