Geothermal energy is the energy naturally present inside the earth crust. When a large volume of hot water and steam is trapped in subsurface porous and permeable rock structure and a convective circulating current is set up, it forms a geothermal reservoir. A geothermal system can be defined as - convective water in the upper crust of earth, which transfers heat from a heat source (in the reservoir) to a heat sink, usually the free surface. A geothermal system is made up of three main elements: a heat source, a reservoir and a fluid, which is the carrier that transfers the heat.

As an alternative source of energy geothermal energy has been under attention of the researchers for quite some time. The reason behind this is the existence of several benefits like clean and renewable source of energy which has considerable environmental advantage, with no chemical pollutants or wastes are generated due to geothermal emissions, and the reliability of the power resource. Hence research has been directed in several directions like exploration of geothermal resources, modeling the characteristics of different types of geothermal reservoirs and technologies to extract energy from them. The target of these models has been the prediction of the production of the hot water and steam and thus the estimation of the electricity generating potential of a geothermal reservoir in future years.

In a geothermal power plant reinjection of the heat depleted water extracted from the geothermal reservoir has been a common practice for quite some time. This started for safe wastewater disposal and later on the technology was employed to obtain higher efficiency of heat and energy extraction. In most of the cases a very small fraction of the thermal energy present in the reservoir can be recovered without the reinjection of geothermal fluid. Also maintaining the reservoir pressure is essential which gradually reduces due to continuous extraction of reservoir fluid without reinjection, especially for reservoirs with low permeabilities. Although reinjection of cold-water has several benefits, the possibility
of premature breakthrough of the cold-water front, from injection well zone to production well zone, reduces the efficiency of the reservoir operation drastically. Hence for maintaining the reservoir efficiency and longer life of the reservoir, the injection-production well scheme is to be properly designed and injection and extraction rates are to be properly fixed.

Modeling of flow and heat transport in a geothermal reservoir due to reinjection of cold-water has been attempted by several researchers analytically, numerically and experimentally. The analytical models which exist in this field deal mostly with a single injection well model injecting cold-water into a confined homogeneous porous-fractured geothermal reservoir. Often the thermal conductivity is neglected in the analytical study considering it to be negligible which is not always so, as proved in this study. Moreover heterogeneity in the reservoir is also a major factor which has not been considered in any such analytical study. In the field of numerical modeling there also exists a need of a general coupled three-dimensional thermo-hydrogeological model including all the modes of heat transport (advection and conduction), the heat loss to the confining rocks, the regional groundwater flow and the geothermal gradient. No study existing so far reported such a numerical model including those mentioned above.

The present study is concerned about modeling the non-isothermal flow and heat transport in a geothermal reservoir due to reinjection of heat depleted water into a geothermal reservoir. Analytical and numerical models are developed here for the transient temperature distributions and advancement of the thermal front in a geothermal reservoir which is generated due to the cold-water injection. First homogeneous geothermal aquifers are considered and later heterogeneities of different kinds are brought into picture. Three-dimensional numerical models are developed using a software code DuMu\textsuperscript{x} which solves flow and heat transport problems in porous media and can handle both single and multiphase flows. The results derived by the numerical models have been validated using the results from the analytical models derived in this study.

