MODELING OF ALCOHOL TRACER TEST IN VAPOR-DOMINATED GEOTHERMAL RESERVOIR

Adrianto[1], Ryuichi Itoi[1] and Toshiaki Tanaka[1]

[1]Department of Earth Resources Engineering, Faculty of Engineering,

Kyushu University, Fukuoka 819-0395, Japan

adrianto@mine.kyushu-u.ac.jp

Keywords: *alcohol, tracer test, injection, reservoir modeling, vapor dominated reservoir*

ABSTRACT

Numerical studies of tracer test in vapor-dominated geothermal reservoir are conducted using two-dimensional cross sectional model. To investigate the flow path of the injected water, we used alcohols (methanol, ethanol, propanol, and butanol) as two-phase tracers. A pair of production-injection well scheme is used. TMVOC module of TOUGH2 simulator is used to simulate alcohol movement in the model.

Sensitivity studies on parameters such as permeability and porosity are conducted over the range of reasonable value applicable to the vapor-dominated geothermal reservoir. Varying injection location is also conducted to observe injected fluid movement toward the production well.

1. INTRODUCTION

Water injection into the reservoir is a common practice in a geothermal development. In the case of vapor-dominated reservoir, water injection mostly aims to recharge water into reservoir. If there is no injection, the reservoir would 'dry out'. Thus, the remaining energy in the reservoir rock cannot be extracted. However, a proper implementation of injection should be applied to avoid some setbacks due to a poor injection strategy. Horne (1985) discussed in detail three main injection problems, *i.e.*: maintaining reliable and consistent injectivity, loss of production performance due to invasion of reinjected water, and determining where the water goes.

To determine where the water goes, tracer test is the most powerful reservoir engineering tool. Development of tracer materials shows a good progress. Liquid-phase, vapor-phase, and two-phase tracers have been employed in many geothermal fields (Fukuda *et al.*, 2004; Hirtz *et al.*, 2010; Iglesias *et al.*, 2010; Maturgo *et al.*, 2010; Mella *et al.*, 2006). They were injected either in a single or in combination.

In addition, several attempts of tracer test analysis have been made by many authors. Pruess (2002) reported mathematical representation and thermodynamic properties of tracers. Shook (2001) provided a method for predicting thermal breakthrough in heterogeneous media from tracer tests. Wu *et al*. (2005) presented a method to calculate swept pore volume and thermal breakthrough under two-phase flow condition.

When cold liquid water is injected into the reservoir, some fraction of injected water will boil and move toward the producer in the vapor phase. In order to understand about the flow of the injected fluid, we need two-phase tracers which can be dissolved both in liquid and vapor water.

Fundamental studies on thermal stability of alcohols to investigate its potential as tracer were reported by Adams *et al*. (2004). Since that time, alcohol is used as a two-phase tracer in some geothermal fields. Fukuda *et al*. (2005) injected four alcohols (methanol, ethanol, i-propanol, and n-propanol) to trace the injectate flow in the Matsukawa field. They analyzed the tracer return curve qualitatively.

A quantitative analysis was conducted by Hirtz *et al*. (2010), to trace the amount of steam derived from water injected into Darajat reservoir using alcohols and perfluorocarbons. Sato *et al*. (2005) carried out numerical simulation of liquid and two-phase tracers by using TOUGH2-EOS7R in a part of Kakkonda geothermal field, Japan. The phase partitioning behaviors of tracer (alcohols) were simplified by assigning Henry's law constant in the model.

In this paper, we simulated the tracer flow in the reservoir using TOUGH2-TMVOC. Instead of using a simplified estimation of phase partitioning behavior of alcohol, we input alcohol property data into the simulator. Example cases were demonstrated to simulate tracer flow in the reservoir. The aim of the present study is to carry out a simulation of tracer test on a simple 2D model of a vapor-dominated geothermal reservoir by providing detail tracer properties in order to produce a more accurate prediction of injection effects.

