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EXHAUST FLUE GAS HEAT RECOVERY POTENTIAL OF HEATING BOILERS OF BUILDINGS

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ABSTRACT

In this study, the heat recovery potential from the flue gases of the boiler a central heating system building was investigated. The energy consumption of the building calculated from Turkish Insulation Standard TS 825 for the example building for the four climate zone. Natural gas are used as fuel. Calculations have been made based on the outdoor temperature. The flue heat energy recovery potential of using natural gas in boilers changes depending on the dew point temperature of the flue gases. The excess air coefficient of the heating boilers is taken as 1.1 and 1.6 for natural gas. The flue gas temperature has been accepted as 150 and 200 ^{0}C. As a result, the energy potential of the flue gases, depending he excess air coefficient and the temperatures of the flue gases, was investigated by using combustion equations. As a result, it was determined that the 50 ^{0}C change in the flue temperature was 53% and the 0.5 change in the excess air coefficient was 41% effective on the potential of heat energy recovered from the flue gas.

Keywords: Exhaust flue gas temperature, dew point temperature, heating boilers, heat energy recovery potential

1. INTRODUCTION

Today, as energy consumption increases rapidly with the development of industry, energy sources such as fossil fuels are consumed very quickly. One way to get optimum benefit from diminishing energy resources is to prioritize waste heat recovery that will occur as a result of burning fossil fuels. Waste heat recovery has direct and indirect advantages. The direct advantages are the reduction of fuel consumption and cost; indirect advantages are the reduction of pollution [1].

It is necessary to take some measures to increase energy efficiency. Some of those are the combustion of fuels by using the existing combustion system in the most efficient way, obtaining the highest efficiency in heating, waste heat recovery, increasing efficiency in converting heat to work, minimizing air pollutant emissions, and minimizing the consumption of energy wastes that pollute the environment [2].

District heating system is widely used in many parts of the world. It has become increasingly common in many countries since the beginning of the 20th century. The district heating system is based on heating and hot water services over a large area consisting of many buildings and a heating plant. District heating is more efficient in the use of energy resources than other heating systems [1].

Waste heat is the part of the heat that comes out of any production process and is above the ambient temperature, which can be recovered. For central or district heating systems, flue gas content plays an important role in flue gas heat loss. This content can be classified as latent heat loss caused by the discharge of dry flue gases that do not contain water vapor, heat loss caused by the removal of the heat contained in the hot water vapor, incomplete combustion products such as CO, and soot, and unburned fuel [2].

Boilers can generally lose approximately 20% of the combustion energy with the flue gas and there is a potential to recover approximately 50% of this lost energy according to the flue gas operating conditions. Sensible heat and latent heat from the flue gas are recovered and the thermal efficiency of the boiler increases. Gas-fired systems are more commonly used because condensation in natural gas is less corrosive than other fuels and there is more moisture in the combustion products [3].

Wei M. et al. installed a steam pump system consisting of a gas condenser, air humidifier, and gas-water heat exchanger. An experimental study has been done. According to the test results, the exhaust flue gas temperature was reduced from 80 ^{0}C to 30.9 ^{0}C. System efficiency improvement exceeded 10%. If the air is heated above 50 ^{0}C, the NOx concentration drops from 33 to 24.6 ppm, the reduction is about 25.4% [4]. Lu D. proposed a new gas-fired absorption heat pump. The high-order sensible heat and low-order latent heat of the flue gas were studied for recovery in the solution preheater and the intermediate evaporator, respectively. The proposed system was found to be suitable for providing near 50 kW district heating for a typical urban residential building, especially in cold regions [5].

