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THE WELLBORE SIMULATOR FLOWELL

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ABSTRACT

This paper discusses a new wellbore simulator FloWell. FloWell is a simple wellbore simulator designed to model single phase, two phase and superheated steam flows in geothermal wells. The paper discusses both features and limitations of FloWell and the assumptions and constraints made in the design phase.

To validate FloWell, data from two geothermal fields, Reykjanes and Svartsengi, in Iceland is used. Emphasis is placed on examining empirical equations used when modeling two phase flows where existing void fraction correlations are studied in depth. A comparison is made between several void fraction correlations and a ranking order established which identifies the correlations that perform the best in simulating the diverse characteristics found in geothermal wells. Furthermore, an attempt is made to improve parameters in the void fraction correlations so simulations with FloWell better fit measured data.

FloWell can be used individually to simulate the behavior of producing geothermal wells but is also designed to be coupled to a reservoir simulator in a moderately simple way. Coupling of the wellbore simulator FloWell and the reservoir simulator TOUGH2 is described in the paper *A Coupled Wellbore-Reservoir Simulator Utilizing Measured Wellhead Conditions* by the same authors, presented at the Thirty-Eighth Workshop on Geothermal Reservoir Engineering at Stanford University.

NOMENCLATURE

d	diameter [m]
E	simplicity factor
F	simplicity factor
F_1	simplicity factor
F_2	simplicity factor
f	friction factor
Fr	Froude number
g	acceleration due to gravity [m/s^2]
G	mass velocity [kg/m^{2}s]
h	enthalpy [J/kg]
H	simplicity factor
$\dot{m}$	mass flow [kg/s]
p	pressure [Pa]
$\dot{Q}$	heat loss [W/m]
Re	Reynolds number
S	slip ratio
u	velocity [m/s]
We	Weber number
x	steam quality
y	simplicity factor
z	axial coordinate
α	void fraction
γ	simplicity factor
ε	roughness [m]
η	simplicity factor
μ	dynamic viscosity [Pa/s]
ρ	density [kg/m^3]
σ	surface tension [N/m]
Φ^2	friction correction factor

Subscripts

l	liquid phase
g	gas or vapor phase

INTRODUCTION

Geothermal energy is classified as a renewable resource and has the potential of contributing greatly to sustainable energy use in many parts of the world. The energy is generated and stored in the Earth. The main source of the heat is the radioactive decay of unstable isotopes within the mantle and the crust but some of the heat stored in the Earth is also from the formation of the planet. Heat flows continuously from Earth's core to the surface, heating rocks and groundwater, and from the surface it is lost to the atmosphere. In terms of a human life time, the geothermal energy is virtually inexhaustible, if used in a sensible manner (Carella, 2001).

Monitoring the behavior of a geothermal reservoir and wells over time leads to greater understanding of the resource's nature and allows extensive databases of geophysical parameters to be created. Mathematical models are developed on the basis of these databases. These numerical models are one of the most important tools in geothermal resource management. They can be used to extract information on conditions of geothermal systems, predict reservoir's behavior and estimate production potential (Axelsson, 2003).

With the growth of the geothermal industry, computer models of geothermal systems have become more sophisticated. The geothermal industry began accepting the concept of geothermal simulations in the 1980s. During that time, a great deal of pioneering work was published, but lack of computer power forced the pioneers to simplify the geometry in their models so computational meshes could be created. As the computer power available increased more complex simulators emerged, producing more accurate results than their predecessors (O'Sullivan et al., 2001).

Even though there are various geothermal simulators available, many of them have limitations in finding a good agreement between simulated and measured field data. The aim of this work was to design a new wellbore simulator, FloWell, to study the heat and pressure propagation inside geothermal wells and to validate it with real data. Emphasis was placed on investigating different void fraction correlations in order to identify which one manages best to simulate the diverse characteristics found in geothermal wells.

This paper discusses in detail the theoretical background of FloWell as well as describes the basic structure of the simulator, its features and limitations. A validation of FloWell with pressure logs from two geothermal fields in Iceland, Reykjanes and Svartsengi is presented and results from void fraction correlation analysis examined.

