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APPLICATION OF RECUPERATOR FOR WASTE HEAT RECOVERY FROM EXHAUST FLUE GAS IN HOT WATER BOILER IN A CENTRAL HEATING PLANT

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ABSTRACT

In general, the outgoing exhaust gasses are released to atmosphere at over temperature of the dew point of water vapor in waste gases. It is well known that recovering a portion of the waste heat enhances the efficiency of boilers and provides fuel savings. In this study, the potential of recovering waste heat emitted by the hot water boiler chimney in a central heating plant of a selected university was investigated. Energy losses were calculated for six months that the central heating system was in full-load operation. As a result of the calculation, it was determined that recovery of the waste heat can be employed as a combustion air preheater by means of a recuperator. It was stated that 53,768 m^3 of natural gas savings per year (44.86 TOE/year) can be achieved with the suggested system.

Keywords: Waste heat recovery, Recuperator, Exhaust flue gas, Energy saving

1. INTRODUCTION

Energy is one of the most significant resources around the world. With the request for energy sources increasing all around the world, fuel prices and pollutions caused by fuel consumption raise quickly. Therefore, energy-saving policies and pollution reducement have to be constituted and carried out in many countries [1]. Energy consumption per unit of main systems (boiler, furnace etc.) is generally much higher than that of international advanced level. The main justification is that more than 50% of energy consumption of a boiler system has not been regained effectively [2]. For this reason, recuperation and usage of the waste heat are thought out to be key precautions for the clean and sustainable future [3].

Boiler efficiency has a great effect on heating-related energy savings. Therefore, maximizing the heat transfer to the water and minimizing the heat losses to around have importance in the boiler systems. Heat can be lost from boilers by several ways; including hot exhaust gases, radiation losses etc. In order to optimize the operation conditions of the boiler systems, it is necessary to describe where energy losses are likely to occur [4].

An important amount of energy is lost through exhaust gases since all the burning fuel cannot be transmitted to water or steam in the boiler. As temperature of the exhaust gas leaving the boiler system generally ranges from 150 to 250 °C, about 10-30 % of the heat energy is lost by way of it [5], [6]. This indicates that there are enormous saving potentials of the boiler systems by minimizing its losses.

Heat recovery technologies usually decrease the operating costs for institutions by enhancing their energy productiveness. Although many recovery technologies are currently well improved and technically demonstrated, there are numerous applications such as preheating the combustion air by

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the recuperator, preheating the feed water with economizer, etc. [7]. Amongst them, recuperators (the most common heat recovery ventilation devices) has attractive advantages such as simple structure, little effects on the thermal system, and reduction of fuel consumption [8], [9]. They recover exhaust waste heat in medium to high temperature applications such as hot water or steam boilers, annealing or soaking ovens, melting furnaces, gas incinerator, reheat furnaces, etc. [9].

In the present study, the potential of waste heat recovery in the central heating plant of the selected university was quantitatively analyzed. At first, energy loss areas of the hot water boiler were determined in the central heating plant. Next, recuperator as a new approach was recommended, which could reduce the temperature of the flue gas and recover waste heat of the flue gas. Finally, economic analysis was performed in the case of the addition of this unit to the system.

2. DESCRIPTION OF THE CENTRAL HEATING PLANT

In the present study, recovery of the waste heat from exhaust gases and usage potential of this waste heat was investigated in the central heating plant of the selected university. Schematic diagram and energy losses of the hot water boiler in the central heating plant are shown in Figure 1. The hot water boiler made by stainless steel has 5.5 m length and 2.3 m diameter. Ambient temperature (T_0) of the steam boiler room was determined and surface temperature of the hot water boiler (T_S) was measured by the multifunctional measuring instrument (TESTO 435) and the thermal camera (TESTO 875-2i), respectively. Since the boiler body was well insulated, surface temperature measurements were taken only from the front and back regions of the boiler. Besides, the components (temperature, CO, O_2, CO_2 etc.) of the exhaust flue gas were identified by a flue gas analyzer (TESTO 310).

