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Exergy Analysis and Efficiency Improvement of a Coal Fired Thermal Power Plant in Queensland

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Additional information is available at the end of the chapter

1. Introduction

Energy security and CO_2 emission reduction are two major concerns of today's world. Improving efficiency of the energy systems is an essential option for the security of future energy and the reduction of CO_2 emissions. With the growing prosperity of the civilization, our consumption of energy is growing very rapidly. Fossil fuels remain the world's dominant primary energy supply, with its use as a versatile primary source of energy in power generation, transport and industry. However, we have finite sources of these non renewable fossil fuels and we are consuming them at a rate that cannot be sustained, leading to the risk on energy security in the future. The Intergovernmental Panel on Climate Change (IPCC), in its Fourth Assessment Report [3], identified carbon dioxide (CO_2) emissions from burning of fossil fuels as the primary contributor to climate change. Therefore, the prudent use of energy is imperative and the importance of improving energy efficiency is now very well realized by all.

Improvement of energy efficiency of power generation plants leads to lower cost of electricity, and thus is an attractive option. According to IEA (IEA 2008a), the average efficiency of coal-fired power generators of the Organisation for Economic Co-operation and Development (OECD) member[1] countries over the 2001 to 2005 period in public sector is 37%. According to this report, the highest average efficiency of coal-fired power plants is observed in Denmark which is 43% and in United States 36%. The average energy efficiency of Australian coal-fired power plants is one of the lowest among the OECD countries which is 33%. Therefore, improving energy efficiency of coal-fired power plant in Australia is very important.

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1 OECD members are economically developed countries.

The energy conversion in a coal-fired power plant is dominantly a thermodynamic process. The improvement of energy efficiency in a thermodynamic process generally depends on energy analysis of the process which identifies measures required to be addressed. The conventional method of energy analysis is based on first law of thermodynamics which focuses on conservation of energy. The limitation with this analysis is that it does not take into account properties of the system environment, or degradation of the energy quality through dissipative processes. In other words, it does not characterize the irreversibility of the system. Moreover, the first law analysis often casts misleading impressions about the performance of an energy conversion device [4-6]. Achieving higher efficiency, therefore, warrants a higher order analysis based on the second law of thermodynamics as this enables us to identify the major sources of loss, and shows avenues for performance improvement [7]. Exergy analysis characterizes the work potential of a system with reference to the environment which can be defined as the maximum theoretical work that can be obtained from a system when its state is brought to the reference or ''dead state'' (standard atmospheric conditions). The main purpose of exergy analysis is to identify where exergy is destroyed. This destruction of exergy in a process is proportional to the entropy generation in it, which accounts for the inefficiencies due to irreversibility.

This research conducts exergy analysis in one unit of a coal-fired power plant in Central Queensland, Australia as a case study. The exergy analysis identifies where and how much exergy is destroyed in the system and its components. Based on the analysis, it assesses and discusses different options to improve the efficiency of the system.

2. Process description of a coal-fired power plant

A coal-fired power plant burns coal to produce electricity. In a typical coal-fired plant, there are pulverisers to mill the coal to a fine powder for burning in a combustion chamber of the boiler. The heat produced from the burning of the coal generates steam at high temperature and pressure. The high-pressure steam from the boiler impinges on a number of sets of blades in the turbine. This produces mechanical shaft rotation resulting in electricity generation in the alternator based of Faraday's principle of electromagnetic induction. The exhaust steam from the turbine is then condensed and pumped back into the boiler to repeat the cycle. This description is very basic, and in practice, the cycle is much more complex and incorporates many refinements.

A typical coal plant schematic is presented in Figure 1. It shows that the turbine of the power plant has three stages: high-pressure, intermediate-pressure and low-pressure stages. The exhaust steam from the high-pressure turbine is reheated in the boiler and fed to the inter-mediate-pressure turbine. This increases the temperature of the steam fed to the intermediate-pressure turbine and increases the power output of the subsequent stages of the turbine. Steam from different stages of the turbine is extracted and used for boiler feed water heating. This is regenerative feed water heating, typically known as regeneration. The improvement of the thermal performance of the power generation cycle with reheat and regeneration is a trade-

off between work output and heat addition [8] and it can be evaluated through the efficiency of the power generation cycle.

In a typical pulverised coal power plant, there are three main functional blocks as shown in Figure 1. They are (1) the boiler; (2) the turbo-generator and (3) the flue gas clean up. The boiler burns coal to generate steam. The combustion chamber of the boiler is connected with the coal pulverisers and air supply. The water pre-heater (also known as the economiser), the super heater and the reheater are all included in this block. The steam produced in the boiler is used in the turbine as shown in Figure 1. The generator is coupled with the turbine where mechanical shaft rotation of the turbine is converted into electrical power and supplied to the power distribution grid through a transformer. The purpose of the transformer is to step up the voltage of the generated power to a level suitable for long distance transmission. The steam leaving the turbine is condensed in the condenser as shown in the Figure 1 using cooling water which discharges low temperature heat to the environment. The condensate produced is pumped back to the boiler after heating through the feed water heaters. The feed water heaters use regenerative steam extracted from the turbine.

The burning of coal in the boiler of a power plant produces flue gas. The main constituents the of flue gas are nitrogen (N_2), carbon dioxide (CO_2) and water (H_2O). It carries particulate matter (PM) and other pollutants. There are traces of some oxides such as oxides of sulphur (SOx) and oxides of nitrogen (NOx) depending on the combustion technology and fuel used. The flue gas clean-up block comprises all the equipment needed for treating the flue gas. The power plant shown in Figure 1 includes a DeNOx plant for NOx removal, followed by electrostatic precipitation (ESP) to remove particulate matter (PM), and wet flue gas desulfurisation (FGD) to remove SOx from the flue gas. An air-preheating unit is situated between the DeNOx and the electrostatic precipitator (ESP). There is a significant amount of heat energy leaving through the flue gas, some of which is recovered by using the air preheater. This improves the thermal performance of the process.

The properties of the coal used in the boiler and the environmental legislation and/or environmental management policy of a plant are two major factors that determine the nature of the flue gas treatment process. In some countries, due to stringent environmental regulation, coal-fired power plants need to install denitrification plants (DeNOx) for nitrogen oxide (NOx) and flue gas desulphurisation plants (FGD) for sulphur oxide (SOx) removal [9, 10]. In Australia, the coal used has a very low sulphur content and therefore, the concentration of SOx from the burning of coal in Australia is relatively low. Dave et al. [11] report an absence of stringent regulatory requirements for limiting NOx or SOx in flue gas streams in Australia. Therefore, Australian coal plants in the past have not been required to have deNOx or deSOx equipment to clean up flue gas.

In this research, a pulverized coal-fired power plant in Central Queensland, Australia has been considered as a case study. One of the units of the said plant was used to develop a process model and to perform energy analysis. This unit has Maximum Continuous Rating (MCR) of 280 MW. It spends less that 5% of its operating time at loads greater than 260 MW. Operation of the unit is mostly in the range of 100 to 180 MW range. The unit plant is a sub-critical power
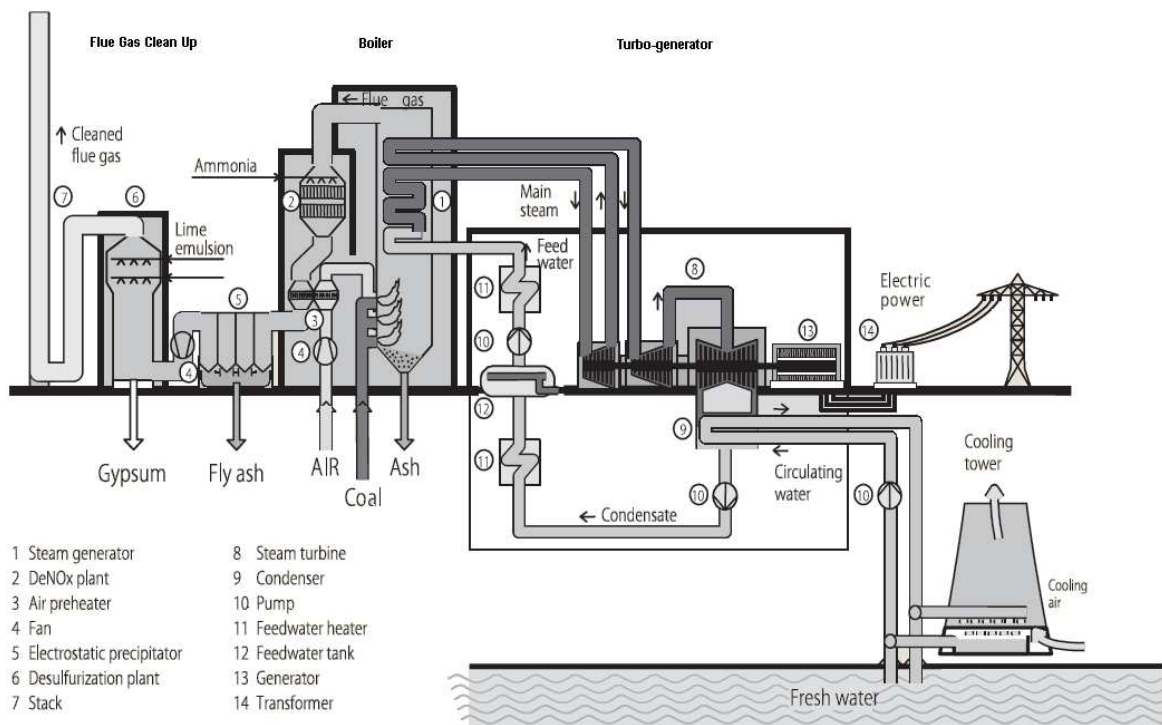
Figure 1. A typical Coal Power Plant

