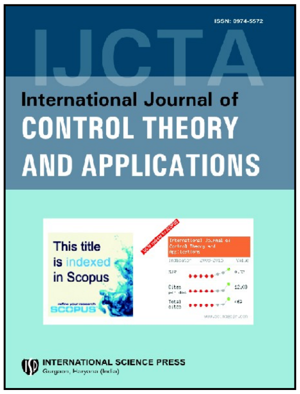

International Journal of Control Theory and Applications

ISSN : 0974-5572

© International Science Press

Volume 10 • Number 10 • 2017

Essence of the waste heat recovery in the process industries

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Abstract: In the present scenario, recovering the waste heat from process plants becoming the most typical challenge for most of the industries like steel plants, cement plants and sponge iron plants etc. By installing waste heat recovery boiler some quantity of heat from waste flue gases can be recovered to produce steam through which electricity can be generated. Temperature of the waste flue gases can be reduced through this emission, harmful gases to the atmosphere can be controlled. In order to protect the planet from global warming and other living organisms, the temperature of the waste flue gases should be reduced. After installing waste heat recovery boiler, industries can expect optimum power consumptions, enhancement in boiler efficiency and emission reduction. In this paper, gross and net calorific values are evaluated considering compositions of different coals and compared with the reported/measured values. The annual emission by clinker formation, the energy saved after waste heat recovery boiler and the anticipated cost savings from the generated electricity are estimated. Maintenance and NDT techniques relevant to monitor the health conditions of boilers are briefly highlighted.

Keywords: Cement plant; Clinker; Coal; CO2 emissions; Energy audit; Gas calorific value; Heat loss; Kiln; Preheater.

1. INTRODUCTION

Huge quantity of hot flue gases generated from boilers, kilns, ovens and furnaces through fuel combustion or chemical reaction in process industries, is being dumped in the environment. By recovering this waste heat, there is a possibility of reducing the utility consumption and costs and process cost in addition to the reduction in the (i) levels of environmental pollution; (ii) sizes of flue gas handling equipment's (viz., fans, stacks, ducts, burners, etc.); and (iii) auxiliary energy consumption (like electricity for fans, pumps, etc.). One can find the subject in great detail from the bureau of energy efficiency- waste heat recovery [1]. Waste heat sources are classified into high temperature range (650-1650^{0}C); medium temperature range (250-650^{0}C); and low temperature range (25-225^{0}C). The industries having high temperature sources (viz., nickel, aluminium, zinc and copper refining furnaces, steel heating and glass melting furnaces, cement kiln, etc.) possess high potential in utilizing waste heat from the flue gases. The waste heat flue gases in the medium temperature arrive from the exhaust of fired process units (viz., steam boilers, gas turbines, heat treating furnaces, drying and baking ovens, annealing furnace cooling systems, etc.). The low temperature waste heat from process steam condensate, welding machines, injection moulding machines, forming dies, pumps IC engines, hot processed solids and liquids, etc., may be useful in a supplementary way for preheating purposes.

The task is involved while selecting suitable heat recovery systems and equipments to recover and utilize the maximum possible energy loss from the waste hot flue gases. The amount of heat (Q) recoverable can be estimated from the product of mass flow rate ($\dot{m}$), the specific heat of the flue gas (C_p), and the temperature difference (ΔT). The common heat recovery devices available commercially are recuperators, economisers, heat pumps and waste heat recovery boilers. Waste heat recovery boilers are ordinarily water tube boilers in which hot exhaust gases from gas turbines, incinerators, etc., pass over a number of parallel tubes containing water. The water is vaporized in the tubes and collected in a steam drum from which it is drown off for use as heating or process steam.

Prasad *et al.* [2] have reported that huge amount of flue gases from sponge iron plant is dumped in the environment as an exhaust gas. Loganathan and Sivakumar [3] have recommended the waste heat recovery steam generator (WHRSG) in place of gas cooler for gas cooling by heat recovery and steam generation. Forni *et al.* [4] have proposed an innovative system for electricity generation in glass, cement and metal industries which dissipate huge amount of heat to the atmosphere. Carbon dioxide (CO_2) is emitted as a by-product of clinker production, an intermediate product in cement manufacture, in which calcium carbonate ($CaCO_3$) is calcinated and converted to lime (CaO), the primary component of cement. CO_2 is also emitted during cement production by fossil fuel combustion [5]. Bennett [6] has indicated the possibility of enhancing the plant efficiency through waste heat recovery.

