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Performance evaluation of a gas fired boiler in commercial dairy plant

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ABSTRACT : Boiler is one of the most important components for dairy processing plant because which provide heating medium as steam at rate of required quantity with optimum quality .The present work is an account of "Performance Evaluation Of A Gas Fired Boiler- A Case Study In commercial Dairy Industry " . The study was aimed at assessing the operational performance of the gas fired boiler by evaluating the thermal efficiency and evaporation ratio. The analysis was carried out and found that the boiler having capacity of 501.6 kg steam production per hour at 6.8 kg/cm^2 with the help of natural gas consumption of 45.56 m^3 OR 27.33 kg. Evaporation ratio was obtained 18.35 per 1 kg of natural gas and 11 per 1 m^3 of natural gas utilized. The thermal efficiency determined by direct method and indirect method was 72.75 per cent and 68.29, respectively. The cost for one kg steam production was obtained 1.866 Rupees.

KEY WORDS : Boiler, Evaporation ratio, Thermal efficiency, Steam, Natural gas

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INTRODUCTION

A boiler is an enclosed pressure vessel that provides a means for combustion heat to transferred into water until it becomes heated water or steam .The hot water or steam under pressure is then usable for transferring the heat to a process. The ASME define steam generating unit is "A combination of apparatus for producing, furnishing or recovering heat together with apparatus for transferring the heat to made available to the fluid being heated and vaporized" (Rao, 2006).

According to content in tube, Boiler may be categorized in two: 1) water tube boiler and 2) fire tube boiler .In fire tube boiler, the flame or hot gases pass through the tubes which are surrounded by water, while in water tube boiler; water is contained inside the tubes which are surrounded by flame and hot gases from outside. Natural type of commercial energy source *i.e.* Coal, oil, lignite and natural gas etc. are mainly used as feed material for fired tube boiler. The boiler consists of the boiler shell, combustion chamber, grate, furnace, heating surface, mounting and accessories. Though Selection of type and size of boiler depends upon the capacity, working pressure, steam pressure, availability of fuel and water, load factor and available space, initial cost and maintenance cost. Boiler should be capable of generating steam at required pressure and of required quality quickly and with minimum fuel consumption (Ahmad, 1985).

Steam is being used as a heating medium in dairy processing equipment such as pasteurizers, UHT plants, milk evaporator, air heater, hot water generator, cheese stretching machine, can washers, ghee boilers etc. It is

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very important to manage efficient steam generation, distribution and utilization of steam along with heat recovery system.

The performance of boiler *i.e.* efficiency, directly affects the overall performance of the steam generation process and it reduce with time, due to poor combustion, heat transfer fouling and poor operation and maintenance. Some methods are used to improve the efficiency of boiler by minimizing the loss of useful heat to the surrounding from the hot flue gas and walls of the boiler. This can be accomplished by incorporation of necessary compact design and close monitoring and operation leading to reduction in quantity of excess air, reduction in temperature of flue gases, reducing in surface temperature of external walls of boilers. The current study puts forward an performance evaluation of gas fired boiler in commercial dairy plant. The technical detail specification of the boiler installed at commercial dairy plant is illustrated in Table A.

MATERIAL AND METHODS

The purpose of the performance evaluation of boiler is to determine actual performance and efficiency of boiler .It is indicator of operational conditions of boiler and basis for improvement of performance (Anonymous, 2007).

Evaporation ratio:

It is ratio of amount of steam generated to the amount fuel consumed by boiler. Evaporation, frequently termed as the capacity of boiler, is the amount of steam, expressed in kg or tonne which it can raise per hour at full load.

$$\text{Evaporation ratio} = \frac{\text{Steam generated in kg}}{\text{Natural gas consumed in m}^2 \text{ x density of gas kg/m}^3}$$

Thermal efficiency of boiler:

Thermal efficiency of boiler is determined as a percentage of the total energy available by burning fuel on gross calorific value (GSV) basis. As per Indian standard IS 8753, following two methods are to be used for determination of efficiency of boiler as given below.

