

Exergy Analysis of Olkaria I Power Plant, Kenya

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ABSTRACT

The processes of electricity production from geothermal resources at Olkaria I Power Plant in Kenya were analysed using exergy analysis method. The objectives of the analysis were to determine the overall second law (Exergy) efficiency of the power plant, pinpoint the locations and quantities of exergy losses and wastes and suggest ways to address the exergy losses and wastes.

In the analysis, the power plant was simplified into sub-systems, each with distinct exergy inflows and outflows and approximated into steady state flow. The theory and mathematical formulations were adapted from the book 'Exergy methods of thermal plant analysis' and several online internet publications. Mathematical models for exergy flows were developed and analysed using the Engineering Equation Solver (EES) software to perform the calculations. The degree of thermodynamic perfection (measure of performance) was based on the rational efficiency concept. Few assumptions and simplifications were made.

The results showed that Olkaria I Power Plant has an overall second law efficiency of 42% and an overall 1st law efficiency of 15%. The analysis revealed that 6 MW exergy is wasted in the separated brine while 11 MW exergy is lost in the steam transmission system. Significant losses were found to occur in the turbines, condensers and the GES system. Although the exergy in the wasted brine is relatively small compared to that in the steam, it could still be put to useful work at some investment cost.

It was concluded that exergy analysis is an important tool for analysing the performance of geothermal plants and should be incorporated into their designs. It was suggested that the steam transmission system should be investigated further to determine the causes of exergy losses and that ways of utilising the exergy in the brine be investigated.

1. INTRODUCTION

The world's energy demands have been increasing rapidly in the recent past as a result of increase in the world's population and economic growth. The high growth in energy demands and its uses have negative impacts on the environment. The increase in energy demands, decline in energy resources and the link between energy utilization and environmental impacts has resulted in calls for sustainable approach to the development and management of the earth's energy resources (Rosen & Dincer, 2001). With finite energy resources and increasing energy demands, it becomes increasingly important to understand the mechanisms which the quality of energy resources degrades and to develop systematic approaches to improving the systems (Gong & Wall, 1997). Systems and processes that degrade the quality of energy resources can

only be identified through a detailed analysis of the whole system. Exergy analysis has been cited by many researchers and practicing engineers to be a powerful tool to identify and quantify energy degrading processes since it enables the types, locations and quantities of energy losses to be evaluated.

Exergy analysis method has been used as an analytical in many optimization studies of energy systems. It uses the principles of the First Law of Thermodynamics (conservation of energy) together with the Second Law of Thermodynamics, for the analysis, design and improvement of energy systems. Exergy is a concept that clearly shows the usefulness of energy and shows what is consumed in the course of energy transfer and conversions.

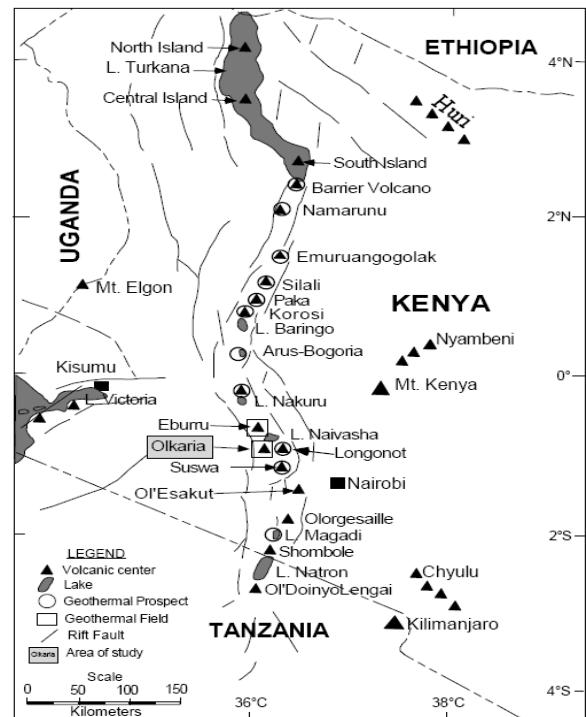


Figure 1: The map of Kenya showing location of geothermal fields including Olkaria.

In this report, the exergy analysis study of Olkaria I geothermal power plant is presented. Olkaria I power plant is located in the Olkaria geothermal area of Kenya, about 120 km North-West of the capital city, Nairobi (Figure 1). The plant has three condensing steam turbine generating units each with nominal rating of 15 MWe. The first unit was commissioned in 1981 followed by the second and third units in 1982 and 1985 respectively. After the third unit was commissioned, steam production declined continuously and by 1994, only 30 MWe could be sustained (Ofwona, 2002). To restore production, makeup wells were drilled and connected and the station rated capacity was restored. This calls for a better utilization strategies in

which all the energy extracted from the reservoir is utilized as best as possible. The plant currently receives steam from 26 production wells located on the Olkaria East production field.

In this analysis, the whole system was simplified into subsystems, each with distinct exergy inflows and outflows. The system and subsystems were simplified to control volumes and the flow processes approximated to steady or quasi-steady state flow processes. The primary exergy input was selected to be the exergy of the two phase fluid from the wells while the desired exergy output was the net electrical energy delivered to the transmission grid. The performance criteria adopted was to compare the desired output exergy to the necessary input exergy or rational efficiency. The difference between the total input exergy and the desired exergy constitute the exergy wasted or destroyed.

The study included literature review, data collection and analysis, mathematical formulations and modeling using EES. By inputting the actual operation and/or design parameters, the exergy balance and exergy performance evaluation was performed. The reference environment was defined as being the ambient conditions at Olkaria geothermal area with mean ambient temperature T_0 of 20°C and Pressure P_0 of 0.86 bar-a. The limitations and simplifying assumptions were stated and finally suggestions for improvement were made.

Many studies applying exergy methods in the analysis of geothermal power plants and other systems have been conducted and published in recent years. All the studies illustrate the importance of exergy analysis in evaluating performances of geothermal plants and identifying exergy wastes. Most of these studies were conducted with the help of the EES Software for solving thermodynamic equations and relationships. In majority of the studies, the biggest exergy losses are located in the turbines, condensers, gas extraction systems and pipelines/accessories.

Some highlights in few of the publications reviewed are summarized below:

Nikulsin et al. (2001) concluded that exergy analysis methods show both the overall exergy efficiency and the relationship between exergy efficiency of individual systems to that of the overall system. Villena (1997) conducted a comparative exergy analysis of the Mindanao I and the Mahanadong I geothermal plants in Philippines using a simulation code and EES. He found that operating at partial load condition and increased gas content increased the irreversibility losses of the individual component system and that most of the pressure drops occurred in the turbine, condenser, the gas extraction system, flow meters and demisters. He recommended the selection of flow meters that do not provide flow restrictions, arrangement of gas extraction equipment and treatment of the cooling water coming from the auxiliary coolers.

Aligan (2001) observed that use of Low-Pressure steam from Mindanao I to generate additional power at Mindanao II greatly increased the overall utilization efficiency of the geothermal resource in the field and concluded that the turbines and the cooling water systems were the major sources of overall exergy losses. Bettagli and Bidini (1996) carried out energy-exergy analysis of the entire geothermal fluid network in Larderello, Italy where they analyzed the various types of losses in the system and found that the exergy losses of the transportation network were much lower than those of the production plant and had little effect

on the overall efficiency. They found that the main exergy losses of were concentrated in the turbine, condenser and the cooling tower. They concluded that it would be pointless to make large investments to improve the other components since they would have minimal effects on the overall system compared to the cited plant components.