Wei M. et al., in another study, they proposed a new system using the residual heat in the sulfur-reduced flue gas using direct contact heat transfer and absorption technologies to reduce the waste flue gas temperature. Waste heat was recovered through low-temperature water from the heat pump and flue gas direct contact cooling. The recovered heat was then used to heat the mains return water [6]. Xu X., in their study, a new type of plate economizer with intermediate transition is proposed. The air-side heat transfer and flow resistance performance of the intermediate plate economizer were investigated by numerical simulation and the results were compared with the experiments [7]. Niu Y. et al. proposed the absorption heat pump to produce cold water to recover the latent heat in the flue gas and applied it to northern China. The optimum flue gas temperature drop in flue gas-solution heat exchangers has been calculated and the maximum investment saving rate has been revealed [8]. Thiyagu S. et al., in their study, the heat exchanger system was investigated to use the thermal energy obtained from the flue gas. A heat exchanger is used to transfer heat from the flue gas to the working fluid. The waste heat from the flue gas can be used to heat the feed water from the condensate drain pump. The 210 MW boiler is numerically examined and its performance is compared with the traditional power plant system [9]. Bukowska M., et al., in order to determine the waste heat recovery possibility of the coal-fired boiler plant and to prepare hot water, heat recovery solutions from the exhaust gases channel between the boiler and the chimney section were investigated.

It has been observed that the efficiency of the boiler affects especially the exhaust gas temperature and the excess air factor. It has been determined that it is possible to increase the boiler efficiency by limiting the excess air factor in the coal burning process in the boilers and using an additional heat exchanger in the exhaust gas channel outside the boilers [10]. Fialko N. et al., in their study, research on improving the environmental characteristics of municipal heat-power boiler plants for heat recovery from the exhaust gases of gas-fired boilers are given. The results of the research, the effect of cooling the water vapor contained in the exhaust gases below the dew point, on the boiler plants with heat recovery system were examined. It has been observed that when exhaust gas heat recovery technologies are used, it provides anti-corrosion protection by preventing the formation of condensation in the exhaust gas channels of boiler plants [11]. Zhao X. et al., in their study, the problems of conventional district heating systems were examined to analyze the waste heat recovery potential and a new process flow was proposed that could reduce the outlet temperature of the flue gas to about 20°C [12].

Terhan M. and Çomaklı K. examined the energy and exergy analyzes of natural gas fired boilers in a district heating syste. The energy and exergy efficiencies of the heating system were investigated and the locations of the irreversibility were indicated and the energy and exergy flow diagrams were shown. [1]. Terhan examined the analysis for moist air and solid fuels such as various types of coal and wood for different provinces of Turkey. Combustion effects were investigated by using different excess air ratios for fuel types. The dew point temperatures of water vapor and sulfuric acid were estimated for various types of solid fuels and for different cities in Turkey. Various factors affecting dew point temperatures, such as extreme air ratio, relative humidity, and city altitude, and the concentration of water and sulfuric acid vapor in the flue gases were investigated [13].

Terhan M., in his master's study, he investigated the recovery of lost energy from the boiler chimneys in Atatürk University Heating Center and the potential for use of this recovered energy. Calculations were made using the heating system data and the energy recovery potential was calculated from the flue gas cooled to 50 ^{0}C [2]. Terhan M. and Çomaklı K, in another study, they investigated the condensation of water vapor in the flue gas to recover the latent heat carried by the exhaust flue gas in a 60 MW natural gas fired district heating system of a university. For this purpose, they designed a waste heat recovery unit and made an economic analysis. The design calculations of the flue gas condenser were made with a computer program using the one-dimensional Finite Difference Method [3].

Yalçın S. E. calculated the cost of hot water or saturated steam for boilers producing hot water or saturated steam for different fuels, including natural gas and coal, and varying air excess coefficients. In order to calculate the costs in the study, the boiler was accepted as a continuous flow open system, and thermodynamic analysis was performed for different fuel inputs, such as natural gas and coal [14]. Kon O. and Yüksel B., in their study, the changes in the properties of combustion gases such as end-of-combustion water vapor partial pressure and dew point temperature, depending on different combustion air temperature and relative humidity, were investigated by using coal, natural gas and fuel-oil fuels in the boilers in the heating centre of the buildings. They calculated the amount of water vapor and CO_2 and SO_2 emissions that will occur after combustion depending on different coal, natural gas and fuel-oil consumption [15].

