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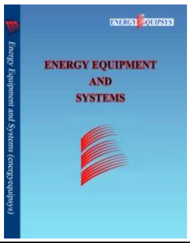

Study on performance and methods to optimize thermal oil boiler efficiency in cement industry

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ABSTRACT

Cement production is an energy-intensive process, so that the cement industry occupies a top position among other energy-consuming industries. Among the equipment used in cement industries, boilers are one of the energy-consuming equipment. Boilers are among the common heating equipment in industrial, commercial, and institutional facilities. In this paper, the performance of thermal oil boiler and useful methods in improving its efficiency and saving energy was investigated. Under normal condition, results showed that the boiler was only working with 55% of its capacity, and in this case, boiler efficiency was 77.48%, based on the heat loss method. Moreover, optimization of excess air level in combustion process as one of the improving performance methods increased the boiler efficiency by about 3%. The volume of fuel was also reduced to about 34.07 m³/HR, using economizer as another method.

Keywords: Boiler Efficiency, Economizer, Excess Air, Thermal Oil Boiler.

1. Introduction

Cement production is an energy intensive process worldwide. Theoretically, the energy consumption is about 4 GJ per ton of cement produced. Moreover, a minimum of about 1.6GJ heat is required to produce one ton clinker. However, the average specific energy consumption varies from about 2.95 GJ/ton for well-equipped advanced kiln to about 5.29 GJ/ton for the wet process. For example, India key plants produce clinker at best practice energy consumption of about 3.06 GJ/ton [1].

Security of supply, environmental sustainability and competitiveness (production of cement by using minimum energy in the most cost effective way possible), are important objectives of energy policy in the European Union [2-3]. One of the most effective methods for the energy consumption management in the cement industry is an energy audit. The main aim of an energy audit is to analyze the energy consumption of different components and to provide accurate information in determining the possible opportunities for energy conservation. Waste heat recovery for the hot gases in the equipment has been recognized as a potential way to improve the overall energy efficiency [4-5].

Boilers are one of the energy-consuming equipment in a cement plant. They are widely used in the cement production process, for heating furnace fuel. The boiler transfers combustion heat to water until it becomes heated steam or water. The hot steam or water under pressure has the ability to transfer the heat through a process known as heating furnace fuel. The steam boiler system comprises the fuel system, feed water system and steam system [6-7].

The fuel system includes all equipment required to supply fuel to produce the necessary heat which depends on the type of

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fuel used in the boiler. The feed water system provides water to the boiler and automatically adjusts it to encounter the steam demand. The steam system collects and supervises the steam in the boiler. Throughout the system, steam pressure is collected using valves and regulated with steam pressure gauges. Thermal oil boiler is also a type of indirect process heating in which maintainable temperatures for the user equipment are provided [6].

The percentage of useful energy input used in the generated heat is indicative of the boiler efficiency. Factors affecting boiler efficiency are, heat loss and excess air used for the fuel combustion. Boilers are most efficient when the combustion air used is only slightly higher than the stoichiometric combustion air [8-9]. Therefore, marinating low excess air levels lead to reduced significant fuel and cost savings. Moreover, additional equipment with boiler (such as economizer) can be used to achieve higher boiler efficiency. An economizer preheats the feed water, using the waste heat in the exhaust fuel gas [10-11].

This paper focuses on the thermal oil boiler performance in the Mazandaran cement plant. It also presents and describes useful methods (excess air control and use of economizer) for increasing boiler efficiency and energy savings.

Abbreviations

η	Boiler efficiency
T_a	Input air temperature
T_g	Output flue gas temperature
Q_l	Heat loss due to evaporate of moisture and combustion of the hydrogen in the fuel
Q_f	Dry flue gas heat loss
S.L	Total stack heat loss

2. Specification of Boiler system

Boilers are used in industries to generate hot water or steam. Stocker fluid boiler, pulverized boilers, package boiler, thermic fluid (oil) boiler, water tube boiler and waste heat boilers are all various types of boilers in industrial, commercial and institutional facilities. Boiler plant operation is energy intensive, hence it is necessary to make the process very efficient at reduced operating cost [6]. In recent times, thermic oil boilers have found wide application in process heating as in the cement industry. Thermal oil boiler is a type of indirect process heating in which oil is heated due to heat transfer from the fluid phase. The thermic fluid (oil) boiler consists of a double coil and three pass construction. The oil is heated up in the heater and circulated to one or more heat energy user equipment within a closed loop system. Then, heat transfers through a heat exchanger and the oil is then refused to the boiler [6].

Technical specification of hot oil boiler in the Mazandaran cement plant is described in Table 1.

The physical and chemical properties of used oil in the boiler are also presented in Table 2.

