

Sensitivity Analysis of the Grid Refinement and Case Study of Reykjanes High Temperature Geothermal Field

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ABSTRACT

Determination of appropriate grid size for geothermal modelling have been frequently discussed in recent years. Results of TOUGH2 simulations are affected by the quality of the grid geometry. The most common approach is lowering the volume of blocks in area of interest. Therefore, number of blocks that are placed in the area of interest will increase, and the accuracy of TOUGH2 will be increased. In this paper, PyTOUGH (Croucher, 2011) scripting library and AUTOUGH2_5 (University of Auckland version) are used to investigate the behavior of Reykjanes high temperature reservoir in different grid size approaches. In order to investigate the sensitivity of the generated grids when comparing measured downhole temperature distribution and the natural state, five different complex grid systems were created, derived from a simple geometry. Although all other parameters except grid sizes were kept constant, slightly different results were found in the natural state temperature and production history pressure distributions.

To summarize, the paper examines the current approaches to horizontal & vertical grid refinement of TOUGH2 models, considering the advantages and disadvantages of each, with reference to the performance of five different grid models for Reykjanes Geothermal Reservoir. Overall results showed that, all the grid systems have quite similar temperature distribution with minor differences except for shallow depth range. Especially, the geometry with the thinnest layers in shallow depths have the lowest temperature range.

1. INTRODUCTION

The application of the approximate solution of partial differential equations by defining flow and transport in geothermal reservoirs led to a wide use of numerical simulation models. Thanks to the developments in geoscience, the increase in data diversity and the decrease in error rate, therefore, require the simulation of more complex numerical models. Many physical processes and important local phenomena can be expressed by block systems (as in TOUGH2 code). The data obtained with this approach vary depending on the shape and size of the mesh applied. Variation in data can be explained by term of numerical distribution, due to connections between blocks associated with the approximation of equations using 'coarse' grids. To deal with this issue accurately, finer grid systems can be used, resulting in smaller truncation errors (Pruess et. al., 1999, Garcia and Pruess, 2000, Croucher, 2015, O'Sullivan, et al., 2019). The easiest way to achieve smaller truncation error is to refine the whole model. On the other hand, this will result in increased computational effort, thereby increasing the computation time. This is because, when the model block volumes become smaller, their number will increase, resulting in larger linear systems to solve and number of time steps required to solve conditions will increase as well.

Since point of interest is known, local refinement approaches can be used to reduce computational effort when compared to refining the whole domain. PyTOUGH (Croucher, 2011) modules have a wide range of applications, especially in the local grid refinement. Detailed information on local grid refinement, approaches and grid optimization can be found in (Croucher and O'Sullivan, 2013). Following recent developments on PyTOUGH modules and layer refinement settings have been published by (Croucher, 2015).

The objective of this paper was to investigate the sensitivity of the applied 3-D grids for the Reykjanes geothermal reservoir. We mainly focus on obtaining a better natural state matching rather than saving computational time. Consequently, local and whole grid refinement were applied by looping from basic geometry to more complex mesh system. PyTOUGH (Croucher, 2011, Croucher, 2018) scripting language is used to form input files for numerical simulator called AUTOUGH2 (the Auckland University version of TOUGH2).

Based on the data provided in this study, all the production wells are in an area of 1.85 km² therefore, we assumed that this area is the inner center of the reservoir. Five different complex grid systems were created, derived from a simple geometry. Geometric appearances of the entire geometry is kept constant, but number of blocks are increased in more complex geometries. Names of the geometries are, the simple geometry (Simple), horizontal refinement geometry (Horizontal-Ref), horizontal and vertical factor two refinement geometry (VER-F2), horizontal and vertical factor three refinement geometry (VER-F3) and double horizontal refinement geometry (D-horizon).

For the simple geometry, the reservoir covers an area of 6.25 km², but the inner center of the reservoir covers an area of 1.85 km². Horizontal block size of the inner center is 175 m x 175 m, for the second model the block size is 87.5 m x 87.5 m, horizontal setup of the third model is same as the second model. For the last model, inner center block size of the reservoir is 44 m x 44 m.

The analysis can be split into 3 main steps:

1. Generation of ‘coarse’ to fine grids (local and whole grid refinement) and appropriate transition columns.
2. Obtaining the natural state of the models.
3. Estimating accuracy of applied grids (relative errors pressure, temperature increments with respect to grids and sensitivity analysis).

2. GEOLOGICAL BACKGROUND OF REYKJANES PENINSULA

There are six high-temperature geothermal areas spread along the Reykjanes peninsula shown in Figure 1. These are Eldvörp, Svartsengi, Krýsuvík-Trölladyngja, Brennisteinsfjöll, Hengill and Reykjanes area. Based on resistivity surveys down to 1000 m depth, it is proposed that Reykjanes covers an area of 10 km² and vertically reaches at least 5000 meters down from the sea level (Friðleifsson, et al. 2009). According to TEM measurements, resistivity of reservoir cap rocks (0.5-3 Ωm) is considerably lower when compared to surrounding rocks (5 - 15 Ωm). In addition, high resistivity (7–15 Ωm) region is detected under the geothermal field (Arnarson, et al. 2008). In the geothermal fields in the Reykjanes peninsula, the temperatures follow the boiling point curve between 400-1000 m, below this point temperature is constant with permeable vertical rocks. Boreholes in the Reykjanes Peninsula penetrate the zone of boiling and below a certain depth only liquid water exist in the reservoir, but wells that are drilled above this point produce only steam. (Arnorrsson, 1995).