The aim of the study is to investigate the exhaust flue gas heat recovery potential from the flue of the heating boilers of a sample building with a central heating system according to four different climate zones in TS 825 (Turkish Building Insulation Standard). Different fuel consumption amount, excess air coefficient, and exhaust flue gas temperature in the flue are taken into account in the heating boilers of the sample building. The effect of flue gas temperature and excess air coefficient on the exhaust flue gas heat recovery potential of the flue is investigated in the study. Natural gas is used as fuel. It is stated in the literature that the temperature of the flue gases of boilers using natural gas as fuel can be reduced to dew point temperature. The excess air coefficient was chosen between 1.1 and 1.6 and the flue gas temperature was between 150 and 200 ^{0}C.

Theoretically, the excess air coefficient is 1.0 and the flue gas temperature is 150 ^{0}C in the natural gas-burning heating boilers used in the heating centers of the buildings. In the calculations, the excess air coefficient and flue gas temperature in the literature were accepted as above. It has been determined how much the flue gas recovery potential will change by increasing these values by a certain amount. It is seen in the literature that the excess air coefficient in heating boilers varies between 1.0-1.5 and the flue gas temperature varies between 150 and 200 ^{0}C. A literature study related to this is given. Reducing the flue gas temperature to dew point temperature in coal-fired heating boilers creates serious problems such as the formation of sulfuric acid in the flue gas [13].

2. METHODOLOGY

2.1. Fuel consumption and energy demand for heating period

Total heat loss for the building for the heating period due to ventilation heat loss [16];

$$HL_T=U_{ow}.(A_{ow}-A_w)+U_w.A_w+0.5\ U_fA_f+0.8\ U_cA_c+U_d.A_d+IV/3 \quad (1)$$

Here; U_{ow} is outer wall, U_w is window, U_f is floor, U_c is ceiling and U_d is door heat transmission coefficint and A_{ow} is outer wall area, A_w is window area, A_f is floor area, A_c is ceiling area, A_d is door area. Accordingly, the fuel consumption for the heating period of the building depends on the heating degree-day (HDD) value and the total heat loss of the building can be calculated below formula [17, 18];

$$m_{fuel}=\frac{86400.HL_T.HDD}{\eta.H_u} \quad (2)$$

Here η is heating system efficiency and H_u is lower heating value.
The dimensions of the sample building are 25×10×15. Roof area 250 m^2, outer wall 1050 m^2, 250 m^2 floor area. The total volume is V=3750 m^3. There is a glass area of 20% (210 m^2) of the external wall area. The hourly air exchange rate was taken as 1. This air exchange rate is the lowest air exchange rate accepted for buildings in the literature. With this accepted lowest air exchange rate, the lowest amount of heat loss will occur for the sample building. The door area is 10 m^2. The HDD value for the first climate zone is 1415, the HDD value for the second climate zone is 2395, the HDD 3179 for the third climate zone, and the HDD 3948 for the fourth climate zone [16].

2.2. Dew Point Temperature of Combustion Products and Water Vapor Partial Pressure of Air

The chemical composition of the fuel and the combustion equation depending on the ambient air [1-3, 13-15];

$$C_eH_dO_cS_kN_m + (a_{min}).\lambda.(O_2 +3.76\ N_2 +0.00145CO_2 +bH_2O) \rightarrow xN_2 + yO_2 + zCO_2 + kSO_2+ (t+a_{min}.\lambda.b)\ H_2O \quad (3)$$

Here a is the minimum amount of air required for the combustion of the fuel and λ is the excess air coefficient. Equation for minimum coefficient a [14];

$$a_{min}=n_C+(n_H/4)+n_S-0.5.n_O \quad (4)$$

Here, C is carbon, H is hydrogen, S is sulphur, O is oxygen and n is number of moles.

Partial pressure of water vapor (moisture) of the air in the sample building;

$$P_{v,air}=\Phi_{air}.P_{saturation,Tort} \quad (5)$$

Here, Φ_{hava} is relative humidity of sample building, $P_{saturation,Tort}$ is the saturation pressure of moisture in the air at the average temperature (T_{ort}) for the sample building.

