Benchmark Testing of the Volsung Reservoir Simulation Software

MARCH 2019

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Contents

1 Introduction and Summary of Testing Results

TOUGH2 is the *de facto* industry standard for geothermal reservoir simulation. *Volsung* is a new software package for geothermal reservoir simulation. In this report we compare the results from a series of test problems run using *Volsung* and *TOUGH2*. *TOUGH2* is widely used and has been thoroughly tested. Accordingly, if *Volsung* gives comparable results to *TOUGH2* on a range of problems then this provides sufficient validation that *Volsung* meets industry standard for accuracy of a reservoir simulation code.

To ensure readability, model descriptions in this report are kept brief and only the key points of each model are summarized. Full details and model input files for testing are available upon request.

Nine test problems were selected for accuracy testing and results from each model were compared between *Volsung* and *TOUGH2*. Six of these test cases were taken from the Stanford Geothermal Code comparison study [1], one is from the *TOUGH2* manual [2] and the other two are new cases. These test problems cover a large range of simulation conditions including transient responses to production, phase change, three dimensional reservoir flow, steam/liquid counter flow and fracture-matrix (MINC) heat and mass flow. In all tests *Volsung* gave results in close agreement with *TOUGH2*.

Four test cases were selected for speed testing. The first of these represented a model natural state run where time stepping was unconstrained. In this case *Volsung* was over 60 times faster than *TOUGH2* through a combination of reduced time taken for each timestep and greater stability at longer timesteps. The next three cases were to represent a production history run where the benefit of longer timesteps may not be realised. In this case *Volsung* was about three times faster than *TOUGH2* on a small model of 18,000 gridblocks and seven times faster than *TOUGH2* on a larger model with 98,000 gridblocks due to reduced time taken for each timestep. These results are summarized in Table 1

Test	Blocks	*Volsung* on GTX1070		*TOUGH2*		Speedup
		Timesteps	Runtime (s)	Timesteps	Runtime (s)	
NS	100,000	94	**212**	1139	**13090**	61
Prod	18,000	301	**50**	339	**145**	3
Prod	50,000	301	**99**	300	**452**	5
Prod	98,000	301	**179**	300	**1232**	7

Table 1: Volsung vs *TOUGH2* speed. Speedup is the runtime of *TOUGH2* divided by the runtime of *Volsung*

The times given above are for *Volsung* run under Linux with a GTX-1070 NVIDIA graphics card. Processing speed with *Volsung* scales with the bandwidth of the graphics card used. *Volsung* has been tested on a GTX-1050 and a GTX-1070 card and these results are included in Table 2. As can be seen, moving from a

GTX-1050 to a GTX-1070 reduced computational time per timestep by a factor of 1.6 to 2.1. The GTX-1050 and GTX-1070 are cheap and relatively low bandwidth graphics cards, further speed up would be possible with better graphics cards and the cost and bandwidth of these is summarised in Table 3. Table 2 also shows the speed of *Volsung* when run under Windows 10 with the GTX-1070 GPU. In this case the performance is compromised and investigations so far indicate this is a feature of the Windows operating system and not something than can easily improved. Although *Volsung* under Windows is still faster than *TOUGH2*, we strongly recommend that *Volsung* is run under Linux if users want full benefit of faster run times.

Test	Blocks	Volsung GTX1050 Runtime (s)	Volsung GTX1070 Runtime (s)	Volsung WIN10 GTX1070 Runtime (s)
NS	100,000	457	212	580
Prod	18,000	62	50	174
Prod	50,000	162	99	356
Prod	98,000	299	179	611

Table 2: Volsung speed on different GPUs and when run on Linux vs Windows

GPU Model	Bandwidth [GB/s]	Approx. Price [USD]
GTX 1050Ti	112	$270
GTX 1070	256	$530
GTX 1080Ti	484	$800
Titan V	652	$3000
P100	900	>$8000

Table 3: GPU bandwidth and cost

2 Accuracy Benchmark Testing

In this section we present the results from each accuracy benchmark test.

2.1 Two-block transient model

In this test case a two block model was initialised with each block having different thermodynamic conditions and the transients in pressure and temperature were observed as the model evolved towards equilibrium. The model grid is shown in Figure 1. Initial conditions for block one were 2 bar and 50 °C while block two was initialised at 4 bar and 100 °C.

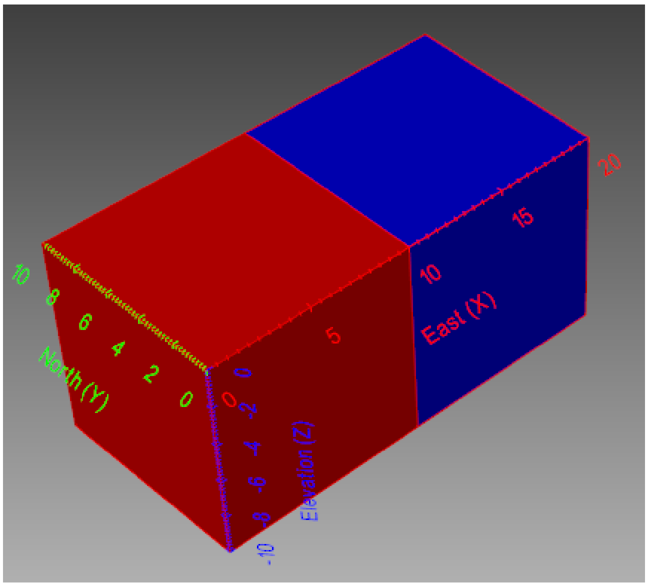


Figure 1: Model grid for two-block equilibrating test case

The model was run for 100,000 seconds. The pressure and temperature responses for *Volsung* and *TOUGH2* are shown in Figure 2.

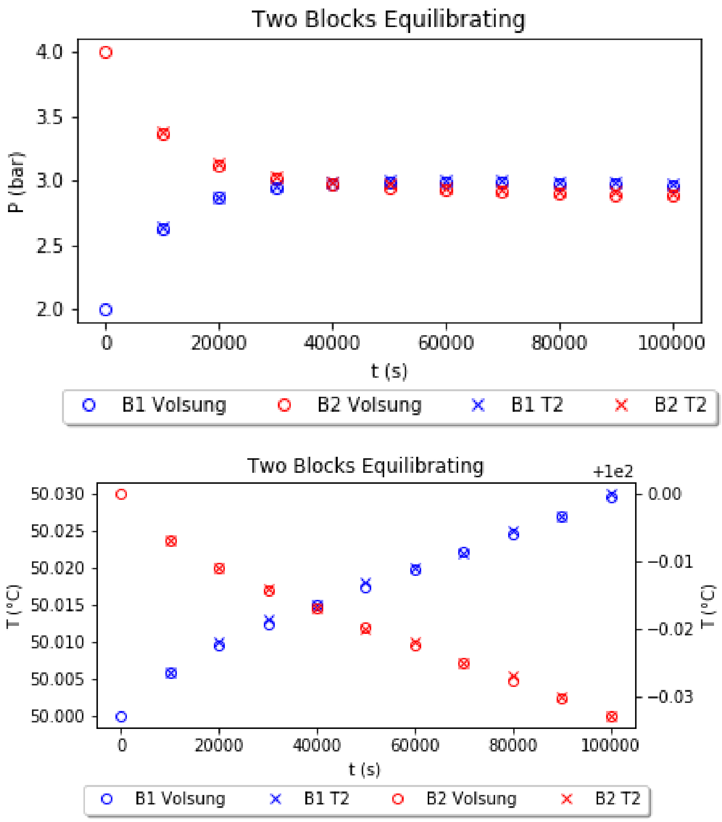


Figure 2: Pressure and temperature transient for each cell in the two block model for *Volsung* and *TOUGH2*

2.2 Five-spot model

This test case is problem number four in the TOUGH2 manual [2] modified to have a greater spatial discretization. The original problem had 36 grid blocks but in this testing a 30 by 30 model grid was used for a total of 900 grid blocks. The model grid is shown in Figure 3.

