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Exploring utilization scenarios for supercritical wells using 3D geothermal reservoir modelling

Alina Yapparova[1], Benoit Lamy-Chappuis[1], Sigrun Tomasdottir[2], Gunnar Gunnarsson[2], Thomas Driesner[1]

[1]Institute of Geochemistry and Petrology, ETH Zurich, Clausiusstrasse 25, 8092 Zurich, Switzerland

[2]Orkuveita Reykjavíkur / Reykjavik Energy , Bæjarháls 1, 110 Reykjavík, Iceland

alina.yapparova@erdw.ethz.ch

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ABSTRACT

The IDDP 1 and 2 wells detected supercritical resources beneath the conventional, high-enthalpy geothermal resources at Krafla and Reykjanes, Iceland. However, developing such resources has remained a major technical challenge and it is at present unclear what the optimal utilization strategy might be - direct production of superheated steam, injection in order to enlarge the resource by recharging from superheated zones below, or multi-well operation schemes.

Numerical reservoir simulation could help assessing this question but current industry standard software tools are not yet ready to perform such simulations. Including deep magmatic heat sources and resulting temperature-dependent permeability distributions have remained challenging, and therefore heat and fluid fluxes at bottom boundary are often used in reservoir models of high temperature geothermal fields.

We have augmented the Control Volume Finite Element Method (CVFEM) scheme of the CSMP++ software framework (Weis et. al., 2014) that has previously been used to perform 2D simulations of supercritical resources (Scott et al., 2015). The augmented version can simulate full 3D geothermal reservoir processes including explicit representation of underlying hot magma bodies, depth and temperature dependent host rock permeability and can extend to 5-10 km below the surface. This allows for more detailed and geologically constrained models.

Moreover, a simple semi-analytical Peaceman well model (Chen, 2007) has been implemented in the CVFEM scheme in order to be able to simulate different utilization scenarios. The need for a well model is necessitated by the fact that the reservoir pressure undergoes most rapid changes in the immediate vicinity of the well, and without such model only extreme mesh refinement near the well can capture those changes.

The 3D CVFEM scheme with an embedded well model has been applied to explore the possible utilization scenarios for deep geothermal wells tapping supercritical resources in Iceland. This paper presents a tentative summary of the pros and cons of different utilization scenarios based on reconnaissance simulations, and discusses the remaining uncertainties of the modelling approach, many of which relate to unknown material properties (permeability, existence of feed zones etc.) at superheated conditions.

1. INTRODUCTION

The Iceland Deep Drilling Project (IDDP) encountered supercritical conditions in both their wells IDDP-1 (450 °C / 150 bar) in the meteoric water dominated Krafla system as well as in IDDP-2 (estimated 500 - 550 °C and 270 to 300 bar) in the saline Reykjanes system. Flow tests at IDDP-1 implied that 35 MW_{el} may be produced from an IDDP-1 type well, which greatly exceeds the average Icelandic well (Axelsson et al., 2014; Ingason et al., 2014).

Scott et al. (2015) showed, by means of numerical simulation, that supercritical resources may be an integral part of many natural high-enthalpy geothermal systems and would underlie the conventional, high enthalpy resource if the magmatic heat source has not yet cooled. There are now several initiatives world-wide to assess if supercritical resources are present also in other geothermal areas and how these may be utilized economically.

So far, it has remained unclear how such supercritical resources could be best utilized. Supercritical wells are expensive and technically challenging, so a sustainable utilization approach will be economically crucial. While direct production of essentially dry, superheated steam may occur a natural approach it is an open question how long the flow can be maintained before cooling occurs, which would likely induce two-phase conditions upon de-pressurization, which may have corrosion implications. An injection scenario may provide enhanced hot recharge to the conventional high-enthalpy reservoir from below, thereby enlarging the resource and the lifetime of the operation.

Answering these questions requires an explicit representation of the magmatic heat source and its cooling due to the operation, a correct simulation of the natural state of the system prior to utilization simulations, advanced permeability models that respond to temperature-induced and other permeability changes, and the incorporation of well models that can handle the numerical challenges of flow under pressure-temperature conditions where the supercritical nature of the fluid leads to rapid changes in density, enthalpy, heat capacity etc. over short spatial distances and time intervals.