Fuel combustion supplies the required heat for heating oil in the boiler. Fuel is any substance that can be burned to produce sufficient heat energy for process heating,

Table 2. Physical and chemical properties of hot oil in boiler

Specification of oil	
Specific heat capacity	2.1 w/mc
Density	0.8 gr/cc
Viscosity at 1000 °c	5.5 cSt
Oil viscosity	112cSt

Table 1. Technical specification of hot oil boiler

Specification of boiler	
Hot oil production capacity	3700000 kcal/hr
Hot oil pressure	10 bars
Fuel	Natural gas
Outlet temperature (oil)	152°C
Back temperature (oil)	132°C
Flue gas temperature	241°C
Volumetric flow rate	251 m^3

using combustion air. The combustion process is the rapid chemical combustion of fuel (carbon and hydrogen) with oxygen from the combustion air which occurs in the combustion chamber (furnace) within the boiler. A successful combustion process depends on the mixing of fuel and air plus turbulence, combustion temperature and combustion time. Less time and a higher combustion chamber temperature is required for the completion of a good combustion process.

Various oils and natural gas are the most common fuels in boilers. Natural gas is the most convenient and clean burning fuel, because it can be easily mixed and does not require on site storage. The prime components of natural gas are methane (CH_4) and ethane (C_2H_6).

Percentage of chemical components in natural gas fuel and exhaust flue gases of boiler in thermal oil boiler of the Mazandaran cement plant is provided in Tables 3 and 4, respectively.

3. Performance evaluation of thermal oil boiler

The performance parameters of a thermal oil boiler, like efficiency boiler, are reduced with time due to various reasons, such as incomplete combustion, poor heat transfer, poor maintenance, poor operation and fuel quality. Therefore, the evaluation of energy (heat loss) and mass (amount of combustion air) balances are required to determine the efficiency of the boiler [8-9].

Energy balance helps to evaluate the boiler efficiency through the determination of avoidable and unavoidable heat loss. Combustion air is also an important parameter which affects the boiler efficiency.

3.1. Boiler efficiency

The thermal efficiency of a boiler is an appropriate measurement of the chosen equipment and operation used transfer the combustion heat to heat oil in oil or steam. In another word, boiler efficiency is defined as "the percentage of useful heat input that effectively used in the generate steam".

There are two different means of assessing boiler efficiency: direct method and indirect method [9].

- Direct method

Direct method measures the boiler efficiency as the ratio of the useful heat output produced by a boiler to the energy content of boiler fuel [9]. That is.

$$\text{boiler efficiency } (\eta) = \frac{\text{boiler heat output}}{\text{boiler heat input (fuel)}} \times 100 \tag{1}$$

The accurate measurements of the useful heat produced by a boiler and of the quantity and heating value of the fired fuel are necessary to calculate the boiler efficiency.

- Indirect method

According the British standard, BS 845:1987 [12] and the USA standard ASME PTC-4-1, boiler efficiency can be measured by subtracting the heat loss fraction from 100 [9]. Thus

$$\text{boiler efficiency } (\eta) = 100 - \text{total heat losses} \tag{2}$$

The indirect method is also known as the heat loss method. Hence, the indirect method can be provided as a better understanding of the effect of individual heat losses on the efficiency of the boiler.

Table 3. The chemical composition of components in natural gas

Component	CH_4	C_2H_6	C_3H_8	C_4H_{10}	C_5H_{12}	CO_2
	96.7%	1.6%	1.22%	0.13%	0.05%	0.3%

Table 4. Specification of exhaust flue gas

Component	O_2	CO_2	CO	NO	NO_2	N_2
	8.78%	6.92%	0.001%	0.005%	0.00005%	84.28%

3.2. Energy balance

The combustion process in a boiler, as shown in Fig.1, is a form of energy flow in a boiler. The energy balance can be described in the following equation:

Boiler energy input = useful energy + energy losses

The sources of heat energy input are air combustion and fuel as a major energy source.

An energy balance is an attempt to balance the total input energy of a boiler against the energy leaving the boiler in different form.

Figure 2 illustrates the different energy losses occurring for thermal oil boiler in the cement industry.

3.2.1. Flue gas heat loss

The heat discharged from the boiler stack, as the flue gas heat loss, is usually the largest heat losses in the burned fuel boiler. Temperature and flue gas analysis can be used to compute the heat loss. The flue gas heat loss consists of two parts which can be calculated separately according to B5845 standard [13]. Hence

- dry flue gas heat loss in stack can be calculated using

$$Q_f = \frac{K_1(T_g - T_a)}{20.9 - \%O_2} \quad . \tag{3}$$

- Heat loss due to evaporation of moisture and combustion of the hydrogen in the is obtained from

$$Q_l = K_2\left[1121.4 + \left(T_g - T_a\right)\right] \tag{4}$$

and

- The total stack heat loss is calculated as

$$S.L = Q_f + Q_l \quad . \tag{5}$$

3.2.2. Radiation and convection heat loss

Radiation is the main form of heat transfer from the boiler to the environment (boiler room). The radiation heat loss of a boiler is primarily a function of the surface temperature and the applied thermal insulation. Moreover, the convection heat loss is a function of temperature and air velocity in the boiler room. Thermal insulation maintains the outside surface boiler at a reliable temperature by reducing heat radiation. The intensity of heat losses depends on the temperature, the pressure and the capacity of the boiler [9].