HISTORICAL REVIEW

As the numerical solution of differential equations became a possibility, the oil and gas industry were quick to adopt the solution methods and use them to simulate the underground behavior in oil and gas reservoirs. However, due to the complexity involved in coupling between mass and energy transport in geothermal reservoirs, the application of these methods in the geothermal industry lagged behind their application in oil and gas industry. As a result, most well-known correlations used in geothermal simulations are originated from the oil and gas industry. These correlations have been modified to suit the conditions found in geothermal areas (O'Sullivan et al., 2001).

Since the geothermal industry began developing numerous geothermal models have been published. The most used models are those which simulate underground flow in geothermal reservoirs and models that simulate the internal flow processes in geothermal wells. Over the years attempts have been made to couple wellbore simulators with reservoir simulators to predict the behavior of geothermal systems with time. Some have been successful while others not.

There has been a steady development in two phase flow models over the years. The separated flow model, where it is assumed that the phases flow concurrently rather than at the same velocity, originates from the work of Lockhart and Martinelli (1949). The Lockhart-Martinelli model is one of the simplest models available for predicting pressure drop in two phase flow.

Poettmann and Carpenter (1952) were the first ones to develop a practical calculation model for vertical two phase flow. It ignored effects of flow patterns and slippage between phases was disregarded. The first ones to consider flow regimes and to develop different correlations for each regime were Duns and Ros (1963). Hagedorn-Brown (1965) constructed one of the more successful pressure drop calculation model. Their model included the effects of slippage but no flow patterns were distinguished. Orkiszewski (1967) approached the two phase flow in a different manner, where he put several previous models together with modifications based on 148 pressure drop measurements.

Gould (1974) developed the first numerical program capable of modeling two phase flow in geothermal wellbores. Gould used a combination of correlations from the petroleum industry and coupled them with heat transfer equations to model the two phase flow.

Goyal et al. (1980) used data from the Cerro Prieto geothermal field in Mexico to study the effect of measured wellhead parameters on downhole pressures in wellbores. With this study the effects caused by scale deposits in wellbores became evident to scientists.

Miller (1980) developed one of the earliest transient wellbore simulators, WELBORE. Unlike previous wellbore simulators a steady state is not assumed, i.e. the mass into the well does not necessarily equal the mass out of it.

Barelli et al. (1982) showed that if the presence of CO_2 is neglected the comparison of pressure and temperature profiles becomes insignificant. They described a steady state wellbore simulator that accounted for non-condensable gases and dissolved solids.

Ortiz-Ramirez (1983) developed a geothermal simulator, WF2, at Stanford University. It was one of few simulators at that time which allowed calculations to start at the top or the bottom of a well.

Bjornsson (1987) developed a geothermal wellbore simulator, HOLA, to simulate one or two phase flow in a vertical well with multiple feedzones. Later, two other simulators, GWELL and GWNACL, were published. They are modified versions of HOLA that can handle H_2O-CO_2 and H_2O-NaCl systems, respectively (Aunzo et al., 1991).

Since the first wellbore simulator was published, scientists have striven for improving modeling techniques and renewing older work. Numbers of wellbore simulators have been discussed in published literature and it is needless to describe all in details here. Other known wellbore simulators include VSTEAM, GEOTEMP2, WELLCARD, PROFILI, BROWN, WELLSIM, GEOWELLS, SIMU93, SIMU2000, MULFEWS and SuperWell.

THE PHYSICAL MODEL OF FLOWELL

Two phase flow occurs frequently in our nature and is most common in geothermal reservoirs, wellbores and surface pipelines. Whether the flow contains two immiscible liquids, a liquid and a solid, a liquid and a vapor, or a solid and a vapor, the internal topology of the flow constantly changes as the phases interact, exchanging energy, momentum and often mass. The following sections describe the mathematical approaches behind the wellbore simulator FloWell, beginning with the most general principles governing the behavior of all matter, namely, conservation of mass, momentum and energy.

The expressions of the governing equations for single and two phase flow proposed by Pálsson (2011) are used in this study.

