International Journal of Chemical, Materials and Biomolecular Sciences
ISSN: 2415-6620
Vol:10, No:4, 2016

Energy and Economic Analysis of Heat Recovery from Boiler Exhaust Flue Gas

Kemal Comakli, Meryem Terhan

***Abstract*—**In this study, the potential of heat recovery from waste flue gas was examined in 60 MW district heating system of a university, and fuel saving was aimed by using the recovered heat in the system as a source again. Various scenarios are intended to make use of waste heat. For this purpose, actual operation data of the system were taken. Besides, the heat recovery units that consist of heat exchangers such as flue gas condensers, economizers or air pre-heaters were designed theoretically for each scenario. Energy analysis of natural gas-fired boiler's exhaust flue gas in the system, and economic analysis of heat recovery units to predict payback periods were done. According to calculation results, the waste heat loss ratio from boiler flue gas in the system was obtained as average 16%. Thanks to the heat recovery units, thermal efficiency of the system can be increased, and fuel saving can be provided. At the same time, a huge amount of green gas emission can be decreased by installing the heat recovery units.

Keywords—Heat recovery from flue gas, energy analysis of flue gas, economical analysis, payback period.

I. Introduction

BECAUSE fossil resources are limited, consumption of fossil fuel is a big problem for climate change, and energy conservation is an important national policy of countries [1]. In Turkey, 34% of the total energy consumption is used in building sector, and this percent is big when compared to the other sectors such as transportation, industry, and agriculture. Therefore; energy efficiency systems in the building sector are very important in the Turkey and other countries [2]. Most of the energy losses in a boiler are because of the high temperature flue waste flue gas [3]. Boilers generally can lose 20% of heat of combustion, and thanks to flue gas condensers, they can recover 50% of this heat loss according to operating conditions [4]. Therefore, recovering the waste heat from flue gas is a major area to increase the thermal efficiency of plants [5].

Flue gas condensers, economizers and air pre-heaters are heat exchangers that recover from flue gas coming out from stacks. Thanks to these heat exchangers, sensible heat and latent heat are recovered from flue gas, and thermal efficiency of the boiler increases observably. The condensing in natural gas boiler is less corrosive and there is more amount of moisture in combustion products. Corrosion on surfaces of condensing heat exchanger tubes is an important problem [6].

Kemal Comakli is with the Atatürk Uni. Mechanical Engineering Dept. 25240 Erzurum, Turkey (e-mail: kcomakli@atauni.edu.tr)
Meryem Terhan is with the Kafkas Uni. Mechanical Engineering Dept. 36100 Kars, Turkey.

A brief review of papers related to the characteristics of heat recovery from flue gas is given in the following paragraph. Levy et al. [7] studied the use of condensing heat exchanger to recover heat from flue gas in a power plant. In their study, the flue gas can be cooled to below 40 ºC. Hill [8] made the design of heat recovery systems for a plant in his thesis study. For this plant, a lot of heat recovery systems were thought, and a condensing economizer design was made. Chen et al. [9] made a feasible single flow shell and tube condenser heat exchanger design that will be added to a 40 MW large scale district heat system. Alkhamis et al. [10] studied on the waste heat recovery of potential sources at the enclosed campus of Mu'tah University. They designed, manufactured, installed and analyzed a heat exchanger to utilize the sensible heat containing in the exhaust gas, which gets out of the kitchen furnace of student's club in the University. The results of their research indicated that more than 60% of the waste heat from flue gas in the kitchen furnace can be recovered, and investing to the heat exchanger system was highly economic. Bhattacharjee [11] installed the economizers in the boilers in a chemical plant. He estimated the reduction of natural gas consumption as 273,803 m^3. Annual savings and implementation cost were $ 104,580 and $ 347,000 respectively, and payback period was 3.32 years. Bujak [12] analyzed the mathematical model of a boiler for thermal performance. He founded out the value of heat recovered from exhaust flue gases, which fluctuates between 4% and 7% in the system by using an economizer at full heat power of the boiler. DeFrees et al. [13] designed a Teflon-covered condensing economizer, which has 37 m^2 of surface area to recover heat from flue gas at 180 °C temperature in a plant. In this study, the temperature of the incoming fresh water to the plant was in the range of 4-16 °C. Temperature of the water was increased to the range between 50 and 60 °C in the condensing economizer. They estimated annual fuel savings as 4357 GJ. Saidur et al. [14] studied energy and exergy flows in a boiler. They founded that energy and exergy efficiencies in a boiler are 72.46% and 24.89% respectively. They calculated that the payback period as 1 year for heat recovery from flue gas in a boiler. Shekarchian et al. [15] examined the economic feasibility of a heat recovery application, which consist of air-preheating methods. They concluded that the fuel consumption of the fired heater can be reduced to up to 7.4% in this case.