The model was initiated with two-phase conditions and production of 1.5 kg/s in one corner and injection of 1.5 kg/s fluid at 500 kJ/kg enthalpy in the other. A comparison between the pressure, temperature and gas saturation after 36.5 years for *Volsung* and *TOUGH2* is shown in Figure 4.

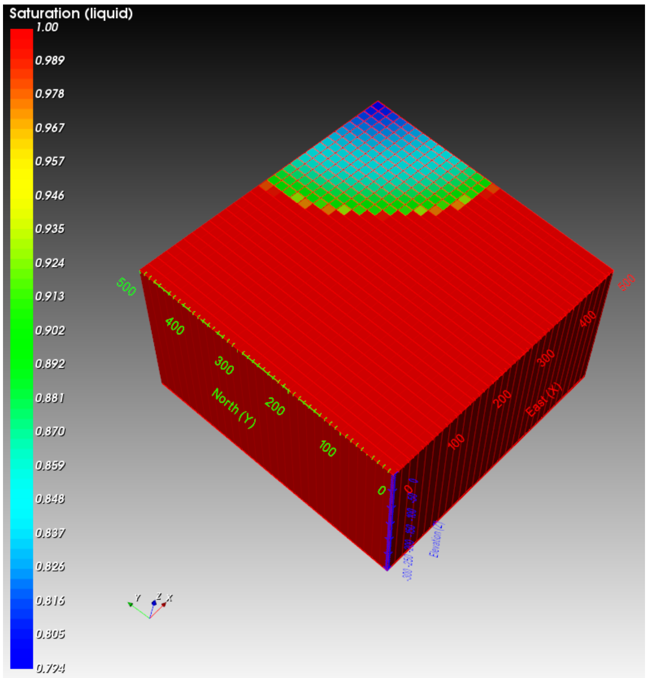


Figure 3: Modified five-spot model grid

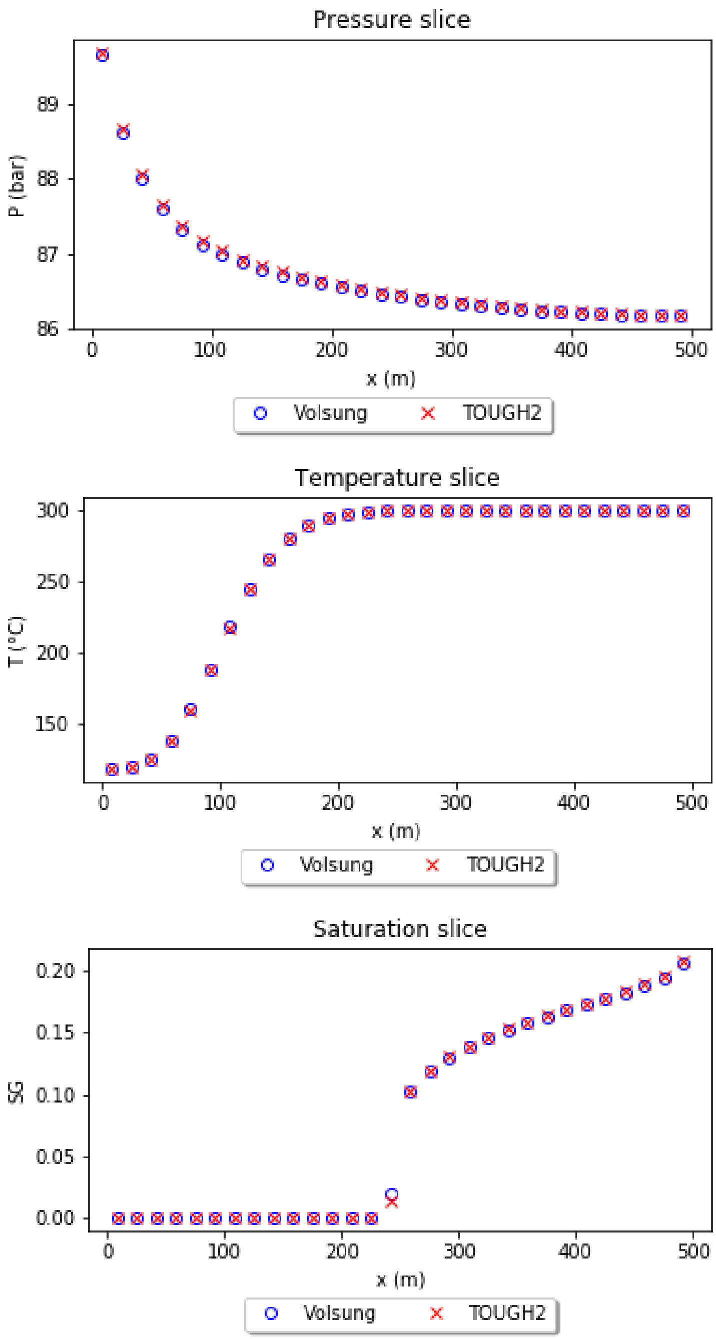


Figure 4: Slices showing pressure, temperature and gas saturation through the five spot model for *Volsung* and *TOUGH2*

2.3 Stanford Problem 1

The first problem from the Stanford code comparison study was a radial model at 170 °C with injection of 160 °C fluid into the centre. Pressure and temperature were fixed at the boundary of the model so a steady state flow was reached quickly while heat transfer was slower. The model grid is shown in Figure 5.

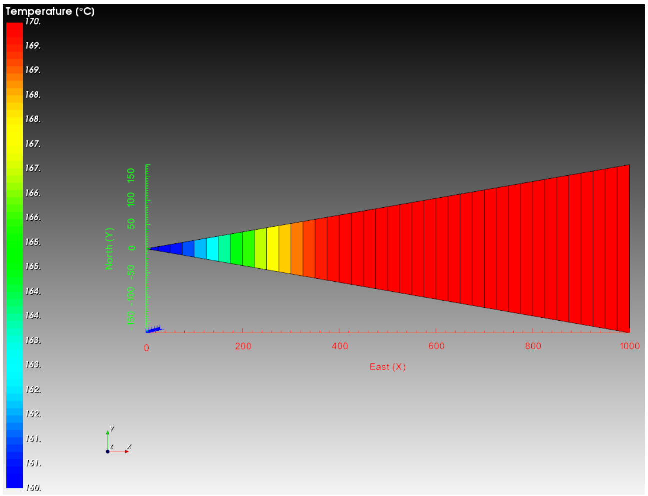


Figure 5: Stanford problem 1 Model grid

The model was initiated with two-phase conditions and a scenario with production in one corner and injection in the other was run for 36.5 years. A comparison between the pressure, temperature and gas saturation for *Volsung* and *TOUGH2* is shown in Figure 6.

