ID: 2016-ISFT-400

Exergy Analysis of Coal Fired Thermal Power Plant: A Review

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Abstract: *In thermodynamics, exergy of a system is the maximum useful work possible during a process that brings the system into equilibrium with a heat reservoir. In case the surrounding is the reservoir, exergy is the potential of a system to cause a change as it achieves an equilibrium with its environment. Exergy, in other words, is the energy that is available to be used.*

As energy analysis is based on the First law of Thermodynamics, it has some inherent demerits like not accounting for properties of the system environment, or degradation of the energy quality through dissipative processes. Also, it doesn't characterize the irreversibility of the processes within the system. In contrast, it characterizes work potential of the system. This is when the exergy analysis comes into play. It represents a good standard to estimate the maximum obtainable work from a given form of energy using the state of the surrounding as reference point. Exergy analysis, however, isn't a substitute for first law analysis. Rather, it is a supplement. Various researchers have conducted a thermodynamic analysis of a subcritical boiler-turbine generator under varying parameters of pressure, temperature and flow rate, in order to determine the ways to enhance plant efficiency. Also, the data on exergy loss distribution manifests that boiler and turbine irreversibilities account for the highest exergy losses in the power plant. Therefore, efforts at improving the power plant performance should be directed at improving boiler efficiency, since this will lead to maximisation of plant efficiency. Another scholar, in his research, found that sliding pressure operation is better than constant pressure operation at part loads due to reduced throttling losses at part-load operation. Also, a large reduction in rate of exergy destruction has been observed for turbine. Hence, turbine should be operated at varying pressure at part load in order to maximise its efficiency.

Keywords: *Energy, exergy, Thermal power plant, efficiency, Rankine cycle.*

1. INTRODUCTION

Throughout the history, the emergence of civilizations has been characterized by the discovery and effective application of energy to society's needs. The *status quo* bolsters the fact as per capita energy consumption determines the level of development of a nation. Currently, 80% of the electricity produced comes from the fossil fuels (coal, petroleum, fuel-oil, natural gas), whereas the rest 20% is derived from different sources such as hydraulic, nuclear, wind, solar, biogas. The sustained dependence on fossil fuels is due to the fact that renewable sources haven't advanced to that state yet, from where they can replace fossil fuels. Moreover, with the increased global awareness that the fossil fuels are limited, steps to ensure judicious utilization of existing resources are being taken painstakingly across the globe [1]. Nations are re-evaluating their existing energy policies and revising the same in order to implement more eco-friendly, energy-efficient technology. Subsequently, it's high time to realize that fossil fuel plants reduce their environmental impact and at the same time, operate more efficiently. It is then when the need of efficient analysis arises and various thermodynamic analyses come into play.

Thermodynamics, by definition, is the science of energy, which deal with the best possible use of the available resources. It has been derived from the Greek words *therme,* meaning heat, and *dynamics,* meaning force [2]. The science of thermodynamics is primarily built on two fundamental natural laws, known as the *First Law of Thermodynamics* and *Second Law of Thermodynamics*, or the first and second laws, respectively. The first law simply states the conservation of energy principle. It asserts that energy is a thermodynamic property, which, while an interaction, changes from one form to another, but is never destroyed. But then, it is the very flaw for which first law analysis or the energy analysis isn't alone sufficient to make an efficient system. In other words, first law doesn't account for the factors which determine quality of energy. An energy analysis doesn't account for the system irreversibilities. It characterizes work potential of the system instead. The energy analysis therefore, isn't complete. [3]

The second law of thermodynamics asserts that energy has both quantity and quality, and actual processes occur in the direction of decreasing quality of energy. In other words, a high temperature thermal energy is degraded as it is transferred to a lower temperature body. This gives rise to the concept of entropy and exergy. Exergy analysis represents a good standard to estimate the maximum obtainable work from a given form of energy using the state of the surrounding as reference point. It, however, isn't a substitute for first law analysis. Rather, it is a supplement. [3]

2. WORKING CYCLE

Coal based thermal power plants generally operate on Rankine cycle. In many ideal vapour power cycles such as Carnot cycle, associated impracticalities can be eliminated by superheating the steam in the boiler and condensing it completely in the condenser.