As most current industry standard tools are challenged by combining explicitly represented magmatic intrusions, advanced permeability models and supercritical fluids, we modified our CSMP++ software framework (Weis et. al., 2014) that has previously been used to perform 2D simulations of supercritical resources (Scott et al., 2015) to accommodate the needed functionality. The augmented version can simulate full 3D geothermal reservoir processes including explicit representation of underlying hot magma bodies, depth and temperature dependent host rock permeability and can extend to 5-10 km below the surface. This paper introduces the main numerical concepts and presents the results of two reconnaissance simulations, for direct production or injection. We discuss the tentative insights obtained from these first-of-their-kind simulations. Future work will include more geologic complexity and a systematic study of the interplay between well operation and supercritical hydrology in utilizing supercritical resources in Icelandic type and other geothermal systems.

2. METHODS

2.1 Governing equations and numerical solution

The Control Volume Finite Element Method (CVFEM) scheme implemented within the CSMP++ software framework has been described in detail in (Weis et al., 2014). The CVFEM allows modelling of two-phase (liquid and vapour) flow in porous media including boiling/condensation in a wide range of temperature (0 to 1000 °C) and pressure (0 to 5000 bar) conditions thanks to the pressure-enthalpy formulation and the IAPS-84 (Haar et al., 1984) water equation of state. The scheme is mass conservative which is essential for modelling of supercritical geothermal resources, as near the critical point of water the fluid density changes rapidly. This paper presents some of the first CVFEM simulation results in 3D.

The most straightforward way of introducing a well into a reservoir model is through the mass sinks/sources Q_f in the pressure equation, which is derived from the mass conservation equation:

$$\rho_f \beta_f \frac{\partial p}{\partial t} = -\nabla \cdot (\vec{v_l}\rho_l) - \nabla \cdot (\vec{v_v}\rho_v) + Q_f - \phi \frac{\partial \rho_f}{\partial t} \quad |_p \tag{1}$$

where ρ_f is the fluid density and ρ_l, ρ_v are liquid and vapour densities, respectively, β_t is the total system compressibility, p is the fluid pressure. The last term in eq.1 takes into account the fluid density change at constant pressure due to change in temperature.

The phase velocities are described by extended Darcy's law:

$$\vec{v_i} = \frac{-kk_{ri}}{\mu_i}(\nabla p - \rho_i \vec{g}), i = l, v \tag{2}$$

where k is the rock permeability and k_{ri} is the relative permeability of the phase i (either liquid or vapour), μ_i is the phase dynamic viscosity, ∇p the pressure gradient and $\vec{g}$ the gravitational acceleration vector.

However, if linear finite elements are used for pressure discretisation, the numerical solution will be not accurate, because according to Muskat's analytical solution for single phase fluid flow near a well fluid pressure drops exponentially in the vicinity of the well (Chen, 2006; Rasmussen et al., 2019):

$$p(r) = p_w - \frac{Q_l \mu_l}{2\pi h \rho_l k} ln\left(\frac{r}{r_w}\right) \tag{3}$$

where p_w is the fluid pressure in the well, r_w is the well radius, r is the radial distance from the well, $p(r)$ is the reservoir pressure at distance r, h is the reservoir thickness and Q_l is the well liquid mass rate.

This is a well-known problem in oil and gas reservoir simulation and already in 1978 Peaceman has developed a semi-analytical formula on the basis of eq.3 for numerical modelling of wells within the control volume method. Peaceman's formula is still widely used both in commercial and research codes (Rasmussen et al., 2019). Chen (2006, 2007) has extended ideas of Peaceman (1978) to the Finite Element and Control Volume Finite Element methods.