plant having steam outlet pressure of 16.2 MPa. The unit/plant uses thermal coal supplied from the nearby Bowen basin.

3. Process modeling and simulation

Mathematical models are effective tools for analysing systems or processes. They can be used to develop a new system or to evaluate the performance of an existing one. Mathematical modelling is widely applied to the solution of engineering problems. Modelling usually describes a system using a set of variables and equations and sets up relationships among the variables. Mathematical models are found to be very useful in solving problems related to process energy efficiency and can be utilised for both static and dynamic systems. SysCAD [1], a process modelling software package, has been found to be very effective for analysing plants for efficiency improvement. It has been used in Australia by a number of process industries, consulting companies and universities as a tool for simulating plant. Therefore, SysCAD has been employed in this study for modelling and simulating the said coal-fired power plant.

3.1. Modelling in SysCAD

SysCAD can work in both static and dynamic modes. In static mode, it can perform process balances known as ProBal. SysCAD process modelling in ProBal is illustrated in Figure 2. It shows the overall approach of developing a process model in SysCAD. A process model is

generally treated as a project in SysCAD. A project may have one process flow sheet or a number of flow sheets. In a project, the flowsheets can interchange data and can be interlinked.

SysCAD uses typical graphical techniques to construct a process flow diagram (PFD). Before constructing a PFD in SysCAD flowsheet, the scope of the project and data required to perform modelling needs to be defined as shown in the Figure 2. In SysCAD there are many built-in process components known as unit models. The components in a process are represented by the unit models. For modelling purposes, these unit models need to be configured based on the system requirements and performance data of the individual components used in the process as shown in Figure 2. All the unit models need to be connected appropriately to construct the PFD in a flowsheet. There are chemical species defined in SysCAD, which are used to calculate physical and chemical properties. The user can also define process components and chemical species as required if they are not available in the SysCAD component library or species database. Chemical reactions are important to perform some process modelling. SysCAD has built in features to define and simulate chemical reactions. Modelling with chemical reactions requires defining all chemical reactions in a reaction editor. The extent of a reaction based on a certain reactant can be provided as a fraction. If multiple reactions are required to define a model, the sequence of each reaction can be provided. SysCAD uses a user-defined sequence during simulation.
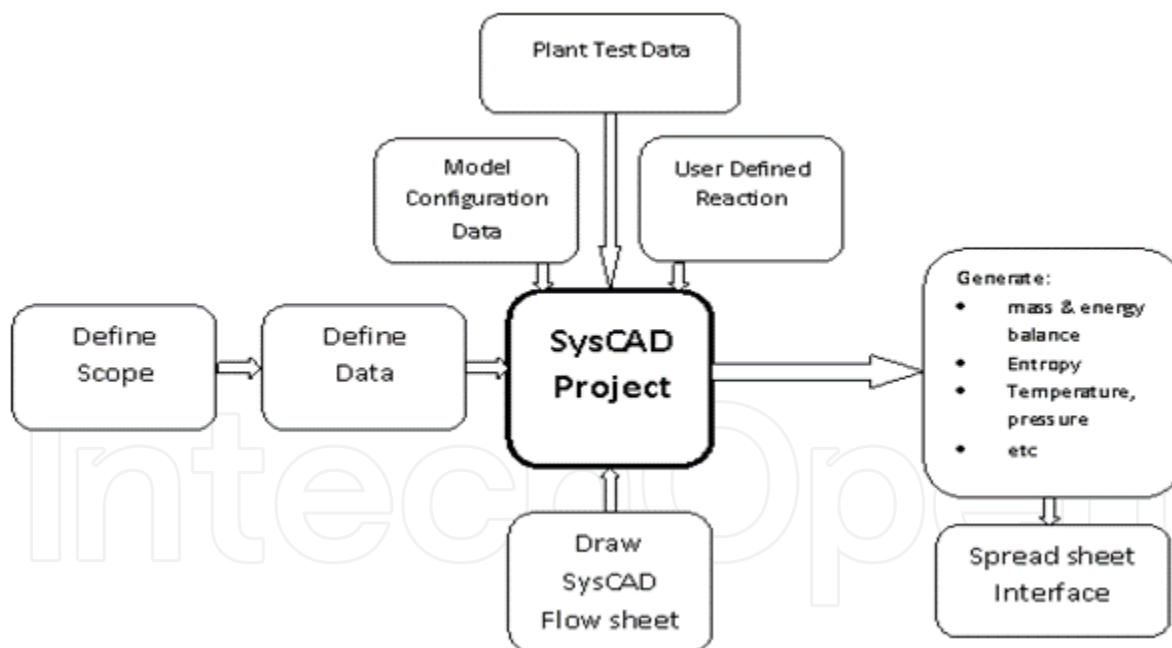

Figure 2. SysCAD Modeling [2]

As shown in Figure 2, SysCAD ProBal function provides a mass and energy balance of a process and its components. The mass balance incorporates all input and output streams together with any mass additions or sinks in unit operations. This balance considers changes due to reactions or phase changes. An energy balance, on the other hand, looks at the input and output streams as well as all sources of heat transfer simply via total enthalpy. The concept is that each stream

has a sum of total enthalpy and if a unit operation is balanced the sum of total enthalpy at T_{in} of all respective streams equals the sum of total enthalpy at T_{out} of all respective streams.

In addition to energy and mass balances, SysCAD offers a wide range of thermo-physical data as shown in Figure 2, which is important for analysing the process and its components (e.g., temperature, pressure, entropy). SysCAD has some common process control models such as PID controller, actuator, transmitter and general controller. The general controller can be defined and used through a built-in programming language called Programmable Module (PGM). It has extended the functionality of the process modelling in SysCAD. Process data can be used in PGM to control a process and to perform calculations required for useful analysis. In addition, data from a process balance can be exported to MS Excel to perform further analysis.

In an efficiency improvement study, process energy analysis is very important for identifying where energy is lost and how effectively the loss can be minimised or recovered in the process. The results of a process modelling and simulation in SysCAD can be further analysed to observe, identify and assess energy lost in a process.

3.2. Brief description of case study

In this study, a power plant model developed based on a unit of a power plant in Central Queensland Australia. The power plant uses pulverised coal supplied through pulverisers and burnt in a boiler. The boiler of the plant is of the radiant tube type. It has natural circulation design with a low and high temperature economiser, a three-stage superheater and a two-stage single reheater. The boiler has a maximum steam outlet pressure of 16.2 MPa and a temperature of 541°C and feed water maximum temperature of 252° C.

The unit plant has a turbine to convert to convert thermal energy of steam into mechanical shaft rotation. The turbine has three pressure stages – high pressure, intermediate pressure and low pressure. In all three stages, there are stream extractors to facilitate regenerative heating of feed water heater. Three low-pressure heaters (LPH), one deaerator and two high-pressure heaters (HPH) use bled steam for regenerative feed heating. A condenser is used in the power plant to condense low pressure steam into water. The condenser is water-cooled type and it has been built for seawater operation. There is a minor loss of water in the plant process. Therefore, makeup water for the boiler feed is added into the condenser hot-well after passing through a deaerating system. It has been found that the requirement for makeup water in the boiler is very low compared to the total requirement. The condensate passes through a series of heat exchangers - LPHs, deaerator and HPHs which take heat from the regenerative bled stream as mentioned earlier.

