Published by :
http://www.ijert.org

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 10 Issue 08, August-2021

Efficiency Analysis of Waste Heat Recovery Systems using the Case Study of A Cement Plant

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Abstract **- This paper analyses the efficiency of Waste Heat Recovery System (WHRS) at a cement manufacturing plant of a Cement major which is a pioneer in sustainable cement manufacturing in India. The paper also identifies factors possibly affecting the efficiency while using data to evaluate models, including a novel mathematical model for the effect of impurity concentration on efficiency. Analyses of a few alternatives have also been provided. Therefore, this paper provides a detailed efficiency analysis of smart energy systems in cement manufacturing and other such industrial processes in order to generate energy or electricity.**

Keywords – Sustainability, Smart Energy, Waste heat recovery system, Thermionic generator. Magnetohydrodynamic generator, Aerodynamic convection energy recovery system.

I.INTRODUCTION

Heat loss or heat dissipation is a major problem faced by most industrial sectors. It leads to losses in efficiency of various industrial processes and results in negative effects such as environmental degradation and monetary loss. Minimizing the negative impacts of this consequence can take two forms, which are heat loss reduction and waste heat utilization. There are various ways to implement these strategies in cement manufacturing processes and this paper will focus on the WHRS or the Waste Heat Reduction System in the plant, which is a pioneer in sustainability and smart energy systems in cement manufacturing processes in India.

I. MINIMIZATION OF HEAT LOSS REDUCTION IN PARTICLE SIZE:

Reduction of particle size in hammer crushers, impact crushers, secondary crushers, VRM hoppers and raw mill hoppers along with nodulization in rotary kilns, all increase the rate of heat transfer, thereby causing reduction in mobility of heated masses and reducing time in which heat is lost. Assuming a constant rate of heat loss, heat loss is therefore, reduced.

$$Rate\ of\ conductive\ heat\ transfer \frac{\Delta Q}{\Delta t} = \frac{kA\Delta T}{l}$$

Where,

$$\frac{\Delta Q}{\Delta t} = \frac{kA\Delta T}{l}$$

$$\Delta Q = Change\ in\ heat\ energy.$$

$$\Delta t = Change\ in\ time.$$

$$k = Constant.$$

$$A = Surface\ Area.$$

$$\Delta T = Temperature\ change.$$

$$l = Length\ of\ exposed\ surface.$$

$$For\ a\ spherical\ mass\ made\ of\ n\ spheres\ with\ radius\ r_2,$$

$$volume\ V_1 = \frac{4\pi n r_2^3}{3},$$

⇨ $r_1 = r_2\sqrt[3]{n}$

⇨ $A_1 = 4\pi r_2^3 n^{\frac{2}{3}}$

$$For\ n\ separate\ spheres\ of\ radius\ r_2, A_2 = 4\pi n r_2^2$$

$$\therefore Assuming\ constant\ l\ and\ \Delta T, A_2 > A_1,$$

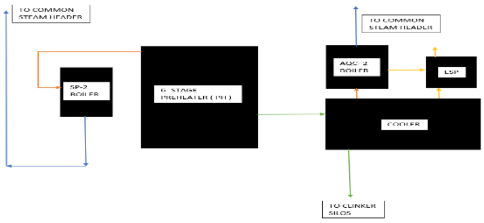
$$\therefore Rate\ of\ conductive\ heat\ transfer\ is\ more\ or\ greater\ for\ separate\ spheres\ rather\ than\ for\ one\ large\ sphere.$$

A. UTILISATION OF HEAT LOSS BY THE WHRS OR THE WASTE HEAT RECOVERY SYSTEM:

INTRODUCTION

The WHRS at the plant uses a thermoelectric approach in order to recover and utilize lost heat energy. Boilers installed at strategic points of greater heat losses and a single turbine compose the main machinery utilized.

PROCESS



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KEY:

→	HEATED GAS FLOW
→	MASS FLOW
→	COOLED GAS FLOW
→	STEAM FLOW

Figure 1: SIMPLIFIED WHRS PROCESS FLOW DIAGRAM IN CEMENT MANUFACTURING PLANT

As seen from Figure 1, boilers have been installed at the Suspended Preheater (SP) and at the Air Quenched Cooler (or the AQC.) These are two areas where heat liberation is the maximum due to greater drops in temperature.