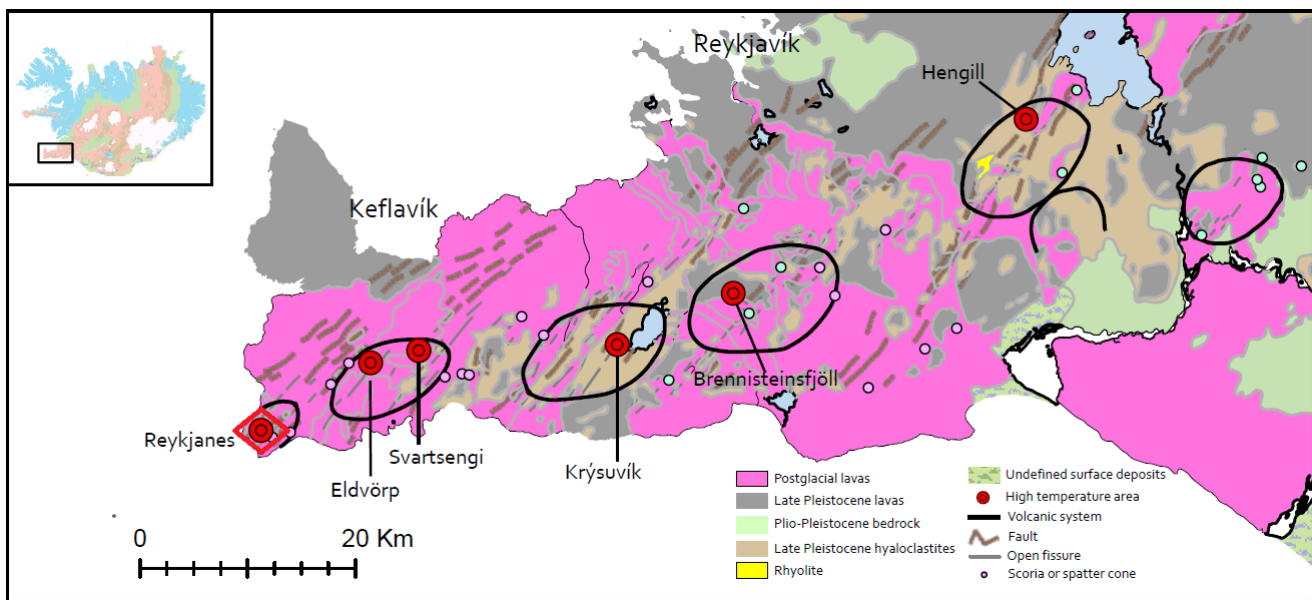


Figure 1 A geological map of the Reykjanes Peninsula. showing the volcanic systems and high temperature areas. Metada of the map taken from (The Icelandic Institute of Natural History, 2013) and updated from (Jóhannesson & Sæmundsson, 1999)

Temperature gradients of the wells drilled in the Reykjanes area clearly show that, reservoir temperature reaches up to 300 °C. The temperature profile of the wells drilled from west to east of Reykjanes area is shown in Figure 2. Especially, wells drilled near the center of the reservoir reach 240°C down to 250 m with a maximum of 320°C at the depth of 2500 meters below sea level. On the other hand, significant reduction in gradient is detected, near the outer sides of the reservoir. RN-16 (outer west), RN-17 (outer south), RN-20 (outer east) reach 140°C at the depth of 750 meters. It is believed that the upflow of hot geothermal fluid occurs in the depths of the reservoir where two main fissures are presented in the conceptual model of Reykjanes (Hjartarson and Juliusson, 2007).

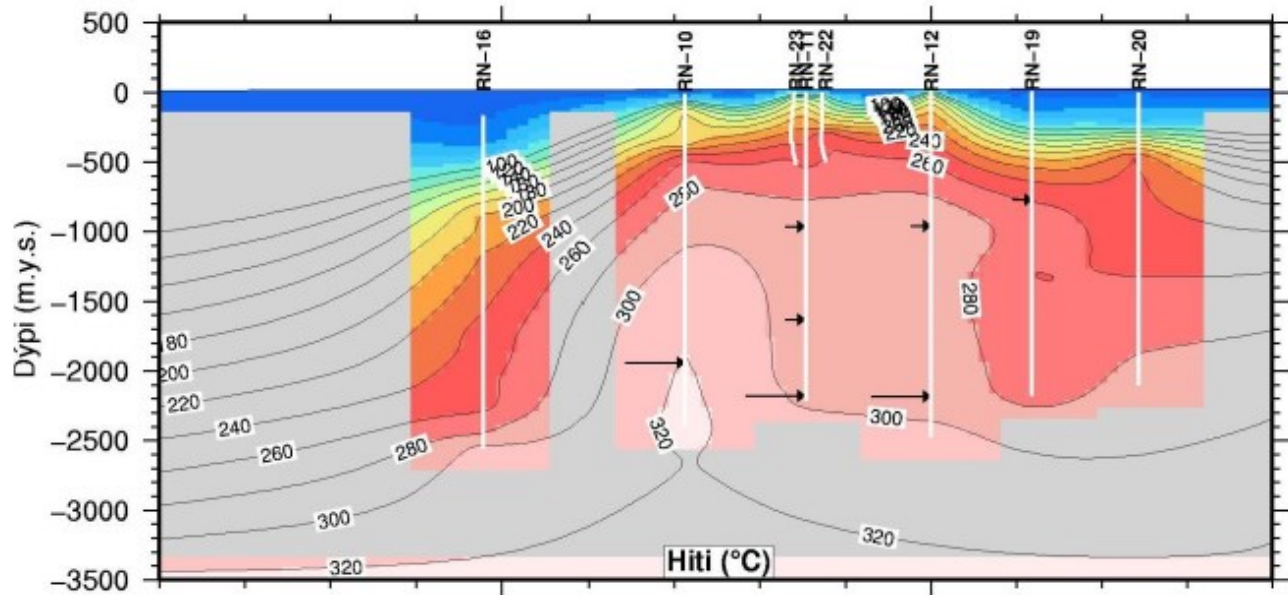


Figure 2 Temperature cross-sectional distribution of wells drilled from west to east of the Reykjanes area taken from (Hjartarson and Juliusson 2007)

Electricity generation through Reykjanes geothermal system has been taking place by HS Orka since 2006 with an installed capacity of 100 MW_e. Based on geodetic and gravity surveys (Magnusson, 2009, Magnusson, 2013) there is no subsidence detected in Reykjanes before May 2006. Right after the exploitation, the average subsidence was measured around 14-16 mm/year between 2004-2008, but the highest drawdown rate over 30 mm/year detected during the first year of exploitation (Keiding, et al. 2010). As a result of utilization the Reykjanes geothermal system with 100 MW_e power plant, the pressure dropped to an average of 19 bar-a, or 190 m between 1976-2010 (Friðleifsson, et al. 2009).

