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Modeling a new design for extracting energy from geopressured geothermal reservoirs

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ABSTRACT

Reducing geothermal energy recovery costs and environmental concerns has led to interest in modeling new borehole heat exchanger designs. These heat exchangers are environment-friendly because they inject all the geofluid back into the reservoir after harvesting its energy, resulting in zero mass withdrawal from the system. This study develops reduced-order reservoir models for quickly estimating production temperature and thermal recovery from borehole heat exchangers using inspectional analysis and predictive modeling. An inspectional analysis suggests that there are nineteen dimensionless numbers necessary to fully scale this design. These dimensionless numbers were used in the statistical modeling. A Box–Behnken experimental design was used to create the simulation runs. A rigorous sensitivity analysis was performed on these designed series of runs to identify the most important dimensionless groups in predicting the dimensionless response for different segments of time. The selected dimensionless groups along with the dimensionless production temperature and thermal recovery factor (response), were used in the regression models. The models were reduced and assessed using training and testing runs. Applications of the developed models are also presented. The approach presented in this paper is general and provides a means to interpret and develop predictive models from simulator outputs in other research areas.

1. Introduction

Securing energy needs and reducing CO^2 emissions are inspiring new heat exchanger designs for extracting renewable energy from geopressured-geothermal reservoirs. A borehole heat exchanger (BHE) may be more economical compared with traditional multiwell heat extraction techniques because it can eliminate the need for injection facilities and reduces the surface footprint by reducing the number of wells needed to exploit the reservoir (Feng, 2012; Akhmadullin, 2016; Akhmadullin and Tyagi, 2017). The injected fluid gains energy and this process helps in the renewability of reservoir. Numerous studies have focused on the numerical simulation and design of BHE technology (Beier et al., 2012; Focaccia and Tinti, 2013; Gorman et al., 2014; Liang et al., 2014; Oppelt et al., 2010; Wołoszyn and Gołaś, 2016). These works, however, either do not consider the heat convection that occurs in a geopressured geothermal reservoir or do not offer any quick predictive model for the results.

This study is focused on the reservoir engineering aspects of downhole heat exchangers in which the production fluid is completely injected back into the reservoir resulting in zero mass withdrawal (ZMW design) from the reservoir. This study offers simple predictive models for dimensionless production temperature and thermal recovery factor of the ZMW designs by combining inspectional analysis (Shook et al., 1992; Novakovic, 2002) and statistical modeling (Wood et al., 2008; Anbar and Akin, 2011; Mishra et al., 2015; Zhong and Carr, 2016).

The paper proceeds as follows: the governing equations describing the reservoir physics of a borehole ZMW system (Fig. 1) are described. The problem is scaled and all the dimensionless numbers associated with this system are derived using inspectional analysis (IA). A sensitivity analysis of these dimensionless numbers is performed and the selected dimensionless numbers are used to create the predictive models. The models are further simplified, tested and their applications are presented.

2. Methods

In this section, the governing equations describing the effects a Zero Mass Withdrawal (ZMW) system (Fig. 1) has on a reservoir are derived from the fundamental partial differential equations. A base case is

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Nomenclature

Roman

c	compressibility (Pa^{-1})
M	matrix/fluid heat capacity ratio (–)
PV	pore volume ($\phi L\ WH$, (m^3))
p	pressure (Pa)
q	flow rate (m^3/day)
T	temperature (K)
t	time (s)
U	internal energy (J)
u_T	injection/production velocity (m day^{-1})
$\mathbf{u}$	interstitial fluid velocity (m day^{-1})
W	reservoir width (m)
C_p	isobaric specific heat capacity (J kg^{-1} K^{-1})
C_v	volumetric specific heat capacity (J kg^{-1} K^{-1})
$\mathbf{g}$	gravity vector (m s^{-2})
H	reservoir thickness (m)
$\mathscr{H}$	enthalpy (J)
$\mathbf{K}$	permeability tensor (m^2)
k_x, k_y, k_z	directional permeabilities (m^2)
L	reservoir length (m)

