Renewable Energy 94 (2016) 223–236

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

A finite element model for high enthalpy two-phase flow in geothermal wellbores

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ARTICLE INFO

Article history:
Received 20 November 2015
Received in revised form
15 February 2016
Accepted 8 March 2016
Available online 25 March 2016

Keywords:
High enthalpy geothermal systems
Wellbore
Drift-flux model
Level set
Airlift

ABSTRACT

This paper introduces a computational model for transient high enthalpy fluid flow through geothermal wellbores. The drift-flux model is utilized to formulate the physical behavior of fluid, and the constitutive relationships are described using relevant equations of state and empirical relationships. The governing equations are solved using the finite element method. All important physical phenomena and processes occurring along the wellbore, including buoyancy, phase change, compressibility, thermal interaction, wall friction and slip between phases are considered. Airlifting of water and air, initially existing in the wellbore before production, is also considered. During airlifting and early stages of production, two fluids exist along the wellbore: airlifted water-dry air fluid, and reservoir water-vapor fluid; giving rise to a discontinuity in thermodynamic properties between the two fluids. The discontinuity is modeled using the level-set method. Two numerical examples illustrating the computational capability and accuracy of the model are presented. The physical phenomena occurring during airlifting and production along the wellbore are highlighted.

1. Introduction

With the growing demand of renewable energy and the associated growth of interest and investment in geothermal energy extraction, the development of computational models for the simulation of a wide range of geothermal systems is inevitable. Predicting the fluid properties along the wellbore, such as temperature, phase composition and mass density is vital for the design and monitoring of geothermal systems. This constitutes the main objective of this research work, which aims at the development of a computational tool for deep high enthalpy geothermal systems consisting of multilevel geothermal reservoirs operated by multiple wellbores.

In deep high enthalpy geothermal systems, the fluid along the wellbore exhibits phase change, manifested by flash evaporation due to pressure reduction accompanied by a certain range of temperature. Below the flash evaporation point, in the upstream, the fluid is liquid, while immediately above it, the fluid is a mixture of water liquid and vapor. This sudden change in material composition can cause significant change in its properties and behavior. Such kind of physical behavior is computationally challenging and demanding. It requires innovative conceptual modeling, descriptive mathematical formulation and robust numerical discretization.

Several geothermal models and simulators are available in literature. Pioneering works have been introduced by Poettmann and Carpenter (1952), Zuber and Findlay (1965) and Gould (1974), who simulated steady-state heat and fluid flow in wellbores with two separated phases with slip between them [1–3]. Miller (1980) was one of the first to developed a transient wellbore simulator, WELBORE [4,5]. Bjornsson and Bodvarsson (1987) stimulated one and two phase flow along a vertical wellbore with multiple feed zones, and developed HOLA code, which later on expanded to handle CO_2–H_2O and NaCl–H_2O systems [6,7]. Gudmundsdottir et al. (2013) developed a steady state model for one and two sliding separated phase flow along a wellbore, and compared their results with measured data and existing models [8]. These models, and most of existing simulators, are based on the finite difference or finite volume methods. On the other hand, Saeid et al. (2013) introduced a finite element model for low enthalpy deep geothermal systems [9].

Here, we solve the heat and fluid flow in a high enthalpy deep

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http://dx.doi.org/10.1016/j.renene.2016.03.034
0960-1481/

geothermal wellbore using the finite element method. We utilize the drift-flux model [10–13] to simulate transient heat flow of a compressible, two-phase fluid travelling along the wellbore. This model adopts the area-averaged approach, where detailed analysis of the local behavior of the involved phases are averaged over the cross-sectional area of the wellbore [14]. All important physical phenomena and processes occurring along the wellbore, including fluid dynamics, buoyancy, phase change, compressibility, thermal interaction, wall friction and slip between phases are considered. Airlifting of water and air, initially existing in the wellbore before production, is also considered. Airlifting is a process to facilitate fluid production by injecting air into an existing fluid to reduce its mass density. During early stages of production, two fluids exist along the wellbore: the wellbore airlifted water-dry air fluid, and the reservoir water-vapor fluid. This process inevitably generates an interface between the two fluids that exhibits a jump in mass density, specific enthalpy and other thermodynamic properties. The jump is modeled here using the level-set method [15,16], and coupled to the drift-flux model.

Numerical discretization of the mathematical model and implementation are conducted using the finite element package COMSOL Multiphysics. As the model is compressible, highly advective, non-linear and involves forces with opposite effects, such as buoyance that tempts to force the fluid to flow against gravity, and drag forces that temp to impede the buoyance, it is not possible to use the standard strong form implementation of the partial differential equations in COMSOL. Instead, the weak form is implemented.

