Design & Analysis of Low-Pressure Economizer Based Waste-Heat Recovery System for Coal-Fired Thermal Power Plant

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Abstract: Low Pressure Economizer plays an important role in reducing exhaust gas temperature & enhancing the thermal efficiency. A 60 MW Thermal Power Plant used to ensure its safe operation and the optimal Economic condition. We put forward to Design of LPE in two Cases by exergy analysis of the various components of the power plant. There are two cases for installing LPE: One, the installation of LPE between Condenser & low Pressure heater, second, the installation of LPE between high pressure heater and low pressure heater. According to the Exergy analysis, it's found that the LPE between the Feed water Heater is more effective then Case-1. It proposed to reduce the flue gas temperature from 155ºC to 131ºC. Thermal Design of LPE defines the area of the heat exchanger found to be 2.56 m^2. Compact type finned tube heat exchanger is more suitable for gas to liquid pass heat exchanger for low pressure economizer. It's proposed to reduce the coal consumption rate and improve the performance of the plant. Also reduce the CO_2 Emission of the flue gas.

***Keywords* - Waste Heat Recovery, Heat Transfer, Exergy Analysis, Low pressure Economizer, Coal based Thermal Power Plant, Compact (Fin & tube) Heat Exchanger.**

I. INTRODUCTION

Fossil fuel resources are limited and consumption of fossil fuels is a major concern for climate change. India is one of the countries which are heavily dependent on coal-based energy supply. According to statistics, coal-fired power generation accounts for 70% of the total electricity generation in India. Therefore, energy conservation is an important national policy in India. Currently, the temperature of the exhaust flue gas of a coal-fired power plant is generally in the range of 160-220 ºC. This makes the heat loss with exhaust flue gas the biggest among the heat losses of a boiler. For coal-fired power generating units equipped with desulphurization systems, the flue gas with high temperature carries away a large amount of water in the process of flue gas desulphurization; it is more desirable to decrease the temperature of the exhaust flue gas entering a flue gas desulphurizer (FGD). Therefore, there is a great potential to recover the waste heat of the exhaust flue gas from a boiler. [1-7]

There are many measures to enhance the waste heat recovery, such as increasing the heat exchanging surface areas of the economizer preheating the feed water of the boiler, and the air pre-heater. These methods have not been widely used due to space constraints or poor economical benefits. [1]

By literature survey; Chaojun Wang **[1]** et al, The energy and water savings and the reduction of CO_2 emission resulted from the LPE installation are assessed for three cases on a 600 MW coal-fired power plant with wet stack. Serpentine pipes with quadrate finned extensions are selected for the LPE heat exchanger which has an overall coefficient of heat transfer of 37 W/m^2 K and the static pressure loss of 781 Pa in the optimized case. The benefits generated include saving of standard coal equivalent (SCE) at 2.4 g/kWh and saving of water at 25 to 35 t/h under full load operation with corresponding reduction of CO_2 emission. [1] Ju Guidong [2] et al, They forward three designs, and considering the overall economic efficiency for low pressure economizer in different inlet temperature of the flue gas. According to the equivalent enthalpy drop method, the thermal economies of the designs are calculated, and the results show that the second design low pressure economizer in 150ºC entering flue gas temperature is better than the other two.[2] Chaojun Wang [3] et al. An LPE (low-pressure economizer) system for a CFPP (coal-fired power plant) is investigated thermodynamically. By taking a 350 MW CFPP as the research object, the analysis of variation of operational parameters for three cases with LPE installation is carried out at the condition of 100% THA (turbine heat acceptance) load by using the principle of thermodynamics [3]. Shengwei Huang [4] et al. In this paper, an author determined efficiently utilizes the low-temperature waste heat from the flue gas of coal-fired power plants based on heat cascade theory. Flue gas used to preheat air for coal combustion but also heat up feed water for low-pressure steam extraction. Air preheating is performed by both the exhaust flue gas in the boiler island and the low-pressure steam extraction in the turbine island. The high-pressure steam is saved for further expansion in the steam turbine, which results in additional net power output. [4]

