OPTIMISATION OF GEOTHERMAL RESOURCES IN KENYA BY ENERGY AND EXERGY CONCEPT LINKING SURFACE AND SUB-SURFACE THROUGH RESERVOIR-WELLBORE COUPLING

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論文題名：**OPTIMISATION OF GEOTHERMAL RESOURCES IN KENYA BY ENERGY AND EXERGY CONCEPT LINKING SURFACE AND SUB-SURFACE THROUGH RESERVOIR-WELLBORE COUPLING** (貯留層－坑井カップリングで地表と地下を連結したエネルギーとエクセルギーの観点によるケニアの地熱資源の最適化)

区　　分：甲

論文内容の要旨

Geothermal energy is ubiquitous, and its utilisation has increased rapidly in the last three decades. The main merits of geothermal energy are low carbon emission, renewability, and sustainability. In the Kenyan case, geothermal energy has displaced hydroelectric power as a reliable baseload due to frequent droughts. Kenya is in the Eastern part of Africa and has geothermal potential exceeding 7 GWe along the East African Rift Valley (EARV). In 2021, Kenya had a peak electricity demand of 2.036 GWe, to which geothermal energy supplied 42%. Historically, geothermal energy exploration started around 1950s in Olkaria and Bogoria regions, and two wells were drilled in Olkaria. The first single flash (SF), Olkaria I power plant, was commissioned in 1981. Kenya's mapped and developed geothermal prospects occur mainly along EARV; other prospects on Western highlands of EARV were studied and updated in the geothermal resource map using geochemistry and Quantum Geographic Information System (QGIS). The utilisation of extracted geofluid includes direct and indirect uses. For indirect applications, the hot fluid from the reservoir is separated into steam when pressure is decreased (flashed) at the wellhead. The steam drives the turbine for power generation, and the separated brine is reinjected back to the reservoir. Flash units are the dominant types of geothermal power plants globally as single flash or double flash. In Kenya, most power plants are operated as single flash. For sustainable development of geothermal resources, there is a need to consider an optimisation strategy; previously, energy and exergy analysis has been applied to optimise the single flash units in Olkaria, Olkaria I, II, and IV power plants. Useable energy is the heat available at the wellhead, and in comparison, exergy is the applicable work that can be achieved from a system at a given state in a defined environment. Since different wells have varied wellhead pressures and geochemistry properties, averaging them at the steam separator can lead to energy loss. At the separator, various safety constraints are usually applied to prevent silica scaling and encourage a single steam pipeline strategy of steam gathering. This study utilised exergy analysis as a tool for informing plant performance and capacity to support additional power generation via topping up and binary units. From the results, the available exergy in Olkaria can generate additional power by topping unit using a backpressure turbine between the separator and condensing steam turbine or Organic Rankine cycles utilising the separated hot brine as the heat source. In addition, optimisation of geothermal resources is not limited to the surface only. There is a need to understand exergetic reservoir conditions to inform how best to set sustainable wellhead exergy parameters. In this research, the wellbore simulator was used to couple the reservoir to the wellbore. In previous studies, simulations have been conducted independently for the reservoir and wellbore. Studies have not linked the surface and sub-surface in Olkaria and other geothermal fields worldwide. The wellbore simulator was used to connect the wellhead and the reservoir simulated pressure and temperature logs for Olkaria Domes in Olkaria, a liquid-dominated geothermal field. The simulation results enabled exergy values at any depth to be calculated using the pressure and temperature values between the reservoir and wellhead. The primary aim of this research was to update the geothermal manifestations map of Kenya and investigate exergy available in the Olkaria field by exergoeconomics analysis. The exergy concept links wellbore and reservoir using the 3-D Kriging method. The outcome of this research will contribute to the overall understanding of optimal utilisation of energy available in surface and sub-surface geofluids in Kenya to improve the sustainable utilisation of geothermal resources.

The contents of the dissertation consist of six chapters below:

Chapter 1: Introduces the background of the study, the introduction of geothermal energy and its uses, the energy situation, and geothermal status in Kenya. This chapter describes the research objectives and methodology.

Chapter 2: Reviews geochemical exploration, energy, exergoeconomics, reservoir simulation, and past reservoir conceptual models in Olkaria geothermal complex and wellbore-reservoir coupling.

Chapter 3: Updates geothermal manifestations in Kenya using geochemistry, isotope analysis and QGIS. Results presented the geochemical analysis of water sampled at six hot spring locations (Kipsegon, Mulot, Eburru, Narosura, Majimoto, and Homa Hills) and literature data from twenty-three geothermal sites (prospects and geothermal wells). The water type was characterised using the ternary plot as carbonate chloride and Mg-bicarbonate, mixed Na-bicarbonate, sodium bicarbonate water and chloride waters with some carbonate and bicarbonate. Temperatures of fluid with depth were estimated using geochemical geothermometers as 219-247°C for Eburru hot spring, while Narosura geothermal reservoir had the lowest reservoir temperatures of 64-95°C with quartz geothermometer. Based on stable isotope, $\delta^{18}O$ and $\delta^{2}H$, analysis of the six hot springs water, the origin of water for the geothermal prospects is mainly meteoric water.

