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Exergy Analysis of Captive Power Plant

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ABSTRACT

Energy sector is one of the important areas in the economic development of any country. Meeting the growing demands at acceptable costs in various sectors like industries, commercial, transport etc. is challenge to energy planner. The present work is an account of energy and exergy losses and distribution in Heat Exchanger of captive power plant of M/S Vardhaman Acrylics ltd, Jhagadia, Bharuch, Gujarat, India. This plant consists of 5.5 MW turbine-generator set with two extraction points which supply the heat energy to meet process demand. The steam is generated in 1×42 TPH capacity 45 kg/cm2 pressure, atmospheric pressure fluidized bed combustion boiler supplied by M/S Thermax Babcock & Wilcox Ltd,Pune ,India. The complete energy & exergy analysis of Heat Exchanger is carried out based on massive data collection over a period of three months. The energetic and exergetic losses of various components & suggestion for improving energetic & exergetic efficiency of the plant form core of this work.

Keywords : Energy, Exergy, Heat Exchanger, Captive Power Plant, Sankey diagram, energetic efficiency, exergetic efficiency

I. INTRODUCTION

The realization that world's energy resources are finite and depleting at fast rate, have simulated interest in the efficient use of existing resource. The renewed interest has led to greater emphasis on the concepts & principles of thermodynamics to improve industrial process efficiency.

The energy analysis gives only energy consumption and energy losses of systems. It does not provide information about internal inefficiency of equipment. The exergy analysis, when applied to process or a whole plant tells us how much is the usable work potential or exergy supplied as input to the system & consumed by process or plant. The loss of exergy or irreversibility provides quantitative measure of process inefficiency. The concept of availability and exergy are concerned with a special type of system, the combined system made up of the control mass and its environment, and the maximum work which can be performed by it. When the control mass passes from its initial state to one in which it is in thermal and mechanical equilibrium with the environment, then there can be no spontaneous change within the control mass or within the environment is called the restricted dead state.

Analysis of multicomponent plant (like combined cycle power plant, captive power plant) based on this concept indicates the total plant irreversibility distribution, pinpointing those components contributing most to overall plant inefficiency. Such an estimate can help in planning the future course of action in energy system design. The feasibility of reduction of losses, so estimated can be found out by economic analysis.

In present work energy & exergy analysis of Heat Exchanger for a captive power plant of 5.5 MW capacities is carried out at full load to study energy losses, exergy destruction, energy and exergy distribution & thermal performance of plant. Suggestions are made to improve both energetic efficiency and exergetic efficiency.

II. Exergy analysis – a Case Study

An energy and exergy analysis is carried out for a captive power plant cycle of M/S Vardhman Acrylic Ltd. Is an acrylic fibre manufacturing industry located at Jhagadia, Bharuch, Gujarat, India. It employs a 5.5 MW-turbine generator set with two extraction points, which supply to the process plant. In process of producing acrylics the power and steam is produced by turbine and boiler. The analysis of this power and steam generating plant is important for the proper functioning at the plant.

The details Heat Exchanger at captive power plant are depicted in the plant layout given at figure 2.1 and details of various terminal point shown in annexure – I. The captive power plant consists of 42T/h AFBC coal fired boiler, 5.5MW turbo generator set and different auxiliaries required for operation of the power plant. Turbo generator set is with two extraction points, which supply to the process plant.
For analysis plant is divided into control volume & data gathered at specified locations. The data is collected for duration of five hours on each unit daily & it is extended up to three months. All performance parameters are finally averaged.

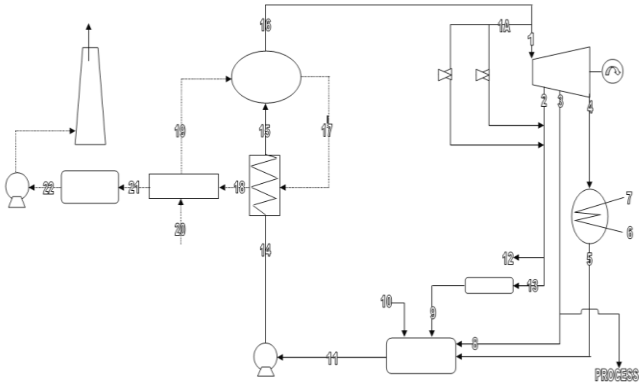

Fig.2.1 Plant Layout

The period selected for the performance test is the during the general shift hours, as during which the load variation of the process plant grid is experienced maximum. Pressure and temperatures for various terminal points are taken from the indications available in the central control panel. In order to increase the accuracy of the indications, flow at various terminal points are taken from flow counters at the interval of one hour. The average value of data acquired during above tests are compiled & tabulated. The thermodynamics properties viz. enthalpy, entropy, energy & exergy are calculated at various terminal points complete plant layout with thermodynamic state points where data is taken.

