Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Computational Study of Two Phase Flow with Flash Boiling in Geothermal Wells

Vijay Chauhan, Gudrun Saevarsdottir, Yonatan A. Tesfahunegn, Einar Asbjornsson, Maria Gudjonsdottir

School of Science and Engineering, Reykjavik University, Menntavegur 1, 101 Reykjavík, Iceland

vijay@ru.is

Keywords: CFD; flashing; geothermal; two-phase flow

ABSTRACT

The paper presents application of Eulerian two phase flow Computational Fluid Dynamics (CFD) model for simulating flash boiling in a geothermal well. The simulation uses a six-equation model with separate mass, momentum, and energy balance equations for the liquid and vapor phases, and, is available in Ansys Fluent. The model takes into account the inter-phase mass, momentum and energy transfer occurring due to phase change. Simulations for a wellbore were carried out and validated using available pressure-temperature data logs and mass flow measurements. Results from the model show agreement with the available data for the location of the point of flashing and steam quality at the wellhead.

1. INTRODUCTION

It is important to evaluate the production performance of any geothermal well in order to optimize the resource utilization for power generation. The wellbore production data obtained from measurements help to identify the permeable zones inside the wellbore, which is used to optimize its geometry and design of surface equipment. A better understanding of wellbore production data can be obtained by the study of fluid flow and the heat transfer processes inside the wellbore. Due to the complexity and the cost required for performing experiments regarding geothermal wells, numerical modelling has been widely used as a tool for this study.

Since the development of geothermal utilization started, a number of wellbore models have been proposed by the researchers for simulating fluid flow in a geothermal well. A multi-feed zone geothermal wellbore simulator, HOLA, was proposed by Bjornsson (1987). The model allows to reproduce the pressure and temperature profiles in flowing wells and determining the contribution of each feed zone. A multipurpose wellbore simulator was presented by Hadgu and Freeston (1990). The code was set up in two versions WFSA (Well Flow Simulator A), which handles dissolved solids but no gases and WFSB (Well Flow Simulator B), which handles the presence of gases. The model allows for simulation of wellbores with flow from multiple feed zones with adequate feed zones information. Later, a wellbore simulator, WELLSIM, was implemented by Gunn and Freeston (1991) which combined WFSA and WFSB with STFLOW (built to model saturated and superheated steam typical of wellbore located in vapour-dominated zones). A model named GEOWELL for simulating one dimensional steady and transient state in a well was proposed by Garcia (2006). The model involves solving mass, momentum, and energy governing equations using a segregated numerical scheme. The simulator was applied with another code ORKISZEWSKI (Orkiszewski, 1967) for modeling the heat and fluid flow processes inside some wells drilled in Mexican geothermal fields. The result shows good agreement with the measured data. Another one-dimensional steady state model named Flowell was proposed by Gudmundsdottir (2012). The simulator solves the continuity, energy, and momentum equation using the built in functions available in Matlab. The model shows good agreement with a simulation done for a liquid dominant well in Svartsengi, Iceland.

Simulating a geothermal wellbore requires the modelling of two phase flow in the well with internal flashing, occurring due to pressure drop because of static head, wall friction, and turbulence. Pressure drop in the geothermal well causes the liquid to become superheated corresponding to the local pressure. The degree of superheat attained, however, has a limit, above which the vaporization occurs and is commonly referred to as flashing or cavitation. The theory of flashing and cavitation is well explained by Pinhasi et al. (2005). The fundamental difference between flashing and cavitation is the pressure (or temperature) level, at which it occurs. Cavitation refers to bubble formation, which occurs at low pressure so that the bubble expansion is mainly controlled by mechanical non-equilibrium or the pressure difference at the bubble interface. During the process of cavitation, a small degree of superheat is enough to initiate and maintain the vaporization process. The cavitation occurs in flows involving a sudden drop in pressure. Flashing on the other hand, is mainly characterized by thermal non-equilibrium or the temperature difference across the interface similar to the normal boiling process. The bubble growth rate is therefore limited by the heat transfer rate across the interface. The flashing process is found to occur in processes involving a gradual change in pressure such as that occurring in a vertical geothermal wellbore.

