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COUPLING WELLBORE SIMULATOR WITH RESERVOIR SIMULATOR

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ABSTRACT

In this project a one dimensional and steady state numerical model (FloWell) for describing wellbore behavior has been conducted. The wellbore simulator solves the continuity, energy and momentum equations using the *ode23* function built in MATLAB. Validation of FloWell shows that the Homogenous (with slip ratio equal to one) and Rouhani-Axelsson void fraction correlations give good results for a liquid dominant well in Svartsengi in Iceland. A numerical analysis is performed with the iTOUGH2-PEST package to improve the model design in FloWell. The case study shows that parameters in void fraction correlations can be adjusted with the package so that simulations with FloWell fits measured data. Further work will include simulations of more wells with different characteristics and the future goal is to couple the wellbore simulator FloWell with the reservoir model TOUGH2.

NOMENCLATURE

A cross sectional area [m^2]
d diameter [m]
f friction factor
g acceleration due to gravity [m/s^2]
G mass velocity [kg/m^2s]
h enthalpy [J/kg]
$\dot{m}$ mass flow [kg/s]
p pressure [Pa]
$\dot{Q}$ heat loss [W/m]
u velocity [m/s]
x steam quality
z axial coordinate
Φ friction correction factor
σ surface tension [N/m]
α void fraction
ρ density [kg/m^3]
μ dynamic viscosity [Pa/s]
ε roughness [m]

INTRODUCTION

By analyzing the behavior of a geothermal reservoir and wells over time an extensive database of geophysical parameters can be created. Databases like these allow scientists to simulate and predict the reservoir's behavior and production performance of geothermal wells. This is one of the most fundamental elements required for optimizing geothermal power production.

Since the geothermal industry began developing and research into the behavior of wells and underground reservoirs expanded, several geothermal simulators have been published. Bjornsson (1987) developed a geothermal wellbore simulator, HOLA, which allowed for number of feedzones in the well. Gunn and Freeston (1991) implemented a wellbore simulation package, WELLSIM, where three codes (WFSA, WFSB and STFLOW) were combined into one. García-Valladares et. al (2006) conducted one dimensional steady and transient numerical model, GEOWELLS, for describing heat and fluid dynamic transport inside geothermal wells.

Currently, models exist which simulate underground flow processes in geothermal reservoirs as well as models that simulate the internal flow processes in geothermal wells. Eclipse, Geosys, Feflow (Blöcher et. al, 2010) and TOUGH2 (Pruess, 1999) are all capable of simulating reservoir characteristics. These models often treat flow in wells in a very simplified manner.

Over the years attempts have been made at coupling reservoir and wellbore models, e.g. Hagdu et. al (1995) described the wellbore simulator WSFA coupled with reservoir simulator TOUGH. More recently, Bhat et. al (2005) developed a coupled model between the reservoir simulator TOUGH2 and wellbore simulator HOLA.

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 is to design a new wellbore simulator (FloWell) to study the fluid and heat and pressure propagation inside geothermal wells. The wellbore simulator is validated to see if its outcome fits measured data from a well in geothermal area in Iceland.

Furthermore, a numerical analysis is performed with the iTOUGH2-PEST package to improve the model design in FloWell. The package is used to assess the simulator's performance and evaluate parameters in known correlations necessary for two phase flow calculations. These correlations are empirical, created under specific conditions and often have some restrictions attached to them. The void fraction is one of the critical unknown parameter involved in predicting pressure loss. Therefore, emphasis will be put on adjusting parameters in chosen void fraction correlations so the outcome from the wellbore simulator agrees with measured data.

In this paper, a physical model of a wellbore simulator is defined. The features, assumptions and computational procedure of FloWell are described as well as the PEST protocol. Finally, results from the simulator and the inverse analysis are presented and discussed.

PHYSICAL MODEL OF A WELLBORE SIMULATOR

A wellbore physical model is often described as vertical or inclined pipe with liquid flow in the deeper zones, which flashes in the upper zones when pressure and temperature drops. From the flashing zone the flow consists of two phases, liquid and vapor. As the mixture progresses up the well the distribution of phases becomes rather complex due to the slippage between them (Álavrez del Castillo et. al, 2011).