III. Energy Analysis

The energy analysis of Heat Exchanger is carried out in order to calculate energy losses and energy distribution in the system. For this law of conservation of mass and energy are applied to each control volume of the system. The boiler is selected as one of the primary control volume. There are two basic ways of determining first law efficiency of boiler.

(a) The Direct Method
(b) The Indirect Method (Loss Method)

3.1. Direct Method
The Direct method is old method and is considered as a standard. It is straight forward and consists of

measuring the heat supplied to the boiler in a given time and the heat added to the boiler in a given time and the heat added to the steam in the boiler thus, the efficiency of non reheat boiler is given by,

$$\eta_{first\ law} = \frac{(Enthalpy\ of\ steam - Enthalpy\ of\ feed\ water)}{Quantity\ of\ fuel \times CV}$$

Disadvantage of this method is that several quantities are difficult to measure accurately such as weight of fuel.

3.2 Indirect Method

In this method, the efficiency of boiler is found calculated by deducting all the losses from input energy. Thus if the losses are known the efficiency can be derived easily. This method has several advantages, one of which is that errors are not so significant. The method is now the usual one for boiler efficiency determination.

In the present analysis, however, both the direct and the indirect methods are used for different purpose. Firstly The Indirect method of efficiency calculation based on British Standard BS-2885 is used for calculating first law efficiency of boiler. Then fuel flow is calculated from the direct method. The detailed procedure for Computing first law efficiency of boiler is shown as below.

The classification of coal is based upon physical and chemical composition of the coal and it is therefore necessary to study about the chemical composition of the coal. The common tests which are used to find the commercial value of the coal are proximate analysis and ultimate analysis of the coal. The Proximate analysis of coal gives the composition of coal in respect of moisture, volatile matter, ash and Fixed carbon. The ultimate analysis gives the elemental composition of fuel. For the computing various losses, first, stoichiometric analysis is performed which gives mass of dry flue gas, mass of total moisture & excess air level. Based on these various losses calculated as follows.

A. Dry gas losses

$$Dry\ gas\ losses = \frac{m_{dry} \times Cp_{fg}(T_{fg} - T_{amb})}{CV_{fuel}}$$

B. Losses in Ash

1. $Loss\ due\ to\ combustibles = \frac{m_{ub} \times CV_{ub}}{CV_{fuel}} \times 100$
2. Sensible heat loss $= \frac{m_{ash} \times Cp_{ash}(T_{ash} - T_{amb})}{CV_{fuel}}$

C. Loss due to H_2 in fuel

Loss due to H_2 in fuel $= \frac{(m_{H2O} \times \Delta H)}{CV_{fuel}} \times 100$

Where,

$\Delta H = 2443 + 1.88(T_{fg} - T_{amb}) + 4.2\ (25 - T_{amb})$ KJ/kg

D. Loss due to moisture In fuel

Loss due to moisture In fuel $= \frac{(m_{moist} \times \Delta H)}{CV_{fuel}} \times 100$

E. Un accounted losses

Radiation losses, blow down losses, losses due unburnt gases etc

3.3 Efficiency of Boiler

$\eta_{first\ law} = 100 -$ Total Losses %

3.4 Energy balance of the turbine

$$m_{inlet} \times h_{inlet} = m_{inlet} \times h_{bleed} + m_{exct} \times h_{exct} + m_{exhst} \times h_{exhst} + w_t$$

3.5 Energy loss in piping and Ejector

The pressure drops due to friction and heat loss to the surroundings are the most important piping losses. The steam produced by the boiler is fed to turbine. Both the pressure drop and heat transfer reduce the availability of steam entering the turbine.

Piping Loss $= (E_{boiler\ outlet} - E_{turbine\ inlet})$

$$\eta_{piping} = \frac{E_{turbine\ inlet}}{E_{boiler\ outlet}} \times 100$$

3.6 First Law Analysis of Plant

The first law analysis of the plant is carried out in this section. The input and output of the plant are as mentioned below.