In this study, several scenarios were thought for heat recovery from waste flue gas in 60 MW district heating system of a university, and applicability of these scenarios was investigated. We made designs of the waste heat recovery units theoretically, and economic analysis to recover heat losses from exhaust flue gas in natural gas fired district heating system. Besides, we aimed to save the fuel by using the recovered energy in the system as a source again. We made economic analysis to predict payback period of these units.

II. Theoretical Analysis

According to measurements by Erzurum Natural Gas Company in Turkey, natural gas consists of gas mixture such as methane, ethane, propane, butane, nitrogen etc. In Table I, closed formulas of the natural gas according to the gas mixtures in fuel are shown.

TABLE I
CLOSED FORMULA OF THE NATURAL GAS

	Chemical formula	Mole fraction	Closed formula
Methane	CH_4	x	C(x+2y+3z+4t+5u+6d+f)
Ethane	C_2H_6	y	
Propane	C_3H_8	z	H(4x+6y+8z+10t+12u+14d)
Butane	C_4H_{10}	t	
Pentane	C_5H_{12}	u	O(2f)
Hexane	C_6H_{14}	d	
Nitrogen	N_2	e	N(2e)
Carbon dioxide	CO_2	f	

The complete combustion reaction of natural gas with dry air is stated as:

$$C_{(x+2y+3z+4t+5u+6d+f)}H_{(4x+6y+8z+10t+12u+14d)}O_{2f}N_{2e} + \lambda a(O_2+3.76N_2) \rightarrow \alpha CO_2 + \beta H_2O + \varepsilon N_2 + \theta O_2 \quad (1)$$

The flue gas (products) consists of CO_2, O_2, N_2 and H_2O. In (1), λ is excess air ratio. Mole numbers of the products can be calculated as:

$$\alpha = n_{CO_2} = (x+2y+3z+4t+5u+6d+f) \quad (2)$$

$$\beta = n_{H_2O} = (2x+3y+4z+5t+6u+7d) \quad (3)$$

$$a = (2x+3.5y+5z+6.5t+8u+9.5d) \quad (4)$$

$$\theta = n_{O_2} = (\lambda-1)\times(2x+3.5y+5z+6.5t+8u+9.5d) \quad (5)$$

$$\varepsilon = n_{N_2} = \lambda \times (7.52x+13.16y+18.8z+24.44t+30.08u+35.72d)+e \quad (6)$$

Total mole number amount of flue gas is shown as:

$$n_{fg} = n_{O_2} + n_{CO_2} + n_{H_2O} + n_{N_2} \quad (7)$$

The mole fraction and molar specific heat at constant pressure of each component in flue gas such as carbon dioxide, water vapor, nitrogen and oxygen can be obtained by using the following formulas [16].

Carbon dioxide,

$$x_{CO_2} = \frac{n_{CO_2}}{n_{fg}} \quad (8)$$

$$\bar{c}_{p-CO_2} = 22\cdot 26 + 5.981\times10^{-2}\times(T_{fg}) - 3.501\times10^{-5}\times(T_{fg}^2) + 7.469\times10^{-9}\times(T_{fg}^3) \quad (9)$$

Water vapor,

$$x_{H_2O} = \frac{n_{H_2O}}{n_{fg}} \quad (10)$$

$$\bar{c}_{p-H_2O} = 32\cdot 24 + 0.1923\times10^{-2}\times(T_{fg}) + 1.055\times10^{-5}\times(T_{fg}^2) - 3.595\times10^{-9}\times(T_{fg}^3) \quad (11)$$