II. LOW PRESSURE ECONOMIZER APPLIED TO WASTE HEAT RECOVERY

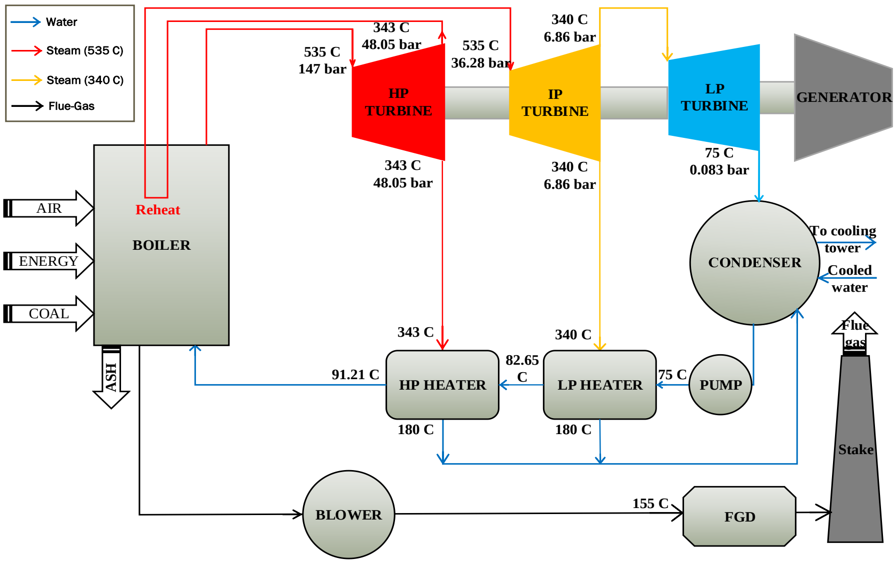

Fig. 1 Layout of Thermal Power Plant after Installation of LPE

Figure 1 shows the thermal system of a power plant with installation of an LPE. In the system, the exhaust steam from the last stage of steam turbine is condensed and the condensed water is recycled back into the boiler as feed water after preheating. All the heat needed for preheating the feed water is from the bled steam.

After installing LPE as shown in Figure 1, the exhaust heat of the flue gas is recovered and utilized to heat the low temperature feed water, replacing a portion of the heat from steam bled from the steam turbine. Thus, the low-grade heat of the exhaust flue gas is utilized with the installation of an LPE.

Overall, if the power output of the unit keeps the same, the mass flow rate of steam will be decreased, leading to the reduction of fuel consumption and the CO_2 emission. If the fuel consumption remains the same, more electrical power will be produced. Either way, the plant operation will become more economical.

III. CASE ANALYSIS

As per the layout of the thermal power plant there are two possibilities to installation of LPE (i) LPE between the Condenser and low pressure heater & (ii) LPE between Low pressure Heater & High Pressure Heater. For case-1 the overall performance of the system is much less then the case-2. By exergy analysis of various components of the power plant after installing the LPE by formula as

Specific Exergy $\psi_1 = (h_1 - h_0) - T_0(s_1 - s_0)$ (3.1)

As shown in Fig 2, the exergy analysis from case-1 for Low pressure Heater & High Pressure Heater is 430.66 KW & & 762.3 KW respectively. After Installing the LPE, the exergy analysis of same system found to be 405.56 MW & 1788.06 MW respectively.