Coolers cause material temperature to drop from around 1400°C to around 130°C. Therefore, the SP- 2 and AQC-2 both have boilers nearby where heated air is passed into.

The heated air transfers heat energy to the cooled water in the tubes, causing the water to vaporize into steam, which is led through pipes to a common steam header where pipes carrying steam from boilers installed near SP- 1 and AQC-1 also lead to. This steam is led through pipes to run a single turbine that generates electricity as it is connected to a generator.

The steam condenses back into water and is recycled. It is passed into the water cooler after the power plant with the generator and turbine and is then lead through pipes and distributed to the various boilers using a water pump to pump the water.

II. DATA GATHERING

K- 1 PREHEATER

Design Preheater-1		Operating
G-Volume	153800	140000
G-Tem	290	280
Steam t/h	9.25	7.0
Power	1.5	1.2

K- 1 COOLER

Design Cooler-1		Operating with Dryer
G-Volume	91000	91000
G-Tem	355	400
Steam t/h	7.9	10
Power	1.38	1.7

K- 2 PREHEATER

Design Preheater-2		Operating
G-Volume	280165	275000
G-Tem	315	335
Steam t/h	20.4	19.7
Power	3.4	3.5

K- 2 COOLER

Design cooler-2		Operating with dryer
G-Volume	61600	75000
G-Tem	355	460
Steam t/h	5.4	6.9
Power	0.95	1.23

III. DATA ANALYSIS/ CALCULATIONS

$$Q_1 = m_1 c_1 \Delta t_1 = \rho_1 V_1 c_1 \Delta t_1$$

By the Method of Mixtures,

$$Q_2 = Q_1$$

$$Q_3 = Q_2$$

$$\Rightarrow \frac{m_3 v^2}{2} = Q_2$$

$$\Rightarrow \frac{m_3 v^2}{2} = \rho_1 V_1 c_1 \Delta t_1$$

Putting η as efficiency of the whole process,

$$Q_3 = \frac{m_3 v^2}{2} = \eta \rho_1 V_1 c_1 \Delta t_1$$

$$P = \frac{Q}{t}$$

$$\therefore P_3 = \frac{\eta \rho_1 V_1 c_1 \Delta t_1}{t}$$

$$\therefore P_3 \propto V_1$$

$$\therefore P_3 \propto \Delta t_1$$

IV. EFFICIENCY

The efficiency of different systems will be evaluated differently. The power should be directly proportional to volume, as it is directly proportional to mass.

K- 1 PREHEATER

DESIGN

$$\Delta t_{1A} = 93°C$$

$$V_{1A} = 153800 m^3$$

OPERATING

$$\Delta t_{1B} = 83°C$$

$$V_{1B} = 140000 m^3$$

$$Ideal\ Power\ output\ P_1 = \frac{V_{1B}}{V_{1A}} \times \frac{\Delta t_{1B}}{\Delta t_{1A}} \times P_A \approx 1.3MW$$

$$Real\ Power\ output\ P_2 = 1.2MW$$

$$Efficiency\ \eta_1 = \frac{P_2}{P_1} \approx 0.92$$

Similarly,

K- 1 COOLER

$$Efficiency\ \eta_2 \approx 1.0$$

K- 2 PREHEATER

$$Efficiency\ \eta_3 \approx 0.90$$

K- 2 COOLER

$$Efficiency\ \eta_4 \approx 0.77$$

$$Total\ Efficiency\ \eta = \sum_{n=1}^{4} \frac{V_{1B}\Delta t_{1B} for\ particular\ boiler\ G_n}{Total\ V_{1B}\Delta t_{1B}} \eta_n \approx 0.80$$

The turbine rated at 9MW generates 7.20MW of electricity or energy, which leads to $\eta \approx 0.80$. This shows that the approximation made earlier is a suitable one and may be used in order to evaluate individual efficiencies of separate boilers.