In this paper, we introduce a detailed formulation of the governing balance equations and their relevant constitutive equations and equations of state. A detailed weak form formulation of the governing partial differential equations, tailored for implementation in COMSOL, is also introduced. We discuss the capability of the model to simulate heat and fluid flow in a vertical wellbore, which might be embedded in a wide range of high enthalpy reservoirs. Comparison to field data is also introduced.

2. Mathematical model formulation

The drift-flux model is utilized to formulate heat and fluid flow of a compressible two-phase mixture along a one-dimensional wellbore subjected to pumping at its upper boundary. Important aspects of fluid dynamics such as the inertia force, buoyancy, wall friction, drift velocity, flow profile, together with the jump in thermodynamic properties between the airlifted mixture and the reservoir mixture, are considered.

2.1. Balance equations

Using the drift-flux model, the transient fluid flow in a one-dimensional wellbore with a constant cross-sectional area can be described as.

Mass balance

$$\frac{\partial \rho_m}{\partial t} + \frac{\partial \rho_m u_m}{\partial z} = 0 \tag{1}$$

Momentum balance

$$\frac{\partial \rho_m u_m}{\partial t} + \frac{\partial}{\partial z}\left(\rho_m u_m^2 + \gamma\right) = -\frac{\partial P}{\partial z} - \frac{f \rho_m |u_m| u_m}{4 r_i} - \rho_m g \sin\theta \tag{2}$$

Energy balance

$$\frac{\partial}{\partial t}\left[\left(\rho_m h_m + \frac{\rho_m u_m^2}{2}\right) - P\right] + \frac{\partial}{\partial z}\left[\rho_m u_m \left(h_m + \frac{u_m^2}{2}\right)\right] = \frac{Q(z)}{\pi r_i^2} - \rho_m u_m g \sin\theta \tag{3}$$

where r_i is the inner radius of the wellbore, ρ_m is the fluid mixture density, u_m is the mixture velocity, P is the pressure, g is the gravitational constant, θ is the inclination angle of the wellbore, h_m is the specific enthalpy of the mixture, f is the wall friction coefficient, Q is the heat exchange between the wellbore and its surrounding formation, and γ is the slip between phases. Detailed formulation of f, Q and γ are given in Appendix A.

In hydrothermal high enthalpy systems, the thermodynamic state quantities, given in Eqs. (1)–(3), play a major role in the fluid flow along the wellbore. The coupling between the fluid mass density, pressure, enthalpy, temperature and velocity significantly affect the mass and volume flow rates along the wellbore and, hence, the amount of energy production, which constitutes the main objectives of constructing geothermal energy systems. As the mass density and temperature are functions of pressure and specific enthalpy, and as the fluid velocity is important in determining the mass flow rate, we select the mixture pressure, P, specific enthalpy, h_m, and velocity, u_m, as the primary state variables. They are explicitly determined from solving the balance equations, Eqs. (1)–(3). The mass density and temperature are determined from the primary state variables via their equations of state and other relevant empirical relationships.

2.2. Constitutive equations

Physical characteristics of the formation water play a significant role on the flow along the wellbore, and their good characterization is essential for the accuracy of computational results. The mass density, in particular, plays a major role in determining the pressure and temperature distribution along the wellbore, and together with the wall friction, slip between phases, and thermal interaction with surrounding rock formation determine the mass and volume flow rates.

The formation water mass density is a function of pressure, temperature, vapor volume fraction and the type and amount of dissolved saline minerals and gases. The proposed model is generic and can be tailored to a wide range of pressure and enthalpy, but for the current research work, the focus is placed on the specific enthalpy range between 900 ($kJ\ kg^{-1}$) and 1100 ($kJ\ kg^{-1}$), and pressure range between 1 *bar* and 117 *bar*. In these ranges, for low saline reservoirs, the salinity effect is not significant [17,18], and accordingly, the properties of the formation water can be described in terms of the equations of state of pure water. The formation water is assumed a mixture of two phases: liquid water and vapor, which, depending on the temperature and pressure, a single phase or both phases can exist in space.

2.2.1. Mixture mass density

The two-phase water mixture density is described as

$$\rho_m = \alpha \rho_g + (1 - \alpha)\rho_l \tag{4}$$

in which α is the vapor volume fraction, and ρ_g and ρ_l are the gas and liquid phase densities, respectively, defined as

$$\rho_l(P, T) = 1 \Big/ \left(\frac{\partial g_1}{\partial P}\right)_T \tag{5}$$