3. NUMERICAL MODEL

3.1 Grid definitions

In order to investigate the sensitivity of the generated grids to the measured downhole temperature distribution and the natural state, five different complex grid systems were created, derived from a simple geometry. Geometric appearances of the entire geometry is kept constant, but number of blocks are increased in more complex geometries. Names of the geometries are, the simple geometry (Simple), horizontal refinement geometry (Horizontal-Ref), horizontal and vertical factor two refinement geometry (VER-F2), horizontal and vertical factor three refinement geometry (VER-F3) and double horizontal refinement geometry (D-horizon). The mesh covers an area of 9 x 9 km. To avoid unnecessary thermodynamic state calculations the outermost blocks are kept larger than the innermost blocks. Overall block size is smaller from sides to center of the mesh. The finest block size is centered in the middle of the reservoir where local refinement is applied. Vertical size of the geometry is set as 3600 m and divided into 14 layers. To achieve more accurate results the thickness of the first three layers are set to 100 meters. For the Horizontal-Ref geometry, vertical settings are kept same as the simple geometry, but horizontal refinement is applied to the entire mesh. For VER-F2, horizontal layout is kept same as second geometry and vertical refinement factor two (factor three for VER-F3) is applied to the vertical layers. The last mesh setting (D-horizon) is integrated from the simple geometry by looping the refinement of entire geometry. Horizontal layout of the meshes are shown in Figure 3. Closer look in inner part of the reservoir and appropriate transition zones can be seen in Figure 4.

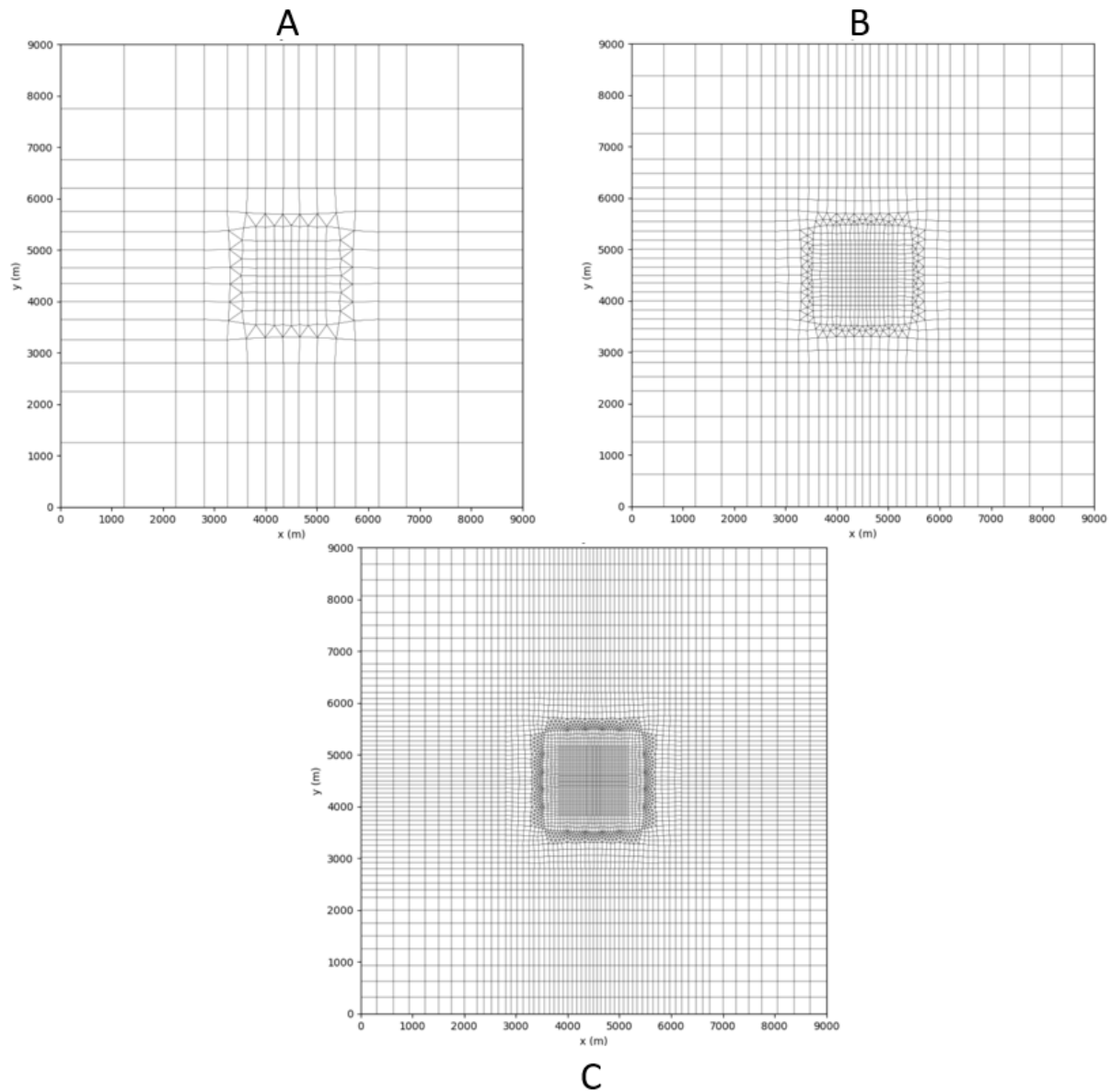


Figure 3 Horizontal meshes of the Reykjanes numerical model. (A) shows for the simple geometry, where inner center reservoir block size is 175 x 175 m, B represents the horizontal refined version of the simple geometry, inner center block size is 87.5 x 87.5 m. C is looped horizontal refinement of the simple geometry, with inner center block size of 44 x 44 m.

The simple mesh consists of 5000 elements, where mass and energy flows through 13440 connections, placed in a total of 14 layers. First three layers have a thickness of 100 m while others are 300 m. Horizontal-Ref mesh consists of 20000 elements and 54600 connections, vertical setting is kept same as the simple mesh. VER-F2 mesh has 40000 blocks and 109200 connections placed in 28 layers. First six-layers are 50 m and the rest are 150 m. VER-F3 mesh has 60000 blocks and 163800 connections separated in a total of 42 layers. First nine layers are 33m and the rest are 100 m. The D-Horizon mesh consists of 80000 blocks and 220080 connections separated through 14 layers, the first three 100 m and rest are 300 m. For the simple mesh, two different local grid refinement are applied to the center of the reservoir. These are triangular and Voronoi hexagonal approaches. Based on PyTOUGH, each column will split into four columns, unless bisect parameter is true, at the end of the procedure transition columns will be created around the refined region (Croucher, 2018). In this study we assume that there are two different transition regions, first region is placed between the inner center and the outer side of the reservoir, second transition zone is placed between the outer side of the reservoir and the outermost region. Therefore, triangular transition zone is formed between outermost and outer side of reservoir, Voronoi transition region is formed between inner center and outer side of the reservoir.