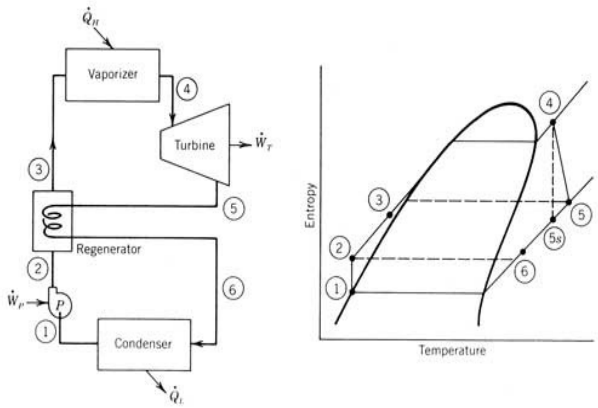

Fig. 1 Simple Rankine cycle.

The fundamental form of energy with which thermal stations are principally concerned are heat and work. Heat produces work and this work is further converted into electrical energy through a medium i.e. electrical generator. For this purpose, a *power cycle* is used. A power cycle continuously converts heat (energy released by the burning of fuel) into work (shaft work), in which a working fluid (here water) repeatedly performs a succession of processes. The working fluid undergoes phase change. Heat is transferred to water in the boiler from an external source (furnace, where fuel is continuously burnt) to raise steam, the high pressure, high temperature steam leaving the boiler expands in the turbine to produce shaft work, the steam leaving the turbine condenses into water in the condenser (where cooling water circulates), rejecting heat, and then the water is pumped back to the boiler. For each process in the vapour power cycle, it is possible to assume a hypothetical or ideal process which represents the basic intended operation and involves no extraneous efforts. For the steam boiler, this would be a reversible constant pressure heating process of water to form steam, for the turbine the ideal process would be a reversible adiabatic expansion of steam, for the condenser it would be a reversible constant pressure heat rejection as the steam condenses till it becomes saturated liquid, and for the pump, the ideal process would be the reversible adiabatic compression of this liquid ending at the initial pressure. When all these four processes are ideal, the cycle is an ideal cycle, called a *Rankine cycle*. [4]

In reheat cycle, the steam, after partial expansion in the turbine is brought back to the boiler, reheated by combustion gases and then fed back to the turbine for further expansion. The main purpose of reheating is to increase the dryness fraction of steam passing through the lower stages of the turbine. [4]

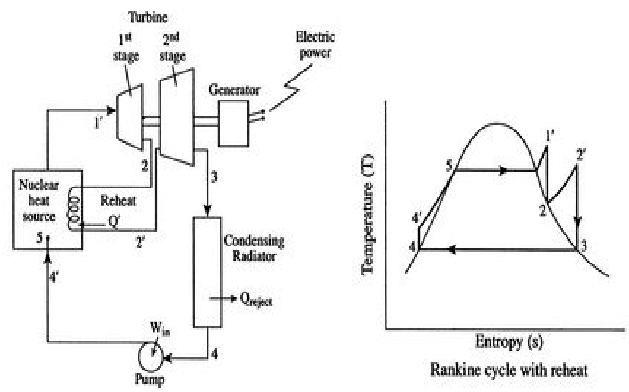

Fig. 2. Rankine Cycle with reheat.