The highest capacity of the power plant is 280 MW of electrical power. This is the maximum capacity rating (MCR) of the power plant. The capacities of all individual process components were configured with appropriate data to produce the rated power. A detailed description of the configuration of all individual process components is provided while describing the model flow sheets in the subsequent section.

3.3. Process model development

In this research, the power plant was represented by two separate flow sheets. They are a) Power Generation Model and b) Boiler Combustion Model. The detailed descriptions of these two model flow sheets are provided in the next sections.

3.3.1. Power generation model

The flow sheet for the power generation cycle is presented in Figure 3. It shows the steam cycle of the power plant. This cycle is known as the Rankine cycle [8] including reheating and regeneration.

The boiler in the power plant has feed water heater, superheater and reheater. The boiler feed water heater and super heater are included in the boiler model while the reheater is represented as a separate heater denoted as 'reheating' as shown in Figure 3.

The whole turbine is modelled using 7 unit turbine models as shown in the figure. This was done to simultaneously facilitate the use of the inbuilt SysCAD turbine model and steam extraction. For example, due to two steam extractions from intermediate pressure stage of the turbine, it is represented by two unit models namely IP_TRB1 and IP_TRB2.

The steam leaving the low-pressure turbine was connected with a condenser, which is described using a shell and tube type heat exchanger in SysCAD. The condenser is supplied with cooling water to perform steam condensation. The pressure of the steam at this stage is very low. The bled steam extracted from the turbine is recycled in to the condenser. The makeup water required in the process is added after the condenser. The condensate pump is located after the condenser, and it boosts the pressure of the condensate high enough to prevent boiling in the low-pressure feedwater heaters. The condensate mixes with the makeup water before entering the condensate pump.

There are three low-pressure heaters connected with the extracted steams from different turbine stages as shown in Figure 3. The feed water is gradually heated, taking heat from steam with increasing temperature and pressure at each stage. In a low-pressure heater, heat exchange occurs in two stages. At first, the steam condenses to its saturation temperature at steam pressure and then occurs sensible heat exchange. All the three heaters were developed based on the same principle.

The main purpose of a deaerator is to remove dissolved gases including oxygen from the feed water. Some heat exchange occurs in the deaerator. In this model, the deaerator is treated as a heat exchanging device where steam and feed water exchange heat through direct contact. The tank model built in SysCAD was used to represent the deaerator. The feed water, after heating in the deaerator, is pumped through the feed water pump. The high pressure feed water is heated through two more high-pressure heaters. The steam for the high pressure heaters is extracted from the high pressure turbine exhaust, and from an inter-stage bleed on the intermediate pressure turbine. Each of the high-pressure heaters is developed using two SysCAD heat exchange models as described earlier for the low-pressure heaters.
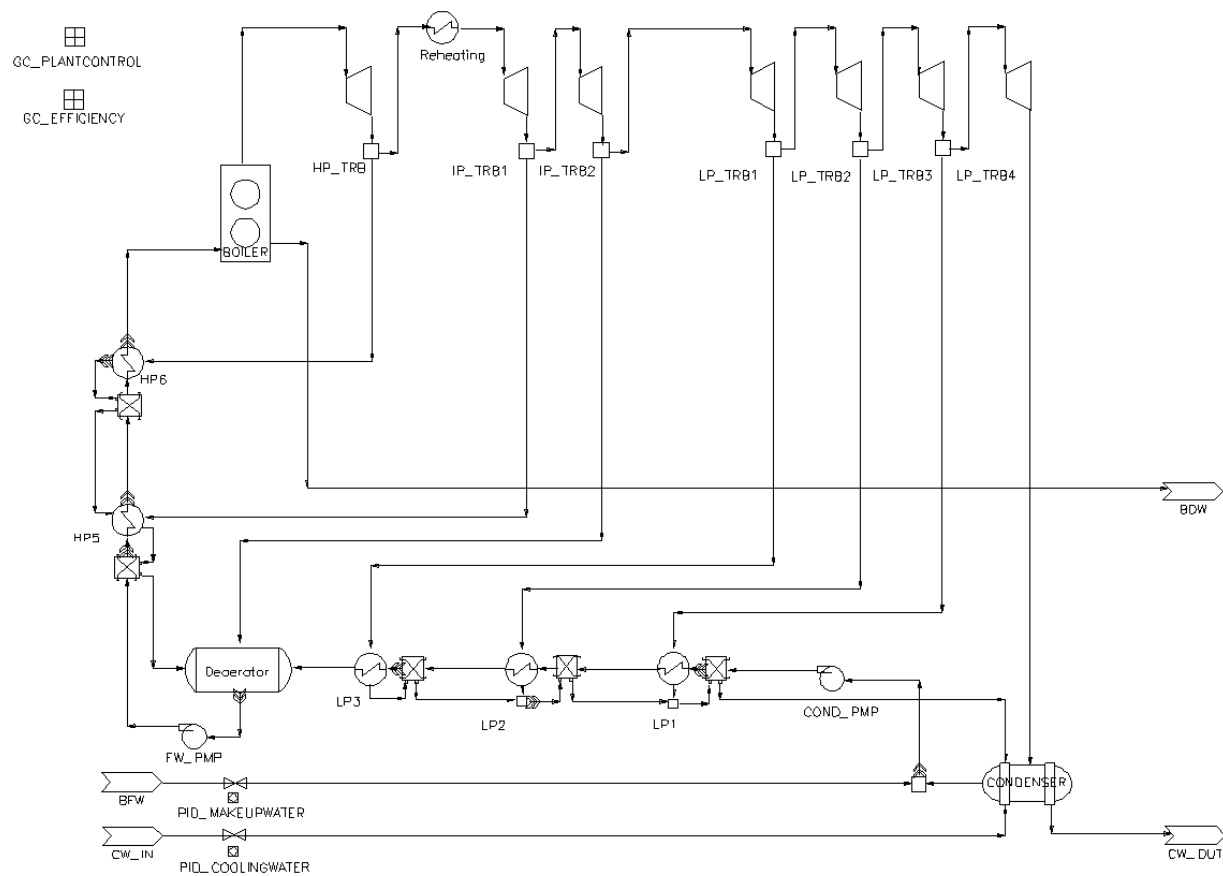
Figure 3. Power Plant Model

The operations of all the individual components used in the model flow sheet are described in detail in the subsequent discussion. The discussion includes data used to configure each component for the modelling.

3.3.1.1. Boiler and reheating

The boiler model in SysCAD calculated energy required by the boiler based on the boiler feed water, the required drum pressure and the superheated steam conditions. It is a very simple model, which does not take into account the type of fuel used or the type of economiser. It heats the high pressure feed water stream to saturation temperature and then to the super-heated condition as specified. A portion of saturated water is blown down from the boiler to discharge impurities and maintain water purity. In this research the operating conditions of the boiler were configured based on plant-supplied data presented below:

- Steam outlet pressure: 16 MPa

- Steam outlet temperature: 540 °C

- Boiler Efficiency: 90%

- Blow down: 0.5%

The high temperature steam from the boiler superheaters enters the high-pressure side of the turbine named HP_TRB. In this turbine stage, part of the steam energy is converted to mechanical shaft rotation and the pressure and temperature of the steam drops based on turbine configuration and supplied data discussed later. The steam leaving HP_TRB is taken to the reheating process where the steam is reheated to 540 °C. A portion of the steam is taken out to regeneration before it goes to reheating. The reheating model is a simple heater for sensible heating and no phase change occurs. The simple heater only calculates the heat required for reheating.