Nitrogen,

$$x_{N_2} = \frac{n_{N_2}}{n_{fg}} \quad (12)$$

$$\bar{c}_{p-N_2} = 28.90 - 0.1571\times10^{-2}\times(T_{fg}) + 0.8081\times10^{-5}\times(T_{fg}^2) - 2.873\times10^{-9}\times(T_{fg}^3) \quad (13)$$

And oxygen,

$$x_{O_2} = \frac{n_{O_2}}{n_{fg}} \quad (14)$$

$$\bar{c}_{p-O_2} = 25.48 + 1.520\times10^{-2}\times(T_{fg}) - 0.7155\times10^{-5}\times(T_{fg}^2) + 1.312\times10^{-9}\times(T_{fg}^3) \quad (15)$$

In the equations, T_{fg} is flue gas temperature. Average molar specific heat of flue gas is expressed as:

$$\bar{c}_{p-fg} = \bar{c}_{p-CO_2}\times(x_{CO_2}) + \bar{c}_{p-O_2}\times(x_{O_2}) + \bar{c}_{p-H_2O}\times(x_{H_2O}) + \bar{c}_{p-N_2}\times(x_{N_2}) \quad (16)$$

Molecular mass of the fuel, air and flue gas are obtained as:

$$Ma_{fuel} = (x\times Ma_{CH_4}) + (y\times Ma_{C_2H_6}) + (z\times Ma_{C_3H_8}) + (t\times Ma_{C_4H_{10}}) + (u\times Ma_{C_5H_{12}}) + (d\times Ma_{C_6H_{14}}) + (e\times Ma_{N_2}) + (f\times Ma_{CO_2}) \quad (17)$$

$$Ma_{air} = Ma_{O_2}\times x_{O_2} + Ma_{N_2}\times x_{N_2} \quad (18)$$

$$Ma_{fg} = x_{CO_2} \times Ma_{CO_2} + x_{H_2O} \times Ma_{H_2O} + x_{O_2} \times Ma_{O_2} + x_{N_2} \times Ma_{N_2} \quad (19)$$

Based on the law of mass conversation, flue gas mass per unit of time is equal to total of fuel and air masses per unit of time. These equations are derived as [16]:

$$\dot{m}_{fuel} + \dot{m}_{air} = \dot{m}_{fg} \quad (20)$$

$$\dot{m}_{air} = \frac{\dot{m}_{fuel} \times 4.76 \times a \times \lambda \times Ma_{air}}{Ma_{fuel}} \quad (21)$$

$$\dot{m}_{fuel} = \dot{V}_{fuel} \times \rho_{fuel} \quad (22)$$

Fuel energy as a result of combustion of the fuel is calculated as:

$$\dot{E}_{fuel} = \dot{V}_{fuel} \times H_u \quad (23)$$

In (23), H_u, is lower heating value of fuel. The energy of the flue gas is consisted of sensible heat energy and latent heat energy, which caused water vapor in flue gas. These heat energies can be obtained by using:

$$\dot{E}_{fg-sen} = \dot{n}_{fg} \times \bar{c}_{p-fg} \times (T_{fg} - T_o) \quad (24)$$

$$\dot{E}_{fg-lat} = (\dot{n}_{fg} \times x_{H_2O}) \times Ma_{H_2O} \times l \quad (25)$$

In (23), (24), T_o is temperature of environment and, l is latent evaporation heat of water vapor. The percent of flue gas heat energy losses can be obtained as:

$$\%E_{fg-loss} = \frac{\left(\dot{E}_{fg-sen} + \dot{E}_{fg-lat}\right)}{\dot{E}_{fuel}} \times 100 \quad (26)$$

For condensation, water vapor in the flue gas must be cooled to below the dew point temperature. A few amount of the water in flue gas condensates if flue gas is cooled below the dew point temperature. The molar amount of condensed water can be calculated as [16]:

$$\dot{n}_{cw} = \frac{P_{fg}\left(\dot{n}_{fg} \times x_{H_2O}\right) - P_{H_2O} \times \dot{n}_{fg}}{P_{fg} - P_{H_2O}} \times 100 \quad (27)$$

According to the below conditions, it is possible to calculate the heat recovery from flue gas per unit of time.