The input to the plant is

(i) Energy of the fuel:

$$E_{fuel} = m_{fuel} \times CV_{fuel}$$

(ii) Power Developed by Turbine (Plant Output):

$$W_T = 3387.5\ kW$$

(iii) Energy difference between outgoing steam and incoming feed water:

$$\Delta E = E_{bleed} + E_{Exct} - E_{feed\ water}$$

Overall efficiency of plant

$$\eta_{first\ law} = \frac{(W_T - \Delta E)}{E_{fuel}} \times 100$$

5. Exergy Analysis or Second Law Analysis

The exergy of a material stream is the maximum obtainable amount of shaft work (or electrical energy) when this stream is brought form actual conditions (T,P) to thermo mechanical equilibrium at ambient conditions (T_0,P_0) by reversible processes and heat being only exchanged with the environment at T_0.

The basic Exergy equation for one kg substance in flowing open systems, disregarding kinetic and potential exergy terms is as follows:

$$E_X = (H - H_0) - T_0(S - S_0)$$

5.1 Exergy Analysis of Heat Exchanger as a Boiler

For Analysis boiler is divided in three sub region

1. Combustion Chamber
2. Heat Transfer to water.
3. Flue gases mixing with atmosphere.

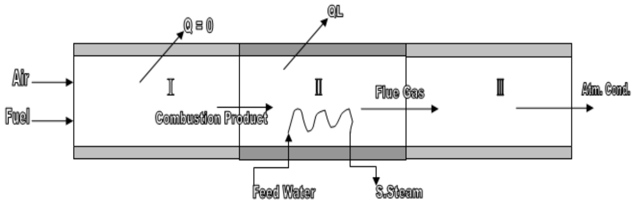

Fig.5.1 Heat Exchanger as Boiler Analysis

5.1 Exergy loss Or Irreversibility in (Region-I)

Air and fuel enters this sub region at atmospheric condition. Fuel is burned and combustion gases are produced in this sub region. The exhausts of this region are the combustion gases. The combustion gases are used to heat up water in the sub region II. The control volume used for analysing this region is shown in figure 5.1.

$$I_1 = Ex_1 - Ex_1$$

Where

$$Ex_1 = Ex_{fuel} - Ex_{air}$$

$$Ex_2 = np_{2.\varepsilon p2} - \sum n.\varepsilon p^h$$

$$\varepsilon p_2 = \sum X_k.\varepsilon - RTo \sum X_k.\ln X_k$$

$$\sum n \times \varepsilon p^h = (T_2 - T_0)\sum n \times Cp^{\varepsilon}$$

$$Ex_{fuel} = m_{fuel} \times \varepsilon_{fuel}$$

$$\eta_{2nd\ law} = \frac{E_{X2}}{E_{X1}} \times 100$$

5.2. Heat transfer to Water (Region - II)

The product of combustion coming out from combustion chamber is used to heat up the feed water. This heat transfer produces steam. This region of heat transfer from combustion product to feed water is the sub region II.This sub region is main part of boiler. Here super heating steam is produce for turbine work and process work. The control volume used for analysing this region is shown in figure 5.1.

To find the heat lost QL from the boiler, energy balance of the sub region II.

$$H_2 + (h_{feed\ water} \times m_{feed\ water}) = H_3 + (h_s \times m_s) + Q_L$$

Where

H_2 = Enthalpy of incoming combustion product.
H_3 = Enthalpy of flue gas.
Q_L = heat lost.
$h_{feed\ water}$ = specific enthalpy of feed water.
$m_{feed\ water}$ = mass of feed water.
h_s = specific enthalpy of super heating steam.
m_s = mass of super heating steam.

Now

$$H_2 = (T_2 - T_0) - \sum n.Cp^h$$

and

$$H_3 = (T_3 - T_0) - \sum n.Cp^h$$

Now Exergy Balance

$$E_{X2} + Ex_{feed\ water} = Ex_3 + Ex_{steam} + I_2$$

Irreversibility

$$I_2 = (Ex_2 - Ex_3) - (Ex_{steam} - Ex_{feed\ water})$$

Where

$$Ex_3 = Ex_{3CG} - Ex_{ph3}$$

Ex_{ph3} = Physical Exergy at temperature T_3

$$Ex_{ph3} = (T_3 - T_0)\sum n \times Cp^{\varepsilon}$$

$Ex_{3CG} = Ex_{2CG}$ = Chemical Exergy of Gas

Hence the efficiency of the sub region II

$$\eta_{2nd\ law} = \frac{E_{Xs} - E_{Xfw}}{E_{X2}} \times 100$$

5.3. Analysis of Sub Region - III

In this sub region the flue gases mix with atmosphere. So the exergy of the flue gases coming out from the boiler is entirely lost as irreversibility.