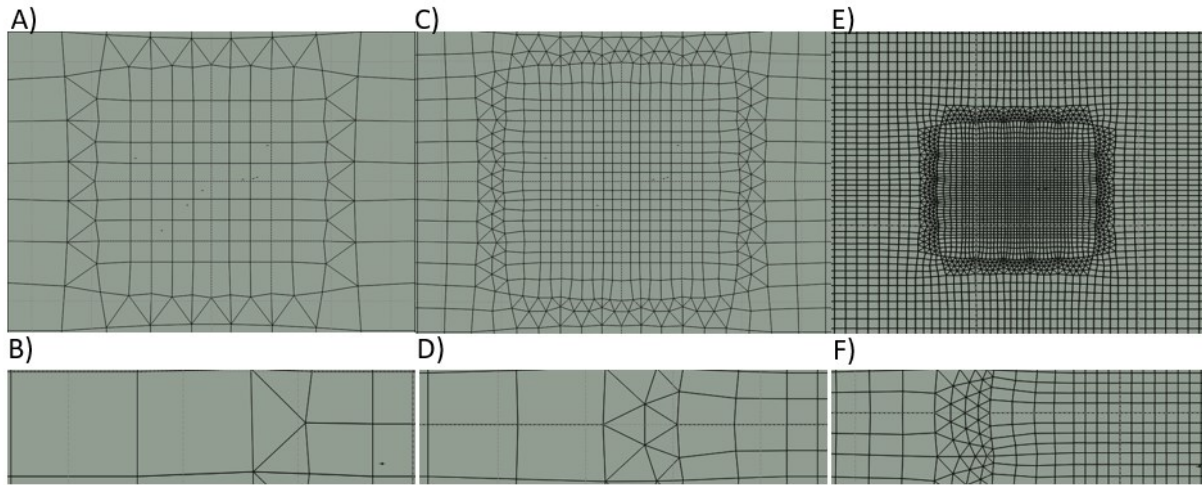


Figure 4 Horizontal comparison of all geometries and transition zones. (A) simple mesh 175 m x 175 m, (C) horizontal refined mesh 87.5 m x 87.5 m, (E) duplicated horizontal refined mesh 44 m x 44 m. (B, D, F) represents transition zones for each geometry.

Figure 5 represents vertical layout of the simple, vertical factor two and vertical factor three mesh systems. To calculate more accurate thermodynamic conditions of the layers that are located close to surface, thickness of the first three, six and nine layers are reduced. Thickness of the rest layers for A, B and C respectively, 300 m, 150 m and 100 meters. For the simple geometry, the first 300 meters are evenly divided into 3 layers. For vertical refinement factor 2 (VER-F2) and factor 3 (VER-F3), first 300 meters are evenly divided into 6 and 9 layers respectively. From simple geometry to VER-F2 number of layers are 14, 28 and 42 respectively.

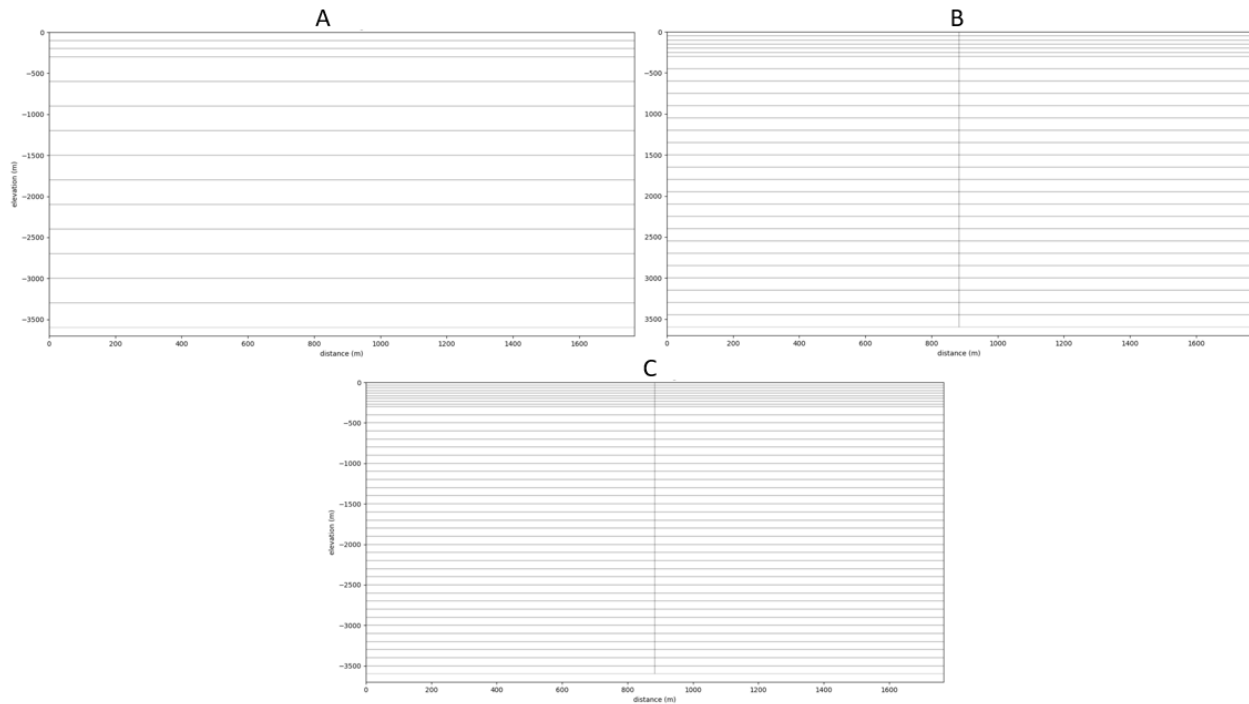


Figure 5 Vertical layout of the mesh systems. (A) addressed the simple mesh, first 3 layers have thickness of 100 m while the rest are 300 m, (B) is vertical refinement factor 2 mesh, first 6 layers have thickness of 50 m and rest are 150 m, (C) is vertical refinement factor 3 mesh setup, first 9 layers have thickness of 33.3 m and the rest are 100 m.