- When flue gas is cooled to a temperature (T) above the dew point temperature,

$$\dot{E}_{rec} = \dot{n}_{fg} \times \bar{c}_{p-fg} \times (T_{fg} - T) \quad (28)$$

- Or flue gas is cooled to a temperature below the dew point temperature(T_{dew}),

$$\dot{E}_{rec} = \dot{n}_{fg} \times \bar{c}_{p-fg} \times (T_{fg} - T_{dew}) + \dot{n}_{cw} \times l \times Ma_{H_2O} \quad (29)$$

The flue gas that is taken from 1 m^3 natural gas theoretically contains in 1.5 kg water vapor and 3.6 MJ of latent heat. The amount of latent heat loss of waste flue gas from gas-fired boilers is very high. If we recover sensible heat and latent heat at the same time, total energy efficiency can be increased about 10% [1].

In economic analysis, parameters that we need to compare are following:

- First investment cost
- Economic life
- Annual maintenance and operation costs
- Annual fuel saving (benefit)
- Junk income
- Interest rate

Annual equivalent worth analysis is preferred in this economic analysis study. In annual equivalent worth analysis, the aim is to transform money to an equivalent uniform annual cost or benefit [17]. Annual equivalent benefit (AEB) is given in (30):

$$AEB = \left[\sum_{n=1}^{t} \frac{F_n}{(1+i)^n} - \sum_{n=1}^{t} \frac{C_n}{(1+i)^n}\right] \times \frac{(1+i)^n \times i}{(1+i)^n - 1} \quad (30)$$

Monthly payback period is calculated with (31). IC in the equation shows first investment cost.

$$MPP = \frac{IC}{AEB/12} \quad (31)$$

III. Materials and Methods

In the district heating system, natural gas fired super-heated water boilers are presented. Produced super-heated water in boilers is used for space heating and domestic hot water supply in buildings on the campus. Therefore, using recovered heat energy from flue gas in the system as a source again, such as, hot water supply, pre-heating combustion air and space heating, provided fuel saving and increased boiler efficiency.

The establishment of a methodology to determine how to use the recovered heat from flue gas is the principal aim of this study. Three scenarios were thought to take advantage of the waste heat from flue gas in heating system. These scenarios' diagrams are shown in Fig. 1. These scenarios are indicated as:

✓Pre-heating combustion air,
✓Space heating
✓Domestic hot water supply

A. Pre-Heating Combustion Air

One of the scenarios considered in this study is preheating of combustion air. To achieve of this, a heat recovery unit, which consists of air pre-heaters, fans, air ducts was designed theoretically. In this scenario, flue gas leaving from the boilers enters to an air pre-heater, and temperature of the combustion air entering to boiler increases to 50 °C from 10 °C while flue gas is cooled to 132 °C from 158 °C. As a result of these, boiler efficiency can be increased, fuel saving can be achieved, and a better combustion can be obtained.

B. Space Heating

In this scenario, a heat recovery unit was designed to take advantage of heat loss in waste flue gas. Space heating of a building near the Heating Plant was aimed with this unit, which consists of economizers, fans, pumps, distribution pipes. In the economizer, temperature of return water in space heating system increases from 70 °C to 90 °C while flue gas is cooled from 158 °C to 75 ºC.

C. Domestic Hot Water Supply

One of the other scenarios is domestic hot water supply by using a condensing heat recovery unit, which consists of flue gas condensers, fans, pumps and hot water distribution pipes. Flue gas enters the condenser and gets cold. Cold fresh water (10 °C) is heated up to 60 °C by recovered heat in the condenser.