So,

Irreversibility

$$I_3 = Ex_3$$

Hence the second law efficiency of boiler is

$$\boldsymbol{\eta}_{2nd\ law\ plant} = \frac{E_{Xs} - E_{Xfeed\ water}}{E_{X1}} \times 100$$

5.4 Exergy Balance for the Turbine

The steam coming out of the boiler is supplied to the turbine for the generator power.

To find the work output of the turbine for the specified inlet and outlet steam conditions, the energy balance across the control volume as below.

$$E_{inlet} = E_{bleed} + E_{exhst} + E_{exct} + W_T + Q_L$$

Energy Balance Equation of the Turbine

$$Ex_{inlet} = Ex_{bleed} + Ex_{exhst} + Ex_{exct} + w_t + I$$

Now the second Law Efficiency of this process is

$$\boldsymbol{\eta}_{2nd\ law} = \frac{W_t}{E_{inlet} - (Ex_{bleed} + Ex_{exhst} + Ex_{exct})} \times 100$$

5.5 Exergy Losses in Piping

The pressure drops due to friction and heat loss to the surroundings are the most important piping losses. The steam produced by the boiler is fed to turbine. Both the pressure drop and heat transfer reduce the availability of steam entering the turbine.

Exergy Balance at the outlet of the boiler and input to the turbine:

$$Ex_{boiler\ outlet} = (Ex_{turbine\ inlet} - I_{piping})$$

Therefore

$$I_{piping} = (Ex_{boiler\ outlet} - Ex_{turbine\ inlet})$$

Hence

$$\boldsymbol{\eta}_{piping} = \frac{E_{X\ turbine\ inlet}}{E_{X\ boiler\ outlet}} \times 100$$

6. Second Law Analysis of Plant

The second law analysis of the plant is carried out in this section. The exergetic efficiency of the plant as a whole is calculated in this section.

The input to the plant is:

(i) Exergy of the fuel:

$$Ex_{fuel} = Ex_1$$

(ii) Power Developed by Turbine (Plant Output):

$$W_T = 3387.5 \text{ kW}$$

(iii) Exergy difference between outgoing steam and incoming feed water:

$$\Delta E_X = Ex_{bleed} + Ex_{exct} - Ex_{feed\ water}$$

So, the Overall efficiency of plant

$$\eta_{2nd\ law\ plant} = \frac{W_T + \Delta E_X}{E_{Xfuel}} \times 100$$

IV. RESULT AND DISCUSSION

Based on energy analysis & exergy analysis Sankey diagram is drawn for plant as shown in fig 7.1 that shows energy & exergy distribution and losses.

The efficiency of boiler is calculated after finding out the various losses, which takes place in boiler. First law analysis shows the efficiency of boiler to be of 81.67%.This causes loss of 18.33% of energy. This loss is reduced by operating boiler at appropriate air-fuel ratio & use of suitable particle size of the coal. The piping and ejector losses reduced by selection of appropriate size & better insulation of pipe. The fist law efficiency of turbine is 88.5%, which is low because the steam is not allowed to expand fully in the turbine. First law efficiency of plant is 43.92%.