Mole of water vapor in the air [15, 19];

$$n_{v,air}=(P_{v,air}/P_{Total}).\ n_{total} \quad (6)$$

Water vapor partial pressure of the products of combustion,

$$P_{v,ysü}=(n_{v,ysü}/n_{ysü}).P_{ysü} \quad (7)$$

Here, $n_{v,ysü}$ mole amount of water vapor in the products of combustion, $n_{ysü}$ is the total mole amount of products of combustion and $P_{ysü}$ is the pressure of the end products of combustion [15, 19].

The dew point temperature of end of combustion products (the temperature at which water vapor begins to condense when the end products are cooled at constant pressure);

$$T_{dew} = T_{doyma,Pvysü} \quad (8)$$

Here, $T_{doyma,Pvysü}$ is the temperature of moist air at saturation pressure [15, 19].

Table 1. Parameters used in calculations [15, 17-20]

Parameter	Value
Chemical Formula of Natural Gas	$C_{1.269}H_{4.516}O_{0.024}N_{0.012}$
Thermal Efficiency of Natural Gas	% 93
Lower Calorific Value of Natural Gas	34.526 10^6 J/m^3
Density of Natural Gas	0.76 kg/m^3
Minimum Oxygen Coefficient for Combustion (a_{min})	2.386
Air Excess Coefficients (λ)	1.1 and 1.6
Flue Gas Temperatures (T_{flue})	150 and 200 ^{0}C
Ambient Temperature (T)	15 ^{0}C
Ambient Relative Humidity (Φ)	% 60
Water Vapor Partial Pressure of Air ($P_{v,air}$)	1.023 kPa
Mole of Water Vapor in Air ($n_{v,air}$)	0.128 kmol

Partial Vapor Pressure of end of Combustion Products (P_{vysu})	17.552 kPa
Dew Point Temperature of end of Combustion Products (T_{dew})	57.1 ^{0}C
Coefficient for Nitrogen (x)	9.875
Coefficient for Oxygen (y)	0.239
Coefficient for Carbon Dioxide (z)	1.273
Coefficient for Humidity ($t+a_{min}.\lambda.b$)	2.386

2.3. Calculation of flue gas recovery

The molar specific heats of each of the components that make up the flue gases [1-3],

$$\overline{C_{pco_2}}=22.26+5.981.10^{-2}.T_{flue}-3.501.10^{-5}.T_{flue}^2+7.469.10^{-9}.T_{flue}^3 \quad (9)$$

$$\overline{C_{pH_2O}}=32.24+0.1923.10^{-2}.T_{flue}+1.055.10^{-5}.T_{flue}^2-3.595.10^{-9}.T_{flue}^3 \quad (10)$$

$$\overline{C_{po_2}}=25.48+1.520.10^{-2}.T_{flue}-0.7155.10^{-5}.T_{flue}^2+1.312.10^{-9}.T_{flue}^3 \quad (11)$$

$$\overline{C_{pN_2}}=28.90-0.1571.10^{-2}.T_{flue}+0.8081.10^{-5}.T_{flue}^2-2.873.10^{-9}.T_{flue}^3 \quad (12)$$

Here, T_{flue}, is the average flue gas temperature measured during the heating period and its unit is K.

The average specific heat of flue gases;

$$\overline{C_{Pavr}}=x_{CO_2}.\overline{C_{PCO_2}}+x_{O_2}.\overline{C_{PO_2}}+x_{H_2O}.\overline{C_{PH_2O}}+x_{N_2}.\overline{C_{PN_2}}+x_{SO_2}.\overline{C_{PSO_2}} \quad (13)$$

Here, is the mole fraction of the flue gas. The fuel molar mass;

$$MA_{fuel}=e.MA_C+d.MA_H+c.MA_O+m.MA_N \quad (14)$$

MA_{fuel} is fuel molar mass, MA_C is carbons' molar mass, MA_H is hydrojens' molar mass, MA_O is oxygens' molar mass and MA_N is nitrojens' molar mass [1-3, 13]. The mole mass of air,

$$MA_{air}=MA_{O_2}.x_{O_2}+MA_{N_2}.x_{N_2}+MA_{CO_2}.x_{CO_2}+MA_{H_2O}.x_{H_2O} \quad (15)$$