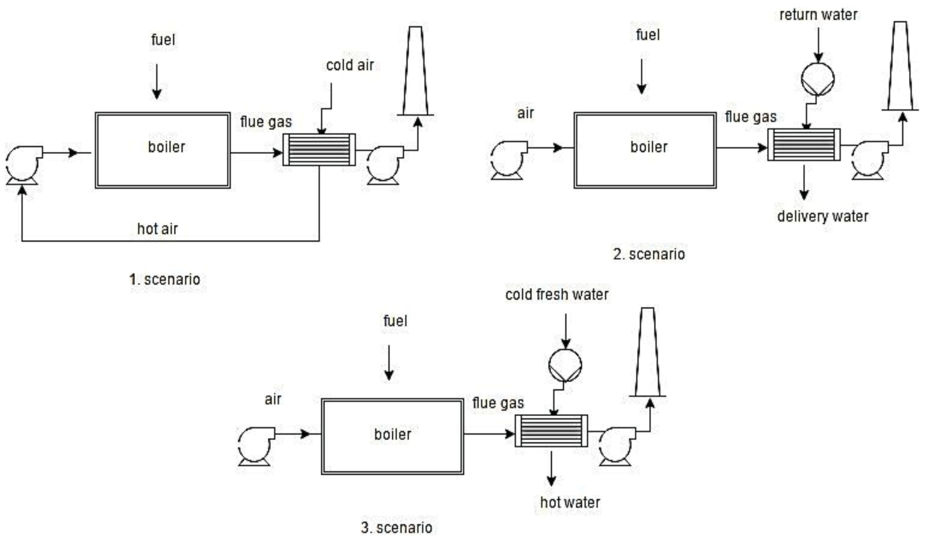

Fig. 1 Diagrams of the heat recovery unit

TABLE II
OPERATION DATA OF THE HEATING SYSTEM

	1. boiler	2. boiler	3. boiler
Excess air ratio λ	1.16	1.17	1.13
Flue gas temperature °C	161	157	158
Fuel consumption m^3/year	4,008,087	4,008,087	4,008,087
Combustion air temperature °C	20	20	20

IV. RESULTS

In the heating system, three natural-gas fired boilers, which have 1,200,000.0 kcal/h equal capacity of each one, have existed. The daily natural gas consumption data of the system during the last five years have been taken. According to the measurements of the Natural Gas Company, the heating system operation data is shown in Table II, natural gas closed formula was obtained as $C_{1.0576}H_{4.0526}N_{0.046}O_{0.0088}$. The combustion equation is given as:

$$C_{1.0576}H_{4.0526}O_{0.0088}N_{0.046} + 2.389(O_2 + 3.76N_2) \rightarrow 1.058CO_2 + 2.026H_2O + 9.007N_2 + 0.323O_2 \quad (32)$$

The heat energy that carried by flue gas is changed with flue gas temperature. Though sensible energy linearly increases with temperature, change of latent heat energy is constant to dew point temperature of water vapor in flue gas. In Fig. 2, the changes are indicated.

Erzurum's atmospheric pressure is 80.90 kPa, because this city's the above from sea level is 1,859 m. Dew point temperature of water vapor in flue gas was calculated about 51.33 °C for 13.28 kPa partial pressure of water vapor and 1.16 of excess air ratio for Erzurum. Chance of dew point temperature with excess air ratio and above from sea level was showed in Fig. 3. As seen in the figure, the dew point temperature of water vapor is decreased by increasing excess air ratio and above from sea level.