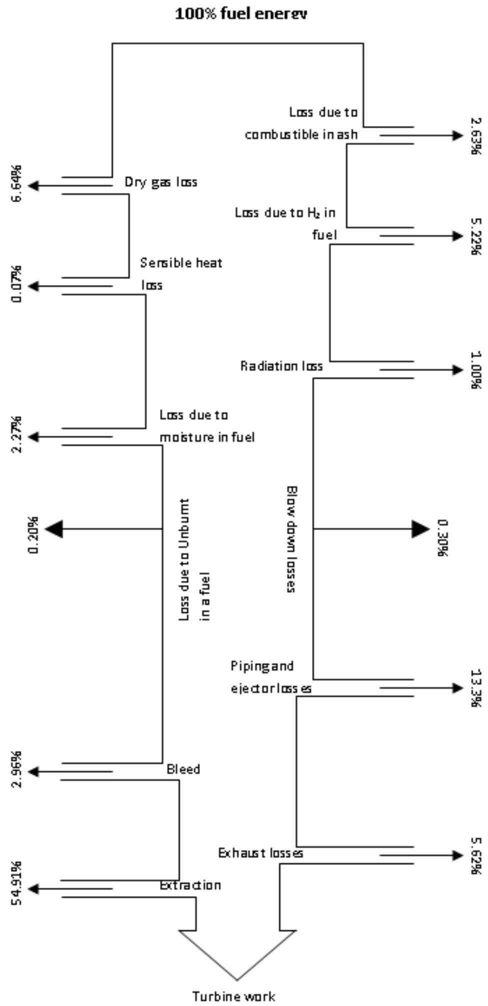

Fig 7.1 Sankey diagram of Plant

In second law analysis maximum loss of exergy is takes place while converting the chemical energy of fuel into heat energy. This is due to high production of entropy during the process of conversion. To reduce this exergy loss one has to supply the air-fuel mixture at maximum possible temperature use suitable combustion catalyst. Both these approaches improve the second law efficiency of boiler but also contribute towards improving first law efficiency.

Second law efficiency of turbine is 74.19%. This is because of fact that steam is not allowed to expand completely in the turbine. The energetic efficiency as 11.67%.One major area of exergy loss is in condenser. This loss may be reduced by adopting absorption cooling i.e. energy of condensing steam may be used to produce cooling through the absorption cycle.

V. CONCLUSION

From energy and the exergy analysis of the captive power plant, it is seen that the energy analysis attributes all the inefficiencies to losses as 56%. The first law efficiency of the plant is 43.928%, while the energetic efficiency of the plant is 11.674% and other details in annexure II and II One can see that there is a huge difference between the first law efficiency and second law efficiency of the plant, which is 43.928% and 11.674% respectively. This is due to large amount of energy degradation. This degradation of energy increases the entropy and hence a decrease in the exergy or second law efficiency.

From exergy analysis of the captive power plant it is also seen that major inefficiencies are due to heat transfer process & combustion process, the Stack Losses are comparatively very less. An energy analysis shows combustion process is 100% efficient and heat transfer process is also highly efficient, while stack gases carry away the majority of the lost energy. Thus first law efficiency is the poor approximation of true efficiency and misleads as far as the performance of plant is concerned.

It has been that the maximum loss of exergy is while converting the chemical exergy such as 20638.91KJ/Kg of fuel to heat. This is due to the high production of entropy during the process of burning of fuel. Maximum of exergy is lost during this process of conversion. By supplying air-fuel at high temperature, use of catalyst and by lowering the product gas temperature, the production of entropy can be reduced and hence higher combustion efficiency may be obtained.

The condenser, piping and ejector losses are found to be quite high and any reduction in this would result in better overall performance.

The energy and exergy are due to unaccounted and leakage loss is of the order of 1.5%. In order to reduce the steam loss, gland leakages, steam traps and miscellaneous leakages should be stopped.

Energy and exergy losses in the turbine may be due to the blade tip losses increase in the inter stage gland leakages. Therefore proper clearance of different labyrinths should be maintained in order to improve its performance.

Second law analysis indicates the destruction of exergy of various components of the plant. Therefore to increase the second law efficiency of plant attempt should be made to reduce the destruction of exergy as far as possible.

In general operating the boiler at proper air-fuel ratio, supplying air-fuel mixture at higher temperature, use of combustion catalyst, selection of appropriate pipe size, proper insulation, reduction in steam and gland leakages & adoption of absorption cooling to utilize heat of condensing steam may help in improving overall energetic & energetic efficiency of plant.

However, these observations and subsequent suggestion to improve the plant performance need to be analysed in the light of the overall techno economic viability.

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NOMENCLATURE

C.V. Calorific Value
m mass flow rate
Cp Specific heat
E Energy KJ/Kg
Ex Exergy KJ/Kg
n Molar fraction
Cph Mean molar isobaric heat capacity for evaluating enthalpy changes
Cps Mean molar isobaric heat capacity for evaluating entropy changes
Xk Molar fraction of flue gas.
I Irreversibility
WT Turbine Work

SUBSCRIPTS

1. Inlet
2. Outlet

0 Environment condition

fg Flue gas

moist moisture

amb ambient condition

ub Unburnt

exct Extraction

ex Exhaust

Q Heat transfer

S Steam

Fw Feed Water

ANNEXURE - I

Average values of data collected at various terminal points of plant.

