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4.4 – Report on optimisation of design of HX

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Version:	2	
Abstract	The current report describes the development of 1D simulation models for the components of this system, as well as calculations for the overall scaling reduction system.	

REVISION HISTORY

Version	**Date**	**Main Authors/Contributors**	**Description of changes**
V1	31.07.2023	FPS	First version
V2	14.08.2023	FPS	Changes and additions to text.

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[1] Dissemination level security:
PU – Public (e.g. on website, for publication etc.) / **PP** – Restricted to other programme participants (incl. Commission services) /
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CONTENTS

SUMMARY

A new software specialized for flow assurance simulations of geothermal installations is under development by partner FPS. The software combines fluid dynamics, thermodynamics, geochemistry (equilibrium and reaction kinetics), heat transfer, structural dynamics, and aims to enable simulation of most situations that arise in design and operation of geothermal installations: power plants, wells, transport pipes, and drilling. The main features of the software are described in GeoSmart deliverable report D5.1 [1].

A novel scaling reduction system consisting of a heat exchanger, scaling reactor, and a retention tank, is under development in GeoSmart WP4. The current report describes the development of 1D simulation models for the components of this system, as well as calculations for the overall scaling reduction system.

OBJECTIVES MET

The work described in this report contributes to the following objectives of Work Package 4:

- Technology transfer developments for designing and optimising the scaling reduction system for the Zorlu Kizildere 2, based on the Icelandic experiences.

The report meets the following objectives in particular:

- Development of physics-based simulation models for the components of the scaling reduction system: Heat Exchanger, Scaling Reactor, and Retention Tank (HX-SR-RT)
- Perform simulations of the HX-SR-RT system coupled with geochemical reaction kinetics

1 INTRODUCTION

Scaling occurs in geothermal wells and power plants, usually because of pressure or temperature drops. Typically, the pressure decreases cause CO_2 to degas, increasing the pH, and resulting in supersaturation of dissolved minerals or salts, leading to precipitation (formation of a solid phase). Similarly, a temperature drop can also cause supersaturation and precipitation. Part of the solids will stick to the surface of the pipes and equipment, i.e. cause scaling. The most common geothermal scales are silica (SiO_2) and calcite ($CaCO_3$). Scaling is a large problem for many geothermal power plants as it can block the pipes and equipment. Production wells and heat exchangers are typical problem areas, but perhaps the largest impact is the need to maintain the pH and temperature at the injection well such as to avoid scaling to happen there. Especially, it makes it necessary to keep the reinjection temperature relatively high, often above 100 °C, thereby significantly reducing the potential energy outtake from the brine. In the GeoSmart project, a system that combines a heat exchanger, a scaling reactor, and a retention tank is under development, wherein the operation will be such that a large part of the solid precipitation happens in the retention tank, where it is easy to remove. With this system, it will be possible to reinject the brine at lower temperature without risking scaling in the injection well, thereby enabling significantly larger energy production.

2 GEOTHERMAL FLOW ASSURANCE SIMULATOR

2.1 Fundamentals

A steady-state as well as dynamic (time-dependent) two-phase pipe network geothermal flow assurance simulator software has been developed by FPS. It is based on conservation equations for mass, momentum, energy, and mass flux of each species. The numerical discretization is based on a finite element approach in space and an implicit time discretization with non-linear Newton-Raphson equilibrium iterations within each timestep. The fluid flow, heat transfer, and silica concentration are solved in a sequential, staggered way. The fluid properties are calculated at the start of each timestep and kept constant during the different physics steps and the N-R iterations. The overall solution strategy and algorithm is shown in the flow chart in Figure 1.1.