In the CVFEM scheme within CSMP++ fluid pressure variables are stored on the nodes, therefore a new node variable has been introduced to store the well pressure, this variable being nonzero only in the nodes that comprise the well. The relationship between the well and reservoir pressure is given by:

$$Q_f = \frac{2\pi hk(p_w - p)}{ln(r_{eff}/r_w)} \left(\frac{k_{rl}\rho_{rl}}{\mu_l} + \frac{k_{rv}\rho_{rv}}{\mu_v}\right) \tag{4}$$

where r_{eff} is the effective radius obtained from the modified Peaceman's formula for CVFEM (Chen 2006, 2007). Eq.4 is used to describe the well mass rate as a function of well and reservoir pressures in eq.1, thus allowing to model wells under constant bottom hole pressure and constant rate controls within the CVFEM scheme.

2.2 Model setup

Our 3D model is 5 km deep and 10 km square in horizontal dimensions. Uniform initial host rock permeability is set to 10^{-15} m^2. All boundaries are open to flow, the top boundary is at atmospheric pressure and ambient temperature of 10 °C. Prior to magma emplacement there is a hydrostatic pressure distribution and temperature distribution governed by the bottom heat flux resulting in a geothermal gradient of 37.5 °C/km.

An elliptical magma body of 3 km horizontal and 1 km vertical radii, with its top at 2 km is instantly emplaced into the host rock. Initial emplacement temperature is 900 °C.

In our simulations we use temperature dependent permeability and temperature dependent rock heat capacity from Hayba and Ingebritsen (1997) adapted to basaltic host rocks as introduced by Scott et al. (2015). Fig. 1 shows the temperature dependence of the decimal logarithm of permeability for a basaltic rock with an onset of the brittle-ductile transition at 550 °C and the rock considered ductile above 700 °C. Temperature dependent heat rock capacity accounts for the latent heat of crystallization, it is 880 J/(kg·°C) below 650 °C, doubled above 700 °C and linearly increasing in between.

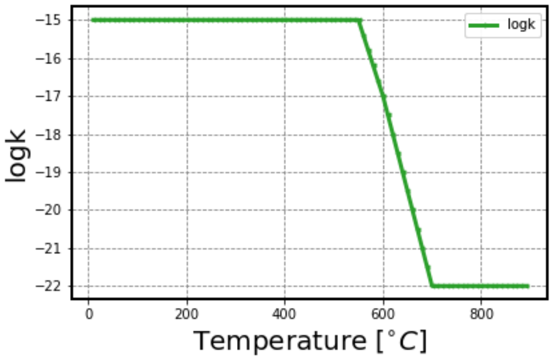

Fig. 1 Logarithm of permeability as a function of temperature for basaltic rocks from Hayba and Ingebritsen (1997)

The unstructured tetrahedral mesh used in our simulations consists of 16897 nodes and 91888 elements, the resolution within the initial magma chamber is 200 m and is 300 m in the host rock. The 100 m long open well section is located along the vertical line through the middle of the model between 2.1 and 2.2 km depth and consists of 5 nodes 25 m apart. The mesh is refined in the vicinity of the well.

3. RESULTS

3.1 Geothermal system evolution prior to development

An instantaneously emplaced hot magma body is progressively cooled and crystallized heating up the surrounding host rock. Already in the early simulation stages convection cells develop above the intrusion with a prominent downflow of cold water from the surface in the model center surrounded by a pipe-like upflow region. This pipe-like structure becomes narrower as the simulation progresses and eventually merges into a single upflow zone that reaches the surface after ca. 2000 years.