Sr.No.	DESCRIPTION	TEMP. ^0C	PRESSURE Bar	FLOW Kg/s
1	Turbine Inlet	393	43.794	7.916
2	Bleed	180.87	8.9076	0.310
3	Extraction	179.75	5.447	5.694
4	Turbine Exhaust Condenser Inlet	50	0.1306	1.911
5	Condenser outlet Deaerator Inlet	48	0.1208	1.911
6	Cooling Water Inlet to Condenser	35	2.533	154.7
7	Cooling Water outlet to Condenser	41	2.190	154.7
8	Deaerator Inlet from Process Plant	160	4.935	0.998
9	Deaerator Inlet from Chiller Plant	80	7.5	0.659
10	Make-up water inlet to Deaerator	40	1.01325	6.310
11	Deaerator outlet to B.F.pump	104	1.01325	9.878
12	Steamer Inlet	180	9.358	0.278
13	Chiller Plant Inlet	180	9.358	0.659
14	Feed Water Inlet in to Economicer	103.666	48.575	9.166
15	Economicer outlet Boiler Inlet	181.733	48.550	9.020
16	Superheating Steam Outlet from Boiler	415.750	45.437	9.00
17	Flue gas inlet in to Economicer-boilerO/l	361	1.00266	17.257
18	Economicer outlet Airpreheater Inlet	192	0.99304	17.257
19	Boiler Inlet From Airpreheater	98	1.5904	17.257
20	Airpreheater inlet from Atmosphere	40	1.5616	17.257
21	Airpreheater outlet FG-ESP inlet	133.125	0.9920	17.257
22	ESP outlet	127.25	0.80	17.257
23	S steam to mp-prv	395	44.652	0.937

ANNEXURE - II

FINAL RESULTS

PARAMETER	QUANTITY
Dry gas Loss (Stack Loss)	6.64000 %
Loss due to combustibles in Ash	2.62520 %
Sensible heat loss in Ash.	0.07080 %
Loss due to H_2 in Fuel.	5.22000 %
Loss due to moisture in fuel	2.27400 %
Radiation Loss	1.00000 %
Blow down Loss	0.30000 %
Loss due to unburned fuel	0.20000 %
TOTAL LOSSES OF FUEL	18.6728 %
Energy loss in piping and Ejector	3897.16 kJ/sec
Energy losses in Turbine	440.103 kJ/sec
Irreversibility of sub- region I	10622.7 kJ/sec
Irreversibility of sub-region II	10879.8 kJ/sec
Irreversibility of sub- region III	1553.93 kJ/sec
Exergitic loss in piping and Ejector	1556.32 kJ/sec
Exergitic losses in Turbine	1178.33 kJ/sec
1^{ST} Law Efficiency of Boiler	81.6728 %
1^{ST} Law Efficiency of Turbine	88.5000 %
1^{ST} Law Efficiency of Piping	86.6300 %
1^{ST} Law Efficiency of Plant	43.9280 %
2^{nd} Law Efficiency of Sub-region I	68.4600 %
2^{nd} Law Efficiency of Sub-region II	46.0900 %
2^{nd} Law Efficiency of Sub-region III	31.5600 %
2^{nd} Law Efficiency of Turbine	74.1920 %
2^{nd} Law Efficiency of Piping	85.7100 %
2^{nd} Law Efficiency of Plant	11.6740 %

ANNEXURE - III

Summary of results of Analysis.

MODE OF OPERATION	RESULT
1^{ST} Law Efficiency of Boiler	81.6728 %
1^{ST} Law Efficiency of Turbine	88.5000 %
1^{ST} Law Efficiency of Plant	43.9280 %
2^{nd} Law Efficiency of Sub-region I	68.4600 %
2^{nd} Law Efficiency of Sub-region II	46.0900 %
2^{nd} Law Efficiency of Sub-region III	31.5600 %
2^{nd} Law Efficiency of Turbine	74.1920 %
2^{nd} Law Efficiency of Plant	11.6740 %

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