Greek

ϕ	porosity (–)
α, α_X, α_Y	dip angle (°)
β	thermal expansivity (K^{-1})
ρ	density (kg m^{-3})
$\boldsymbol{\tau}$	Geothermal gradient (K m^{-1}))
π	scale group (-)
$\boldsymbol{\lambda}$	thermal conductivity tensor (J m^{-1} day^{-1} K^{-1})
λ	thermal conductivity (J m^{-1} day^{-1} K^{-1})
κ	thermal diffusivity (m^2 day^{-1})
μ	viscosity (Pa s)

Subscripts

1 or 2	scale factor number
avg	average
D	dimensionless
f	fluid
i	initial
inj	injection
ins	insulation
prod	production
r	rock
ref	reference
t	total
ϕ	pore

Superscripts

*	denotes a scale factor

Other symbols

∀	for all
∇ .	divergence
∇	gradient

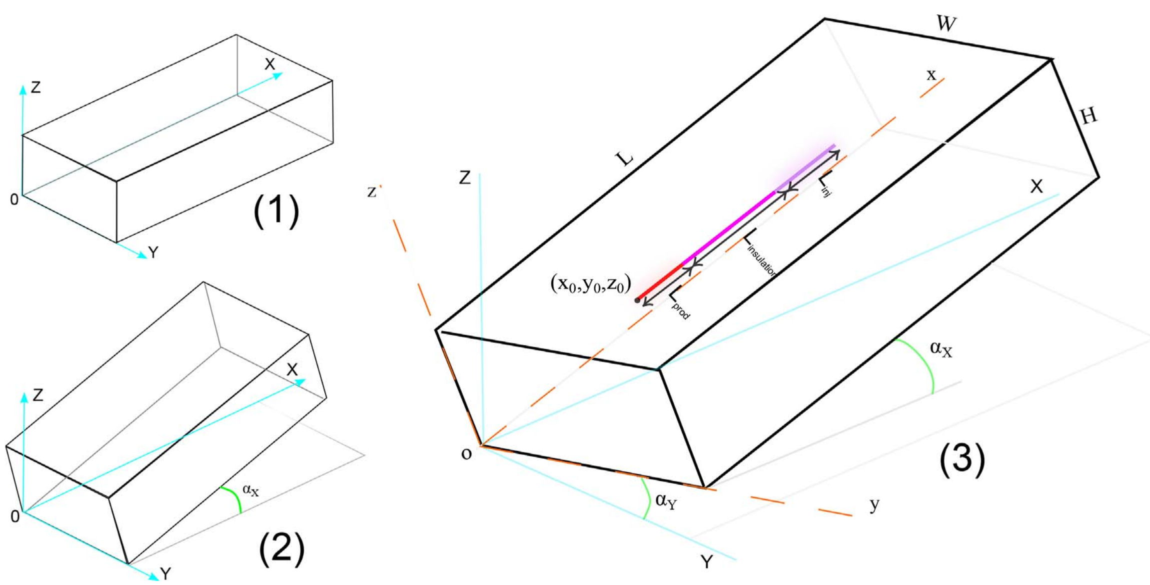

Fig. 1. A borehole Zero Mass Withdrawal (ZMW) design. This design is based on Feng et al. (2014) and Novakovic (2002) work for studying the effect of downhole heat exchangers on the geopressured geothermal reservoirs using a single horizontal wellbore. The horizontal system is first rotated α_X degrees along the Y axis and then rotated α_Y degrees along the X axis.

simulated and the spatial dimensions of the problem are scaled using available analytical solutions. Then, the dimensionless numbers are derived using inspectional analysis (Appendix A and explained relative to similar systems by the authors Ansari, 2016).

2.1. Zero Mass Withdrawal (ZMW) model

2.1.1. Continuity equation

The general continuity equation for single phase flow in porous media shows that the divergence of the mass transport determines the change in the water mass in the medium if no water is generated in the rock (Eq. (1)).