The direct method :

Where the energy gain of the working fluid (water and steam) is compared with the energy content of the boiler fuel. This is also known as ‘input-output method’.

$$\text{Bioler efficiency} = \frac{[Q \text{ x } (h_g - h_f)]}{q \text{ x Gcv}} \text{ x } 100$$

where,

h_g = Enthalpy of saturated steam, kJ/kg

h_f = Enthalpy of feed water, kJ/kg of water

Parameters to be monitored for the calculation of boiler efficiency by direct method are:

– Quantity of steam generated per hour (Q) in kg/hr.

– Quantity of gas used per hour (q) in m^3/h.

– The working pressure (in bar) and superheat temperature (K), if any

– The temperature of feed water (K)

– Type of fuel and gross calorific value of the gas in kJ/m^3

The steam production was determined by steam flow meter installed in the steam pipe line. The flow meter was mounted on the feed water side of the boiler which

Table A : Boiler specification: technical specifications of J.N. Marshall

General specification			
Boiler type	Three pass wet back fire tube boiler	Heating surface area	59.54 sq.m
Draught type	Forced draught	Steam space	1.32 cubic meters
Steam generation	3000 kg/hr at 10.54 kg/cm^2	Water space	4.33 cubic meters
Thermal efficiency	83.75%GCV of fuel	Working pressure	10.5 kg/cm^2
Dry weight	8.64 MT	Hydraulic test Pressure	10.9 kg/cm^2
Flooded weight	14.29 MT	Height of chimney	30 meters
Fuel			
Type	Natural gas	GCV	37686.55 kJ/m^3
Density	0.6	Flame Temp.	1954 ^{O}C
Burner			
Make	Forbes Marshall Pvt. Ltd.	Sr. No	147
Size	3.0 TPH Step less Modulating	Fuel type gas	Natural Gas –ESR

was observed for hourly measurements. The temperature of feed water was observed by digital thermometer indicator. The pressure of the steam produced was measured from the steam pressure gauge mounted on the boiler. The enthalpy of steam and feed water were correspondingly determined by steam table.

The indirect method:

Where the efficiency is the difference between the losses and the energy input. In this method, the efficiency can be obtained by subtracting the heat loss fraction from 100.

Boiler efficiency by indirect method = 100 - (L_1 + L_2 + L_3 + L_4 + L_5 + L_6)

where L_1 –Loss due to dry flue gas (sensible heat)
L_2 - Loss due to hydrogen in fuel (H_2)
L_3 - Loss due to moisture in fuel (H_2O)
L_4 - Loss due to moisture in air (H_2O)
L_5 - Loss due to carbon monoxide (CO)
L_6 -Loss due to surface radiation, convection and other unaccounted*.

*Losses which are insignificant and are difficult to measure.

Flue gas analysis :

Flue gas analysis is used for both efficiency and emission purposes. Flue gas contains Oxygen (O_2), Carbon Monoxide (CO), Carbon Dioxide (CO_2) and its analysis was performed by flue gas analyser which is inserting a probe into the chimney exhaust of the boiler. By keeping its values into the following formula we can get excess air, actual mass of air, actual mass of dry flue gas, and heat losses in the dry flue gas.

The fuel gas analysis was done using the standard procedure described by the Bureau of Energy Efficiency (Ministry of power, Government of India, New Delhi), (Anonymous, 2007). The mathematical formula utilized for calculating the fuel gas analysis is given below:

– Theoretical or stoichiometric air fuel ratio can be determined as

$$= \frac{\left[(11.6 \text{ x } C) + \left(34.8 \text{ x} \left(H_2 - \frac{O_2}{8}\right)\right)\right]}{100} \text{ kg/m}^3 \text{ of gas}$$

where C, H_2 and O_2 are percentage of carbon, hydrogen, oxygen and sulphur, respectively

$$\text{– Theoretical } CO_2 \text{ \%} = \frac{\text{Moles of C}}{\text{Moles of } N_2 + \text{Moles of C}}$$

– The per cent excess air can be estimated from CO_2

$$EA = \frac{7900 \text{ x } [(CO_{2\%})_t - (CO_{2\%})_a]}{(CO_{2\%})_a \text{ x } [100 - (CO_{2\%})_t]}$$

where $(CO_2)_a$ – Actual CO_2 measured in flue gas
$(CO_2)_t$ - Theoretical CO_2

– Actual mass of air supplied /kg of fuel

$$= \left\{1 + \frac{EA}{100}\right\} \text{ x theoritical air}$$

– Actual mass of dry flue gas

= Mass of CO_2 + Mass of N_2 content in the flue+ Mass of N_2 in the combustion air supplied + Mass of oxygen in the flue gas

Heat losses in boiler :

There are various losses after combustion of fuel in the boiler.