V. PROBABLE FACTORS AFFECTING THE EFFICIENCIES OF THE FOUR INDIVIDUAL BOILERS

A. INLET SMOKE DUST DENSITY

Let $m = mass$, $V = volume$ and $\rho = density$. Smoke dust is likely to have a lower c or specific heat capacity than air, therefore, depending on the concentration density in the inlet air C, the mixture will have a c of $\frac{\frac{CV}{\rho_{IMPURITIES}} c_{IMPURITIES} + \left(V - \frac{CV}{\rho_{IMPURITIES}}\right) c_{AIR}}{V} =$, assuming the c will be in proportion to the proportion of volumes of different components in the mixture. Similarly,

$$m = CV + \left(V - \frac{CV}{\rho_{IMPURITIES}}\right) \rho_{AIR}$$

Assuming constant Δt to meet energy production requirements,

$$Q_A = \left[CV + \left(V - \frac{CV}{\rho_{IMPURITIES}}\right) \rho_{AIR}\right] \left[\frac{\frac{CV}{\rho_{IMPURITIES}} c_{IMPURITIES} + \left(V - \frac{CV}{\rho_{IMPURITIES}}\right) c_{AIR}}{V}\right] \Delta t$$

Without impurities,

$$Q_B = V \rho_{AIR} c_{AIR} \Delta t$$

On evaluating,

$$\eta = \frac{Q_A}{Q_B} = C^2 \left(\frac{c_{IMPURITIES}\rho_{IMPURITIES} - \rho_{IMPURITIES}c_{AIR} - c_{IMPURITIES}\rho_{AIR} + \rho_{AIR}c_{AIR}}{\rho_{IMPURITIES}^2 \rho_{AIR} c_{AIR}}\right) + C\left(\frac{\rho_{IMPURITIES}c_{AIR} + c_{IMPURITIES}\rho_{AIR} - 2\rho_{AIR}c_{AIR}}{\rho_{IMPURITIES}\rho_{AIR}c_{AIR}}\right) + 1$$
$$= C^2 \left[\frac{(\rho_{IMPURITIES} - \rho_{AIR})(c_{IMPURITIES} - c_{AIR})}{\rho_{IMPURITIES}^2 \rho_{AIR} c_{AIR}}\right] + C\left(\frac{\rho_{IMPURITIES}c_{AIR} + c_{IMPURITIES}\rho_{AIR} - 2\rho_{AIR}c_{AIR}}{\rho_{IMPURITIES}\rho_{AIR}c_{AIR}}\right) + 1$$
$$= AC^2 + BC + 1$$

Evaluating, if real roots exist,

a. If $(\rho_{IMPURITIES} - \rho_{AIR})(c_{IMPURITIES} - c_{AIR}) < 0$,
Maxima is at $C = -\frac{B}{2A} = \frac{-\left(\frac{\rho_{IMPURITIES}c_{AIR} + c_{IMPURITIES}\rho_{AIR} - 2\rho_{AIR}c_{AIR}}{\rho_{IMPURITIES}\rho_{AIR}c_{AIR}}\right)}{2\frac{(\rho_{IMPURITIES} - \rho_{AIR})(c_{IMPURITIES} - c_{AIR})}{\rho_{IMPURITIES}^2 \rho_{AIR} c_{AIR}}} = \frac{-\rho_{IMPURITIES}(\rho_{IMPURITIES}c_{AIR} + c_{IMPURITIES}\rho_{AIR} - 2\rho_{AIR}c_{AIR})}{2(\rho_{IMPURITIES} - \rho_{AIR})(c_{IMPURITIES} - c_{AIR})}$.
Efficiency will be maximized in this case if $C = \frac{-\rho_{IMPURITIES}(\rho_{IMPURITIES}c_{AIR} + c_{IMPURITIES}\rho_{AIR} - 2\rho_{AIR}c_{AIR})}{2(\rho_{IMPURITIES} - \rho_{AIR})(c_{IMPURITIES} - c_{AIR})}$.