Under similar conditions of fuel quality and combustion method, an increase in the size and capacity of the boiler reduces the heat loss by radiation, thereby increasing the boiler efficiency. Moreover, radiation loss is independent of the type of fuel burned [12].

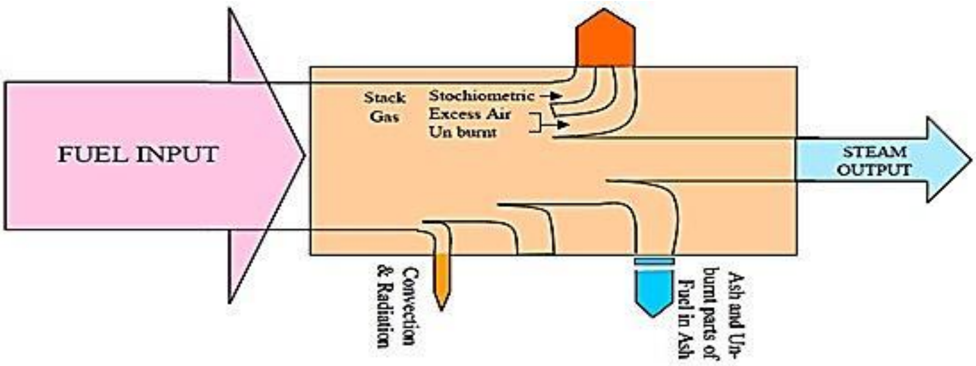

Fig. 1. Energy balance diagram of a boiler [9]

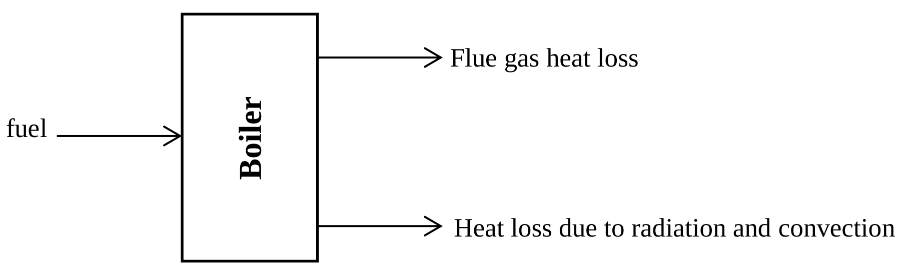

Fig. 2. Typical losses from thermal oil boiler [9]

3.3. Excess air

In theory, for the most efficient combustion (stoichiometric combustion), combustion process should be done using a perfect ratio of fuel and air, with no unburned fuel and unused air. But, in practice, excess air beyond the theoretical air needs to be added to the combustion process, because stoichiometric combustion is never achieved.
Moreover, if excess air is not added to the boiler combustion operation, carbon monoxide (CO) and smoke will create additional surface fouls and emissions.
Complete combustion equations of natural gas are given as

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O\,, \tag{6}$$

$$C_2H_6 + 3.5O_2 \rightarrow 2CO_2 + 3H_2O\,, \tag{7}$$

$$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O\,, \tag{8}$$

$$C_4H_{10} + 6.5O_2 \rightarrow 4CO_2 + 5H_2O\,, \tag{9}$$

and

$$C_5H_{12} + 8O_2 \rightarrow 5CO_2 + 6H_2O\,. \tag{10}$$

4. Results and Discussion

4.1. Boiler performance of Mazandaran cement plant

The radiation heat loss emitted from the surface casing of the boiler is shown in Fig.3.
Moreover, total stock heat loss of the boiler, which includes the heat loss due to dry as stock and evaporated moisture and combustion of hydrogen in the fuel was given as 22.52%. This is calculated using

$$S.L = \frac{K_1(T_g - T_a)}{20.9 - O_2} + K_2[1121.4 + (T_g - T_a)] = \frac{0.615 \times (241 - 21)}{20.9 - 8.78} + 0.0083 \times [1121.4 + (241 - 21)] \tag{11}$$
$$= 22.52\%.$$

According to the heat loss method (indirect method) and total heat loss, efficiency of thermal oil boiler in the Mazandaran cement plant was obtained as 77.48%. That is

$$\eta = 100 - \text{S.L} = 100 - 22.52 = 77.48\,\%.$$

Moreover, the boiler operated at a 55%capacity level. Thus

$$Q = m\,cp\,\Delta T$$
$$= 200800\,(\tfrac{kg}{s}) \times 2.1 \times 20$$
$$= 8433600\,\frac{kj}{hr} = 2056975.6\,\frac{kcal}{hr} \tag{12}$$