2. MODEL DESCRIPTION

TMVOC is an extension of TOUGH2 general-purpose simulation program developed at the Lawrence Berkeley National Laboratory. TMVOC is implemented as a specialized module in the framework of TOUGH2, and it retains the general process capabilities and user features of TOUGH2 (Pruess *et al*., 2002). Simulation of multicomponent mixtures of volatile organic chemicals (VOCs) such as alcohol can be conducted by using TMVOC. Therefore, we use TMVOC to examine example cases of tracer flow in a geothermal reservoir in this work.

2.1 Initial and Boundary Conditions

A generic 2D-cross sectional model of vapor-dominated geothermal reservoir based on Darajat geothermal field was developed by Kaya *et al*. (2010). Rock parameters assignment and boundary condition of their model are mostly implemented to construct our model. However, our model applying constant rate production rather than a prescribed flowing bottom-hole pressure with a productivity index.

Model dimensions are 5,000m length × 10m width ×3,800m depth. The grid system used in this simulation study is 44×1 laterally, and 31 layers. Eight different rock materials were assigned in the model as shown in Figure 1. Permeabilities, porosities and other petrophysical properties are summarized in Table 1 and Table 2.

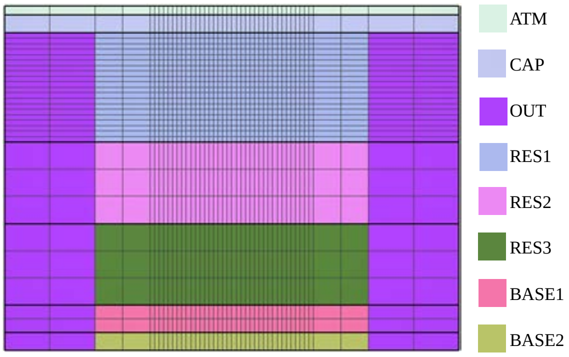

Figure 1: Distribution of rock materials

Table 1. Assignment of permeability and porosity

Material	Horizontal permeability (10^{-15} m^2)	Vertical permeability (10^{-15} m^2)	Porosity (-)
ATM	1,000	1,000	1
CAP	0.008	0.008	0.05
RES1	125	100	0.1
RES2	40	20	0.1
RES3	8	4	0.1
BASE1	1	1	0.01
BASE2	0.5	0.5	0.01
OUT	0.05	0.05	0.01

Table 2. Other rock properties

Heat conductivity (W/m-°C)	2.5
Specific heat (J/kg-°C)	1,000
Relative permeability	Grant's curve
S_{lr}	0.3
S_{gr}	0.05

The atmospheric conditions of 1bar pressure and 15°C temperature were maintained at the top boundary. It is not possible to produce a stable steady-state vapor-dominated system by applying constant mass and energy flows at the base of the model (O'Sullivan, 1990). McGuinness *et al.* (1993) showed that a vapor-dominated reservoir must have saturation control at depth. Thus, we set a constant pressure and saturation boundary conditions (120bar pressure and 0.3 vapor saturation) at some grids at the most bottom layer. Conductive heat flux (0.06 W/m^2) was also applied at the bottom layer (see Figure 2).