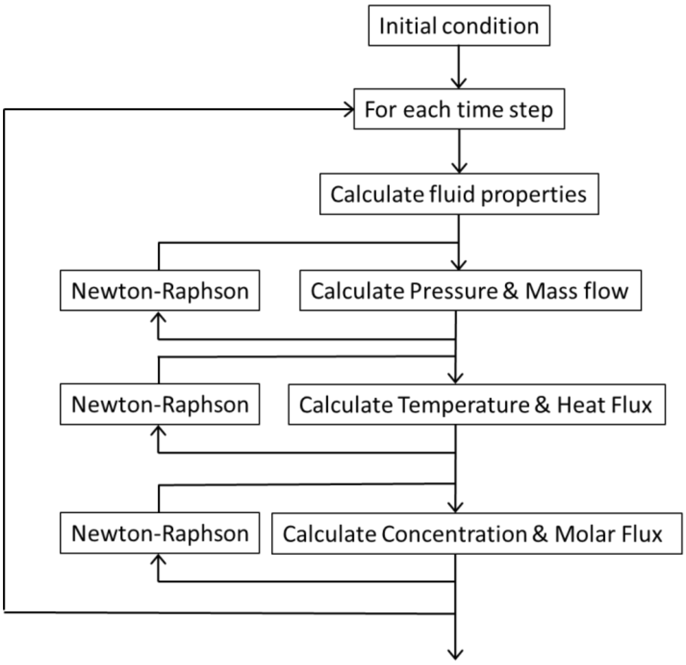

Figure 1.1: Flow chart of overall solution methodology

The software has many features, for example single- and two phase flows, geochemical calculations through coupling to PhreeqcRM, models for non-Newtonian fluids, corrosion, erosion, scaling, annulus flows, structural dynamics, coupling to native 3D FEM solver for heat transfer in the rock formation, device models such as pumps, fans, valves, thermal energy storages, and more, see GeoSmart D5.1 report for details [1].

2.2 Extension to the Reaction-Advection-Diffusion problem

In the GeoSmart project, a scaling reduction system that combines a heat exchanger, a scaling reactor, and a retention tank is under development, wherein the operation will be such that a large part of the solid precipitation happens in the scaling reactor and retention tank, where it is easy to remove. This leads to significantly lower silica concentration in the brine, which enables reinjection at lower temperatures and/or reduced inhibitor usage without risking scaling in the injection well. In order to analyze the solids formation in the brine, it is necessary to take into account the reaction kinetics. This was developed in GeoSmart D5.1 through extension of the FEM flow assurance solver to also include the species concentration transport equations and a model for silica polymerization reaction kinetics. The resulting governing equations are:

$$\begin{cases} \dfrac{A}{a^2}\dfrac{\partial p}{\partial t} + \dfrac{\partial \dot{m}}{\partial x} = 0 \\ \dfrac{\partial \dot{m}}{\partial t} + \dfrac{\partial U\dot{m}}{\partial x} + A\dfrac{\partial p}{\partial x} + \rho g A \dfrac{\partial z}{\partial x} + \dfrac{f\dot{m}|\dot{m}|}{2\rho D A} = 0 \\ \dfrac{\partial}{\partial t}(\rho C T A) + \dfrac{\partial}{\partial x}(C T \dot{m}) = \dfrac{\partial}{\partial x}\left(\lambda A \dfrac{\partial T}{\partial x}\right) + \phi \\ \dfrac{\partial}{\partial t}\left(c_{SiO_{2(aq)}}\right) + \dfrac{\partial}{\partial x}\left(U c_{SiO_{2(aq)}}\right) = \dfrac{\partial}{\partial x}\left(K_L \dfrac{\partial c_{SiO_{2(aq)}}}{\partial x}\right) - k\left(c_{SiO_{2(aq)}} - c_{SiO_{2(aq),eq}}\right)^4 \end{cases} \tag{2.1}$$

where A is the cross-sectional area, a is the speed-of-sound, p is the pressure, $\dot{m}$ is the mass flow rate, U is the mean velocity, ρ is the density, g is the gravity constant, D is the pipe diameter, C is the heat capacity, T is the temperature, λ is the heat conductivity, p is a heat source/sink, $c_{SiO_{2(aq)}}$ is the silica concentration, K_L is the longitudinal dispersion coefficient, and k is the reaction rate constant.

3 SCALING REDUCTION SYSTEM

For single-phase flows, the Darcy-Weisbach flow friction factor in circular pipes is calculated as follows:

$$f = f_L = \frac{64}{Re} \qquad Re < 2000\ (laminar\ flow) \tag{3.1}$$

$$f = f_t = \left\{-1.8 log_{10}\left[\frac{6.9}{Re} + \left(\frac{\varepsilon}{3.7D}\right)^{1.11}\right]\right\}^{-2}, \qquad Re > 4000\ (fully\ turbulent\ flow) \tag{3.2}$$

$$f = y f_t + (1-y) f_L\,,\ \ y = \frac{Re}{2000} - 1\ ,\ \ 2000 < Re < 4000\ (transitional\ flow) \tag{3.3}$$

where ε is the pipe wall roughness, D is the pipe diameter, and ε /D is the relative roughness. Note that the Darcy-Weisbach definition of the friction factor is used, wherein the pressure drop is calculated as

$$\Delta p = f\rho \frac{Lv^2}{2D} \tag{3.4}$$

where L is the pipe length and v is the flow speed.