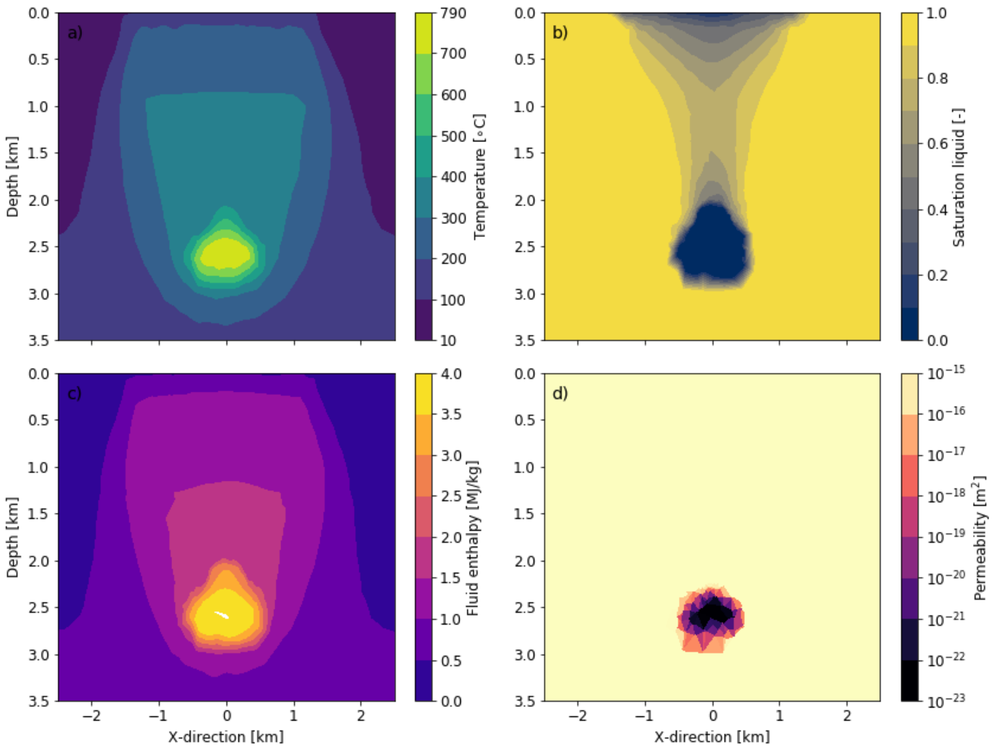

Fig. 2 Temperature (a), liquid saturation (b), fluid enthalpy (c) and rock permeability (d) after 2700 years of magma cooling

After 2500 years, the boiling extends from the surface to 2 km depth and between 2.1 and 2.2 km depth a single phase, potentially supercritical resource of ~600 m diameter develops. This hot zone is sustained between 2500 and 3000 years, and at 3200 years the magma body has completely crystallized and boiling is confined to the upper 1 km below the surface.

Fig.2 provides an overview of the geothermal reservoir state with a potential supercritical resource prior to development. Temperature, fluid enthalpy, liquid saturation and rock permeability are displayed on a vertical slice through the model center, cropped for better visualization. A single phase area with temperatures above 400 °C and fluid enthalpy above 2.8 MJ/kg is located between 2.1 and 2.2 km depth, where the initial magma chamber used to be before it crystallized and became permeable, and the boundary to the low-permeability ductile region retreated to the depth ~2.3 km. We chose to target this supercritical zone by installing a vertical well completion, which is further referred to by simply 'well'.

3.2 Injection well simulations

In the first simulation scenario cold water at 80 °C is injected in the center of the single phase region between 2.1 and 2.2 km at a constant rate of 3.2 kg/s for 100 years. Injection starts after 2700 years of geothermal system evolution (pictured in Fig. 2, initial reservoir temperature near the well is between 420 and 490 °C) and results in the well pressure around 300 bar compared to the initial reservoir pressure around 190 bar. Fig. 3 shows the temperature (a) and liquid saturation (b) in the vicinity of the well prior to injection in a vertical slice through the model center, the temperature (c) and liquid saturation (d) in a vertical slice and (e,f) in a horizontal slice through the middle of the open well section (2150 m depth) after 100 years of cold water injection. The injection results in the cooling of the area around the well, with the radius of the cooled zone reaching ~200 m after 100 years and the fluid within this zone being single phase liquid, the single phase supercritical zone has reduced to a pipe-like structure surrounding the cold water zone.