Here, The masses are as follows; MA_{air} is airs, MA_{O2} is oxygens', MA_{N2} is nitrojens', MA_{CO2} is carbon dioxides' and MA_{H2O} is waters'. Its units are kg/kmol and x is the mole ratio of the components that make up the air. Molar mass of flue gases;

$$MA_{flue}=x_{CO_2}.MA_{CO_2}+x_{H_2O}.MA_{H_2O}+x_{O_2}.MA_{O_2}+x_{N_2}.MA_{N_2} \quad (16)$$

MA_{flue} is the molar mass of the flue gases; MA_{CO2} is carbon dioxides', MA_{H2O} is water vapors', MA_{O2} is oxygens' and MA_{N2} is nitrojens' molar masses and their units are kg/kmol'dur. Mass of flue gases per unit time can be calculated below formula (kg/s);

$$m_{flue}=m_{fuel}+\frac{m_{fuel}.4.76.\lambda.MA_{air}}{MA_{fuel}} \qquad (17)$$

m_{Fuel} in the formula; mass of fuel per unit time, m_{Air}; mass flow rate of air per unit time and m_{flue} shows mass flow rate of flue gases per unit time. The mole amount of flue gases per unit time is calculated as follows.

$$n_{flue}=\frac{m_{flue}}{MA_{flue}} \qquad (18)$$

Some of the fuel energy obtained by the combustion of the fuel is thrown out with the flue gases. The energy carried by the flue gases; It is the sensible energy arising from the flue gas temperature and the latent energy carried by the water vapor in the flue gases.

By cooling the flue gases to a certain temperature T, some water condenses. Condensed amount of water (n_{cw});

$$n_{cw}=\frac{P_{flue}.\left(n_{flue}.x_{H_2O}\right)-P_{water}.n_{flue}}{P_{flue}-P_{water}} \qquad (19)$$

Here, n_{cw} is the number of moles of condensed water per unit time, P_{flue} is the total pressure of the flue gases (kPa), and P_{water} is the saturated vapor pressure at the temperature at which the flue gases are cooled.

Energy recovered by cooling the flue gases; cooling to a temperature below the dew point,

$$E_{Recovery}=n_{flue}.\overline{C_{Pavr}}.(T_{flue}-T_{dew})+n_{cw}.h_{fg}.MA_{H_2O} \qquad (20)$$

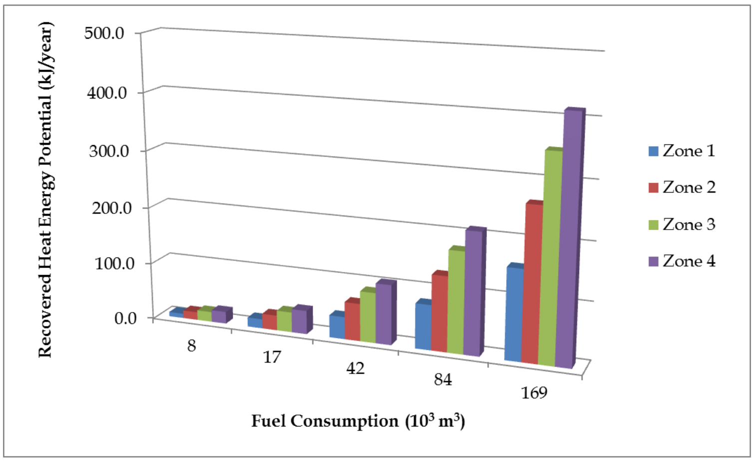
Here T_{dew} is fuels dew point temperature [1-3, 13, 18].