Single phase flow

The continuity equation derives from conservation of mass and can be written as

$$u\left(\frac{\partial\rho}{\partial p}\frac{dp}{dz}+\frac{\partial\rho}{\partial h}\frac{dh}{dz}\right)+\rho\frac{du}{dz}=0 \qquad (1)$$

The energy equation contains a kinetic energy part, gravitational potential energy part and thermal energy part. The equation can be written as

$$\dot{m}u\frac{du}{dz}+\dot{m}\frac{dh}{dz}+\dot{m}g+\dot{Q}=0 \qquad (2)$$

The momentum equation contains inertia, pressure changes, hydrostatic pressure and head loss part. The relation is written as follows

$$\rho u\frac{du}{dz}+\frac{dp}{dz}+\rho g+\frac{\rho f}{2d}u^2=0 \qquad (3)$$

where f is the friction factor and d is the pipe diameter. Possible relations for the friction factor are the Blasius equation for smooth pipes

$$f=\frac{0.316}{Re^{1/4}} \qquad (4)$$

and the Swamee-Jain relation, where the effect of pipe roughness is included;

$$f=\frac{0.25}{\left(log\left(\frac{\varepsilon}{3.7d}+\frac{5.74}{Re^{0.9}}\right)\right)^2} \qquad (5)$$

The Reynolds number used for the evaluation of the friction factor is defined as

$$Re=\frac{\rho u d}{\mu} \qquad (6)$$

Two phase flow

In two phase flow the flow consist of liquid and vapor states. Assuming constant pipe diameter, using the void fraction definition and introducing the uniform velocity u instead of the actual velocities, the continuity equation becomes

$$u\frac{\partial\rho_l}{\partial p}\frac{dp}{dz}+\rho_l\frac{du}{dz}=0 \qquad (7)$$

Similar to single phase flow, the energy equation can be written as

$$\frac{d}{dz}\left(\dot{m}_l\left(\frac{u_l^2}{2}+gz+h_l\right)+\dot{m}_g\left(\frac{u_g^2}{2}+gz+h_g\right)\right)+\dot{Q}=0 \qquad (8)$$

By using the mass fraction x, the uniform velocity u and the partial derivatives the energy equation can be expressed on the form

$$\gamma u\frac{du}{dz}+\frac{u^2}{2}\frac{\partial\gamma}{\partial p}\frac{dp}{dz}+\left(1+\frac{u^2}{2}\frac{\partial\gamma}{\partial h}\right)\frac{dh}{dz}+g+\frac{\dot{Q}}{\dot{m}}=0 \qquad (9)$$

where γ is defined as

$$\gamma=\frac{(1-x)^3}{(1-\alpha)^2}+\frac{\rho_l^2x^3}{\rho_g^2\alpha^2} \qquad (10)$$

The momentum equation for two phase flow can be written as

$$\eta\rho_l u\frac{du}{dz}+\left(1+\rho_l u^2\frac{\partial\eta}{\partial p}+\eta u^2\frac{\partial\rho_l}{\partial p}\right)\frac{dp}{dz}+ \qquad (11)$$
$$\rho_l u^2\frac{\partial\eta}{\partial h}\frac{dh}{dz}+\left((1-\alpha)\rho_l+\alpha\rho_g\right)g+\frac{\Phi^2\rho_l f}{2d}u^2=0$$

where Φ^2 is the frictional correction factor for pressure loss in two phase flow and η is defined as

$$\eta=\frac{(1-x)^2}{1-\alpha}+\frac{\rho_l}{\rho_g}\frac{x^2}{\alpha} \qquad (12)$$

Since u is based on a fluid with liquid properties, the friction factor is evaluated based on

$$Re_l=\frac{\rho_l u d}{\mu_l} \qquad (13)$$

Friction correction factor

Various relations exist for the friction correction factor Φ^2. Here, two relations will be presented, the

Friedel and Beattie approximations. The Friedel (1979) correction factor is defined as

$$\Phi^2 = E + \frac{3.24FH}{Fr^{0.045}We^{0.035}} \quad (14)$$

where

$$E = (1 - x^2) + x^2 \frac{\rho_l}{\rho_g}\frac{f_g}{f_l} \quad (15)$$

$$F = x^{0.78}(1 - x^2)^{0.24} \quad (16)$$

$$H = \left(\frac{\rho_l}{\rho_g}\right)^{0.91}\left(\frac{\mu_g}{\mu_l}\right)^{0.19}\left(1 - \frac{\rho_g}{\rho_l}\right)^{0.7} \quad (17)$$

$$Fr = \frac{\rho_l{}^2 u^2}{g\rho_x^2 d} \quad (18)$$

$$We = \frac{\rho_l{}^2 u^2 d}{\sigma\rho_x^2} \quad (19)$$

$$\frac{1}{\rho_x} = \frac{x}{\rho_g} + \frac{1 - x}{\rho_l} \quad (20)$$

The ρ_x is the homogenous density based on steam quality. The Beattie (1973) correction factor is much simpler, and can be calculated by a single equation.

