Effect of Well Diameter on Productivity of High Temperature Geothermal Wells

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30 ECTS thesis submitted in partial fulfillment of a
Magister Scientiarum degree in Mechanical Engineering

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Abstract

The purpose of this project is to create a method which can help designers choose a diameter when designing a well. This method can then show the effect of well diameter on the productivity of high temperature geothermal wells. There are generally two diameters used for wells in Iceland. It can be difficult to decide which diameter to use due to the unpredictability of the well characteristics. The basic idea of the method is to implement information from another well in production to create a simulation of the well to be drilled. The diameter can be changed in the simulation which then predicts which diameter is more productive. The numerical analysis calculation proved to perform very well but better void fraction correlation models for geothermal wells are needed so that the method can really work properly. The drawback of this method is that it does not take into account the changes of mass flow from the reservoir into the well when the diameter is changed, to be able to use this method a mass flow correction factor needs to be added to the method. Another fact is that to be able to show the effect of well diameter on the productivity of wells much more data is needed than the data from eight wells. It is also important that the data is accurate since little changes in measurements can alter the simulation results dramatically.

Útdráttur

Tilgangur þessa verkefnis er að skapa aðferð sem getur auðveldað ákvarðanatöku hönnuða að velja þvermál borhola. Þessi aðferð getur einnig sýnt áhrif þvermáls á afkastagetu háhitaborhola. Tvö þvermál eru algeng fyrir háhitaborholur á Íslandi svo valið stendur á milli þeirra tveggja. Það getur reynst erfitt að velja þvermál háhitaborhola því erfitt er að vita með vissu hvernig hegðun borholunnar mun verða. Grundvöllur aðferðarinnar er að nota upplýsingar frá annari borholu sem er í rekstri og byggja módel út frá henni. Það módel getur svo spáð fyrir um hvernig hegðun borholunnar verður og þannig sýnt hvort þvermálið er ákjósanlegra. Niðurstöður sýna að númeríska aðferðin notuð til hermunar er góð en til þess að hún nýtist betur er nauðsynlegt að finna betri módel fyrir rúmhlutfall gufu. Aðferðin sem notast er við gerir ekki ráð fyrir breytingu á massaflæði inn í holuna frá jarðhitageymi þegar þvermáli borholunnar er breytt. Nauðsynlegt er að bæta við leiðréttingarstuðli sem leiðréttir útkomu hermunarinnar með tilliti til þessarar breytingar. Til þess að sýna áhrif þvermáls á afköst borhola er þörf á meiri mælingum en frá átta borholum. Þær mælingar þurfa einnig að vera nákvæmar því litlar skekkjur í mælingum geta haft mikil áhrif á hermun borholunnar.

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Nomenclature

A	Area inside a pipe, m^2
A_g	Area of pipe where only gas exists, m^2
A_l	Area of pipe where only liquid exists, m^2
C_T	Tracer concentration
d	Inner diameter of pipe, m
E	Dimensionless factor
F	Dimensionless factor
f	Friction factor
f_g	Friction factor if mixture has the same density as gas
f_l	Friction factor if mixture has the same density as liquid
Fr	Friedel factor
G	Mass flux, kg m^2/s
g	Acceleration due to gravity, m/s^2
H	Dimensionless factor
h	Enthalpy of fluid, J/kg
h_g	Enthalpy of gas phase in mixture, J/kg
h_l	Enthalpy of liquid phase in mixture, J/kg
$\dot{m}$	Total mass flow in the well, kg/s
$\dot{m}_g$	Mass flow of steam, kg/s
$\dot{m}_l$	Mass flow of liquid, kg/s
$\dot{m}_T$	Mass flow of tracer, kg/s
p	Pressure, Pa
p_c	Critical pressure, Pa

Δp	Differential pressure, Pa
$\dot{Q}$	Heat loss, W/m
S	Slip ratio
u	Velocity, m/s
u_g	Average velocity of gas phase, m/s
u_l	Average velocity of liquid phase, m/s
u_m	Average velocity of mixture, m/s
Re	Reynolds number
Re_l	Reynolds number for liquid phase
Re_g	Reynolds number for gas phase
T	Temperature, K
T_c	Critical temperature, K
$\dot{V}_g$	Volume flow of gas, m^3/s
$\dot{V}_l$	Volume flow of liquid, m^3/s
We	Webber factor
x	Steam quality of mixture
z	Depth, m
α	Void fraction
ε	Symbol for void fraction correlation
γ	Simplification parameter
μ_g	Dynamic viscosity of gas phase, Pa s
μ_l	Dynamic viscosity of liquid phase, Pa s
η	Simplification parameter
σ	Surface tension, N/m
Φ	Friction correction factor
ρ	Density, kg/m^3

ρ_g	Density of gas phase, kg/m^3
ρ_l	Density of liquid phase, kg/m^3
ρ_m	Density of mixture with respect to steam quality, kg/m^3
ρ_α	Density of mixture with respect to void fraction, kg/m^3
v_g	Kinematic viscosity of gas phase, m^2/s
v_l	Kinematic viscosity of liquid phase, m^2/s

1 Introduction

It is common to define geothermal utilization as production of electricity and direct use. Electricity production requires steam from a high temperature geothermal fluid to rotate a turbine which then turns a generator generating electricity. Direct use of geothermal energy is used in various industries and often simply for house heating or snow melting. The temperature needed depends on the use, to dry timber effectively 160°C of water or steam is needed and to melt snow only 30°C hot water is needed (Lindal, 1973). In 2010 there were 79 countries recorded utilizing geothermal energy. The countries generate about 10716 MWe of electricity and utilized 438071 TJ/a of direct use (2010).

The traditional method of producing electricity from geothermal energy is to extract hot water from high temperature reservoirs. Deep wells are drilled into the ground carrying hot geothermal fluid to the surface which is then separated into steam and liquid. Drilling a well is an expensive procedure, the deeper and wider the well the more it costs. Reducing drilling cost only by percentages can return a substantial amount of savings for an energy company and its clients.

There are generally two diameters used for wells in Iceland. Well designers choose the diameters from certain parameters. Although the skilled designers are very experienced in choosing a diameter it is often difficult to decide which diameter to use due to the unpredictability of the well characteristics. The purpose of this project is to develop a method which can help designers choose a diameter when designing a well. Exploiting the method it is possible to study the effect of well diameter on the productivity of high temperature geothermal wells.

1.1 Geothermal wells

A high temperature well is usually 1500 – 2500 meter deep constructed out of four casings. First there is a surface casing which reaches the depth of 80 – 100 meters. An anchor casing is placed through the surface casing and reaches a depth of 250 – 350 meters. A production casing is then threaded through the anchor casing and reaches a depth of 650 – 800 meters. Finally a slotted liner is threaded through the production casing and reaches a depth of 1500 – 2500 meters. These depths can vary with wells, for shallow wells all casings will usually be shorter and for deeper ones the casings are usually longer. Figure 1 shows a casing program of a vertical well.

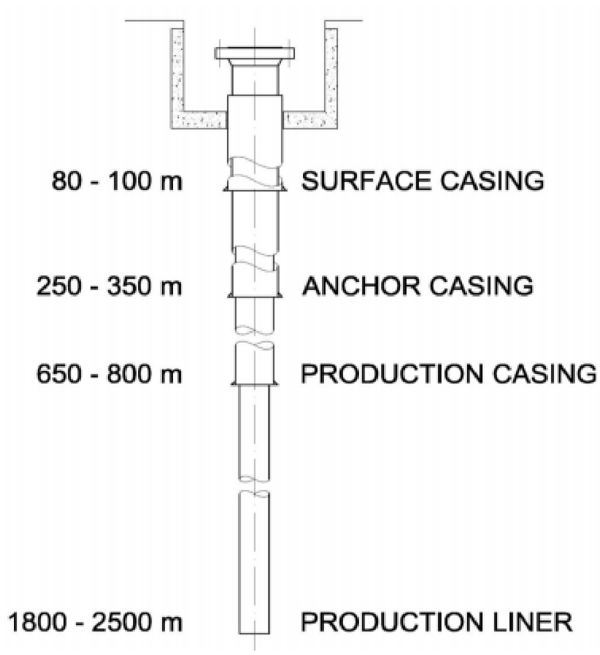


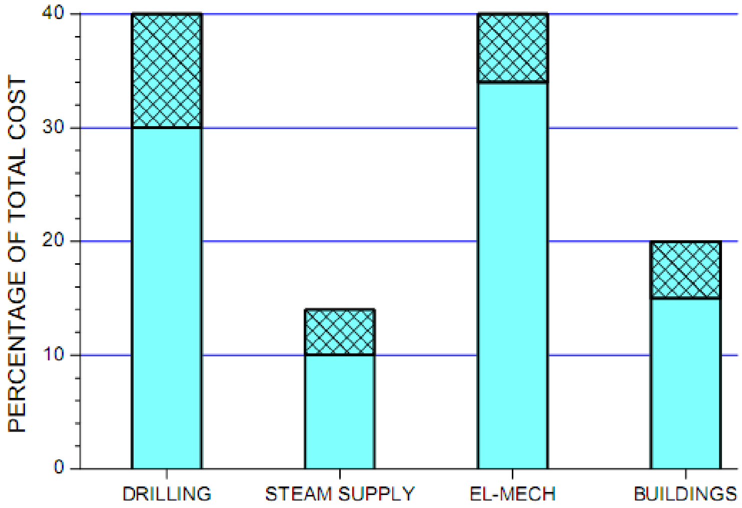
Figure 1. Casing program for a vertical well (Ingason & Matthíasson, 2006).

A good casing program withstands the tremendous forces that are applied to the structure while maximizing the output of the well. Maximizing the output means blocking out cold feed zones, letting hot feed zones in and minimizing the pressure drop while the geothermal fluid ascend up the well. The diameter of the well, among other features, determines the pressure drop. A bigger diameter returns less pressure drop but in some cases a small diameter well is sufficient and much cheaper, therefore possibly the better option.

It is common to use Ø9 5/8 or Ø13 3/8 inch high temperature wells in Iceland today. There are exceptions but these are the most common diameters (Ingason, 2011). The diameter mentioned is the diameter of the production casing. It is customary to use inches as units since the geothermal well technology is originated in the American petroleum industry (Karlsson, 1982).