The unique feature of ideal regenerative cycle is that the condensate, after leaving the pump, circulates around the turbine casing, counter-flow to the direction of vapour flow in the turbine. Thus it is possible to transfer heat from the vapour as it flows through the turbine to the liquid flowing around the turbine. [4]

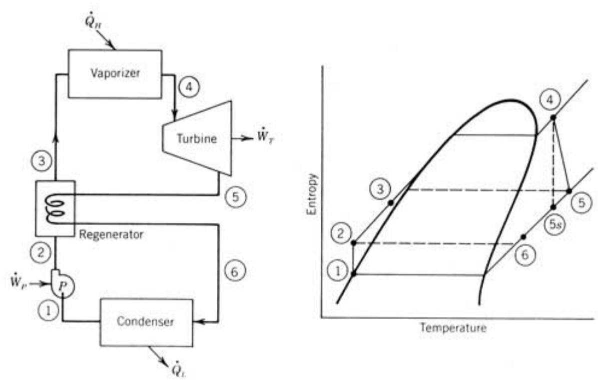

Fig. 3. Rankine cycle with regeneration

3. DESCRIPTION OF COAL-FIRED PLANT

We are considering that the coal-fired thermal power plant under analysis is equipped with all efficiency increasing techniques such as lowering the condenser pressure, superheating the steam to high temperatures, increasing the boiler pressure, reheat and regenerative Rankine cycle. A continuous mass flow diagram for one unit of the power plant modelled in this study includes the main components such as high, intermediate and low pressure turbines (HPT, IPT & LPT), number of pumps, a boiler (B), a de-aerator

(D), a generator (Gen.), a condenser (C), low and high pressure feed water heaters (LPH & HPH). These thermodynamic models are based on fundamental mass and energy balances. By using the same for each component in the power plant model, it is possible to compute energy and exergy contents in terms of turbine power outputs, pump power consumptions, boiler heat requirements, energy and exergy flows at each node of the plant, component first and second efficiencies, component irreversibilities in the plant, and so on**.** [5]

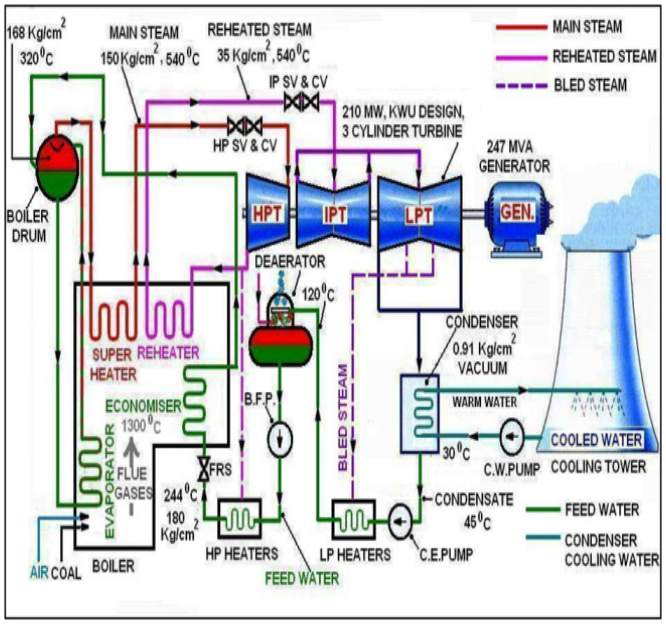

Fig. 4. Coal-fired Thermal Power plant

4. EXERGY ANALYSIS

Exergy is defined as the maximum amount of work which can be produced by a system or a flow of matter or energy as it comes to equilibrium with a reference environment. Exergy is a measure of the potential of the system or flow to cause change, as a consequence of not being completely in stable equilibrium relative to the reference environment. Unlike energy, exergy is not subject to a conservation law (except for ideal, reversible processes). Rather, exergy is consumed or destroyed, due to irreversibilities in any real process. The exergy consumption during a process is proportional to the entropy created due to irreversibilities associated with the process.

For exergy analysis, the state of the reference environment, or the reference state, must be specified completely. This is commonly done by specifying the pressure, temperature and chemical composition of the reference environment. The result of exergy analysis, consequently, are relative to the specified reference environment, which in most applications is modelled after the actual local environment. The exergy method is useful for furthering the goal of more efficient energy-resource use, for it enables the location, types, and true magnitudes of wastes and losses to be determined. In general, more meaningful efficiencies are evaluated with exergy analysis rather than the energy analysis, since exergy efficiencies are always a measure of approach to the ideal case. Therefore, exergy analysis can reveal whether or not and by how much it is possible to design more efficient energy systems by reducing the inefficiencies in existing systems. Many engineers and scientists suggest that the thermodynamic performance of a process is best evaluated by performing an exergy analysis in addition to or in place of conventional energy analysis because exergy analysis happens to provide more insights and to be more useful in efficiency improvement efforts than energy analysis.

