Thermodynamic Analysis Of An Organic Rankine Cycle Based Waste Heat Recovery System In Cement Plant

Zunaid Ahmed, Dimbendra Kr. Mahanta

Abstract:— Clinkerization is a subprocess in cement manufacturing plant that consumes three-fourths of the total energy used, as process heat. However, in this process significant amount of heat is wasted by the flue gases and the air-cooling of the clinker (about 35%-40% of the process heat). A heat recovery system could be used to utilized this waste heat to increase the efficiency of the cement plant. The purpose of this paper is to perform energy and exergy analysis on a Waste Heat Recovery (WHR) system employing an Organic Rankine Cycle (ORC) to evaluate its feasibility.

Index Terms:— Waste heat recovery, Organic Rankine Cycle, Exergy analysis, Cement plant, Sankey diagram, Grassmann diagram

1 INTRODUCTION

Cement manufacturing comprises of various subprocesses – raw meal grinding, preheating, precalcining, clinkerization, and grinding. Energy is consumed in each of the subprocesses. In a typical cement plant, the major portion of the energy consumed is thermal energy (about 80-90%) and rest is electrical. The clinkerization subprocess consumes the largest share of the thermal energy whereas cement grinding mills consume the highest electrical energy [1]. Clinkerization is a subprocess by which raw meal (mixture of limestone and clay in form of fine powder) is heated to a sintering temperature as high as 1450°C in a cement kiln which, by chemical reaction, to form rounded nodules known as clinker. The clinker needs to cooled down before mixing with gypsum and grinding into cement. The clinkerization process is a substantially energy intensive industry accounting for 50-60% of the production costs and consuming the 75% of the energy used in cement production [2]. However, in this process significant amount of heat is wasted by the flue gases and the ambient air-cooling of the clinker (about 35%-40% of the process heat) [3]. The efficiency of a cement plant could be increased by installing a waste heat recovery system. Moreover, it would lower the temperature of the exhaust gases released to the environment [4]. Waste heat can be captured from combustion exhaust gases, heated products, or heat losses from systems [5]. Otherwise, the waste heat can be utilized in order to preheat the raw material before the clinkering process [6]. Waste heat recovery systems are already in operation in various industries with success. The objective of this study is to perform a thermodynamic analysis of an ORC based WHR system to determine its performance and its feasibility for a cement production plant. Five working fluid for the ORC were examined. The configuration of the cycle and its different components were optimized in order to improve the efficiency and determine the design of an optimum system.

An energy and exergy analysis were performed in order to find the various efficiencies to define cycle's working fluid with the best performance. The performance is assessed with the help of thermodynamic models and simulation

2 WASTE HEAT RECOVERY

For the configuring a waste heat recovery system to improve the process efficiency of a cement plant, the identification of the waste heat sources is of high importance. This study examines a cement manufacturing plant in Meghalaya, India which produces 2600 tons/day clinker. The plant is based on dry process rotary kiln technology with five-stage pre-heaters with no additional heat recovery system. The two main waste heat sources are:

(1) The flue gases from combustion of pulverized coal in the rotary kiln, which after passing through the raw material preheater, are at the mass flow rate of 37.53 kg/s and at a temperature of about 290^{O}C

(2) The waste heat from the clinker cooler, in the form of hot air, at the mass flow rate of 16.65 kg/s and at an average temperature of about 250^{O}C.

These waste heat sources as shown in the Fig. 1. can be efficiently used to cogenerate electricity.