3. ANALYSIS

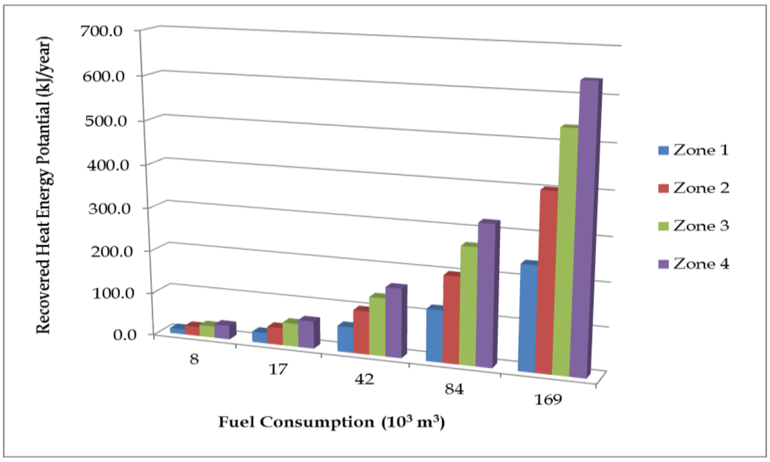
Assuming that the boilers in the heat center of the sample building work for 24 hours and the indoor temperature of the building is 19 ^{0}C, it has been determined that 181 days for the first and second climate zones and 243 days for the third and fourth climate zones are heated.

For excess air coefficient of 1.1 and a flue gas temperature of 150 ^{0}C, for the 1st climate zone, depending on the between 8-169 10^3 m^3 natural gas consumption, the heat energy recovery potential of the flue gas was calculated as 7,835-156,994 kJ/year. For the 2nd climate zone, based on the between 14-283 10^3 m^3 natural gas consumption, it is calculated as 13,840-263,304 kJ/year. For the 3rd climate zone for 19-380x10^3 m^3 natural gas consumption, the heat energy recovery potential of the flue gas was calculated as 17.531-350.641 kJ/year, for the 4th climate zone, depending on the 23-452 10^3 m^3 natural gas consumption, it is calculated as 21,079-414,886 kJ/year. For excess air coefficient of 1.1 and a flue gas temperature of 200 ^{0}C, 12,010-240,581 kJ/year flue gas heat energy recovery potential was calculated in the 1st climate zone. Heat recovery potential of 21,221-403,439 kJ/year in the second climate zone, 26.874-537.456 kJ/year heat recovery potential in the third climate zone, and 32.312-636.029 kJ/year heat recovery potential in the fourth climate zone was calculated. These are given in figure 1.

For excess air coefficient of 1.6 and a flue gas temperature of 150 ^{0}C, In the 1st climate zone, 11,088-217,874 kJ/year flue gas heat energy recovery potential was calculated. The heat recovery potential of 18,453-373,789 kJ/year in the 2nd climate zone, 24,774-501,827 kJ/year heat recovery potential in the 3rd climate zone, and 29,204-584,884 kJ/year heat recovery potential in the 4th climate zone was calculated. For excess air coefficient of 1.6 and a flue gas temperature of 200 ^{0}C, 16,983-333,927 kJ/year flue gas heat energy recovery potential was calculated in the 1st climate zone. Heat recovery potential of 28,290-570,458 kJ/year in the 2nd climate zone, 37,980-765,863 kJ/year heat recovery potential in the 3rd climate zone, and 44,720-896,453 kJ/year heat recovery potential in the 4th climate zone was calculated. These values are given in Figure 2.