3.3.1.2. Steam turbine

The built-in steam turbine model in SysCAD transforms steam energy into electrical power. In a flow sheet, it needs to be connected with one single steam input and one single stream output. The inlet conditions of the steam, such as temperature, pressure, mass flow and quality of steam need to be defined. Using steam inlet data and specified turbine efficiency, SysCAD calculates turbine output power and the condition of the outlet stream. The simplified energy balance calculation against a turbine is provided in the following equation:

$$W = H_{in} - H_{out} \tag{1}$$

where, W is work output of the turbine, and Hin and Hout are enthalpy of stream into and out of the turbine

The high-pressure turbine was modelled using a turbine unit model named HP_TRB. The steam exiting HP_TRB was connected with the reheating system. The reheater heats up the steam to a high temperature to improve the quality of steam. A portion of the steam is extracted before the reheater and fed to a high-pressure heater named HP6. In Figure 3, the reheated steam enters the intermediate-pressure turbine. This stage was modelled using two turbine unit models. The two models were named as IP_TRB 1 and IP_TRB 2. Bled steam from both models is taken out – from the IP_TRB 1 to the high pressure heater, HP5 and from IP_TRB 2 to the deaerator. The steam from IP_TRB2 is connected with the low-pressure turbine. The low-pressure turbine is defined using four interconnected models named LP_TRB 1, LP_TRB 2, LP_TRB 3 and LP_TRB 4. There are bled steam flows from LP_TRB 1, LP_TRB 2 and LP_TRB 3. The bled steam flows are connected with three low-pressure heaters namely, LP3, LP2 and LP1 consecutively as shown in Figure 3.

It should be noted here that the SysCAD turbine model ignored changes of potential and kinetic energy since the changes are negligible. The turbine efficiency, mechanical efficiency, outlet pressure and steam bleed of the turbine in different stages are configured with data supplied by the plant and provided in Table 1.

	HP Turbine Stage(s)	IP Turbine Stage(s)		LP Turbine Stage(s)			
Turbine efficiency (%)	85						
Mechanical Efficiency (%)	98						
Outlet Pressure (kPa)	4000	1450	800	230	90	20	10
Bleed (%)	10	3	7	5	5	2	

Table 1. Input Data for Turbine Configuration

3.3.1.3. Condenser

The condenser was represented by a shell and tube heat exchanger, and it transfers energy from one stream to another. The primary use of this model is to transfer latent heat by steam condensation. The model performed the following calculations as defined in SysCAD.

For the heat exchanger:

$$Q = UA\Delta T_{LM} \qquad (2)$$

where

Q - Rate of Heat Transfer

U - Overall coefficient of Heat Transfer

A - Area available for Heat Transfer

ΔT_{LM} - Log Mean Temperature Difference (LMTD) calculated as

$$\Delta T_{LM} = \frac{\Delta T_2 - \Delta T_1}{ln\ (\Delta T_2 / \Delta T_1)}$$

For Counter Current Flow $\Delta T_2 = T_{H_{in}} - T_{C_{out}}$ and $\Delta T_1 = T_{H_{out}} - T_{C_{in}}$

Where

$T_{H_{in}}$ – temperature of hot stream in

$T_{H_{out}}$ – temperature of hot stream out

$T_{C_{in}}$ – temperature of cold stream in

$T_{C_{out}}$ – temperature of cold stream out

This has been described for a counter flow heat exchanger in Figure 4.

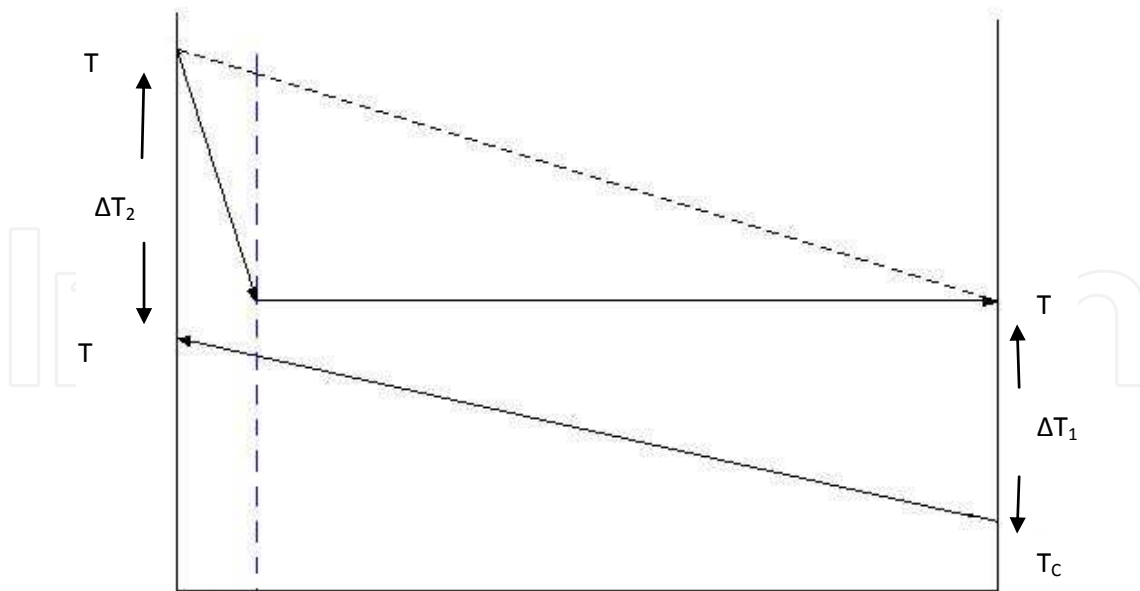For the heat transfer to the individual stream

Figure 4. Log mean temperature difference [1]

$$Q = m\left(h_{in} - h_{out}\right) \tag{3}$$

where

Q - Rate of Heat Transfer

m - Mass flow of the stream

h_{in} – Specific enthalpy of entering stream

h_{out} – Specific enthalpy of leaving stream

In this model, the vapour entering the condenser first comes to the saturation temperature and is then condensed. No further cooling of the liquid occurs. The area of the heat exchanger and the cooling water required to condense the whole of the steam flow to the condenser are specified.

3.3.1.4. Low pressure and high pressure heaters

The low pressure and high-pressure heaters were developed primarily using the shell and tube heat exchanger model as described earlier. Each of the heaters uses two models to achieve its desired functionality. The first one was used to condense steam into saturated water and the second exchanger was used to cool the saturated water to a temperature below the saturation temperature through sensible cooling. In SysCAD, a heat exchanger model has only one desired functionality. If one heat exchange model performs condensation of steam from some temperature above the saturation temperature, it cannot perform any further cooling to the stream. Therefore, the second heat exchanger was used to achieve the desired functionality as

required by the process. All the low-pressure heaters named LP1, LP2 and LP3 and the high-pressure heaters HP5 and HP6 were developed based on the same principle.

3.3.1.5. Deaerator

The fundamental purpose of a deaerator in power generation is to remove oxygen and dissolved gases from boiler feed water. This helps prevent corrosion of metallic components from forming oxides or other chemical compounds. However, in the power generation model the deaerator was treated as a direct contact heat transfer component in order to describe it for the desired purpose of this study. In the deaerator, steam comes in direct contact with liquid water and therefore heat transfer occurs.

A tank model in SysCAD is a multipurpose model. There are sub-models available with a tank model such as reaction, environmental heat exchange, vapour liquid equilibrium, heat exchange, make-up, evaporation, and thermal split. It was used here for defining the deaerator. This tank model was configured to achieve vapour liquid equilibrium only. The other sub-models were not used. The size of the deaerator tank was kept at 10 m³ and all the streams were brought to the lowest pressure through a built-in flashing mechanism.

3.3.1.6. Pumps

There are two pump models used in the power generation model. One is a condensate pump and the other is a feed water pump. The pump model boosts pressure of liquid to a specified pressure. In order to configure a pump in SysCAD it needs to be connected with an incoming stream and an output stream. The energy balance across a pump was achieved through using the following equation:

$$W = H_{in} - H_{out} \tag{4}$$

It was assumed that the process is adiabatic and there were negligible changes of potential and kinetic energy, and they were therefore ignored. The two pump models were configured with their required pressure boost data as provided in Table 2.

Pump	Pressure Boost in kPa
Feed Water Pump	21670
Condensate Pump	1200

Table 2. Pump Configuration Data

3.3.1.7. Pipe

The pipe model in SysCAD is used to transfer material between two units. There is a large amount of information on the stream displayed in the pipe model. It also allows some user-defined calculations using data found on the pipe. The pipe model can take pipe friction loss

into consideration. However, in this project the loss in the pipe was considered to be insignificant and was therefore ignored. In the pipe model, at different points of the power generation model code was applied to perform an exergy flow calculation. This is called Model Procedure (MP) in SysCAD and the code used here is similar to the codes in PGM described earlier. The details of exergy calculation are discussed later in section 4.2.