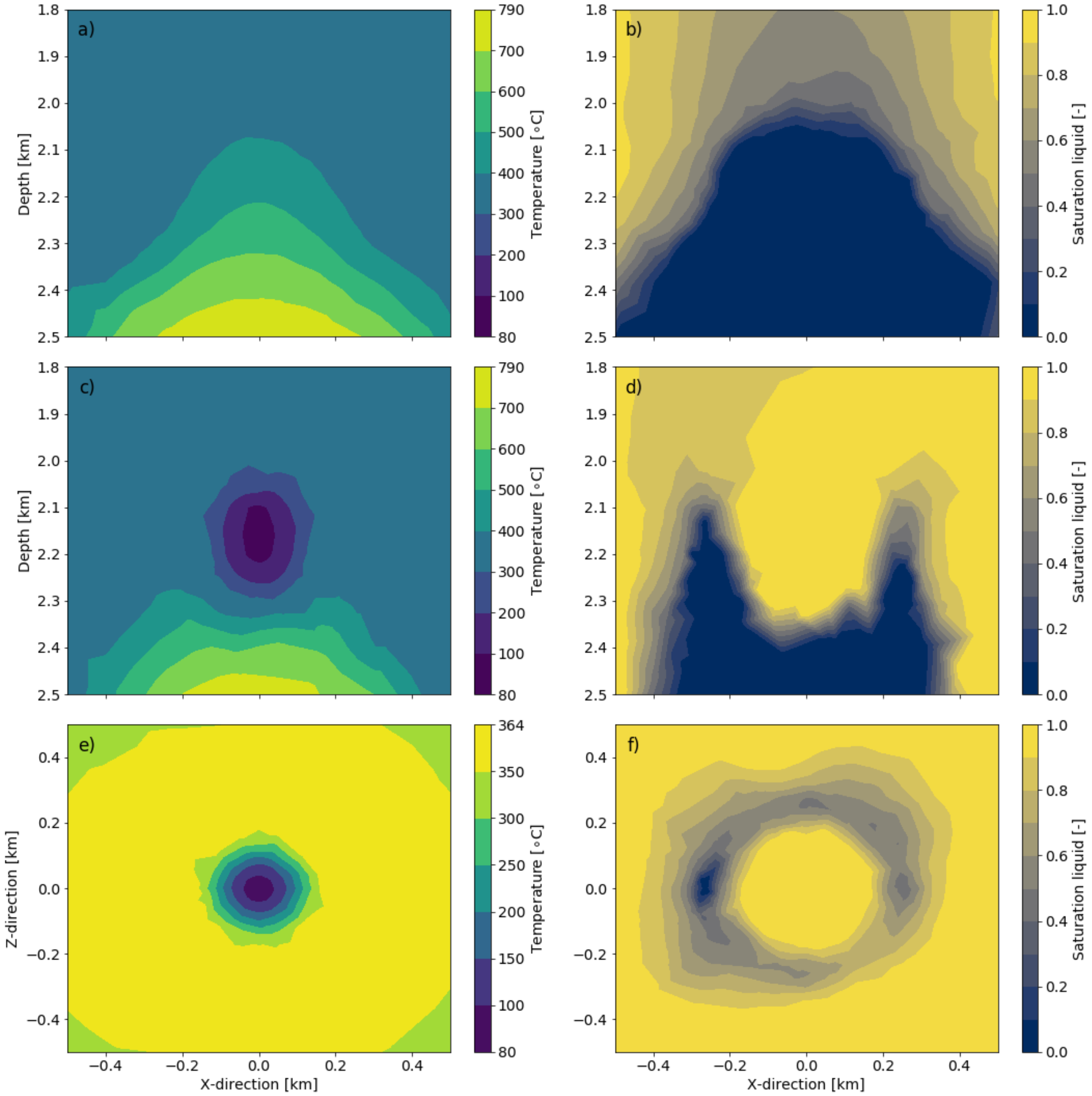

Fig. 3 Temperature (a) and liquid saturation (b) prior to injection, and after 100 years of cold water injection with rate=3.2 kg/s in the vertical slice along the well (c,d) and the horizontal slice (e,f) through the well middle

