OPTIMIZATION AND THE EFFECT OF STEAM TURBINE OUTLET QUALITY ON THE OUTPUT POWER OF A COMBINED CYCLE POWER PLANT

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ABSTRACT

A narrow path exists to a sustainable solution which passes through careful steps of efficiency improvement (resource management) and provides environmental friendly energies. Thermal power plants are more common in many power production sites around the world. Therefore, in this current research study a comprehensive thermodynamic modeling of a combined cycle power plant with dual pressure heat recovery steam generator is presented. Since the steam turbine outlet quality is a restrictive parameter, optimization of three cases with different steam quality are conducted and discussed. In other hand, energy and exergy analysis of each components for these three different cases estimated and compared. Obtained results show that it is really important to keep the quality of the vapor at turbine outlet constant in 88% for the results to be more realistic and also optimization and data are more technically feasible and applicable.

INTRODUCTION

Energy is one of the main driving forces, which helps to sustain human life. Energy is available in several forms, e.g., heat, light, electricity. Energy, economic and environmental impact considerations have gained a lot of attentions during the last three decades. Energy resources in the market are getting less and at higher prices as the industrial revolution progress. This is due to several reasons such as the growth in global economy, depletion of energy resources, and the environmental impacts of energy production. Therefore, these energy issues are now threatening many aspects of human lives on the planet. Concerns exist regarding energy conversion from thermal sources to electrical sources. In this regard, power plants play main role in electricity production. Among different kinds of power plants, combined cycle power plants (CCPPs) gained a lot of attentions due to the fact that they are attractive in power generation field because of higher thermal efficiency rather than individual gas turbine or steam power plants. In addition, they are also important due to their relatively high energy efficiencies, low pollutant and greenhouse gas emissions, and operational flexibility. Literature on the subject shows that several efforts have been carried out on the plant optimizations. Energy consumption minimization, optimization of annual return and other approaches were used. Unlike energy, exergy is a measure of the quality of energy that can be considered to evaluate, analyze and optimize the system. Exergy analysis is utilized to define the maximum performance of a system and to specify its irreversibility. Therefore, exergy is a powerful tool for evaluating the performance of the cycle and also one objective approached usually with the lack of economic, technical and environmental feasibilities. Recently, combination of tools like exergy, economic and environmental assessments have received increasing attention around the word. Therefore the method which considered all the objectives and provides a feasible solution is currently needed by CCPPs plant designers. In this respect, different studies have been carried out to investigate the combined cycle power plants, however a few multi-objective optimization of such plant which accounts for all the three main issues simultaneously have done to the best of our knowledge.

Exergy analysis is a useful tool to find the locations, types and magnitudes of true inefficiencies (irreversibility) and recommend ways to improve the overall efficiency of the system. In the literature, there have been various studies associated with exergy analyses of plants. Lior proposed a concept about future power generation systems and the role of exergy analysis in their development. He illustrated some thoughts to meet the power demands under the constraints of increased population and land use when holding the environmental impact to a tolerable one. Next he focused on exergy analysis which would be essential in the conception and development of such processes. Finally he discussed about Surface modification is a generic term now applied to a large field of diverse technologies that can be gainfully harnessed to achieve increased reliability and enhanced performance of industrial components. The incessant quest for higher efficiency and productivity across the entire spectrum of manufacturing and engineering industries has ensured that most modern-day components are subjected to increasingly harsh environments during routine operation. Critical industrial components are therefore, prone to more rapid degradation as the parts fail to withstand the rigors of aggressive operating conditions and this has been taking a heavy toll of industry's economy. In an overwhelmingly large number of cases, the accelerated deterioration of parts and their eventual failure have been traced to material damage brought about by hostile environments and also by high relative motion between mating surfaces, corrosive media, extreme temperatures and cyclic stresses. Simultaneously, research efforts focused on the development of new materials for fabrication are beginning to yield diminishing returns and it appears unlikely that any significant advances in terms of component performance and durability can be made only through development of new alloys. As a result of the above, the concept of incorporating engineered surfaces capable of combating the accompanying degradation phenomena like wear, corrosion and fatigue to improve component performance, reliability and durability has gained increasing acceptance in recent years. The recognition that a vast majority of engineering components fail catastrophically in service through surface related phenomena has further fuelled this approach and has led to the development of the broad interdisciplinary area of *surface modifications*. Thus, a protective coating deposited to act as a barrier between the surfaces of the component and the aggressive environment that it is exposed to during which kind of development is essential for the power generation units in the coming century. The results indicated that exergy analysis will help the designers to come up with a good decision on how to improve the system performance. Rosen and Dincer conducted a comprehensive study of industrial steam heating process through exergy analysis. The results showed that using energy analysis and the technical factors that influence the feasibility of steam supplied for other energy sources in industrial heating. They presented an example for the Bruce Energy Center in Ontario, Canada to demonstrate the importance of using energy analysis to assess the feasibility of industrial steam process heating. The results suggested xergy analysis should be used as an important tool in process optimization while the use of large quantities of the steam in energy centers is considered. In recent decades, thermoeconomics and exergoeconomics have been increasingly utilized by researchers, combining thermodynamics with economics. Many such studies have been reported, especially for power generation.