3.3.1.8. Controls and calculation of power generation model

There are two general controllers and two PIDs used to control the model to perform its set objectives. The general controllers were named as GC_PLANTCONTROL and GC_EFFICIEN-CY. GC_PLANTCONTROL was used to set the model simulation at the plant's desired rated capacity. Codes were also used to calculate the net power output and the feed water requirements. PID_MAKEUPWATER works in conjunction with GC_PLANTCONTROL to achieve the net power output set point through controlling the boiler feed water. GC_EFFICIENCY was used to calculate overall efficiency of the power plant by dividing net power output by fuel energy input rate. The net power output was calculated by deducting power used in the pumps from the generated power in the turbine. PID_COOLINGWATER was used to regulate supply of the required amount of cooling to the condenser.

3.3.2. Boiler combustion model

The boiler combustion model was developed to supply the desired amount of heat to the boiler. The model flow sheet is presented in Figure 5. As shown in the figure, the main components of this model are a (boiler) combustion, a water heater (economiser), a superheater, a reheater and an air preheater. The combustion model was developed using a tank model, three heaters by simple heaters and the air preheater by a heat exchanger model built in SysCAD.
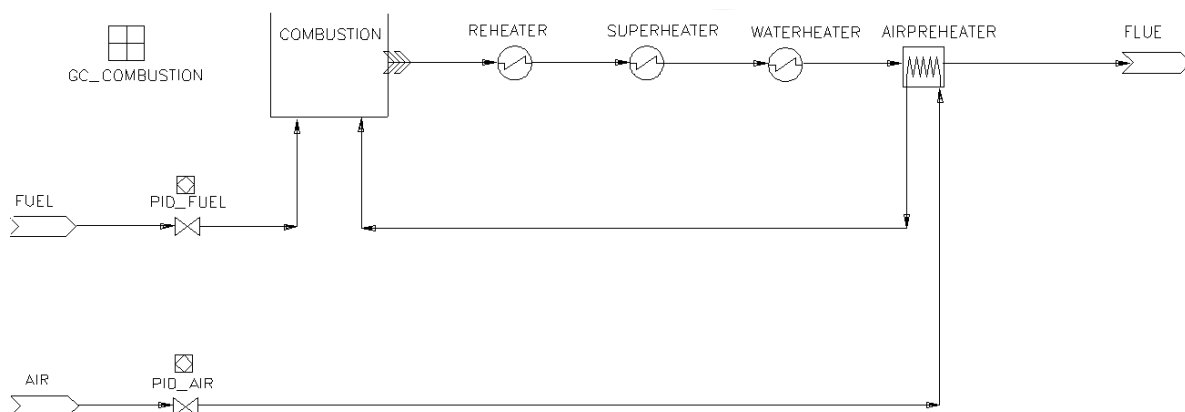

Figure 5. Boiler Combustion Model

3.3.2.1. (Boiler) combustion

The combustion model used a tank model built in SysCAD to perform the transformation of chemical energy to heat energy. A reaction sub-model was configured to perform that transformation. The chemical composition of the fuel was supplied by the plant and defined in the feed of the combustor named FUEL. The reactions and their extent were defined in a reaction editor of the tank model. The chemistry of combustion is complex and depends on many different factors. It was assumed that there is sufficient air supplied to complete the combustion of coal in air. Nevertheless, the stoichiometric chemical equations used here were placed in a logical order based on the chemical affinity of the components.

The power plant uses thermal coal supplied from nearby coal mines. The gross calorific value (GCV) of the coal at dry ash free (daf) conditions is 30.06 MJ/kg while at air dried (ad) conditions it is 20.80 MJ/kg. Data on the composition of the coal was supplied by the power plant and is presented in Table 3.

Proximate Analysis	Ultimate Analysis
Moisture 10.9% Ash 18.9% Volatile Materials 23.7% Fixed carbon 46.5%	Carbon 78.1% Hydrogen 3.9% Nitrogen 1.1% Sulphur 0.2% Oxygen 16.7%

Table 3. Coal Property Data

As mentioned earlier, chemical reactions were performed in reaction editor in SysCAD. In the reaction editor reaction, extent and sequence is provided. The combustion reaction for this modelling purpose is provided in Table 4.

Reaction	Extent	Sequence
$2\ H_2(g) + 1\ O_2(g) = 2\ H_2O(g)$	Fraction $H_2(g) = 1$	1
$1\ S(s) + 1\ O_2(g) = 1\ SO_2(g)$	Fraction $S(s) = 1$	2
$1\ C(s) + 1\ O_2(g) = 1\ CO_2(g)$	Fraction $C(s) = 1$	3
$1\ H_2O(l) = 1\ H_2O(g)$	Fraction $H_2O(l) = 1$	4

Table 4. Combustion Reaction

Using the SysCAD property database the simulation calculates the heat of reaction (HOR) of each reaction in the combustor and then sums up all HORs to calculate overall HOR of full combustion. An environmental heat exchange is configured to allow for some heat lost to the environment from the combustor.

3.3.2.2. Water heater (economiser), superheater and reheater

These three components were modelled using the simple heater model built in SysCAD. The simple heater does not consider heating media or heater size. It only provides an estimation of heater duty required at stream outlet temperature or stream outlet temperature for specific heater duty. It can also be configured to specify heater duty irrespective of temperature. In this model, the heaters were configured to supply a specific amount of heat through heater duty calculated in the boiler and reheater in the power generation model by a so-called duty method in SysCAD. Only the duty of such heating was calculated for these heaters.

3.3.2.3. Air preheater

The air preheater in this flowsheet was built using the heat exchanger model described previously. The process is air/air heat transfer and the heat transfer coefficient used here is 150 w/m^{2}K, which is lower than the value used for most of the liquid/liquid heat transfer.

3.3.2.4. Control and calculation in combustion model

In this model, three control elements were used. One was GC_COMBUSTION, a general controller and the other two were PIDs, one for fuel and the other for air. GC_COMBUSTION calculates the amount of fuel and excess air required to complete the combustion in the combustor. The two PIDs for fuel and air regulate the required fuel and excess air to achieve a set point. The set point for excess air was 10% as supplied by the plant. The fuel requirement of the combustion was set dependent on the energy requirements in boiler and reheating in power generation model. This has increased the functionality of the model to produce any set amount of power output. Similar to the power generation model, in pipes at different points of the boiler combustion model, code was applied to perform the exergy calculation using the Model Procedure (MP) of SysCAD.

4. Energy analysis and efficiency improvement

Energy analysis of a process is very important for identifying where energy is lost. It is performed through a process energy balance. This essentially considers all energy inputs in and outputs out of the system. When the system is balanced, the sum of all energy inputs equals the sum of all energy outputs. In a power generation plant, the objective is to convert the maximum possible energy input into useful work. According to the second law of thermodynamics, due to thermodynamic irreversibility not all energy input is converted in to useful work.

Traditionally, the energy analysis of a process is performed through energy balance based on the first law of thermodynamics. It focuses on the conservation of energy. The shortcoming of this analysis is that it does not take into account properties of the system environment, or degradation of energy quality through dissipative processes [12]. In other words, it does not take account of the irreversibility of the system. Moreover, the first law analysis often gives a

misleading impression of the performance of an energy conversion device [4-6]. Getting an accurate estimate warrants a higher order analysis based on the second law of thermodynamics, as this enables us to identify the major sources of loss and shows avenues for performance improvement [7]. This essentially refers to exergy analysis that characterises the work potential of a system with reference to the environment.

4.1. Energy balance calculation

The energy balance was performed for the whole power generation process. As it was assumed that the energy lost in pipes is negligible, the loss of energy in process components represents the loss of energy of the whole process. The analysis was, therefore, performed to balance energy flow against all process components such as the boiler, turbine, and heat exchangers. This calculation provided information about where and how much energy is lost. The process model developed in SysCAD performs mass and energy balances considering all the input and output streams and heat and work into and out of each component. The equations used for these balances are provided in Equations 5, 6 and 7.