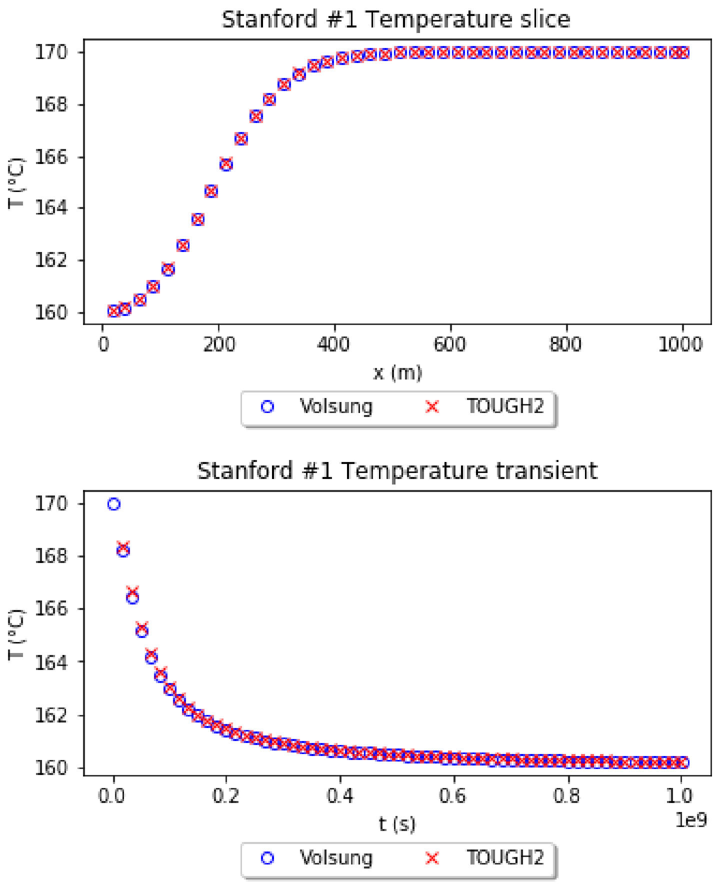


Figure 6: Results from Stanford Problem 1 for *TOUGH2* and *Volsung*

2.4 Stanford Problem 2

The second problem from the Stanford code comparison study involved constant discharge from a radial model while the transient effects on model thermodynamics were observed. The model was run over three different thermodynamic conditions A, B, and C. In all cases the model grid was as per Figure 7.

2.4.1 Problem 2A

In Problem 2A initial conditions were 90 bar and 260 °C, production rate was 14 kg/s and the scenario was run for one day. Pressure drawdown away from the well and model pressure response at r = 0.5m are shown in Figure 8 for *Volsung* and *TOUGH2*.

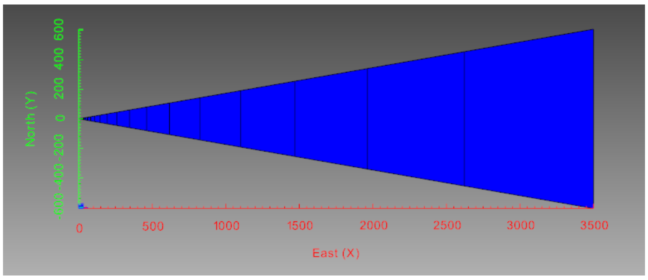


Figure 7: Stanford Problem 2 model grid

2.4.2 Problem 2B

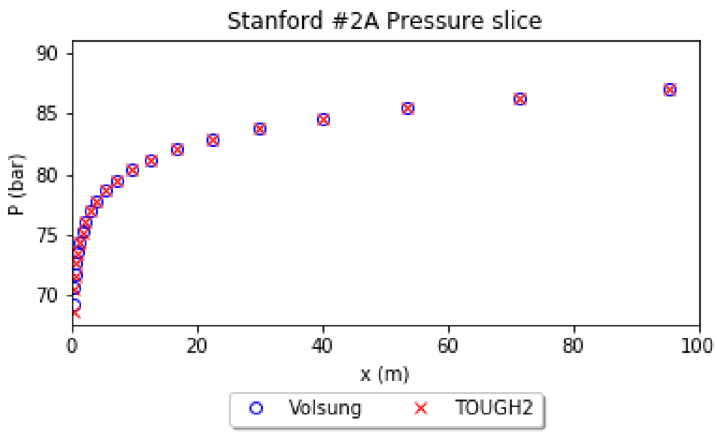
In Problem 2B initial conditions were 30 bar and 0.35 gas saturation, production rate was 16.6 kg/s and the scenario was run for one day. Pressure drawdown away from the well and model pressure and gas saturation response at r = 0.5m are shown in Figure 9 for *Volsung* and *TOUGH2*.

2.4.3 Problem 2B - one node

In this variant of problem 2B the same initial conditions and production rate was used but the model was a radial grid with a single node of radius 1m and thickness of 100m. The scenario was run for 0.01 days. Model pressure and gas saturation response are shown in Figure 10 for *Volsung* and *TOUGH2*.

2.4.4 Problem 2C

In Problem 2C initial conditions were 90 bar and 300 °C, production rate was 14 kg/s and the scenario was attempted to be run for one day. *Volsung* ran the simulation for one day but *TOUGH2* failed after 8e4 seconds. Pressure drawdown away from the well and model pressure response at r = 0.5m are shown in Figure 11 for *Volsung* and *TOUGH2*. Figure 11 shows a small difference between *Volsung* and *TOUGH2*. This was not unexpected. This case involved transition to two-phase and the propogation of a flash front away from the well. In addition, the block selected to compare the transient response was only 0.5m away from well. Any slight difference in steam tables, timestepping, onset of boiling, numerical implementation of relative permeability or grid would lead to slight deviations between simulators for this problem.