3.2 Geological features

The most common approach for TOUGH2 simulations is grouping the rock distributions (Pruess et. al., 1999). For this reason, eight different rock types are grouped at specific depths to form the Reykjanes geothermal reservoir. Geological settings are kept constant for all mesh systems, graphical illustration is shown at Figure 6. We assume that a less permeable reservoir cap rock starts at the depth of 600 meters and surrounded by relatively permeable surroundings. To demonstrate side boundary conditions, outermost side of the model is covered with a low permeable rock. Initial conditions for temperature and pressure is set at 15°C and atmospheric pressure for top layer, 345°C and 265 bar-a for the bottom layer.

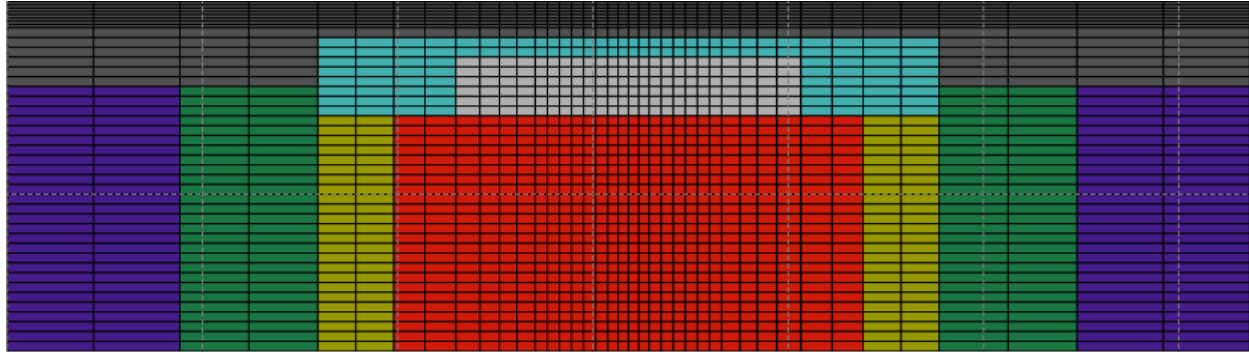


Figure 6 Rock distribution of the Reykjanes Model. Dark grey represents cap rock, light blue represents first surrounding rocks of the reservoir cap (light grey), purple rocks low permeable side rocks to provide boundary conditions, green and yellow rocks surroundings of the reservoir. Red rock represents the central reservoir.

By grouping the rock types horizontally and vertically, we aimed to compute the possible physical properties of these rocks and set more accurate boundary conditions. However, more accurate results may be achieved, if the upflow of the geothermal fluid is provided by adding two fissure zones to certain depths of the reservoir as mentioned in (Hjartarson and Juliusson, 2007). Constant physical parameters of rock types are shown in Table 1. For the simulations, we assumed that the geothermal fluid is pure water, therefore, the EOS1 module was used. To simulate the model, the first possible permeability range estimates are made within the ranges specified in (Hjartarson and Juliusson, 2007). These are horizontal permeability for surroundings within the range of 2-7 mD and 0.0-0.05 mD in the vertical. Permeability of rocks in the center of the reservoir, horizontally within the range of 2-20 mD and vertically 0.1-1 mD. As can be expected, highest permeability was set at the fissures in the center of reservoir, horizontally 2-200 mD and vertically 5-500 mD.

Table 1 Rock Properties of the numerical model.

NAME	DENSITY	POROSITY	PER (X)	PER (Y)	PER (Z)	CWET
	kg/m ³	%	m ²	m ²	m ²	W/m°C
Cap rock	2600	10	2.45E-15	1.00E-15	1.00E-15	2
Side (blue)	2600	10	1.00E-15	1.00E-15	5.00E-17	2
Side (green)	2600	10	3.00E-15	2.40E-15	8.00E-16	2
Side (yellow)	2600	10	4.20E-15	3.40E-15	9.00E-16	2
Reservoir cap	2600	10	1.00E-15	1.00E-15	2.00E-16	2
Surroundings rc	2600	10	1.00E-14	1.00E-14	1.00E-14	2
Reservoir	2600	10	1.00E-14	1.00E-14	9.00E-15	2

3.3 Mass and heat generators

TOUGH2 type simulators assume that the model will consist of a layer stack, each with the same block structure and the top of the model containing an atmosphere block. Therefore, each block will have a volume and flow generators should be distributed in proportion to this volume. In our model, represented in Figure 7 shows distribution of mass generators based on block volumes. For the simple mesh 80 kg/s hot water is injected through 13 generators, the horizontal refined model (B) consist of 52 mass generators and model (C) looped horizontal refinement of simple mesh contains 208 mass generators.

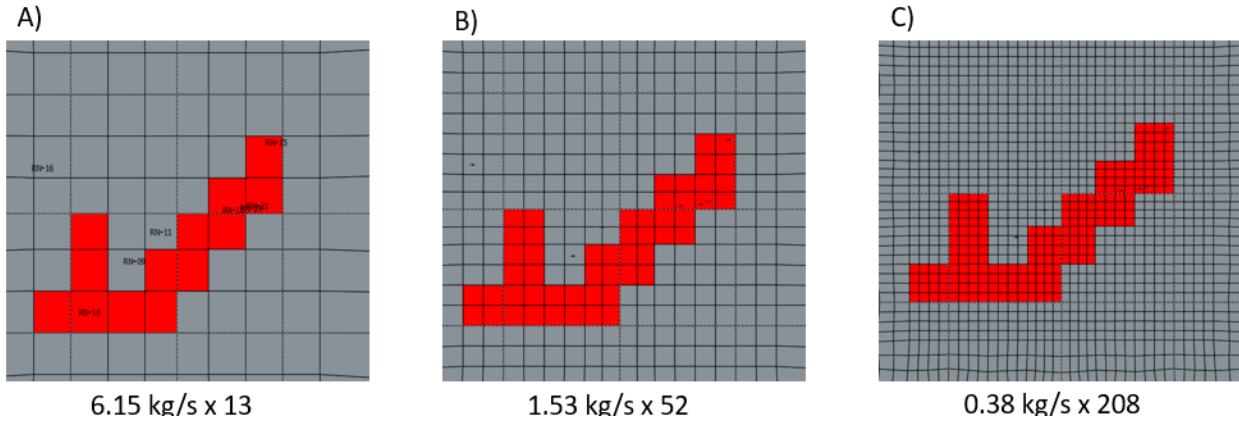


Figure 7 Mass generator distribution for different block volumes. Overall 80 kg/s hot water injected through 13, 52, 208 blocks. For the setup (B) layer refinement factor 2, 80 kg/s hot water injected through 104 generators distributed into last two layer, for the factor 3, 156 mass generators distributed into last three layer.