The cement industries play an important role in the economy and consume a huge amount of natural resources during cement production. Madlool *et al.* [7] have made a review on energy use and savings in the cement industries. By installing waste heat recovery boiler some quantity of heat from waste flue gases can be recovered to produce steam through which electricity can be generated. Through this emission, temperature of the waste flue gases can be reduced and harmful gases to the atmosphere can be controlled, which protect the planet from global warming and other living organisms. After installing waste heat recovery boiler, industries can expect optimum power consumption, enhancement in boiler efficiency and emission reduction. Several researchers have performed energy audit analysis in cement industries [8-15].

Priyadarshini and Sivakumar [16] have carried out thermal energy audit analysis utilizing the measured data (viz., exhaust gas temperature, dust concentration, surface temperature, velocity, etc.) of Dalmia Cement Unit-2, Trichy, India. The major heat losses identified by them are due to preheater exhaust gas, hot air from cooler stack, and radiation from kiln surfaces. Their energy audit analysis indicates the possibility of cost reduction in production, and power consumption through waste heat recovery of hot flue gases. However, there is a need to correct their heat balance of the kiln system (which calls for the energy audit reassessment), and to assess the carbon dioxide emissions (which takes place in cement plants by clinker formation and by coal combustion). In this paper, gross and net calorific values are evaluated for different composition of coals useful in the energy audit analysis. Annual emission by clinker formation is estimated. Cost analysis is performed to estimate the anticipated savings from the generated electricity through waste heat recovery of boilers in cement plants. Maintenance and NDT techniques, which are essential for the health condition monitoring, are briefly highlighted.

2. GROSS CALORIFIC VALUE (GCV) OF COALS

The initial decomposition of buried accumulated vegetation matter into carbonaceous product takes place through several biochemical processes and starts the process of transformation into coal. The effect of heat and pressure due to further consolidation results in the expulsion of moisture and volatile constituents giving rise to higher grade coals. Continuation of this process of dynamo chemical transformation produces varieties of coal. The larger deposits of coal in India are in Bihar, Bengal, Jharkhand, Madhya Pradesh, Chhattisgarh, Orissa and Tamilnadu. Coal is a very important fuel being used in industries, power plants and locomotives. Hence it has topmost economic value. It consists of carbon with moisture, volatile matter and some mineral residuals. The quality of coal depends on the relative proportion of carbon in relation to volatile matter and moisture. The better quality of coal possesses greater carbon content.

The amount of heat (*kJ*) evolved by the complete combustion of 1 *kg* of fuel is known as the calorific value of a fuel (*kJ/kg*) [17]. When the products of combustion are cooled down to the surrounding air temperature, the quantity of heat obtained by the complete combustion of 1 *kg* of a fuel is referred as the gross or higher calorific value (GCV_f).When the products of combustion are not sufficiently cooled down to condense the steam formed during combustion, the quantity of heat obtained by the combustion of 1 *kg* of a fuel is termed as the net or lower calorific value (LCV_f).The bomb calorimeter is used for evaluating the calorific value of fuel [17]. From the chemical analysis of a fuel, the gross or higher calorific value can be obtained from the Dulong's formula [18]:

$$GCV_f = 33800 \times C + 144000 \times \left(H_2 - \frac{O_2}{8} \right) + 9270 \times S, \; kJ/kg \tag{1}$$

Here C, H_2, O_2 and S represent the mass of carbon, hydrogen, oxygen and sulphur in 1 kg of fuel. The numerical values in equation (1) represent their respective calorific values. The amount of heat per *kg* of steam (i.e., the latent heat of vaporization of water corresponding to a standard temperature of 15^0C) is 2466 *kJ/kg*. The mass of steam formed in *kg* per *kg* of fuel is $9H_2$. The net or lower calorific value (LCV_f) can be obtained by reducing GCV_f with the amount of heat carried away by products of combustion [18]:

$$LCV_f = GCV_f - 22194 \times H_2 \qquad kJ/kg \tag{2}$$

Table 1
Comparison of gross and net or lower calorific values (GCV_f and LCV_f) with those of net heat value being used in energy auditing of cement plants.