Soekono (1995) conducted an exergy and energy audit of the Darajat Geothermal Plant in Philippines after pressure declined in its reservoir. He found that most of the exergy losses were located at the condenser and turbine and considerable losses also occurred in the well bore pipes and valves. He suggested that the performance of the turbine can be improved through retrofitting so that the inter-stage temperature drops can be equal as required. Dorj (2005) demonstrated that exergy analysis plays a great role in plant and system design because locations for potential exergy losses can be identified in advance and focused on at the design stage.

2. THEORETICAL ANALYSIS

2.1 The concept of exergy

In the real world, states of complete equilibrium are hardly attainable. Any system that is at a temperature, pressure or chemical composition above or below that of its surrounding is not in equilibrium with its surroundings and has a potential to do work. This work potential is referred to as *the exergy of the system*. When the properties of a system are equal to those of its environment, the exergy of the system is zero. The state at which a system and its surroundings are in equilibrium is known as the *dead state*. Exergy is therefore a measure of how a system deviates from a state of equilibrium with its environment and is a property of the system and its surroundings.

Exergy is another word used to describe available energy or the measure of energy available to do work above a heat sink (Rosen & Dincer, 2001). Exergy presents the most natural and convenient universal standard of energy quality by using environmental parameters as the reference states and is a common standard for examining exploitability of a reservoir. The exergy of a resource gives an indication of how much work can be done by the resource within a given environment. The exergy concept explicitly shows the usefulness (quality) of energy and matter in addition to what is consumed in the course of energy transfer or conversion steps. When exergy loses its quality, it results in exergy destroyed. Other terms commonly used to refer to exergy include: *available energy, availability and essergy*.

Kotas (1995) states that 'the exergy of a steady stream of matter is equal to the maximum amount of work obtainable when the stream is brought from its initial state to the dead state by processes during which the stream may interact only with the environment'. Thus, the exergy of a stream is a property of the state of the stream and the state of the environment. Once a system is in equilibrium with its surroundings, it is not possible to use the energy within the system to produce work. At this point, the exergy of the system has been completely destroyed.

Exergy like energy exists in kinetic, potential, chemical and physical exergy forms. The kinetic and potential exergies are high grade exergy forms associated with ordered forms of matter and fully convertible to useful work. Chemical and physical exergies on the other hand are low grade forms associated with disordered forms of matter and cannot be easily converted to work.

2.2 Exergy and energy

Energy is defined as motion or the ability to cause motion and is always conserved in a process (obeys the 1st law of thermodynamics). On the other hand, exergy is defined as work or the ability to cause work and is always *conserved in a reversible process*, but is *always consumed in an irreversible process* (obeys the 2nd law of thermodynamics). While energy is a measure of *quantity*, exergy is a measure of *quantity and quality*. Exergy like energy can be transported across the boundary of a system. For each energy transfer, there is a corresponding exergy transfer.

The First Law of Thermodynamics states that *energy can neither be created nor destroyed*. Energy is available in many different forms and may be converted between these forms. The Second Law of Thermodynamics states that *conversions of energy are possible only if the total entropy increases*. By introducing exergy, energy and entropy may be treated simultaneously. The quality of energy is described by the concept of entropy. High entropy is equal to low quality of energy. Different energy forms have different qualities, indicating to what extent they are theoretically convertible to mechanical work. This limitation, a law of nature, implies that the total energy quality always decreases in each conversion (the Second Law of Thermodynamics).

2.2 Exergy analysis

Figure 2 illustrates exergy flow in through a system or process. One of the main uses of the concept of exergy is an exergy balance in the analysis of thermal systems. An exergy balance (exergy analysis) can be looked at as a statement of the law of degradation energy (Kotas, 1995). An exergy analysis is a mathematical tool for evaluation of exergy flows through a system and has been cited as a powerful tool for optimization studies and as a primary tool in addressing the impact of energy resource utilisation on environment. A careful evaluation of processes using exergy analysis enables identification of the source of inefficiencies and wastes which leads to improved designs and resultant savings. Exergy analysis is a tool for identifying the types, locations and magnitudes of thermal losses. Identifying and quantifying these losses allows for the evaluation and improvement of the designs of thermodynamic systems. It is an effective method using conservation of mass and conservation of energy principle together with the second law of thermodynamics for design and analysis of energy systems.

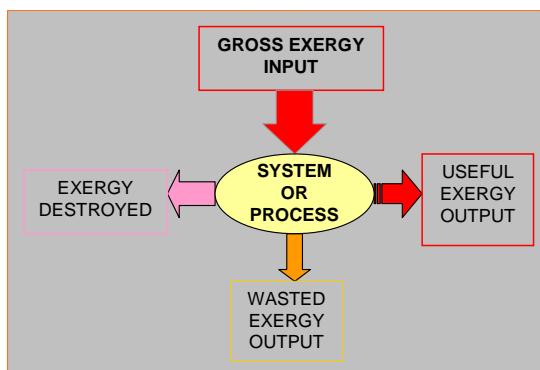


Figure 2: Illustration of the exergy flow process in system or process.

Exergy balance methods, commonly known as exergy analysis, can indicate the quantity and quality of heat losses and the locations of energy degradation (quantify and

identify causes of energy degradation). Most cases of thermodynamic imperfection cannot be detected by an energy analysis (Rosen, 2002). Certain processes like throttling, heat transfers, expansion and friction involve no energy losses but they degrade the quality of energy and its ability to do work and therefore involve exergy losses.

2.3 Mathematical expressions of exergy balance

General exergy expressions

For a stream of matter, total exergy flow can be expressed as:

$$E_{total} = E_{KE} + E_{PE} + E_{PH} + E_O \quad (1)$$

Where E_{KE} , E_{PE} , E_{PH} and E_O refer to Kinetic, Potential, Physical and Chemical exergies respectively. Both E_{KE} and E_{PE} are associated with high-grade energy and fully convertible to work, while E_{PH} and E_O are low-grade energy where the energy stream has to undergo physical and chemical processes while interacting with the environment.

For this study, only physical-exergy, E_{PH} shall be considered since the process involves only fixed composition flows (Rosen, 1999). Therefore, exergy will be expressed as equal to the maximum work when the stream of substance is brought from its initial state to the environmental state defined by P_0 and T_0 by physical processes involving only thermal interaction with the environment (Kotas, 1995).

$$E_{total} = E_{PH} = m_i [(h_i - h_0) - T_0(s_i - s_0)] \quad (2)$$

Where i , 0 , m , h , s and T refer to *state points, environmental state, mass flow rates, Enthalpy, Entropy and temperature (K)* respectively

Control volume exergy balance

For a control volume, an exergy balance equation can be expressed as:

$$E_{input} = E_{desired} + E_{waste} + E_{destroyed} \quad (3)$$

Where E_{input} is the total exergy inflow into the control volume, $E_{desired}$ the total desired exergy output (net work output), E_{waste} sum of exergy from the system other than the desired and $E_{destroyed}$ the sum of exergy lost in the system as a result of irreversibilities. $E_{destroyed}$ is directly related to entropy generation by the equation:

$$E_{destroyed} = T_0 S \quad (4)$$

Where T_0 is the ambient temperature in Kelvin while S is the entropy

Criteria of performance

The performance criteria of exergy systems depend on exergy transfer rates in and out of control volumes. Kotas (1995) categorized exergy transfers as those that represent the *desired output of the process* and those which represent the *necessary input*. Exergy inputs and outputs may be work, exergy associated with heat transfer, exergy associated with the flow of matter in or out of a control region or *change* of exergy of a stream of matter passing

through a control region such as a throttle valve or a heat exchanger.