In order to accurately deal with block volume and injected mass as a result of local grid refinement process, PyTOUGH (Croucher, 2018) scripts were used. In this model we assume that all the wells have a single feed zone. For this reason, we only deal with the bottom layer generators. If the wells have multiple feed zones and their locations are known, the mass flow should be distributed proportionally to the local grid refinement factor.

4. RESULTS

In order to obtain the natural state of Reykjanes reservoir, all models prepared for this study reached a thermodynamic equilibrium after a process of approximately 300.000 years. The steady state of the reservoir as a result of the thermodynamic equilibrium indicates that historical comparisons can be made with the measured data between 1977-2009 in the region. Stable pressure and temperature distribution have been reached in all wells except wells named RN-15 and RN-19. It should be noted that, achieving historical temperature distribution was quite challenging, especially, since the wells in the center of the reservoir reach 240°C at the depth of 250 m.

Based on the benchmark results given in Table 2, maximum time steps required to achieve natural states of the given model increase with number of blocks. As already mentioned, 3-D layout of the geometry is kept constant, the decrease of block volumes resulted in an increase of the number of blocks therefore, required computation time is increased for more complicated mesh systems. Required time can be decreased by increasing number of CPUs. For this study there is only one CPU used. As expected, simulation of increasing resolution models using AUTOUGH2 can result in high computational costs. By using multi CPUs allowed simulators (e.g. Waiwera) computational cost can be offset (O'Sullivan et. al., 2019).

Table 2 Comparison of the models

Model	Total number of blocks	Number of connections	Number of nodes	Vertical layer definition	Maximum time steps achieved	Run time
Simple	5000	13440	341	3 x 100 11 x 300	405	97s
Horizontal - Ref	20.000	54600	1301	3 x 100 11 x 300	1134	4.8h
VER-F2	40.000	109200	1301	6 x 50 22 x 150	1215	10h
VER-F3	60.000	163800	1301	9 x 33 33 x 100	1620	15h
D-horizon	80.000	220080	5081	3 x 100 11 x 300	8430	44h

Based on temperature distributions shown in Figure 8 all models have almost same curve between 750 - 3400 m but there is a significant temperature difference detected at the depth range of 100 - 400 m in wells RN-09, RN-10 and RN-12. Especially, geometry Ver-F3 has the lowest temperature range at this depth. Based on the thickness differences, Ver-F2 is more accurate than F3. D-horizon, Ver-F2 and horizontal refinement geometries have almost same curves at the depth of 100 to 400 m.

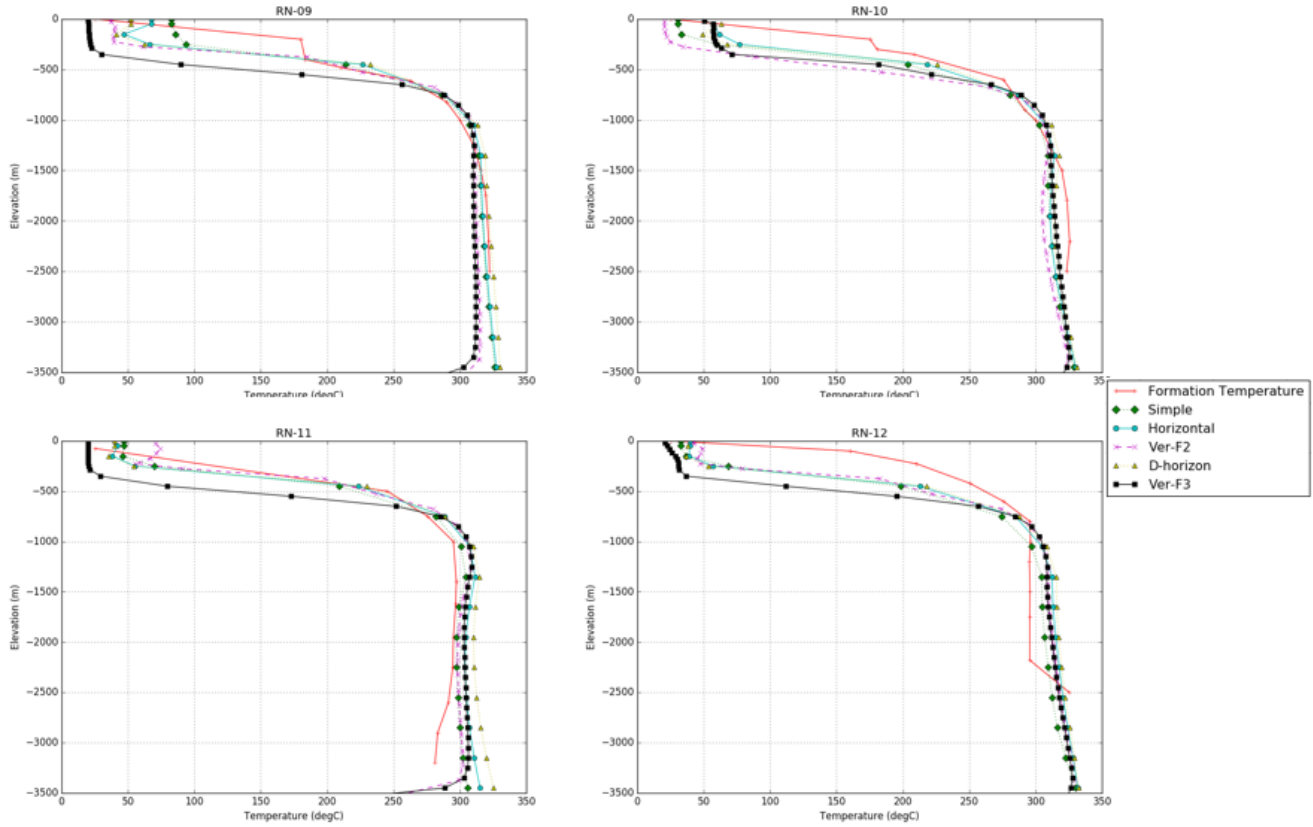


Figure 8 Temperature distribution of RN-09, RN-10, RN-11 and RN-12.