Single phase flow

The continuity equation

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

$$\frac{d}{dz}(\dot{m}) = 0 \tag{1}$$

If the pipe diameter is constant this simplifies to

$$\frac{d}{dz}(\rho u) = 0 \tag{2}$$

This relation is differentiated by parts; the result is (Palsson, 2011)

$$u\left(\frac{\partial\rho}{\partial p}\frac{dp}{dz} + \frac{\partial\rho}{\partial h}\frac{dh}{dz}\right) + \rho\frac{du}{dz} = 0 \tag{3}$$

The energy equation

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

$$\frac{d}{dz}\left(\dot{m}\left(\frac{u^2}{2} + gz + h\right)\right) + \dot{Q} = 0 \tag{4}$$

By differentiating the equation by parts, the energy equation can also be written as (Palsson, 2011)

$$\dot{m}u\frac{du}{dz} + \dot{m}\frac{dh}{dz} + \dot{m}g + \dot{Q} = 0 \tag{5}$$

The momentum equation

The momentum equation contains inertia, pressure changes, hydrostatic pressure and head loss part. The relation is written as follows (Palsson 2011)

$$\rho u\frac{du}{dz} + \frac{dp}{dz} + \rho g + \frac{\rho f}{2d}u^2 = 0 \tag{6}$$

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

$$f = \frac{0.316}{Re^{1/4}} \tag{7}$$

and the Colebrook-White equation, where the effect of pipe roughness is included,

$$\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{\varepsilon}{0.37d} + \frac{2.51}{Re\sqrt{f}}\right) \tag{8}$$

Eq. (8) needs iterative search for the correct value of *f*, which can be quite time-consuming. The Swamee-Jain relation can however be used to solve directly for *f*;

$$f = \frac{0.25}{\left(\log\left(\frac{\epsilon}{3.7d} + \frac{5.74}{Re^{0.9}}\right)\right)^2} \tag{9}$$

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

$$Re = \frac{\rho u d}{\mu} \tag{10}$$

Two phase flow

The continuity equation

In two phase flow the flow consist of liquid and vapor states. Eq. (1) alters to

$$\frac{d}{dz}(\dot{m}_l + \dot{m}_g) = 0 \tag{11}$$

$$\frac{d}{dz}(\rho_l u_l A_l + \rho_g u_g A_g) = 0 \tag{12}$$

Assuming constant pipe diameter, using the void fraction definition and introducing the uniform velocity u instead of the actual velocities, the continuity equation becomes

$$\frac{d}{dz}(\rho_l u) = 0 \tag{13}$$

As for single phase flow, the relation can be differentiated by parts, which results in (Palsson, 2011)

$$u\frac{\partial\rho_l}{\partial p}\frac{dp}{dz} + \rho_l\frac{du}{dz} = 0 \tag{14}$$

The energy equation

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

$$\frac{d}{dz}\left(\dot{m}_l\left(\frac{{u_l}^2}{2}+gz+h_l\right)+\dot{m}_l\left(\frac{{u_l}^2}{2}+gz+h_l\right)\right)+\dot{Q}=0 \quad (15)$$

By using the mass fraction x and the uniform velocity u, eq. (11) can be written as

$$\dot{m}\frac{d}{dz}\left(\frac{(1-x)^3}{(1-\alpha)^2}\frac{u^2}{2}+\frac{\rho_l^3 x^3}{\rho_g^2\alpha^2}\frac{u^2}{2}\right)+\dot{m}g+\dot{m}\frac{dh}{dz}+\dot{Q}=0 \quad (16)$$

Finally, with the partial derivatives evaluated, the energy equation can be expressed on the form

$$\gamma u\frac{du}{dz}+\frac{u^2}{2}\frac{\partial\gamma}{\partial p}\frac{dp}{dz}+\left(1+\frac{u^2}{2}\frac{\partial\gamma}{\partial h}\right)\frac{dh}{dz}+g+\frac{\dot{Q}}{\dot{m}}=0 \quad (17)$$

where γ is defined as (Palsson, 2011)

$$\gamma=\frac{(1-x)^3}{(1-\alpha)^2}+\frac{\rho_l^2x^3}{\rho_g^2\alpha^2} \quad (18)$$

The momentum equation

The momentum equation for two phase flow can be written as (Palsson, 2011)

$$\eta\rho_l u\frac{du}{dz}+\left(1+\rho_l u^2\frac{\partial\eta}{\partial p}+\eta u^2\frac{\partial\rho_l}{\partial p}\right)\frac{dp}{dz}+\rho_l u^2\frac{\partial\eta}{\partial h}\frac{dh}{dz}+\left((1-\alpha)\rho_l+\alpha\rho_g\right)g+\frac{\Phi^2\rho_l f_l}{2d}u^2=0 \quad (19)$$

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

$$\eta=\frac{(1-x)^2}{1-\alpha}+\frac{\rho_l}{\rho_g}\frac{x^2}{\alpha} \quad (20)$$

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

$$Re_l=\frac{\rho_l u d}{\mu_l} \quad (21)$$

Friction correction factor

Various relations exist for the friction correction factor Φ^2. Here, only two relations will be presented, the Friedel and Beattie approximations.