Abusoglu and Kanoglu surveyed a review of exergoeconomic analysis and optimization of combined heat and power production. This paper was a review on the exergoeconomic analysis and optimization of combined heat and power production systems. They gather brief historical information on the exergoeconomics analysis and optimization. They also discussed the concept of exergy cost and cost accounting methods. Ahmadi and Dincer performed a comprehensive thermodynamic modeling of a dual pressure (HRSG). To find the best design parameters for HRSG, they applied a multi objective optimization. In this regard for this optimization two objective functions are considered. Results showed that increasing the drum pressures results to increase in HRSG exergy efficiency and a decrease in the HRSG exergy destruction rate. Nevertheless, increasing the pinch temperatures resulted in decrease in HRSG exergy efficiency and also increases in HRSG exergy destruction. One of the most important concerns for human is to reduce environmental impact of energy system and make use of sustainable energy technologies to mitigate global warming. Some exergy methods are tried to reduce exergy losses and increase exergy efficiency, But there are some ways that exergy assist to understand and reduce environmental impact. In this regards, many reports in the literature consider environmental aspects of thermal systems . Lazzaretto and Toffolo optimized an energy system from energy, economy and environmental aspects. They defined an environmental impact objective function in terms of cost by weighting CO and NO emissions considering their unit damage costs. In optimization approach, three objective functions are selected to find the optimal solutions by using evolutionary algorithm. They applied an additional objective which was the cost related to NOx and CO emissions in cost terms. In this sense, they proposed the non-abbreviated term thermoenviroeconomic for this objective.

Barzegar Avval et al. studied the thermoeconomic environmental multi objective optimization of a gas turbine power plant using evolutionary algorithm. They used multi-objective optimization in order to optimize the system for the better performance assessment. Optimization results showed the overall exergoeconomic factor of the system increases from 32.79% to 62.24% compared with the actual power plant. In another research a comprehensive thermodynamic modeling and exergoenvironmental analysis of a trigeneration system based on a micro an organic Rankine cycle and gas turbine for heating, cooling and electricity purposes are studied by Ahmadi et al.

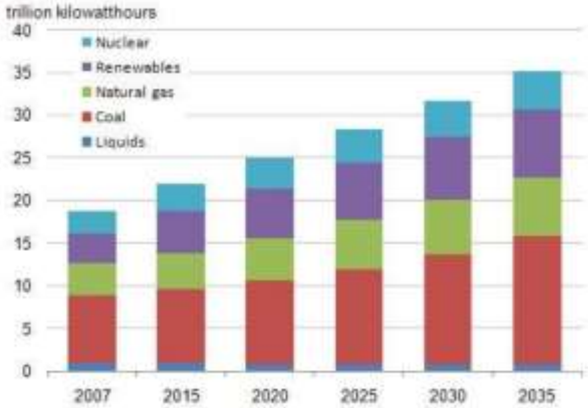
Objectives

1. A development model for a CCPP based on thermodynamic principles and energy balances. Considering three different objective functions to handle the optimization process for three different cases with different steam quality at steam turbine outlet.
2. To have a good verification results, energy efficiency, energy efficiency of the mentioned cases are evaluated and compared.
3. The environmental impacts for three different cases with different steam quality at steam turbine outlet are determined

LITERATURE REVIEW

The importance of energy and exergy analysis of different supercritical cycles is presented in Chapter 1. In view of this, literature on supercritical cycle/ultra supercritical cycle/advanced ultra-supercritical cycles, and their improvements have been reviewed thoroughly and presented in this chapter.