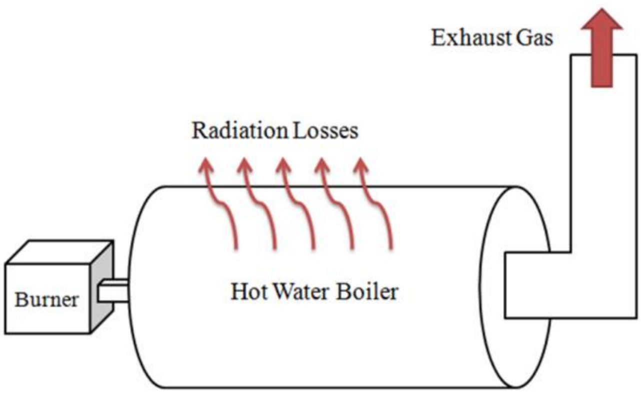

Figure 1. Schematic diagram and energy losses of the hot water boiler

Natural gas is used as fuel in the central heating plant. Natural gas consumption data, measured temperatures of exhaust gas for six months from 2015 to 2016 of the central heating plant are given in Figure 2. As seen, the temperatures of exhaust gas are above the line and directly proportional with natural gas consumption. The total annual fuel consumption and uptime of the boiler are estimated to be about 1 149 748 m^3 and 3232 hours, respectively.

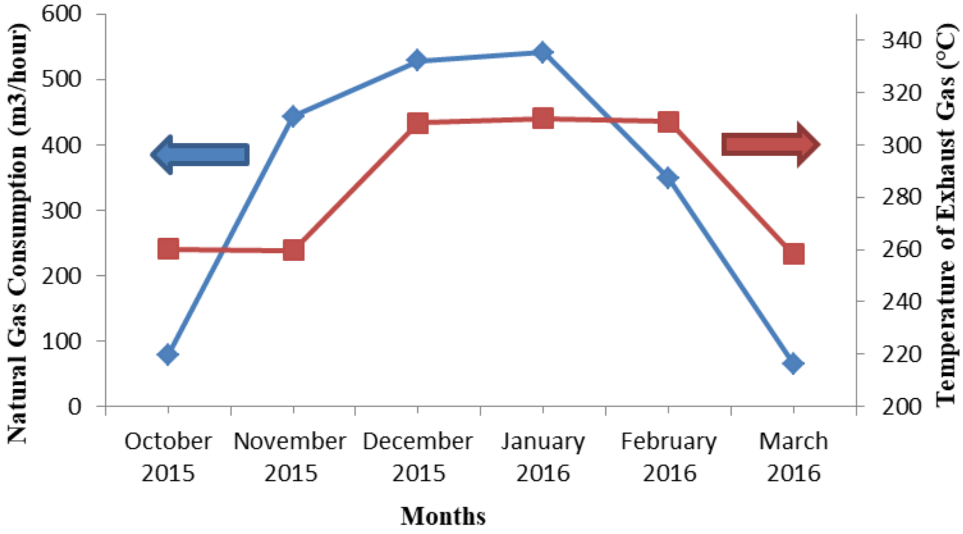

Figure 2. Natural gas consumptions and temperatures of exhaust gas of the boiler

It is known from the literature that the average excess oxygen/air rate in a boiling system for a good combustion is in the range of 3-5 % [10]. However, Figure 3 shows that percentage of oxygen values for the selected boiler system are higher than the standards causing higher excess air ratios [11]. This situation obviously indicates that air/fuel ratio of boiler burners should be readjusted to convert the operating range. By this way, over heat losses can be prevented due to the excess combustion.