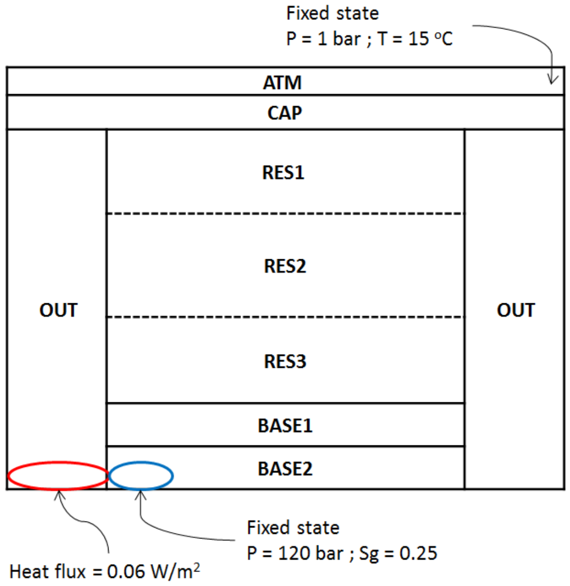

Figure 2: Boundary conditions for natural state simulation

2.2 Natural State Simulation

Figure 3 to Figure 5 show the distribution of vapor saturation, pressure and temperature under a stable steady-state condition. High vapor saturation mostly located in the upper reservoir (RES1). A heat source from the eastern part of the bottom reservoir creates gradual decrease of temperature in the reservoir zone from west to the east. Figure 6 illustrates pressure and temperature profiles at depth throughout the A-A' (in Figure 5). Vapor-dominated zone with 229-233 °C and 34-37 bar was formed in the upper reservoir (RES1).

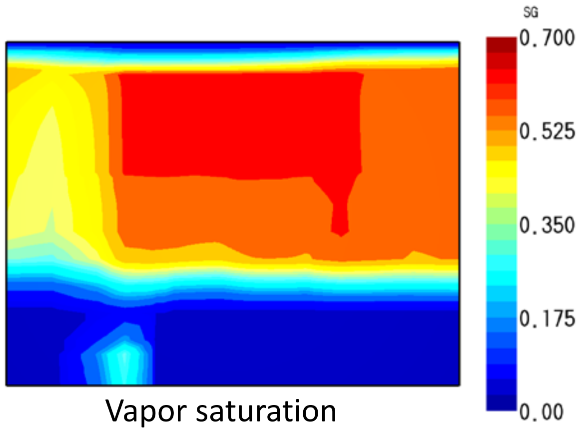

Figure 3: Vapor saturation distribution under natural state condition

Energy extraction was introduced by producing 1 kg/s constant mass rate from a single production well. Figure 7 plots vapor saturation history of produced fluid during the first year of production phase. During a year period of production, the produced fluid evolves from two-phase water into saturated steam.

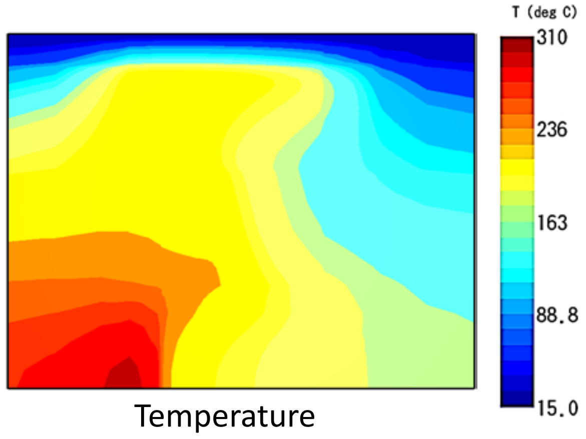

Figure 4: Temperature distribution under natural state condition

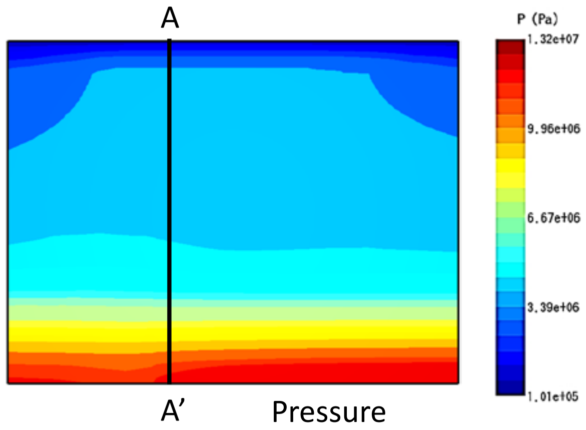

Figure 5: Pressure distribution under natural state condition

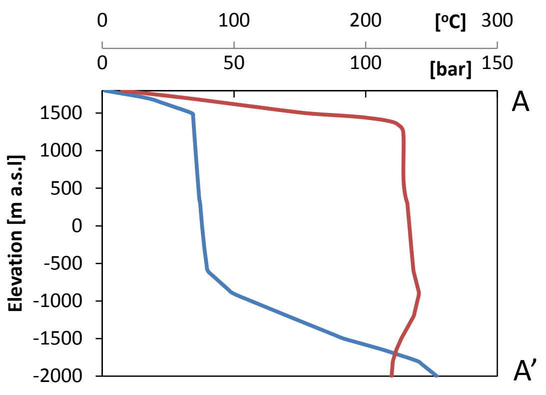

Figure 6: Pressure and temperature profiles along A-A'