Lodhi revealed that fossil fuels account for about 80%, renewable energy resources contribute 14% and nuclear 6% of world annual energy use. These numbers will soon change as the world's population grows, energy demand rises, inexpensive oil and gas deplete, global warming effects continue to rise and urban pollution worsens the living conditions. The development of alternative energy sources and devices will emerge more rapidly to address the world's energy and environmental situation. Thus, the establishment of a sustainable energy is one of the most pressing tasks of humanity. With the exhaustion of fossil resources, the energy economy will change to a chemical and an electrical base. Mahendra Lalwani and Mool Singh revealed that, India consumes 7% of coal of the world where as China, U.S, Japan and rest of the world consumes 43%, 9%, 4% and 20%, respectively. 68% of world's consumption of coal for the generation of electricity. Coal-fired generation increases by an annual average of 2.3 percent, making coal the second fastest-growing source for electricity generation. World net electricity generation upto year 2007 and projected generation upto year 2035 by different fuels is shown in the Fig



World net electricity generation by fuel (trillion kilowatt-hours)

Wikipedia reveals that, the energy policy of India is largely defined by the country's burgeoning energy deficit and increased focus on developing alternative sources of energy, particularly nuclear, solar and wind energy. About 70% of India's energy generation capacity is from fossil fuels, with coal accounting for 40% of India's total energy consumption followed by crude oil and natural gas at 24% and 6% respectively. India is largely dependent on fossil fuel imports to meet its energy demands; by 2030 India's dependence on energy imports is expected to exceed 53% of the country's total energy consumption. In 2009-10, the country imported 159.26 million tons of crude oil which amount to 80% of its domestic crude oil consumption where as 31% of the country's total imports are due to oil.

Maximum efficiency of the power cycle together with a minimum investment costs and highest reliability are the overall design targets of power plant. According to International Energy Agency [135] the worldwide demand for power will increase significantly over the next decades, and the current power plant capacity will double by the year 2030. To save primary energy resources i.e. to reduce fuel consumption, and to reduce emissions, maximum power plant efficiency is a crucial parameter. Therefore, steam parameters will have to be maximized to an economically reasonable extent, so that supercritical, ultra supercritical and advanced ultra-supercritical Rankin cycles are essential to improve the efficiency.

RANKINE CYCLE: ENERGY AND EXERGY ANALYSIS

The Rankin power cycle which converts the thermal energy into mechanical energy, does not differ between critical, sub-critical, supercritical, ultra supercritical and advanced ultra-supercritical cycles.

Energy can neither be created nor destroyed. It just changes forms such as potential, chemical, electrical energy, heat and work. Energy analysis based on the first law of thermodynamics embodies the principle of conservation of energy and is the traditional method used to assess the performance and efficiency of the energy systems and processes.

The word 'Exergy' was derived from Greek words ex (meaning out) and ergon (meaning work). Exergy is the useful work potential of the energy. Exergy is not conserved. Once the exergy is wasted, it can never be recovered. When we use energy we are not destroying any energy; we are merely converting it to a less useful form, a form of less exergy. The useful work potential of a system is the amount of energy we extract as useful work. The useful work potential of a system at the specified state is called exergy (also called availability or essergy).

Exergy analysis helps in improving plant efficiency by determining the origin of exergy losses, and hence providing a clearer picture. Exergy helps in identifying components where high inefficiencies occur, and where improvements are merited. The thermodynamic cycle can often be optimized by minimizing the irreversibilities.

The ability to perform useful work in a natural environment has been suggested and investigated as a measure of energy quality by Gibbs, A. Stodola, G. Gouy, J.H. Keenan, F. Bosnjakovic and many other researchers [52]. The term exergy was suggested by Zoran Rant in 1956 to denote 'technical working capacity' but the concept was developed by J. Willard Gibbs in 1873. A complete definition was given by H.D.Baehr in 1965; exergy is that part of energy that is convertible into all other forms of energy. Exergy is a measurement of how far a certain system deviates from a state of equilibrium with its environment (Wall, 1977).

Khan described the second-law assessment of regenerative- reheat coal-fired electricity generation plant in terms of irreversibility analysis. He reported reduction in irreversible losses with the addition of backward, cascade type feedwater heater. He concluded that, incorporating reheating in a regenerative steam power cycle in subcritical range can further improve its efficiency and the total irreversible losses in the plant. These improvements become slower as the number of feed water heaters increase. The reduction in the total irreversible rate due to backward cascade feedwater heating is nearly 18%, which correspond to a 12% improvement in thermal efficiency. These estimates were increased to 24% and 14% respectively, with incorporation of reheat in addition to feedwater heating. The second-law indicates that maximum exergy is destroyed in the boiler and these thermodynamic losses are significantly reduced by the incorporation of feedwater heating.

The thermodynamic deviations resulting in non-ideal or irreversible functioning of various steam power plant components have been identified by Hermann [22]. He concluded that known exergy reservoirs and flows within our sphere of influence are more than enough to provide energy services for the increasing population and activity of humankind.