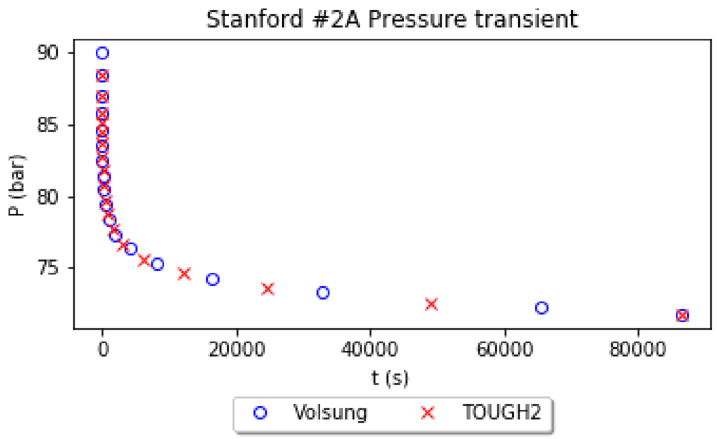


Figure 8: Results from Stanford Problem 2A for *TOUGH2* and *Volsung*

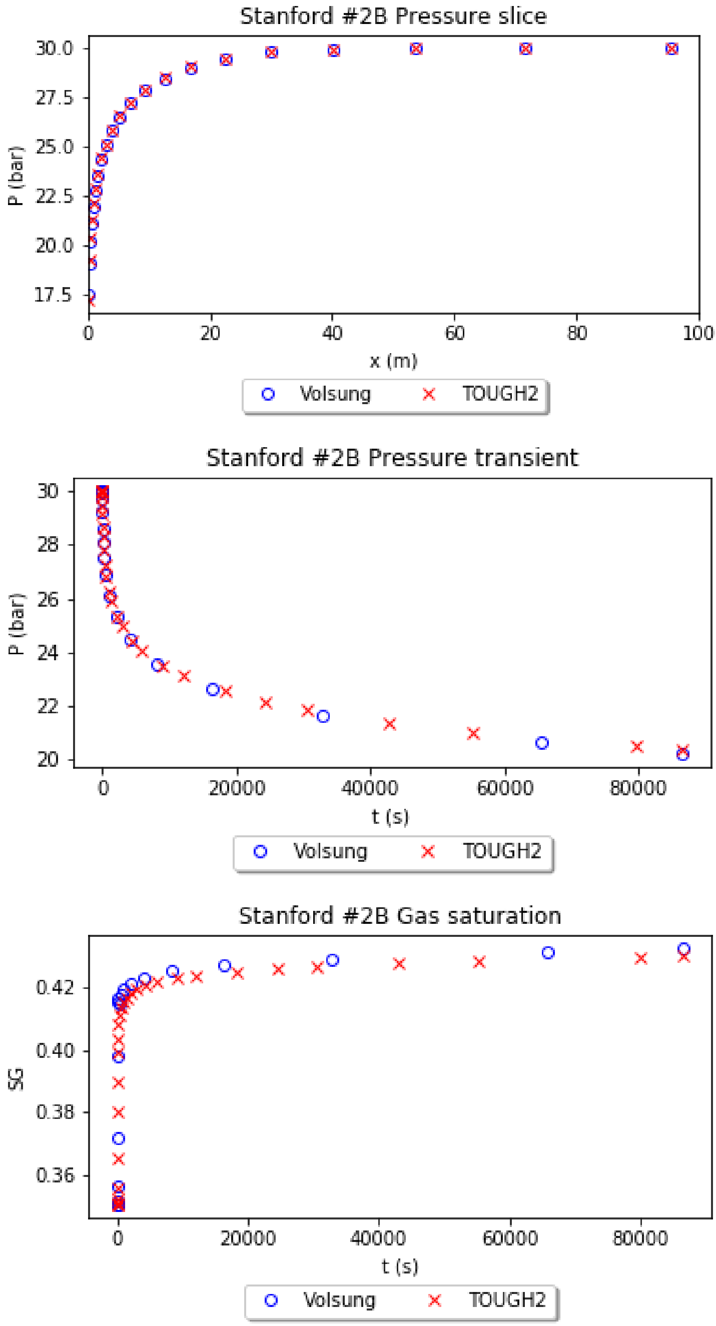


Figure 9: Results from Stanford Problem 2B for *TOUGH2* and *Volsung*

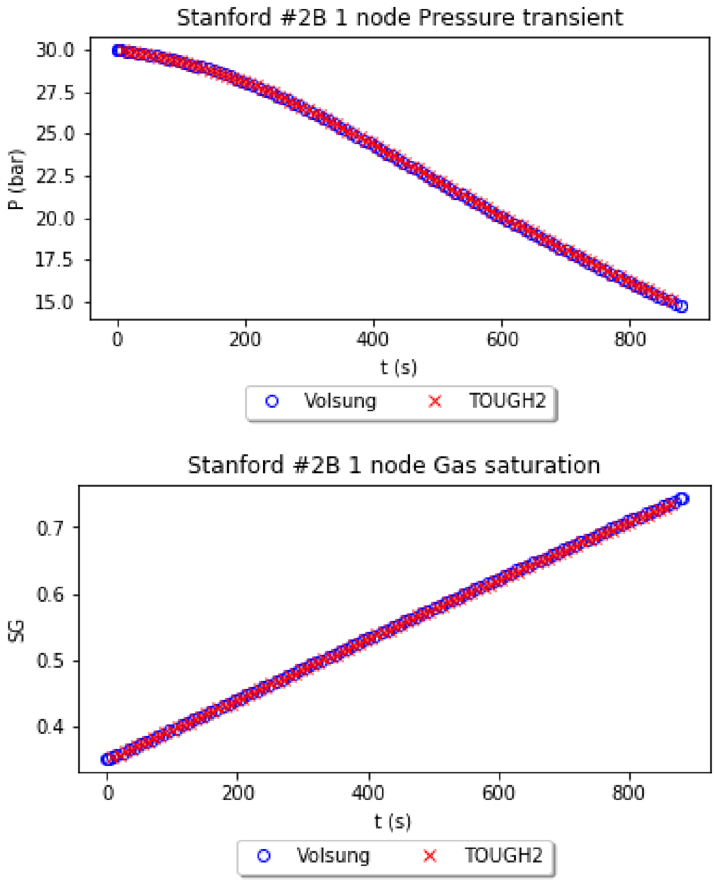


Figure 10: Results from Stanford Problem 2B single node model for *TOUGH2* and *Volsung*

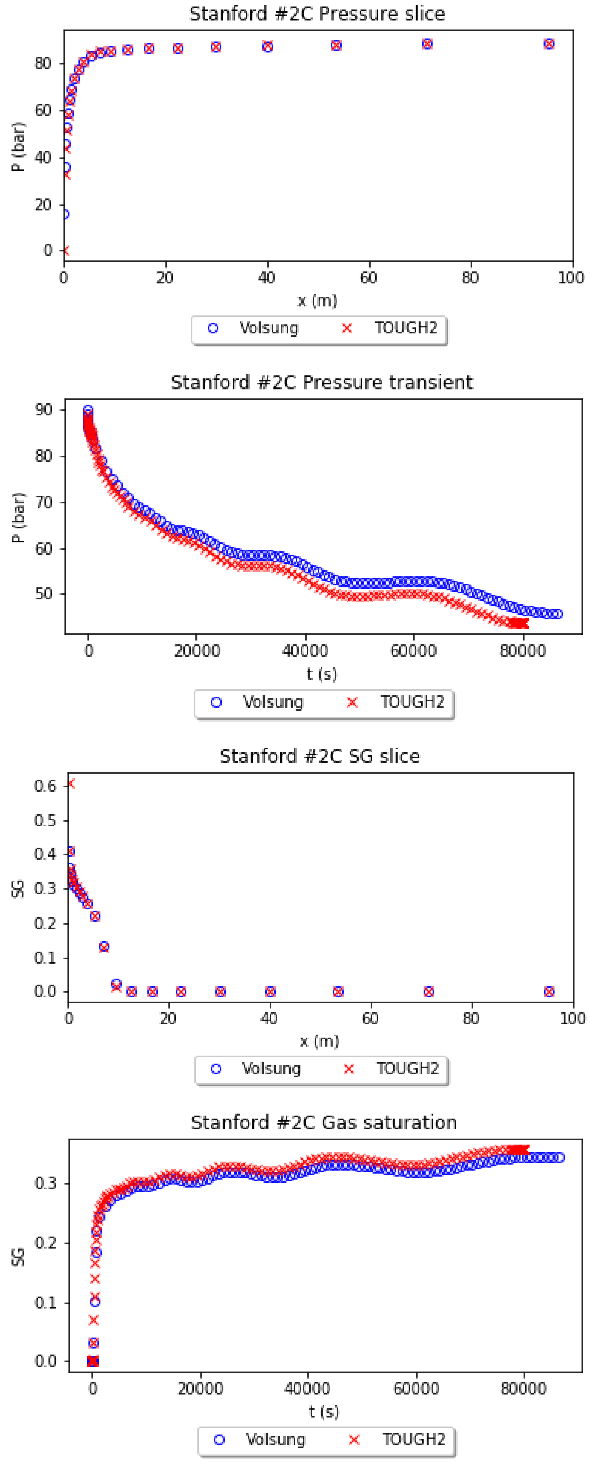


Figure 11: Results from Stanford Problem 2C for *TOUGH2* and *Volsung*

2.5 Stanford Problem 3

The third problem from the Stanford code comparison study was a radial model with horizontal and vertical flow including flow through a high permeability fracture and low permeability blocks. The problem definition was ambiguous and several participants in the code comparison study had different interpretations and hence different results. To simplify the problem we implemented a rectilinear grid with a high porosity, high permeability well block, a high permeability fracture and low permeability blocks based on the suggested mesh for Problem 3 shown in Figure 12.