b. Therefore, if $(\rho_{IMPURITIES} - \rho_{AIR})(c_{IMPURITIES} - c_{AIR}) > 0$,
Minima is at $C = -\frac{B}{2A} = \frac{-\left(\frac{\rho_{IMPURITIES}c_{AIR} + c_{IMPURITIES}\rho_{AIR} - 2\rho_{AIR}c_{AIR}}{\rho_{IMPURITIES}\rho_{AIR}c_{AIR}}\right)}{2\frac{(\rho_{IMPURITIES} - \rho_{AIR})(c_{IMPURITIES} - c_{AIR})}{\rho_{IMPURITIES}^2 \rho_{AIR} c_{AIR}}} = \frac{-\rho_{IMPURITIES}(\rho_{IMPURITIES}c_{AIR} + c_{IMPURITIES}\rho_{AIR} - 2\rho_{AIR}c_{AIR})}{2(\rho_{IMPURITIES} - \rho_{AIR})(c_{IMPURITIES} - c_{AIR})}$.
Efficiency will be minimized in this case if $C = \frac{-\rho_{IMPURITIES}(\rho_{IMPURITIES}c_{AIR} + c_{IMPURITIES}\rho_{AIR} - 2\rho_{AIR}c_{AIR})}{2(\rho_{IMPURITIES} - \rho_{AIR})(c_{IMPURITIES} - c_{AIR})}$.

c. Therefore, if $(\rho_{IMPURITIES} - \rho_{AIR})(c_{IMPURITIES} - c_{AIR}) = 0$, the relationship is linear.
Generally, $\left(\frac{\rho_{IMPURITIES}c_{AIR} + c_{IMPURITIES}\rho_{AIR} - 2\rho_{AIR}c_{AIR}}{\rho_{IMPURITIES}\rho_{AIR}c_{AIR}}\right) < 0$,
There will be a negative linear relationship.
If, $\left(\frac{\rho_{IMPURITIES}c_{AIR} + c_{IMPURITIES}\rho_{AIR} - 2\rho_{AIR}c_{AIR}}{\rho_{IMPURITIES}\rho_{AIR}c_{AIR}}\right) > 0$,
There will be a positive linear relationship
As seen from the quadratic model if $\eta > 1$, the machinery may have been made assuming 100% pure air with negligible C.

B. AIR LEAKAGE

Let $x = Fraction\ of\ air\ leaked.$

$$V_{EFFECTIVE} = V(1 - x)$$
$$Power\ P \propto V\ and\ \eta \propto V$$

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$$\therefore \eta = \frac{V_{EFFECTIVE}}{V} = \frac{V(1-x)}{V} = 1 - \frac{x}{V}$$

Therefore, there is a negative linear relationship between x and η or efficiency.
However, air leakages are a maximum of 2% or 0.02 of the total volume of air and therefore, do not account much for the total reduction in efficiency.

C. CONVECTIVE HEAT TRANSFER LOSSES WHILE TRANSMISSION OF STEAM THROUGH THE PIPES:

$$q = h_c A \Delta T \qquad (1)$$

where

$$q = heat\ transferred\ per\ unit\ time$$

$$A = heat\ transfer\ area\ of\ the\ surface$$

$$h_c = process\ convective\ heat\ transfer\ coefficient$$

$$\Delta T = temperature\ difference\ between\ the\ surface\ and\ the\ fluid$$

$$A = \pi r^2 l$$

$$\therefore q \propto l$$

$$q = h_C\, \pi r^2 l \Delta T$$

Let

$$k = constant = h_C\, \pi r^2 \Delta T$$

⇨ $q = kl$

$$\therefore \eta = \frac{Q_{EFFECTIVE}}{Q} = \frac{Q-q}{Q} = 1 - \frac{kl}{Q}$$

Therefore, there is a negative linear relationship between l and η or efficiency.
These three factors seem to be the most prominent factors in reduction of efficiency of the WHRS of the cement plant, since most other factors seem to be constant or have negligible variations.