The mass balance for a unit process

$$\sum_{i=1}^{i} m_i = \sum_{o=1}^{o} m_o \tag{5}$$

where m is mass flow rate in Kg/s

The energy balance for a unit process

$$\sum_{i=1}^{i} E_i + \dot{Q} = \sum_{o=1}^{o} E_o + \dot{W} \tag{6}$$

where E is energy flow, $\dot{Q}$ heat flow and $\dot{W}$ is work flow in Kg/s

The energy flow of the stream was calculated as

$$E = \dot{m}h \tag{7}$$

where h is specific enthalpy in kJ/Kg and the potential and kinetic energy of the stream are ignored.

In order to obtain a balance of energy flow against different components of the power plant Figure 6 is used. The points in these figures were chosen very carefully so that they could describe the inflow and outflow of energy carried by streams to and from each component. The work inflows and outflows were observed from the SysCAD process energy balance and were used in balance calculations where they applied.
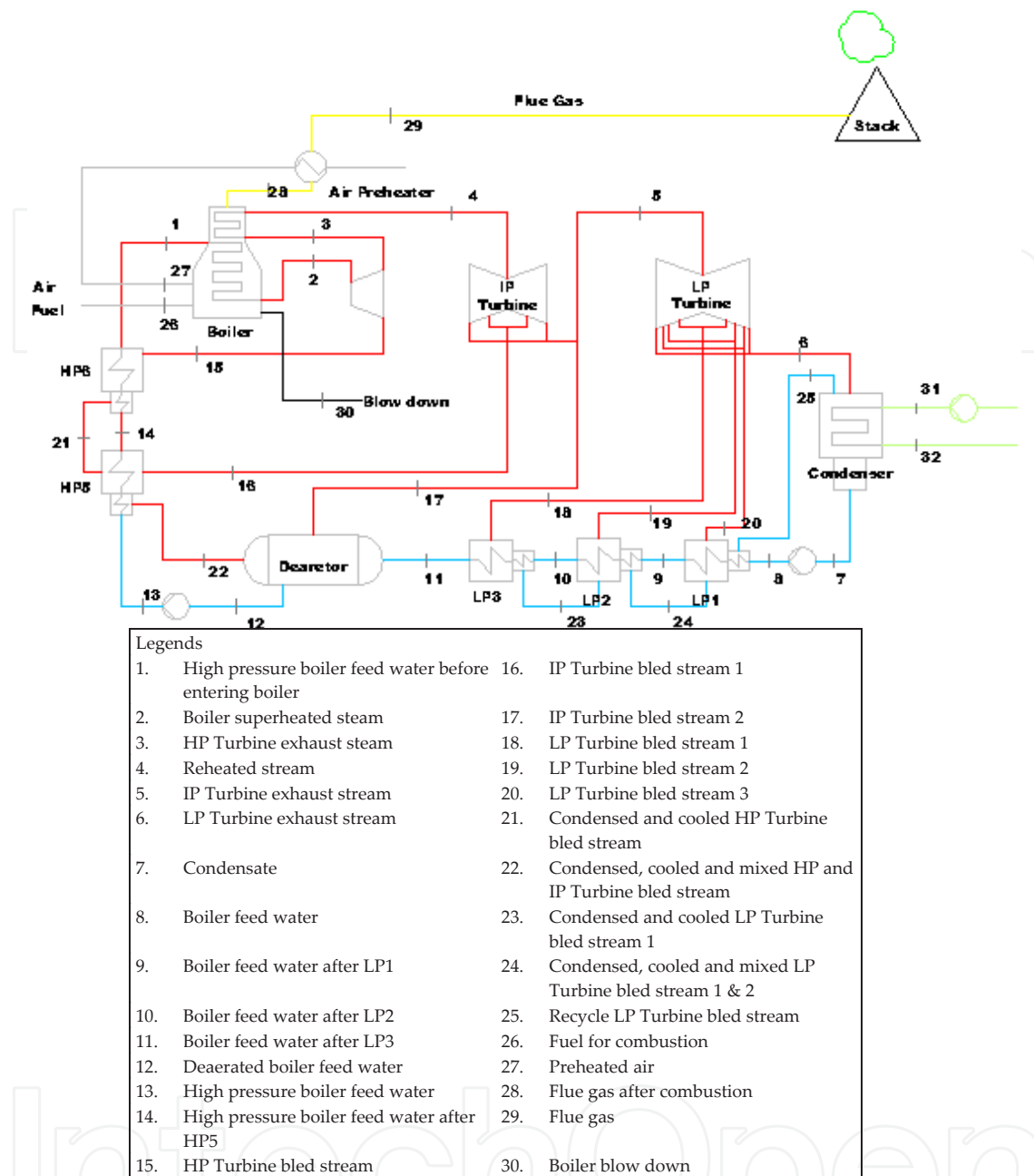
Figure 6. Points of Energy and Exergy Flow in Power Plant

The energy flows at the mentioned points were obtained directly from the SysCAD process balance at each mentioned point and exported to Microsoft Excel. It is important to note here that as potential and kinetic energy of the stream was ignored, SysCAD calculated the energy flow of the stream using Equation 7. The work in and out of the components, particularly in different stages of turbine and pumps, were found in the SysCAD process balance. Therefore, the balance of energy flow was calculated observing all energy into and out of each component in the form of either heat or work. The details of energy balance calculations were performed in Microsoft Excel across various process equipment using equations provided in Table 5.

Components	Energy Balance Equation
Boiler	$E_{26} + E_{27} + E_1 + E_3 = E_2 + E_4 + E_{28} + E_{30} + E_{l(Boiler)}$
HP Turbine	$E_2 = E_3 + E_{15} + W_{(HP\ Turbine)} + E_{l(HP\ Turbine)}$
IP Turbine	$E_4 = E_5 + E_{16} + E_{17} + W_{(IP\ Turbine)} + E_{l(IP\ Turbine)}$
LP Turbine	$E_5 = E_6 + E_{18} + E_{19} + E_{20} + W_{(IP\ Turbine)} + E_{l(LP\ Turbine)}$
Condenser	$E_{25} + E_6 = E_7 + E_{l(Condenser)}$
Condensate Pump	$E_7 + W_{(Condensate\ Pump)} = E_8 + E_{l(Condensate\ Pump)}$
LP1	$E_{24} + E_{20} + E_8 = E_9 + E_{25} + E_{l(LP1)}$
LP2	$E_{23} + E_{19} + E_9 = E_{10} + E_{24} + E_{l(LP2)}$
LP3	$E_{18} + E_{10} = E_{11} + E_{23} + E_{l(LP3)}$
Deaerator	$E_{22} + E_{17} + E_{11} = E_{12} + E_{l(Deaerator)}$
Feed Pump	$E_{12} + W_{(Feed\ Pump)} = E_{13} + E_{l(Feed\ Pump)}$
HP5	$E_{22} + E_{21} + E_{16} = E_{14} + E_{22} + E_{l(HP5)}$
HP6	$E_{14} + E_{15} = E_{21} + E_{l(HP6)}$

Table 5. Energy Balance in Power plant and Capture Process

Here, E represents energy flow in kW. The subscripts used in the energy balance represent point numbers in Figure 6. E with subscript l represents energy lost and the corresponding process is mentioned in the subscript within the bracket. W represents work and the corresponding process component is mentioned in the subscript within the bracket.

4.2. Exergy balance calculation

Exergy can be defined as 'work potential', meaning the maximum theoretical work that can be obtained from a system when its state is brought to the reference or ''dead state' (under standard atmospheric conditions). The main purpose of exergy analysis is to identify where exergy is destroyed. This destruction of exergy in a process is proportional to the entropy generation in it, which accounts for the inefficiencies due to irreversibility. Exergy analysis helps in identifying the process of irreversibility leading to losses in useful work potential and thus pinpointing the areas where improvement can be sought.

Rosen [6] identified various exergy studies conducted by different researchers and found the significance of application for process energy analysis whether it is small or large but particularly more important for energy intensive ones e.g., power generation where large scale energy conversion happens. From this point of view, exergy analysis for power plants can be useful for identifying the areas where thermal efficiency can be improved. It does so by providing deep insights into the causes of irreversibility.