At least, there are two losses due to absence of mass recharge. Firstly, if the production from this well is continued, as time passes the produced fluid would become superheated steam. Geothermal power plant requires saturated steam for its supply. For instances, design condition for units in The Geysers range from saturated to more than 30^{o}F superheat (Fesmire, 1993). If the superheat degree from produced steam exceeds the design condition, steam should be desuperheated prior to use in the turbine. Steam desuperheating will decrease the available energy, which would tend to decrease generation. Thus, producing superheated steam is a disadvantage for geothermal power operation. Secondly, the reservoir would 'dry out', so the remaining energy in the reservoir cannot be extracted.

Water injection is necessary to overcome the lack of fluid mass in the reservoir. However, not all injection schemes could achieve beneficial impact. Therefore, tracer test should be carried out to examine the prospect of injection scenario.

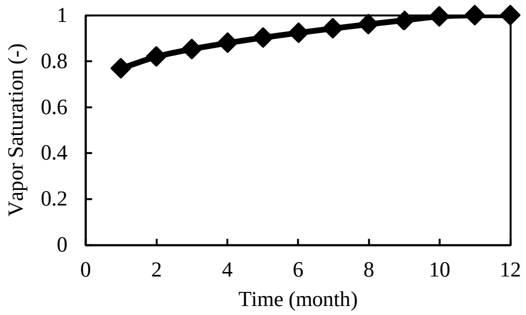

Figure 7: Vapor saturation history at production well before tracer injection

3. TRACER TEST SIMULATION

Due to the existence of both steam and water in the reservoir, we need to employ tracer that can partition in both phase. For that reason, low-carbon alcohol was selected to be examined in this study. Physical and chemical properties of alcohol are widely available in the literature. In this study, we used four types of alcohol as tracer.

The necessary alcohol properties for TMVOC input data are available in the literature. Table 3 summarizes the thermodynamics properties of methanol, butanol, propanol and butanol given by Reid *et al.* (1987). Simulation using alcohol is restricted by alcohol critical temperature. Reservoir temperature should not exceed the alcohol critical temperature; otherwise the simulation run will crash.

Methanol has the lowest critical temperature (512.6 K ≈ 239.45 ^{o}C) among the four alcohol used in this study. From natural state simulation, the highest temperature in the reservoir zone is 233 ^{o}C. Thus, we can utilize all of four alcohols to simulate tracer flow in our model.

3.1 Base case

Water injection is carried out after one year production. Temperature of injected fluid is 30^{o}C. Due to large density difference between injected fluid (liquid) and reservoir fluid (almost all vapor), gravity force will dominate the flow of injected fluid. Thus, we allocate injection point above the production point. The position of injection well is illustrated in Figure 8. Both of them are situated in the upper reservoir (RES1). The vertical distance and horizontal distance between those wells are 180 and 100 m, respectively.

In the base case model we used ethanol as tracer. Ethanol properties are not available in TMVOC database. Therefore we created a new VOC material which represents ethanol.

Firstly, injection-production scheme was run for 10 days. After 10 days of water injection, a slug tracer was injected into the reservoir along with cool water. The total injection rate is 1 kg/s, which consists of 50% water and 50% ethanol. It took 1000 s to inject 500 kg of ethanol into the reservoir (RES1). The simulation was run for 2 years simulation time.

Figure 8: Position of producer and injector

Figure 9 shows the tracer distribution in the reservoir: 10 days, 1 month, 3 month and 5 month after tracer injection. TMVOC displays the ethanol concentration in mole faction. We may convert the unit of ethanol concentration from mole fraction to mass fraction by using following formula (Pruess, 2002):

$$X^{\kappa} = \frac{x^{\kappa} M_{\kappa}}{\sum_j x^j M^j} \cong \frac{x^{\kappa} M^{\kappa}}{18.016} \quad (1)$$

Where X denotes the mass fraction and x is the mole fraction. M_{κ} is the molecular weight of component κ. The sum appearing in the denominator may be approximated by just retaining the water contribution, because ethanol is treated as dilute aqueous solution.