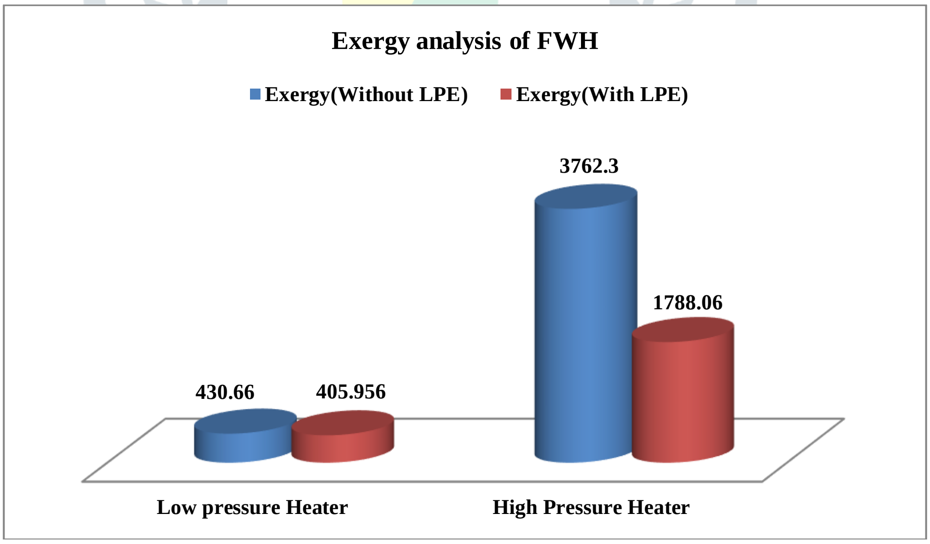

Fig. 2 Exergy analysis of Feed water heater

As per analysis, the exergy reduction for case-2 is much higher than case-1. Almost reduce exergy by 1980 KW for case-2 while exergy reduced by 25 KW fro case-2. Hence from exergy analysis, the LPE between Low Pressure Heater & High Pressure Heater is more effective to conserve the heat energy leaving by exhaust gas to the Atmosphere.

IV. DESIGN OF LOW-PRESSURE ECONOMIZER:

From Literature, the liquid-Gas type of Heat Exchanger is Conventional to design Low Pressure Economizer. Therefore, Finned & Tube Type of Compact Heat Exchanger is used for designing LPE.

4.1 Compact (Finned-Tube) Heat Exchanger:

A compact heat exchanger may be of plate-fin type or fin and tube type. CHEs are widely used in power engineering, cryogenics, automobiles and chemical engineering applications such as compressors, intercoolers, air coolers and fan coils. The distingue features of CHEs are its high surface area density and thermal effectiveness, resulting in reduced size, weight, and space compared to STHEs.

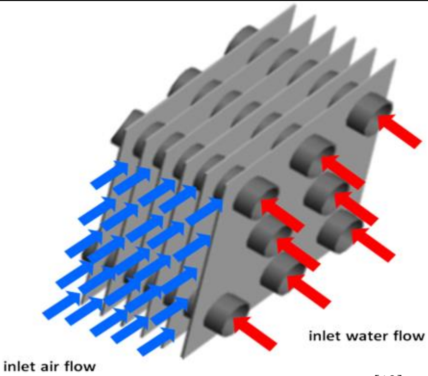

Fig. 3 AutoCAD Model of CHE [10]

As Shown in Figure 3, the CAD Models of Compact Finned Tube Heat Exchanger. At tube Side the water at mass Flow rate of 41.405 Kg/m^2 are flows which divided into the tubes of the heat exchanger. Only single pass section has convent to the required heat duty. At Fin Side the Flue gas at mass flow rate of 83.475 Kg/m^2 has flows over the tubes of the heat exchanger. At the fin side, hot flue gas while the tube side Cold Water.

4.2 Thermal Design of Compact (Finned Tube) heat exchanger:

By Primary analysis and from the industrial data, the basic design criteria should be calculated. LMTD analysis determines the area and overall heat duty of the Heat exchanger.

$$Q = \left(m \cdot c_p\right)_c (T_{c2} - T_{c1}) \tag{4.1}$$

Above equation shows the total heat duty of the heat exchanger from cold and hot side.

$$\Delta T_m = \frac{\Delta T_1 - \Delta T_2}{\ln \frac{(\Delta T_1)}{(\Delta T_2)}} \tag{4.2}$$

LMTD shows the temperature of the heat exchanger to determine the heat duty of the heat exchanger.

$$Q = UAF\theta_m \tag{4}$$

The above equation determines the overall heat transfer by which transfer the heat to its wall skins.