S.C. Kaushik et al had carried out a detailed exergetic analysis of the coal fired thermal power plant by ignoring the kinetic and potential change. The flow availabilities of different species at inlet and outlet of the boiler have been evaluated with respect to an exergy reference thermodynamic state of $P_r = 101.35$ KN/m^2, $T_r = 298.15$ K with mole fractions of constituents as $x_r^{O_2} = 0.2035$, $x_r^{CO_2} = 0.0003$, and $x_r^{H_2O} = 0.0303$ as recommended by Morian and Shapiro. Som et al. prepared a theoretical model of exergy balance (based on availability transfer and flow availability) in order to evaluate the total thermodynamic irreversibility and second law efficiency of the process at various operating conditions. The fuel considered in this analysis is as follows: 70.2% C, 5.7% H, 13.4% O, 1.9% N, and 8.8% ash. He observed that the second law efficiency decreases with increase in inlet air pressure, while the combustion efficiency varies directly with respect to inlet pressure. Naterer et al. presented exergy and energy analysis of a subcritical boiler-turbine generator for a 32 MW coal-fired plant. He inferred that largest exergy losses occur in the boiler although it appears that energy loss in the boiler is high.

Dincer and Rosen demonstrated that**,** although energy and exergy values are dependent on the intensive properties of the reference state, the main results, however, are not sensitive to reasonable variations in these properties. However, evaluation of exact energy and exergy values are required to be taken care of in extreme cases, such as a rocket taking off from ground and flying to space, because of very high fluctuations in the dead state. Saidur et al. determined the energy and exergy efficiency of a boiler to be 72.46% and 24.89% respectively. Dincer and Rosen presented that a systematic correlation appears to exist between exergy loss rate and capital cost. Isam H. Aljundi [6], in his study, presented the energy and exergy analysis of Al-Hussein power plant in Jordan. He found in his energy balance study that about two-third of the fuel energy is lost in the condenser while only 6% is lost in the boiler. However, exergy analysis reveals that exergy destruction rate of boiler alone accounts for the 77% losses in the plant, while the condenser accounts for merely 9%.

Of the few researches done on exergy analysis of power plants, an analysis which was done on a 210 MW power plant under full-load conditions, states that the boiler produced highest exergy destruction (72 MW) followed by that of a high pressure turbine [7]. Sairam Adibhatla and S.C. Kaushik [8], in their research over a super critical thermal power plant at various load conditions over constant pressure and pure sliding pressure operations, found that sliding pressure operation of the unit at part load have several benefits. These benefits include significant reduction in the Brake fuel power consumption (BSFC), reduction in exergy destruction associated with control valve throttling leading to improved exergetic efficiency of all turbine sections and exergy destruction in BFP. P. Regulagadda et al. [9], in their research performed on a 32 MW coal-fired plant, determined that the energy and exergy efficiency for gross generator output are 30.12% and 25.38% respectively. Also, the maximum exergy destruction occurs in the boiler.

Thus, it is important to highlight that exergy analysis can lead to a substantially reduced rate in the use of natural resources and the environment pollution by reducing the rate of discharge of waste products.

5. CONCLUSIONS

The elevating interest in efficient and judicious use of energy demands an exergy method of optimization since it gives logical solutions for improving the power production potential in power plants. From the first law analysis, we infer that major energy loss occurs in the condenser. The second law analysis, on the other hand, concludes that combustion chamber is the main source of irreversibility, thereby making maximum exergy destruction in the boiler.

This may owe to the factors such as improper insulation, entropy generation and incomplete combustion in the sub-system. The irreversibility in the condenser is however insignificant because the energy lost is of low grade.

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