The Friedel correction factor is defined as

$$\Phi^2=E+\frac{3.24FH}{Fr^{0.045}We^{0.035}} \quad (22)$$

where

$$E=(1-x^2)+x^2\frac{\rho_l}{\rho_g}\frac{f_g}{f_l} \quad (23)$$

$$F=x^{0.78}(1-x^2)^{0.24} \quad (24)$$

$$H=\left(\frac{\rho_l}{\rho_g}\right)^{0.91}\left(\frac{\mu_g}{\mu_l}\right)^{0.19}\left(1-\frac{\rho_g}{\rho_l}\right)^{0.7} \quad (25)$$

$$Fr=\frac{{\rho_l}^2u^2}{g\rho_m^2 d} \quad (26)$$

$$We=\frac{{\rho_l}^2u^2 d}{\sigma\rho_m^2} \quad (27)$$

$$\frac{1}{\rho_m}=\frac{x}{\rho_g}+\frac{1-x}{\rho_l} \quad (28)$$

The Bettie correction factor is much simpler, and can be calculated by a single equation (García-Valladares et.al, 2006)

$$\Phi^2=\left(1+x\left(\frac{\rho_l}{\rho_g}-1\right)\right)^{0.8}\left(1+x\left(\frac{3.5\mu_g+2\mu_l}{(\mu_g+\mu_l)\rho_g}-1\right)\right)^{0.2} \quad (29)$$

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 slip ratio is often estimated differently by various investigators. The model can be written as

$$\alpha=\frac{\frac{x}{\rho_g}}{\frac{x}{\rho_g}+\frac{1-x}{\rho_l}S} \quad (30)$$

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.

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 *Physical Model of a Wellbore Simulator* and MATLAB is used as a programming language.

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

- Inner diameter of the well
- Depth of the well
- Roughness of the well
- Mass flow
- Down-hole pressure and enthalpy

Features and assumptions

The wellbore simulator is capable of:

- modeling liquid, two phase and superheated steam flows;
- allowing users to choice between various friction, void fraction and friction correction factor correlations;
- performing wellbore simulations from the bottom hole to wellhead section; and
- providing simulated results, such as pressure and temperature distribution as well as steam quality, friction, velocity, enthalpy and void fraction at each dept increment.

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

- the flow is steady and one dimensional;
- 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 depth increment; and
- the presence of non-condensable gases and dissolved solid is ignored.

Computational procedure

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 simultaneously second and third order Runge-Kutta formulas 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.

Validation of FloWell

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; and
- 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.

INVERSE ANALYSIS

Inverse problems often lead to difficult optimization routines with no straightforward solution. Therefore, no general method is at hand to solve all inverse problems. The most common formulation is based on system identification techniques and least-squares fitting of parameterized models to measured data. In brief, inverse modeling consists of estimating model parameters from measurements of system response at discrete points in time and space.

A number of mathematical models and data processing techniques can be used in solution of an inverse problem. A basic simulation package called iTOUGH2 is frequently used. iTOUGH2 is a computer program for parameter estimation and sensitivity and uncertainty analysis. The program contains various minimization algorithms for adjustment of model against measured data. It 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. In that way the iTOUGH2 can be used as an inverse analyzing tool for models such as the wellbore simulator FloWell (Finsterle, 2007).

To be able to link non-TOUGH2 models with iTOUGH2, a protocol called PEST has been implemented in iTOUGH2. The protocol enables interaction between the non-TOUGH2 model and iTOUGH2 through a clear and simple communication format. The iTOUGH2-PEST structure is shown in Figure 1 (Finsterle, 2010).