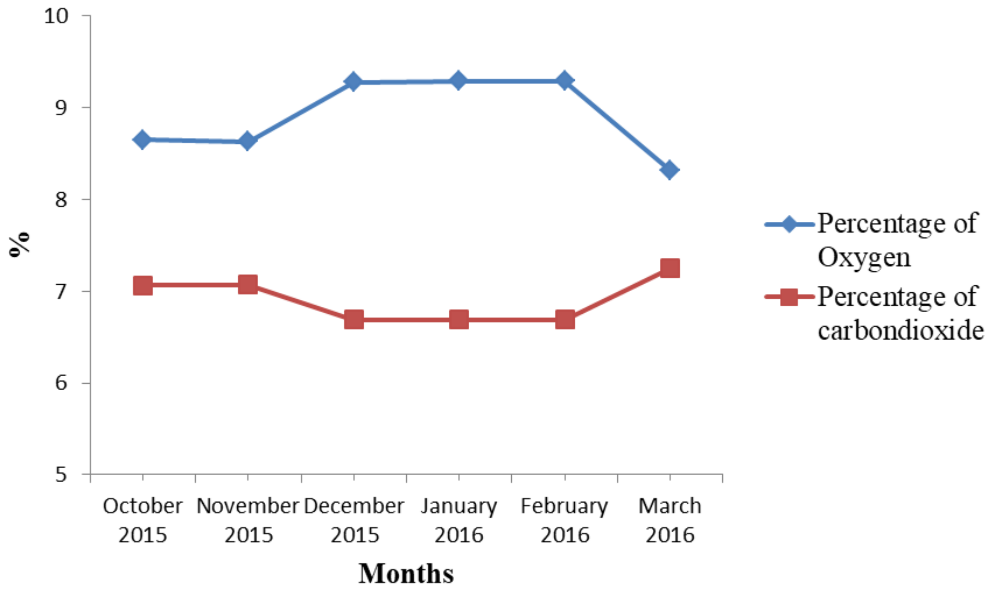

Figure 3. Variation of % oxygen and carbondioxide with the months

The data for the chemical composition and volume percentage values of the natural gas used in the calculations is received from the local fuel supplier are as shown in Table 1. The closed formula of the used natural gas in accordance with received data is determined as $C_{1.197}H_{4.620}O_{0.0083}N_{0.0599}$.

Table 1. Physical properties and analysis of natural gas (all the data is provided by fuel supplier)

Parameter	Unit	Quantity
C1 (Methane)	%	92.17
C2 (Ethane)	%	3.29
C3 (Propane)	%	0.96
I-C4 (I-Butane)	%	0.18
N-C4 (N-Butane)	%	0.25
I-C5 (I-Penthane)	%	0.071
N-C5 (N-Penthane)	%	0.053
C6+ (Hexane)	%	0.054
N_2 (Nitrogen)	%	2.60
CO_2 (Carbondioxide)	%	0.36
HHV	Kcal/Sm^3	9250.14
LHV	Kcal/Sm^3	8344.32
Specific weight	-	0.61
Density	kg/Sm^3	0.74
Atmospheric Pressure	bar	0.89

3. MEASURED VALUES AND GENERAL MATHEMATICAL TOOLS FOR ANALYSIS

This section gives measured values and mathematical formulas for energy analysis of the hot water boiler. Energy balances are fulfilled around the control volume, determined by the external surface of the hot water boiler. The energy balances are acquired by combination of both average measurement values and calculations based on the following assumptions:

1. The hot water boiler works at steady state conditions.
2. The composition of the natural gas, given in Table 1, and the average inlet of the natural gas at ambient temperature do not change over time.
3. Although surface temperature changes along the hot water boiler, it is accepted that the average surface temperature of hot water boiler (T_S, °C) does not change in time.
4. Average surface temperature of the boiler system was calculated by using temperatures of front and back face of the hot water boiler due to the well-insulated of its lateral surface.
5. The average ambient temperature (T_0, °C) is constant for every month throughout the study.
6. All gas streams are assumed to be ideal gases [12, 13].

3.1. Energy Losses, Boiler Efficiency and Excess Air Ratio Calculations

Heat losses through flue gases can be analyzed in three parts; dry flue gas, moisture and unburned carbon in the flue gas. Also, some of heat is lost from the surface of the boiler by radiation and convection. Ultimately, all parts of energy losses from the hot water boiler can be calculated from the following equations (Eq.1-8).

Heat loss through dry flue gas (L_{DFG})

$$L_{DFG} = \frac{K\ x\ (T_{FG} - T_0)}{CO_2} x \frac{HHV}{LHV} \quad (1)$$

$$K = \frac{69{,}7\ x\ C_{fuel}\ x\ (LHV)^2}{(HHV)^3} \quad (2)$$

Heat loss due to moisture in the flue gas (L_{MFG})

$$L_{MFG} = \frac{(9\ x\ H_2) x\ (50{,}00 - T_0 + (0{,}50 * T_{FG}))}{HHV}\ x \frac{HHV}{LHV} \quad (3)$$

Heat loss due to unburned carbon in the flue gas (L_{COFG})

$$L_{COFG} = \frac{K_2 \, x \, CO}{CO_2 + CO} \, x \, \frac{HHV}{LHV} \quad (4)$$

Heat loss from boiler surface by radiation and convection (L_{RC})

$$L'_{RC} = (U_r + U_c) x \, A \, x \, (T_S - T_0) \quad (5)$$

$$U_r = \frac{E \, x \, 5{,}67}{(T_S - T_0)} x \left[\left(\frac{T_S}{100}\right)^4 - \left(\frac{T_0}{100}\right)^4 \right] \quad (6)$$

$$U_c = B \, x \, (T_S - T_0)^{0{,}25} \quad (7)$$

$$L_{RC} = \frac{L'_{RC}}{Heat\ supplied\ by\ the\ fuel} x100 \quad (8)$$

Total heat loss (L_{total}) and boiler efficiency (η)