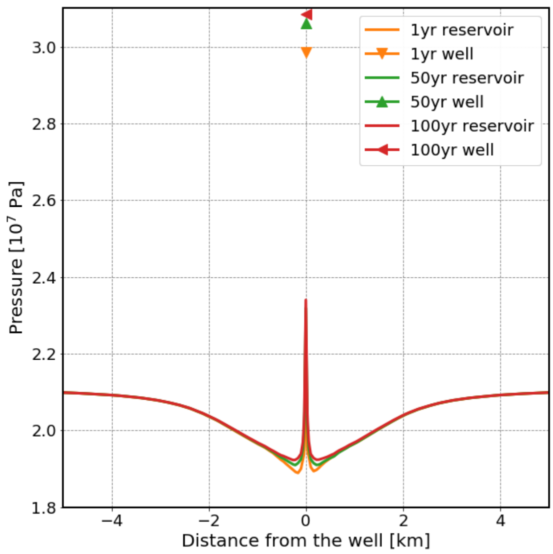

Fig. 4 Reservoir and well pressure along the horizontal line cutting through the middle of the open well section (2150 m depth) after 1, 50 and 100 years of cold water injection with rate=3.2 kg/s

Fig.4 illustrates the drastic pressure increase in the immediate vicinity of the well which cannot be captured without a semi-analytical well model. Continuous cold water injection results in the pressure build-up due to both mass input without outflow possibility through the production wells or model boundaries, and cooling and consequent increase of hydrostatic pressure gradient.

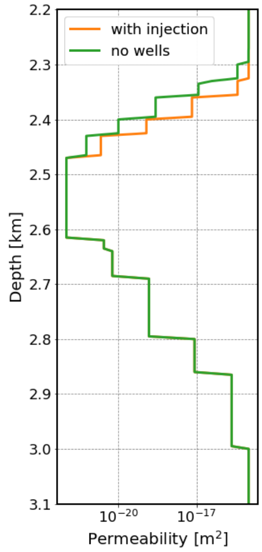

Fig. 5 Permeability along the vertical line through the model center after 100 years of cold water injection with rate=3.2 kg/s compared to natural geothermal system evolution

Cold water injection facilitates system cooling affecting the magma crystallization speed. The brittle-ductile transition layer is ~30m deeper after 100 years of cold water injection than it would have been if the system evolved naturally (Fig. 5).

3.3 Production well simulations

The second simulation scenario involves a single production well operated under constant bottom hole pressure for 100 years, the production starts after 2900 years of magma chamber cooling (200 years later than the injection well simulation), when the initial reservoir temperature near the well cools down to 396-446 °C. Fig. 6 shows the temperature and liquid saturation before and after 100 years of fluid production with a constant bottom hole pressure of 100 bar in the well. The simulation results show an overall decrease in temperature due to fluid production. An extended region of liquid saturation ~0.92 forms in the upflow boiling zone above the magma chamber between 1.5 and 2 km and single phase supercritical fluid region shrinks in size in all directions.

In the following Figures 7 and 8 we compare the results from two single production well simulations: one with the bottom hole pressure (bhp) fixed at 100 bar and the other one with a lower bhp of 60 bar. The lower bhp results in almost double production rate, which results in a faster decline of bottom hole temperature (Fig. 7a). As the temperature at the bottom of the well drops below the critical temperature of 374 °C, the produced fluid's state changes from single phase supercritical to two phase (Fig. 7b). This results in an instant drop of fluid enthalpy around 79 years from the start of fluid production for bhp=60 bar and around 98 years for bhp=100 bar (Fig. 7c).