Chapter 1 of the thesis gives a brief introduction about different types of geothermal reservoirs, followed by discussion on the governing differential equations, the conceptual
model of a geothermal reservoir system, the efficiency of geothermal reservoirs, the modeling and simulation concepts (models construction, boundary conditions, model calibration etc.). Some problems related with geothermal reservoirs and geothermal power is also discussed. The scenario of India in the context having a huge geothermal power potential is described and different potential geothermal sites have been pointed out. In Chapter 2, the concept of reinjection of the heat depleted (cold) water into the geothermal reservoir is introduced. Starting with a brief history of the geothermal reinjection, the chapter describes the purpose and the need of reinjection of geothermal fluid giving examples of different geothermal fields over the world where reinjection has been in practice and benefitted by that. The chapter further discusses on the problems and obstacles faced by the geothermal projects resulting from the geothermal reinjection, most important of which is the thermal-breakthrough and cooling of production wells. Lastly the problem of this thesis is discussed which is to model the transient temperature distribution and the movement of the cold-water thermal front generated due to the reinjection. The need of this modeling is elaborated which represents the motivation of taking up the problem of the thesis. Chapter 3 describes an analytical model developed for the transient temperature in a porous geothermal reservoir due to injection of cold-water. The reservoir is composed of a confined aquifer, sandwiched between rocks of different thermo-geological properties. The heat transport processes considered are advection, longitudinal conduction in the geothermal aquifer, and the conductive heat transfer to the underlying and overlying rocks of different geological properties. The one-dimensional heat transfer equation has been solved using the Laplace transform with the assumption of constant density and thermal properties of both rock and fluid. Two simple solutions are derived afterwards, first neglecting the longitudinal conductive heat transport and then heat transport to confining rocks. The analytical solutions represent the transient temperature distribution in the geothermal aquifer and the confining rocks and model the movement of the cold-water thermal front in them. The results show that the heat transport to the confining rocks plays an influential role in the transient heat transport here. The influence of some parameters,
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e.g. the volumetric injection rate, the longitudinal thermal conductivity and the porosity of the porous media, on the transient heat transport phenomenon is judged by observing the variation of the transient temperature distribution with different values of the parameters. The effects of injection rate and thermal conductivity have been found to be high on the results.

Chapter 4 represents another analytical model for transient temperature distribution in a heterogeneous geothermal reservoir underlain and overlain by impermeable rocks due to injection of cold-water. The heterogeneity of the porous medium is expressed by the spatial variation of the flow velocity and the longitudinal effective thermal conductivity of the medium. Simpler solutions are also derived afterwards first neglecting the longitudinal conduction, then the heat loss to the confining rocks depending on the situation where the contribution of them to the transient heat transport phenomenon in the porous media is negligible. Solution for a homogeneous aquifer with constant values of the rock and fluid parameters is also derived with an aim to compare the results with that of the heterogeneous one. The effect of heat loss to the confining rocks in this case is also determined and the influence of some of the parameters involved, on the transient heat transport phenomenon is assessed by observing the variation of the results with different magnitudes of those parameters. Results show that the heterogeneity plays a major role in controlling the cold-water thermal front movement. The transient temperature distribution in the geothermal reservoir depends on the type of heterogeneity. The heat loss to the confining rocks of the geothermal aquifer also has influence on the heat transport phenomenon.

In Chapter 5 another analytical model is derived for a heterogeneous reservoir where the heterogeneous geothermal aquifer considered is a confined aquifer consisted of homogeneous layers of finite length and overlain and underlain by impermeable rock media. All the different layers in the aquifer and the overlying and underlying rocks are of different thermo-hydrogeological properties. Results show that the advancement of the cold-water thermal front is highly influenced by the layered heterogeneity of the aquifer. As the cold-water thermal front encounters layers of different thermo-hydrogeological
properties the movement of it changes accordingly. The analytical solution derived here has been compared with a numerical model developed by the multiphysics software code COMSOL which shows excellent agreement with each other. Lastly it is shown that approximation of the properties of a geothermal aquifer by taking mean of the properties of all the layers present will lead to erroneous estimation of the temperature distribution.

Chapter 6 represents a coupled three-dimensional thermo-hydrogeological numerical model for transient temperature distribution in a confined porous geothermal aquifer due to cold-water injection. This 3D numerical model is developed for solving more practical problems which eliminate the assumptions taken into account in analytical models. The numerical modeling is performed using a software code DuMuX as mentioned before. Besides modeling the three-dimensional transient temperature distribution in the model domain, the chapter investigates the regional groundwater flow has been found to be a very important parameter to consider. The movement of the thermal front accelerates or decelerates depending on the direction of the flow. Influence of a few parameters involved in the study on the transient heat transport phenomenon in the geothermal reservoir domain, namely the injection rate, the permeability of the confining rocks and the thermal conductivity of the geothermal aquifer is also evaluated in this chapter. The models have been validated using analytical solutions derived in this thesis. The results are in very good agreement with each other.

In Chapter 7 the main conclusions drawn from the study have been enlisted and the scope of further research is also pointed out.