Siva Reddy V et al. [26] have reviewed on energy analysis and exergy analysis of thermal power plants. They reviewed a thermodynamic analysis of a coal based thermal power plant and gas based cogeneration power plant in terms of energy and exergy analysis for the different components of the power plants in subcritical range. They concluded that, the major energy loss was found to occur in condenser. The exergy analysis showed that combustion chamber in both steam and gas turbine thermal power plants is main source of Irreversibility. The Irreversibility in condenser is insignificant as the low quality energy is lost in the condenser. An Exergy method of optimization gives logical solution improving the power production opportunities in thermal power plants.

METHODOLOGY

Energy analysis

Energy analysis is used to determine the temperature profile in the plant. We need the properties of each point of the cycle to do the exergy analysis. Exergy analysis is used to find the exergy efficiency and exergy destruction rate and also it is necessary to do the exergo economic and environmental analysis. Energy analysis is done usually through the physical modeling. The major portion of this modeling consists of the application of the mass and energy balance equations. The energy balance equations for various parts of the CCPP are as described in the following subsections.

Air compressor (AC)

Air enters to the air compressor at ambient temperature and pressure. The outlet temperature is a function of compressor inlet temperature T1, compressor isentropic efficiency g AC, compressor pressure ratio rC and specific heat ratio ca.

$$T_2 = T_1\left\{1 + \frac{1}{\eta_{AC}}\left[r_c^{\frac{\gamma_a-1}{\gamma_a}} - 1\right]\right\} \quad W_{AC} = \dot{m}_a c_{pa}(T_2 - T_1)$$

Combustion chamber

The outlet properties of the combustion chamber are a function of air mass flow rate, fuel lower heating value (LHV) and combustion efficiency (gCC), and are related as follows:

$$\dot{m}_a h_3 + \dot{m}_{f-cc} \mathrm{LHV} = \dot{m}_g h_4 + (1 - \eta_{cc})\, \dot{m}_{f-cc} \mathrm{LHV}$$

Gas turbine

The gas turbine outlet temperature can be written as a function of gas turbine isentropic efficiency (gGT), the gas turbine inlet temperature (GTIT) and gas turbine pressure ratio (P3/P4) as follows:

$$\dot{W}_{GT} = \dot{m}_g \cdot c_{pg}(T_3 - T_4) \quad \frac{P_4}{P_3} = (1 - \Delta p_{cc})$$

Duct burner (DB)

For this CCPP the hot gases, before entering the heat recovery steam generator, enter the duct burner to raise their temperature around 70 C. The outlet properties of the duct burner are a function of gas mass flow rate, fuel lower heating value (LHV) and duct burner efficiency (gDB), and are related as follows:

$$\dot{m}_g h_4 + \dot{m}_{f-DB} \mathrm{LHV} = (\dot{m}_g + \dot{m}_{f-DB}) h_5 + (1 - \eta_{DB}) \dot{m}_{f-DB} \mathrm{LHV}$$

Dual pressure heat recovery steam generator

A HRSG with two stage pressure (low pressure (LP) and high pressure (HP)) is used in this CCPP. The pinch-point is defined as the difference between the temperature of the gas at the entrance of the evaporator (economizer side) and the saturation temperature. The dual-pressure HRSG has two pinch points (PPHP and PPLP). The temperature differences between the water leaving the economizers and the saturation temperature are the approach points (APHP and APLP), which depend on the economizer's tube layout. Note that the pinch point and approach temperatures are considered constant here. Energy balances for each element of the HRSG are expressed as follows:

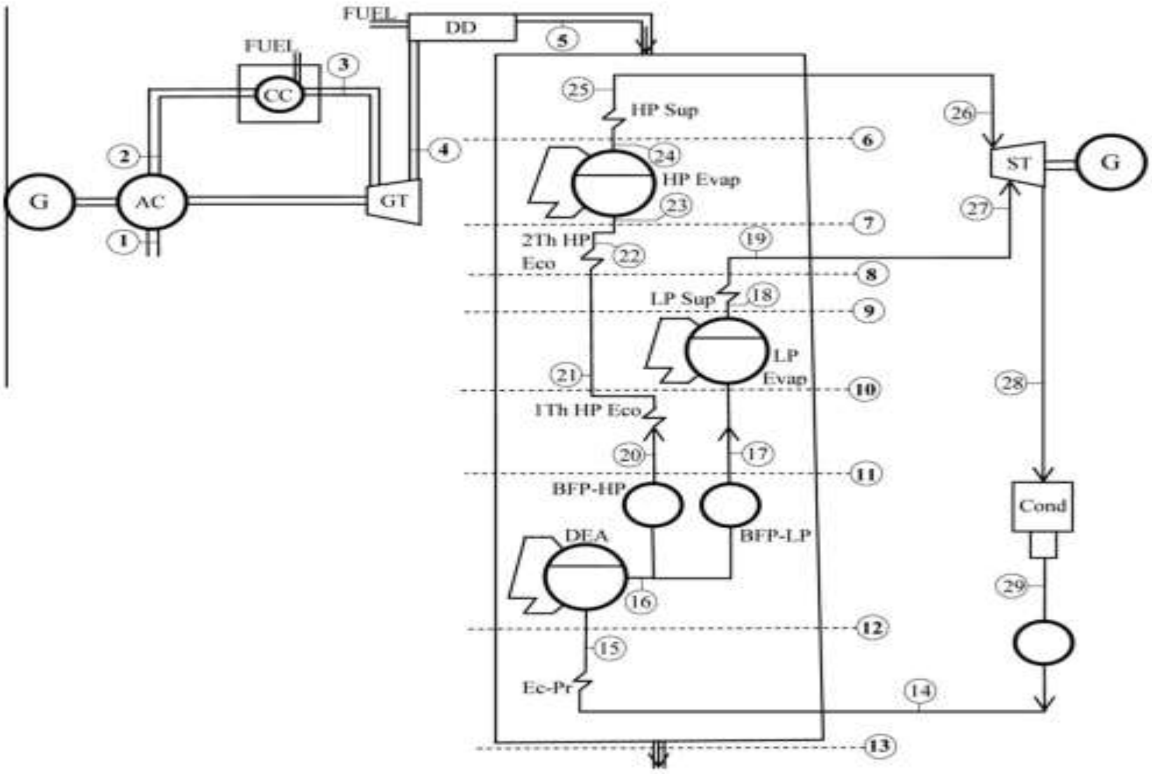


Fig. 1. Thermal schematic diagram of Neka combined cycle with dual pressure HRSG and supplementary firing unit.

Table (S/N ratio) for erosion rate is given as table and the effects of control factors on erosion rate are shown in figure.

Test Run	Impact velocity A (m/sec)	Impingement angle B (degree)	Erodent size C (micron)	Erodent temperature D (Deg. cent.)	Erosion rate Er (Mg/kg)	S/N Ratio (dB)
1	33(1)	30(1)	50(1)	30(1)	22.760	-27.1434
2	33(1)	60(2)	100(2)	50(2)	23.989	-27.6002
3	33(1)	90(3)	200(3)	75(3)	25.367	-28.0854
4	47(2)	30(1)	100(2)	75(3)	27.125	-28.6674
5	47(2)	60(2)	200(3)	30(1)	28.362	-29.0547
6	47(2)	90(3)	50(1)	50(2)	28.975	-29.2405
7	57(3)	30(1)	200(3)	50(2)	31.027	-29.8348
8	57(3)	60(2)	50(1)	75(3)	31.311	-29.9139
9	57(3)	90(3)	100(2)	30(1)	31.743	-30.0330

Table: L_9 Orthogonal Array and Erosion Test Results along with S/N Ratios

Level	A	B	C	D
1	-27.61	-28.55	-28.77	-28.74
2	-28.99	-28.86	-28.77	-28.89
3	-29.93	-29.12	-28.99	-28.89
Delta	2.32	0.57	0.23	0.15
Rank	**1**	**2**	**3**	**4**

Table: S/N ratio response table for erosion rate

It is evident from the figure and the response table, that as far as the erosion rate is concerned, the factor combination A_1, B_1, C_2 and D_1 will give the minimum erosion rate. Further, table indicates the hierarchical-order of the control factors as impact velocity (A), impingement angle (B), erodent size (C) and erodent temperature (D) in decreasing order according to their significance on the erosion rate. It can also be concluded that the erodent temperature (D) has negligible effect on the wear rate.

Analysis and Prediction of Erosion Response using ANN

As mentioned earlier, artificial neural network (ANN) is a technique that involves database training to predict input-output evolutions. In this attempt to simulate the erosion wear process and to predict the erosion rate under different operating conditions for titania coatings, four input parameters are taken, each of which is characterized by one neuron in the input layer of the ANN structure.