Due to the complexity of the nature of flashing occurring in geothermal wellbores, simplified and empirical assumptions are often adopted in wellbore simulation models. One-dimensional or so called the system code approach is adopted for modelling. The system code modelling approach assumes parameters to be varying only in one direction, which is in the direction of fluid flow in the geometry. In addition, non-equilibrium effects are either ignored completely or considered partially. As explained by Pinhasi et al. (2005), flashing phenomena involving a two-phase mixture is strongly of three-dimensional nature. A number of investigations using two or three-dimensional Computational Fluid Dynamics (CFD) have been published recently (Liao and Lucas, 2017). The CFD approach offers an advantage of providing detailed information about the spatial distribution of the phases. For an application involving simulation of a wellbore, a more detailed information regarding the flow characteristics can be obtained using the CFD approach. Also, the CFD approach involves solving conservation equations along with the geometrical co-ordinates, unlike that of the system or component based approach, which mainly relies on empirical relations. The CFD approach is thus found to be more reliable for complex geometries such as a wellbore with inclined axis and varying cross-sectional area. The three-dimensional CFD approach, however, faces a drawback with regards to the normal system based simulators. Wellbore simulations using the CFD approach involve high computation cost compared to the normal system based wellbore models. The computational cost is however justified by the degree of detailed information obtained using the CFD approach.

Some promising research has been published on flashing flow using the CFD approach based on the two-fluid model for bubbly flow. A four-equation model assuming a common velocity field of both phases was applied by Maksic and Mewes (2002) for simulating flashing flows in pipes and nozzles. The model assumes that interphase heat transfer occurs due to conduction. The work done by Wallis (1980), however, shows convection as a dominating mechanism for heat transfer in a two-phase flow. Ignoring the convective term due to slip velocity between the phases, therefore leads to an underestimation of the vapour generation rate. Laurien and Giese (2003) applied a five equation model for modelling flow through a three-dimensional pipeline involving steady state pressure change. The model includes two continuity equations and two momentum equations for liquid and vapour phase respectively and one energy equation for the liquid phase. Frank (2007) applied a five-equation model for simulating the well-known blow-down test (Edwards and O´Brien, 1970) using a one-dimensional simplified mesh in CFX, a code from Ansys. The application of a two-phase model requires interfacial area density for calculating the interface exchange terms. For this, a simplified assumption of constant bubble diameter was assumed. Another work from Laurien (2003) presumes bubble number density instead of bubble diameter. This allows bubble size to grow, which corresponds better to an actual boiling process. The assumption, however, requires an additional transport equation for the bubble number density with appropriate source terms. In the work done by Laurien (2003), the momentum interaction was taken into account by modelling the drag force only. Later work from Liao and Lucas (2014) shows the effect of non-drag forces on the spatial distribution of phases. A six-equation model using the Euler two-phase approach, available in ANSYS FLUENT was used by Marsh and O´Mahony (2009) for simulating flashing flow through a nozzle. The model consists of separate equations for mass, momentum and enthalpy balance for liquid and vapour. The model takes into account the inter-phase mass, momentum, and energy transfer occurring due to phase change and nucleation. Another work from Mimouni et al. (2008) shows the application of a six-equation model for simulating cavitating flows.

The present work shows the application of the Euler two-phase, six equation model available in ANSYS FLUENT for simulating flashing in a geothermal well. The thermal phase change model is applied for calculating the mass transfer due to phase change. The simulation pertains to a geothermal well with available data log for temperature, pressure, and mass flow rate.

2. MATHEMATICAL MODEL

The six equation model consists of an ensemble-averaged mass, momentum, and energy equations for individual phases. The steam is assumed to be in the saturated state corresponding to the local absolute pressure. The thermal phase change model selected considers only thermal non-equilibrium during the flashing process with common liquid and gas phase pressure. A common pressure field p is, therefore, assumed for both phases.

Equations for the mass, momentum and energy conservation for the individual phase i are given as follows (Liao et al. 2013):

$$\frac{\partial}{\partial t}(\alpha_i \rho_i) + \nabla \cdot (\alpha_i \rho_i \boldsymbol{U}_i) = M_i \tag{1}$$

$$\frac{\partial}{\partial t}(\alpha_i \rho_i \boldsymbol{U}_i) + \nabla \cdot (\alpha_i \rho_i \boldsymbol{U}_i \boldsymbol{U}_i) = -\alpha_i \nabla p + \nabla \cdot \left[\alpha_i \mu_{eff,i} (\nabla \boldsymbol{U}_i + (\nabla \boldsymbol{U}_i)^T)\right] + \alpha_i \rho_i g + M_i \boldsymbol{U_i} + F_i \tag{2}$$