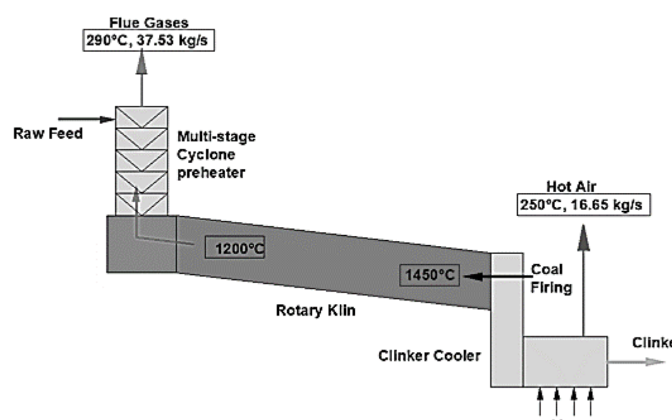

***Fig. 1**. Waste heat sources in a Rotary Kiln*

3 WASTE HEAT RECOVERY SYSTEM USING ORC

A method to recover the waste heat from the clinkerization process is an indirect ORC. The ORC is used in low-temperature energy sources, because of the low critical point of the organic fluids. In this paper, four different organic fluids

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were examined in order to select the most suitable working fluid regarding the thermodynamic performance for the given temperature limits. The four working fluids considered are dry-type organic fluids namely, R600, isopentane, neopentane and R245fa. In an indirect ORC based heat recovery system there is an intermediate heat transfer fluid (HTF) used to transfer the heat from the heat sources to the working fluid through heat exchangers. This is necessary for safety reasons, as many organic fluids are flammable and in case of failure of the heat exchanger the hot medium of the heat source and the organic fluid would get in contact resulting in an explosion. High-temperature heat transfer oils is ideal for this purpose. The system is presented in Fig. 2.

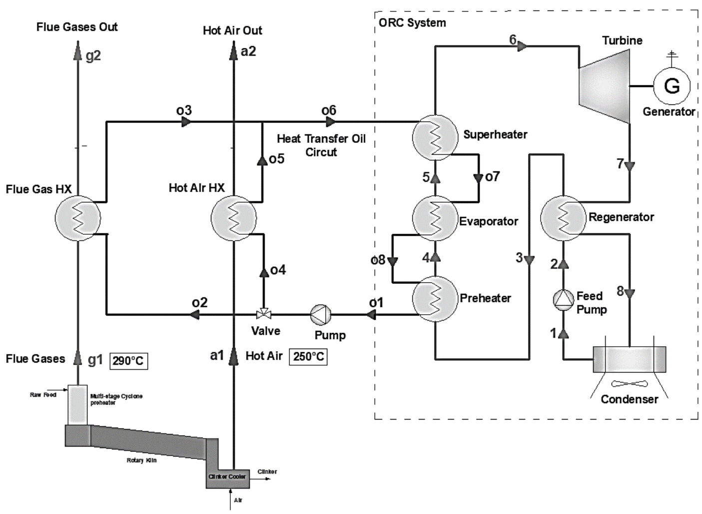

***Fig. 2**. Layout of the ORC based WHR system*

There are two different circuits, one with the working fluid and the other with HTF. The HTF circuit absorbs heat from the flue gas and from the hot air, using two heat exchangers in parallel (one for each waste heat stream), in order to transfer this heat to the organic fluid. The HTF absorbs the waste heat to the extent that the temperature of both the waste heat streams fall to 140^{O}C. The heat is then exchanged from HTF to the working fluid through the heat exchangers, which are the preheater, the evaporator and the superheater. At the inlet of the turbine, the working fluid has a maximum temperature 185^{O}C. The turbine exhaust enters the regenerator, before the condenser, in order to preheat the working fluid. This way the system recovers some of the energy released to environment through the condenser. The maximum pressure at the inlet of turbine (evaporation pressure) depends on the exit temperature of waste heat streams determined by the setting a minimum pinch point temperature difference of 10^{O}C between the HTF and working fluid in the evaporator. A pinch point temperature difference of 10^{O}C is also set between the waste heat streams and HTF in the waste heat exchangers. The minimum pressure is the condensing pressure at the condensation temperature of 45^{O}C. These thermodynamic processes on the working fluid can be seen in the T-s diagram (Fig. 3.) alongwith flue gas, hot air and heat transfer streams. The system operating parameters, concerning the various efficiencies and ambient conditions are as shown in Table 1.