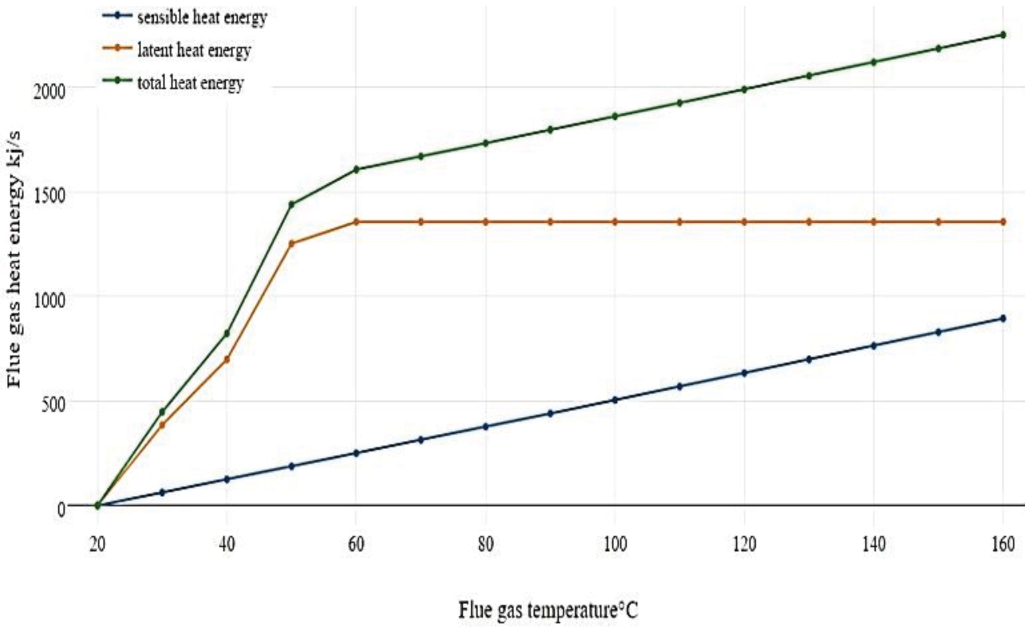

Fig. 2 Heat energy carried by flue gas

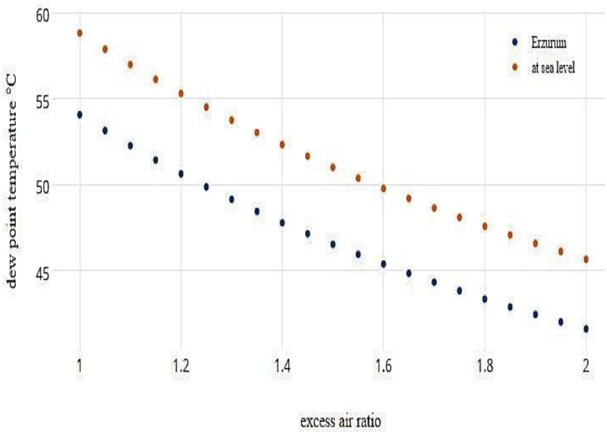

Fig. 3 Chance of dew point temperature with excess air ratio

TABLE III
RESULTS OF ENERGY ANALYSIS ACCORDING TO THE OPERATION DATA

	1. boiler	2. boiler	3. boiler
Sensible heat loss of flue gas %	6.82	6.65	6.48
Mole fraction of H_2O in flue gas	0.1619	0.1611	0.1668
Latent heat loss of flue gas %	10.16	10.16	10.16
Total heat loss of flue gas %	16.98	16.81	16.64
Dew point temperature °C	51.16	51.05	51.78
Mass flow rate of fuel kg/s	0.1	0.1	0.1
Heat of combustion kJ/s	4,448	4,448	4,448
Mass flow rate of air kg/s	1.81	1.82	1.75
Mass flow rate of flue gas kg/s	1.90	1.92	1.85

According to results of energy analysis, total heat loss ratio of flue gas was calculated as about 16%. The heat recovery units are very important for energy efficiency because of this amount is very high. The yearly cost of flue gas heat losses for the heating system was found out as about $ 663,718. In Table III, results of energy analysis according to the operation data are shown.

The results of design heat recovery units in the scenarios are given as follows:

A. Pre-Heating Combustion Air

In this scenario, the heat recovery unit consists of air-preheater, fan, air duct. In order to decrease the flue gas temperature from 158 ºC to 132 ºC, required heat transfer surface area was calculated as 19.8 m^2.

The temperature of combustion air entering to boiler increases to 50 °C from 20 ºC while flue gas is cooled in the air-preheater. Each tube used for the air-preheater has 25 mm external diameter and 1.2 mm wall thickness. Tube material is carbon steel (type St 37.2). The air-preheater consists totally of 252 in-line tube bundle arrangement as 28 tubes on the y direction (width) and 9 tubes on the z direction (height). In the heat exchanger, while cold air flows inside the tubes, hot flue gas flows on horizontal tube bundles from up to down. With this recovered heat, we aimed to provide fuel saving and better combustion in boilers. Thanks to this unit, 1.3% of fuel saving can be achieved. This unit's payback period was calculated as 5 months for winter season.

B. Space Heating

In this scenario, the heat recovery unit consists of economizer, fan, distribution pipes and pump. To decrease the flue gas temperature from 158 ºC to 75 ºC, required heat transfer surface area was calculated as 85.45 m^2. In the economizer, temperature of return water in space heating system increases the delivery water from 70 °C to 90 °C while flue gas is cooled from 158 °C to 75 ºC.