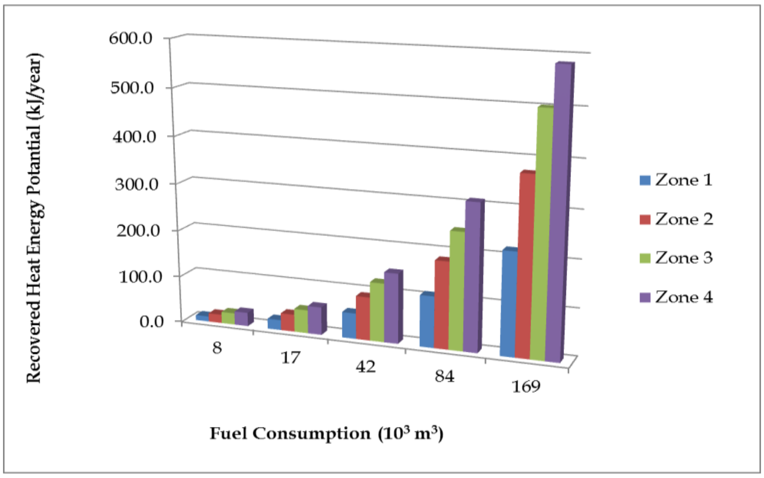


(a)



(b)

Figure 1. a) Excess air coefficient for 1.1 and flue gas temperature 150 ^{0}C b) Potential change of recovered heat energy from flue gas for air excess coefficient 1.1 and flue gas temperature 200 ^{0}C



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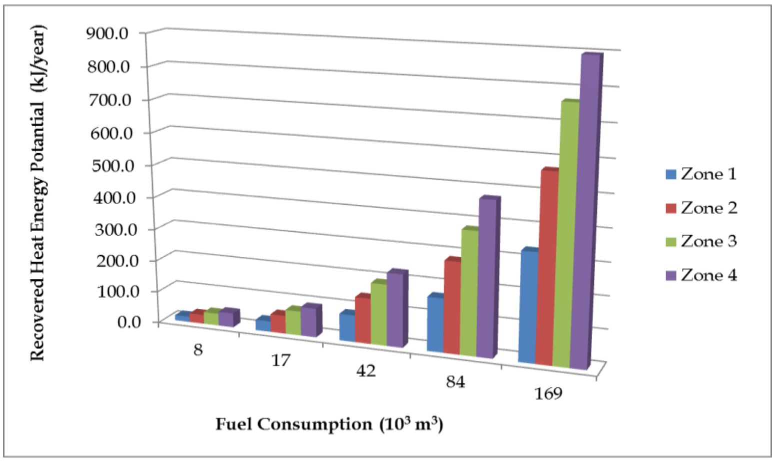

(b)

Figure 2. a) For air excess coefficient 1.6 and flue gas temperature 150 ^{0}C b) For air excess coefficient 1.6 and flue gas temperature 200 ^{0}C, potential change of recovered heat energy from flue gas

4. CONCLUSIONS

For excess air coefficient of 1.1 and a flue gas temperature of 150 ^{0}C, it was assumed that natural gas was used as fuel between 8-452 10^3 m^3 in the heating period in four climate zones, and the heat energy potential recovered from the flue gas was calculated as 7,835-414,886 kJ/year. Assuming that 8-452x10^3 m^3 of natural gas is used as fuel during the heating period in four climate zones for an excess air coefficient of 1.1 and a flue gas temperature of 200 ^{0}C, the heat energy potential recovered from the flue gas is calculated to be 12,010-636,029 kJ/year.

For excess air coefficient of 1.6 and a flue gas temperature of 150 ^{0}C, it is assumed that natural gas is used as fuel between 8-452 10^3 m^3 in the heating period in four climate zones, and the heat energy potential recovered from the flue gas is calculated to be 11,088-584,884 kJ/year. The heat energy potential recovered from the flue gas is calculated as 16,983-896,453 kJ/year, assuming that natural gas is used as fuel between 8-452 10^3 m^3 in the heating period in four climate regions for an excess air coefficient of 1.6 and a flue gas temperature of 200 ^{0}C.

If the results obtained from the study are examined; as the climate zone increases, the fuel consumption of the sample building and accordingly the heat energy potential recovered from the flue gas increases. In addition, the recovered heat energy potential increases by 53% on average when the flue gas temperature rises from 150 ^{0}C to 200 ^{0}C for both 1.1 and 1.6 excess air coefficient. When the air excess coefficient is increased from 1.1 to 1.6 for both the flue gas temperature at 150 ^{0}C and 200 ^{0}C, the recovered heat energy potential increases by 41% on average.

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