The most commonly used measure of performance of a system in terms of exergy is the exergy efficiency which is a measure of the performance of a system relative to the maximum theoretical performance of the system. There are three kinds of exergy efficiency terms often used namely; simple, rational and efficiency with transiting exergy. *Simple efficiency* is defined as a ratio of the sum of exergy outputs to the sum of exergy inputs. *Rational efficiency* is defined as sum of desired exergy outputs to the sum of the necessary exergy inputs. *Efficiency with transiting exergy* is ratio of exergy outputs minus the unused exergy outputs to the total exergy input. *Rational analysis concept* will be used for this study since it is the most appropriate measure of performance.

In equation, the rational exergy efficiency is expressed as:

$$\eta_e = \frac{E_{desired}}{E_{input}} \quad (5)$$

$$E_{input} = E_{output} + E_{destroyed} \quad (6)$$

$$E_{output} = E_{desired} + E_{waste} \quad (7)$$

Where $E_{desired}$ is the sum of desired exergy outputs (net positive work by the system) $E_{destroyed}$ the exergy rate lost in the system as a result of irreversibilities of the system and E_{waste} the exergy exiting the system which still has capacity to do work.

2.4 Conceptual framework

This study is based on the concept that for a system that undergoes a process under steady or quasi-steady conditions, the exergetic efficiency (second law efficiency, effectiveness or rational efficiency) is a valid measure of the performance of the system from a thermodynamic point of view. Thus, a physical exergy analysis of a geothermal plant used in conjunction with an energy analysis enables the locations, types and true magnitudes of wastes and losses to be determined. More revealing insights can be

made if the analysis is conducted using varying reference environments and compared using the same reference environment.

2.5 Reference environment

Exergy is evaluated with respect to a reference-environment model. The state of the reference environment is specified by its temperature, pressure and chemical composition. The results are relative to the specified reference environment, which in most applications is modeled after the actual local environment.

The environment is assumed to be a very large simple compressible system modelled as a thermal reservoir with a uniform and constant temperature T_0 and pressure P_0 . The environment must be a large reservoir so that its intensive properties are not significantly changed by the processes taking place. For practical analysis, the earth's atmosphere, the earth's crust, the ocean or large rivers or lakes are often considered as environments although they are not absolutely uniform and their properties may not be constant.

A global standard environment can be defined in terms of standard atmospheric conditions at sea level and a universal chemical composition. Since temperature conditions and air pressure vary from place to place, it is necessary to introduce local standards. The more a system deviates from its environment, the more exergy it carries. For this analysis, the reference environment will be the local environment at Olkaria geothermal area of Kenya, at an altitude of 1900 metres above sea level. The mean ambient temperature T_0 is 20°C and atmospheric pressure P_0 is 0.86 bar-a. The standard international air composition modelled by Dincer and Cengel (2001) will be assumed.

3. THEORETICAL ANALYSIS

3.1 Overall exergy flow analysis

Process Description

Figure 3 shows a flow diagram for the exergy flow at Olkaria I power plant. The exergy flow processes have been simplified to consist of a well-separation, steam transmission, steam expansion-energy conversion, steam condensing and cooling water systems.

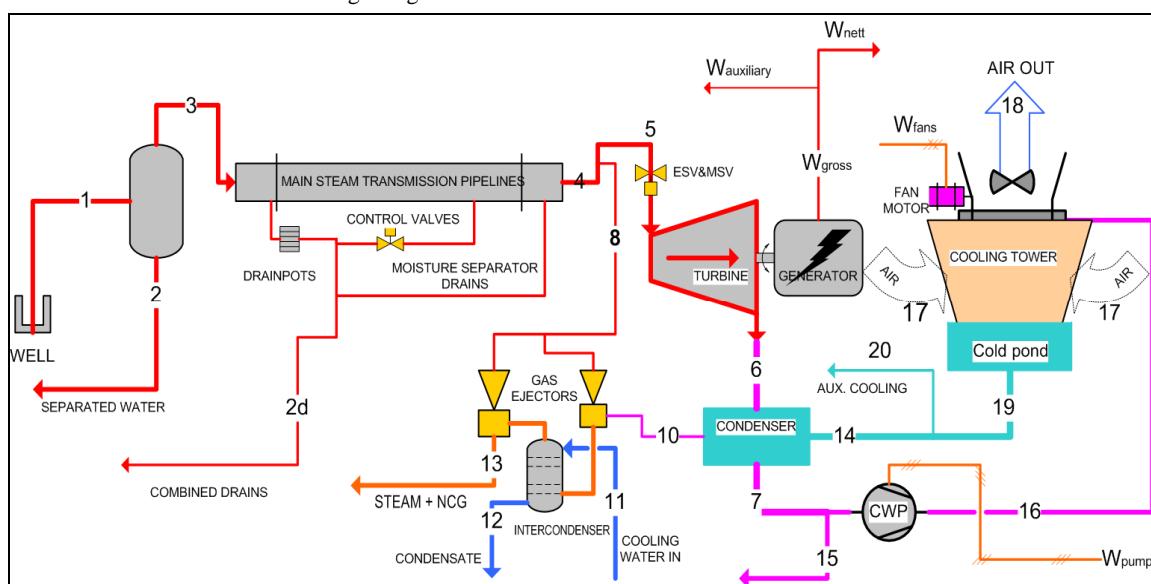


Figure 3: Overall exergy flow diagram for a unit at Olkaria I power plant.

A quantity of exergy is received from the production wells connected to the system. The steam is passed through the processes (subsystems) and from each process; some desired exergy output is obtained which goes to the next subsystem. The overall desired output from the plant is the net electrical energy which is fed to the national grid.

Overall exergy balance (For Normal steady state conditions)

The exergy entering the system consist of the exergy of the two phase flow from the wells and the exergy of air entering the cooling towers. The exergy leaving the system consist of the net electrical energy sent out (W_{nett}), exergy of separated brine disposed(E_2), exergy lost through drains, leakages and vents(E_{2d}), exergy of GES exhaust(E_{13}), exergy of condensate overflowing at the seal pit(E_{15}), exergy of air leaving the cooling towers(E_{18}). Some exergy ($I_{processes}$) is destroyed due to the internal irreversibilities of the processes. With reference to Figure 4, this can be expressed as below:

$$\sum E_1 + \sum E_{17} = \sum E_2 + \sum E_{2d} + \sum E_{13} + \sum E_{15} + \sum E_{18} + \sum I_{processes} \quad (8)$$

Performance criteria

The overall objective of this system is to convert the exergy received from the wells into net electrical energy which is the desired output. The rational efficiency will be the ratio of the net electrical energy produced to the total exergy of the geothermal fluids from connected production wells. This is expresses as:

$$\eta_{overall} = \frac{\sum W_{nett}}{\sum m_1 \epsilon_1} \quad (9)$$

Assumptions

1. Wells output is constant
2. Generated power is constant
3. Heat and pressure losses are negligible

3.1 Production and separation processes

System Description

Figure 4 shows a simplified arrangement of the wellhead equipment at Olkaria I plant. The geothermal wells produce a mixture of steam and water from a liquid dominated geothermal reservoir ($h_{mean}=2230 \text{ kJ/kg}$). The fluids reach the wellhead at well output conditions ($WHP_{mean}=7 \text{ bar a}$) and enter the separator vessel tangentially. The fluid expands in the separator ($P_{mean}=6 \text{ bar a}$) and the steam and water is separated by cyclone action and density difference. The hot water leaves the separator and is discharged into the wellhead silencer for onward disposal. The steam leaves the separator and is fed into the steam gathering system.