Each tube used for the economizer has 34 mm external diameter, 1.2 mm wall thickness and U-shaped tube bundles.

Tube material is stainless steel (type 304). The economizer consists totally of 800 in-line tube bundle arrangement as 25 tubes on the y direction (width) and 32 tubes on the z direction (height). In the heat exchanger, while the water flows inside the tubes, hot flue gas flows on horizontal tube bundles from up to down. Thanks to this unit, 3.85% of fuel saving can be achieved. This unit's payback period was calculated as 4 months for winter season.

TABLE IV
RESULTS OF ENERGY AND ECONOMIC ANALYSIS FOR SCENARIOS

		1. Scenario	2. Scenario	3. Scenario
Economizer	$T_{water\text{-}inlet}$ (°C)		70	10
	$T_{water\text{-}outlet}$ (°C)		90	60
	$m_{water\text{-}inlet}$ kg/s)		2.06	1.25
	$m_{fg\text{-}inlet}$ (kg/s)		1.89	1.89
	$T_{fg\text{-}inlet}$ (°C)		158	158
	$T_{fg\text{-}outlet}$ (°C)		75	50
	Surface area (m^2)		85.5	50.7
Air pre-heater	$T_{air\text{-}inlet}$ (°C)	20		
	$T_{air\text{-}outlet}$ (°C)	50		
	$M_{air\text{-}inlet}$ (kg/s)	1.79		
	$T_{fg\text{-}inlet}$ (°C)	158		
	$T_{fg\text{-}outlet}$ (°C)	132		
	Surface area (m^2)	19.8		
Recovered sensible energy (kW)		169.9	535.6	695.5
Amount of condensing water (kg/s)				0.046
Recovered latent energy (kW)				103.6
Heat loss on distribution pipes (kW)			21.5	12.2
Total recovered energy (kW)		169.9	514.1	786.9
Investment cost ($)		17,175.36	45,146.99	67,521.77
Annual fuel saving ($/year)		48,890.49	143,845.87	219,922.46
Interest rate		0.05	0.05	0.05
Economic life (year)		20	20	20
Fuel saving (%)		1.3	3.85	5.9
Payback period (month)		5	4	4

C. Domestic Hot Water Supply

In this scenario, the heat recovery unit consists of flue gas condenser, fan, pump and hot water distribution pipes. Because flue gas outlet temperature is below the dew point temperature, the condensation occurs in the flue gas. In order to decrease the flue gas temperature from 158 ºC to 50 ºC, required heat transfer surface area was calculated as 50.7 m^2. In the flue gas condenser, cold water at 10 °C can be increased up to 60 °C while flue gas is cooled. Each tube used for the condenser has 34 mm outer diameter, 1.2 mm wall thickness and U-shaped tube bundles. Tube material is stainless steel (type 316). The condenser consists totally of 475 in-line tube bundle arrangement as 25 tubes on the y direction (width) and 19 tubes on the z direction (height). In the heat exchanger, while the cold water flows inside the tubes, hot flue gas flows on horizontal tube bundles from up to down. Thanks to this unit, hot water need of 103 flats can be supplied and 5.9% of fuel saving achieved. This unit's payback period was calculated as 4 months for winter season. Annual fuel saving was calculated as $ 219,922.46 with Annual Equivalent Analysis Method. In Table IV, the results of energy and economic analysis are showed.

V. CONCLUSIONS

In this study, the potential of heat recovery from waste flue gas was examined in 60 MW district heating system of a university, and fuel saving aimed by using the recovered heat in the system as a source again. Besides, the green gas emissions can be decreased when installing the heat recovery units. The obtained results are specified below:

- According to the measurements of the Natural Gas Company and heating system operation data, natural gas closed formula was obtained as $C_{1.0576}H_{4.0526}N_{0.046}O_{0.0088}$.
- Total heat loss ratio of flue gas in the district heating system was calculated as about 16%. The yearly cost of flue gas heat losses for the heating system was found out as about $ 663,718.
- Dew point temperature of water vapor in flue gas was calculated as about 51.33 °C for 13.28 kPa partial pressure of water vapor and 1.16 of excess air ratio for Erzurum.
- In the first scenario, 1.3% of fuel saving can be achieved. The heat recovery unit's payback period was calculated as 5 months for winter season. Annual fuel saving was found out to be $ 48,890.49 with Annual Equivalent Analysis Method.
- In the second scenario, 3.85% of fuel saving can be achieved. The unit's payback period was calculated as 4

months for winter season. Annual fuel saving was found out as $ 143,845.87 with Annual Equivalent Analysis Method.