***Table 1:** System parameters*

Turbine isentropic efficiency (%)	*85*
Turbine mechanical efficiency (%)	*99*
Pump isentropic efficiency (%)	*85*
Generator electrical efficiency (%)	*98*
Generator mechanical efficiency (%)	*98*
Ambient temperature (^{O}C)	*25*
Ambient pressure (kPa)	*101.3*

4 THERMODYNAMIC ANALYSIS

The entire system is thoroughly investigated with the help of thermodynamic models and simulations in order to assess the performance of the system.

4.1 Energy analysis

For analysing this system, energy balance is applied in the control volume of every component and various efficiencies are calculated.

The efficiency of heat-exchange system is defined:

$$\eta_{hex} = \dot{Q}_f / \dot{Q}_{hs} \tag{1}$$

$\dot{Q}_{hs}$ is the heat source energy given by:

$$\dot{Q}_{hs} = \dot{m}_g\left(h_{g.1} - h_{g,ambient}\right) + \dot{m}_a\left(h_{a,1} - h_{a,ambient}\right) \tag{2}$$

where $\dot{m}_g$ and $\dot{m}_a$ is mass flow rate of flue gases and hot air respectively and h is the enthalpy. $\dot{Q}_f$ is the heat that the working fluid absorbs from the heat sources via the HTF given by:

$$\dot{Q}_f = \dot{m}_g\left(h_{g,1} - h_{g,2}\right) + \dot{m}_a\left(h_{a,1} - h_{a,2}\right) = \dot{m}_f(h_6 - h_3) \tag{3}$$

The thermal efficiency of the cycle is defined:

$$\eta_{th} = \dot{W}_{el} / \dot{Q}_f \tag{4}$$

where $\dot{W}_{el}$ is the electric power produced by the generator after taking in to account the isentropic, mechanical and electrical efficiencies.

The overall efficiency of the system is defined:

$$\eta_{sys} = \dot{W}_{el} / \dot{Q}_{hs} \tag{5}$$

4.2 Exergy analysis

After the energy analysis of the systems, an exergy analysis is performed. Exergy is the maximum amount of work that can be produced by a system when a heat stream is brought to equilibrium in relation to the ambient conditions (p_o & T_o). Exergy analysis is a very useful tool for analysing thermodynamic systems, as it is possible to determine the performance of each component by considering its exergy losses. The calculation of exergy is the result of the use of four thermodynamic properties which are the temperature (T), the pressure (p), the enthalpy (h) and the entropy (s). The expression that gives the physical exergy at each point of the cycle is the following:

$$e_i = (h_i - h_o) - T_o(s_i - s_o) \tag{6}$$

Where h_o and s_o are the enthalpy and entropy at ambient condition. The exergy value of power output is equal to the power. The exergy losses due to mechanical and electrical inefficiencies is taken in consideration but the heat losses of the system units are ignored. The exergy destruction is symbolized as $I_{i,des}$. Taking an exergy balance in a control volume, gives the following expression:

$$\sum E_{i,in} = \sum E_{i,out} + \sum E_{i,loss} + I_{i,des} \tag{7}$$

For the system, exergetic efficiency can be defined as:

$$\eta_{ex} = \frac{\sum E_{i,out}}{\sum E_{i,in}} \quad (8)$$

with $\sum E_{i,in}$ is all the exergy flowing in the component from other components and $\sum E_{i,out}$ is the exergy flowing out of a component to other components and $\sum E_{i,loss}$ is the exergy loss to the surroundings.