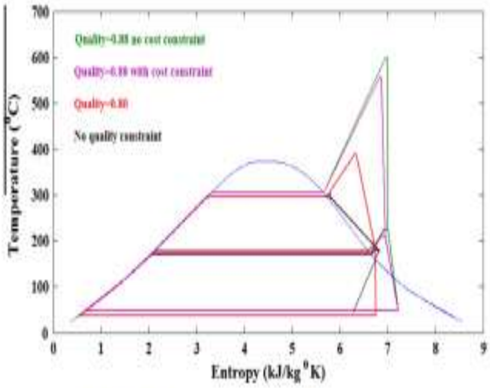


Fig. 9. T–S diagram of steam cycle for different cases.

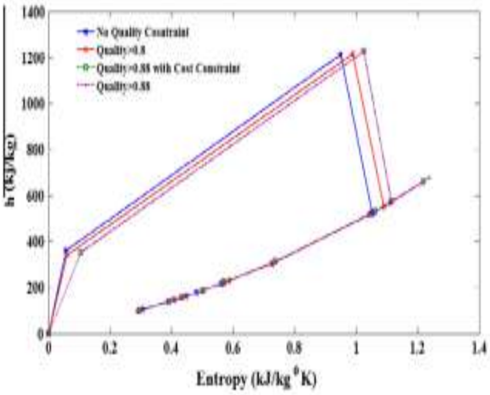
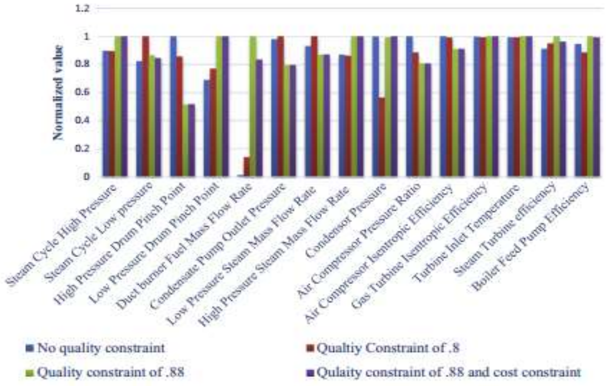


Fig. 10. h–S diagram of gas cycles for different cases.

ANN structures with varying number of neurons in the hidden layer are tested at constant cycles, learning rate, error tolerance, momentum parameter, noise factor and slope parameter. Based on least error criterion, one structure, shown in table 4.3, is selected for training of the input-output data. The optimized three-layer neural network used in this simulation is shown in figure 4.2. A software package NEURALNET for neural computing based on back propagation algorithm is used as the prediction tool for erosion wear rate of the coatings under various test conditions.

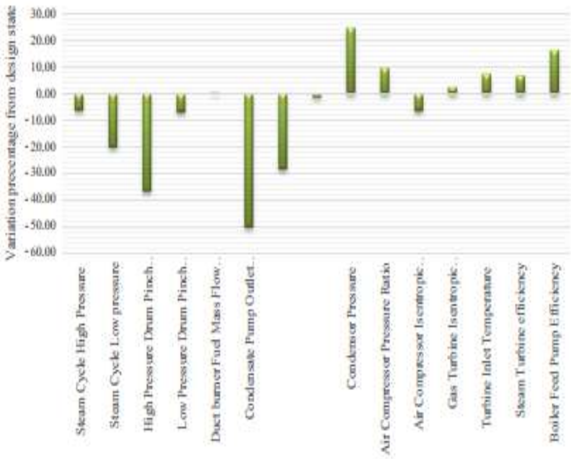
Input Parameters for Training	Values
Error tolerance	0.001
Learning rate (ß)	0.002
Momentum parameter(α)	0.002
Noise factor (NF)	0.001
Number of epochs	1000,000
Slope parameter (£)	0.6
Number of hidden layer neurons(H)	10
Number of input layer neurons (I)	4
Number of output layer neuron (O)	1

Table: Input parameters selected for training

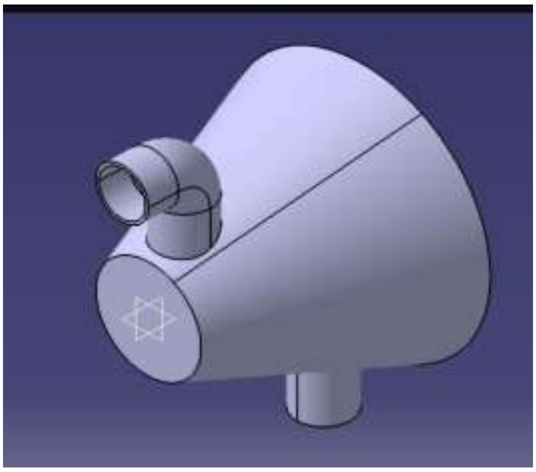


Comparative presentation of decision variables for different case.