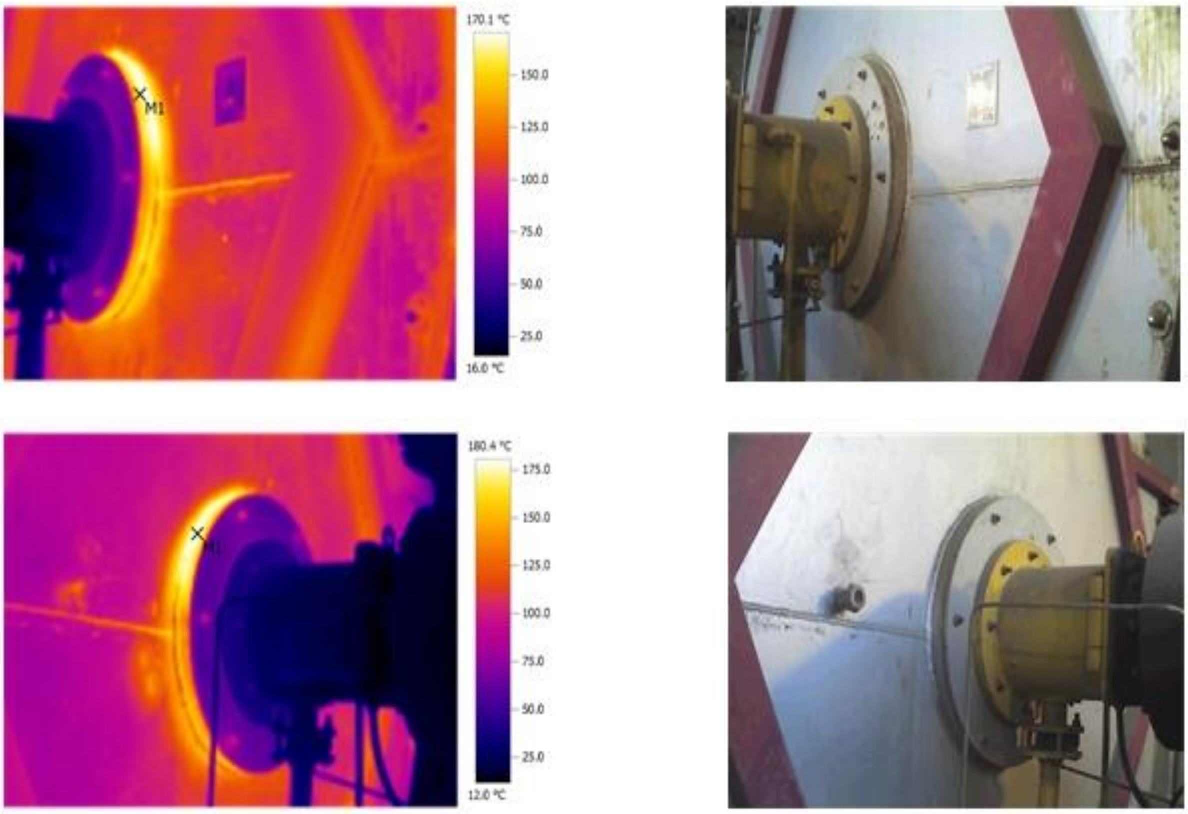

Fig. 3. Radiation heat loss from the boiler surface casing

$$\beta = \frac{\text{boiler performance}}{capacity} = \frac{2056975.6}{3700000} = 55\% \quad (13)$$

In this paper, the volume of fuel and excess air used in the boiler was calculated by considering the following assumptions:

1. Fuel and air were considered ideal gases and the ideal equation of state was used in the calculations.
2. Complete combustion in the boiler was assumed, although adverse reactions such as the formation of CO and NO_X in the combustion process were carried out.
3. Penetration of air into the boiler was ignored.
4. Mole fraction of gas was equal to the volume fraction.

Primary components in the flue gas per 100 kmol of dry gas based on assumptions is shown in Table 5.

Volume of consuming fuel and excess air in thermal oil boiler were also obtained as 356.05 cm^3/h and 63.43%, respectively. Hence

$$\text{Fuel Volume} = \begin{pmatrix} CH_4(kmol/hr) \\ +C_2H_6(kmol/hr) \\ +C_3H_8(kmol/hr) \end{pmatrix} \times 24.45 = 360.12 m^3/hr \quad (14)$$

and

$$\text{Excess air} = \frac{O_2 - 0.5CO}{0.2682N_2 - (O_2 - 0.5CO)} \times 100 = \frac{8.78 - (0.5 \times 0.001)}{(0.2682 \times 84.29) - (8.78 - (0.5 \times 0.001)} = 63.43\%. \quad (15)$$

Mathematical calculation of flue gas analysis and natural gas consumption in the boiler of the Mazandaran cement plant are provided in Appendix A.

4.2. Methods of improving boiler efficiency

Thermal energy cost in boilers represents a considerable proportion of the total cement production. Because part of the combustion energy in boilers is wasted, opportunities exist to address the subject of low– medium boiler efficiency. Energy losses and therefore saving energy opportunities in a boiler can be related to avoidable heat loss, heat transfer and combustion.