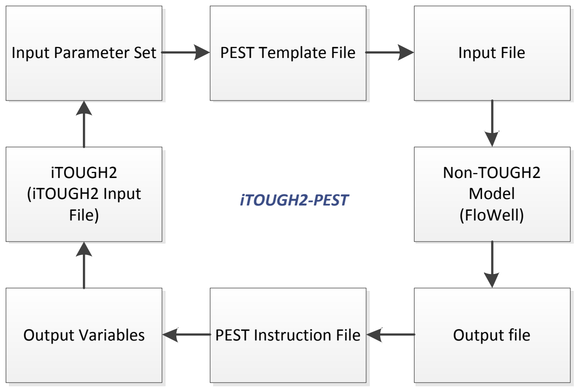

Figure 1: iTOUGH2-PEST structure.

In the PEST Template File, the input variables which are subject to parameter estimation are identified. The input variables are written to the Input File and updated through the inverse analysis.

The PEST Instruction File is used to extract output variables that will be compared to measured data. These variables are calculated by the forward Non-TOUGH2 Model and stored in the Output File.

To start the parameter estimation with the PEST protocol, an iTOUGH2 Input File is run with a corresponding executable file. A parameter-selection command is used in the iTOUGH2 Input File to indicate that the parameters refer to the Non-TOUGH2 Model, and will be adjusted through the PEST Template File. In the iTOUGH2 Input File a guess value is assigned to the parameters and observation data is defined along with executable instructions.

The iTOUGH2 Input File calls for the Non-TOUGH2 Model to run with the updated parameters in the Input File. The Non-TOUGH2 Model calculates output parameters at calibration points. Adjustment of the output parameters against observation data is performed using the iTOUGH2 capabilities, which are the local and global algorithms, the sensitivity, residual and error and uncertainty analysis. This will give an estimation of new input parameters for the Non-TOUGH2 Model. The inverse analysis continues until stopping criteria as been met (Finsterle, 2010).

CASE STUDY

This case study examines a well, SV-21, located at Svartsengi in Iceland. It is a low enthalpy well which indicates that it is liquid dominant. The well was drilled in 2001 and its current depth is 1475 m. The well is only simulated down to the bottom of the production casing. The reason for this is to minimize uncertainty for there is not sufficient data available to locate feedzones and their volume of inflow.

Main parameters of SV-21 necessary for simulation are listed in table 1.

Table 1: Main parameters of SV-21

Depth of production casing	844 m
Inner diameter of prod. casing	0.3153 m
Pressure at bottom of prod. casing	40 bar-a
Well enthalpy	1030 kJ/kg
Total mass flow	70 kg/s
Estimated well roughness	0.1 mm

Simulations are compared to pressure distribution in SV-21, obtained 26. February 2007. Some uncertainty lies in the reading of measured data, which is handled by estimating error bars.

Validation of FloWell

Validation of FloWell involves two cases. Firstly, simulations for smooth well and secondly, simulations for well with roughness. Each case includes three simulations. Their structure is as follows:

- *Simulation 1*: Using the Homogenous model (with slip ratio equal to one) for void fraction and Friedel model for friction correction factor.
- *Simulation 2:* Using the Lockhart-Martinelli model for void fraction and Friedel model for friction correction factor.
- *Simulation 3*: Using the Rouhani-Axelsson model for void fraction and Beattie model for friction correction factor.

Simulated pressure propagations for SV-21 can be seen in fig. 2 and 3, along with measured data.

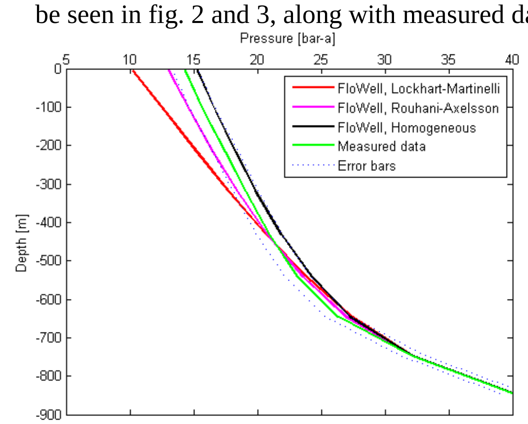

Figure 2: Simulation with FloWell for smooth SV-21.

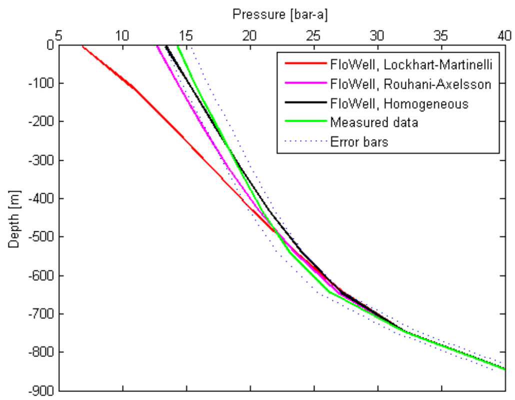

Figure 3: Simulation with FloWell for SV-21 with roughness.