$$\frac{\partial}{\partial t}\left(\alpha_i \rho_i \left(H_i - \frac{p}{\rho_i}\right)\right) + \nabla \cdot \left(\alpha_i \rho_i \boldsymbol{U}_i H_{tot,i}\right) = \nabla \cdot [\alpha_i \lambda_i \nabla T_i] + M_i H_{tot,i} + E_i \tag{3}$$

where α_i, ρ_i, λ_i, and $\boldsymbol{U}_i$ are the volume fraction, density, heat conductivity and velocity field of phase i. The effective viscosity (μ_{eff}) is the sum of molecular and eddy viscosity. The last terms in equations M_i, F_i, and E_i represents the interphase mass, momentum and energy transfer respectively and $H_{tot,i}$ is the total energy of phase i given in terms of specific heat capacity ($C_{p,i}$), temperature (T_i) and phase velocity (U_i) as:

$$H_{tot,i} = C_{p,i} T_i + \frac{1}{2} |\boldsymbol{U}_i|^2 \tag{4}$$

As discussed in the introduction section, the interphase mass transfer is assumed to occur by phase change (thermal non-equilibrium) which is given as:

$$M_i = \frac{E_l}{H_{tot,g} - H_{tot,l}} \tag{5}$$

where subscripts g and l defines the gas and liquid phase respectively and E_l is the sensible heat flux from the bulk water transferring from the steam-water interface given as:

$$E_l = h_l (T_l - T_{sat}) A_i \tag{6}$$

where h_l is the heat transfer coefficient calculated using Ranz-Marshall correlation (Ranz and Marshall, 1952).

The interfacial area density (A_i) is calculated as a function of volume fraction and bubble diameter (d_g), given by the following relation:

$$A_i = 6 \frac{\alpha_g}{d_g} \tag{7}$$

The effect of nucleation which initiates the phase change process is not modelled directly. Therefore in order to assure successful initiation of phase change, an average initial diameter for bubbles has to be provided along with a minimum steam volume fraction (Liao et al. 2013). The present study assumes a minimum bubble diameter of 1mm with an inlet volume fraction of 10^{-8}.

Interphase momentum transfer occurs between the phases, caused by interfacial forces acting on each phase due to interaction with the other phase. The present work takes into account lift force, drag force, lubrication force and turbulent dispersion force. The net interphase momentum transfer term is given as:

$$F_i = F_{lift} + F_{drag} + F_{wall\ lubrication} + F_{turbulent\ dispersion} \quad (8)$$

The details of the physical model for each force is available in literature (Liao and Lucas, 2017).

Solving the conservation equations requires the value of eddy viscosity, which is to be provided by reasonable turbulence modelling. In the present work, so called dispersed phase turbulence model is used for estimating the steam eddy viscosity. The eddy viscosity of the water is calculated using the Standard k-ω turbulence model. The influence of the bubble phase on the turbulence is taken into account by selecting the Sato model as described inthe Ansys user guide (ANSYS 15.0). The simulation requires a value of surface roughness for calculating the wall shear stress. A constant value is assigned for the present study. The computation model enables the inclusion of heat transfer along the surface wall. The present study, however, assumes adiabatic wall conditions.

3. RESULTS

To demonstrate the application of the CFD model for simulating flash boiling in a geothermal wellbore, simulations were done for flow in a geothermal wellbore in Þeistareykir, Iceland. The temperature and pressure log data from the wellbore shows the presence of two-phase state of the fluid at the wellhead. The inner diameter of the wellbore casing is 178 mm. Though the total wellbore depth including the slot liners is 2493 m, the size of the geometry used for simulation was 400 m long. The length of the geometry of the wellbore includes the two-phase region above the flashing point and a portion of the single-phase liquid zone. The selected volume of the wellbore used for the simulation can be justified by the fact that the temperature before the flashpoint in the liquid zone is almost constant. In addition, no other contribution to the mass flow occurs in the liquid zone due to additional feed zones in the region. Simulating liquid zone below the flashpoint, therefore does not add much information. The initial boundary conditions for the simulation are from the data log measurement and assumptions given in Table 1.