3.1 Heat Exchanger Model

Pressure loss model:

The pressure drop in the heat exchanger is modelled in a similar way as for pipes, but with the friction factor based on the Kumar correlation. The hydraulic diameter is based on the width W of the plates, measured from center-to-center of the ports,

$$D_h = \frac{4WB_{plate}}{2(W + B_{plate})} \tag{3.5}$$

where B_{plate} is the distance between the plates. The Reynolds number based on D_h is

$$Re_h = \frac{\rho v D_h}{\mu} \tag{3.6}$$

The friction factor varies with Reynolds number according to

$$f_1 = 19.4{Re_h}^{-0.589} \qquad 10 < Re_h < 100 \tag{3.7}$$

$$f_2 = 2.990{Re_h}^{-0.183} \qquad Re_h > 400 \tag{3.8}$$

$$f = yf_1 + (1 - y)f_2\,,\ \ y = \frac{4}{3} - \frac{Re_h}{300}\,,\ \ 100 < Re_h < 400 \tag{3.9}$$

From which the pressure drop is calculated as

$$\Delta p = f\rho \frac{Lv^2}{2D_h} \tag{3.10}$$

where L is the plate length. It is possible to also add models for the inlet/outlet manifolds, however, the above model was found to agree very well (<1% error for the hot side) with the pressure drop specified by the manufacturer of the plate heat exchanger used in the GeoSmart project.

Thermal model:

The heat exchanger in the scaling reduction system extracts heat that can be used for additional power production or district heating. From the perspective of the scaling reduction system, the function of the heat exchanger is to extract heat, which is modelled as a heat sink.

3.2 Scaling Reactor Model

Pressure loss model:

The scaling reactor has a complicated structure that can be considered as a long meandering rectangular channel with baffles. The hydraulic diameter for a rectangular channel with width W and height H is

$$D_h = \frac{4WH}{2(W+H)} \tag{3.11}$$

The same Haaland approximation for the turbulent friction factor as for circular pipes, with the Reynolds number based on the hydraulic diameter, has been used. The Reynolds number at transition to turbulence varies with channel aspect ratio, but transition is typically initiated at Re=2300-2700 based on half-channel height, or Re_h=4600-5400 for a square channel. The baffles will cause earlier transition to turbulence; this will be dependent on baffle and channel geometry. For the GeoSmart geometry, the transition to turbulence is estimated to start at around $Re_h = 2500$. The baffles will significantly increase the pressure drop; this will be dependent on baffle size. For circular pipes, baffles increased pressure drop with a factor of about 3.7 at Re=100 (laminar) and about 172 at Re=10000 (turbulent). For the GeoSmart scaling reactor, the total length of the meandering channel is about 5.8 times longer than the scaling reactor length. The pressure drop model for the scaling reactor becomes as follows:

$$f = f_L = 3.7 * 5.8 * \frac{64}{Re_h} \qquad Re_h < 2500\ (laminar\ flow) \tag{3.12}$$

$$f = f_t = 172 * 5.8 * \left\{-1.8log_{10}\left[\frac{6.9}{Re_h} + \left(\frac{\varepsilon}{3.7D_h}\right)^{1.11}\right]\right\}^{-2}, Re_h > 4000\ (fully\ turbulent\ flow) \tag{3.13}$$

$$f = yf_t + (1-y)f_L\,,\ y = \frac{4000}{1500} - \frac{Re_h}{1500}\,,\ 2500 < Re_h < 4000\ (transitional\ flow) \tag{3.14}$$

where ε is the pipe wall roughness.

The pressure losses caused by the pipe fittings at the entrance and at the exit of the scaling reactor are modelled as sudden expansion and contraction with sharp corners, resulting in pressure losses

$$\Delta \mathrm{p} = K_L \frac{\rho v^2}{2} \tag{3.15}$$

where the loss factors are K_L=1.0 for the expansion and K_L=0.5 for the contraction.

Thermal model:

A layer of insulation material (e.g. Rockwool) is put on the outside of the scaling reactor. To model the heat losses to ambient, an equivalent thermal diameter pipe is used, for which the circumference is the same as for the scaling reactor. The heat losses corresponding to the heat transfer through the scaling reactor wall and scaling reactor insulation layer to the ambient air is then calculated as [2]

$$q_r = \frac{T_{Fluid} - T_{Ambient}}{\frac{1}{2\pi r_1 L h_1} + \frac{ln\frac{r_2}{r_1}}{2k_A \pi L} + \frac{ln\frac{r_3}{r_2}}{2k_B \pi L} + \frac{1}{2\pi r_3 L h_3}} \tag{3.16}$$

where qr is loss per meter scaling reactor [W/m], kA is the conductivity of the scaling reactor wall, kB the conductivity of the insulation layer, h1 is the heat transfer coefficient between the fluid and the inner scaling reactor wall, and h3 is the heat transfer coefficient between the outside of the insulation layer and the ambient air. The heat transfer coefficient h3 can be approximated as [3]

$$h_3 = 8 + 0.04(T_{Ambient} - T_3) \tag{3.17}$$

where T3 is the temperature on the outside of the insulation layer. The heat transfer coefficient at the inner wall, h1, is calculated through a modified Gnielinski [4] correlation.