Total heat loss from the hot water boiler is found by the sum of all parts of heat losses according to following equation (Eq.9);

$$L_{total} = L_{DFG} + L_{MFG} + L_{COFG} + L_{RC} \quad (9)$$

Accordingly, the boiler efficiency can be calculated as follows:

$$\eta = 100 - L_{total} \quad (10)$$

Excess air ratio (λ)

The excess air ratio for a boiler system is directly related to its thermal efficiency. A little excess air ratio is to assure perfect combustion, but large excess air ratio will enhance the flue gas amount [14]. Therefore, it is important that the excess air ratio should be remained in a specific range. The excess air ratio can be calculated by using the measured percentage of oxygen from the following equation (Eq. 11):

$$\lambda = 1 + \frac{O_2}{21 - O_2} \quad (11)$$

Energy Saving Calculations

A waste heat recovery unit, namely recuperator, was applied to recover the heat loss from the flue gas in the natural gas-fired central heating system. By this way, required quantity of the waste heat to warm up combustion air was recovered.

As it already mentioned, all gas streams are assumed to be ideal gases. The average specific heat capacities at constant pressure and fractions of the gas species that compose the exhaust gas, as well as its temperature and enthalpy are shown in Table 2.

Table 2. Energy balance data of the hot water boiler

	V_{fuel} (m^3/hour)	M_{FG} (kg/hour)	T_{FG} (°C)	T_{BHR} (°C)	T_{AHR} (°C)	h_{FG} (kJ/kg)	h_{BHR} (kJ/kg)	h_{AHR} (kJ/kg)
October 2015	78	733.6	260	22	141	537	295	415
November 2015	443	4162.3	259	20	139	536	293	414
December 2015	528	5213.9	308	17	162	587	290	437
January 2016	541	5345.1	310	14	162	589	287	436
February 2016	348	3438.2	308	15	161	588	288	432
March 2016	65	596.8	258	18	138	535	291	412

Total potential of the heat energy recovery and natural gas savings can be calculated by using following formulas (Eq. 12-15):

$$Q_{BHR} = M_{FG}\ x\ (h_{FG} - h_{BHR}) \quad (12)$$

$$Q_{AHR} = M_{FG}\ x\ (h_{FG} - h_{AHR}) \quad (13)$$

$$Q_{recovery} = Q_{BHR} - Q_{AHR} \quad (14)$$

$$Natural\ gas\ savings = \frac{Q_{recovery}}{(LHV\ x\ \eta)} \quad (15)$$

Economic analysis

By using following equations (Eq. 16-17) and data in Table 3, cost savings and payback period for applying recuperator to warm up combustion air of the boiler by reducing flue gas temperature and associated energy savings can be estimated [15].
Savings cost was;

$$Savings\ cost = \frac{\text{Natural gas savings}}{\text{year}} \text{x unit price of fuel} \quad (16)$$

Finally, payback period was calculated by the following equation;

$$Payback\ period = \frac{Investment\ cost}{Savings\ cost} \quad (17)$$

Here, price of the fuel and investment cost of the heat recovery system are around 0.35 \$/Sm^3 and 10150 \$ (contains price of recuperator unit and transfer and setup costs), respectively.

Table 3. Datas for economic analysis

	Natural gas saving (Sm^3/hour)	Working hours (hours/month)	Natural gas saving (Sm^3/month)
October 2015	3.00	434	1303
November 2015	17.18	540	9276
December 2015	26.21	620	16249
January 2016	27.23	620	16883
February 2016	16.93	522	8836
March 2016	2.46	496	1221
TOTAL		**3232 (hours/year)**	**53768 (Sm^3/year)**

4. RESULTS AND DISCUSSION

Considering the assumptions as explained in Section 3 and taking the measured data, into consideration energy losses and the hot water boiler efficiency in the central heating plant for six months calculated step by step. Results of heat losses and boiler efficiency calculations are summarized in Table 4.

Table 4. Results of heat losses and boiler efficiency calculations (%)

	L_{DFG}	L_{MFG}	L_{COFG}	L_{RC}	L_{total}	η	λ
October 2015	8.66	2.38	0.01	5.02	16.06	83.94	1.70
November 2015	8.62	2.74	0.01	0.87	12.24	87.76	1.70
December 2015	10.98	2.76	0.02	0.72	14.47	85.53	1.79
January 2016	11.04	2.75	0.02	0.71	14.52	85.48	1.79
February 2016	11.00	2.37	0.02	1.13	14.51	85.49	1.79
March 2016	8.36	2.37	0.00	6.03	16.77	83.23	1.66

According to Table 4, a major part of heat losses was due to very high flue gas temperatures. In addition, it is obviously seen that heat losses by radiation and convection from the boiler was in negligible level by comparison with heat losses by high flue gas temperatures because of the well-insulated boiler. Furthermore, together with high flue gas temperatures, higher excess air ratios are another reason for energy losses by increasing the flue gas amount.