$$\Phi^2 = \left(1 + x\left(\frac{\rho_l}{\rho_g} - 1\right)\right)^{0.8}\left(1 + x\left(\frac{3.5\mu_g + 2\mu_l}{(\mu_g + \mu_l)\rho_g} - 1\right)\right)^{0.2} \quad (21)$$

Void fraction definition

One of the critical unknown parameter in predicting pressure behavior in a wellbore is the void fraction, which is the space occupied by gas or vapor. Countless void fraction correlations have been created and it can often turn out to be a difficult task choosing the appropriate correlation.

The homogeneous model is the most simplified. The two phases, liquid and vapor, are considered as homogeneous mixture, thereby traveling at the same velocity. Another approach is to assume that the phases are separated into two streams that flow with different velocities. The modified homogeneous model introduces the slip ratio, *S*, which is the ratio between the flow velocities at given cross section. The model can be written as

$$\alpha = \frac{1}{1 + \left(\frac{1 - x}{x}\right)\left(\frac{\rho_g}{\rho_l}\right)S} \quad (22)$$

In the homogenous model it is assumed that the slip ratio is equal to one. Other models extend the simple homogenous flow model by using other derived relations as the slip ratio. Zivi (1964) proposed that the slip ratio was only dependent on the density ratio of the phases;

$$S = \left(\frac{\rho_l}{\rho_g}\right)^{1/3} \quad (23)$$

Chisholm (1973) arrived at the following correlation for the slip ratio:

$$S = \left(\frac{\rho_l}{\rho_x}\right)^{1/2} \quad (24)$$

One of the more complex void fraction based on slip ratio is the one introduced by Premoli et al. (1970). Their slip ratio is defined as

$$S = 1 + F_1\left(\frac{y}{1 + yF_2} - yF_2\right) \quad (25)$$

where

$$F_1 = 1.578Re_l^{-0.19}\left(\frac{\rho_l}{\rho_g}\right)^{0.22} \quad (26)$$

$$F_2 = 0.0273We_lRe_l^{-0.51}\left(\frac{\rho_l}{\rho_g}\right)^{-0.08} \quad (27)$$

$$y = \frac{1}{\left(\frac{1 - x}{x}\right)\left(\frac{\rho_g}{\rho_l}\right)} \quad (28)$$

$$We_l = \frac{G^2 d}{\sigma\rho_l} \quad (29)$$

$$Re_l = \frac{Gd}{\mu_l} \quad (30)$$

The Lockhart-Martinelli correlation (1949) is often chosen due to its simplicity. In this model, the relationship between void fraction, steam quality, density and viscosity is derived as

$$\alpha = \left(1 + 0.28\left(\frac{1-x}{x}\right)^{0.64}\left(\frac{\rho_g}{\rho_l}\right)^{0.36}\left(\frac{\mu_l}{\mu_g}\right)^{0.07}\right)^{-1} \quad (31)$$

Rouhani and Axelsson (1970) proposed a void fraction computed by a semi-empirical equation given as

$$\alpha = \left(\frac{x}{\rho_g}\right)\left(\left(1 + 0.12(1 - x)\right)\left(\frac{x}{\rho_g} + \frac{1-x}{\rho_l}\right) + \frac{(1.18(1-x))\left(g\sigma(\rho_l - \rho_g)\right)^{0.25}}{G\rho_l^{0.5}}\right)^{-1} \quad (32)$$

This model is more extensive than previous model, where it takes into account the effects of cross sectional are of the pipe, mass flow rate of the mixture, surface tension and gravitation.

THE WELLBORE SIMULATOR FLOWELL

Basic Architecture of FloWell

For this study, a numerical wellbore simulator has been developed and named FloWell. The simulator is built around eq. (1)-(32) defined in the chapter The *Physical Model of FloWell* and MATLAB is used as a programming language.