Table 4.1 Specification of Heat Exchanger:

	Units	Value
Water Inlet Temperature	^oC	82.65
Water Outlet Temperature	^oC	92.40
Area	m^2	2.567
Heat Transfer Conductance	KW/^{o}K	30.804
Heat Transfer Rate	KW	1663.216
NTU	-	0.437
Heat capacity Ratio	-	0.406
Effectiveness	-	0.327

Table 4.1 shows the basic specification of the heat exchanger determined from the primary analysis procedure to know actual design.

For Actual design of heat exchanger the following design procedure should be follow:

- Calculation for Tubes & Fin: [11]

Number of tubes:

$$H = [(N_t \cdot d_o) + (N_t + 1)\, P_t] \tag{4.3}$$

Number of Fins:

$$W = [(N_f \cdot \delta)] + (N_f \cdot P_f) + 1 \tag{4.4}$$

Minimum Free Flow Area:

$$A_{min} = [(W \cdot H) - (N_t \cdot d_o \cdot W) - (N_t \cdot \delta \cdot H)] \tag{4.5}$$

Frontal Area of Heat Exchanger (Flue gas Side):

$$A_{ft} = [W \cdot H] \tag{4.6}$$

$$\sigma = \left[\frac{\text{Minimum Free Flow Area}}{\text{Frontal Area}}\right] = \left[\frac{A_{min}}{A_{ft}}\right]$$

As the Ratio< 0.75, It is Acceptable

- Calculation of Heat Transfer co-efficient:

Heat transfer Co-efficient at Fin side h_o:

By using McAdams Correction for Shell Side (Fin) Heat transfer Coefficient as:

$$\frac{h_o \cdot D_e}{K} = 0.36 \left(\frac{D_e \cdot G_s}{\mu}\right)^{0.55} \left(\frac{C_p \cdot \mu}{K}\right)^{0.33} \left(\frac{\mu_s}{\mu_w}\right)^{0.14} \tag{4.7}$$

Heat Transfer Coefficient for Tube side:

$$h_i = \frac{Nu_b\, K}{d_i} \tag{4.8}$$

Petukhov-Kirillov Correction:

$$Nu_b = \left[\frac{(f/2) \cdot (Re) \cdot (Pr)}{1 + 12.7 \cdot (f/2)^{0.5} \cdot (Pr^{0.667} - 1)}\right] \tag{4.9}$$

- Overall Heat Transfer Coefficient:

With considering fouling factor:

$$U_f = \left[\frac{1}{\left(\frac{d_o}{d_i \cdot h_i}\right) + d_o \cdot R_{ft} + \left(\frac{d_o \cdot \ln\left(\frac{d_o}{d_i}\right)}{2K}\right) + R_{fo} + \left(\frac{1}{h_o}\right)} \right] \tag{4.10}$$

Without considering Fouling Factor:

$$U_c = \left[\frac{1}{\left(\frac{d_o}{d_i \cdot h_i}\right) + \left(\frac{d_o \cdot \ln\left(\frac{d_o}{d_i}\right)}{2K}\right) + \left(\frac{1}{h_o}\right)} \right] \tag{4.11}$$

- Pressure Drop at Tube side:

$$\Delta P_t = \left(4f \cdot \frac{L \cdot N}{d_i} + 4N\right)\left(\frac{\rho \cdot U_m^2}{2}\right) \tag{4.12}$$

- Pressure Drop at Fin or Tube Side:

$$\Delta P_f = f \cdot \frac{G^2}{2 \cdot \rho_g} \cdot \frac{A_t}{A_{min}} \tag{4.13}$$

V. DESIGN OF LOW-PRESSURE ECONOMIZER (HTRI SOFTWARE)

The HTRI Software is used to compare the actual design of LPE by calculation. Our main purpose of HTRI is to compare the calculated values & HTRI values for achieving actual design of LPE. The HTRI Software is use to validate the calculated values of heat exchanger. By using this, the overall heat transfer coefficient and Pressure drop at Shell side as well Tube side can be known. The main aim is to reduce the pressure drop beyond the specified limit. The pressure drop can be changed by taking different values of the input data.