The exergy is thermodynamically synonymous to 'availability' of maximum theoretical work that can be done with reference to the environment. Som and Datta [13] define specific exergy, a (in kJ/Kg) in general terms as in Equation 8.

$$a = k + \varnothing + (u - u_r) + p_r(v - v_r) - T_r(s - s_r) + a_{ch}$$
$$\underbrace{\qquad\qquad\qquad\qquad\qquad}_{\text{Physical Exergy}} \quad \underbrace{\qquad}_{\text{Chemical Exergy}} \tag{8}$$

where k (in kJ/kg) is the specific kinetic energy of the system and $\varnothing$ (in kJ/kg) is the potential energy per unit mass due to the presence of any conservative force field. T (in K), p (kN/m2), u (in kJ/kg), v (m3/Kg) and s (kJ/Kg-K) are the temperature, pressure, specific internal energy, specific volume and specific entropy, respectively, while a_{ch} represents the specific chemical exergy. The terms with the subscript r are the properties of the exergy reference environment. The generalised equation above can be simplified or specified based on a process. The kinetic and potential energies are small in relation to the other terms, and therefore they can be ignored.

The exergy flow was calculated at different points before and after the process components in different streams. The exergy of a stream was treated for both physical and chemical exergy. The physical exergy accounts for the maximum amount of reversible work that can be achieved when the stream of a substance is brought from its actual state to the environmental state.

According to Amrollahi et.al. [14] this can be evaluated as

$$a = (h - h_r) - T_r(s - s_r) \tag{9}$$

where h is the specific enthalpy in kJ/Kg.

This equation was applied for all liquid streams in the power plant. For gas streams this equation was reorganised in terms of specific heat of gas c_p and evaluated as

$$a = c_p(T - T_r) - c_p T_r ln\left(T / T_r\right) \tag{10}$$

where c_p is the specific heat in kJ/kgK.

The reference environment mentioned earlier was considered as temperature 27.8 °C and pressure 101 kPa. At this temperature and pressure, the enthalpy and entropy were obtained for water. Using Equation 9 exergy flow at different points of the power plant steam cycle was

calculated. Equation 10 was applied to the different gas streams such as the air stream entering combustion and the flue gas following combustion.

The exergy flow rate can be calculated with the following equation

$$A = ma \tag{11}$$

where A is exergy flow rate in kJ/s

The fuel enters the combustion at the reference environmental condition. Therefore, it enters the boiler combustor with only the chemical exergy with it. The chemical exergy flow of the fuel was calculated through Equation 12.

$$A = \sum_{i=1}^{i} \Psi_i {}^* \Phi_i \tag{12}$$

where A in kJ/s, Ψ is Molar flow in kmol/s and Φ is Molar Exergy in kJ/kmol.

Standard Molar Exergy at 298 °C and 1 atm was found in the appendix of Moran and Shapiro [8] and used in Equation 12 to calculate exergy flow with fuel. The values of molar exergy of important chemical species in standard conditions are presented in Table 5. The reference temperature is slightly higher than this temperature. At this small temperature difference, the change of molar exergy is negligible and therefore ignored.

Components	Molar Exergy in (kJ/kmol)
Carbon	404590
Hydrogen	235250
Sulphur	598160
Oxygen	3950
Water Vapour	8635
Nitrogen	640

Table 6. Molar Exergy in Standard Condition

Once the exergy flows of all input and output streams were calculated, and the work inputs or outputs were obtained from different components, the destruction of exergy could be calculated by using Equation 13 after calculating all exergy inputs and outputs for a unit operation.

$$\sum_{i=1}^{i} A_i = \sum_{o=1}^{o} A_o + A_d \tag{13}$$

where subscripts i, o and d are input, output and destruction.

The simulation of the whole process model produces process a mass and energy balance. The simulation performed the balance at steady state using the configuration inputs provided to each component described in section 3.3. There is a wide range of thermo-physical data available in addition to process mass and energy balances. Using those data the exergy flow calculation was performed at the different points. Equations 9~12 are used to calculate specific exergy and exergy flow at different points.

The balance of exergy flow against different components of the power plant was performed individually for each component observing exergy flows into and out of the component. Equation 13 is used to calculate an exergy balance which is similar to energy balance calculation described earlier. The same points in the power plant were used to observe the exergy flow of the streams as in the energy balance calculation. Similar to the energy flow calculation, the work inflow and outflow were obtained from the SysCAD process energy balance and were used in exergy balance calculations where they applied. The details of the exergy balance calculations of the power plant are presented in Table 7. As was the case for the energy balance calculation, the results of the exergy balance were exported to Microsoft Excel where, using equations described in Table 7, the exergy balance for all individual components was performed.

Components	Exergy Balance Equation
Boiler	$A_{26} + A_{27} + A_1 + A_3 = A_2 + A_4 + A_{28} + A_{30} + A_{d(Boiler)}$
HP Turbine	$A_2 = A_3 + A_{15} + W_{(HP\ Turbine)} + A_{d(HP\ Turbine)}$
IP Turbine	$A_4 = A_5 + A_{16} + A_{17} + W_{(IP\ Turbine)} + A_{d(IP\ Turbine)}$
LP Turbine	$A_5 = A_6 + A_{18} + A_{19} + A_{20} + W_{(IP\ Turbine)} + A_{d(LP\ Turbine)}$
Condenser	$A_{25} + A_6 = A_7 + A_{d(Condenser)}$
Condensate Pump	$A_7 + W_{(Condensate\ Pump)} = A_8 + A_{d(Condensate\ Pump)}$
LP1	$A_{24} + A_{20} + A_8 = A_9 + A_{25} + A_{d(LP1)}$
LP2	$A_{23} + A_{19} + A_9 = A_{10} + A_{24} + A_{d(LP2)}$
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Feed Pump	$A_{12} + W_{(Feed\ Pump)} = A_{13} + A_{d(Feed\ Pump)}$
HP5	$A_{22} + A_{21} + A_{16} = A_{14} + A_{22} + A_{d(HP5)}$
HP6	$A_{14} + A_{15} = A_{21} + A_{d(HP6)}$

Table 7. Exergy Balance in Power Plant

In Table 7, the notation A represents exergy flow rate in kW. The subscript number in this table represents the point number in Figure 6. A with subscript d represents exergy destruction in the corresponding process mentioned within the bracket. W represents work and the corresponding process component is mentioned in a subscript within the bracket.

5. Result and discussion

As mentioned earlier, exergy analysis is performed to assess the loss of useful work potential; that is, the exergy destruction. The result of the exergy balance performed in the power plant is presented in Figure 7. In this figure, the exergy destruction is shown in percentages for different components of the power plant. The reason behind choosing percentage of total exergy destruction in different components is that these figures can easily be used to locate where the maximum exergy is destroyed. In other words, they can help direct the focus of the improvement by considering the components where most of the exergy is destroyed. The reason why this amount of exergy is destroyed is also important for identifying how best to reclaim the lost energy back in the process.
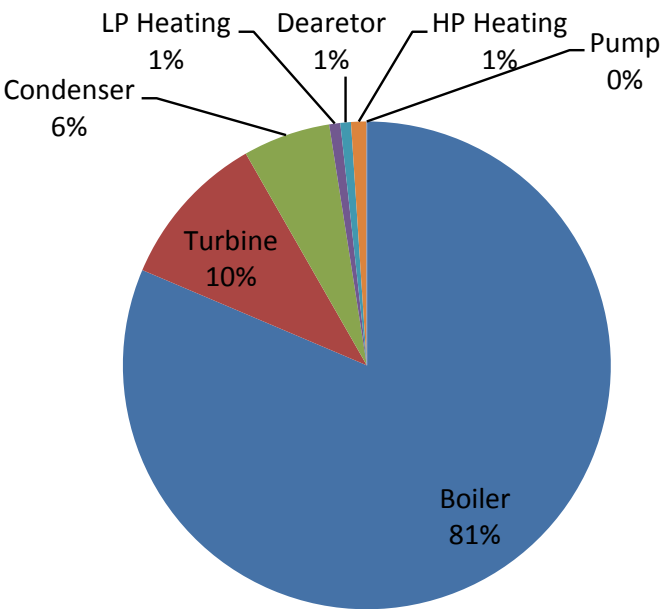

Figure 7. Exergy Destruction (%) in Power Plant

Figure 7 shows the result of this exergy destruction analysis. Most of the exergy is destroyed in the boiler, which accounts for 81% of total exergy destroyed in the power plant. It is important to note that the boiler includes both reheating of steam after expansion in the high-pressure turbine and preheating of air coming into the combustor. The second-largest source is the turbine where about 10% of the exergy is destroyed. These two components of the plant contribute more than 90% of the total exergy loss of the whole plant. The condenser is the third-largest contributor with about 6% of the exergy loss. The results of exergy analysis are markedly different from the results of the energy balance, which shows most of the energy being lost in the condenser.