To perform a simulation with FloWell the following input parameters are needed:

- Inner diameter and depth of a well

- Roughness of the walls in the well
- Total mass flow rate at the wellhead
- Enthalpy of the working fluid
- Bottomhole pressure or wellhead pressure

Features and assumptions

The wellbore simulator is capable of:

- Modeling liquid, two phase and superheated steam flows
- Allowing users to choose between various friction, friction correction factor and void fraction correlations
- Performing wellbore simulations from the bottomhole to wellhead section, or from the wellhead to the bottom of the well
- Providing simulated results, such as pressure and temperature distribution as well as steam quality, friction, velocity, enthalpy and void fraction at each dept increment
- Providing graphical plots of simulated pressure and temperature profiles

Some general assumptions have been made in the development of the simulator. It is assumed that:

- The flow is steady and one dimensional
- Multiple changes of the wellbore geometry, such as diameters and roughness, do not occur
- Simulations will be restricted to wells with single feedzones
- The fluid is pure water and IAPWS Industrial Formulation 1997 is used for the thermodynamic properties of liquid and vapor phases (IAPWS, 2007). The dynamic viscosity is obtained from the IAPWS Formulation 2008 for the viscosity of ordinary water substance (IAPWS, 2008)
- Phases are in thermodynamic equilibrium
- Fluid properties remain constant within a step
- The presence of non-condensable gases and dissolved solids is ignored

The simulator solves the continuity, energy and momentum equations up the well using numerical integration. The *ode23* function built in MATLAB is used to evaluate the differential equations. The function uses second and third order Runge-Kutta formulas simultaneously to obtain the solution (The MathWorks, 2011). The depth interval is adjusted by the integration function and at each depth node the function produces velocity, pressure and enthalpy values.

To validate the wellbore simulator FloWell, simulated output needs to be compared to measured data. Comparison is essential for the credibility of the simulator but many factors can affect the outcome of the simulation. The accuracy of the wellbore simulator depends mainly on:

- The amount and accuracy of measured data available
- The accuracy of any estimated data, such as well roughness and in some cases well diameter which may have been reduced by scaling
- The validity of correlations coded into the simulator, i.e. friction, void fraction and friction correction correlations

Moreover, inaccurate prediction can be caused by the use of physical properties of water that do not represent actual thermodynamic behavior of geothermal fluid.

Verification and Validation of FloWell

Simulating geothermal wells can provide vital information about the geothermal reservoir and is an essential tool in geothermal resource management. Verification and validation help to ensure that simulators are correct and reliable. Validation is usually achieved through model calibration, that is comparing results from the simulation to actual system behavior. To validate FloWell, data, provided by the Icelandic company HS Orka, from wells at two geothermal fields, Reykjanes and Svartsengi, in the Reykjanes peninsula is used. Fig. 1 shows the locations these two geothermal fields.

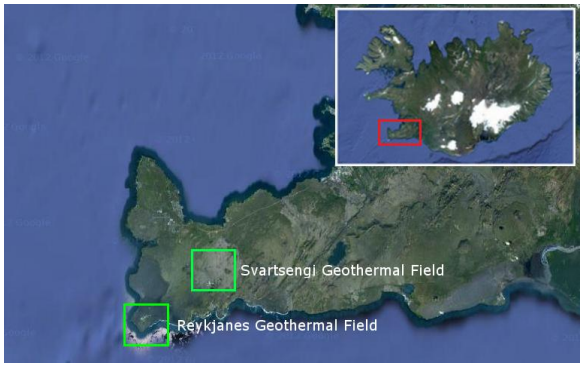

Figure 1: Location of geothermal fields used in the validation of FloWell.

FloWell offers a considerably wide selection of empirical correlations for two phase calculations. Which correlation performs best is a question many scientists and researches struggle to answer. More often than not, there is no one right answer to this question as it can prove to be difficult to find one correlation to simulate the diverse characteristics found in geothermal wells.