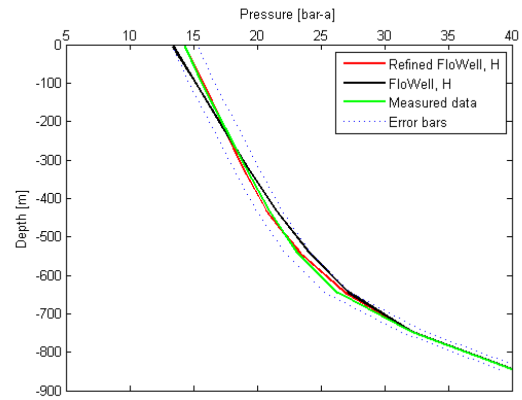

Figure 4: Refined slip ratio in Homogeneous (H) model for SV-21 with roughness.

In both cases the Lockhart-Martinelli model for the void fraction performs rather poorly. The other two models show better result and their outcome is closer to the measured data.

Inverse analysis with iTOUGH2-PEST

Homogenous model

In the validation of FloWell, it is assumed that the slip ratio in eq. (30) is equal to one (that is, the liquid and steam travel with the same velocity up the well). This is highly possible since SV-21 is liquid dominant. Despite of this it is interesting to see how the slip ratio develops in the well. If the slip ratio is defined as a function of the steam quality it is possible to use iTOUGH2-PEST to find a better value for the slip ratio. The output of the inverse analysis on SV-21 with roughness is listed in table 2.

Table 2: Original and estimated values for slip ratio in the Homogeneous model.

Steam quality x	*Original value of slip ratio*	*Estimated value of slip ratio*
0	1.00	1.00
0.04	1.00	1.48
0.08	1.00	0.34
0.10	1.00	0.88

The pressure distribution obtained using the estimated values of the slip ratio is shown in fig. 4.

It seems from fig. 4 that the estimated values of the slip ratio give a better fit to the measured data. However, if these values are examined more closely it is clear that they do not follow the laws of physics. The slip ratio should increase up the well since the magnitude of steam is rising and the velocity of steam is higher than that of liquid's. The high possibility that the slip ratio is close to one and inaccuracy in measured data may cause the estimated values to be under one rather than over in the inverse analysis.

Lockhart-Martinelli model

The parameters adjusted in the Lockhart-Martinelli (LM) void fraction in eq. (31) are a_1, a_2, a_3 and a_4.

$$\alpha = \left(1 + a_1 \left(\frac{1-x}{x}\right)^{a_2} \left(\frac{\rho_g}{\rho_l}\right)^{a_3} \left(\frac{\mu_l}{\mu_g}\right)^{a_4}\right)^{-1}$$

The estimated values of these parameters produced by iTOUGH2-PEST are listed in table 3.

Table 3: Original and estimated values for Lockhart-Martinelli (case 1: smooth well, case 2: well roughness).

	Original values	*Values for case 1*	*Values for case 2*
a_1	0.28	0.03	0.15
a_2	0.64	1.56	1.81
a_3	0.36	0.43	0.79
a_4	0.07	-0.28	-0.73

Fig. 5 and 6 show simulated pressure propagations (FloWell) with these new values on the LM parameters.

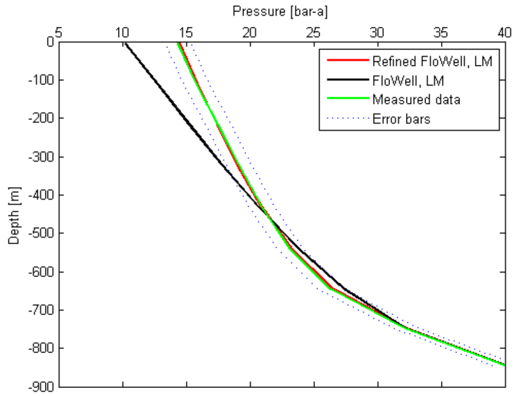

Figure 5: Refined Lockhart-Martinelli (LM) model for smooth SV-21 (case 1).