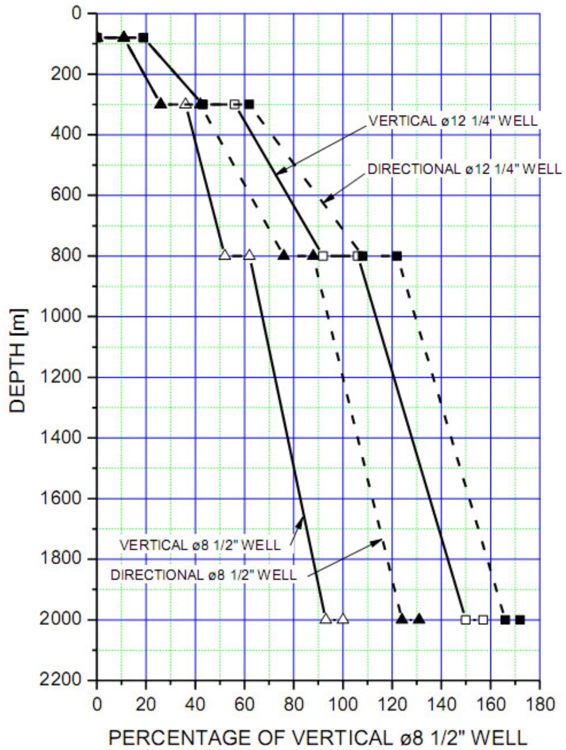
1.1.1 Cost of wells

The cost of drilling wells is 30% - 40% of a total cost of building a geothermal power plant. Graph 1 shows the rough breakdown of the total cost of building a geothermal power plant.



Graph 1. Rough breakdown of the total cost of a geothermal power plant (Ingason & Matthíasson, 2006).

The importance of minimizing the drilling cost can be seen in graph 1. A deeper and wider well requires bigger, stronger and more expensive equipment. Graph 2 shows the cost of a well dependent on width, type and depth as a percentage of a vertical well with an Ø8 1/2 inch slotted liner. Ingason and Matthíasson use the same two casing programs as this project, they indicate the width of the well from the diameter of the slotted liner as where this project indicates the width of the well from the diameter of the production casing.



Graph 2. Cost of a well with respect to width, type and depth compared to a vertical well with an Ø8 1/2 inch slotted liner (Ingason & Matthíasson, 2006).

According to their study drilling a vertical well with a slotted liner of Ø12 1/4 inches when a well with a slotted liner of Ø8 1/2 inches is sufficient is an unnecessary 60% cost increase. Drilling a directional well with a Ø12 1/4 inch slotted liner when the narrower one is sufficient is a 30% cost increase (Ingason & Matthíasson, 2006). The problem is knowing when it is sufficient to use a narrower well.

1.2 From reservoir to well top

The geothermal fluid undergoes changes when it travels from the reservoir to the well top. During this travel the fluid can boil, due to pressure drop, which leads to two phase flow. In low temperature wells the fluid does not boil at all and only fluid reaches the well top. Engineers often prefer that boiling occurs inside the well while the fluid ascends up the well, the reason being that the permeability of the rock surrounding the well can decrease over time due to precipitation (Tulinius, 2011). When boiling occurs in the well single-phase fluid flow exists in the bottom of the well but two-phase flow at the top of the well.

1.2.1 Flow in a high temperature geothermal well with flashing in the well

As mentioned before, the fluid undergoes pressure loss while traveling through the reservoir to the well bottom. In most cases only fluid exists at the well bottom which ascends up the well. While the fluid travels up the well it endures pressure loss due to friction with the walls of the well, acceleration and elevation of the flow. The flow is single phase until the fluid reaches its boiling point due to high temperature and lowered pressure. After that point the flow is in two phases where steam and liquid travel through the well simultaneously. The flow still endures pressure drop due to friction with the well walls, acceleration and change in elevation but it also looses pressure due to friction between the two phases.

Calculating single-phase flow accurately can be done without complicated calculations but calculating two-phase flow is difficult and requires complicated calculations.

1.3 Two-phase flow

A state of matter like gas, liquid or solid is called phase. In Multi-phase flow multiple phases exist simultaneously in flow. Two-phase flow can also be two-component flow where there are two components with different density and viscosity flowing simultaneously. Two-phase flow is the simplest type of multiphase flow. In geothermal wells there is geothermal fluid and steam flowing with a small amount of other gases (Wallis, 1969).

1.3.1 Flow regimes

Flow regimes describe types of two phase flow, different flow regimes indicate different friction between the phases and the inside wall of the well. Figure 2 shows how the flow regime changes while a fluid transforms from liquid state to steam. Each regime has different characteristics with different friction between the phases and between the phases and the wall of the well.

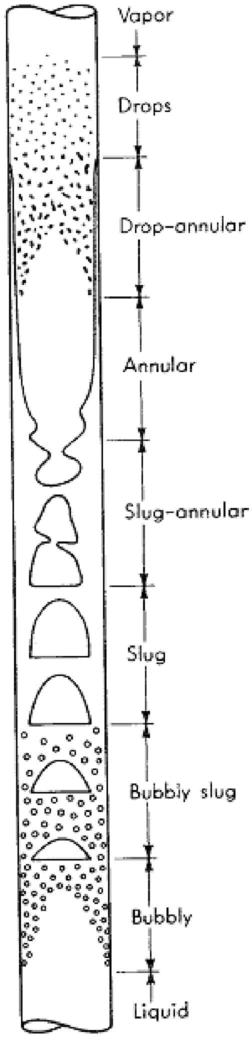


Figure 2. Possible flow regimes for a geothermal fluid that ascends up a well while boiling (Wallis, 1969).

The different regimes make it difficult to calculate pressure drop in a well. When pressure drop occurs and the amount of vapor increases the flow regime changes which leads to a different amount of friction which in the end leads to some pressure drop. It is difficult to know which regime occurs for different situations and it is very difficult to analyze two phase flow with great accuracy even though the flow regime is known (Wallis, 1969).

1.4 Methods for analyzing two phase flow

There are three main approaches to simulate a well: empirical models, numerical models and semi-analytical models. Numerical and semi-analytic models use analytic relations but often they require some empirical correlations due to the difficulty of understanding all aspects of two phase flow. Empirical methods are commonly used due to their simplicity.

1.4.1 Numerical methods

Numerical models solve the Navier-Stokes equations using numerical schemes that represent processes found in two phase flow. This method is complicated but has the ability to simulate time dependent two phase flow in multiple dimensions (Gorine, 2002). The disadvantage is the method can be time consuming and demand a lot of computer power.

1.4.2 Mechanistic methods

Semi analytic or mechanistic models are analytic models which only use a part of the total physics of the process. The fundamental and most important relations of a process are used but other parts of the analytic model are neglected to simplify the model. The model is then tested with field data and tuned to fit the data. The advantage to this method is that it can be fairly quick and give accurate results. Mechanistic models can also be extrapolated to regions beyond the range of data used to develop the model. The disadvantage is that it can be difficult and time consuming to tune mechanistic models to fit the test data (Zhao, 2005).

1.4.3 Empirical methods

Empirical models are created from correlations in test data. They can be very simple correlations between two parameters and more complex correlations which involve multiple parameters. The disadvantage of empirical models is that they are limited to the data range used to create the correlation. These ranges can often be very specific and therefore only used in very limited situations (Vijayarangan, Jayanti, & Balakrishnan, 2007).

When simulating a geothermal well it is very common to use empirical correlation like void fraction correlations because it is too complicated to simulate it numerically.

2 Method of Analysis

The principle of the method is to look at the well as an investment. The initial cost for the wider well is more than for the narrow one but its income return can also be greater. The decision is then a classic investment problem between two options. To be able to make a decision between the two options, wide or narrow, the initial cost has to be known along with the income and operating cost over the lifetime of the well.

The initial cost of the well can be estimated with fair accuracy since there have been many wells drilled and the energy companies usually have contracts with drilling companies like the Iceland Drilling Company Ltd. The operating cost of wells is little compared to the initial cost and income thus it can be neglected. The most difficult part of this method is to estimate the income from the well over its lifespan.

To predict the income from a well one needs to know many parameters. Assuming the inflow to be single phase flow these parameters are for example permeability of the rock, reservoir pressure, pressure at the bottom of the well, pressure drop of the fluid while ascending up the well, temperature of the fluid at the bottom of the well and heat loss. It is difficult to predict many of the parameters, even if the inflow is single phase flow, simply because it is difficult to know exactly what kind of feed zones the well will connect with.

The unpredictability is greater when the first well is drilled into an area, the reason being that there is no experience from the area from older wells. The engineers can learn much about a hot area just by drilling one well. To minimize the unpredictability extensive research is performed before drilling. It usually starts by mapping all the faults in the area, after that subsurface resistivity is measured to see if there is or was heat in the ground. If there are warm pools or steam rising from the ground it is chemically measured to estimate the temperature of the area. It is believed that seismic activity can indicate good permeability, therefore seismic activity is often measured and recorded. A location in the hot area with high seismic activity often becomes a target for a well. There are other available measurements like heat gradient holes and slim holes, but they are not used much in high temperature areas. Heat gradient holes are 30 – 100 meters deep and measure the temperature change with respect to depth. Heat gradient holes are used more in low temperature fields where there are fewer surface indicators of heat. Slim holes are deeper and puncture the high temperature volume, these holes can tell the temperature and permeability of the reservoir (Tulinius, 2011). The use of slim holes is not practiced in Iceland because they are quite expensive and cannot be used as production wells. Engineers rather drill a narrow production well in hope of getting good results and if the well is not suitable then it is used as a measurement well (Ingason, 2011).

The method can be used when drilling a first well but the accuracy of the method can be little due to the uncertainty of the parameters. The accuracy of the method increases with the knowledge derived from an older well in production. By using known parameters from another well it is possible to predict the performance of the well to be drilled for different diameters. By simulating the production well it is possible to create a good simulation model, the accuracy of the model can be tested by comparing measured values to the simulated results. If the results are sufficiently accurate the diameter of the simulated well is changed and the performance of the two wells can be compared. Another advantage when using parameters from a production well is knowing the accuracy of the method.