3.2 Sensitivity study

History matching is one of the most important phase in reservoir simulation. It includes pressure matching, temperature matching as well as enthalpy matching. By using TMVOC, simulated tracer return history should also be matched with the measured data. This sensitivity study aims to investigate the effect of parameters in the model on generated tracer return curve.

3.2.1 Injection well location

In order to obtain the maximum benefit from injection, several aspects of injection should be properly designed. Determination of injection well location is one of the main issues in reservoir engineering.

Table 3. Alcohol properties for TMVOC input data

Parameter	Methanol	Ethanol	1-Propanol	1-Butanol
Molecular Weight, AMO (g/mol)	32.042	46.069	60.096	74.123
Normal Boiling Point, TBOIL (K)	337.7	351.4	370.3	390.9
Critical Temperature, TCRIT (K)	512.6	513.9	536.8	563.1
Critical Pressure, PCRIT (bar)	80.9	61.4	51.7	44.2
Critical Volume, VOLCRIT (cm^3/mol)	118	167.1	219	275
Critical compressibility, ZCRIT	0.225	0.24	0.253	0.259
Pitzer's Acentric Factor, OMEGA	0.556	0.644	0.623	0.593
Dipole Moment, DIPOLM (debyes)	1.7	1.7	1.7	1.8
Ideal Gas Heat Capacity Constant, CPA	2.115E+01	9.014E+00	2.470E+00	3.27E+00
Ideal Gas Heat Capacity Constant, CPB	7.092E-02	2.141E-01	3.325E-01	4.18E-01
Ideal Gas Heat Capacity Constant, CPC	2.587E-05	-8.390E-05	-1.855E-04	-2.24E-04
Ideal Gas Heat Capacity Constant, CPD	-2.852E-08	1.373E-09	4.296E-08	4.69E-08
Vapor Pressure Constant, VPA	-8.54796	-8.51838	-8.05594	-8.00756
Vapor Pressure Constant, VPB	0.76982	0.34163	0.0425183	0.53783
Vapor Pressure Constant, VPC	-3.1085	-5.73683	-7.51296	-9.3424
Vapor Pressure Constant, VPD	1.55481	8.32581	6.89004	6.68692
Density for NAPL, RHOREF (kg/m^3)	791	789	804	810
Ref. Temperature for NAPL, TDENREF (K)	293	293	293	293
Liquid NAPL Viscosity Constant, VLOA	-2.687E+01	-6.210E+00	-1.228E+01	-9.722E+00
Liquid NAPL Viscosity Constant, VLOB	1.150E+03	1.614E+03	2.666E+03	2.602E+03
Liquid NAPL Viscosity Constant, VLOC	1.8710E-01	6.1800E+03	2.0080E-02	9.5300E-03
Liquid NAPL Viscosity Constant, VLOD	-5.2110E-04	-1.1320E-05	-2.2330E-05	9.9660E-06
Ref. Binary Diffusivity of VOC in Air, DIFVO (m^2/s)	1.5978E-05	1.2200E-05	1.0184E-05	8.8975E-06
Ref. Temperature for Gas Diffusivity, TDIFREF (K)	298.15	298.15	298.15	298.15
Chemical Diffusivity Exponent, TEXPO	1.75	1.75	1.75	1.75