Utilizing the features the program iTOUGH2 has to offer, a measure of how each void fraction correlation

performs in simulating the pressure and temperature profiles in a well can be found. iTOUGH2 is a computer program for parameter estimation and sensitivity and uncertainty analysis. The program contains various minimization algorithms to find the minimum of an objective function which is the difference between model results and measured data. iTOUGH2 is usually run in combination with TOUGH2, a forward simulator for non-isothermal multiphase flow in porous and fractured media, but can also be linked to non-TOUGH2 models by implementing a protocol called PEST.

Since FloWell is a non-TOUGH2 model, an inverse run with iTOUGH2-PEST is initialized to calculate an objective function. The objective function describes how a simulation with FloWell fits measured data, in this case data points from pressure logs. If, for example, the objective function calculated using the void fraction correlation by Rouhani-Axelsson is lower than the one found with the Homogenous correlation, the Rouhani-Axelsson correlation is more likely to simulate the expected behavior of the well.

The objective function is calculated for each well and for all void fraction correlations. The calculated objective functions are compared within each well and the correlation which yields the lowest objective function is identified. With that, a ranking of the correlations can be established for each well. These individual rankings can be summarized to find an overall ranking for the wells. Several feedzones are present in a well but since FloWell is a single feedzone simulator the most reliable simulations would be the ones that only reach the bottom of the production casing. Simulating further down the well is also an option but it may invite unreliable predictions.

The results from the void fraction comparison show that the model by Chisholm most often yields results closest to measured data. The model by Premoli et al. is the one that is most often in second place, the model by Rouhani-Axelsson is most often in third place and the model by Lockhart-Martinelli is most often in fourth place. The model by Zivi is the one that produces the worst predictions, placing most often in the last two places. To further summarize the results the correlation by Rouhani-Axelsson ranks most often in the top three while the model by Zivi ranks most often in the lower three as before. These results can be seen in Table 1.

Table 1: Ratio, in percentages, of how often a void fraction correlation ranks in the top three and the bottom three when simulating with FloWell down to the bottom of the production casing (H:Homogenous, Z:Zivi, C:Chisholm, P:Premoli et al., LM:Lockhart-Martinelli, RA:Rouhani-Axelsson).

	H	*Z*	*C*	*P*	*LM*	*RA*
1st-3rd	8	0	22	21	17	32
4th-6th	25	33	11	13	17	1

Although simulating down to the bottom of the well is not as accurate as simulating down to the bottom of the production casing, it is interesting to examine whether the results deviate from the ones above. The results are shown in Table 2. The model by Premoli et al. produces simulations that are most often closest to measured data while the Homogenous model generates most often the worst fit. Compared to the results above, the model by Zivi seems to perform better when simulating all the way down to the bottom.

Table 2: Ratio, in percentages, of how often a void fraction correlation ranks in the top three and the bottom three when simulating with FloWell down to the bottom of the well (H:Homogenous, Z:Zivi, C:Chisholm, P:Premoli et al., LM:Lockhart-Martinelli, RA:Rouhani-Axelsson).

	H	*Z*	*C*	*P*	*LM*	*RA*
1st-3rd	2	20	26	30	6	16
4th-6th	31	14	7	3	27	18

To better understand how FloWell performs, visual results are of great help. Wells RN-11, RN-12, RN-21, RN-24 and SV-21 have similar characteristics (RN:Reykjanes, SV:Svartsengi). They are vertical wells with low enthalpy fluid and steam fraction between 9-13% at the wellhead. Simulations for wells RN-12 and SV-21 can be seen in Fig. 2 and 3. For these simulations the Blasius equation and the model by Friedel are used to calculate the friction factor and friction correction factor.

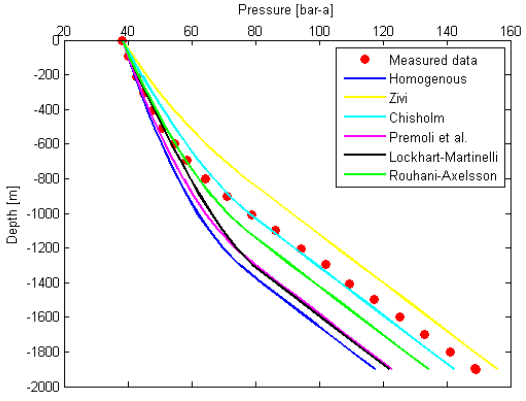

Figure 2: Simulations for well RN-12 with FloWell.