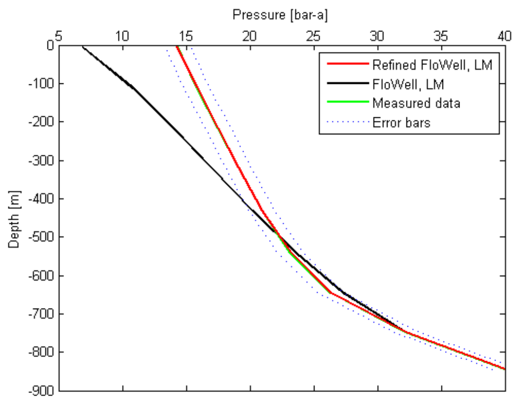

Figure 6: Refined Lockhart-Martinelli (LM) model for SV-21 with roughness (case 2).

The wellbore simulator with the refined LM model produces a simulation that is a good match to the measured data. In both cases, the objective function is significantly reduced which indicates that a better fit has been obtained. The error analysis in iTOUGH2 determines that the parameters are strongly correlated to each other. High parameter correlation may indicate uncertainty in the estimated parameters and sometimes overparameterization. A similar fit may be obtained by leaving some parameters out of the analysis.

Rouhani-Axelsson model

Unlike the inverse analysis of the LM model, only one parameter is adjusted in the Rouhani-Axelsson (RA) void fraction correlation (See eq. (32)).

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

The estimated value of this parameter can be seen in table 4 and simulated pressure propagation in fig. 7 and 8.

Table 4: Original and estimated value for Rouhani-Axelsson (case 1: smooth well, case 2: well roughness).

	Original value	*Value for case 1*	*Value for case 2*
b	0.12	0.076	0.066

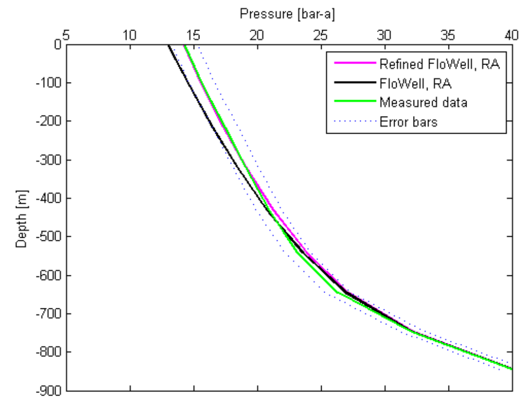

Figure 7: Refined Rouhani-Axelsson (RA) model for smooth SV-21 (case 1).

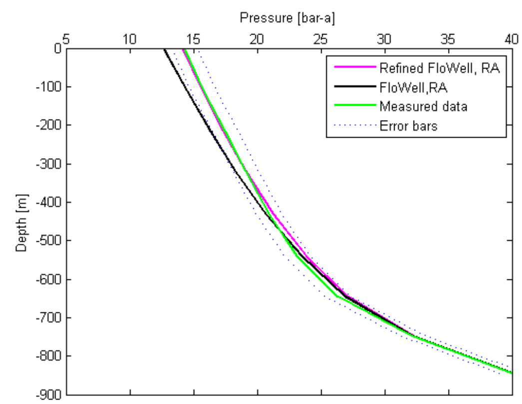

Figure 8: Refined Rouhani-Axelsson (RA) model for SV-21 with roughness (case 2).

A good match is accomplished by only changing one parameter in the RA model. As for the LM model the objective function is significantly reduced so it can be concluded that the new value produces better fit than the original. Several unsuccessful attempts were made to introduce more parameters into the analysis.

CONCLUSIONS AND FUTURE WORK

A wellbore simulator (FloWell) was developed to simulate liquid, two phase and superheated steam flows in geothermal wells. The simulator solves the continuity, energy and momentum equations up the well using the *ode23* function in MATLAB. Various correlations of friction factor, void fraction and friction correction factor were included in the simulator. The iTOUGH2-PEST program was used to perform an inverse analysis on FloWell to improve parameters in void fraction correlations to produce a better match to measured data.

The validation of FloWell shows that the Homogenous and Rouhani-Axelsson void fraction correlations produce adequate simulations while Lockhart-Martinelli void fraction performs rather poorly. The case study presented above shows also that a numerical model like iTOUGH2 can be used to improve parameters in void fraction correlations. By adjusting parameters in both Lockhart-Martinelli and Rouhani-Axelsson models the simulations yielded significantly better fit to the data than original values. Although a better fit was obtained for SV-21 by using the estimated parameters there is no basis for using these parameters in simulations for other wells. In order to do so further simulations are needed in similar wells.