Exergy balance equations

The exergy entering the system is the exergy of the two phase fluid discharging from the wells into the separators (1). The exergy leaving the system is the sum of the exergy of the steam (3) and of the separated hot water going to the silencer (2). The exergy of the steam is the desired output. Some exergy is consumed (destroyed) in the process. These

are neglected in this analysis. The exergy balance equation is stated as follows:

$$\sum E_{total} = \sum E_{steam} + \sum E_{water} + \sum I_{separation} \quad (10)$$

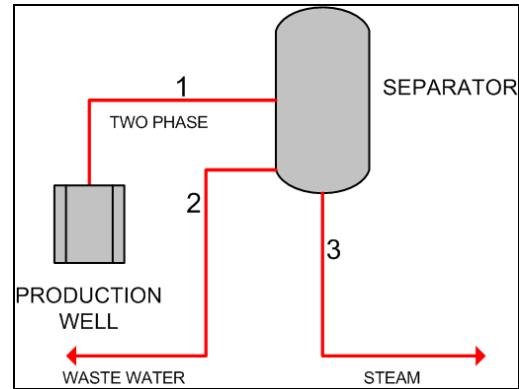


Figure 4: Simplified arrangement of wellhead equipment at Olkaria I steam field.

Where E_{total} is the exergy rate contained in the two phase flow from the wells, E_{steam} the exergy rate in the steam from the wells E_{water} the exergy rate in the separated water from the well and $I_{separation}$ exergy destruction rate in the separation processes (Exergy destruction is neglected for this study)

The exergy rate E is expressed as:

$$E = m\epsilon = m[(h - h_0) - T_0(s - s_0)] \quad (11)$$

Where m h and ϵ are the mass flow rates, enthalpy and the specific exergy of the fluid respectively

With reference to Figure 4 above, the exergy balance equation becomes:

$$\sum m_1 \epsilon_1 = \sum m_2 \epsilon_2 + \sum m_3 \epsilon_3 + \sum I_{separation} \quad (12)$$

Performance criteria

The role of this system is to separate the two phase fluids into water and steam, dispose the waste water and deliver the steam to the steam gathering and transmission system. Normally, the performance of separators is a measure of the dryness of the steam leaving the separators. In exergy terms, the desired exergy output is the exergy of the steam considering that the hot water goes to waste. In this case, the criteria of performance will be the ratio of the exergy of steam leaving the separators (desired exergy) to the exergy of fluids entering the separators (rational efficiency).

$$\eta_{separation} = \frac{\sum E_3}{\sum E_1} = \frac{\sum m_3 \epsilon_3}{\sum m_1 \epsilon_1} \quad (13)$$

Assumptions

1. Production rates from the wells is smooth and constant
2. Changes in wells output rates since September 2002 are negligible
3. The separation processes are isenthalpic and adiabatic

3.3 Steam transmission processes

Description

The transmission system arrangement is shown in Figure 5 above. The steam from the connected (3) wells is fed into steam gathering pipes which feed into three steam transmission pipes. Heat and pressure losses in the steam pipelines result in exergy drops which cause condensation of some steam. The condensate is collected in drain pots and disposed via steam traps or orifice plates. Pressure on the main steam pipeline is kept within the desired value by pressure controllers installed on the main steam pipeline. Excess steam is vented out by steam pressure control valves. A moisture separator collects and drains out any residual moisture in the steam before the steam enters the turbines. All the drains and vents discharge to the atmosphere (2d). The steam flow metering devices (one for each unit) is located after the outlets of the moisture separators and is the exit point of this system (4).

Exergy balance equations

The exergy into this system is the sum of the exergy of the steam leaving the separators of the connected wells (3). The exergy leaving the system is the exergy of steam flowing through the flow meters (4). The exergy wasted (leakage and vent out) and exergy destroyed (heat loss and pressure drops) shall be treated as exergy lost (2d) and is the difference between the sum of exergy in and sum of exergy out. The exergy balance for this system can be expressed as:

$$\sum m_s \epsilon_s = \sum m_t \epsilon_t + \sum E_{lost} \quad (13)$$

Where m_s , ϵ_s , m_t , ϵ_t and E_{lost} are respectively the mass flow rate of steam from the well, the specific exergy of steam from the well, the mass flow rate of steam into the orifice flow meters, the specific exergy value of steam at entry into the flow meters and the exergy lost in the transmission processes

With reference to Figure 6, the exergy balance is expressed as:

$$\sum m_3 \epsilon_3 = \sum m_5 \epsilon_5 + \sum E_{lost} \quad (14)$$

$$\begin{aligned} \sum E_{lost} = & \sum E_{drains} + \sum E_{leakages} + \sum E_{vented} \\ & + \sum E_{heatloss} + \sum E_{pressuredrop} \end{aligned} \quad (15)$$

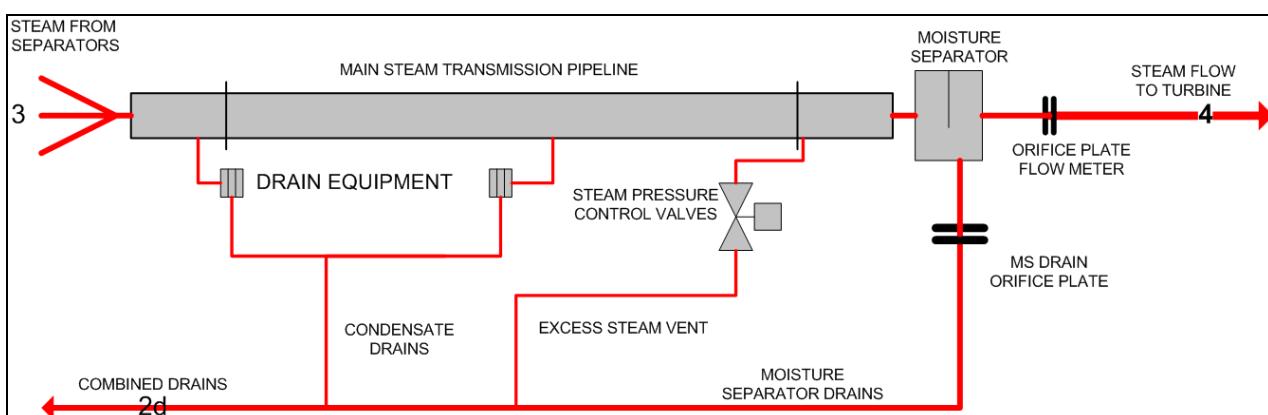


Figure 5: Simplified arrangement of steam transmission equipment at Olkaria I steam field.