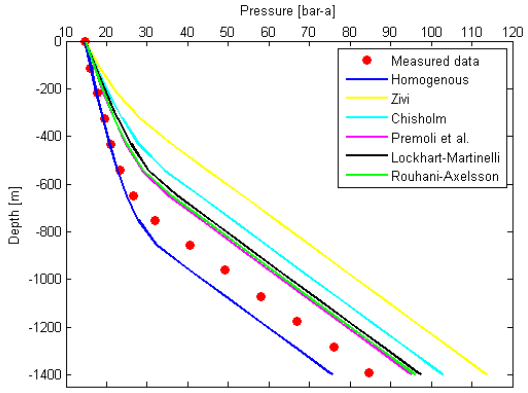

Figure 3: Simulations for well SV-21 with FloWell.

For well RN-12 the Rouhani-Axelsson and the Chisholm void fraction correlations perform the best. For well SV-21 the Homogenous correlation shows simulations closest to the measured data. The Homogenous correlation usually yields adequate simulations for wells with a low steam fraction, for it assumes that the phases travel at the same velocity. This is the case in well SV-21, the steam fraction in the well is between 9-10%, while the steam fraction in well RN-12 is little over 13%.

The downhole conditions in a well can be rather sensitive to changes in wellhead parameters. Well RN-13B is a good example of this. The enthalpy gathered from an available report about the well testing in RN-13B is estimated to be around 1590 kJ/kg. Using this value for the enthalpy, along with the wellhead pressure and estimated mass flow rate, FloWell yields simulations which do not imitate the known pressure profile in the well. The fluid flashes before it enters the well and two phase flow is present in the well from the bottom to the top. By changing the enthalpy value, simulations that better fit measured data can be obtained. This may indicate that the enthalpy in the well is overestimated, but it is also possible that other uncertainties involved in the well testing play a part in producing inadequate simulations. This phenomenon is illustrated in Fig. 4.

Since FloWell is also capable of starting at the bottom of a well and calculating up, it is interesting to see a simulation up the well versus down the well. Simulations up well SV-21 are presented in Fig. 5. Comparing Fig. 3 and 5 it can be seen that considerable difference is between simulating up the well and down the well. Despite this difference, the homogenous correlation still performs best and the model by Zivi the worst. From this discussion the question which option is more accurate arises. As it is easier to measure wellhead parameters than downhole ones, wellhead conditions are constantly

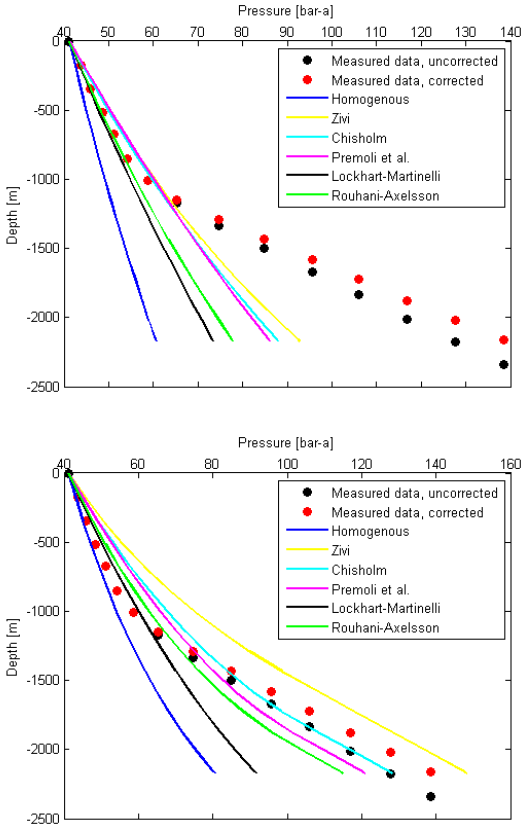

Figure 4: Simulations with FloWell for well RN-13B for the original enthalpy 1590 kJ/kg (top) and the enthalpy 1400 kJ/kg (bottom).

being monitored and noted. From that alone it may be concluded that simulating down the well is more accurate but if carefully measured parameters exist at the top and at the bottom it may prove difficult to favor one over the other.