	Chemical Composition (%)				*Calorific Value (kJ / kg – coal)*		
	Carbon	*Hydrogen*	*Oxygen*	*Sulphur*	*Gross(GCV_f) Eq.(1)*	*Net (LCV_f)Eq.(2)*	*Net heat value*
1	48	3	4	5	20287	19622	23800 [8]
2	76	5	8.1	2.1	31500	30388	30600 [9]
3	87.54	11.9	0.32	-	46667	44026	40687 [10]
4	54.6	3.54	-	-	23552	22767	23422 [12, 13]
5	68.6	4.39	7.19	1.11	28317	27342	28000 [15]
6	48	3	4	5	20287	19622	30600 [16]
7	39.79	2.46	8.47	0.41	15505	14959	15180 [19]

In order to examine the adequacy of the empirical relations (1) and (2), the gross calorific value (GCV_f) and the net or lower calorific value (LCV_f) are estimated for the reported chemical composition of different coals, and compared with those of net heat value used in energy auditing of cement plants. The estimated net calorific values in Table-1 are found to be reasonably in good agreement with most of the reported ones. The net heat value of 30600 kJ/kg-coal reported by Priyadarshini and Sivakumar [16] is found to be very high for the specified chemical composition of the coal, whereas for the same chemical composition, the estimated value of 19622 kJ/kg-coal is comparable with the reported net heat value (of 23800 kJ/kg-coal) by Khurana *et al.* [8]. The empirical relations (1) and (2) can be expected to estimate the calorific values within ± 15% of the test values. However, it is preferable to use the test data of the net calorific value of the coal to carry out the energy audit analysis [19].

3. ENERGY AUDIT ON A TYPICAL CEMENT PLANT

Traditional methods of thermal system analysis are based on the first law of thermodynamics. They use an energy balance of the system to determine heat transfer between the system and its environment. For a general steady state, steady flow process, the mass balance and the energy balance can be expressed as [20]

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{3}$$

$$\sum E_{in} = \sum E_{out} \tag{4}$$

$$Q_{net,in} + \sum \dot{m}_{in} h_{in} = W_{net,out} + \sum \dot{m}_{out} h_{out} \tag{5}$$

Here $\dot{m}$ is the mass flow rate, E is the rate of energy transfer, h is the specific enthalpy, Q is the rate of heat input, and W is the rate of the work output. The subscript 'in' stands for inlet and 'out' for outlet. $Q_{net,in} = Q_{in} - Q_{out}$, is the rate of net heat input. $W_{net,out} = W_{out} - W_{in}$, is the rate of net work output. Assuming no change in kinetic and potential energies with any heat or work transfer, the energy balance given in equation (5) can be simplified to flow enthalpies only:

$$\sum \dot{m}_{in} h_{in} = \sum \dot{m}_{out} h_{out} \tag{6}$$

Raw materials preparation, pyroprocessing, grinding and blending clinker with other products, are the basic steps in the cement manufacturing. The cement plant considered by Priyadarshini and Sivakumar [16] is the pyroprocessing unit, which includes the preheater, the calciner, the kiln and the clinker cooler. Schematic of the pyroprocessing in Figure 1 shows the flow of solid, air and fuel. The streams into the system are the raw material, the air into the cooler, and the coal fired into the kiln and the calciner. The streams leaving the system are clinker out from the cooler, the exhaust gases from the preheater and the hot air out from the cooler. The plant