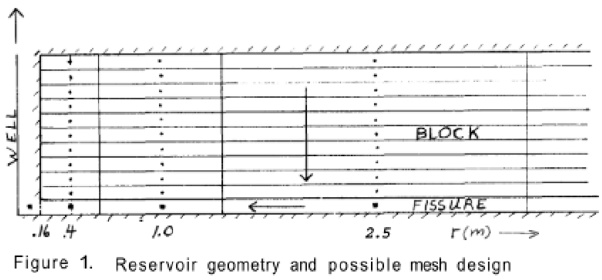
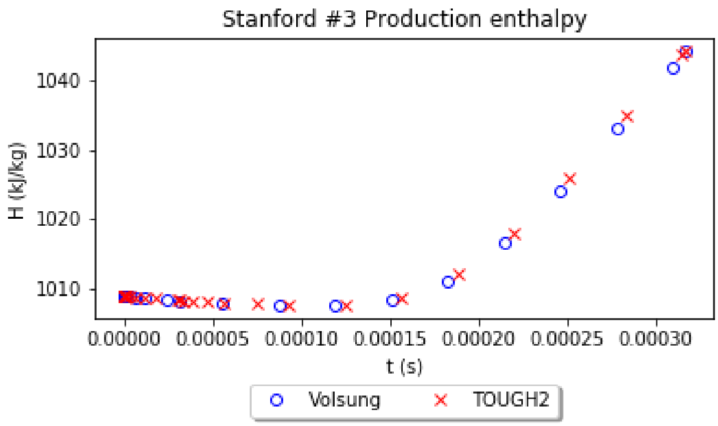


Figure 12: Stanford Problem 3 suggested mesh.

Model initial conditions were 30.5 bar and 234 °C as per the original problem definintion and production of 0.028 kg/s was from a high permeability well block connected to the fracture. A comparison between the pressure in the well block and production enthalpy for *Volsung* and *TOUGH2* is shown in Figure 13.



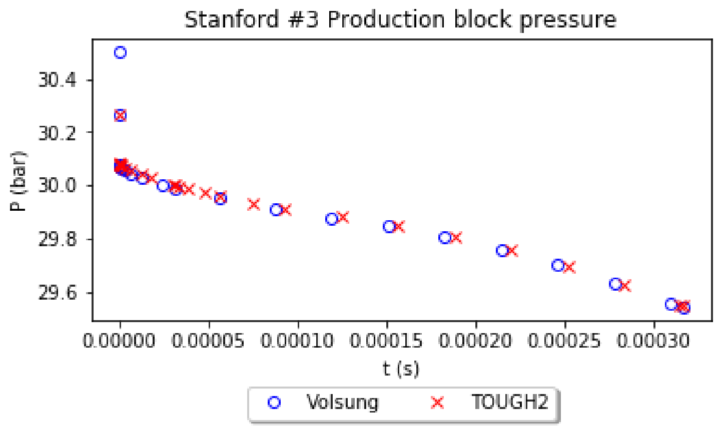


Figure 13: Results from Stanford Problem 3 for *TOUGH2* and *Volsung*

2.6 Stanford Problem 4

The fourth problem from the Stanford code comparison study was a single column model with 20 equal sized (1000m x 1000m x 100m) blocks. The model covered a 2000m vertical extent and the top 1000m was low permeability with a conductive gradient and the bottom 1000m was higher permeability with a more convective gradient. Production was from the deeper layer at a rate of 100kg/s and the top layer was fixed. In response to production a boiling zone appeared at the top of the higher permeability zone and cool recharge downflowed. The model grid for this test case is shown in Figure 14

A comparison between production enthalpy and pressure and saturation through the model for *Volsung* and *TOUGH2* are shown in Figure 15.