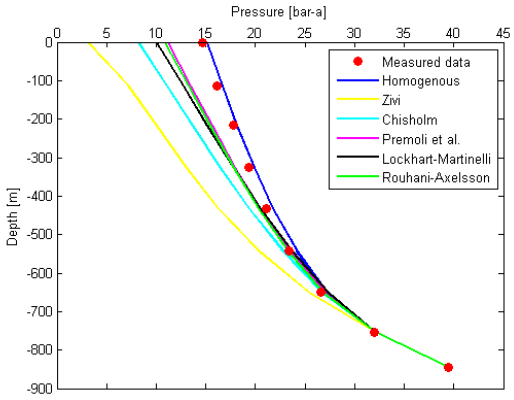

Figure 5: Simulations for well SV-21 starting at the bottom and simulating up.

FloWell manages to simulate the behavior of geothermal wells to some extent but no correlation simulates the exact pressure profile in a well. It is intriguing to use inverse analysis with iTOUGH2-

PEST to improve parameters in the void fraction correlations so simulations with FloWell better fit measured data. Using the Homogenous model in Eq. (22) to calculate the void fraction in well RN-11, FloWell yields a simulation that is not very close to the known pressure profile. It is assumed that the slip ratio is equal to one in the Homogenous correlation. If inverse analysis is applied to well RN-11 and the slip ratio evaluated, several iterations with iTOUGH2-PEST result in a new value for the slip ratio, *S=1.68*. Using this value instead of one in the Homogenous correlation, almost a perfect match to the measured data is obtained with FloWell as seen in Fig. 6.

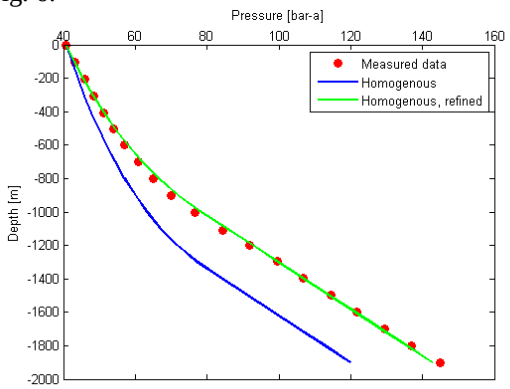

Figure 6: Simulations for well RN-11 with the original Homogenous model (blue) and with improved slip ratio (green).

CONCLUSIONS AND FUTURE WORK

The wellbore simulator FloWell created for this study is a single feedzone and one dimensional simulator that utilizes bottomhole or wellhead pressures, mass flow rates and well enthalpies to solve general equations for conservation of mass, momentum and energy. The validation of FloWell displayed that in most wells the simulations were in good agreement with pressure logs from wells at Reykjanes and Svartsengi geothermal fields. Furthermore, a comparison was made between available void fraction correlations in FloWell, resulting in the Rouhani-Axelsson correlation fitting the data best in most cases while the Zivi correlation produced the worst fit. Despite these results it is difficult to favor one correlation over the others, to reach conclusive results more extensive data must be obtained and tested with FloWell. It should be kept in mind that if great uncertainties are involved in measured data necessary for simulations no gain is to be had by choosing a complex correlation over a simpler one.

FloWell can be used individually to simulate the behavior of producing geothermal wells. The program is also designed to be coupled to a reservoir simulator in a moderately simple way. Coupling of the wellbore simulator FloWell and the reservoir simulator TOUGH2 is described in the paper *A Coupled Wellbore-Reservoir Simulator Utilizing Measured Wellhead Conditions* by the same authors, presented at the Thirty-Eighth Workshop on Geothermal Reservoir Engineering at Stanford University.

In the future, several improvements could be made to the wellbore simulator FloWell. The option of multiple feedzones in a well as well as diverse changes of a wellbore geometry could be incorporated into FloWell. Moreover, adding more options for the void fraction and friction correction factor correlations would allow the simulator to become more user-friendly. Problems due to scaling could be considered when simulating the flow in wells, especially in wells in Reykjanes. The geothermal fluid in the area is very rich in salinity and along with the high temperatures found in the reservoir causes the magnitude of dissolved solids to increase, contributing heavily to scaling.

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