There are two methods of energy saving in a boiler system:

1. Energy saving throughout the year has been to frequently monitor and control excess air level.
2. The use of economizer with boiler

4.2.1. Optimization of excess air level

One method of maintaining low air levels in fuel combustion and improving the efficiency of the boiler is to frequently control and calibrate excess air levels. Often, air/fuel ratio in a boiler is calibrated one or twice per year in high fire. This is referred to as the excess air re-correction system, and is the ideal method to increase boiler efficiency, because it applies the analysis of the combustion flue gas as the true final measure of the combustion effectiveness. A combustion flue gas analysis can be used to manually or automatically adjust the excess air. The amount of excess air depends on various factors such as type of boiler, burner and fuel [14-16].

The theoretical curves of excess air show that carbon dioxide (CO_2) or oxygen (O_2) can be used to specify the excess air in the combustion process. It is important to note that measurement of carbon dioxide alone does not determine on which side the stoichiometric combustion is operating. In contrast, this obscurity does not exist in the excess air– oxygen relationship. For this reason, the measurement of O_2 is perfected. An examination of oxygen of each fuel at a given excess air setting is reasonably constant. The curves show the different contents of each fuel effect the produced CO_2 content [17].

The excess air theoretical curves are shown in Figs. 4 and 5.

As earlier mentioned, thermal oil boiler of the Mazandaran cement plant worked only with 55% of its capacity. So, it seems that the optimum amount of excess air for maximum boiler efficiency is 30 percent higher than the stoichiometric combustion air. In other words, excess air reduction of up to 30% is feasible and the boiler will operate with a maximum efficiency.

Table 5. Flue gas composition per 100 kmol of dry natural gas

Component	CH_4	C_2H_6	C_3H_8	C_4H_{10}	C_5H_{12}
	6.66%	0.11%	0.08%	0.008%	0.003%

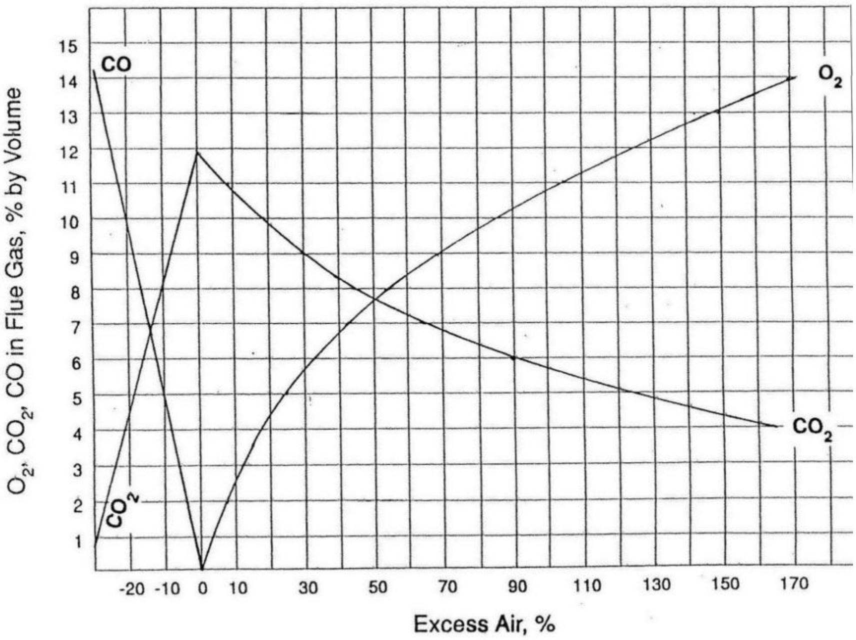

Fig. 4. Volume of O2, CO2 and CO in flue gas versus excess air [17]