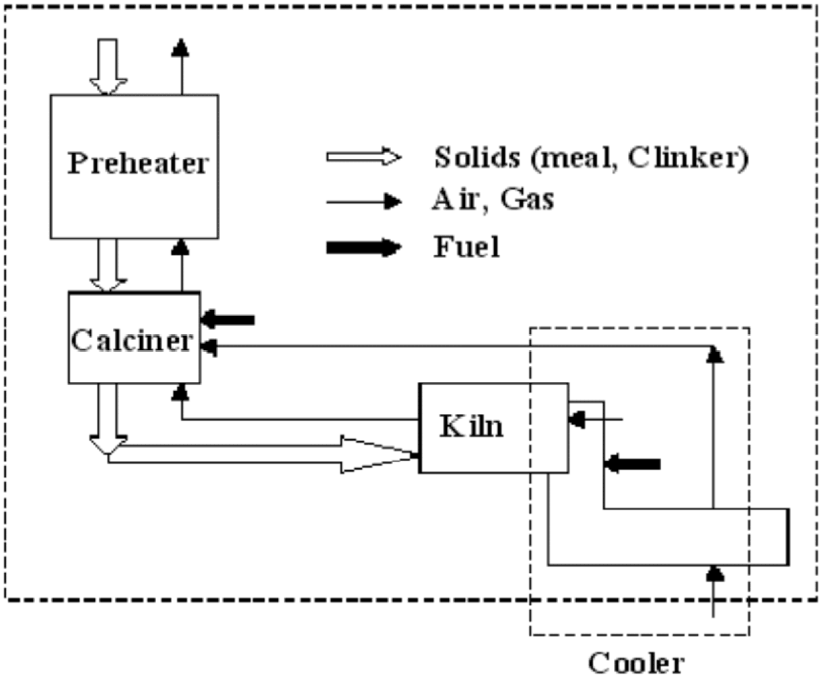


Figure 1: Pre-processing displaying flow of solid, air and fuel

runs on dry process with a four stage suspension preheater and an inline calciner. The raw materials from the quarry are crushed, ground and mixed as slurry in the wet process and a powder in the dry process. This mixture is then fed into a calciner and preheater before being fed into the kiln, for pyroprocessing (clinker formation). The production capacity is 3018 tonne per day.

Based on the coal composition (see Figure 2), the net heat value has been found from equation (2) to be 19622 kJ/kg-coal, whereas the reported value is 30600 kJ/kg-coal [16]. For the same chemical composition, Khurana et al. [8] have presented the net calorific value as23800kJ/kg-coal, which is comparable with the gross calorific value obtained from equation (1).

In the mass balance of the kiln system (see Figure 3), the total mass output exceeds the total mass input by 1 kg/kg-clinker. For a general steady state, steady flow process, equation (3) indicates that the total mass flow rate input is equal to the total mass flow rate output. Based on the clinker composition, one can compute the reaction energy, RE (kJ/kg-clinker) from equation (7) [21]:

$$\mathrm{RE} = 17.196 \times Al_2O_3 + 27.112 \times MgO + 32 \times CaO - 21.407 \times SiO_2 - 2.469 \times Fe_2O_3 \quad (7)$$