– Heat loss due to dry flue gas (L_1) : This is the highest loss in boiler.

$$L_1 = \frac{mg \text{ x } C_P \text{ x } (T_f - T_a)}{\text{GCV of fuel}} \text{ x } 100$$

where mg – mass dry flue gas = (mf + ma)
mf - mass of fuel
ma – mass of air
Cp – specific heat of flue gas
T_f – flue gas temperature
T_a - ambient temperature

– Heat loss due to evaporation of water formed due to H_2 in fuel (L_2): The combustion of hydrogen cause heat loss because of the product of combustion is water.

$$L_2 = \frac{9 H_2 [584 + C_P (T_f - T_a)]}{\text{GCV of fuel}} \text{ x } 100$$

where H_2 – kg of hydrogen present in 1 kg of fuel.
C_p – specific heat of flue gas
T_f – flue gas temperature
T_a - ambient temperature

– Heat loss due to moisture present in fuel (L_3) : The moisture entering the boiler with the fuel leaves as a superheated vapor

$$L_3 = \frac{M \text{ x } [584 + C_P (T_f - T_a)]}{\text{GCV of fuel}} \text{ x } 100$$

where M – kg of moisture per kg of fuel

Cp – specific heat of flue gas

T_f – flue gas temperature

T_a - ambient temperature

– Heat loss due to moisture present in air (L_4) : Vapor is present in form of humidity in the incoming air. The mass of vapor which air contains can be obtained from psychrometeries charts.

Dry bulb Temp °C	Wet bulb temp °C	Relative humidity %	Kg water /kg dry air (Humidity factor)
20	20	100	0.016
20	14	50	0.008
30	22	50	0.014
40	30	50	0.024

$$L_4 = \frac{(\text{AAS x Humidity factor x } C_p (T_f - T_a))}{\text{GCV of fuel}} \text{ x } 100$$

where AAS –Actual mass of air supplied per kg of fuel.

Humidity factor – kg of water / kg of dry air

Cp – specific heat of flue gas

T_f – flue gas temperature

T_a - ambient temperature

– Heat loss due to incomplete combustion (L_5): This loss occurs due to insufficient air supply. Products formed by incomplete combustion include CO, H_2 and various hydrocarbons.

Heat loss due to partial conversion of C to CO:

$$L_5 = \frac{\% \text{ CO x C}}{\% \text{ CO} + \% \text{ CO}_2} \text{ x } \frac{5744}{\text{GCV of fuel}} \text{ x } 100$$

where CO - Volume of CO in flue gas leaving economizer in per cent

CO_2 - Actual volume of CO_2 in flue gas in per cent

– Heat loss due to radiation and convection (L_6) :

$$L_6 = 0.548 \text{ x } \left[\left(\frac{T_s}{55.55}\right)^4 - \left(\frac{T_a}{55.55}\right)^4\right] \text{ x } (T_s - T_a)^{1.25} \text{ x sq.rt of } \left[\frac{196.85 \text{ Vm} + 68.9}{68.9}\right]$$

where T_s = Surface temperature of the boiler = 333 °F

T_a = Atmospheric temperature = 303°F

V_m = Wind velocity

RESULTS AND DISCUSSION

The results of the present study as well as relevant discussions have been presented under following sub heads:

Thermal efficiency by direct method :

During experiment, observations recorded for calculating the boiler performance presented in form of boiler flow sheet are shown in Table 1. Steam enthalpy corresponding to steam pressure was determined from steam pressure enthalpy chart and was obtained 2616.01 kJ/kg at operating pressure 6.8 kg/cm², while the water enthalpy was 125.58 kJ/kg.