VI. EVALUATION OF EFFICIENCY OF THE DERIVED MODELS IN TERMS OF PREDICTING EFFICIENCY OF WHRS

BOILER NAME/ NUMBER/ NO.	AIR LEAKAGE	SMOKE/ DUST DENSITY	PIPE LENGTH TILL THE TURBINE
SP- 1	2%	**75g/Nm3**	**195m**
AQC- 1	1%	**20g/Nm3**	**120 m**
SP- 2	2%	**106g/Nm3**	**620m**
AQC- 2	1%	**20g/Nm3**	**435m**

$$Efficiency\ \eta_2 \approx 1.0$$

$$0.95 \le 1 - \frac{kl}{Q} \le 1.0$$

$$0 \le \frac{kl}{Q} \le 0.05$$

For AQC- 2, same air leakage and smoke/ dust density causes $\frac{435}{120} \times \frac{91000}{75000} \times \frac{290}{380}$ times the decrease due to greater length of the pipe, lesser gas volume and greater temperature difference.

$$0.83 \le \eta_4 \le 1.0$$

The additional 0.06 decrease in efficiency from 0.83 to 0.77 may be due to a factor not accounted for such as differing gas densities or specific heat capacities at different temperatures. However, this approximation seems to be adequately accurate upto 1 significant figure when efficiency of the AQC- 1 boiler is taken as 0.95. Therefore, efficiency of the AQC- 1 boiler will now be considered to be 0.95.

$$AC^2 + BC + 1 = 1$$

⇨ $A(0.020)^2 + B(0.020) = 0$
_(a)

For SP-1,

As before, decrease in efficiency due to length of the pipe will be $\frac{195}{120} \times \frac{91000}{140000} \times \frac{290}{83}$ that of AQC- 1 boiler.

$$\eta_1 = 0.82$$

if efficiency loss due to greater concentration of smoke and dust is negligible. However, it is not. In order for efficiency to be equal to 0.92,

$$AC^2 + BC + 1 = 1.1$$

⇨ $A(0.075)^2 + B(0.075) = 0.1$
_(b)

From (a) and (b),

$$A = -\frac{80}{11}$$

$$B = \frac{8}{55}$$

For SP- 2,

Decrease in η_3 due to l is $\frac{620}{120} \times \frac{91000}{275000} \times \frac{290}{145}$ times that the decrease in η_2.

Taking $\eta_3 = AC^2 + BC + 1 - other\ decreases,$

$$\eta_3 = [-\frac{80}{11}(0.106)^2 + \frac{8}{55}(0.106) + 1] - (\frac{620}{120} \times \frac{91000}{275000} \times \frac{290}{145} \times 0.05) \approx 1.1$$

However, practically, $\eta_3 = 0.90$. Even upto a single significant figure, there is a deviation of 0.1. Without the application of the quadratic model relating efficiency with concentration of impurities, $\eta_3 = 0.83$. Although the deviation may be smaller, the increase in 0.83 to 0.90 is difficult to explain given that specific heat capacities and the density of air would be expected or estimated to be lowered by heat losses on fluid mixing and air, gas or fluid transmission, which would yield a lower value of efficiency. Therefore, it can be concluded that the quadratic model may provide an explanation for the aforementioned increase in efficiency. Deviations may be due to heat losses not considered or fluctuations in values such as specific heat capacity and densities of air.

VII. EVALUATION OF ALTERNATIVES

A. DIRECT HEAT UTILIZATION:

Heated gases may be redirected to points of the cement manufacturing processes where heat is required, for example, as a replacement of or supplement to the Hot Air Generator or the HAG feeding heated air into the VRM or Vertical Roller Mill. This maximizes efficiency since efficiency reduction in energy or electricity generation machinery and in boilers reduces. The number of heat exchanges is also reduced, thereby reducing heat losses due to imperfect thermal system isolations. Energy requirements for water cooling and pumping are also reduced. Water requirements are reduced for the boilers. Boilers may not be required and therefore, capital costs may be reduced. However, according to the Second Law of Thermodynamics, there will be energy losses and this may not be an infinitely sustaining system. Reduction in velocity of hot or heated gases during transportation may require pumping and leakages may cause the requirement of supplementary HAGs.