Table 1: Parameters for the model simulation

Parameter	Boundary	Value
Mass flow rate	Inlet	31.42 kgs^{-1}
Temperature	Inlet	458.6 K
Wellhead pressure	Outlet	4.2 bar (absolute)
Heat flow	Wall	0 W/m2 (adiabatic)
Roughness constant	Wall	0.5

Figure 1 (left) shows the variation of total pressure along the depth of the wellbore. As seen from the figure, the values obtained from the simulation agree with that from the data log. A shift in the simulation curve is observed with respect to the curve from the data log. The deviation is supposed to occur due to the approximate value of the surface roughness chosen. It is to be noted that the pipe roughness is an independent variable and needs to be determined by measurement. The value of surface roughness, however, varies with changing pipe surface conditions due to fluid chemistry. An approximate value of surface roughness is thus chosen for the simulation, given in Table 1. Figure 1 (right) shows the variation of the fluid temperature along the depth of the wellbore. The temperature profile obtained from the simulation agrees to a reasonable extent with that from the data log. A deviation in the temperature values is observed in the two-phase region of the fluid near the wellhead. This can be explained based upon the data logger gauges accuracy and the applied approximate relation used for the saturation temperature and pressure based on linear interpolation. At low pressure, the saturation temperature is more sensitive to the change in the value of pressure. A more accurate relation for the saturation temperature as a function of saturation pressure can improve the accuracy.

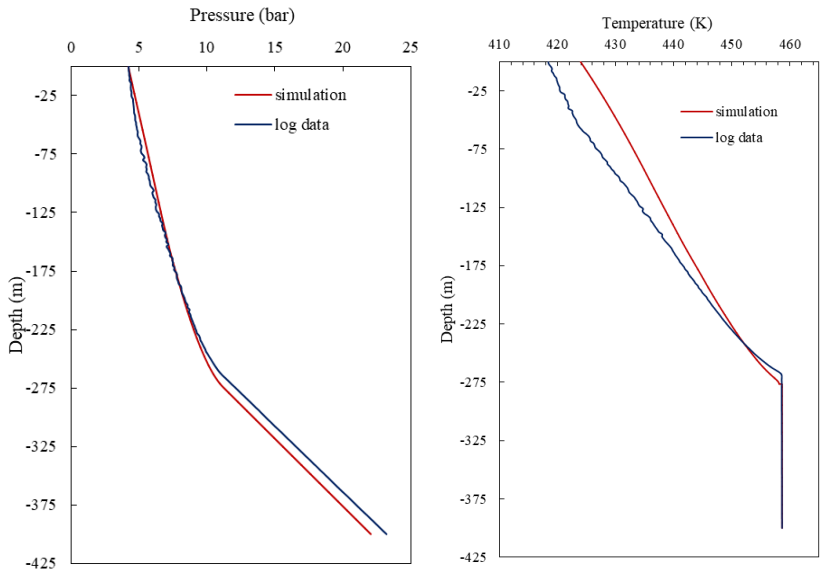

Figure 1: Variation of total pressure and temperature along the wellbore depth

Figure 2 shows the simulated values of the volume fraction of steam along the axis of the well. The steam volume fraction remains zero until flashing occurs when the surrounding pressure drops below the saturation limit. The bubble generation then occurs due to nucleation. The steam volume fraction then starts to increase due to bubble expansion caused by pressure decrease, and heat transfer because of thermal non-equilibrium between the bubble and the surrounding liquid. Minor fluctuations in steam volume fraction along the depth can be seen in the figure, which can be overcome by increasing the simulation time and mesh refinement.

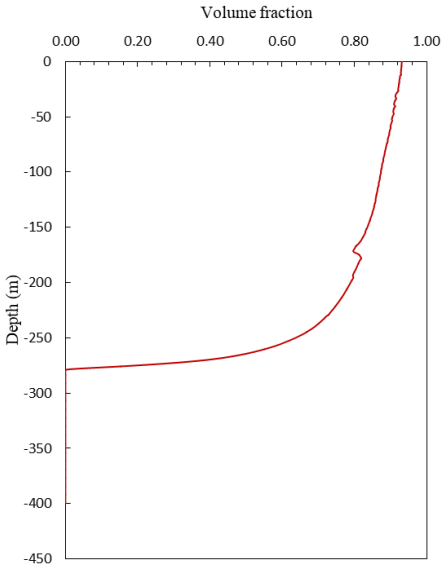

Figure 2: Variation of vapour volume fraction along the well depth

Figure 3 shows the volume fraction of steam along the radial direction at different cross-sections along the wellbore. The curve with blue marks shows the cross-section area in the liquid zone with no steam fraction, while the other two curves represent the saturated two-phase region. As seen from the figure, the computational model calculates the variation of flow variables in three-dimensions. Since flashing is a three-dimensional phenomenon as mentioned earlier in section 1, the vapour fraction is found to vary both axially and radially in the wellbore. As shown in the Figure 3, the vapour fraction is found to be high in the near wall region. This is due to the lift force which pushes the bubbles towards the wall in a vertically upward flow as explained by Colin et al. (2000).