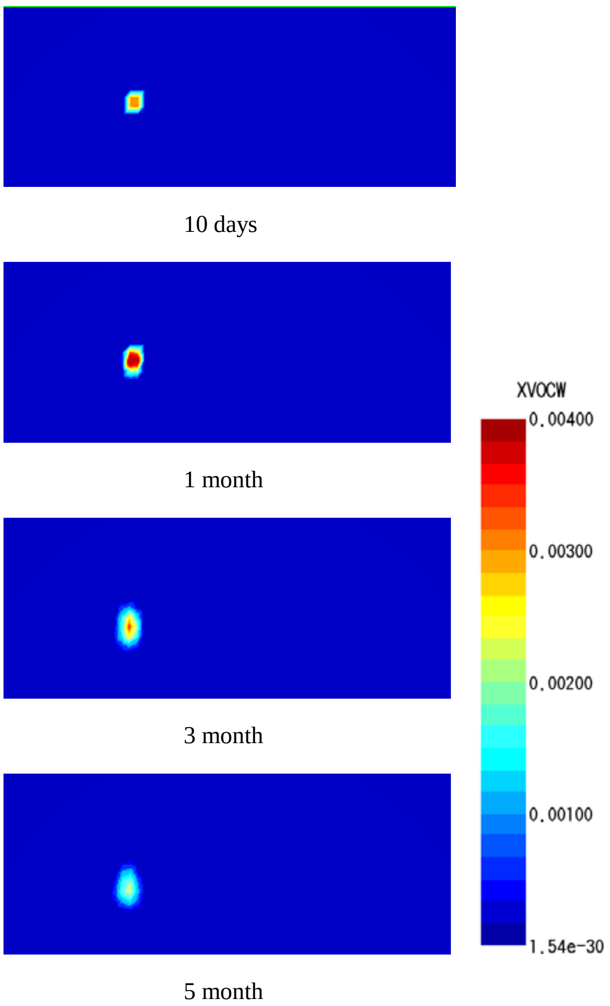

Figure 9: Distribution of tracer in RES1: 10 days, 1 month, 3 months and 5 month after tracer injection (base case model)

We built three pairs of injection-production pattern with different distance in vertical and horizontal directions. In Case 1, injection point is allocated 180 m above the production point. Case 2 is the base case. In Case 3, injection point is placed at the same depth with production point. Figure 10 illustrates the situation of injection and production well for each case.

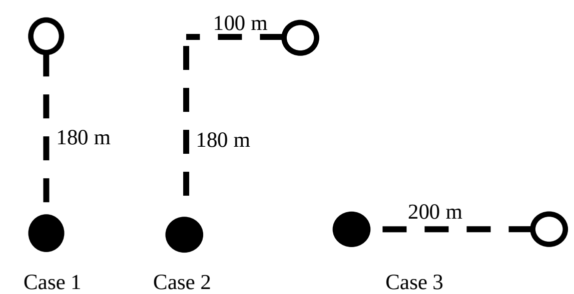

Figure 10: Position of injector and producer for Case 1, Case 2, and Case 3

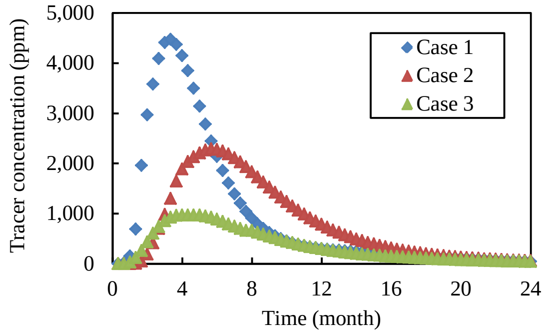

Figure 11: Tracer return curve for different position of injection well

Figure 11 shows the tracer return curve for Case 1, Case 2 and Case 3. Case 1 gives the highest peak concentration among others. As mentioned before, injected fluid flows mostly dominated by gravity force. In line with this reason, Case 3 has the lowest peak concentration and also the lowest tracer recovery.

3.2.2 Rock parameters

A real geothermal reservoir is a heterogeneous anisotropic fractured porous medium. Well testing, well logging and coring are usually conducted to estimate the distribution of petrophysical properties in the subsurface. Then several rock materials are assigned on the basis of these information. However, sometimes a good history matching is difficult to be achieved. Therefore, we need an adjustment of rock parameters, such as porosity and permeability.

In this section, we investigated the effect of rock parameters, porosity and permeability, on tracer return curve. Figure 12 shows that the lower the reservoir porosity, the higher the peak concentration of tracer return curves. In addition, the peak time also appears earlier. A lower porosity reservoir has a smaller fluid storage. Thus, the higher fraction of injected fluid will occupy the reservoir pore volume.