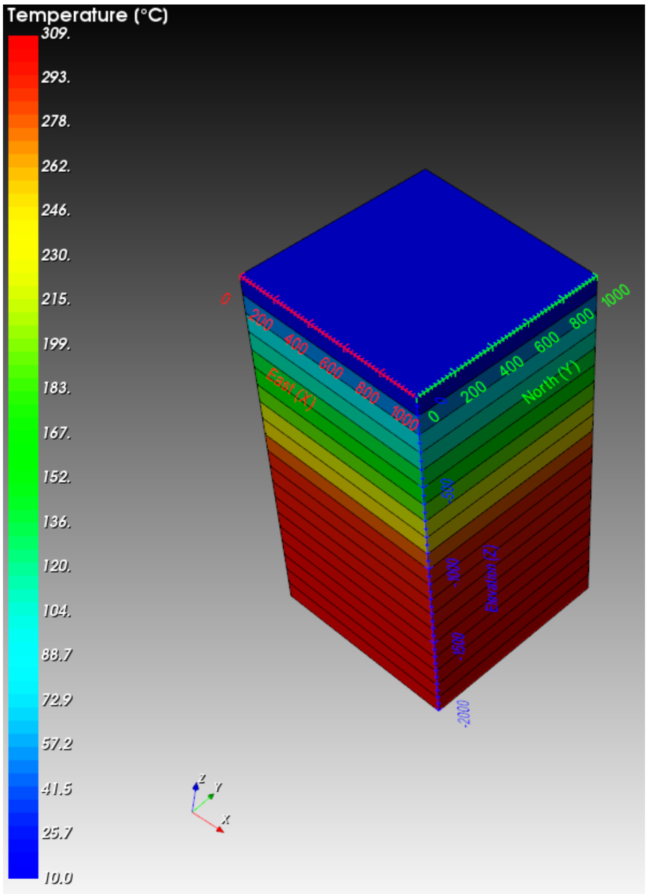


Figure 14: Stanford Problem 4 model grid

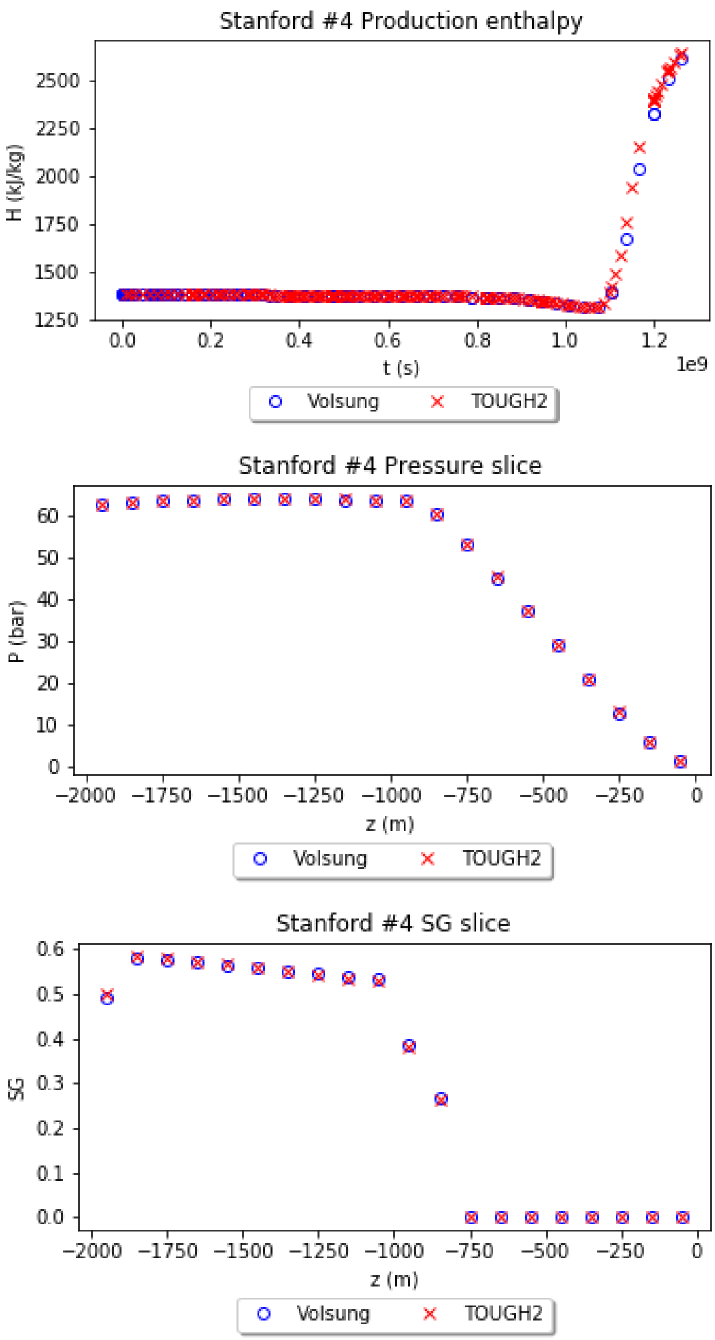


Figure 15: Results from Stanford Problem 4 for *TOUGH2* and *Volsung*

2.7 Stanford Problem 5

The fifth problem from the Stanford code comparison study was a 2-dimensional model covering a 300m by 200m rectangle. The model was initialised with a temperature gradient as can be seen in Figure 16. Production of 5 kg/s was

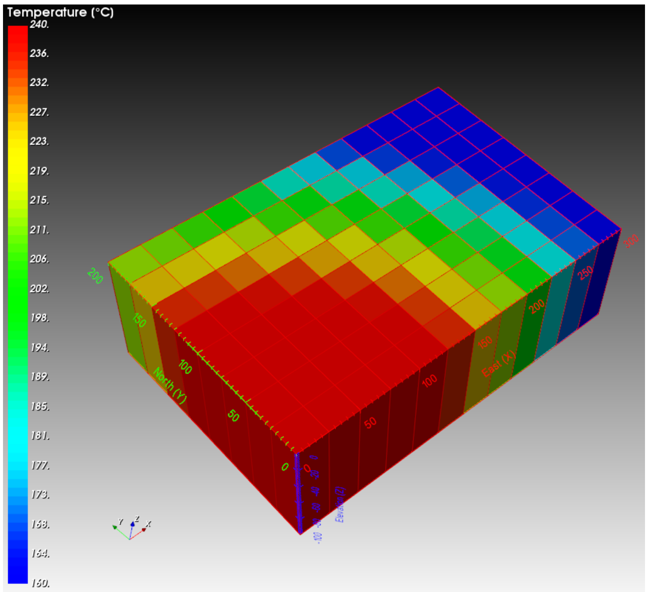


Figure 16: Stanford Problem 5 model grid

from the hot region of the model and a forecast was run for 10 years. A comparison between production enthalpy and gas saturation in the well block for *Volsung* and *TOUGH2* is shown in Figure 17.

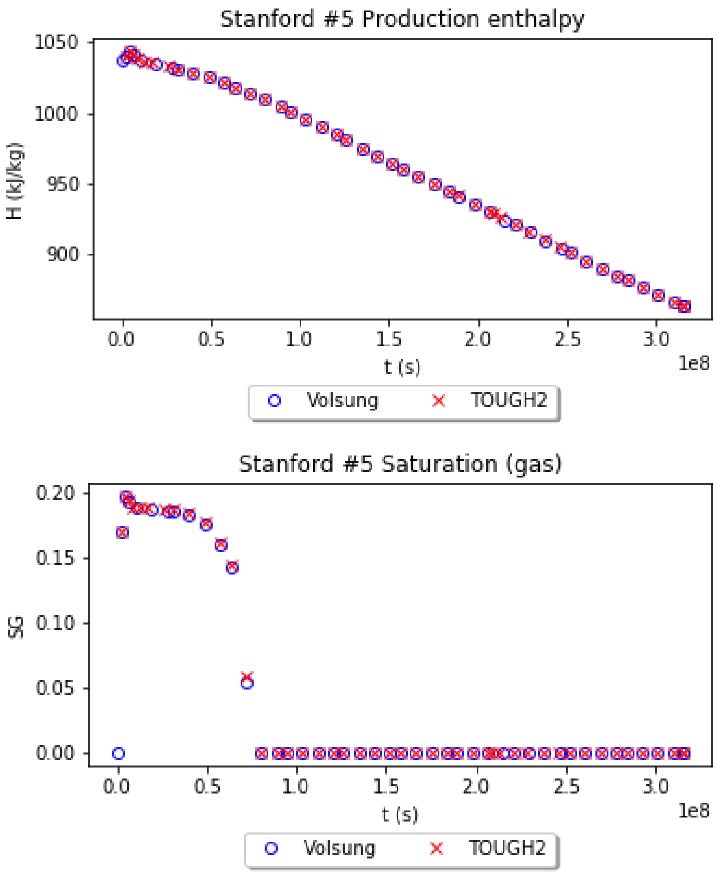


Figure 17: Results from Stanford Problem 5 for *TOUGH2* and *Volsung*

2.8 Stanford Problem 6

The sixth problem from the Stanford code comparison study was a three-dimensional model with single phase liquid at depth sitting under a two-phase zone with immobile steam. At the top of the model was a zone of colder single phase water. Production was from below the two-phase zone at a rate of 1000 kg/s for the first 2 years, 2500 kg/s for the next 2 years, 4000 kg/s for the following 2 years and 6000 kg/s for the final 2 years for a proposed 8 year forecast. In both *Volsung* and *TOUGH2*, and in the simulators used in the original study, the 6000 kg/s production rate caused catastrophic pressure decline in the production zone terminating the simulations. Gas saturation and the model grid for Stanford Problem 6 is shown in Figure 18. A comparison between production enthalpy and pressure in the well block for *Volsung* and *TOUGH2* is shown in Figure 19.