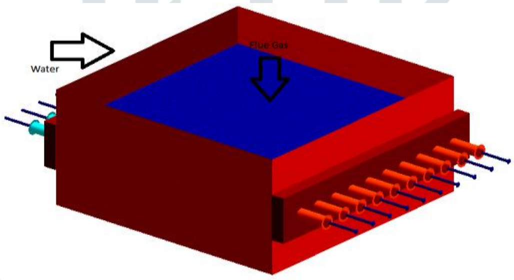

Fig. 4 3D Model of LPE from HTRI

As shown in figure 4, 3D CAD model of low pressure economizer by which water with mass flow rate of 41.405 kg/s are divided into the inlet nozzles of the heat exchanger. There are 10 nozzles in row of diameter 80.7 mm & same to exit. The tubes connected with the header of the heat exchanger and, the header connected to the nozzles of the exchanger. Flue gas with mass flow rate of 83.475 kg/s is flow from shell side. The shell side fin made from 304 stainless steel by which thermal conductivity of 31 W/m^{2}K. While, the tube also made from 304 Stainless steel which thermal conductivity of 31 W/m^{2}K.

VI. COMPARISON OF ACTUAL DESIGN & HTRI VALUES:

The basic input variables are used to design the Low pressure economizer (heat exchanger). We accept the design when pressure drop from shell side & Tube side beyond the limit. Also the actual & require overall heat duty and overall heat transfer coefficient are same. But in case of HTRI, we have to change the input variables till the pressure drop from shell side & tube side beyond the limit. Also the actual & required overall heat transfer coefficients are same. To check the design calculations are feasible or not, the HTRI software is used to validate the values of design.

As per the output results, the input values to be changed to variable design in acceptable limit. While in case of HTRI design, the input values of different variable to be changed as per the allowable pressure drop limit and balance the required heat transfer coefficient and Actual Heat transfer coefficient.

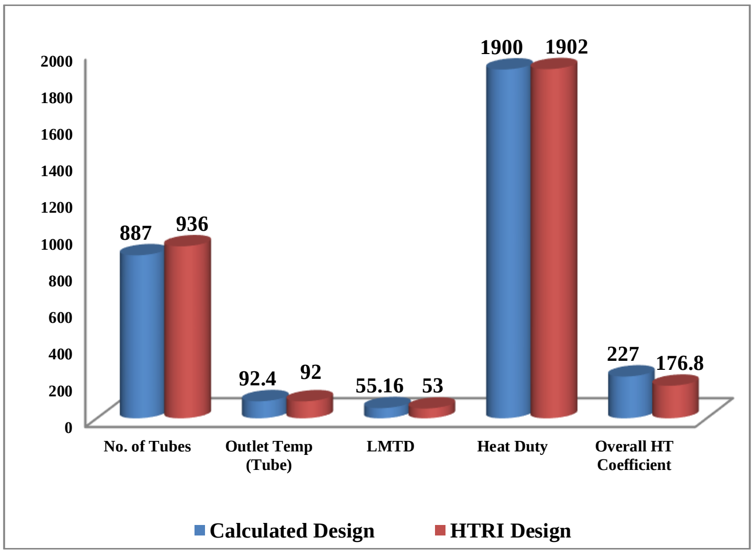

Fig. 5 Comparison of Actual & HTRI Values

As shown in figure 5, the comparison of various values of the LPE. Blue color bar shows the value of calculated design while red color bar shows the values of HTRI design. By comparison, almost values of actual and HTRI design are same. Number of tubes in actual design found to be 887 while HTRI design found to be 936. The heat duty found in calculated design and HTRI specify almost similar value.