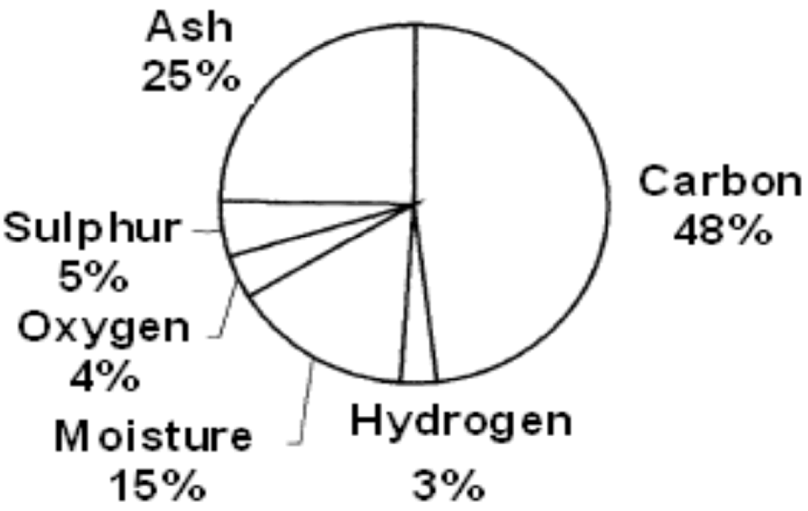


Figure 2: Composition of coal

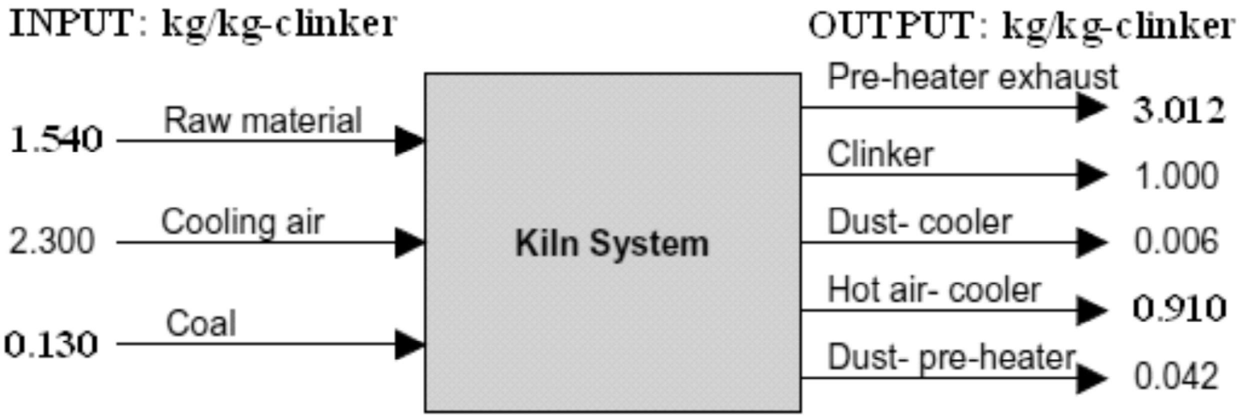


Figure 3: Mass balance of the kiln system [16]

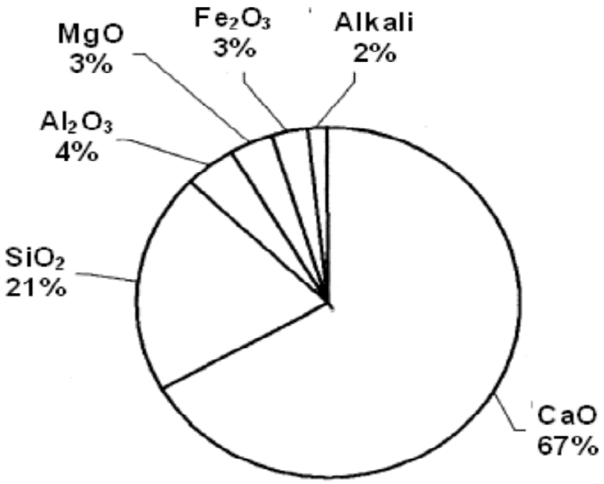


Figure 4: Composition of clinker [8]

For the clinker composition (see Figure 4), the reaction energy is worked out to be 1837 kJ/kg-clinker. Since, the mass balance of the kiln system in [16] is not appropriate, the relevant data for energy auditing is taken from Ref. [8].

For combustion of coal, the energy (CCE) is computed from

$$\begin{aligned} CCE &= mass\ flow rate\ of\ coal \times net\ heat\ value = \dot{m}_{coal} \times LCV_f \\ &= 0.15 \times 23800 = 3570\, kJ/kg - clinker \end{aligned} \qquad (8)$$

In general, the flow rate of raw feed is estimated from the clinker composition and reactions, whereas a species balance on nitrogen, oxygen and carbon dioxide gives the flow rate of the exhaust gases. The final flow rates of the different streams [8] are given in Table-2. It is noted that the specific enthalpy of various components is obtained from the cement manufacturers' handbook [21]. By taking the reference enthalpy at ^{0}C as zero kJ/kg, heat balance of the kiln system has been made with various streams in Table 2. The mass balance and the energy balance of the kiln system in Table-2 obey equations (3) and (4) respectively.