2.1 Simulation of a well

It is possible to create a very complex model of a well where the reservoir is simulated and coupled with the well model. It is also possible to make simple and crude simulations which only account for few parameters to predict the behavior for some rough estimates. The information needed often demand certain accuracy, more accuracy means more complicated simulations (Wallis, 1969). In this project the simulation needs to be quite accurate which means it has to take into account many parameters. The difficult and unfortunate reality is that many of these parameters have to be estimated, the reason being that it is not possible to measure them. Wall roughness, for example, is a parameter that affects the friction between the fluid and the wall of the well. This parameter can be measured before a well goes into production but after production starts some scaling can occur and change the roughness of the wall. For reasons just like the one mentioned it is necessary to estimate parameters.

In this project the wells to be simulated are real wells that do exist. This means that it is possible to compare the simulation to the actual well which instantly indicates the quality of the simulation.

The parameters that are measured or known are:

- Casing program
- Down-hole pressure and temperature
- Mass flow with some uncertainty

The well is only simulated down to the bottom of the production casing, the reason is to minimize uncertainty. Below the production casing is a slotted liner where fluid can flow into the well. It is very difficult to find where inflow or outflow occurs and the temperature and volume of the inflow or outflow. To eliminate this uncertainty the well is simulated from the bottom of the production casing and up. The reservoir is also excluded from the simulation due to the uncertainties that follow simulating it. It is very difficult to estimate most parameters of a reservoir, the estimate would therefore make the simulation less trustworthy. The method is also based on using parameters measured from a production well which is connected to the same reservoir. The effect of the reservoir can therefore be seen in tests from the production well.

To simulate single phase flow the following parameters are needed:

- Inner diameter of production casing
- Length of production casing
- Pressure
- Density
- Enthalpy
- Dynamic viscosity
- Mass flow

These parameters are sufficient to simulate single phase flow in a vertical well. To simulate two phase flow the following parameters are needed:

- Inner diameter of production casing
- Length of production casing
- Pressure
- Fluid and steam density
- Fluid and steam enthalpy
- Fluid and steam velocity
- Dynamic viscosity of both phases
- Density of the mixture
- Surface tension
- Mass flow

There are few additional parameters needed and they will be explained in more detail in chapter three.

The numerical method solves the system of three equations simultaneously, these equations are the momentum, energy and continuity equations (Pálsson, 2011). If a well is to be simulated in three dimensions and time dependent this method would be very complicated. For this project it is sufficient to simulate the wells independent of time in one dimension. Simulating a well in one dimension and independent of time is much simpler and faster and it can produce accurate models for stable wells like production wells (Wallis, 1969).

3 Theory

The numerical method described here simulates flow of water and steam in a vertical circular tube with a constant diameter. Steady conditions are assumed by neglecting time dependent variations. The three equations, energy, momentum and continuity equations, form a coupled first order set which can be solved with finite difference methods or integrated from bottom to top (Pálsson, 2011). Both single phase flow and two phase flow can occur in the well so both situations will be accounted for. Lastly parameters like dimensionless parameters are explained.

3.1 Single phase flow

Single phase flow is where only one fluid is flowing in the pipe, this fluid can be liquid or gas phase. The primary parameters needed are u, p and h. Another important parameter is ρ, it is a function of p and h so it can easily be determined.

3.1.1 Continuity equation

The continuity equation describes the conservation of mass and can be written as (Pálsson, 2011)

$$\frac{d}{dz}(\dot{m}) = 0 \tag{3.1}$$

The diameter of the pipe is constant so the equation becomes

$$\frac{d}{dz}(\rho u) = 0 \tag{3.2}$$

3.1.2 Momentum equation

The momentum equation can be written as (Pálsson, 2011)

$$\rho u \frac{du}{dz} + \frac{dp}{dz} + \rho g + \frac{\rho f}{2d}|u|u = 0 \tag{3.3}$$

The first part of the equation represents the inertia, the second is the pressure changes, the third part is the hydrostatic pressure and the last part of the equation is the head loss. The f stands for friction factor, which will be explained in more detail later in the chapter, and d stands for pipe inner diameter.

3.1.3 Energy equation

The energy equation can be written as (Pálsson, 2011)

$$\dot{m}u \frac{du}{dz} + \dot{m}\frac{dh}{dz} + \dot{m}g + \dot{Q} = 0 \tag{3.4}$$

The first part of the equation is the kinetic part, the second is the enthalpy part and the third is the potential energy. The $\dot{Q}$ represents heat loss per unit length of pipe.

3.1.4 Matrix form of the equations

The three equations (3.2), (3.3) and (3.4) can be put forward in the following matrix form (Pálsson, 2011)

$$\begin{bmatrix} \rho & u\frac{\partial \rho}{\partial p} & u\frac{\partial \rho}{\partial h} \\ \dot{m}u & 0 & \dot{m} \\ \rho u & 1 & 0 \end{bmatrix} \frac{d}{dz}\begin{bmatrix} u \\ p \\ h \end{bmatrix} + \begin{bmatrix} 0 \\ \dot{m}g + \dot{Q} \\ \rho g + \frac{\rho f}{2d}|u|u \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \tag{3.5}$$

This system can be solved using numerical integration from the well bottom to the well top.

3.2 Two phase flow

The method of numerical analysis of two phase flow is the same as for single phase flow, the three equations simply have to take into account both phases and their relations. To understand the three equations to be solved for two phase flow it is necessary to introduce some primary parameters

3.2.1 Primary parameters

The steam quality of the mixture, x, is the ratio between mass flow of gas and total mass flow through a given cross section of the pipe (Wallis, 1969).

$$x = \frac{\dot{m}_g}{\dot{m}_g + \dot{m}_l} \tag{3.6}$$

Another way to determine the steam quality is (Pálsson, 2011)

$$x = \frac{h - h_l}{h_g - h_l} \tag{3.7}$$

where h_l and h_g are the enthalpies of the liquid phase and gas phase and h is the enthalpy of the mixture. The gas holdup, α, is the ratio between the area of which the gas holds up and the total area of a cross section of a pipe. It can be determined as (Wallis, 1969)

$$\alpha = \frac{A_g}{A} \tag{3.8}$$

It is difficult to determine α due to slippage. The phases can be traveling with different velocities which creates slippage between the phases. This slippage is commonly termed slip ratio, S, and is defined as the ratio between the average velocity of the gas phase and the average velocity of the liquid phase in gas-liquid flow (Zhao, 2005)

$$S = \frac{u_g}{u_l} \tag{3.9}$$

The average phase velocity is found by

$$u_i = \frac{\dot{V}_i}{A_i} \tag{3.10}$$

where $\dot{V}_i$ is the volume flow of either gas or liquid. A relationship between the gas hold up, steam quality, slip ratio and phase densities exists (Pálsson, 2011)

$$\alpha = \frac{x\rho_l}{\left((1-x)\rho_g S + x\rho_l\right)} \tag{3.11}$$

Due to the difficulty of measuring the gas hold up correlations, often termed void fraction correlations, equations have been created to determine the gas hold up as a function of different parameters. Void fraction correlations will be explained later in the chapter. A new velocity parameter, u_m, is introduced where m stands for mixture. It is determined as if the liquid was flowing in the pipe alone but with the mass flow of the total flow of the mixture (Pálsson, 2011).

$$u_m = \frac{\dot{m}}{\rho_l A} \tag{3.12}$$

3.2.2 Continuity equation

The continuity equation for two phase flow can be written as (Pálsson, 2011)

$$\frac{d}{dz}\left(\dot{m}_l + \dot{m}_g\right) = 0 \tag{3.13}$$

$$\frac{d}{dz}\left(\rho_l u_l A_l + \rho_g u_g A_g\right) = 0 \tag{3.14}$$

A_l is the total area of which liquid holds up over a cross sectional area of the pipe, A_g is therefore the area of which gas holds up. The sum of the two equals the cross sectional area of the pipe. A_l and A_g can be written in terms of α. Since the pipe diameter is constant formula (3.14) can be written as (Pálsson, 2011)

$$\frac{d}{dz}\left(\rho_l u_l (1-\alpha) + \rho_g u_g \alpha\right) = 0 \tag{3.15}$$

Introducing u_m the equation becomes

$$\frac{d}{dz}(\rho_l (1-\alpha) u_m + \rho_l \alpha u_m) = 0 \tag{3.16}$$

which can be simplified to

$$\frac{d}{dz}(\rho_l u_m) = 0 \tag{3.17}$$

3.2.3 Energy equation

The energy equation for two phase flow can be written as (Pálsson, 2011)

$$\frac{d}{dz}\left(\dot{m}_l \left(\frac{u_l^2}{2} + gz + h_l\right) + \dot{m}_g \left(\frac{u_g^2}{2} + gz + h_g\right)\right) + \dot{Q} = 0 \tag{3.18}$$

By introducing the parameter γ defined as

$$\gamma = \frac{(1-x)^3}{(1-\alpha)^2} + \frac{\rho_l^2 x^3}{\rho_g^2 \alpha^2} \tag{3.19}$$

the energy equation can then be written as (Pálsson, 2011)

$$\gamma u \frac{du_m}{dz} + \frac{u_m^2}{2}\frac{\partial \gamma}{\partial p}\frac{dp}{dz} + \left(1 + \frac{u_m^2}{2}\frac{\partial \gamma}{\partial h}\right)\frac{dh}{dz} + g + \frac{\dot{Q}}{\dot{m}} = 0 \tag{3.20}$$