3.3 Retention Tank Model

Pressure loss model:

For the retention tank, the pressure losses caused by the pipe fittings at the entrance and at the exit of the tank are modelled in the same way as for the retention tank, i.e. as sudden expansion and contraction with sharp corners, using loss factors K_L=1.0 for the expansion and K_L=0.5 for the contraction.

Thermal model:

The retention tank has an insulation layer, which is modelled in the same way as for the scaling reactor.

4 SIMULATION OF SCALING REDUCTION SYSTEM

Using the Flowphys Flow Assurance software, a 1D FEM model of the scaling reduction system, i.e the HX, SR, and the RT, with connecting pipes in between, was created, see Figure 4.1, with corresponding finite element mesh shown in Figure 4.2.

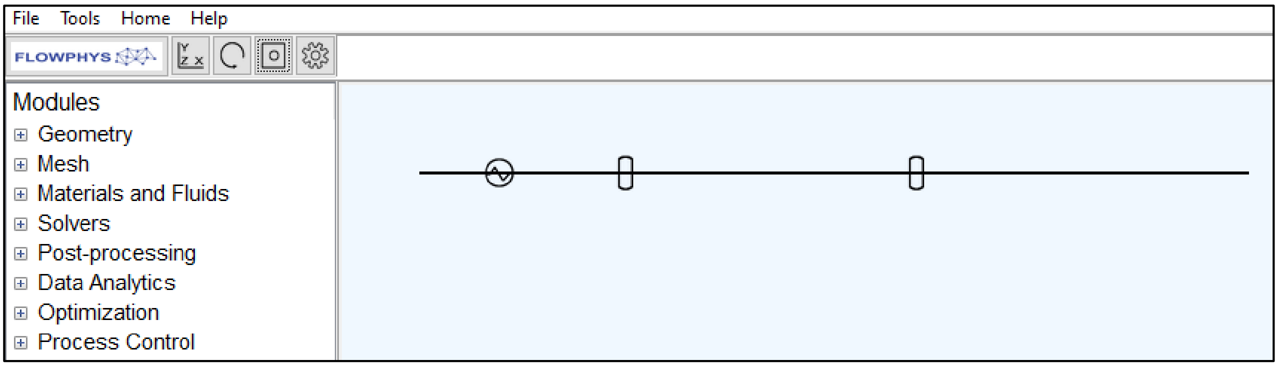

Figure 4.1: Model of the HX-SR-RT system

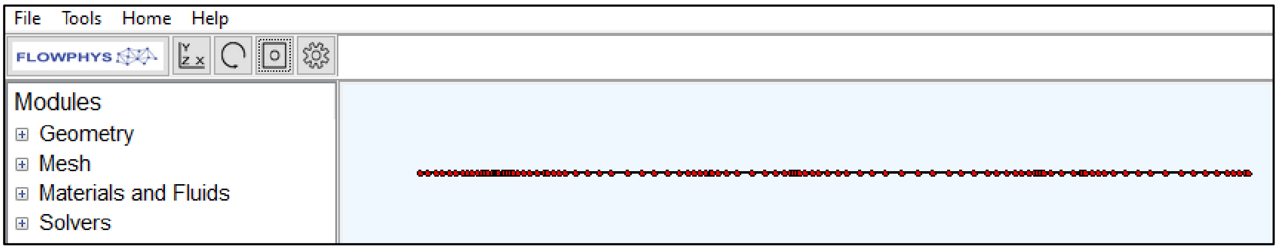

Figure 4.2: FEM mesh of the HX-SR-RT system

The flow assurance simulations capture concentration distribution and changes both in time and location in the system. A time-history plot of the concentration right after the retention tank is shown in Figure 4.3. For this case, the temperature was made constant at 40°C throughout the system by disabling the heat convection to ambient, the pH was set to about 7.4, the initial SiO2 concentration was set to 480 ppm, and the flow velocity was set very low. With these settings, it was possible to compare with the test results (Exp. #1, GeoSmart D4.1 report [5]), and it was found that the implemented and updated model is in good agreement with the experimental results.