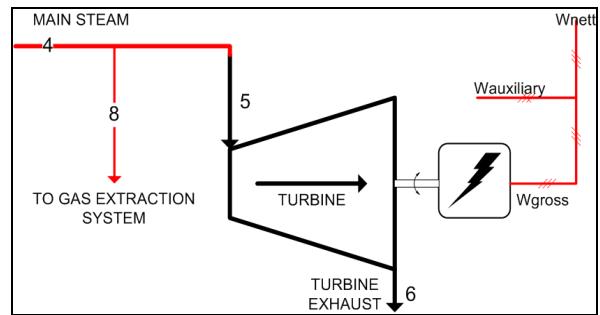


Figure 6: Simplified flow process of steam expansion through the turbines at Olkaria I.

Performance criteria

The purpose of this system is to transmit the separated steam from the wellhead separators to the turbines as efficiently as possible. The desired exergy output is the exergy of steam entering the flow meters. The criteria of performance will therefore be the ratio of exergy of steam reaching the flow meters to the exergy of steam entering the system. For an ideal system, the exergy entering the system will be equal to the exergy leaving the system.

$$\eta_{ts} = \frac{\sum E_5}{\sum E_3} = \frac{\sum m_5 \epsilon_5}{\sum m_3 \epsilon_3} \quad (16)$$

Assumptions

1. The SSC rates of 1997, 2000 and 2004 are still valid measures
2. The exergy wasted and exergy destroyed has been grouped under exergy lost.

3.3 Steam expansion through the Turbines

Process Description

The flow processes for the steam expansion and energy conversion is shown in Figure 6. Auxiliary steam (8) is tapped from the main steam pipe after the orifice flow meters but before the steam enters the turbines. The steam enters the turbine (5) with properties characterized by inlet condition.

The inlet into the turbines is controlled by emergency stop valves and governor valves. At the inlet, the steam first enters the steam chest which balances the thrust on the first stage turbine blades.

The steam is then guided into the 1st stage row of blades by steam nozzles and expands through the first row of blades. The steam is then expanded through the 2nd, 3rd and 4th rows of blades and is exhausted into the condenser (6) which is kept at a vacuum pressure of 0.1 bar-a by condensing of the steam. This process is shown by process 5-6_{actual} on the T-S diagram (Figure 7).

As the steam is expanded through the rows of blades (stages), significant part of the exergy is converted into mechanical energy in the form of rotation of the turbine rotor. Most of the exergy in the steam is converted by the 1st stage blades and the steam exits this stage at a mean pressure of 1 bar gauge. The turbine and the generator rotors are coupled together and therefore rotate together at 3000RPM. The generator rotor carries the magnetic field and by rotation, converts the mechanical energy (rotor rotation) into electrical energy (W_{gross}). The amount of gross electrical energy generated depends on the efficiency of the turbines and generators.

Exergy balance equations

The exergy input is the exergy of steam entering the turbine (5). The exergy output consist of the work produced (W_{gross}) and the exergy of steam exhaust from the turbine (6). The electrical energy produced is the desired exergy output. The exergy of the steam exiting the turbine is part of the exergy waste. Some exergy is destroyed due to the irreversibilities of the processes involved.

With reference to Figure 7, the exergy balance is written as:

$$\sum E_5 = \sum E_{Wgross} + \sum E_6 + \sum I_{process} \quad (17)$$

Where E_5 is the exergy rate of steam entering the turbine, E_{Wgross} the exergy rate of gross electrical energy from

generator, E_6 the exergy rate of steam exiting turbine and $I_{Process}$ the exergy destruction rate in exergy conversion processes

Applying exergy terms:

$$E_5 = m_5 [(h_5 - h_0) - T_0 (s_5 - s_0)] \quad (18)$$

$$E_6 = m_6 [(h_6 - h_0) - T_0 (s_6 - s_0)] \quad (19)$$

$$m_5 = m_6 \quad (20)$$

$$E_{Wgross} = MW_e \quad (21)$$

Where m_5 , h_5 and s_5 are respectively the mass flow rate, enthalpy and entropy of steam at entry into turbine while T_0 , h_0 and s_0 the reference environment temperature (°K) enthalpy and entropy of the steam at environment condition.

Ideal expansion process

For an *ideal process*, the expansion of steam through the turbine is isentropic which means that $s_5 = s_6$

Therefore the ideal quality of steam (x) at exit (6) becomes:

$$x_6 = \frac{s_6 - s_{f0.1bar-a}}{s_{g0.1bar-a} - s_{f0.1bar-a}} \quad (22)$$

Where s_f and s_g are the liquid and gas phase entropies at exit conditions (0.1 bar-a)

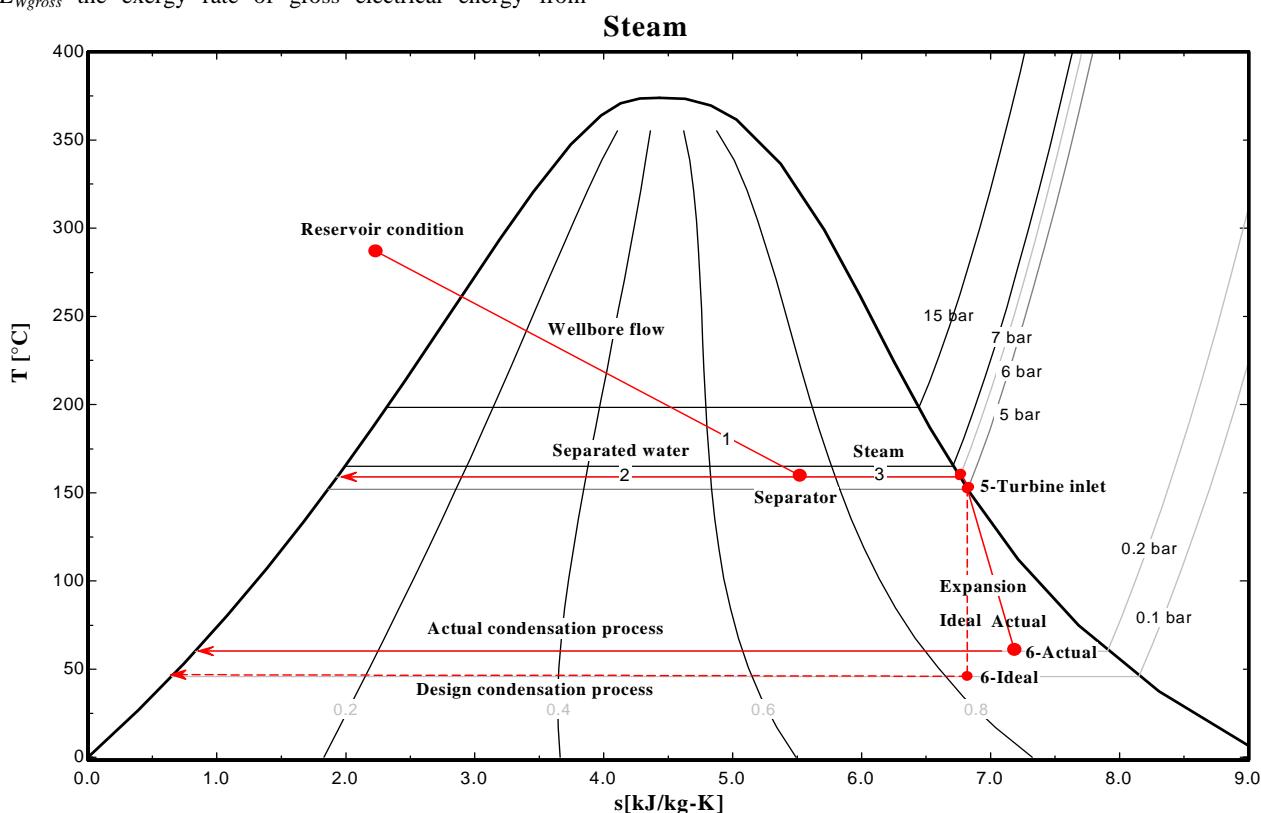


Figure 7: T-S diagram illustrating the flow processes from the reservoir to the condenser.