VER-F3, which has the lowest layer thickness grid system, showed a lower temperature distribution than other grid systems, especially in layers close to the surface. Apart from this, no major differences were observed, and all grid systems simulated, had almost the same curves between 750 and 3500 meters as seen in Figure 9. Historical pressure distribution of the RN-12 and RN-16 are shown Figure 10. At the end of 35 years, observed drawdown at RN-12 is 35 bar and 24 bar for RN-16. Based on the simulation results, the grid systems Ver-F2 and Ver-F3 have an average bottom hole pressure of 168 bar, while the simple and D-horizon grid system have an average of 158 bar. Since there are no significant bottom hole pressure differences between the simple, horizontal and D-horizon mesh settings, the pressure drop can be associated with the layer thickness of the grid system. After six years of production simulations (35 years in total), Ver-F2 and Ver-F3 grid systems have a reasonable pressure drop when compared to the pressure drop measured from the wells. Average mean absolute deviation, mean absolute percentage error and root mean squared error results of the geometries between 600 to 2250 meters are shown in Table 3.

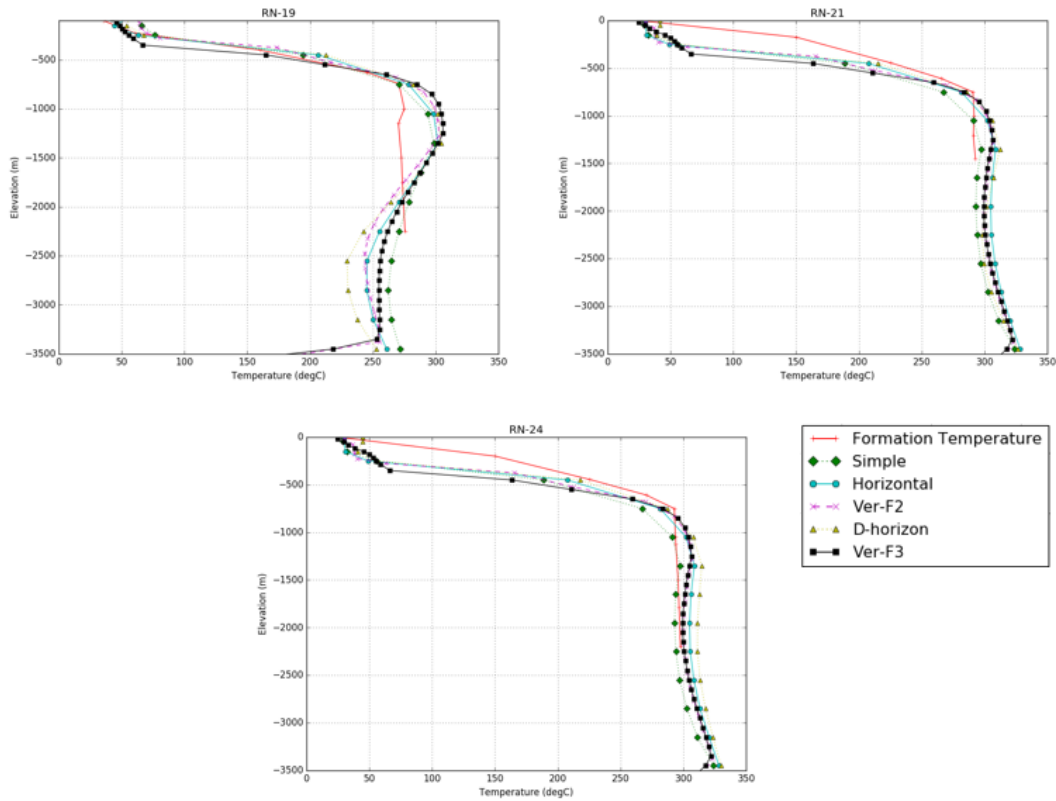


Figure 9 Temperature distribution of RN-19, RN-21 and RN-24.

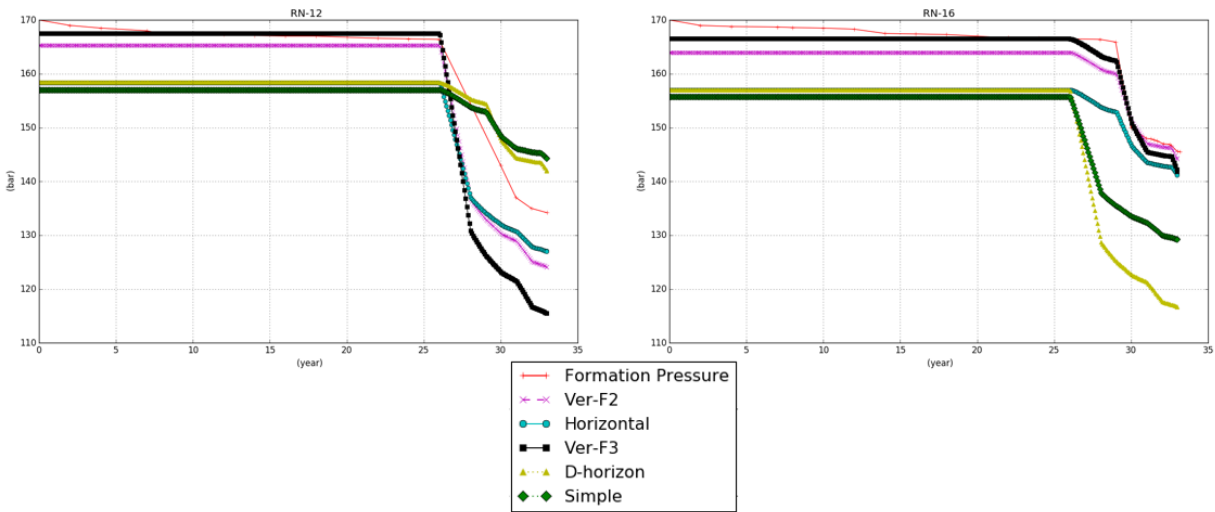


Figure 10 Production history pressure distribution between 1975-2010. RN-12 was drilled in the center of the reservoir. RN-16 is located on the northwestern border of the reservoir.

Absolute temperature errors divided by measured formation temperature for all wells and mesh settings are shown in Figure 11. Although all mesh settings have similar error distribution after 600 meters, relatively high error distribution was detected at shallower depths. Based on the same graph, the simple geometry has the lowest error distribution at shallow depths compared to other geometries and VER-F2 is the second best. If a new mesh system is required in the light of these results, it may be better to keep the thickness of the layers formed down to 600 meters between 50 and 100 meters.