The total energy recovery using heat recovery unit, recuperator, was calculated by using related equations (Eq.12-15) and taking measured data from Table 2. The results of heat recovery calculations were given in Table 5 in terms of quantity of energy usage before and after the heat recovery, the quantity of recovered energy, percentage of energy recovery values and lastly natural gas saving amounts for each month.

Table 5. Results of heat recovery calculations

	Q_{BHR} (kJ/hour)	Q_{AHR} (kJ/hour)	$Q_{recovery}$ (kJ/hour)	% Recovery	Natural gas saving (Sm^3/hour)
October 2015	177490	89445	88045	49.6	3.00
November 2015	1014250	510596	503654	49.7	17.18
December 2015	1551182	782755	768427	49.5	26.21
January 2016	1615242	816841	798401	49.4	27.23
February 2016	1031541	535228	496313	48.1	16.93
March 2016	145816	73617	72199	49.5	2.46

It is clearly seen in Table 5 that the method of the heat recovery from flue gas is one of the effective ways to save energy in the hot water boiler. Although the quantity of recovered energy peaks up the maximum values for December 2015 and January 2016, the percentage of the heat recovery exhibits about half of the total energy for all months.

5. CONCLUSION

The obtained results of the case study about the heat recovery from the flue gases of the hot water boiler in the central heating plant are listed below:

- The measured flue gas temperatures of the hot water boiler ranging between 250 °C ~ 300 °C. On the grounds that these temperatures were far above from the standards [11], it was decided to apply heat recovery system.

- After that the excess air ratios were calculated by using the measured percentage of oxygen in the flue gas for six months, it can be clearly seen from the results that large excess air ratios were in existence causing excess flue gas amount.
- Heat losses from the flue gas of the hot water boiler varied between 10% ~ 14%. The annual amount of waste heat from the flue gas of the hot water boiler to the atmosphere was 421 235 041 kJ/year.
- The total annual fuel consumption of the hot water boiler and its monetary value were estimated to be about 1 149 748 m^3 and 402 412 \$, respectively. Natural gas savings by applying recuperator for preheating combustion air and its monetary value were calculated 53 768 m^3/year (44.86 TOE/year) and 18 711 \$/year, respectively. By taking this precaution, energy savings can be achieved up to 50 %.
- Investment cost and payback period for heat recovery system in the hot water boiler system were found to be 10 150 \$ and 6.5 months, respectively, which is economically very viable.

Nomenclatures

A	Surface area of related region of boiler (m^2)
B	Surface coefficient (1.20 for horizontal cylinder)
C_{fuel}	Total carbon ratio in the fuel (%)
CO	CO ratio in the flue gas (%)
CO_2	CO_2 ratio in the flue gas (%)
E	Emissivity coefficient (0.77)
h_{AHR}	Enthalpy @ average temperature (kJ/kg)
h_{BHR}	Enthalpy @ ambient temperature (kJ/kg)
h_{FG}	Enthalpy @ flue gas temperature (kJ/kg)
H_2	H_2 ratio in the flue gas (%)
HHV	Higher heating value (kcal/kg)
K_2	Constant (32 for natural gas)
L_{COFG}	Heat loss due to unburned carbon in the flue gas (%)
L_{DFG}	Heat loss through dry flue gas (%)
L_{MFG}	Heat loss due to moisture in the flue gas (%)
L_{RC}	Heat loss from boiler surface by radiation and convection (%)
L_{total}	Total heat loss (%)
LHV	Lower heating value (kcal/kg)
M_{FG}	Flow rate of flue gas (kg/hour)
O_2	O_2 ratio in the flue gas (%)
Q_{AHR}	Using heat after heat recovery (kJ/hour)
Q_{BHR}	Using heat before heat recovery (kJ/hour)
$Q_{recovery}$	Recovered heat by recuperator (kJ/hour)
T_0	Ambient temperature (°C)
T_S	Surface temperature of the hot water boiler (°C)
T_{FG}	Flue gas temperature (°C)
U_c	Total heat transfer coefficient for convection (watt/m^2 K)
U_r	Total heat transfer coefficient for radiation (watt/m^2 K)
V_{fuel}	Fuel consumption (m^3/hour)

Greek Symbols

η	Boiler efficiency (%)
λ	Excess air ratio

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