Table 2
Heat balance of the kiln system

Stream	*Flow rate (kg/kg-clinker)*	*Specific heat (kJ/kg^{0}C)*	*Temperature (^{0}C)*	*Enthalpy (kJ/kg-clinker)*
Entering the system				
Combustion of coal	Equation (8)	3570 (95.5%)		
Sensible heat by coal	0.15	0.9	50	6.8 (0.2%)
Heat by raw material	1.56	0.9	50	70.2 (1.9%)
Heat by cooling air	2.98	1.0	30	89.4 (2.4%)
Total				3736.4 (100%)
Leaving the system				
Reaction energy	Equation (7)			1837 (49.1%)
Clinker	1.0	0.8	100	80 (2.1%)
Preheater exhaust	2.27	1.0	280	635.6 (17%)
Hot air from cooler	1.42	1.0	400	568 (15.3%)
Unaccounted losses				615.8 (16.5%)
Total				3736.4 (100%)

To manufacture cement, about half of the CO2 emissions come from combustion and the other half are produced in the decomposition of the calcium carbonate in clinker production [15]. The annual emissions by clinker formation worked out as in Ref.[5] is the product of the emission factor (EF), clinker production per day and the number of working days.

Emission factor, $$EF = Factor\ CaO \times \frac{44.01\, g/mol\, CO_2}{56.08\, g/mol\, CO} = 0.67 \times 0.785 = 0.526 \tag{9}$$

For 330 working days in a year with clinker production rate of 3800 tonne per day, annual emissions estimation is about 660000 tons of CO_2 per year. Reference [22] explains about carbon dioxide production per kilowatt hour when generating electricity with fossil fuels, whereas Ref. [23] provides details on the usage of coal to generate a kilowatt hour of electricity.

The total energy used in the process is 3736 kJ/kg-clinker, and the main heat source is the coal, giving a total heat of 3570 kJ/kg-clinker (95.5%). There is a good agreement between the overall energy input to the kiln system and output of the kiln system, with an inconsistency of about 615.8 kJ/kg-clinker which amounts about 16.5% of the input energy. This inconsistency is mainly due to non-accounting of radiation and convection losses from cooler, kiln, preheater, dust, etc. Peray's handbook on cement manufacturing [21] provides the physical properties and the empirical relations for accounting the radiation and convection losses. The primary efficiency of the process is about 49%. Energy carried with the preheating exhaust stream is 17%. Energy carried with the hot air from the cooler is 15.3%. It is very interesting to note that for the estimated net calorific value (i.e.,19622 kJ/kg- coal) obtained from equation (2) for the composition of coal, the heat balance of the kiln system indicates negligible unaccounted losses in the leaving system. That means the energy balance is in good agreement. However, this case can be treated as coincidental due to the nature of the data sources and simplifications.

The kiln exhaust gas and the clinker cooler discharge are found to be the cost effective waste heat losses. A waste heat recovery steam generator (WHRSG) can be utilized for steam generation. This steam can be used to power a steam turbine driven electrical generator. It is noted from Ref. [8] that the preheater exhaust stream gets cooled from 280 to 178^0C, while the hot air stream gets cooled from 400 to 140^0C. The enthalpies have been calculated for the temperatures of both streams to estimate the available heat energy (Q_a).

The mass flow rate of the exhaust gas, $\dot{m}_{eg}$ = 2.27 kg/kg-clinker (10)

The mass flow rate of the hot air from cooler, $\dot{m}_{air}$ = 1.42 kg/kg-clinker (11)

The enthalpy difference of the preheater exhaust stream,

$$\Delta h_{eg} = h_{eg}(280^0 C) - h_{eg}(178^0 C) = 280 - 100 = 180\, kJ/kg\ , \tag{12}$$

which gets cool from 280 to 178^0C.