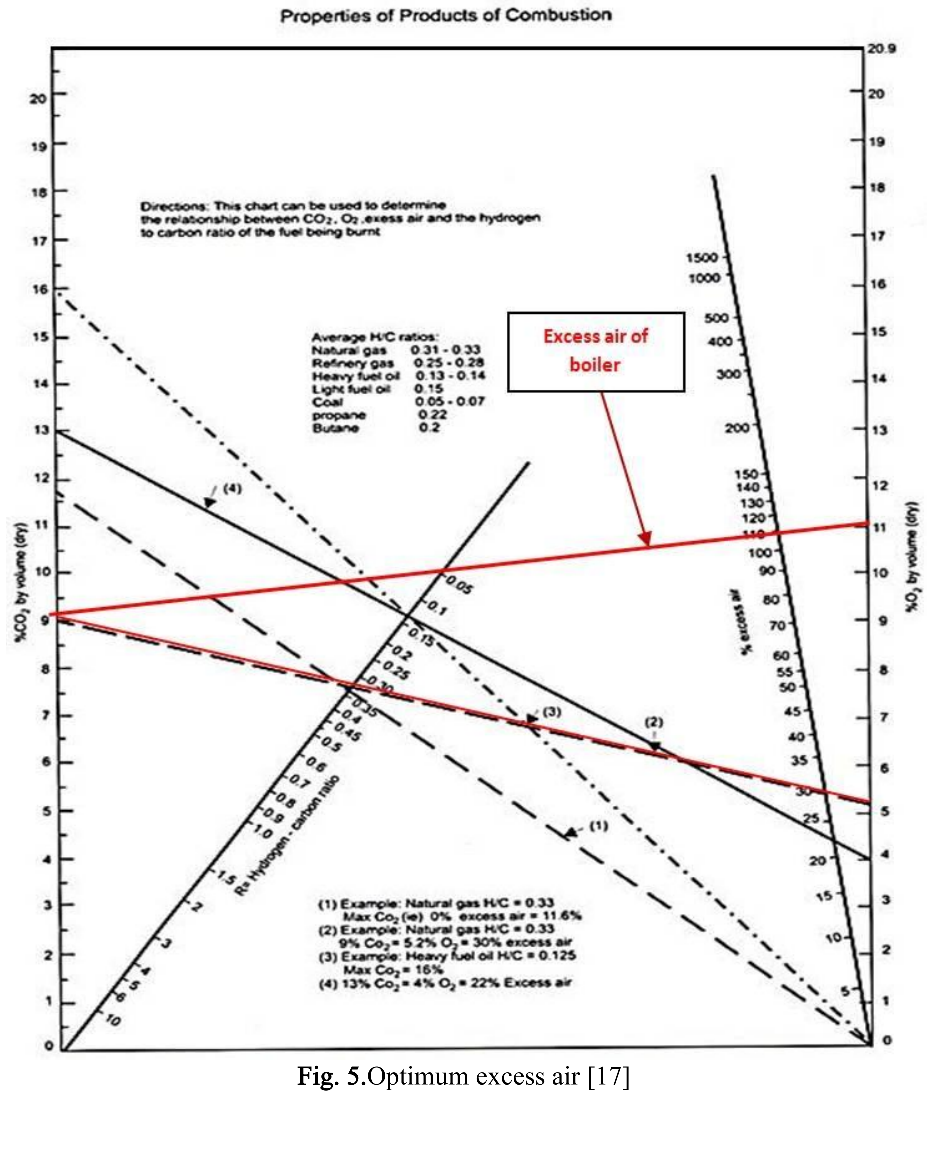

Fig. 5. Optimum excess air [17]

Moreover, controlling excess air to an optimum value always results in a reduction in the sum of heat loss of flue gas and heat loss due to incomplete combustion. Thus

$$S.L = \frac{K_1(T_g - T_a)}{20.9 - O_2} + K_2\left[1121.4 + (T_g - T_a)\right]$$
$$= \frac{0.615 \times (241-21)}{20.9-5} + 0.0083 \times \left[1121.4 + (241-21)\right]$$
$$= 19.81\%$$

$$\eta = 100 - S.L = 100 - 19.81 = 80.19\% \ .$$

4.2.2. Economizer

Economizer is a mechanical device intended to reduce the energy consumption by extracting heat from the flue gas leaving the boiler, and transferring the heat to the feed water. Therefore, an economizer can recover more useful energy heat in order to improve the boiler efficiency. The boiler efficiency directly depends on the efficiency of heat produced. The combustion of natural gas needs a flow of excess air in order to achieve complete combustion. The temperature of the combustion products and quantity of used excess air in the boiler are two key variables in evaluating the boiler efficiency [7,9].

Economizer is made of a stainless steel or aluminum alloy which can be fitted inside the main boiler casing or separately positioned outside the boiler. The exhaust gases pass through the cylindrical tubes which are either plain steel or finned to improve the heat transfer.

Non-corrosion economizer by acidic compounds is a significant point in the design, because sulfur compounds can be found in most fuels. Sulfur compounds are converted to sulfur dioxide in the combustion process. Moreover, water vapor is produced by the combustion of hydrocarbons, and sulfuric acid will then be produced by the reaction of water vapor and dioxide sulfur [7].

The produced steam from the distillation of acid leads to the corrosion of economizer. Therefore, a consideration of this point is of great importance in the design of an economizer.

In this paper, the ASPEN AEEROTRAN software was used to design of an economizer. Hot gas recuperator specification in the boiler is given in Table 6. The thermal and mechanical details of designed economizer are also represented in Appendix B.

Based on the natural gas combustion and improved combustion efficiency of thermal oil boiler in the Mazandaran cement plant, the theoretical combustion data and volume of fuelis given in Table 7.

5. Conclusion

This paper described the performance of boiler's Mazandaran cement plant and two methods useful in improving the efficiency of a boiler, based on optimization of excess air and installation of an economizer. Of the two methods, the controlling of excess air in the boiler was more difficult than using the economizer.