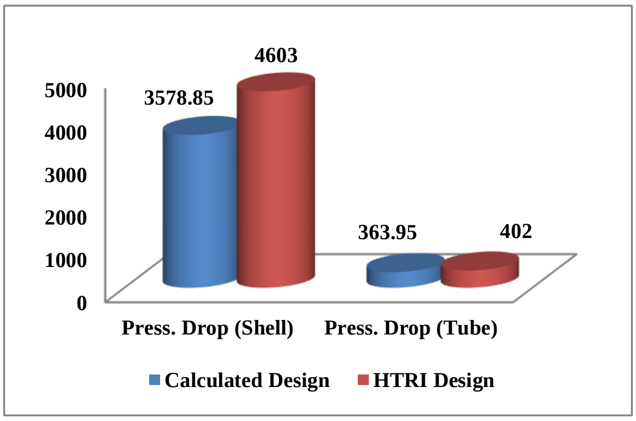

Fig. 6 Pressure Drop Comparison

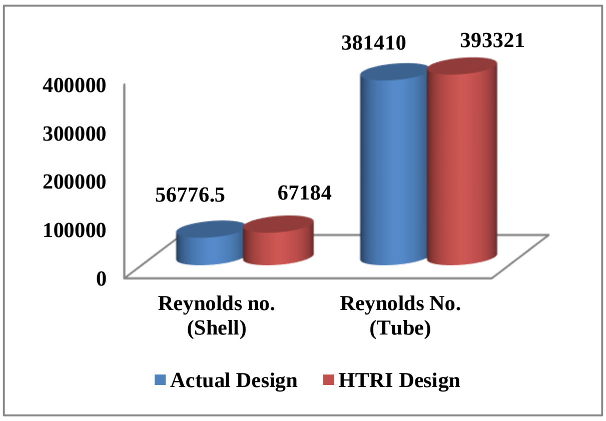

Fig. 7 Reynolds Number Comparison

As shown in figure 6, the comparisons of Pressure drop on shell side and tube side. Blue column shows the pressure drop for Actual Design and red column shows the pressure drop for the HTRI design. Pressure drop in tube shell side for actual design is lower than the pressure drop for HTRI design due to Transaction error in actual design.

As shown in figure 7, the comparisons of Reynolds number on shell side and tube side. Blue column shows the Reynolds number for Actual Design and red column shows the Reynolds number for the HTRI design. Reynolds number in tube shell side for actual design is lower than the Reynolds number for HTRI design due to Transaction error in actual design.

VII. CONCLUSIONS

Its extreme case for implementation of LPE between two cases, each case has its advantages of lower attraction of pressure to exhaust gas exit stage. Following conclusions were observed while referring and examine various parameters of power plant:

- The exergy destruction in LPH is 1% while 5% in HPE for both cases.
- The pump work require for the series connection system because the reduction in mass flow rate.
- The LPE can reduce the flue gas temperature from 155ºC down to 130-140ºC at exit point.
- The energy saving is relatively well under high-loading Condition of Power Plant operation in both the two cases.
- Installation of LPE causes very little increase of the back pressure of the steam turbine, which means that installation of the LPE in the flue gas system has little negative impacts on the operation of the boiler thermal system.
- Low temperature acid corrosion must be considered while selecting LPE installation scheme.
- By the installation of LPE, the expected benefits include reduction of the fuel consumption at approx 2.31 g SCE/ (kWh), water consumption in FGD at approx 5.86 t/h and CO_2 emission at approx, 2.55 t /h.
- The gas-to-water type of heat exchanger is more efficient then gas-to-gas heat exchanger.
- The compact (fin & tube) heat exchanger is more effective, by which the flue gas transfer to shell side and the water passed through the tube of the heat exchanger.
- It is mandatory to consider the fouling factor of heat exchanger at outer surface area of the tube of heat exchanger.
- Uncertainty in temperature, mass flow rate, and other factor should not exceed to 0.02%
- As comparison of Actual design with HTRI, the values of variables are same and pressure drop on Tube & Fin side are under limit.

VIII. ACKNOWLEDGEMENT

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