The enthalpy difference of the hot air stream,

$$\Delta h_{air} = h_{air}(400^0 C) - h_{air}(140^0 C) = 400 - 375 = 25\, kJ/kg \tag{13}$$

For the mass flow rate of the clinker, $\dot{m}_{cli}$ = 10kg/sec, the available heat energy,

$$\begin{aligned} Q_a &= (\dot{m}_{eg}\Delta h_{eg} + \dot{m}_{air}\Delta h_{air}) \times \dot{m}_{cli} \\ &= (2.27 \times 180 + 1.42 \times 25) \times 10 = 4441 kJ/\sec = 4441 kW \end{aligned} \tag{14}$$

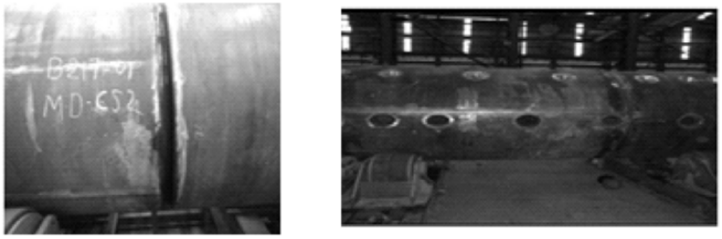
Considering the efficiency of the steam generator, $\eta = 0.85$, the energy (Q_w) that can be transferred through the WHSRG is

$$Q_w = \eta \times Q_a = 0.85 \times 4441 = 3775\,kW \tag{15}$$

A suitable steam turbine generator set has to be designed to utilize this energy (Q_w). The power generated for the system is about 3.8MW with a production rate of 3800 tonne per day. For a working of 330 days in a year, the energy saved is estimated from the product of the power generated (Q_w), and 7920 hours of usage. Taking the average unit price of electricity as US$0.07 per kWh, and assuming the annual labour and maintenance costs of US$92860, the savings become US$2 million per year.

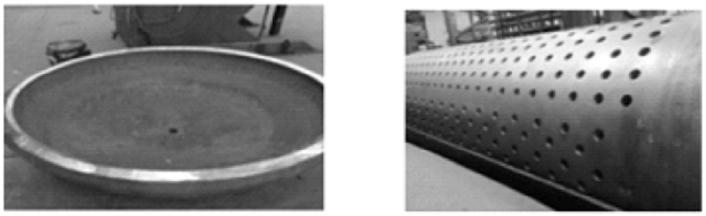
4. REALIZATION OF A STEAM DRUM IN BOILERS

Studies made in the previous sections are relevant to the cost saving in process plants utilizing the waste heat energy assuming that the boilers are in good conditions. An attempt is made to highlight briefly the manufacturing process of boilers, necessity for maintenance and NDT requirements. Various quality control checks (viz., verification of dimensional tolerance in approved drawings and quality assurance plan, identification of raw materials, etc.) have to be carried out during fabrication of steam drum/vessels. Figure-5 shows fabrication aspects of a typical steam drum. Location of internals inside the drum are marked 90^0 apart circumferentially as per the approved drawings assembly and welding of internals have been carried out prior to the final inspection and post-weld heat treatment (viz.,. parts for surface cooler, heat treatment, steam separator, feed water heater, sparger pipe, shroud plates for risers and down comers, vortex breaker for down comer).



Cirseam welding

Drilling of nozzle for steam drum



Dish end closure

Drilling of holes for connecting tubes

Nozzle fitting and welding

Steam drum

Figure 5: Fabrication aspects of a typical steam drum

In order to identify the leakages (if any) and to verify the design adequacy, hydrostatic testing will be carried out prior to drum use in service. After successful hydrostatic test, the task is to complete draining of water and proper drying of inside surfaces; surface cleaning and painting; inspection before using it in service. Pneumatic testing is also done to identify the leakages at the weld joints by applying soap solution [24].

5. CONCLUDING REMARKS

To carry out the energy audit analysis, the mass balance of the kiln system requires that the total mass flow rate input is equal to the total mass flow rate output. The energy balance is simplified to flow enthalpies. Estimates of net calorific value based on the composition of coal are comparable to the measured/reported data. The energy required for the reaction has been estimated using the correlations given in the cement manufacturers' handbook [21]. There is a possibility of optimum power consumption in cement industries by installing waste heat recovery boiler and a suitable steam turbine generator set. Thereby, the cement plants can expect enhancement in boiler efficiency and emission reduction. NDT and maintenance requirements are mandatory for monitoring the health conditions of boilers.

ACKNOWLEDGEMENT

The first author wishes to thank the authorites of Thermal^{R} Systems Private. Limited, Hyderabad, India for giving training and guidance in fabrication and maintenance of waste heat recovery boilers.

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