The results of the investigation are as follows:

- In normal conditions, boiler worked with 55% of its capacity. In this case, the amount of excess air and boiler efficiency were 63.43 percent and 77.48 percent, respectively.
- Excess air was required in a fuel combustion process to ensure complete combustion. On the other hand, the minimum heat losses and thus maximum boiler efficiency occurred when the optimum excess air level was used.
- Controlling of excess air level to an optimum level (oxygen analyzer) resulted in a reduction in the volume of fuel and flue gas heat losses. Moreover, with 32% reduction in the excess air level, there was approximately 3% rise in the boiler efficiency.
- The results have shown that the installation of economizer on the boiler can decrease the operation cost by reducing the volume of fuel. It also will lead to an increase in the boiler efficiency.

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Table 6. Hot gas recuperator specification in boiler

1	Company:					
2	Location:					
3	Service of Unit:		Our Reference:			
4	Item No.:		Your Reference:			
5	Date:	Rev No.:	Job No.:			
6	Size & Type	1762 / 1079.73				
7	Surf/Unit-Finned Tube	85.4	m²	Bare area/bundle	7.9	m²
8	Heat exchanged	96.9	kW	MTD, Eff	59.25	°C
9	Transfer Rate-Finned	19.2 Bare, Service	206.7	Clean	214.8	W/(m² K)
10	PERFORMANCE DATA - TUBE SIDE					
11	Fluid Circulated	Oil				In/Out
12	Total Fluid Entering	kg/h	210000	Density, Liq	kg/m³	833.7 / 833.7
13			In/Out	Density, Vap	kg/m³	/
14	Temperature	°C	132 / 132.79	Specific Heat, Liq	kJ/(kg K)	2.114 / 2.114
15	Liquid	kg/s	58.3333 / 58.3333	Specific Heat, Vap	kJ/(kg K)	/
16	Vapor	kg/s	/	Therm. Cond, Liq	W/(m K)	0.1133 / 0.1133
17	Noncondensable	kg/s	/	Therm. Cond, Vap	W/(m K)	/
18	Steam	kg/s	/	Freeze Point	°C	
19	Water	kg/s	/	BubblePointDewPoint	°C	/
20	Molecular wt, Vap		/	Latent heat	kJ/kg	
21	Molecular wt, NC			Inlet pressure (abs)	bar	11
22	Viscosity, Liq	mPa s	5.5941 / 5.4689	Pres Drop, Allow/Calc		0.68948 / 0.02971
23	Viscosity, Vap		/	Fouling resistance	m² K/W	
24	PERFORMANCE DATA - GAS SIDE					
25	Gas Quantity	kg/s	1.1	Viscosity	mPa s	0.0266 / 0.0235
26	Temperature In	°C	241 / 160	Density, Liq	kg/m³	0.67 / 0.8
27	Static Pressure	bar	1.00009	Specific Heat, Liq	kJ/(kg K)	1.097 / 1.08
28	Pres Drop, Allow/Calc	Pa	249 / 29	Therm. Cond, Vap	W/(m K)	0.0382 / 0.0328
29	Altitude	m		Fouling resistance	m² K/W	0.00088
30	Face Velocity 1.71 m/s	Bundle velocity 2.27 kg/s/m²		Design Ambient		°C
31	DESIGN-MATERIALS-CONSTRUCTION					
32	Design pressure 16.47848bar	Test Pressure Code		Design temperature 207.78 °C		
33	TUBE BUNDLE	Header		Tube		
34	Size 1762	Type Plug		Material CS		
35	Number/bay 1	Material		Specifications Welded		
36	Tube Rows 6	Passes 1		OD 30 Min Thk. 1.65 mm		
37	Arrangement	Plug Mat.		No./Bun 84 Lng 1 m		
38	Bundles 1 par 1 ser	Gasket Mat.		Pitch 68.35 / 59.19 Staggered		
39		Corr. Allow. 3.18mm		FIN		
40	Bundle frame Galvanized steel	Inlet nozzle (1) 254mm		Type I-type weld		
41	MISCELLANEOUS	Outlet nozzle(1) 254mm		Material CS		
42	Struct. Mount.	Special Nozzles		OD 62 Tks 0.58mm		
43	Surf.Prep	Rating		No. 197#/m Des Temp °C		
44	Notes:					
45	Economiser For Boiler (Oil Heater)					

Table 7. Theoretical combustion data after improving of boiler efficiency

	Actual performance of boiler	Optimizing excess air	Installation of economizer
CO_2 (kmol/hr)	14.86	13.99	13.50
CH_4 (kmol/hr)	14.26	13.43	12.90
C_2H_6 (kmol/hr)	0.294	0.17	0.21
Volume of fuel (m^3/hr)	360.12	332.66	321.98
Velocity (m/s)	16	12	9.7