B. AERODYNAMIC CONVECTION KINETIC ENERGY RECOVERY SYSTEM (ACKERS)

Heated gases may be lead to a container containing a turbine through an air inlet. Convection will lead to the formation of electricity as the kinetic energy of the heated gases will be converted to the kinetic energy of the turbine. There may be one air outlet to let out cooled gases and allow more heated gases to enter. The air outlet may have an ESP or electrostatic precipitator installed. This may lead to reduction in steam transmission losses, reduction in water usage and elimination of the need or the requirement for the boilers. However, it may lead to greater fluid or gas leakage, unequal electric outputs due to multi- directional or fluctuating gas particle or gas velocities. This is also a technology proposal as of today and not a tested technology.

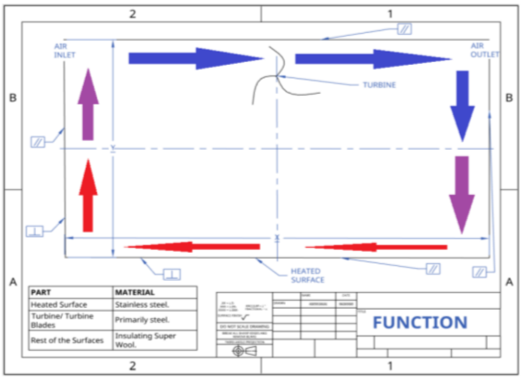
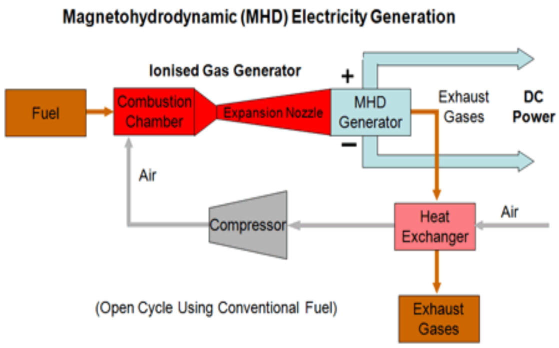


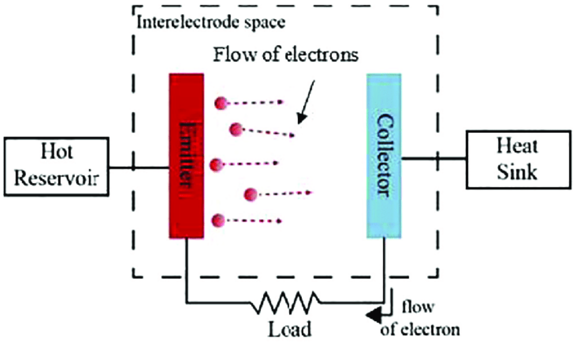
Figure 2 Function

C. ELECTRICITY GENERATION USING MAGNETOHYDRODYNAMIC (MHD) GENERATORS:



As seen from the diagram, MHD generators collect heated gases and creates electricity, working similarly to a fluid dynamo utilizing plasma. Although this technology may be extremely beneficial in terms of reducing water and boiler usage, it generally has low efficiency and is expensive. Heated gases also must be at a very high temperature.

D. UTILIZING THERMIONIC GENERATORS TO CONVERT HEAT ENERGY OF HEATED GASES TO ELECTRICAL ENERGY:



The riser tube of boilers may be installed with the cathode and anode of a thermionic generator. Thermionic generators may also be used without boilers, thereby, once again eliminating the needs of water and boiler usage. However, high costs for materials like the cathode or the emitter of the thermionic generator may be a disincentive to install such technology.

Although many of these alternative technologies may reduce water and boiler usage, capital costs may be high. Given the already high efficiency of cement manufacturing at the plant, a cost- benefit analysis would be preferred before switching to alternative technologies that may lead to restructuring of the PFD and the infrastructure of the plant. However, from the view of sustainability, the first option may lead to multiple cycles through the ESP, thereby increasing pollutant retention and decreasing the pollutant concentration in emissions from the plant.

VIII. CONCLUSION

The cement manufacturing plant is truly a pioneer in terms of sustainable design and its WHRS. Although alternative technologies for the WHRS may be proposed, high efficiency values in its present WHRS may act as a disincentive to switch technologies without great efficiency gains or sustainability gains. Other cement manufacturing plants in India and other industrial plants should consider similar technologies in order to reduce emissions and take a collective step towards carbon neutrality along with waste heat recovery and heat loss utilization.

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