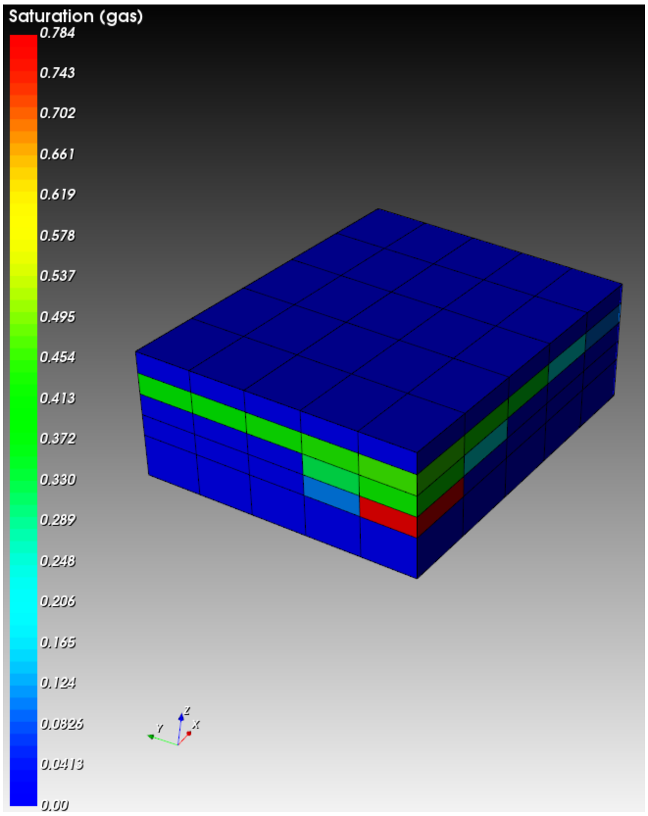


Figure 18: Stanford Problem 6 model grid coloured by gas saturation

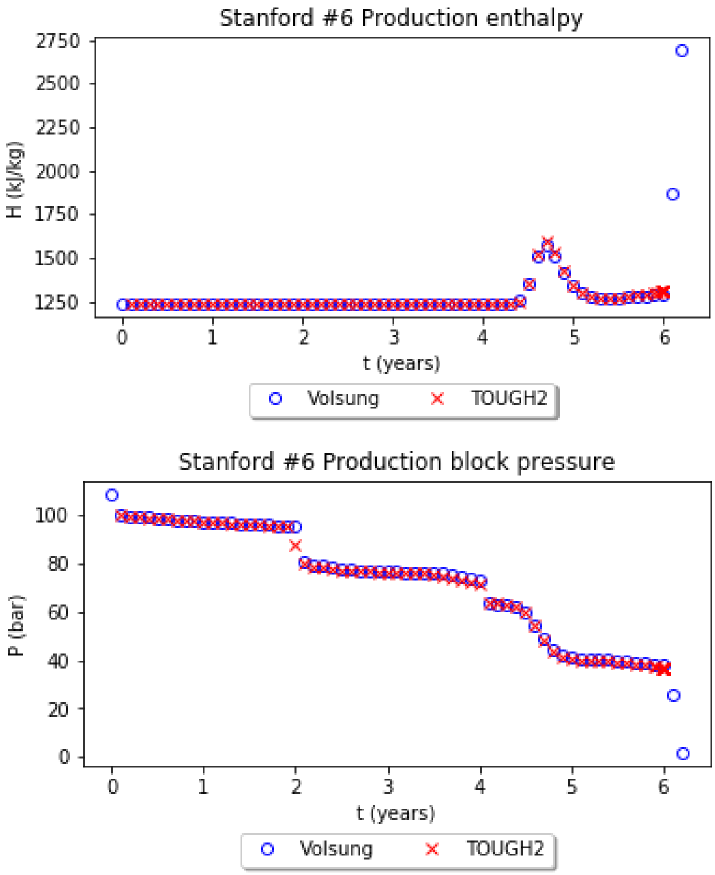


Figure 19: Results from Stanford Problem 6 for *TOUGH2* and *Volsung*

2.9 MINC Problem 1

This case was designed to test the MINC formulation of *TOUGH2* vs *Volsung*. A rectilinear model with a 500m by 500m areal extent was discretized into gridblocks of 20m x 20m horizontally. The model had a single vertical layer of 100m thickness and each grid block was divided into one fracture and two matrix elements. The basic model is shown in Figure 20. Initial conditions for the model were 304 °C and 100 bar. A 10 year simulation was run with production of 12.6 kg/s and injection of 12.6 kg/s at 220 °C. The model was run with a fracture spacings of 50m and 300m and results are shown in Figure 21

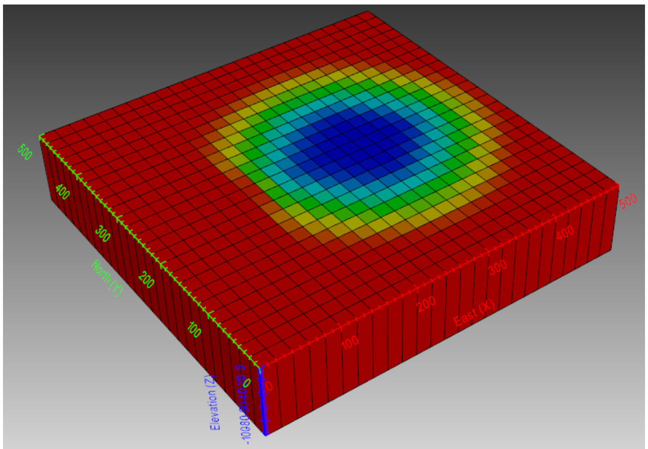


Figure 20: MINC Problem 1 model grid coloured by fracture temperature

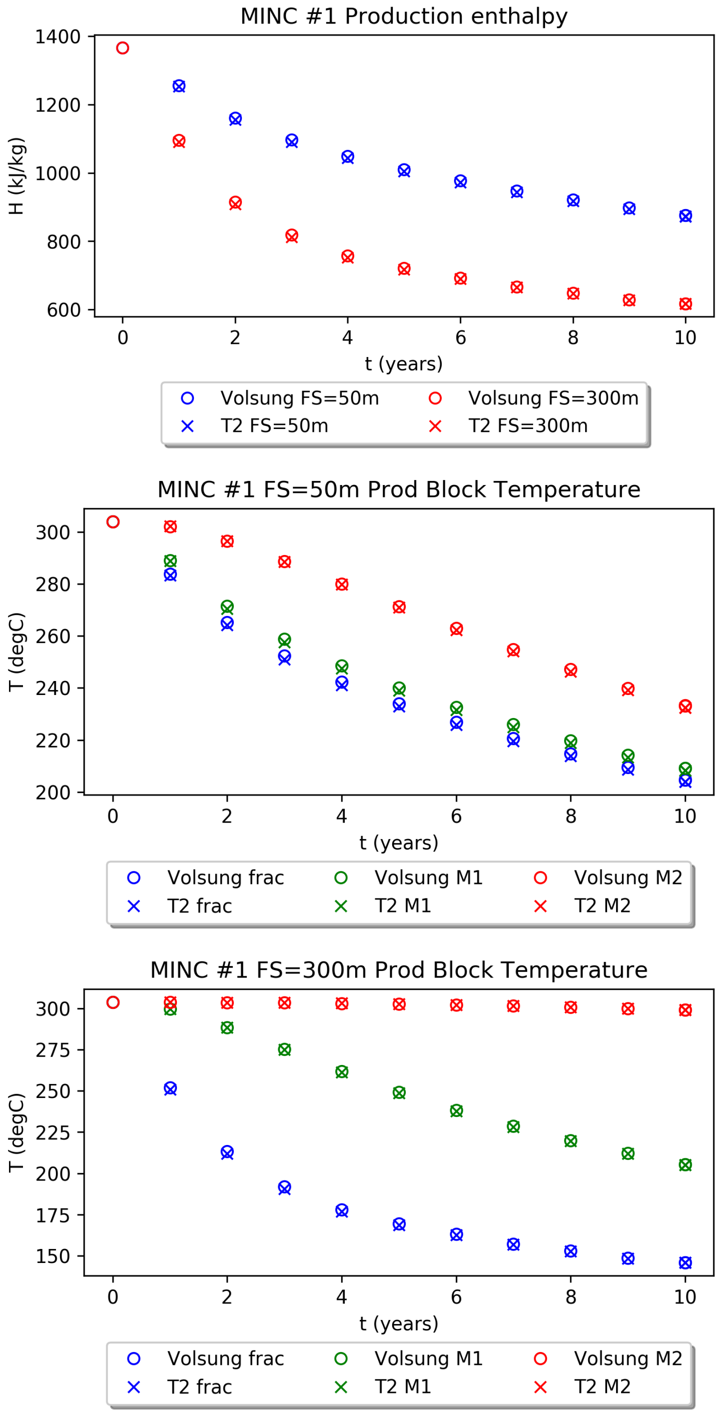


Figure 21: Results from MINC Problem 1 for *TOUGH2* and *Volsung*

3 Performance Testing

In this section model run times are assessed for *Volsung* and *TOUGH2*.