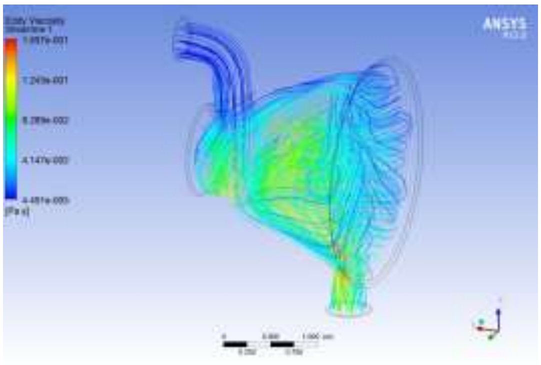
It is interesting to see that the erosion rate presents an exponential type evolution with the impact velocity. As the velocity of impact of the erodent increases, the kinetic energy carried by it also increases. This causes transfer of greater amount of energy to the target coating surface upon impact and leads to higher material loss due to erosion. Erosion rate (Er) depends on velocity (V) by a power law, given as $Er = kV^n$, where k is a material constant. However, the exponent 'n' is reported to be material independent and is governed by test conditions including particle characteristics and the erosion test apparatus.



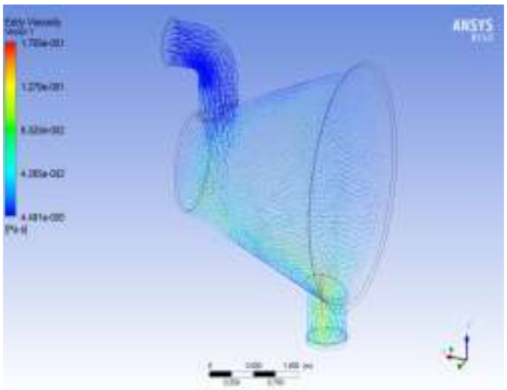
Functional coatings have to fulfill various requirements when employed in tribological applications. The wear rate is one of the requirements as it is directly related to the service life period of the coatings. In order to achieve certain degree of erosion wear resistance accurately and repeatedly, the influence parameters of the process have to be controlled accordingly. Neural computation can be used as a predictive tool in such a case to process very large data related to a real time erosive situation and to simulate any desired parameter in a space larger than the domain of experimentation.



3D-model



Eddy viscosity



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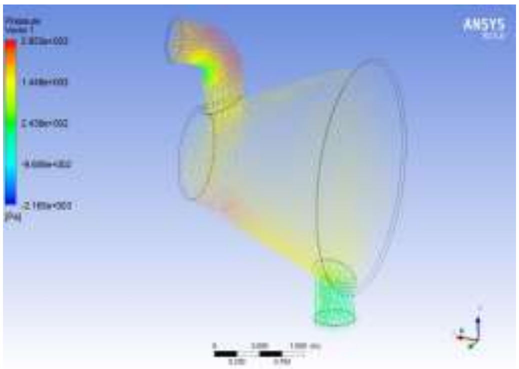
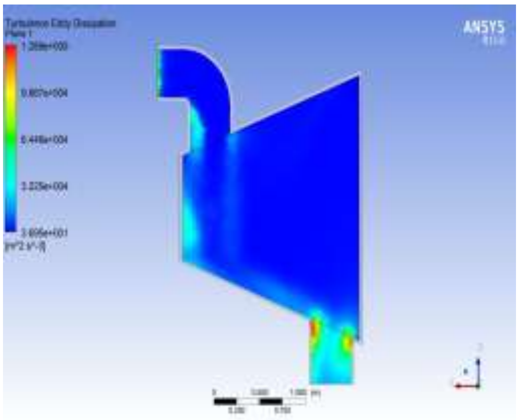
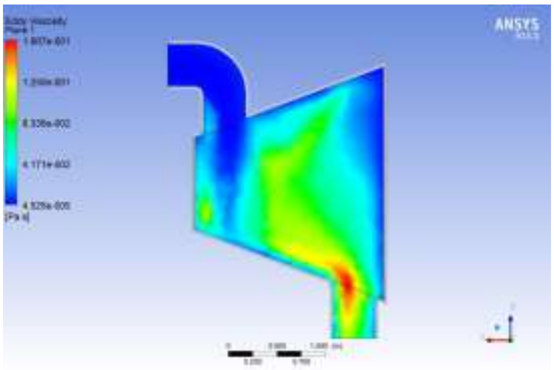
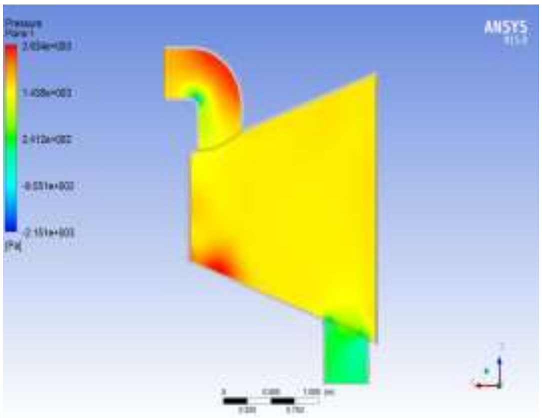