$$\text{Boiler efficiency} = \frac{[Q \text{ x } (h_g - h_f)]}{q \text{ x GCV}} \text{ x } 100$$

$$= \frac{(2508\text{"}(\text{"}[(2616.01 - 125.58)]}{227.8\text{"}(\text{"}37686.55)} \text{ x } 100$$

$$= \frac{6245998.44}{8584996.09} \text{ x } 100 = 72.75\%$$

The total steam produced and natural gas consumed during the five hours of experiment was 2508 kg and 227.8 m³, respectively. The average calculated thermal efficiency of the boiler was 72.75 per cent.

Thermal efficiency by indirect method :

The following are the data collected for a boiler using natural gas as the fuel as shown in Table 2.

Flue gas analysis:

During experiment, Exhaust flue gas was analyzed by flue gas analyzer and its composition is given in Table 3. Flue gas outlet temperature was observed as maximum up to 172°C. The similar trends were mentioned by Upadhyay (1998) that O_2 per cent in flue gas ideally should be < 3 per cent and CO_2 content should be at least 12 per cent (13-14 % CO_2 for oil fired and 10-11% for coal fired boiler).

– Calculation of theoretical air requirement for complete combustion (air fuel ratio):

Table 1 : Gas fired boiler performance flow sheet

Sr. No.	Time	Ambient air		Natural gas		Feed water		Steam			Flue gas analysis				Surface temp of boiler, (^{O}C)
	Hr:Min	Dry bulb temp. (^{O}C)	Wet bulb temp. (^{O}C)	Flow rate (m^3/hr)	Temp. (^{O}C)	Flow rate (m^3/hr)	Temp. (^{O}C)	Flow rate (kg/hr)	Pressure (kg/cm^2)	Temp. (^{O}C)	O_2 (%)	CO_2 (%)	CO (ppm)	Temp. (^{O}C)	
1.	0:00	39.5	29.7	45.96	30	0.55	30	508.3	6.8	164	5.1	9.1	3.0	169	60.0
2.	1:00	40.2	30.1	45.03	30	0.53	30	491.6	6.8	164	5.6	9.0	2.0	172	59.7
3.	2:00	40.1	30.0	46.71	30	0.56	30	516.6	6.8	164	5.2	9.3	2.0	169	60.2
4.	3:00	40.0	30.0	44.90	30	0.52	30	491.6	6.8	164	5.3	9.2	2.5	169	59.8
5.	4:00	40.2	30.1	45.21	30	0.53	30	500.0	6.8	164	5.3	9.1	2.0	172	60.3
Average		40.0	30.0	45.56	30	0.54	30	501.6	6.8	164	5.3	9.13	2.3	170	60.0

Table 2 : Natural gas composition (Ultimate analysis)

Sr. No.	Constituent	Unit
1.	Carbon	74.8097 %
2.	Hydrogen (H_2)	24.8926 %
3.	Nitrogen (N_2)	0.1697 %
4.	Oxygen (O_2)	0.1253 %
5.	GCV of fuel	90001 Kcal
6.	Surface temperature of boiler	333 ^{O}K
7.	Surface area of boiler	59.54 m^2
8.	Wind speed	0.5 m/s

$$= \frac{\left[(11.6 \text{ x } C) + \left(34.8 \text{ x}\left(H_2 - \frac{Q_2}{8}\right)\right)\right]}{100} \text{ kg/m}^3 \text{ of gas}$$

$$= \frac{\left[(11.6 \text{ x } 74.8097) + \left(34.8 \text{ x}\left(24.892 - \frac{0.125}{8}\right)\right)\right]}{100} = 17.33 \text{ kg/m}^3 \text{ of gas}$$

– Calculation of theoretical CO_2 per cent generation in flue gas :

$$(CO_2)t = \frac{\text{Moles of C}}{\text{Moles of } N_2 + \text{Moles of C}}$$

$$= \frac{0.062325}{0.48 + 0.0623} \text{ x } 100 = 11.49\%$$

$$\text{where Moles of } N_2 = \frac{17.33 \text{ x } 77}{2800} + \frac{0.1697}{28} = 0.48606$$

$$\text{Moles of C} = \frac{0.7480}{12} = 0.062325$$

– Calculation of percentage excess air supplied (EA):