3.2.4 Momentum equation

For two phase flow the momentum equation has to account for velocities for both phases in the inertia part and the density in the gravity part should be the average of both phases. The density can be defined by

$$\rho_\alpha = (1-\alpha)\rho_l + \alpha\rho_g \tag{3.21}$$

the momentum equation can then be written as (Pálsson, 2011)

$$\frac{d}{dz}\left(\dot{m}_l u_l + \dot{m}_g u_g\right) + A\frac{dp}{dz} + \left((1-\alpha)\rho_l + \alpha\rho_g\right) gA + \Phi^2 \frac{\rho_l f A}{2d} u_m^2 = 0 \tag{3.22}$$

where f is the friction factor and the Φ is the friction correction factor. To simplify the equation η is defined as

$$\eta = \frac{(1-x)^2}{1-\alpha} + \frac{\rho_l}{\rho_g}\frac{x^2}{\alpha} \tag{3.23}$$

which simplifies the equation considerably (Pálsson, 2011)

$$\eta\rho_l u_m \frac{du_m}{dz} + \left(1 + \rho_l u_m^2 \frac{\partial \eta}{\partial p} + \eta u_m^2 \frac{\partial \rho_l}{\partial p}\right)\frac{dp}{dz} + \rho_l u_m^2 \frac{\partial \eta}{\partial h}\frac{dh}{dz}$$
$$+ \left((1-\alpha)\rho_l + \alpha\rho_g\right) g + \Phi^2 \frac{\rho_l f}{2d} u_m^2 = 0 \tag{3.24}$$

3.2.5 Matrix form of the equations

The three equations (3.17), (3.20) and (3.24) can be put forward in the following matrix form (Pálsson, 2011)

$$\begin{bmatrix} \rho_l & u_m \frac{\partial \rho_l}{\partial p} & 0 \\ \gamma u_m & \frac{u_m^2}{2}\frac{\partial \gamma}{\partial p} & \left(1 + \frac{u_m^2}{2}\frac{\partial \gamma}{\partial h}\right) \\ \eta\rho_l u_m & \left(1 + \rho_l u_m^2 \frac{\partial \eta}{\partial p} + \eta u_m^2 \frac{\partial \rho_l}{\partial p}\right) & \rho_l u_m^2 \frac{\partial \eta}{\partial h} \end{bmatrix} \frac{d}{dz}\begin{bmatrix} u \\ p \\ h \end{bmatrix}$$
$$+ \begin{bmatrix} 0 \\ g + \frac{\dot{Q}}{\dot{m}} \\ \left((1-\alpha)\rho_l + \alpha\rho_g\right) g + \frac{\Phi^2 \rho_l f}{2d} u_m^2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \tag{3.25}$$

This system can be solved using numerical integration from the well bottom to the well top.

3.3 Evaluation of the friction factor and friction correction factor

The friction factor is defined by the Blasius equation. The Blasius equation assumes the wall roughness to be smooth and is defined as (Wallis, 1969)

$$f = \frac{0{,}316}{Re^{\frac{1}{4}}} \tag{3.26}$$

The friction factor is based on

$$Re_l = \frac{\rho_l u d}{\mu_l} \tag{3.27}$$

The velocity parameter u being either the normal velocity in the single phase flow or the u_m velocity for the two phase flow. The parameter μ_l is the dynamic viscosity of water. In this project the geothermal fluid is assumed to be water of which the dynamic viscosity can be obtained from the International Association for the Properties of Water and Steam (IAPWS, 2008).

The friction correction factor can be evaluated using various relations, in this project the correction factor is based on the Friedel approximation defined as (Hewitt, 1978).

$$\Phi^2 = E + \frac{3{,}24FH}{Fr^{0{,}045}We^{0{,}035}} \tag{3.28}$$

where

$$E = (1 - \alpha^2) + x^2 \frac{\rho_l}{\rho_g}\frac{f_g}{f_l} \tag{3.29}$$

$$F = x^{0{,}78}(1 - x^2)^{0{,}24} \tag{3.30}$$

$$H = \left(\frac{\rho_l}{\rho_g}\right)^{0{,}91} \left(\frac{\nu_g}{\nu_l}\right)^{0{,}19} \left(1 - \frac{\rho_g}{\rho_l}\right)^{0{,}7} \tag{3.31}$$

$$Fr = \frac{\rho_l^2 u_m^2}{g\rho_m^2 d} \tag{3.32}$$

$$We = \frac{\rho_l^2 u_m^2 d}{\sigma \rho_m^2} \tag{3.33}$$

The parameters ν_g and ν_l are the kinematic viscosity of the gas and liquid which are defined as

$$\nu_i = \frac{\mu_i}{\rho_i} \tag{3.34}$$

where i can either be g or l. In the formulation of E the two friction factors f_g and f_l are presented, these factors are defined as

$$f_g = \frac{\rho_g u_m d}{\mu_g} \tag{3.35}$$

$$f_l = \frac{\rho_l u_m d}{\mu_g} \tag{3.36}$$

Another parameter ρ_m is introduced in the formulation of *Fr* and *We*, this parameter defines the density of the mixture using steam quality instead of void fraction (Pálsson, 2011)

$$\frac{1}{\rho_m} = \frac{x}{\rho_g} + \frac{1-x}{\rho_l} \tag{3.37}$$

3.4 Void fraction correlations

There exists a lot of void fraction correlations for different situations. As mentioned earlier these correlations are based on test data and are therefore limited to the range of the test data. It can be difficult to find correlations that perform well with two phase flow in geothermal wells. It is very expensive and over all difficult to create test data for such high pressures, high temperatures and large pipe size. Earlier work recommend using the Rouhani and Axelsson (1970) model for geothermal wells (Valladares, Upton, & Santoyo, 2005). The Rouhani and Axelsson (1970) model is defined as

$$\alpha = \left(\frac{x}{\rho_g}\right)\left\{[1 + 0.12(1-x]\left[\left(\frac{x}{\rho_g}\right) + \left(\frac{1-x}{\rho_l}\right)\right] + \frac{[1.18(1-x)][g\sigma(\rho_l - \rho_g)]^{0.25}}{G\rho_l^{0.5}}\right\}^{-1} \tag{3.38}$$

The parameter σ is the surface tension of water and can be calculated as follows (IAPWS, 2007)

$$\sigma = 0.2358\left(1 - \frac{T}{T_c}\right)^{1.256}\left(1 - 0.625\left(1 - \frac{T}{T_c}\right)\right) \tag{3.39}$$

Where T is in Kelvin, T_c = 647.096 K and σ is in N/m. M.A. Woldesemayat and A.J. Ghajar performed an extensive research testing multiple void fraction correlations (Woldesemayat & Ghajar, 2007). They tested 68 void fraction correlations for different situations like incline and pressure. They also recommend using the Rouhani and Axelsson (1970) correlation. They also recommend the Premoli et al. (1970) correlation.

Premoli et al. (1970)

$$\alpha = \left[1 + A_{PRM}\left(\frac{1-x}{x}\right)\left(\frac{\rho_g}{\rho_l}\right)\right]^{-1} \tag{3.40}$$

where

$$A_{PRM} = 1 + F_1\left(\frac{y}{1+yF_2} - yF_2\right) \tag{3.41}$$

$$F_1 = 1.578Re_l^{-0.19}\left(\frac{\rho_l}{\rho_g}\right)^{0.22} \tag{3.42}$$

$$F_2 = 0.0273 We_l Re_l^{-0.51} \left(\frac{\rho_l}{\rho_g}\right)^{-0.08} \tag{3.43}$$

$$y = \left[\left(\frac{1-x}{x}\right)\left(\frac{\rho_g}{\rho_l}\right)\right]^{-1} \tag{3.44}$$

$$We_l = \frac{G^2 d}{\sigma \rho_l} \tag{3.45}$$

$$Rel = \frac{Gd}{\mu_l} \tag{3.46}$$

Other recommended void fraction correlation tested in this project are the

Lockhart and Martinelli (1949)

$$\alpha = \left[1 + 0.28\left(\frac{1-x}{x}\right)^{0.64}\left(\frac{\rho_g}{\rho_l}\right)^{0.36}\left(\frac{\mu_l}{\mu_g}\right)^{0.07}\right]^{-1} \tag{3.47}$$

Zivi (1964)

$$\alpha = \left[1 + \left(\frac{1-x}{x}\right)\left(\frac{\rho_g}{\rho_l}\right)^{0.67}\right]^{-1} \tag{3.48}$$

Smith (1969)

$$\alpha = \left[1 + \left(0.4 + 0.6\sqrt{\left[\frac{\rho_l}{\rho_g} + 0.4\left(\frac{1-x}{x}\right)\right] / \left[1 + 0.4\left(\frac{1-x}{x}\right)\right]}\right)\left(\frac{1-x}{x}\right)\right]^{-1} \tag{3.49}$$

3.5 Numerical integration

A numerical integration is used to solve equations (3.5) and (3.25) over the length of the production casing. A function called ode23 in MATLAB can be used to solve these equations. The ode23 function is based on the Bogacki-Shampine version of the Runge-Kutta method (Mathworks). The Bogacki-Shampine method is a third order and four stage method with an adaptive step size (Bogacki & Shampine, 1989). The ode23 function splits the length of the production casing into equal size intervals. For each interval the ode23 calculates the pressure, enthalpy and velocity change. Plotting the velocity, pressure and enthalpy vectors against the position vector the characteristics of the simulated well are revealed.

4 Geothermal well data

Originally the plan was to use four wells in this project as field data. It was decided to use two narrow wells, one with high enthalpy and one with low enthalpy. Along with the narrow wells two wide wells would be used, one with high enthalpy and one with low enthalpy. By using four wells with these characteristics it is possible to see a range of possible outcomes. Data from these wells was obtained from Reykjavík Energy. Later in the project, more data was granted from the Icelandic energy company HS-Orka and a decision was made to add them to the project.