A comparison of results of the energy and exergy balances in the power plant was conducted and the results are presented in Figure 8. It shows that there are very significant differences between exergy destruction and energy lost for different process components. It is important

to mention here that only major components in the power plant, where most of energy or exergy loss or destruction take place, are considered in this comparison.

The energy balance showed that the primary source of energy loss is the condenser where 69% of the total loss occurs. In contrast, the exergy analysis showed that the loss from the condenser was only 6% of the total. According to the energy balance, the second-largest source of energy loss is the boiler, which accounts for 29%. However, the exergy balance revealed that the loss of useful work potential is in the boiler, with losses of more than 80%. It has been observed that there is a huge amount of energy lost in the condenser but the amount of useful energy, that is, exergy, is not very significant. In other words, it indicates that the waste heat in the condenser does not have much potential to be utilised as a source of work and to improve the efficiency the power plant. On the other hand, further investigation of the exergy lost in the boiler may show some opportunities for improvement.
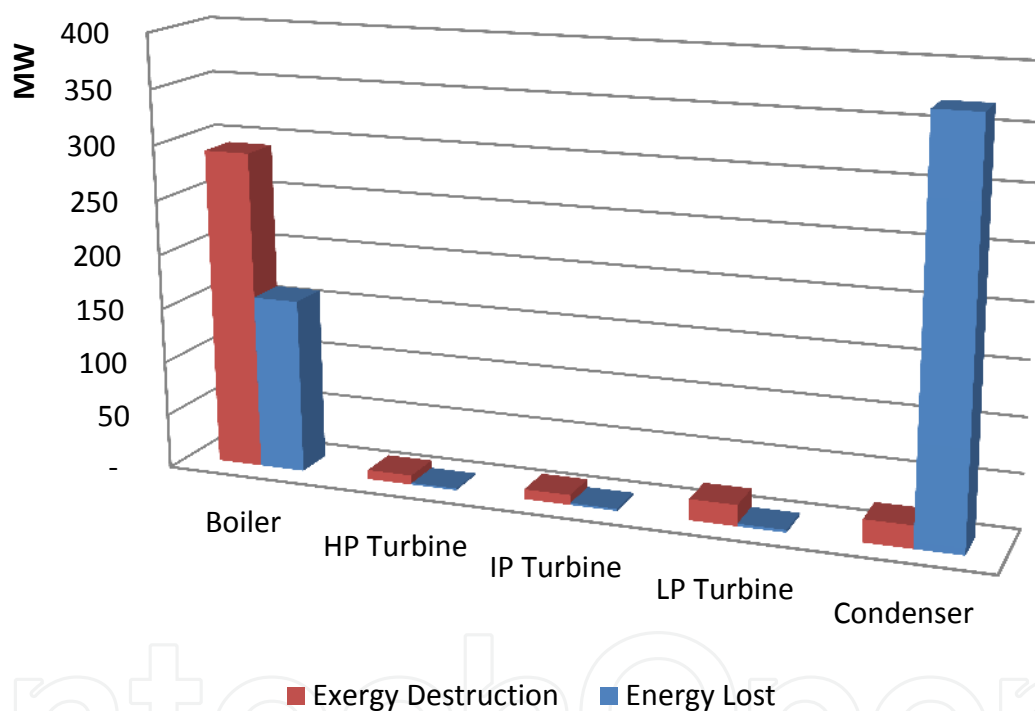

Figure 8. Exergy Destruction vs. Energy Loss in Power Plant

In an attempt to improve the efficiency of the power plant, the exergy analysis was revisited. It is found that the largest exergy destruction in the process occurs in the boiler. Therefore, it is considered first for a detailed investigation. It has been found that there are three elements which contribute to the huge boiler loss. They are 1) the boiler's internal heat transfer mecha‐ nism from the combustor to the heating medium, which determines the boiler's internal efficiency, 2) the heat loss in the departing flue gas stream and 3) the loss in the blowdown stream of the boiler. The contribution of the three losses of exergy flow in the boiler is presented in Figure 9. The simulation at steady state (280 MW electrical power output) showed that the flue gas after air preheating is leaving with an exergy flow of 4871 kW which constitutes about

2% of the total boiler exergy lost. The blowdown stream of the boiler is another source of boiler exergy destruction. It carries about 718 kW exergy flow. The boiler's internal heat transfer mechanism is responsible for most of the exergy loss occurs in the boiler.
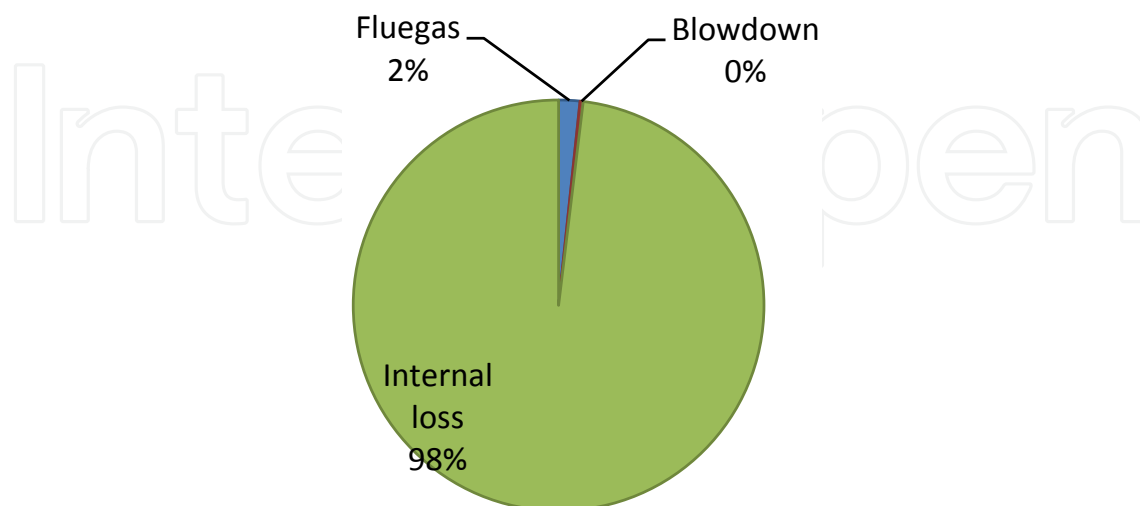

Figure 9. Boiler Exergy Losses in %

The exergy loses from flue gas and blowdown stream could be easily reutilised in the process through some heat recovery systems. However, the greatest single amount of exergy is destroyed in the boiler's internal heat transfer arrangement. If the exergy lost through the boiler could be utilised in the system, this would improve the efficiency of the power plant very significantly. The chemical reactions occur in the boiler at a temperature of 1885ºC and produce huge amounts of exergy. However, due to the limitations of the material used in the boiler, it is not capable of transferring the full amount of useable heat energy or exergy to the boiler feed water which is heated to only 540ºC. In modern power plants, this limitation has received much attention with the invention of new materials for heat transfer used in boilers. However, the power plant used as the subject of this study was an aging plant. The improvements needed to address such a big loss would require huge physical changes of the boiler system and may need further detailed investigation in terms of both technical and economic viability.

The exergy lost in the turbine is investigated by looking at the losses at different stages of the turbine. The exergy lost in all three turbine stages is found to be due to the turbine's internal performance. This can be better described as converting thermal energy to mechanical energy and then to electrical power. The turbine system used in the plant is highly compact and specially designed for the process. Therefore, the task of reducing exergy destruction or improving the efficiency of the turbine system is very specialised (in terms of its internal system). Similar to the boiler system improvement, it also needs further detailed investigation to assess the technical and economic feasibility of such changes.

It is noted that there are opportunities to improve energy efficiency of power plants by improving the performance of the boilers and the turbine system. The current trends towards ultra-supercritical power plant cycles are consistent with this aim.

6. Conclusions

In this study, exergy analysis of the power plant identifies areas where most of the useful energy is lost and discusses potential of the lost energy for improvement of the plant energy efficiency. It shows that the boiler of a subcritical power generation plant is the major source of useful energy lost. Only negligible amounts of useful waste energy can be recovered through implementing some heat recovery system. In order to achieve significant improvement of energy efficiency the boiler and turbine systems need to be altered, which require further techno-economic study.

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