Actual CO_2 measured in exhaust flue gas = 9.13 per cent

Theoretical CO_2= 11.49 per cent

$$EA = \frac{7900 \text{ x } [(CO_{2\%})_t - (CO_{2\%})_a]}{(CO_{2\%})_a \text{ x } [100 - (CO_{2\%})_t]}$$

$$= \frac{7900 \text{ x } [11.49 - 9.13]}{9.13 \text{ x } [100 - 11.49]}$$

$$= \frac{18644}{808.096} \text{ x } 23.07\%$$

– Actual mass of air supplied / m^3 of gas

$$= \left\{1 + \frac{EA}{100}\right\} \text{ x theoritical air}$$

$$= \left\{1 + \frac{23.07}{100}\right\} \text{ x } 17.33 = 21.32 \text{ kg/m}^3 \text{ of gas}$$

– Actual mass of dry gas

= Mass of CO_2 + Mass of N_2 content in the flue + Mass of N_2 in the combustion air supplied + Mass of oxygen in the flue gas

$$= \frac{0.7480 \text{ x } 44}{12} + 0.0016 + \frac{21.32}{100} \text{ x } 77 + \frac{(21.32 - 17.33)}{100} \text{ x } 23$$

= 2.742 + 0.0016 + 16.4164 + 0.9777

= 20.1377 kg/m^3 of gas

Upadhyay (1998) mentioned that an efficient natural gas burner required 1 per cent to 2 per cent excess oxygen

Table 3 : Flue gas analysis

Sr. No.	Particulars	Unit
1.	Theoretical air required for complete combustion of m^3 of natural gas is	17.33 kg
2.	Theoretical CO_2 generated in flue gas is	11.49 %
3.	Excess air supplied	23.07%
4.	Actual mass of air supplied per m^3 of natural gas	21.32 kg
5.	Actual mass of dry flue gas produced per m^3 of natural gas	20.13 kg

or 5 per cent to 10 per cent excess air in the flue gas to proper combustion of fuel. He has also stated that the theoretical CO_2 in flue should be 11.8 per cent and actual CO_2 in flue should be 7-11 per cent.

Heat losses in boiler :

– Heat loss due to dry flue gas (L_1):

$$L_1 = \frac{mg \times C_P \times (T_f - T_a)}{GCV\ of\ fuel} \times 100$$

$$= \frac{20.1377 \times .24 \times (170 - 30)}{9001} \times 100 = 7.51\%$$

– Heat loss due to evaporation of water formed due to H_2 in fuel (L_2):

$$L_2 = \frac{9\ H_2\ [584 + C_P\ (T_f - T_a)]}{GCV\ of\ fuel} \times 100$$

$$= \frac{9 \times 0.24 \times [584 + 0.45\ (170 - 30)]}{9001} \times 100 = 15.52\%$$

Heat loss due to moisture present in fuel (L_3):

Moisture present in natural gas is zero then

$$L_3 = \frac{M \times [584 + C_P\ (T_f - T_a)]}{GCV\ of\ fuel} \times 100 = 0.0\%$$

Heat loss due to moisture present in air (L_4) :

$$L_4 = \frac{(AAS \times Humidity\ factor \times C_p\ (T_f - T_a))}{GCV\ of\ fuel} \times 100$$

$$= \frac{21.32 \times 0.024 \times 0.45 \times (170 - 30)}{9001} \times 100$$

$$\frac{32.2358}{9001} \times 100 = 0.35\%$$

Heat loss due to incomplete combustion (L_5):

$$L_5 = \frac{\%\ CO \times C}{\%\ CO + \%\ (CO_2)_a} \times \frac{5744}{GCV\ of\ fuel} \times 100$$

$$= \frac{2.3 \times 10^{-4} \times 0.748097}{2.3 \times 10^{-4} + 9.13} \times \frac{5744}{9001} \times 100$$