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Appendix A

Mathematical calculation of flue gas analysis and consumption natural gas in the boiler of the Mazandaran cements plantis done as follows:

1. Flue gas analysis:

✓ **Primary components in flue gas per 100 kmol of dry gas:**

===6.66
= =6.61=0.11
= =6.61=0.083
= =6.61=0.008
= =6.61=0.003

✓ **Primary components in flue gas per kilo mole of dry gas:**

= % / 100=0.97
= ==0.02
= =12
= ==0.001
= ==0.0004
= ==3.28

✓ **Molar mass of fuel:**

=16a+30b+44c+58d+72e=160.97+300.02+440.012+580.001+720.0004=16.7

2. Fuel / air ratio:

✓ **Mole flow rate ratio:**

=

✓ **Mass flow rate ratio:**

=9.57=16.52

3. The volume of gas consumption:

= 0.2(m^2)x16(m/s) x 3600 = 11520 m^3/hr
==701.37
=654.12/44=14.86

4. Mass flow rate of fuel and air:
=+
=+=16.52+=17.52

Appendix B:

Table B.1. Thermal details of economizer

Thermal Details - General

		Outside		Tube Side	
Gases (in/out)	kg/s	1.1	1.1		
Liquids (in/out)	kg/s			58.3333	58.3333
Temperature (in/out)	°C	241	160	132	132.79
Dew point or bubble point	°C				
Film coefficients	W/(m² K)	34		591.3	
Fouling resistance	m² K/W	0.00088			
Velocity	m/s	3.09		1.49	
Pressure drop (allow./calc.)	Pa/ bar	249/ 29		0.68948/ 0.02971	

Total heat exchanged	kW	96.9	Size 1762 x 1079.73 mm
Overall coef. - dirty	W/(m² K)	19.5	Bundles 1 par 1 ser 1
Effective surface area	m²	85.4	Fin 197 #/m OD 62 mm
MTD corrected	°C	59.25	Tube OD 30 Tks 1.65 mm
MTD correction factor		1	Tube passes 1 hor

Thermal Details - Thermal Resistances

		Clean	Spec. foul	Max. foul
Area reqd.	m²	82.1	83.9	85.4
Excess surface	%	3.94	1.69	
Overall coefficient	W/(m² K)	19.9	19.5	19.2
Overall resistance	m² K/W	0.05019	0.0513	0.05217
Outside fouling	m² K/W	0.0	0.00088	0.00198
Tube side fouling (at tube ID)		0.0		
Distribution of overall resistance				
Outside film	%	58.56	57.29	56.34
Outside fouling	%		2.13	3.79
Tube wall 0.00003	%	0.66	0.65	0.64
Tube side fouling	%	0.0		
Tube side film	%	40.82	39.93	39.27

Thermal Details - Coefficients

		Outside	Tube Side
Film coefficients	W/(m² K)		
As calculated by program		34	591.3
As specified by user in input			
User specified multiplier		1	1
As used in design		34	591.3
Desuperheating coefficient			
Condensing coefficient			
Sensible coefficient		34	591.3
Boiling coefficient			
Liquid cooling coefficient			
Reynolds number		2155.97	5981.47
Fin efficiency factor		0.79	
Mean metal temperature	°C		160.29

Thermal Details - Pressure Drop

	Outside	Tube Side
Pressure drop	Pa	bar
Allowable	249	0.68948
Calculated, clean	29	0.02971
Calculated, dirty		0.02971
User specified multiplier	1	1

Velocity and pressure drop

Outside	%dp
Fan	
Bundle	100
Accessories	
Bundle velocity	3.09 m/s
Face velocity	1.71 m/s

Tube Side	m/s	%dp
Inlet nozzle	1.38	13.34
Entering tubes	1.49	15.48
Through tubes	1.49	42.36
Exiting tubes	1.49	15.48
Outlet nozzle	1.38	13.34

Table B.2. Mechanical details of economizer

Mechanical Details - Tubes

Tube material		Carbon Steel
Tube length	m	1
Tube OD	mm	30
Tube wall thickness	mm	1.65
Tube pitch face row	mm	68.35
Tube pitch rows deep	mm	59.19
Tube pattern		Staggered
Pass type		
Area ratio Ao/Ai		12.11

Fin material		
Fin type		I-type weld
Fin OD	mm	62
Fin thickness	mm	0.58
Fin density	#/m	197
Fin segment width	mm	

Mechanical Details - Bundle

Unit arrangement				Per bundle	Per Unit
Unit length/width	1762 / 1079.73	mm	Number of tubes	84	84
Bays in par/ser	/		Tube passes	1	1
Bundles per unit			Tubes in face row	14	14
In parallel	1		Tube rows deep	6	6
In series	1				

Pass number	1
Tubes in face row	14
Tube rows deep	6

Nozzles		Inlet	Outlet	Intermediate
Nominal ID	mm	254	254	
Number per bundle		1	1	
Rho*V2	kg/(m s²)	1590	1590	