Table 3 Comparison of the average mean absolute deviation, mean absolute percentage and root mean squared error of the geometries(Calculations were made based on temperature simulation results between depths of 600 and 2250 meters).

	SIMPLE	HORI	V2	V3	D-HOR
MAD	6.43	10.35	7.65	9.11	11.00
MAPE	3.25	5.62	3.14	3.75	5.00
RMSE	10.84	16.03	10.92	13.82	15.88

MAD represents the sum of the absolute differences between measured formation and simulated temperatures divided by numbers of observations. Simple and VER-F2 geometries had lower differences when compared to the others. Based on the average of absolute errors divided by measured formation temperatures (MAPE) results, VER-F2 had the best result amongst the other mesh systems.

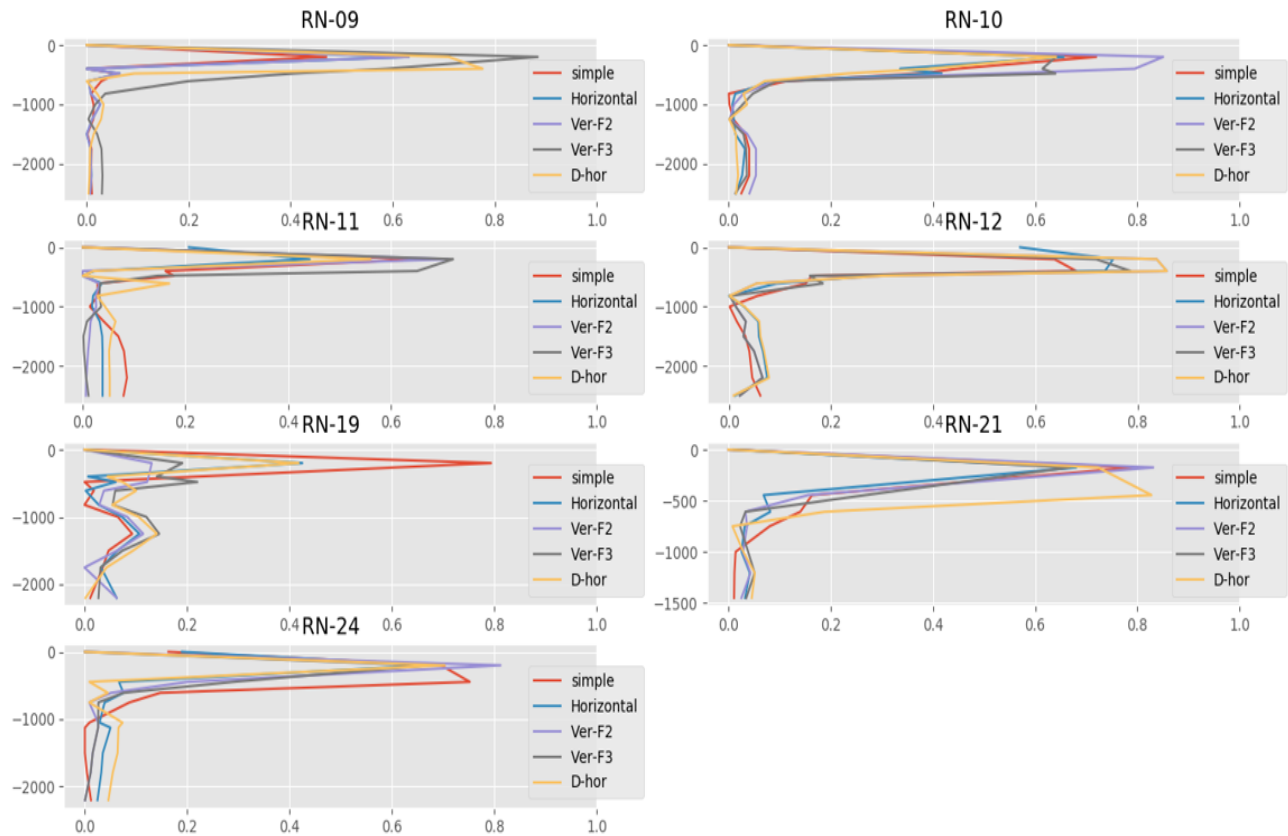


Figure 11 Absolute temperature errors divided by measured formation temperature vs depth.

5. DISCUSSION & CONCLUSIONS

When applying local grid refinement (same as layer refinement) to the mesh system, the mass injected into a block should be divided into blocks formed by the factor of refinement to maintain upflow. Otherwise, the simulation results may be different than expected, leading to changes in geological settings of given model and ending in fatal errors. Likewise, mistake in proportional distribution of the heat generators to the block volume may cause the model to overheat or cool down, leading to optimistic / pessimistic results in the future forecast.

The results for natural state temperature distributions (Figure 8, Figure 9) show that all the grid systems have quite similar trend with minor differences. Based on Table 3, the simple and VER-F2 geometries have mean absolute temperature deviation of 6.43 °C and 7.65°C respectively at the depth range of 600 to 2250 meters. In the same table mean absolute percentage error distribution showed that overall

accuracy of VER-F2 is greater than the simple geometry. Only horizontally refined grid systems, Horizontal and D-horizon have the greatest average mean absolute temperature deviation and mean absolute percentage error. This may indicate that, the accuracy of the model can be increased by applying horizontal and vertical refinement jointly rather than separately.

But there were significant differences detected at the shallow depths for all applied mesh systems. Especially, grid system Ver-F3 has the lowest temperature range at the shallow depths. The second lowest temperature curve belongs to the Ver-F2. This may indicate that reducing the layer thickness may reduce the temperature distribution. At shallow depths the simple grid system showed similar results, except for the RN-19 and RN-09 wells, when compared to the VER-F2 grid system. Better results can be obtained by setting the thickness between 50 - 100 meters for the layers down to 600 meters. In addition to this, by integrating additional geological data (two fissure zones to certain depths of the reservoir as mentioned in (Hjartarson and Juliussón, 2007)) it may be possible to minimize the heat distribution error at shallow depths and obtain a more accurate temperature distribution.

With the data available in this study, the natural state of the Reykjanes reservoir was obtained by measurements taken from 7 wells. The pressure drop in the production process was compared with 2 production wells. In order to investigate the natural state of the reservoir more accurately and up to date, it is necessary to add the production wells currently used to this model and compare the pressure change.

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