3.1 Natural State simulation

The first speed test conducted was to simulate a Natural State run. In this case a model was run from cold initial conditions for one million years. *Volsung* ran the one million year simulation in 212 seconds while *TOUGH2* took 13090 seconds showing *Volsung* was over 60 times faster. This test demonstrated there were two aspects that differed between *TOUGH2* and *Volsung*: time step length and processing time for each timestep. *Volsung* was much more stable at longer timesteps and it reached the one million year simulation in 94 time steps with a maximum timestep length of 4.4e12s while *TOUGH2* took 1139 timesteps with a maximum timestep length of 3.4e10s. The average processing time per timestep was 11.5s for *TOUGH2* and 2.25s for *Volsung*.

The model for this natural state test is shown in Figure 22. It was initialised with conditions of 300 bar and 20 °C. A block in the lower corner of the model was set to have a fixed pressure and temperature boundary condition of 500 bar and 250 °C. Mass was extracted from a block in the upper oposite corner at a rate of 1 kg/s. In this manner the model slowly heated up as cooler fluid was extracted from the top of the model and hotter fluid entered the model via the fixed block at bottom.

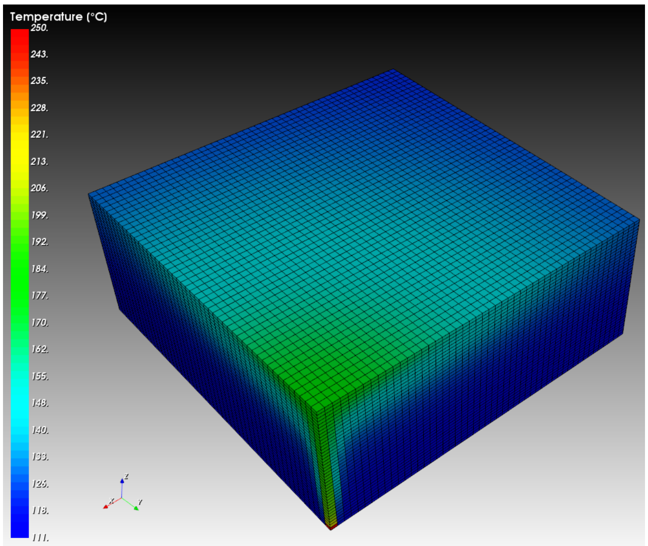


Figure 22: Natural State test model grid

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3.2 Production simulation

In a natural state run a user would get the benefit of increased stability at larger timestep sizes, but in a production run the timestep may be constrained due to the need to simulate particular well flow rates or transient processes in the reservoir. Accordingly, a series of production history tests were run. The Stanford Problem 4 was used as a base for this, but instead of a column model it was converted into a rectilinear grid with varying degrees of spatial discretization. Three model grids were tested with dimensions 30x30x20 (18,000 gridblocks), 50x50x20 (50,000 gridblocks) and 70x70x20 (98,000 gridblocks). The 98,000 gridblock model is shown in Figure 23

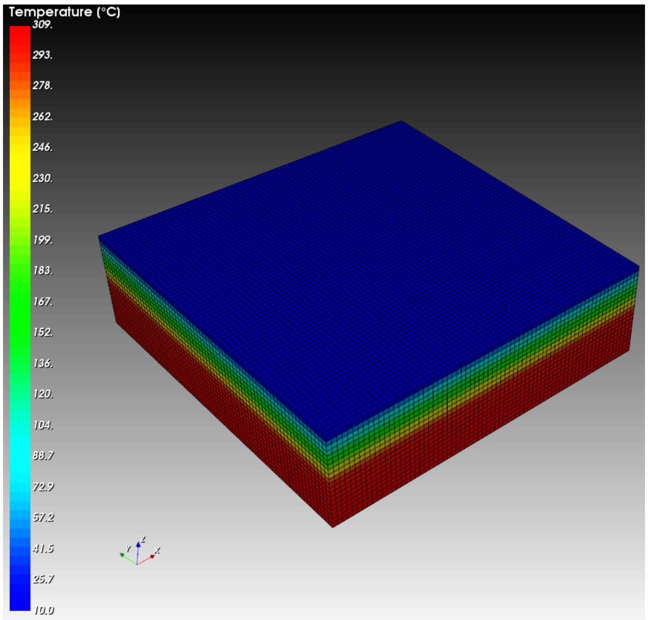

Figure 23: Production model with 98,000 gridblocks

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Because timestep size was restricted in the production simulations this test provides a comparison of how quickly the simulators calculate each timestep. Because a similar model was run with various levels of spatial discretization it's possible to see how this difference in run time scales with model size. In the 18,000 block model *Volsung* took 50s and *TOUGH2* took 145s for a speedup factor of about 3. In the 98,000 block model *Volsung* took 179s and *TOUGH2* took 1232s for a speedup factor of about 7. Runtime results for the models are summarised in Table 4.

Test	Blocks	Volsung on GTX1070		TOUGH2		Speedup factor
		Timesteps	Runtime (s)	Timesteps	Runtime (s)	
NS	100,000	94	**212**	1139	**13090**	61
Prod	18,000	301	**50**	339	**145**	3
Prod	50,000	301	**99**	300	**452**	5
Prod	98,000	301	**179**	300	**1232**	7

Table 4: Volsung vs TOUGH2 speed. Speedup factor is the runtime of TOUGH2 divided by the runtime of *Volsung*

3.3 Graphics cards and operating systems

Results in the previous section were given for *Volsung* run under Linux with a GTX-1070 NVIDIA graphics card. These models were also run under Linux with a GTX-1050 GPU and also under Windows 10 using a GTX-1070. The simulation code was identical in each of these cases so it took the same number of steps independent of the GPU or operating system. The time taken to solve the simulation was different though and these simulation runtimes are summarised in Table 5.

Test	Blocks	Volsung GTX1050	Volsung GTX1070	Volsung WIN10 GTX1070
		Runtime (s)	Runtime (s)	Runtime (s)
NS	100,000	457	212	580
Prod	18,000	62	50	174
Prod	50,000	162	99	356
Prod	98,000	299	179	611

Table 5: Volsung speed on different GPUs and when run on Linux vs Windows

References

[1] Department of Energy. PROCEEDINGS SPECIAL PANEL ON GEOTHERMAL MODEL INTERCOMPARISON STUDY. Technical Report December, Stanford, 1980.

[2] Karsten Pruess, Curt Oldenburg, and George Moridis. *TOUGH2 User's Guide, Version 2.0*. Number November. LBNL-43134, 1999.