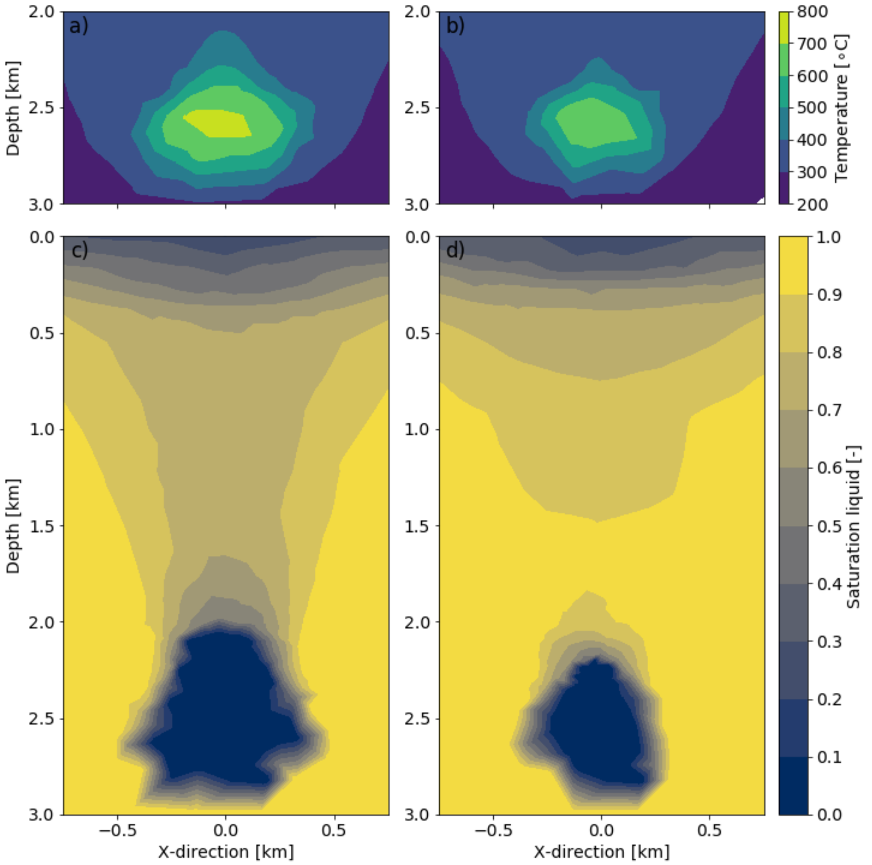

Fig. 6 Temperature (a) and liquid saturation (c) prior to production and (b,d) after 100 years of fluid production with a bottom hole pressure of 100 bar in a vertical slice through the model center

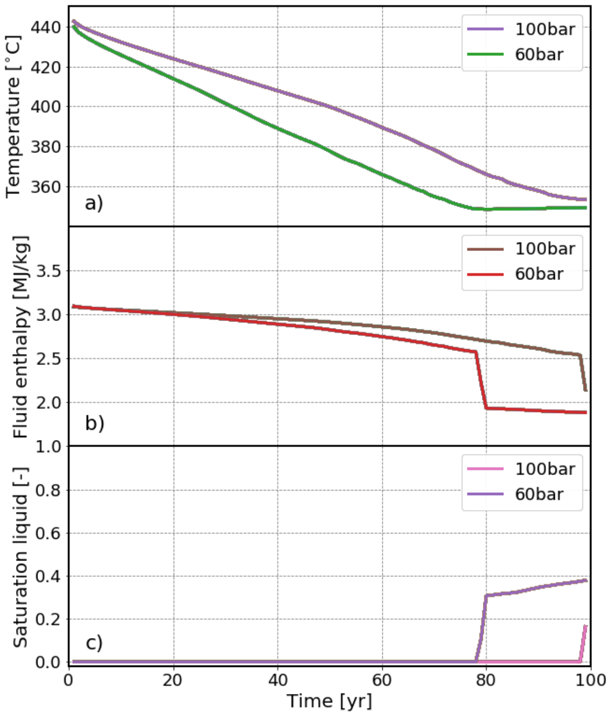

Fig. 7 Time evolution of bottom hole temperature (a), fluid enthalpy (b) and liquid saturation (c) for two single production well simulations with bhp set to 60 and 100 bar