High permeability will result in a faster fluid flow. By increasing permeability from 60 md to 120 md, Figure 13 confirms that rationale. The highest peak concentration and the earliest arrival time are found for the case with 120 md.

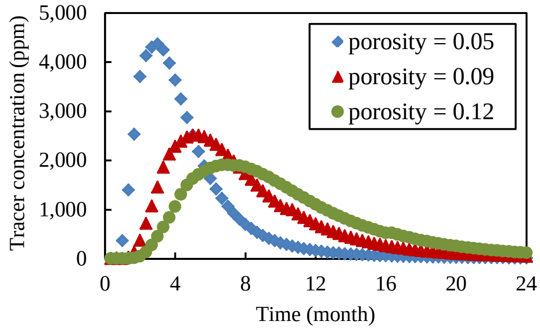

Figure 12: Tracer return curve for different reservoir rock porosity

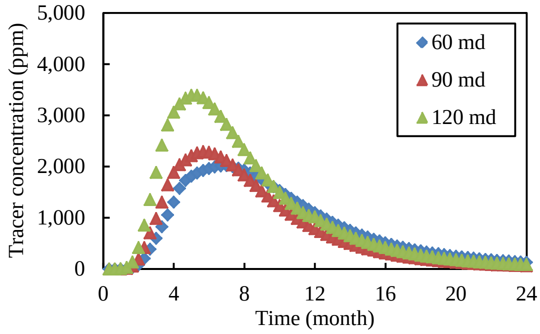

Figure 13: Tracer return curve for different reservoir rock permeability

3.2.3 Alcohols

We investigated four tracer injection scenarios with different alcohols used as tracer. Methanol, ethanol, propanol and butanol were examined. Figure 14 shows that peak concentration value varies from the highest to the lowest in the following order: methanol-ethanol-propanol-butanol. In other words, the most detectable alcohol is methanol. However, it should be noted that the critical temperature of methanol is the lowest among the others. Therefore, we cannot use methanol if the reservoir temperature exceeds the critical temperature of methanol.

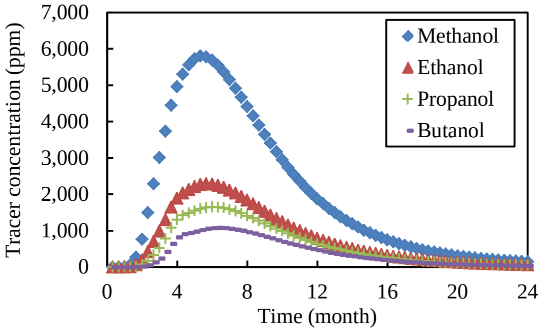

Figure 14: Tracer return curve for different alcohol

From Figure 14, the first return of each tracer seems appear at the same time. However, if we zoom in the time scale into day, we can see that there are differences among them. The earliest return of alcohol happened when we used methanol. It took 31 days after injection (cut-off concentration = 10 ppm). While, the first return of butanol was detected at the latest time among the four alcohols. The order of peak concentration time for each alcohol follows the order of initial detection time (see Table 4).

Table 4. Initial detection and peak concentration time for each alcohol

Alcohol used	Initial detection time (day)	Peak concentration time (day)
Methanol	31	160
Ethanol	40	170
Propanol	47	180
Butanol	56	190

4. CONCLUSION

A 2D cross-sectional model of vapor dominated geothermal reservoir is constructed using TMVOC module of TOUGH2 simulator. Our model shows that TMVOC is able to simulate alcohol tracer injection in a geothermal reservoir. With graphical interface, we can see where the tracer goes.

Sensitivity studies of rock parameters give us knowledge on how the tracer return curve affected by reservoir porosity and permeability. From our simulation, methanol is the most detectable alcohol tracer. However, due to a relatively low critical temperature compared to other alcohols, we need to make it sure that reservoir temperature is not higher than methanol critical temperature for numerical simulation.