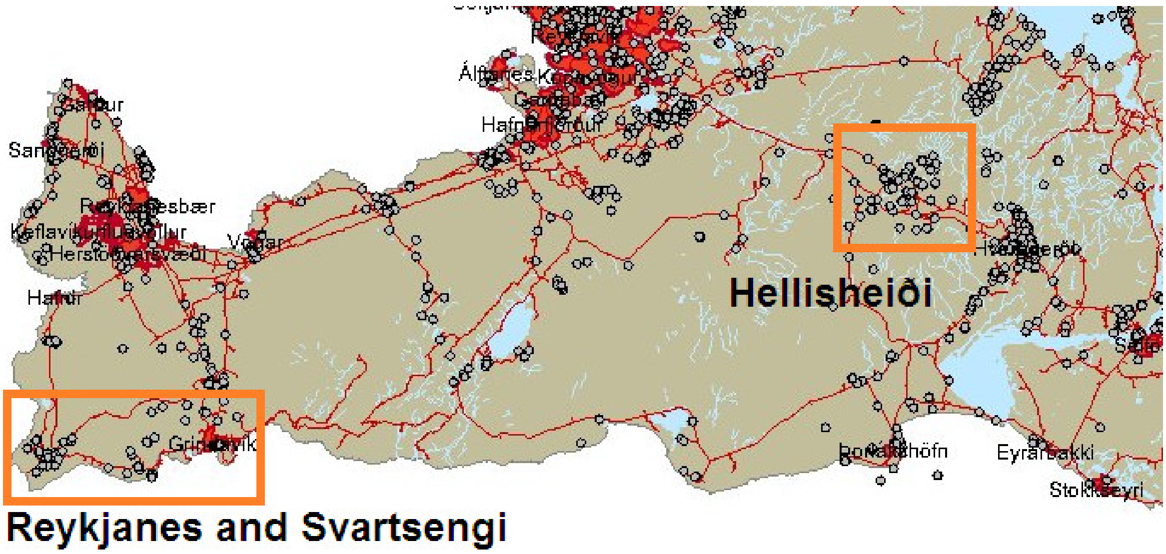


Figure 3. Location of the wells used as data (Orkustofnun, 2011).

The well data from Reykjavík Energy come from wells at Hellisheiði and the well data from HS-Orka come from wells at Reykjanes and Svartsengi which can be seen in figure 3.

4.1 Wells from Reykjavík Energy

The four wells to be simulated from Reykjavík Energy are HE-05, HE-41, HE-48 and HE-54. The following table shows the main parameters of each well.

Table 1. Main parameters for the four wells at Hellisheiði (Gunnlaugsson, Guðlaugsson, & Árnason, 2011).

Wells at Hellisheiði	HE-05	HE-41	HE-48	HE-54
Depth of well [m]	1741	2530	2281	2061
Depth of surface casing [m]	91	84.8	85	86
Depth of anchor casing [m]	286	281	445	283
Depth of production casing [m]	791	782	829	752
Depth of slotted liner [m]	1221	2033	1442	1650
Diameter of production casing [in]	9 5/8	13 3/8	13 3/8	9 5/8
Inside diameter of prod. casing [mm]	220	315	315	315
Welltop pressure [bar-a]	19	69	15	65
Wellbottom pressure [bar-a]	119	188	122	126
Welltop temperature [°C]	206	10	197	280
Wellbottom temperature [°C]	260	294	255	300
Pressure at bottom of prod. casing	52	72	35	69
Temp. at bottom of prod. casing [°C]	260	289	242	292
Well enthalpy [kJ/kg]	1194	2704	1072	1821
Massflow [kg/s]	49	N/A	39.2	N/A
Coordinates in Orkustofnun database				
X	384109.09	383892.72	385059.346	N/A
Y	396154.32	394428.85	396868.874	N/A
Date of test	31.5.2007	15.4.2008	3.12.2008	20.11.2009

4.2 Wells from HS-orka

The four wells to be simulated from HS-orka are SV-21, SV-22, SV-23 and RN-25. The following table shows the main parameters of each well.

Table 2. Main parameters for the four wells from HS-orka (Þórólfsson, 2011).

Wells at Reykjanes and Svartsengi	SV-21	SV-22	SV-23	RN-15
Depth of well [m]	1470	740	695	2137
Depth of surface casing [m]	N/A	N/A	120	N/A
Depth of anchor casing [m]	N/A	127	N/A	299
Depth of production casing [m]	839	380	488	700
Depth of slotted liner [m]	N/A	740	652	2135
Diameter of production casing [in]	13 3/8	13 3/8	13 3/8	13 3/8
Inside diameter of prod. casing [mm]	315	315	315	315
Welltop pressure [bar-a]	13.5	18	22.5	40
Wellbottom pressure [bar-a]	90	27	24	102
Welltop temperature [°C]	195	207	217.5	245
Wellbottom temperature [°C]	238	228	222	304
Pressure at bottom of prod. casing	39	20	23.5	51
Temp. at bottom of prod casing [°C]	239	211	221	267
Well enthalpy [kJ/kg]	1030	1930	2800	1570
Massflow [kg/s]	70	28.7	11.6	35.8
Coordinates in Orkustofnun database				
X	330938.821	331671.979	331654.61	318255.77
Y	379568.845	379673.117	379839.601	374205.536
Date of test	26.02.2007	17.03.2008	13.11.2008	30.04.2008

5 Measurements

Measurements and measurement accuracy is important for measuring the power of geothermal wells. These measurements are often used to scale control systems and forecast the production capabilities of a power plant (Gunnlaugsson & Oddsdóttir, 2007).

Neither Reykjavik Energy nor HS-Orka perform down-hole measurements after a well is connected for production. This causes problems because it is necessary to have down-hole measurements to simulate a geothermal well. Due to the lack of down-hole data from wells in production data from tests done before connecting the wells are used. It is optimal to get measurements from a well in production which is stable. This could affect the validity of the results since the wells might not have fully stabilized when the data is collected.

Before the wells are connected to a power plant they are usually tested. An Icelandic company called Iceland Geosurvey has a measurement team which commonly measure or assist measurements of geothermal wells. The reason is they have equipment that the energy companies usually do not have. Using the down-hole and mass flow measurements from Iceland Geosurvey it is possible to simulate a geothermal well.

5.1 Pressure and temperature measurements

The down-hole pressure and temperature measurements are done with the K10 Geothermal logging tool from the Kuster Company. It is a subsurface, high temperature and pressure recording device. The K10 is fitted into an Ø1.75 inch and 60 inch long protective cylinder which protects the electronics from the high temperature and corrosive geothermal fluid. It can measure pressure up to 5000 psi or 344 bar-a with an accuracy of 0.024%. The K10 can stay in the well for 6 hours if the temperature is 300°C and 4 hours if the temperature is 350°C. The temperature accuracy is ±0.25 °C with a response time of 1.5 sec /10°C. The minimum sample rate is 1 second (Company, 2011). The K10 sensor seems to be very accurate the only concern is the size of it. It is possible that the sensor can affect the flow by creating an extra resistance within the well. Although this is possible it will be assumed that the sensor does not affect the flow and the data measured is correct.

5.2 Mass flow measurements

The mass flow of a geothermal well is estimated by measuring other parameters that can indicate the mass flow. The most common ways to estimate mass flow are the Russell James method and the trace flow test method.

5.2.1 Russell James method

The method is to measure the critical pressure and estimating the mass flow by using the following formula (Jónsson & Eyjólfsdóttir, 2009)

$$\dot{m} = K * A * \frac{{p_c}^m}{h^n} \tag{5.1}$$

where K = 1835000 is a constant, p_c is the critical pressure in bar-a, m = 0.96 and n = 1.102 are constants.

To verify the mass flow of steam the measuring team from Iceland Geosurvey measure the differential pressure in the steam outlet of a steam separator and use the following formula (Jónsson & Eyjólfsdóttir, 2009)

$$\dot{m}_s = 2.733 * \sqrt{\Delta P} \tag{5.2}$$

where ΔP is the differential pressure. The fluid flow is also measured by measuring the water height through a V-notch from the fluid outlet of the steam separator (Jónsson & Eyjólfsdóttir, 2009).

5.2.2 Trace flow test method

The method is to inject chemical tracers into two-phase flow and measure their concentrations further down the flow line. This way the mass flow can be determined without disrupting the production. The method requires injecting precise amounts of both liquid- and vapor tracers into the stream and collecting liquid and vapor samples far enough down the stream to ensure complete mixing. The liquid and steam samples are analyzed for tracer content and the mass flow rate of each face is estimated by the following formulas

$$\dot{m}_l = \frac{\dot{m}_T}{C_T} \tag{5.3}$$

$$\dot{m}_g = \frac{\dot{m}_T}{C_T} \tag{5.4}$$

where $\dot{m}_T$ and C_T are the mass flow of each tracer and measured concentration by weight (Hirtza, Kunzmana, Broaddusb, & Barbittaa, 2001).

6 Results

The following chapter shows the down-hole measurements compared to simulations for a wide and a narrow well. For each well one model is created where all parameters are the same as the well measured. If a good model is found that simulates the measured data with sufficient accuracy then the well is also simulated for a different diameter. If the simulations for both diameters are successful it is possible to calculate how much income the well generates with respect to both diameters. The cash flow for each well over its lifespan can then be plotted which will determine which diameter will be more profitable. All wells are simulated using the numerical method explained in chapter three but they can have different void fraction correlations. Some wells have very low enthalpy while others have almost no liquid phase flowing in the pipe, this information is used to choose a model that suits each well the best.