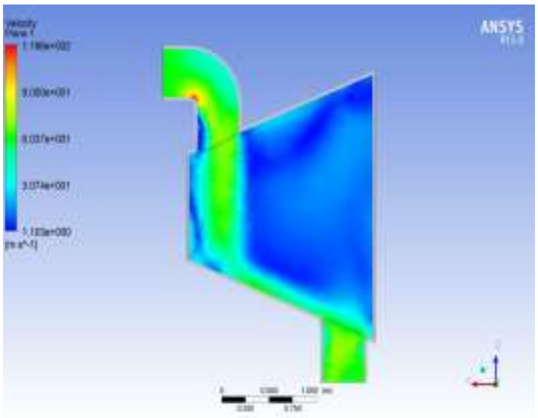
Turbulence eddy dissipation



Eddy viscosity



Pressure



Velocity plane

CONCLUSIONS

The comprehensive thermodynamic modeling and multi-objective optimization of a combined cycle power plant with different vapor quality at steam turbine outlet provides good information.

A complete thermodynamic modeling for this CCPP is performed. Exergy, exergoeconomic and exergoenvironmental of case also are conducted. In optimization process three cases with different quality at steam turbine outlet are analyzed and compared. Results show the system with 88% quality at steam turbine outlet is the most realistic in respect to efficient, economic and environmental aspects. Other significant conclusions are as follow: By increasing steam turbine outlet vapor quality, the temperature and pressure at steam turbine inlet flow will be increased.

An increase in HRSG high pressure and decrease HRSG low pressure, increases system exergy efficiency and decreases the total rate of the system. An increase in GTIT and also combustor working temperature result in an increase in system exergy efficiency an increase in total cost of the system. By applying the cost constraint reduces the overall cost of the cycle while increases the steam cycle quality. An increase in mass flow rate of HP steam and decreases LP steam mass flow rate result in an increase the exergy efficiency of the bottoming cycle.

REFERENCES

- Bandopadhyaya P. P., (2000). Processing and Characterization of Plasma Sprayed Ceramic Coatings on Steel Substrate, Ph.D. Thesis, IIT, Kharagpur, India.
- Taylor P. R., (2002). Thermal Plasma Processing of Materials, Power Beams and Materials Processing, PBAMP 2002, Ed. A. K. Das et al., Allied Publishers Pvt. Ltd., Mumbai, India, pp13-20.
- Satapathy A., (2005). Thermal Spray Coating of Red Mud on Metals, Ph.D. Thesis, NIT,

Rourkela, India.

- Sundararajan G. and Roy M., (1997), Solid particle erosion behaviour of metallic materials at room and elevated temperatures, Trib. Int., v30 (5), pp339-359.
- Finnie I. and Oh, H., (1966). An analysis of rock drilling by erosion, In: Proc. 1st Cong. Int. Soc. Rock Mech., Lisbon, v2, pp99–104.
- Hocking M. G., Vasantasree V. and Sidky P. S., (1989). Metallic and Ceramic Coatings: Production, High Temperature Properties and Applications, Long. Scient. and Tech., UK.
- Young E. J., Mateeva E., Moore J. J., Mishra B. and Loch M., (2000). Low Pressure Plasma Spray Coatings, Thin Sol. Films, v377–378, pp788–792 Berget J., Rogne T. and Bardal E., (2007).
- Erosion–corrosion properties of different WC–Co–Cr coatings deposited by the HVOF process—influence of metallic matrix composition and spray powder size distribution, Surf. and Coat. Tech., v201 (18), pp7619– 7625.
- Rateick Jr. R. G., Karasek K. R., Cunningham A. J., Goretta K. C. and Routbort JL., (2006). Solid-particle erosion of tungsten carbide/cobalt cermet and hardened 440C stainless steel—A comparison, Wear, v261 (7-8), pp773–778.
- Wang B. Q. and Shui Z. R., (2002). The hot erosion behavior of HVOF chromium carbide-metal cermet coatings sprayed with different powders, Wear, v253 (5), pp550–557.

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