Abstract

Geothermal energy refers to naturally occurring thermal energy stored within the Earth's crust. The effectiveness of geothermal exploration is strongly governed by subsurface temperature and depth, both of which are driven by the geothermal gradient. With an average gradient of $\sim 30\,^{\circ}\mathrm{C/km}$ in the upper crust, regions exhibiting anomalously high gradients offer favourable conditions for heat extraction and utilization. Owing to its renewable and environmentally benign nature, geothermal energy has gained increasing attention worldwide, prompting research in exploration methods, reservoir characterisation, and extraction techniques.

This dissertation evaluates geothermal resource potential in three different geological settings of the Indian continent—hot-spring reservoir of the Eastern Ghats Belt (EGB), depleted oil and gas fields of the Upper Assam Basin (UAB), and the fire-affected Jharia coalfield (JCF). For the Eastern Ghats Belt (EGB) area, geothermometric analyses combined with wellbore simulations demonstrate reservoir temperatures of $\sim 150\,^{\circ}\mathrm{C}$ and an estimated heat-in-place/volume of $8.1 \times 10^5\,\mathrm{kJ/m^3}$. In the Upper Assam Basin, corrected bottom-hole temperatures from the Lakadong+Therria Formation indicate a heat-in-place/volume of $1.4 \times 10^6\,\mathrm{kJ/m^3}$. The Jharia coalfield (JCF) basin, where long-standing coal fires have created zones of anomalous heat at shallow depths, presents a unique opportunity for waste-heat recovery; its heat-in-place/volume (HIP) is estimated at $10.5 \times 10^5\,\mathrm{kJ/m^3}$.

Coal fires in the Jharia Coalfield (JCF) have persisted for over a century, resulting in elevated subsurface temperatures, land subsidence, greenhouse-gas emissions, and significant constraints on mining operations. However, these thermally anomalous zones, characterised by geothermal gradients ranging from 0.05 to $0.14\,^{\circ}\mathrm{C/m}$ based on temperature logs from 50 wells, represent a substantial yet largely untapped geothermal energy resource.

This study presents the first comprehensive framework integrating experimental investigations and numerical simulations to evaluate and engineer geothermal energy extraction from India's only producing prime coking-coal producing coalfield affected by long-term coal fires.

The thesis undertakes detailed geological investigations, including site characterization, mineralogical analysis, and microstructural evaluation of rocks collected from the JCF basin. Thin-section microscopy and Scanning Electron Microscopy (SEM) imaging reveal thermally induced mineral fragmentation along with widespread intergranular and intragranular cracking. The geomechanical study of rocks shows a non-linear trend in rock-mechanical attributes signifying a rock-strengthening and weakening mechanism. Integrating temperature, porosity, permeability, and heat-in-place maps forms the basis for defining a geothermal play concept in the JCF basin that identifies geothermal hotspots for pilot implementation. Detailed thermophysical analyses of rocks and fluids, including brines and engineered nanofluids and their impact on heat recovery, as demonstrated through wellbore simulations. These findings could provide critical inputs for reservoir-scale heat transport modelling.

A major contribution of this work is the design and fabrication of coupled laboratory-scale flow-loop systems for geothermal heat recovery processes. These represent the first integrated geothermal experimental heat-transfer setups developed in India. The bench-scale experimental setup is designed to determine the overall heat transfer coefficient (HTC) of different fluids and rock systems, with the aim of understanding fluid–fluid and rock–fluid interactions. The bench-scale (HEX–HEGRES) setup demonstrated that the use of nanofluids improves heat-recovery efficiency by roughly 5–8% relative to base fluids. The noted thermal enhancement is additionally validated by a 500 m field-scale closed-loop coaxial wellbore system (CCGS), which forecasts similar increases in production-fluid temperature.

Building upon the experimental findings, the field-scale geothermal simulations were conducted using analytical and numerical approaches to evaluate heat extraction from the coal-fired JCF reservoir. Closed-loop coaxial geothermal systems (CCGS), closed-loop U-tube systems (UCGS), and open-loop geothermal doublets were modelled to assess their thermal performance under actual geological conditions. The simulations indicate that insulated closed-loop wellbores at depths of 1550 ft (472 m) and 3050 ft (929 m) can achieve outlet fluid temperatures of 57°C and 86°C, respectively. Furthermore, the thermo-hydro-mechanical (THM) coupled simulations—the first performed fo a burning coalfield geothermal reservoir—demonstrate strong interactions among injection-induced cooling, pore-pressure evolution, rock deformation, and long-term reservoir stability. After ten years of operation, temperature redistribution around the injection and production wells showcases high sensitivity to geological heterogeneity and operational parameters.

This thesis presents a comprehensive workflow for geological–geomechanical study, thermophysical characterisation of rocks and fluids, experimental heat-transfer testing, and reservoir-scale numerical modelling for geothermal development in the Jharia basin. It advances India's geothermal research by quantifying the heat resource of the Jharia basin ($\sim 10.5 \times 10^5\,\mathrm{kJ/m^3}$), demonstrating viable extraction strategies, and providing engineering insights that can guide sustainable, safe energy recovery from extreme thermal environments. The comprehensive experimental and numerical framework developed in this study is relevant to both conventional hydrothermal systems and unconventional geothermal resources, such as coal-fired reservoirs, depleted hydrocarbon fields, and engineered geothermal systems.

Keywords: Geothermal energy; hot-spring reservoir; depleted oil & gas field reservoir; coal fires; Jharia coalfield; geothermal play; numerical simulations; fluid–fluid interactions; rock–fluid interactions; heat transfer coefficient; thermo-hydro-mechanical coupling.