Chapter 4: Focuses on optimising Olkaria I, II, and IV SF power plants, proposing topping unit and three Organic Rankine Cycle (ORC) configurations using different working fluids applying energy and exergy concepts. In Olkaria I, combined water-cooled and air-cooled binary power plants were optimised using eight different working fluids by the thermo-economic concept and sustainability index (SI). Net work generated per heat transfer surface area was the optimised objective function, (f(obj)). Optimisation of exergy at the separated brine of Olkaria II was a combination of exergy and pinch point analysis for ordinary and a regenerative ORC using six different working fluids. The separated brine at a temperature of 156°C at Olkaria I and II with flow rates of 67 kg/s and 206 kg/s, respectively, are the energy sources for ORCs. For Olkaria IV SF, optimisation was considered for a backpressure topping unit and a binary bottoming unit using two working fluids (trans-2-butene and isopentane). Power plant models were modelled and optimised using EES code by energy, exergy, and exergoeconomic analysis. Exergy of 239 MW is being supplied to Olkaria IV SF power plant that generates 140 MWe. Proposed power plants can generate additional 29.29 MWe power by a topping unit. By introducing a backpressure topping unit, exergy efficiencies improved from 56% to 70% and decreased total exergy destruction by 4,056 kW. Bottoming of ORC at Olkaria IV generated 8,788 kWe, and 7,927 kWe net power for trans-2-butene and isopentane, respectively, at optimum turbine inlet pressures between 1,000-3,100 kPa. Trans-2-butene has thermal and second utilisation efficiencies of 13.7% and 49.86%, respectively. On the other hand, isopentane has an optimum turbine inlet pressure of 1,090 kPa, with thermal and second utilisation efficiencies of 12% and 43.96%, respectively. Separated brine at Olkaria I has 7,187 kW exergy into the proposed binary power plant. On the energy and exergy concept, the most suitable plant is a water-cooled type for isobutane and R600a that can generate 2,590 kWe and 2,594 kWe net work, respectively, while R600a is the suitable fluid for air-cooled binary plant generating 2,469 kWe net work with 59.37% utilisation efficiency. Net work of 1,628 kWe to 2,594 kWe was generated in a wet-cooled unit with SI of 1.34 to 1.68 for f(obj) of 1.6 to 1.8. For air-cooled plant, SI ranges were from 1.29 to 1.61 for the net work from 1,446 kWe to 2,469 kWe with utilisation efficiencies of 34.77% to 59.37% and f(obj) values of 0.59 to 0.87. Combining pinch point analysis and exergy optimisation of proposed binary power plants at Olkaria II showed that the optimum pinch point is 8°C for reinjection temperatures above 80°C by varying the turbine inlet pressure and pinch points. For the pinch point of 10°C, the working fluid with a lower net power is trans-2-butene at 5,936 kWe and the highest reinjection temperatures at 89°C. The pinch point affects the heat transfer rates and effectiveness in the heat exchangers. The best pinch point is 10°C since the reinjection temperatures are higher between 83 and 89°C. The exergy and sustainability index analysis method optimised Olkaria II by varying turbine inlet pressure and reinjection temperatures. Heat exchangers contributed about 60% (2,900 - 4,200 kW) of total exergy destruction. The second utilisation efficiencies were between 26-45%. A Grassman diagram summarised the exergy flow in relation to the input exergy of 19,685 kW into the system.

Chapter 5: Couples reservoir with wellbore simulator. The research investigated liquid-dominated Olkaria Domes wells, OW-901, OW-902, OW-903, OW-904, OW-908, OW-909, OW-910, OW-914, OW-921, and OW-924. Reservoir temperatures from the wellbore simulator are high at 296.8°C in OW-916. The formation pressures simulated are between 1,077 to 12,487.9 kPa for wellhead pressure of 459 to 1,720 kPa. The thermodynamic parameters (temperature and pressure) from the wellbore simulator were input parameters in the EES code for calculating entropy, enthalpy, and specific exergy. Python console implemented the 3 D Kriging method to couple the wellbore and reservoir. At any required depth, two-dimensional (2-D) contour maps were plotted for Olkaria Domes between the surface and the reservoir for depths between -2,100 to 1,800 m.a.s.l.

Chapter 6: Summarises the conclusions and recommends future work optimising geothermal resources in Kenya by energy, exergy, exergoeconomic analysis, and wellbore-reservoir coupling.