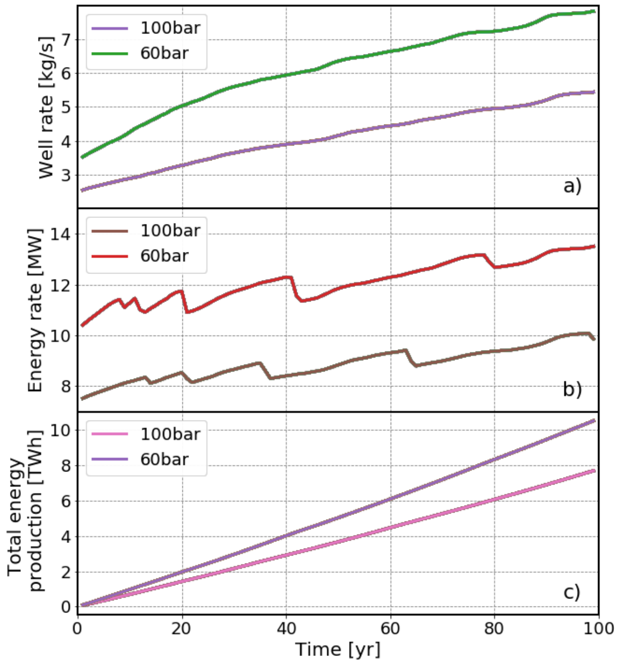

Fig. 8 Time evolution of well rate (a), energy rate (b) and total energy production (c) for two single production well simulations with bhp set to 60 and 100 bar

Figure 8 presents the well mass (a) and energy (b) rates and the total energy production (c). The well rate is calculated by summing up the individual rates at each well node (the well consists of 5 nodes spaced by 25m), and the energy rate is calculated by first multiplying the rates and the fluid enthalpies in each well node and then calculating the sum. The total energy production is a cumulative sum of energy rate in time.

Well mass rate is continuously increasing, as the density of produced fluid is increasing with decreasing temperature. The kinks in energy rate are due to the well discretisation and correspond to the points in time when the conditions in the next well node change from single phase supercritical to two phase due to decrease in temperature (as pressure is constant in the well nodes). The steady increase following each drop in the energy rate is due to increasing well rate. For an ideal geothermal well without a finite discretisation the energy rate would look monotonously increasing.

The total energy production from a single well is 20 to 30% higher for the well with a bottom hole pressure of 60 bar compared to a well with 100 bar bhp and is growing steadily for 100 years.

4. DISCUSSION

Our single injection well simulations do not immediately show any expansion of the superheated fluid zone due to potential mixing of injected cold fluid with the hot initial fluid, but rather just the progressive cooling of the hot zone and the reduction of the single phase region size. This topic requires further investigation, as system behaviour during cold water injection could be sensitive to injected fluid temperature and the well rate, and there could exist an injected temperature/initial supercritical zone temperature ratio at which the resource doesn't cool that quickly and the high-temperature zone is expanding. Another important factor is the pressure gradient near the injection well. One could imagine that in the presence of production wells surrounding the injection well, the flow patterns would be different.

Our single production well simulations give hope that if a well could be drilled to tap the supercritical geothermal resource a continuous production of superheated fluids could be sustained for decades. The rate of decline in produced fluid temperature and enthalpy is largely governed by the pressure control of the well: the lower the bottom hole pressure, the faster the single phase resource will be exhausted, but even the two phase fluid produced immediately afterwards would have a very high energy content.

In the first simulation results presented in this paper we have modelled a well with a completion of only 100 m length. Our modelling assumption can be interpreted differently, one could look at it as a thickness of a productive interval. In real geothermal wells open slotted liner completions could extend to 1-1.5 km and there could be several productive intervals with variable thickness, therefore the total mass rates of such wells could be much higher than the well rates considered in this paper, which would in turn result in much higher energy output of a single well. In future work, more realistic well geometries will be considered together with more geologically constrained reservoir models mimicking real geothermal fields.

5. CONCLUSION

This paper presented first utilization scenarios' simulations for geothermal wells tapping the potential supercritical resources. A semi-analytical Peaceman well model coupled to the CVFEM scheme allowed us to model injection of cold water into a region with initial temperatures exceeding 400 °C and supercritical fluid production from that area. Our production well simulations make in seem likely that the superheated fluid production could be carried out for decades, which would make a big difference for geothermal energy production if such wells could be explored routinely.

The results presented in this paper show the capabilities of the augmented CVFEM scheme with a well model and give a glimpse on the future modelling possibilities: different combinations of injection and production wells operated under fixed rate or constant bottom hole pressure could be integrated in a large scale 3D geothermal reservoir model comprising the magmatic heat sources and the evolution of such systems could be monitored for an extended period of time.

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