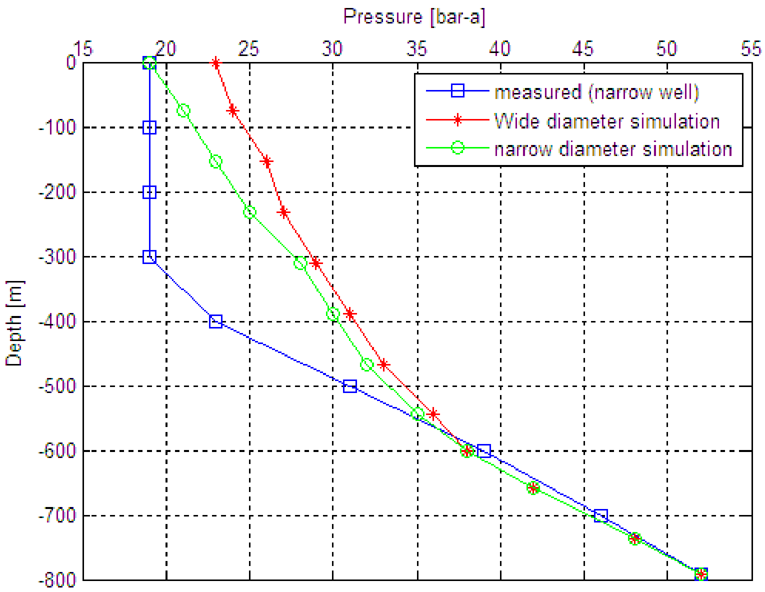
To be able to calculate the cash flow for each well some assumptions are necessary. The initial cost of drilling an Ø13 3/8 inch wide well which reaches a depth of 2500 meters is assumed to be 3.880.000 USD and for an Ø9 5/8 inch wide well the cost is assumed to be 3.020.000 USD. These assumptions are based on wells that have been drilled over the last few years (Árnason, 2011). It is also assumed that the relation between depth and initial cost of a well behaves linearly. This assumption is based on a study which indicates this linearity for wells deeper than 800 meters (Ingason & Matthíasson, 2006). The lifespan of one well is assumed to be 20 years. Since only steam is used to generate electricity it is necessary to assume the separation pressure, this pressure indicates the amount of steam that can be used from the well. It is common to use a separation pressure of either 10 bar-a or 8 bar-a and for this project an 8 bar-a separation pressure will be used. To turn steam into income a conversion factor is needed, it is common to assume that 2 kg of steam produce 1 MW of electricity (Bóasson, 2011). To find out how much 1 MW is in ISK the financial statements of Reykjavík Energy are useful to find the average price of 1 MW. The annual report from 2009 states that the income for electricity sales was 12,540 million ISK and the total electricity produced was 2703.9 GWH (OR, 2009). The average price for 1 KWH is therefore 4.63 ISK. The price list at the website of Reykjavik Energy confirms this (OR, 2011).

6.1 Results for wells at Hellisheiði

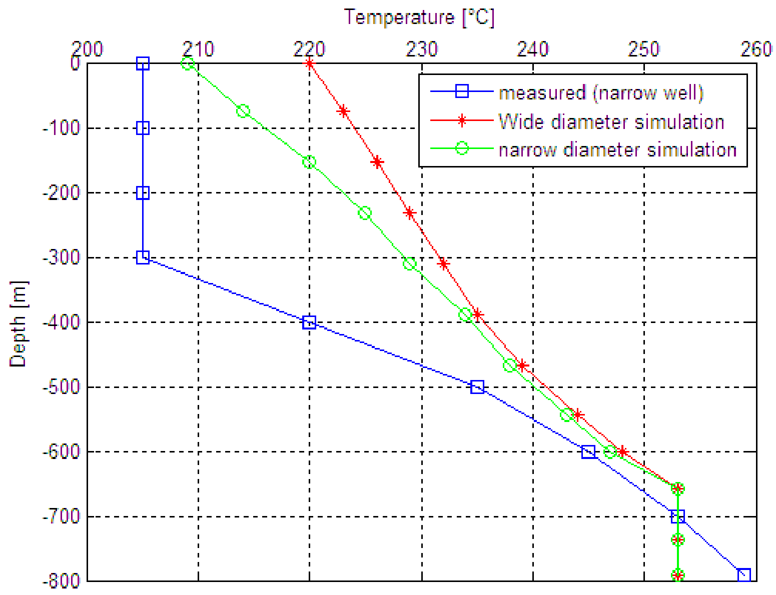
Unfortunately the mass flow measurements for wells HE-41 and HE-54 were not taken at the same time as the down-hole measurements. Over the time from which the down-hole measurements were performed and the time from which the mass flow measurements were performed the well characteristics changed. It seems that only a small change in mass flow can change the well characteristics. If a well is stable it is not necessary to measure the down-hole properties and the mass flow at the same time although it is preferred for a sensitive process like numerical simulations. Due to this error in measurements HE-41 and HE-54 were excluded from this project and the other two wells were simulated.

6.1.1 HE-05

The void fraction models tested for this well are the Rouhani and Axelsson (1970) model, Premoli et al. (1970), Lockhart and Martinelli (1949), Zivi (1964) and Smith (1969).The constant slip ratio formulation (3.11) with the slip ratio equal to one performed the best thus indicating high ratio of liquid in the pipe. The enthalpy in the simulation of the well was also lowered to 1100 kJ/kg from 1194 kJ/kg. This was done to fit the simulation curve closer to the measured curve creating a better simulation. The simulation can be seen in graph 3 and graph 4. HE-05 is a narrow well so the narrow diameter model should follow the measured data.

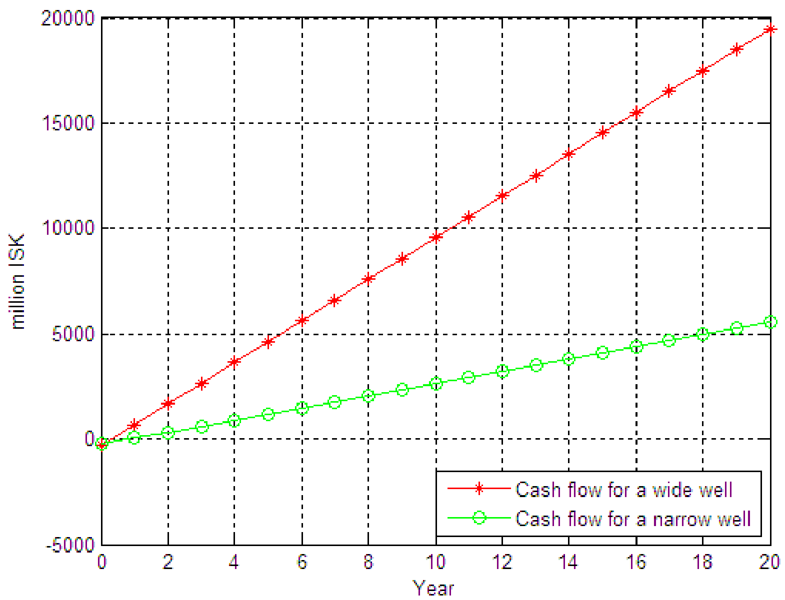


Graph 3. Down-hole pressure measurements compared to a simulation for HE-05.



Graph 4. Down-hole temperature measurements compared to a simulation for HE-05.

The simulation does predict the well top pressure correctly and the well top temperature is only 4°C higher than the measured value. Although the well top values are good it is easy to see that the model is not very good. Judging from the down-hole measurements it seems like the slip ratio is greater than one and the steam quality is higher than estimated. Since this is the best simulation the cash flow for both diameters will be based on this model. The cash flow model is therefore based on the actual measurements of the well and the simulation of the well with a wider diameter and the assumptions mentioned earlier.

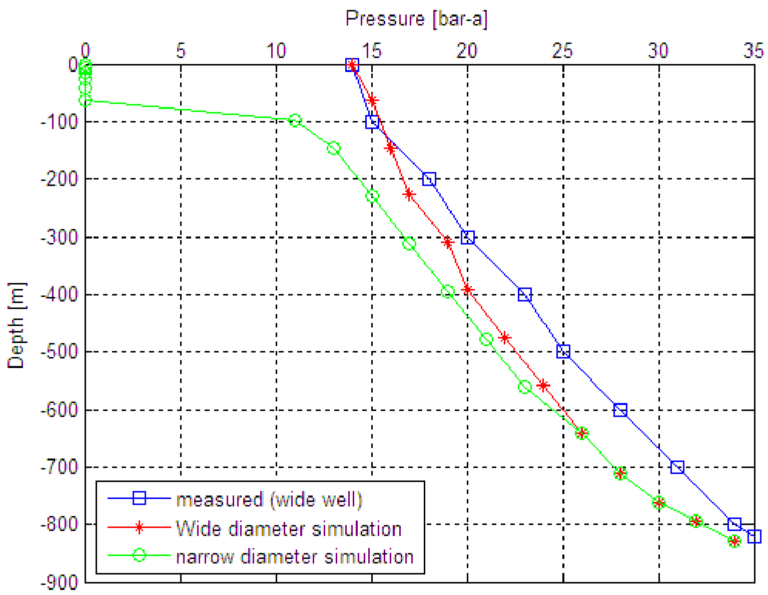


Graph 5. Cash flow comparison for HE-05 between the two diameters.

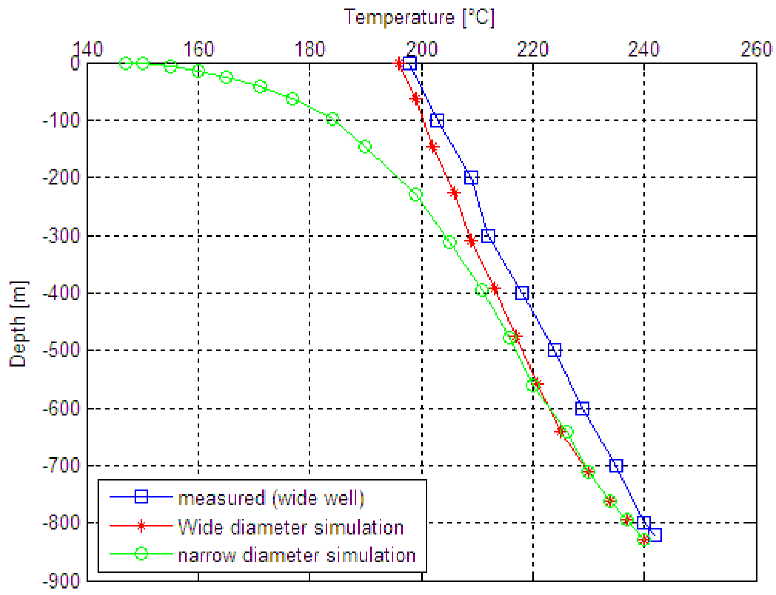
The cash flow in graph 5 shows that the wider well will return more income over the lifespan of the well. The reason why the wide well is more productive is because the steam quality at 8 bar-a separation pressure is equal to 1 for the wide well but 0.3 for the narrow well. This means that the wide well produces over three times more steam than the narrow well. It is necessary to mention that no interest rate or finance cost is taken into account. Reason being that it only requires more assumptions and increases the complexity of the information behind the cash flow. The cash flow graph only takes into account the initial cost and yearly income.