$$= \frac{429839.0288}{82181.200} = 5.23\%$$

– Heat loss due to radiation and convection (L_6)

$$L_6 = 0.548 \times \left[\left(\frac{T_s}{55.55}\right)^4 - \left(\frac{T_a}{55.55}\right)^4\right] \times (T_s - T_a)^{1.25} \ \times \text{ sq.rt of } \left[\frac{196.85\,Vm + 68.9}{68.9}\right]$$

$$= 0.548 \times \left[\left(\frac{333}{55.55}\right)^4 - \left(\frac{303}{55.55}\right)^4\right] + 1.957 \times (60 - 30)^{1.25} \ \times \text{ sq.rt of } \left[\frac{196.85 \times 0.5 + 68.9}{68.9}\right]$$

= 0.548 x [1291 - 885.18] + 1.957 x 70.21 x 1.55

= 222.57 + 212.97 = 435.54 W/m² = 435.54 x 0.86 = 374.56 kcal/m²

Total radiation and convection loss= 374.56 × 34 = 12735.04 kcal

Percentage radiation and convection loss =

$$\frac{12735.04 \times 100}{9001 \times 45.56} = 3.10\%$$

Heat balance:

A simple heat balance would give the efficiency of the boiler. The efficiency is the difference between the energy input to the boiler and the heat losses calculated (Table 4).

Boiler evaporation ratio:

$$Evaporation\ ratio = \frac{Steam\ generated\ in\ kg}{Natural\ gas\ consumed\ in\ m^2 \times density\ of\ gas\ kg/m^2}$$

Table 4 : Boiler heat balance

Input/Output parameter		Kcal / m^3 of fuel	%
Heat input in fuel	=	9001	100
Various heat losses in boiler	=		
1. Dry flue gas loss	=	675.97	7.51
2. Loss due to hydrogen in fuel	=	1396.95	15.52
3. Loss due to moisture in fuel	=	0.00	0.00
4. Loss due to moisture in air	=	31.50	0.35
5. Partial combustion of C to CO	=	470.70	5.23
6. Surface heat losses	=	279.03	3.10
Total Losses	=	2854.21	31.71

Boiler efficiency = 100 – (1+2+3+4+5+6)
= 100- 31.71 = 68.29%

Table 5 : Cost economics

Sr. No	Particulars		Unit
1	Total steam production	=	2508 kg
2	Total natural gas utilized	=	227.80 m^3
		=	136.68 kg
2.1	Gas utilized for producing 1 kg steam	=	0.0908 m^3
		=	0.0544 kg
2.2	1 kg natural gas price	=	34 rupees
2.3.	Cost for producing 1 kg steam	=	1.845 rupees
3	Total electricity consumed	=	6.6 kWh
3.1	Rate of electricity per 1kWh	=	8 Rupees
3.2	Total electricity cost	=	52.80 Rupees
3.3	Electricity cost per kg steam generated	=	0.0210 Rupees
4	Total cost of 1 kg of steam production	=	1.845 + 0.0210
			= 1.866 Rupees

$$\mathbf{ER} = \frac{\mathbf{501.6}}{\mathbf{45.56\,x\,0.6}} = \mathbf{18.35}$$

Evaporation ratio is 18.35 means that 18.35 kg of steam (6.8 kg/cm^2 pressure) is generated by consuming 1 kg of natural gas or 11 kg steam is produced per 1 m^3 of natural gas utilized.

Conclusion :

Keeping this in view energy analysis of boiler has been conducted in a commercial dairy plant having one lakh litre per day milk handling capacity. During experiment, we found that the boiler having capacity of 501.6 kg steam produced per hour at 6.8 kg/cm^2 with the help of natural gas consumption of 45.56 m^3 or 27.33 kg. Evaporation ratio was calculated as 18.35 per 1 kg of natural gas and 11 per 1 m^3 of natural gas utilized. The thermal efficiency by direct method and indirect method was 72.75 per cent and 68.29, respectively. The excess air is 23.07 per cent which is slightly higher than the sufficient limits. Heat losses in boiler 31.71 which is quite higher than the other boiler performance. The cost of production 1 kg of steam was 1.866 Rupees.

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