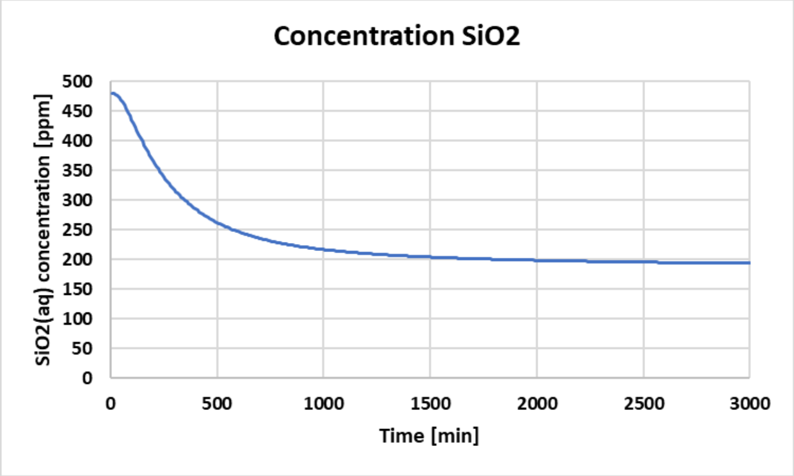

Figure 4.3: Time-history of the silica concentration in the HX-SR-RT system calculated with the flow assurance simulator using an updated version of the UoI silica polymerization model

Further simulations were done with values more representative for a functional system. The spatial distribution of the concentration throughout the whole system and the corresponding Temperature and pH levels are shown in Figure 4.4. Here, the inlet flow rate was 0.05 m^3/h and 5 m^3/h at temperature 80°C. Notice the temperature drop over the heat exchanger, as well as the pH increase at this location. Regarding the SiO2 polymerisation concentrations, the convection of the moving fluid creates a "concentration front", which will be sharper the higher the velocity is. This was seen also for the Flow assurance simulations as well as analytical solutions presented in the D5.1 report. The models will be further tuned when the pilot test data becomes available.

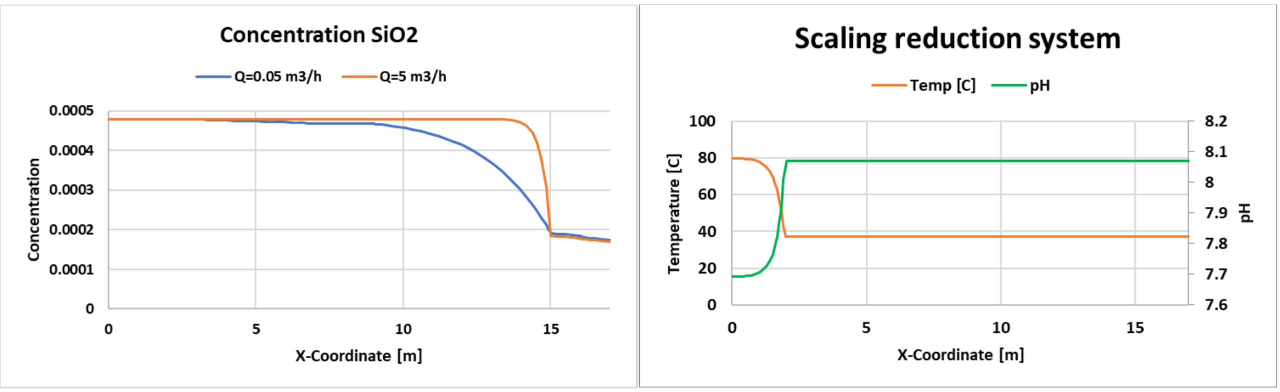

Figure 4.4: a) Instantaneous concentration distribution in the system. Notice that higher flow speeds creates sharper concentration "fronts"; b) Temperature and pH distribution in the system.

5 CONCLUSIONS

The Flowphys1D flow assurance finite element software has been extended with models for components of the scaling reduction system, i.e. a plate heat exchanger, scaling reactor, and retention tank. Transient calculations were carried out, from which it was found that the silica concentration dropped to less than half in 15 hours. The concentration profile indicates that most of the precipitation takes place in the retention tank. However, it should be noted that there are significant uncertainties regarding scaling rate in the system related to the increase of polymerization rate due to the baffles in the scaling reactor, the correlation between polymerization rate in the bulk fluid and the amount of scaling that will attach to baffles and other surfaces, and time needed for the silica particles to, after polymerization, fall to the bottom of the scaling reactor and retention tank. Therefore, the numerical models will be tuned by using the test results from the HX-SR-RT system when they become available later in the project.

6 REFERENCES

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