- In the latest scenario, thanks to the condensing heat recovery unit, hot water need of 103 flats can be supplied, and 5.9% of fuel saving achieved. This unit's payback period was calculated as 4 months for winter season. Annual fuel saving was calculated as $ 219,922.46 with Annual Equivalent Analysis Method.

ACKNOWLEDGMENT

The authors gratefully acknowledge that this work was financially supported by TUBITAK-BIDEB.

REFERENCES

[1] Y. Wang, Q. Zhao, Q. Zhou, Z. Kang and W. Tao, Experimental and numerical studies on actual flue gas condensation heat transfer in a left-right symmetric internally finned tube, International Journal of Heat and Mass Transfer 64 (2013) 10-20.
[2] C. T. Yucer and A. Hepbasli, Thermodynamic analyses of a building using exergy analysis method, Energy and Buildings 43 (2011) 536-542.
[3] M. Osakabe, K. Ishida, K. Yagi, T. Itoh and K. Ohmasa, Condensation heat transfer on tubes in actual flue gas, Heat Transfer-Asian Research 30 (2) (2001) 139- 151.
[4] M. Cortina, Flue gas condenser for biomass boilers, MSc Thesis, Lulea University of Technology, 2006.
[5] Y. Yang, C. Xu, G. Xu, Y. Han, Y. Fang and D. Zhang, A new conceptual cold-end design of boilers for coal-fired power plants, Energy Conversion and Management 89 (2015) 137-146.
[6] T.A. Butcher and W. Litzke, Condensing economizers for small coal-fired boilers and furnaces, New York, 1994.
[7] E. Levy, H. Bilirgen, K. Jeong, M.J. Kessen, C. Samuelsen and C. Whitcombe, Recovery of water from boiler flue gas, Final Technical Report, Lehigh University, Energy Research Center, Bethlehem, 2008.
[8] J.M. Hill, Study of low-grade waste heat recovery and energy transportation systems in industrial applications, Thesis, Alabama University, Department of Mechanical Engineering, Alabama, 2011.
[9] Q. Chen, K. Finney, H. Li, X. Zhang, J. Zhou, V. Sharifi and J. Swithenbank, Condensing boiler applications in the process industry, Applied Energy 89 (2012) 30- 36.
[10] T.M. Alkhamis, M.A. Alhusein and M.M. Kablan, Utilization of waste heat from the kitchen furnace of an enclosed campus, Energy Conversion and Management 39 (1998) 1113-1119.
[11] K. Bhattacharjee, Energy conservation opportunities in industrial waste heat recovery systems, Energy Engineering 107 (2010) 7-13.
[12] J. Bujak, Mathematical modeling of a steam boiler room to research thermal efficiency, Energy 33 (2008) 1779-1787.
[13] J. DeFrees, R. Stuckey and J. Foote, Condensing economizers, Ashrae Journal (2007) 16-23.
[14] R. Saidur, J. U. Ahamed, H.H. Masjuki, Energy, exergy and economic analysis of industrial boilers, Energy Policy 38 (2009) 2188- 2197.
[15] M. Shekarchian, F. Zarifi, M. Moghavvemi, F. Motasemi and T.M.I. Mahlia, Energy, exergy, environmental and economic analysis of industrial fired heaters based on heat recovery and preheating techniques, Energy Conversion and Management, 71 (2013) 51-61.
[16] Y.A. Cengel and M.A. Boles, Thermodynamics an engineering approach, Guven Scientific Press, Izmir, Turkey, 2008.
[17] O. Okka, Theory of engineering economics, problems and solutions, Nobel Press, Ankara, Turkey, 2009.