For an isentropic expansion, the expression for enthalpy at exit (h_6) becomes:

$$h_{6s} = h_{f0.1bar-a} + x_{6s} h_{fg0.1bar-a} \quad (23)$$

The ideal work done is given by:

$$W_{ideal} = m_5 [h_5 - h_6] \text{ kW} \quad (24)$$

The ideal steam exit temperature will be given by:

$$T_{6s} = T_{sat}(P=0.1bar-a, S=S_5) \quad (25)$$

Actual expansion process

In practice, the turbine isentropic efficiency (η_{ts}) is given by the manufacturer after construction of turbines. Therefore, the actual work done will be given by:

$$W_{actual} = (\eta_{ts} W_{ideal}) \text{ kW} \quad (26)$$

The actual exit enthalpy will be given by:

$$m_5 (h_5 - h_{6actual}) = W_{actual} = \eta_{ts} W_{ideal} \quad (27)$$

The actual steam quality at exit will be given by:

$$X_{6actual} = \frac{h_{6actual} - h_{f0.1bar-a}}{h_{g0.1bar-a} - h_{f0.1bar-a}} \quad (28)$$

The actual exit temperature will be given by:

$$T_{6actual} = T_{sat}(p = 0.1bar-a, h = h_{6actual}) \quad (29)$$

Actual Exergy value of steam at turbine exit (6) becomes:

$$E_6 = m_6 [(h_{6actual} - h_0) - T_0 (s_{6actual} - s_0)] \quad (30)$$

Performance criteria

The objective of this process is to convert as much of the exergy of the steam entering the turbine into electrical energy. The measure of performance will be a ratio of the gross work output (electrical energy produced) to the exergy of steam used to produce the work. The exergy used is the exergy yielded by the steam as it expands through the turbine, the difference between the exergy of steam at inlet and the exergy of steam at outlet). With reference to Figure 7, the exergy efficiency of the turbine-generator will be given by:

$$\eta_e = \frac{\sum W_{gross}}{\sum E_5 - \sum E_{6actual}} \quad (31)$$

Assumptions

1. The process is adiabatic
2. No leakages of steam

3.3 Steam condensing processes

Description

The flow processes in steam condensation are illustrated in figure 8. Steam leaving the turbine (6) is exhausted into the condenser where it is mixed with a spray of cold water (14) from the cooling towers. The steam condenses on the water droplets and the condensate drains through a barometric leg (7) into a seal pit tank located 9m below the bottom of the condenser to overcome atmospheric pressure. Non-condensable gases (NCG) are sucked from the condenser (10) by gas ejectors.

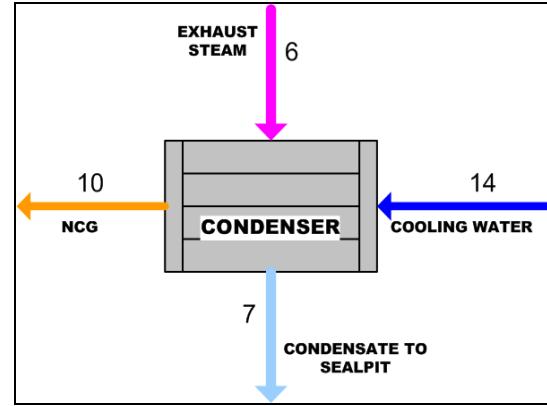


Figure 8: Schematic diagram showing the Condensing processes.

Exergy balance equations

The Exergy into the process is the sum of the exergy of the cooling water (14) and the exergy of exhaust steam (6). Exergy leaving the system is the sum of the exergy of the condensate (7) and exergy of the NCG (10). Some exergy is destroyed/lost due to irreversibilities of the process. In equation form:

$$\sum E_{exhaust} + \sum E_{c-water} = \sum E_{condensate} + \sum E_{NCG} + \sum I_{process} \quad (32)$$

With reference to Figure 7, this equation becomes:

$$\sum E_6 + \sum E_{14} = \sum E_7 + \sum E_{10} + \sum I_{process} \quad (33)$$

Where E_6 , E_{14} , E_7 , E_{10} , and $I_{process}$ are respectively exergy contained in the turbine exhaust steam, exergy of cooling water entering the condenser, exergy in condensate leaving the condenser, exergy in NCG leaving the condenser and exergy destroyed by irreversibilities of the process. Being a steady state process:

$$\sum m_6 + \sum m_{14} = \sum m_7 + \sum m_{10} \quad (34)$$

Criteria of performance

The desired function for this process is to effectively condense exhaust steam by maximizing the exergy of the mixed stream. The performance criteria will be the ratio of the exergy gained by cold fluid to the exergy lost by the exhaust steam (effectiveness of the heat transfer units): This is expressed as:

$$\eta_{condenser} = \frac{m_{14} (\mathcal{E}_7 - \mathcal{E}_{14})}{m_6 (\mathcal{E}_6 - \mathcal{E}_7)} \quad (35)$$

Assumptions:

1. Steady state process (mass flow rates are constant):
 $\sum m_i = 0$

2. Adiabatic process (no heat losses): $Q=0$

3.4 Non-condensable gas extraction

Description:

The flow arrangement for the gas extraction system is given in Figure 9. Motive steam is tapped from the main steam line (8) and delivered to the gas extraction system (GES). The high velocity steam creates suction by passing through a convergent-divergent nozzle. The low pressure point of the first stage ejector nozzle is connected to the gas cooler section of the condenser. The non-condensable gases (NCG) with some water vapour flow into the ejector nozzle (10) as a result of the low pressure suction. The NCG together with the motive steam is condensed in the inter-condenser by cold water (11) from the cooling tower. The NCG is sucked again from the inter-condenser by the second stage ejector nozzle and is discharged into the atmosphere (13) for dispersal. The condensate from the inter-condenser drains into the seal pit (12).

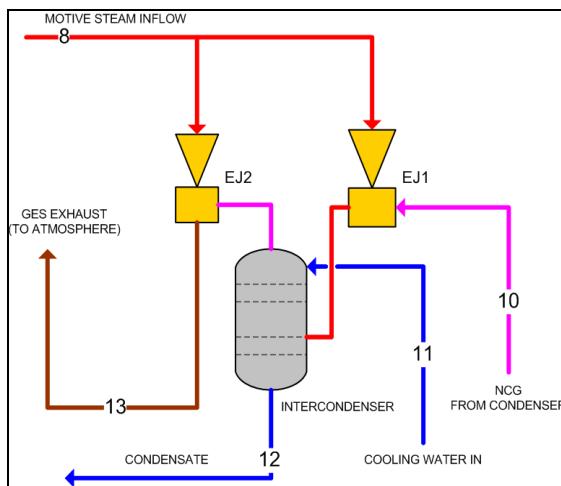


Figure 9: Illustration of the exergy flow processes in the NCG extraction system.