6.1.2 HE-48

HE-48 is a low enthalpy well which again indicates that it is liquid dominant. All of the void fraction models were tested and the constant slip ratio model with the slip ratio equal to one returned the best simulation. The simulation showed top values for pressure and enthalpy that were too high. To lower the top values a model with lower enthalpy was tested. A model with an enthalpy of 1040 kJ/kg instead of 1072 kJ/kg produced the best simulation, which can be seen in the following graphs.



Graph 6. Down-hole pressure measurements compared to a simulation for HE-48.



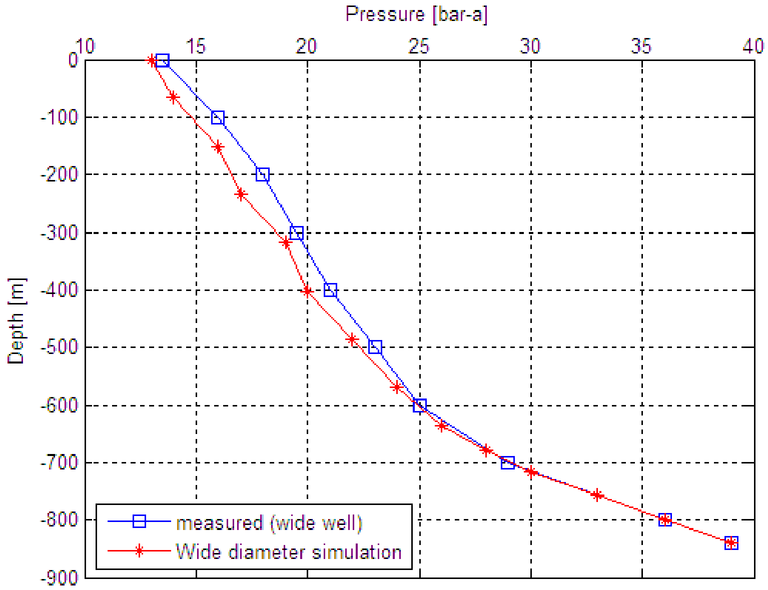
Graph 7. Down-hole temperature measurements compared to a simulation for HE-48.

The simulation is predicting the well characteristics quite accurately. It can be seen on the graphs that it is not possible to use a narrow pipe for HE-48. The pressure drop is too great and the well top pressure is below the 8 bar-a separation pressure. Since the narrow well will perform much worse it is obvious that the wider well is the better option.

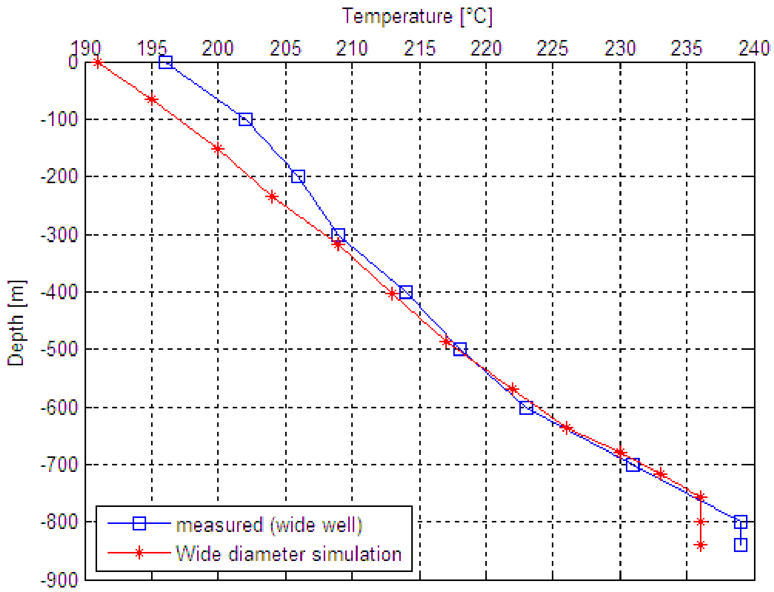
6.2 Results for wells at Reykjanes and Svartsengi

6.2.1 SV-21

SV-21 is another low enthalpy well, all the void fraction models were tested and the constant slip ratio model returned the best simulation. The model returned a very good simulation of the well when the slip ratio was set equal to one. If the enthalpy of the well in the simulation is set equal to 1020 kJ/kg instead of 1030 kJ/kg the simulation was even better. SV-21 is a wide well and when it was simulated as a narrow well the simulation showed an increase in pressure drop. The pressure drop was enough to bring the pressure down to vacuum before the well reaches the surface. It is clear that a narrow well cannot function as well as the wide well for SV-21thus the wide well is the better option.



Graph 8. Down-hole pressure measurements compared to a simulation for SV-21.



Graph 9. Down-hole temperature measurements compared to a simulation for SV-21.

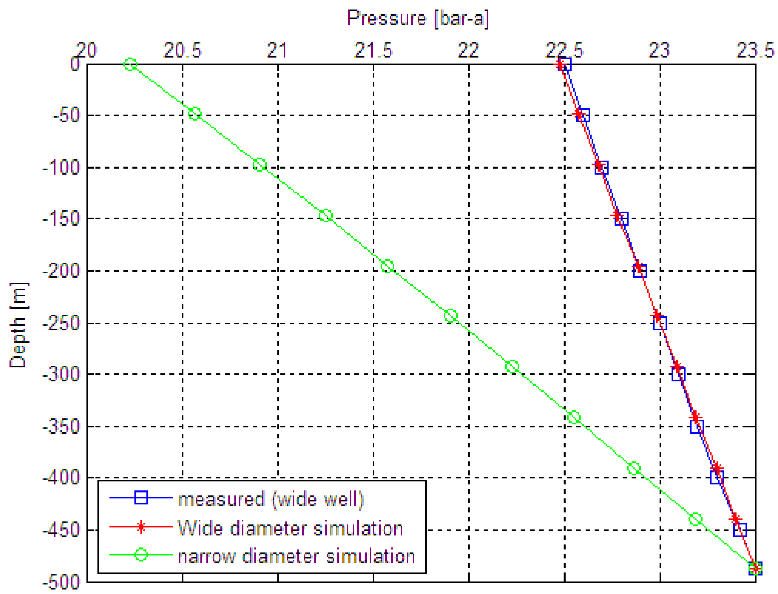
The comparison graphs for SV-21 show that the simulation is good. It is a good indicator of how well the numerical method can perform. This simulation also indicates that the bottom pressure of the well needs to be high enough to overcome the added friction from using a narrower well.

6.2.2 SV-22

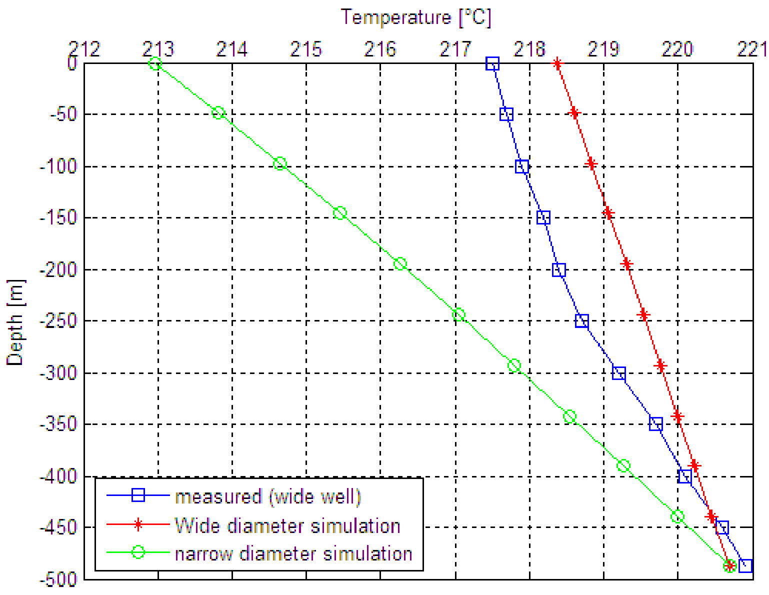
The team that measured SV-22 reported that both steam and liquid was ascending through the well top. It is likely that the steam quality for this well is high due to high enthalpy. To be able to simulate this well a void fraction model is needed. The void fraction models tested were the Rouhani and Axelsson (1970) model, Premoli et al. (1970), Lockhart and Martinelli (1949), Zivi (1964) and Smith (1969). Unfortunately the numerical method was not able to find a solution using any of the models. There are two possible reasons for this, one being that the void fraction models are not good enough for geothermal wells and the second being that the error in the measurements is too great for the sensitivity of the numerical method. In the report from the measurement team that measured SV-22 it is noted that the mass flow measurement are done with an unusual method (H. Björnsson et al., 2008). Knowing this the numerical method was tested for different mass flows but with no success. As a last resort an empirical method was tested which is not as sensitive as the numerical method but it was not able to find a solution. Unfortunately it seems that the void fraction models are not good enough to simulate SV-22. A void fraction model which predicts a value within ±15% error from the measured value for all datasets is termed as a good model (Woldesemayat & Ghajar, 2007). The fact is that these correlations are not created from data of high temperature geothermal wells and are therefore not very accurate for simulations of high temperature wells.

6.2.3 SV-23

The measurement team that measured SV-23 reported that it only produced steam, the low pressure and high enthalpy measurements confirmed that observation (Jónsson & Eyjólfsdóttir, 2009). Since the well was only producing steam the flow was simulated as single phase steam flow. The mass flow of steam was measured 11.6 kg/s but the best simulation was when the mass flow was set to 25.6 kg/s.