It should be mentioned that though a better fit was obtained, the Fisher Model Test in iTOUGH2 was never successfully passed. That indicates that the model does not match the measured data sufficiently. It is possible that the reason for this is inaccurate data. It is assumed in the case study that the measure data is exact. However, considerable uncertainty is involved in the measurements of pressure, temperature, mass flow and other important parameters. Along with inaccurate data, some error may be encountered in the calculation of thermodynamic properties. It is assumed that the fluid is pure water but the geothermal fluid in Svartsengi is salted so the calculated density should be quite higher.

In continuation of this study, the future goal is to couple the wellbore simulator FloWell with the reservoir model TOUGH2. This coupled model is to be used to examine a geothermal area in Iceland. The wellbore simulator needs some improvements before the coupling can take place. FloWell is sensitive to changes and some well characteristics may cause stability problems in the simulator. In order to validate FloWell further as a useful analysis tool more simulations are needed for wells with diverse characteristics.

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REFERENCES

Álavarez del Castillo, A. Santoyo, E. and García-Valladares, O. (2011), “A new void fraction correlation inferred from artificial neural networks for modeling two-phase flows in geothermal wells,” *Computers and Geosciences*, doi:10.1016/j.cageo.2011.08.001

Bhat A., Swenson D. and Gosavi S. (2005). “Coupling the Hola Wellbore Simulator with TOUGH2”, *Proceedings*, 30th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA.

Bjornsson, G. (1987). “A Multi-Feedzone, Geothermal Wellbore Simulator”, Earth Science Division, Lawrence Berkeley Laboratory Report LBL-23546, Berkeley, USA.

Blöcher G., Kranz S., Zimmermann G., Frick S., Hassanzadegan A., Moeck I., Brandt W., Saadat A. and Huenges E. (2010). “Conceptual Model for Coupling Geothermal Power Plants with Deep Reservoirs”, *Proceedings*, World Geothermal Congress 2010, Bali, Indonesia.

Finsterle, Stefan (2007). “iTOUGH2 User’s Guide”, Lawrence Berkeley National Laboratory, Berkeley, USA.

Finsterle, Stefan (2010), “iTOUGH2 Universal Optimization Using the PEST Protocol, User’s Guide”, Lawrence Berkeley National Laboratory, Berkeley, USA.

García-Valladares, O., Sánchez-Utpon, P. and Santoyo, E. (2006), “Numerical modeling of flow processes inside geothermal wells: An approach for predicting production characteristics with uncertainties”, *Energy Conversion and Management*, 47:1621-1643.

Gunn, C. and Freeston, D. (1991), “An integrated steady-state wellbore simulation and analysis package”, *Proceedings,* 13th New Zealand Geothermal Workshop, Auckland, New Zealand.

Hagdu T., Zimmermann R. and Bodvarsson G. (1995). “Coupling of the Reservoir Simulator TOUGH2 and the Wellbore Simulator WFSA”, Lawrence Berkeley National Laboratory, Berkeley, USA

Lockhart, R.W. and Martinelli, R.C. (1949). “Proposed Correlation of Data for Isothermal Two-Phase, Two Component Flow in Pipes”, *Chemical Engineering Progress Symposium Series*, 45: 39-48.

Palsson, H. (2011), “Simulation of two phase flow in a geothermal well”, Lecture notes in the course

VÉL203F Geothermal Systems at the University of Iceland.

Pruess, K., Oldenburg, C. and Modidis G. (1999). “TOUGH2 User’s Guide, Version 2.0”, Lawrence Berkeley National Laboratory, Berkeley, USA

IAPWS (2007). “Revised Release on the Iapws Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam”, The International Association for the Properties of Water and Steam, Lucerne, Switzerland.

IAPWS (2008). “Release on the Iapws Formulation 2008 for the Viscosity of Ordinary Water Substance”, The International Association for the Properties of Water and Steam, Berlin, Germany.

Rouhani Z. and Axelsson G. (1970). “Calculations of volume void fraction in the subcooled and quality region”, *Int J Heat Mass Transfer*, 13:383-93.

The MathWorks (2011). ode23, ode45, ode113, ode15s, ode23s, ode23t, ode23tb, The MathWoks^{TM}, Inc.