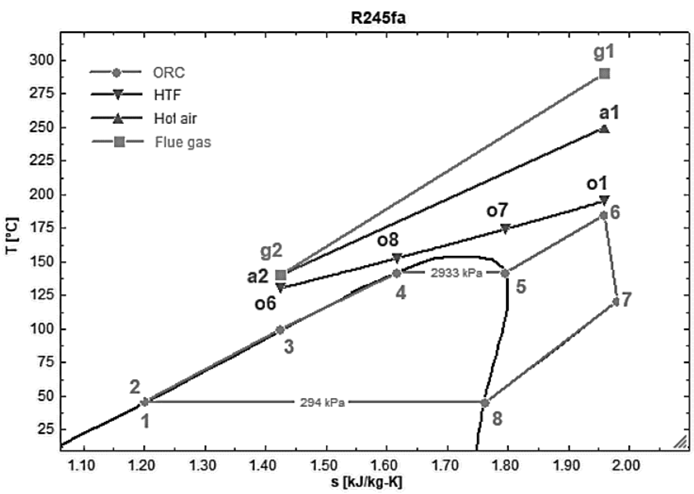

Fig. 3. *T-s diagram of processes of the system*

The simulation and optimization of the system is done for each of the working fluids using EES [7]. The objective is to achieve the best performance at an evaporation pressure from a range with the constraints of pinch points in the heat exchangers. After performing the thermodynamic analysis on the system, it can be seen from Table 2., R245fa is the working fluid that achieves the best system efficiency at an evaporation pressure of 2933 kPa and thus it is selected as the working fluid for the ORC.

Table 2: *Performance parameters of working fluids*

Working Fluid	P_{max} *(kPa)*	η_{hex}	η_{th}	η_{sys}	η_{ex}
R600	*2278*	*58.60*	*15.36*	*9.00*	*32.48*
Isopentane	*1780*	*50.72*	*17.76*	*9.01*	*32.50*
neopentane	*2333*	*54.66*	*16.55*	*9.05*	*32.65*
R245fa	*2933*	*54.66*	*18.25*	*9.98*	*36.00*

5 RESULTS

The system using R245fa as the working fluid is simulated. The results of energy analysis are summarised in Table 3. The ORC system has a system efficiency of 9.98% producing 1492 kW of electric power. The main energy loss is the heat rejected in the condenser. The other major energy loss is in the stream of flue gases leaving the heat exchanger since its exit temperature is limited to 140°C. The other thermodynamic tool that is used is the exergy analysis. The results of exergy analysis are summarised in Table 4. The exergetic efficiency of the system is calculated at 36%. The main exergy loss is also located in the waste streams in in the two heat exchangers and the condenser. The existence of the intermediate HTF circuit in the ORC causes additional exergy destruction.

Table 3*: Energy balance*

Energy - Sources	*(kW)*	*(%)*
Flue gases	*11189*	*74.82*
Hot air	*3765*	*25.18*
Total	*14954*	*100.00*
Energy Transfer	*(kW)*	*(%)*
Energy Loss: Flue gases	*4855*	*32.47*
Energy Loss: Hot air	*1924*	*12.87*
Energy Loss: Condenser	*6599*	*44.13*
Energy Used: Pump & Losses	*84*	*0.56*
Electrical Power	*1492*	*9.98*
Total	*14954*	*100.00*
Energy Exchange	*(kW)*	*(%)*
Flue gases HX	*6334*	*42.35*
Hot air HX	*1841*	*13.31*
	8175	*54.66*
Energy Losses	*6779*	*45.33*
Total	*14954*	*100.00*

Table 4: *Exergy balance*

Exergy Destroyed in Component	*(kW)*	*(%)*
Turbine	*306.20*	*7.39*
Regenerator	*62.13*	*1.50*
Preheater	*95.30*	*2.30*
Evaporator	*94.93*	*2.29*
Superheater	*90.88*	*2.19*
Pump	*13.40*	*0.32*
Condenser	*0.97*	*0.02*
Flue gases heat exchanger	*443.10*	*10.69*
Hot air heat exchanger	*84.28*	*2.03*
Exergy Losses	*(kW)*	*(%)*
Flue gases	*749.30*	*18.08*
Hot air	*297.12*	*7.17*
Condenser	*415.28*	*10.01*
Product Exergy	*(kW)*	*(%)*
Power	*1492.00*	*36.00*
Total	*4144.89*	*100.00*