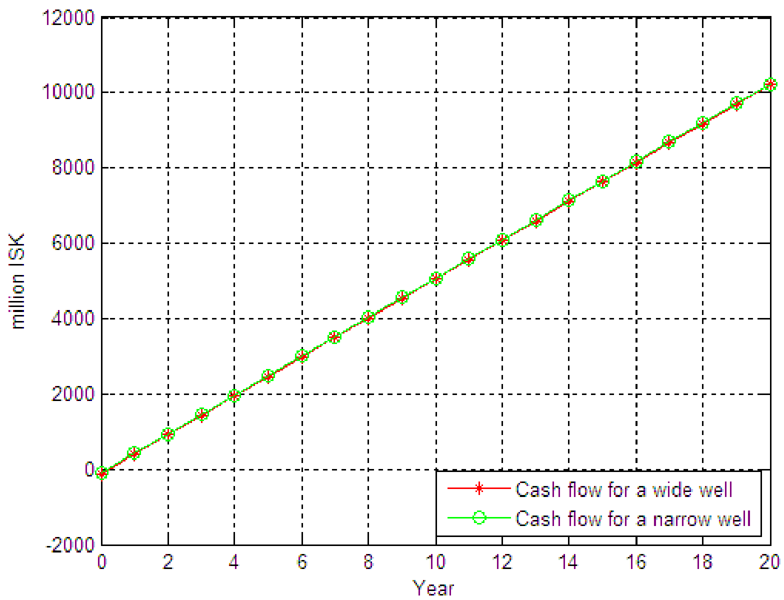


Graph 10. Down-hole pressure measurements compared to a simulation for SV-23



Graph 11. Down-hole temperature measurements compared to a simulation for SV-23.

The comparison graphs for SV-23 show that the simulation is good and the assumption that only single phase steam flow exists in the well to be correct. SV-23 is a wide well thus the measured values and the narrow well simulation are compared in graph 12.



Graph 12. Cash flow comparison for SV-23 between both diameters.

Although that the temperature and pressure drop is greater for the narrow well it returns the same amount of income over the lifespan of 20 years. The reason is that the enthalpy is high enough that at 8 bar-a separation pressure only steam exists. Due to the fact that the income is equal for both diameters it would be better to choose the narrower well since it is cheaper to drill. It is necessary to point out that this does not account for mass flow changes from the reservoir into the well due to diameter changes. It is possible that the mass flow will drop because of the increased friction from the narrower well. Only a small amount of mass flow drop makes the wide well the better choice.

6.2.4 RN-25

The measurement team that measured RN-25 recorded that the well was oscillating. They estimated that the boiling interface in the well was oscillating between the depth of 1400 meters and well bottom (Jónsson & Friðriksson, 2008). The fact is that since the well is not stable it is very difficult to measure the well accurately and even more difficult to simulate it. The numerical method used in this project assumes steady state which means that the simulation will never be correct. Although the simulation will not be correct it is interesting to see if the numerical method is able to find a solution. The void fraction models tested were the Rouhani and Axelsson (1970) model, Premoli et al. (1970), Lockhart and Martinelli (1949), Zivi (1964) and Smith (1969). The numerical method did not find a solution for any of the void fraction models used. An empirical method was also tested and surprisingly it was able to find a solution using the Lockhart and Martinelli (1949) void fraction model but the well top values were not close to the measured values.

7 Conclusion

The objective of the project was to study the effect of well diameter on the productivity of a high temperature geothermal well. The idea was to create a method that could help engineers decide what diameter suits each well best. This method was then tested to see if the method works and if the information acquired is credible.

The numerical analysis method performed very well if one phase was flowing in the pipe or if the slip ratio could be assumed equal to one. For those situations the numerical method showed that it can predict the characteristics of the well with good accuracy. The assumption that the wall roughness of the pipe was smooth did not seem to have a great impact on the results. The assumption that the heat loss from the well can be neglected is also a valid assumption seeing that wells like SV-21 were almost simulated perfectly.

The biggest drawback of this method is that in reality the mass flow from the reservoir into the well changes when the diameter of the well is changed. The method used in this project does not take this change into account. This fact reduces the validity of the method since the change in mass flow can lead to a change in flow regime which can than lead to different frictional forces. The mass flow change due to diameter change is dependent on the connection between the well and the reservoir. Simulators like HOLA exist where a reservoir model is coupled with the wellbore model (G. Björnsson, Arason, & Böðvarsson, 1993). The reason why the reservoir was excluded from this project was the uncertainties that follow modeling the reservoir. It seems like it is necessary to include some kind of mass flow correction factor. Another drawback is the void fraction correlations, although other researchers have found them to perform well for some dataset they do not seem to perform well for geothermal wells. Some trial and error effort was put into adjusting the correlations to see if their performance could be increased but it returned no increase in performance. For this method to work properly better void fraction correlations are needed.

To be able to study the effect of well diameter on the productivity of high temperature wells much more data is needed. The quality of measurements is also vital to this type of study. To be able to find valuable results many wells would have to be tested with great accuracy for the single purpose of creating data for simulations. This is a lot of work and expensive but it could return valuable information which could benefit the energy companies and its clients.

It is necessary to note that although some simulations in the project indicate that a well should have been designed with another diameter does not indicate that the diameter used is the worse diameter. This project only considers the productivity of geothermal wells, the fact is that productivity is only one part of many parts that need to be considered when designing a well. Parameters like velocity, flow regimes and forces applied to the structure have to be considered when designing a well and this project only looks at the productivity part of that design process. The wells simulated in this project were used to test the method of comparing productivity of two diameters.

Until a good void fraction correlation is created for vertical flow in geothermal wells other methods are possible to determine the effect of well diameter on the productivity of high temperature wells. It is for example possible to perform this study with a statistical approach. A statistical approach also depends on the quality and quantity of measurements. No matter what approach is applied a good database will always be needed and the creation of one would help modeling drastically.

Bibliography

Árnason, A. B. (2011). [Personal communication].

Björnsson, G., Arason, P., & Böðvarsson, G. S. (1993). The Wellbore Simulator HOLA. Version 3.1. User´s guide. In Orkustofnun. Reykjavík.

Björnsson, H., Friðriksson, Þ., Jónsson, P., Þorgilsson, G., Þórhallsson, S., & Tryggvason, H. (2008). *Upphleyping holu SV-22 og mælingar í blæstri í mars 2008*. Reykjavík.

Bogacki, P., & Shampine, L. F. (1989). A 3(2) pair of Runge - Kutta formulas. *Applied Mathematics Letters, 2*(4), 321-325.

Bóasson, H. Á. (2011). [Personal communication].

Company, Kuster. (2011). K10 Geothermal Retrieved April 10th, 2011, from www.kusterco.com

Gorine, A. V. (2002). *Two phase flow governing equations for transient geothermal well and pipeline simulation.* Paper presented at the 24th NZ geothermal workshop, New Zealand.

Gunnlaugsson, E., Guðlaugsson, J. B., & Árnason, A. B. (2011). Data from wells at Hellisheiði. In O. Reykjavíkur (Ed.). Reykjavík.

Gunnlaugsson, E., & Oddsdóttir, A. L. (2007). *Hellisheiði - Gufuborholur 2007*. Nýjar virkjanir. Orkuveita Reykjavíkur. Reykjavík.

Hewitt, G. F. (1978). *Measurement of Two Phase Flow Parameters*. Minnesota: Academic Press of the University of Minnesota.

Hirtza, P. N., Kunzmana, R. J., Broaddusb, M. L., & Barbittaa, J. A. (2001). Developments in tracer flow testing for geothermal production engineering. *Geothermics, 30*, 727-745.

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

IAPWS. (2008). Release on the IAPWS Formulation 2008 for the viscosity of Ordinary Water Substance (pp. 1-9). Berlin: International Association for the Properties of Water and Steam.

IGA. (2010). Geothermal in the World Retrieved May 1st, 2011, from http://www.geothermal-energy.org

Ingason, K. (2011). [Personal communication].

Ingason, K., & Matthíasson, M. (2006). *Kostnaður við borun og frágang háhitaborhola*. Paper presented at the Setning málþings Jarðhitafélags Íslands. Háhitaborholur - hönnun, borun, frágang og rekstur., Iceland.

Jónsson, P., & Eyjólfsdóttir, E. I. (2009). Upphleyping holu SV-23 og mælingar í blæstri í nóvember 2008. Reykjavík.

Jónsson, P., & Friðriksson, Þ. (2008). *Upphleyping holu RN-25 og mælingar í blæstri í apríl 2008*. Iceland Geosurvey. Reykjavík.

Karlsson, T. (1982). *Optimization of Geothermal Well Diameter*. Paper presented at the International Conference on Geothermal Energy, Florence, Italy.

Lindal, B. (1973). *Industrial and Other Applications of Geothermal Energy*. Paper presented at the UNESCO, Paris.

Mathworks. ode23, ode45, ode113, ode15s, ode23s, ode23t, ode23tb Retrieved 12/05/2011, 2011, from http://www.mathworks.com/help/techdoc/ref/ode23.html#f92-998740

OR. (2009). Reykjavík Energy 2009 Annual Report. In J. Guðmundsdóttir (Ed.), *Reykjavik Energy annual report*. Reykjavík: Reykjavik Energy.

OR. (2011). Verðskrá og skilmálar. Rafmagn. Retrieved May 5th, 2011, from http://www.or.is/Fyrirtaeki/Verdskraogskilmalar/Rafmagn/

Orkustofnun. (2011). Gagnavefsjá. from Orkustofnun http://gullhver.os.is/Website/gagnavefsja_net/viewer.htm

Pálsson, H. (2011). *Simulation of two phase flow in a geothermal well*. Lecture notes. University of Iceland.

Tulinius, H. (2011). [Personal communication].

Valladares, O. G., Upton, P. S., & Santoyo, E. (2005). Numerical modeling of flow processes inside geothermal wells: An approach for predicting production characteristics with uncertainities. *Energy Conversion and Management 47*, 1621-1643.

Vijayarangan, B. R., Jayanti, S., & Balakrishnan, A. R. (2007). Pressure drop studies on two-phase flow in a uniformly heated vertical tube at pressures up to the critical point. *International Journal of Heat and Mass Transfer, 50*, 1879-1891.

Wallis, G. B. (1969). *One-dimensional Two-phase Flow*. New York: McGraw-Hill.

Woldesemayat, M. A., & Ghajar, A. J. (2007). Comparison of void fraction correlations for different flow patterns in horizontal and upward inclined pipes. *International Journal of Multiphase flow, 33*, 347-370.

Zhao, X. (2005). *Mechanistic-based models for slug flow in vertical pipes.* Ph.d, Texas Tech University.

Þórólfsson, G. (2011). Data from wells at Svartsengi and Suðurnes. In HS-orka. Reykjanesbær.