Exergy Equations

Exergy input is the sum of the exergies of the motive steam (8), NCG (10) and cooling water (11) entering the GES. The exergy output is the sum of the exergies of condensate leaving the inter condenser (12) and the NCG-steam mixture leaving the 2nd stage ejector (13). Some exergy is lost due to irreversibilities of the processes.

The exergy flows are expressed in the equations below:

$$\begin{aligned} \sum E_{steam} + \sum E_{ncg} + \sum E_{cw} = \\ \sum E_{con} + \sum E_{exhaust} + \sum I \end{aligned} \quad (36)$$

$$E_{ges} = m_{ges} \mathcal{E}_{steam} =$$

$$m_{ges} [(h_{ges} - h_0) - T_0 (S_{ges} - S_0)] \quad (37)$$

$$E_{ncg} = m_{ncg} \mathcal{E}_{ncg} =$$

$$m_{ncg} [(h_{ncg} - h_0) - T_0 (S_{ncg} - S_0)] \quad (38)$$

$$E_{cw} = m_{cw} \mathcal{E}_{cw} =$$

$$m_{cw} [(h_{cw} - h_0) - T_0 (S_{cw} - S_0)] \quad (39)$$

$$E_{con} = m_{con} \mathcal{E}_{con} =$$

$$m_{con} [(h_{con} - h_0) - T_0 (S_{con} - S_0)] \quad (40)$$

$$E_{exhaust} = m_{exhaust} \mathcal{E}_{exhaust} =$$

$$m_{exhaust} [(h_{exhaust} - h_0) - T_0 (S_{exhaust} - S_0)] \quad (41)$$

Performance criteria

The desired function for this process is to maximize the extraction of the NCG from the condenser. Looking at the system as a heat exchanger, the desired action is to maximize the energy gained by the NCG stream and the cooling water at the expense of the exergy lost by the motive steam. Therefore, the performance criteria will be expressed as a ratio of the sum of the exergy gained by the condensing fluid and the NCG steam to the exergy lost by the GES motive steam (effectiveness of the heat transfer). In equation form with reference to Figure 10:

$$\eta_{ges} = \frac{m_{10} (\mathcal{E}_{13} - \mathcal{E}_{10}) + m_{11} (\mathcal{E}_{12} - \mathcal{E}_{11})}{m_{8a} (\mathcal{E}_8 - \mathcal{E}_{13}) + m_{8b} (\mathcal{E}_8 - \mathcal{E}_{12})} \quad (42)$$

Where m_{8a} , m_{8b} , m_{10} and m_{11} are respectively mass flow rates of motive steam into ejector 1 and 2, mass flow rate of NCG from condenser and mass flow rate of cooling water into the inter-condenser

Assumptions made

1. NCG is pure CO₂ and is 0.25% of steam by weight
2. NCG in the motive steam is neglected
3. All the motive steam in the 1st stage condenses in the inter condenser and only NCG goes to 2nd stage
4. NCG leaving the 2nd stage ejector has equal conditions as the motive steam

3.5 Cooling processes

Description

Figure 10 shows the flow arrangement for the cooling system. This system covers the seal pit and the cooling towers (Figure 11).

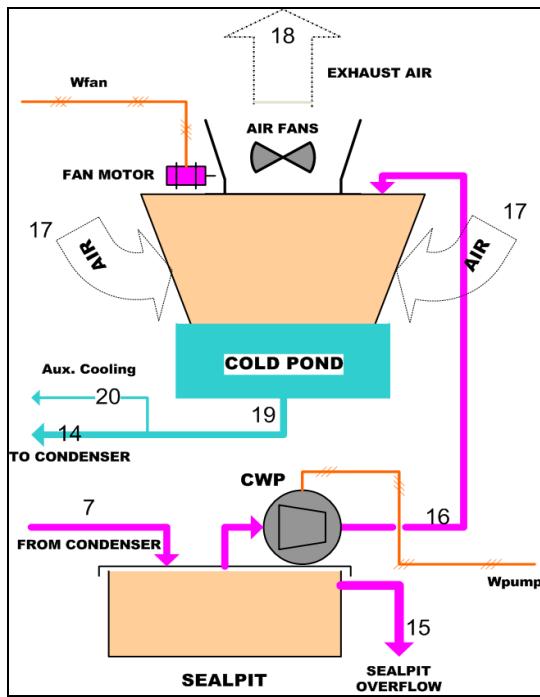


Figure 10: Flow processes in the cooling system of Olkaria I Power station.

The condensate leaves the condenser and enters the seal pit (7). Excess condensate overflows at the seal pit (15). The circulating condensate (16) is pumped by circulating water pump (CWP) to the top of the cooling towers. Water reaches the top of the cooling towers at state and is poured onto hot water basins where it falls down through spray nozzles. The hot water falls through a splash bar grid and the water droplets are split into very fine droplets by the grid. As the water droplets fall down and break up into fine droplets, a stream of air (17) flows across the water droplets thus creating cooling by evaporation and convection-conduction mechanisms. The stream of air is created by suction of air fans (W_{fans}) located at the top of the cooling towers.

The water droplets eventually fall into the cold pond from where it is syphoned into the condenser inlet pipeline (19). Some water goes to the auxiliary cooling (20) and the rest into the condenser (14). Warm moist air leaves the cooling tower (18) driven out by air fans (W_{fans}). Some condensate is lost to the air.

Exergy balance equations

Exergy into this system consists of sum of exergies of the condensate leaving the condenser, the exergy of air entering the cooling towers and the work done by the fans and pumps. The exergy leaving the system consist of exergies of the moist air leaving the cooling towers, the condensate overflowing at the seal pit and the cold water leaving the cooling tower pond. Some exergy is lost by the irreversibilities in the processes. In equation form with reference to Figure 9:

$$\sum E + \sum E_{17} + \sum W_{pumps} + \sum W_{fans} = \sum E_{18} + \sum E_{19} + \sum E_{15} + \sum I \quad (43)$$

- E₇ is the exergy rate of condensate leaving the condenser
- E₁₅ the exergy rate of condensate overflowing at seal pit
- E₁₇ the exergy rate of air entering the cooling tower
- E₁₈ the exergy rate of warm moist air leaving the cooling tower
- E₁₉ the exergy rate of water leaving the cold pond of cooling tower
- I the exergy destroyed or lost in the processes
- W_{fans}, W_{pumps} are the exergy rate of work done by the fans and pumps respectively