ACKNOWLEDGEMENTS

The first author would like to thank to Monbukagakusho for the scholarship and GCOE program, Kyushu University for their support to this research.

REFERENCES

Adams, M.C., Yamada, Y., Yagi, M., Kasteler, C., Kilbourn, P., Dahdah, N.: Alcohols as two-phase tracers. *Proc. 29th Workshop on Geothermal Reservoir Engineering*, Stanford University. (2004).

Fesmire, V.R.: The Geysers Steam Field Decline Study. *GRC Transaction*. Vol. 37, pp. 235-241. (1993).

Fukuda, D., Asanuma, M., Hishi, Y., Kotanaka, K.: Alcohol tracer testing at the Matsukawa vapor-dominated geothermal field, Northeast Japan. *Proc. 30th Workshop on Geothermal Reservoir Engineering*, Stanford University. (2005).

Hirtz, P.N., Kunzman, R.J., Adams, M.C., Roberts, J.W., Sugandhi, A., Mahagyo, P., Iman, A.S.: First Multi-well vapor and two-phase tracer test in a geothermal reservoir, using perfluorocarbons and alcohols. *Proc. World Geothermal Congress 2010*, Bali, Indonesia. (2010).

Horne, R.N.: Reservoir engineering aspects of reinjection. *Geothermics*, Vol.14, No. 2/3, pp. 449 – 457. (1985).

Iglesias, E.R., Arment, R.F., Torres, R.J., Montes, M.R., Picasso, N.R., Delgado, L.R.: Simultaneous liquid- and vapor-phase tracer study in Tejamaniles area of the Los Azufres, Mexico, geothermal field. *Proc. World Geothermal Congress 2010*, Bali, Indonesia. (2010).

Kaya, E. and O'Sullivan, M.: Modelling of injection into vapor-dominated geothermal systems. *Proc. World Geothermal Congress 2010*, Bali, Indonesia. (2010).

Maturgo, O.O., Sanchez, D.R., Barroca, G.B.: Tracer test using naphthalene dissulfonate in Southern Negros geothermal production field, Philippines. *Proc. World Geothermal Congress 2010*, Bali, Indonesia. (2010).

McGuinness, M.J., Blakeley, M., Pruess, K., O'Sullivan, M.J.: Geothermal heat pipe stability: solution selection by upstreaming and boundary conditions. *Transport in Porous Media 11*, pp. 71-100. (1993).

Mella, M., Rose, P., McCulloch, J., Buck, C.: A tracer test using ethanol as a two-phase tracer and 2-naphtalene sulfonate as a liquid-phase tracer at the Coso geothermal field. *GRC Transaction*. Vol. 30, pp. 919-921. (2006).

O'Sullivan, M.J.: A simple model of a vapor dominated geothermal reservoir. *Proceedings of the TOUGH Workshop,* Lawrence Berkeley Laboratory. Berkeley, California, pp. 37-43. (1990).

Pruess, K. and Battistelli, A.: TMVOC, a numerical simulator for three-phase non-isothermal flows of multicomponent hydrocarbon mixtures in saturated-unsaturated heterogeneous media. *LBNL-49375*, Lawrence Berkeley National Laboratory, Berkeley, CA, USA. (2002).

Reid, R.C., Prausnitz, J.M., Poling, B.E.: The properties of gases and liquids. *McGraw-Hill*, New York, (1987).

Sato, K., Sakagawa, Y., Omiya, T.: Numerical Simulation of liquid and two-phase tracers in a part of the Kakkonda geothermal field, Japan. *Proc. 30th Workshop on Geothermal Reservoir Engineering*, Stanford University. (2005).

Shook, G.M.: Predicting thermal breakthrough in heterogeneous media from tracer tests. *Geothermics* Vol. 30, pp. 573-589. (2001).

Wu, Xingru., Pope, G.A., Shook, G.M., Srinivasan, S.: A method of analyzing tracer data to calculate swept pore volume and thermal breakthrough in fractured geothermal reservoirs under two-phase flow conditions. *Proc. 30th Workshop on Geothermal Reservoir Engineering*, Stanford University. (2005).