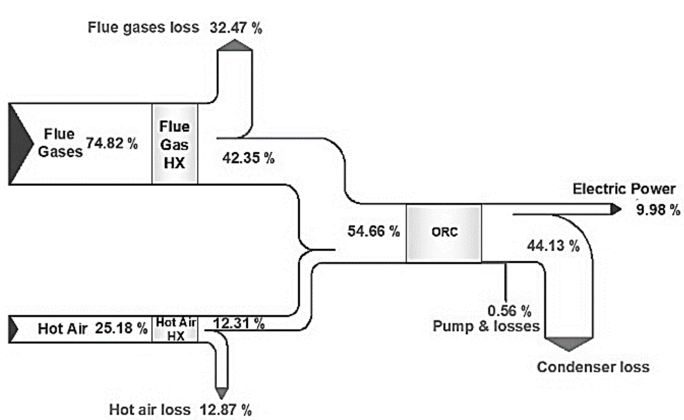

Fig. 4*. Sankey diagram for the system*

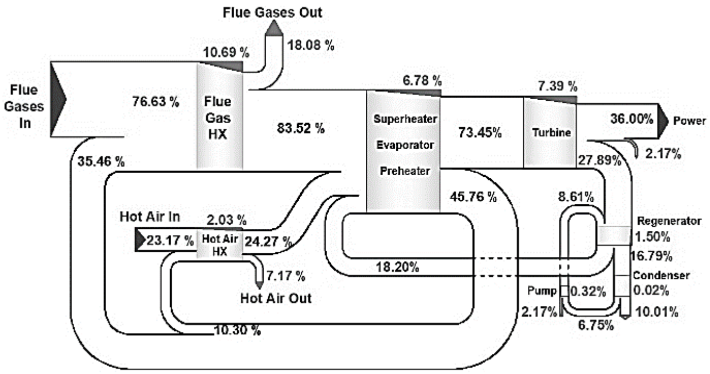

Fig. 5. *Grassmann diagram for the system*

Another useful tool for the thermodynamics analysis of the ORC system are Sankey diagram and Grassmann diagram which are presented in Fig. 4. and Fig. 5. for the ORC system. From these diagrams it is clear that the main energy loss is in the condenser amounting to 44.13%, maximum exergy destruction is in the flue gas exchanger amounting to 18.08%.

6 CONCLUSION

Waste heat recovery can be applied to a cement industry and it can offer about 1492 kW of electric power for a typical cement plant. The flue gases from the furnace and clinker cooler hot air are the heat sources for the heat recovery system. The cycle investigated for the system is an Organic Rankine Cycle. Analysis was done to determine the best working fluid and it was found to be R245fa. The energy and exergy analysis were performed on the ORC system. The performances are system efficiency of 9.98% and exergetic efficiency of 36%. The energy and exergy analysis have provided important results for the evaluation of the heat recovery systems indicating its feasibility. Further study is to be carried out from the economical point of view to determine its payback period on investment.

REFERENCES

[1] S.S. Krishnan, N, Balasubramanian, "Treatise on Process Metallurgy: Industrial Processes, Volume 3, Chapter.3.31.6.3, Pages 1193-1247, ScienceDirect, 2014

[2] Wang J, Dai Y, Gao l. Exergy analyses and parametric optimizations for different cogeneration power plants in cement industry. Applied Energy 2009; 86:941-8.

[3] Madlool NA, Saidur R, Hossain MS, Rahim NA. A critical review on energy use and savings in the cement. Renewable and Sustainable Energy Reviews 2011: 2042e60.

[4] Saneipoor P, Naterer GF, Dincer I. Heat recovery from a cement plant with a Marnoch heat engine. Applied Thermal Engineering 2011; 31:1734-43.

[5] Johnson I, Choat B, Dillich S. Waste heat recovery: opportunities and challenges. Minerals, Metals and Materials Society; 2008. EPD Congress.

[6] Ahamed JU, Madlool NA, Saidur R, Shahinuddin MI, Kamyar A, Masjuki HH. Assessment of energy and exergy efficiencies of a grate clinker cooling system through the optimization of its operational parameters. Energy October 2012;46(1):664-74.

[7] F-Charts Software, "Engineering Equation Solver - EES32", v6.883 (Academic)