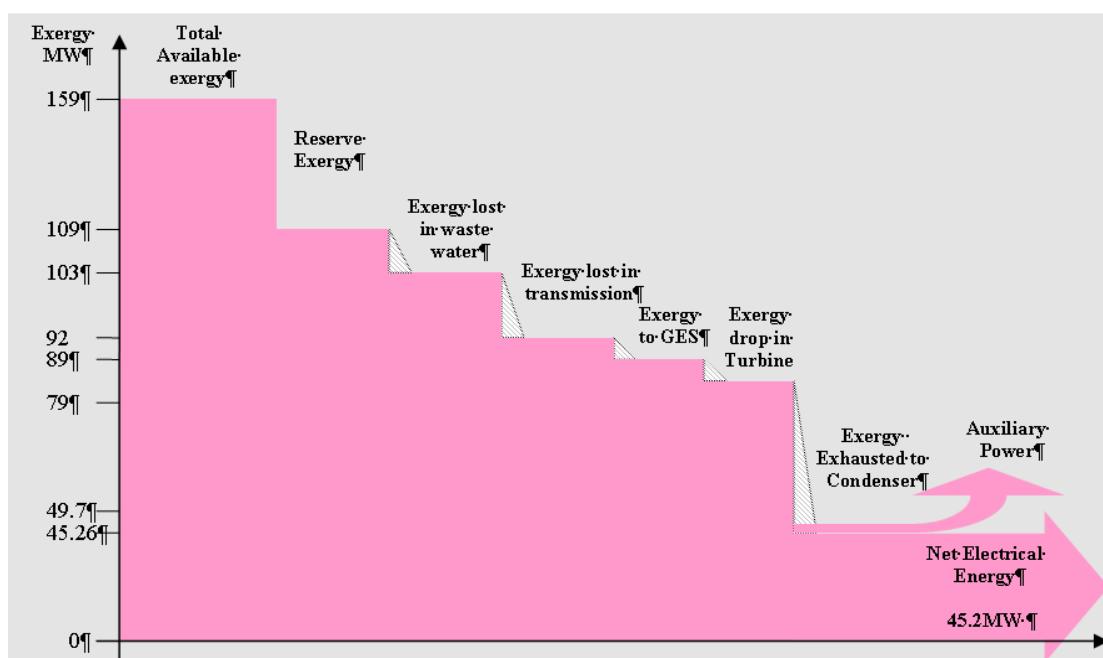


Figure 11: SANKEY diagram illustrating flow of exergy through Olkaria I system and the locations and amounts of exergies destroyed along the process.

Performance criteria

The desired function for this process is to cool the condensate by transferring the exergy in the condensate to the atmospheric air. Looking at the system as a heat exchanger, the objective is to maximize the exergy gained by the stream of cooling air at the expense of the exergy lost by the condensate. Therefore, the performance criteria will be expressed as the ratio of exergy gain of cold fluid to the exergy loss of condensate (effectiveness of the heat transfer):

$$\eta_{cs} = \frac{m_{17}(\mathcal{E}_{18} - \mathcal{E}_{17})}{m_{16}(\mathcal{E}_{16} - \mathcal{E}_{19})} \quad (44)$$

However, a more reasonable performance measure is the coefficient of performance (COP) which is ratio of exergy lost by the condensate (desired action) to sum of work of pumps and fans (work input). In equation, this becomes

$$cop_{cs} = \frac{m_{16}(\mathcal{E}_{16} - \mathcal{E}_{19})}{W_{fans} + W_{pumps}} \quad (45)$$

Assumptions

1. Carryover and drift losses are 5% of condensate entering the cooling towers
2. Only the water leaving the cooling tower shall be considered to be cooled
3. CWP are assumed to operate at 60% of the rated capacity

4. RESULTS AND DISCUSSIONS

The overall exergy flows at Olkaria I are illustrated in the SANKEY diagram (Figure 11) below. The results show that the total available exergy at Olkaria I power plant is 159 MW. Of this available exergy, 7.6 MW exergy exist in the brine which is disposed at the wellheads 152 MW is contained in the steam.

From the wells connected to the system at the time of analysis, a total of 103 MW exergy was received in form of steam and 6 MW was wasted in the separated brine. A total of 11 MW of the steam exergy is lost in the transmission and 1.9 MW exergy goes to the gas extraction system. The total exergy received at the turbine inlets is 89 MW. The exergy drop through the turbines amounted to 60 MW against a gross work developed by the turbine amounting to 49.5 MW. The total exergy in the steam exhausted into the condenser amounted to 30 MW.

The overall exergy efficiency of the power plant was found to be 42% with reference to the total exergy from the connected wells. For comparison, the overall plant energy efficiency was found to be 15%. The large difference in the efficiencies shows that most of the energy received at the wells exits the plant while still containing substantial exergy. The turbines showed high exergy efficiencies because most of the exergy is exhausted into the condensers and not consumed or destroyed. This means that an improvement on the turbines will enable them to extract more work from the fluids or alternatively, device other ways of using the exergy from the fluids exiting the system.

The greatest exergy losses occur in the condensers where most of the exergy is rejected and destroyed. Substantial

exergy losses occur in the transmission system and this can be addressed. The exergy in the waste water is relatively small but is significant and can be used to do more work either with a binary system or by direct use. The exergy losses in the turbines are largely intrinsic but the effects of inter-stage leakages are likely to contribute to the low efficiencies.

5. CONCLUSIONS

The importance of exergy analysis in evaluation of performance of power plants has been proven. The exergy analysis of Olkaria I power plant has been carried out and the locations and quantities of exergy losses, wastes and destructions in the different processes of the plant pinpointed. In addition, the exergy analysis has enabled the degree of thermodynamic imperfections for the processes to be determined. The modelling of the plant in EES computer package resulted in a detailed simulation. The major exergy losses occur in the steam transmission, turbines, condensers and gas ejectors. The irreversibilities in the turbines are a result of metallurgical limitations.

The 6 MWt exergy wasted in the separated brine which is disposed at the wellheads can be utilized by employing a binary plant to generate more electricity. With a typical produced. The wasted brine can further be utilized for direct uses such as hot spas and medicinal uses which can generate a lot of revenues as is the case with the Blue Lagoon of Iceland. Besides getting more from the resource, it will also be a way to address environmental issues.

The exergy lost in the steam transmission system amounting to 11 MW needs to be investigated. The insulation, condensate drains and pressure venting devices should be given attention. The effectiveness of the insulation for the entire pipeline should be studied and all missing insulation replaced. The performance of the condensate drains equipment need to be inspected to identify those which are continuously draining. The orifice plate drains are ineffective since they vent continuously and should be replaced with steam traps. Some of the steam traps are faulty and result in continuous draining and need to be replaced or repaired. A study should be conducted into the viability of installing an additional pressure control valve at wellheads of a few large production wells so that excess steam is contained in the well bore instead of being vented. Such control valves could be designed to be the first to respond before the main vent station takes over.

The causes of exergy destruction in the turbines are mainly related to their design and frictional losses. A large amount of exergy is exhausted into the condensers because of constrain by the metallurgical requirements which limit the minimum dryness of steam at the turbine exit. However, the influence of inter-stage leakages should be investigated and rectified as necessary. It is possible that some inter-stage seals are worn thereby allowing some steam to pass without doing work. The impact of the partial openings of the governor valves also need to be investigated. For all the turbines, the openings of the governor valves at full load were about 60% (Appendix 2). This throttling of steam flow destroys part of its exergy and the governors should operate as close to fully open as possible.

A detailed exergy analysis and plant optimization studies should be conducted combining both Olkaria I & II power plants using actual operating conditions. This should be preceded by checking the accuracy of all the instruments by calibration, especially for Olkaria I and all relevant measuring instruments should be installed. Exergy analysis

should be incorporated in any future designs of geothermal plants in Kenya.

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