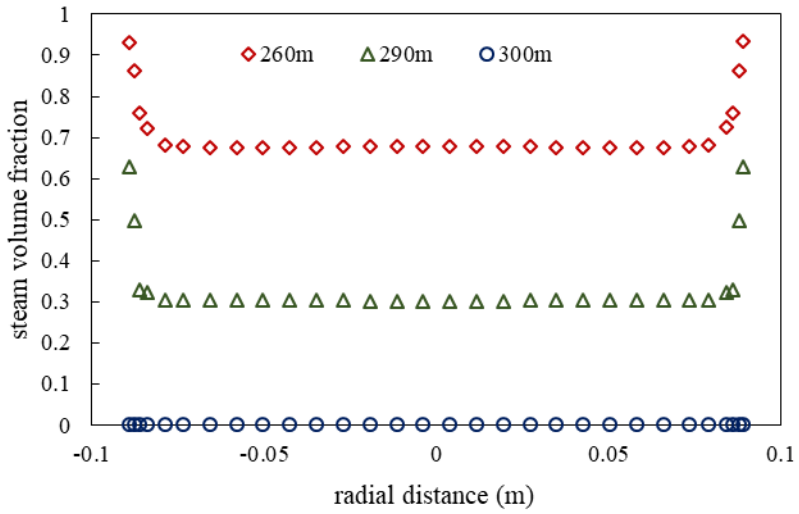

Figure 3: Variation of vapour volume fraction along the radial direction for different cross-sections of the well

4. CONCLUSION

Fluid flow in a geothermal wellbore was modelled using the Euler two-phase fluid model. Simulation results for temperature and pressure for the case of a geothermal wellbore in Þeistareykir, Iceland, shows agreement with that of the well log data. The present work is mainly focused on the validation of the two-fluid CFD approach for simulating fluid flow with flashing in geothermal wells. The CFD model simulation is based on solving conservation equations for each phase in three-dimensions, thus giving a more realistic representation of the phenomena of flashing, which is a three-dimensional process. Since the model is not built using geometry based empirical relations for obtaining the fluid flow field variables as used in system based simulators, the CFD model can be used for

studying geothermal wellbores with more complex geometries and additional feed zones in order to obtain a better understanding of the fluid flow and heat transfer processes in two-phase flow in geothermal wells.

ACKNOWLEDGEMENTS

The work was funded by Rannis Technology Development Fund. The authors like to thank Iceland Geological Survey (ISOR) and Landsvirkjun for providing data from borehole measurements.

REFERENCES

Ansys, Release 15.0. ANSYS Fluent Theory Guide, ANSYS 2013.

Bjornsson, G.: A Multi-Feedzone, Geothermal Wellbore Simulator, Earth Science Division, *Lawrence Berkeley Laboratory Report LBL-23546*, Berkeley, USA (1987).

Colin, C., Legendre, D., and Fabre, J.: Bubble distribution in a turbulent pipe flow, Microgravity Research and Applications in Physical Sciences and Biotechnology, *Proceedings of the First International International Symposium*, European Space Agency, (2001), 91-98.

Edwards, A.R., and O´Brien, T.P.: Studies of phenomena connected with the depressurization of water reactors. *J. Br. Nucl. Energy Soc*., **9**, (1970), 125-135.

Frank, T.: Simulation of flashing and steam condensation in subcooled liquid using ANSYS CFD, *Proceedings*, *5th Joint FZR & ANSYS Workshop: Multiphase Flows: Simulation, Experiment and Application*, Dresden, Germany, 26-27 April (2007).

Garcia-Valladares, O., Sanchez-Upton, P., and Santoyo, E.: Numerical Modeling of Flow Processes Inside Geothermal Wells: An Approach for Predicting Production Characteristics with Uncertainities, *Energy Conversion and Management*, **47**, (2006), 1621-1643.

Gudmundsdottir, H., Jonsson, M.T., and Palsson, H.: Coupling Wellbore Simulator with Reservior Simulator, *Proceedings,* 37th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA (2012).

Gunn, C.I.M., and Freeston, D.H.: An Integrated Steady Wellbore Simulator and Analysis Package. Proceedings, *13th New Zealand Geothermal Workshop*, Auckland, New Zealand, (1991), 161-166.

Hadgu, T., and Freeston, D.H.: A Multi-Purpose Wellbore Simulator, *Geothermal Research Council Transactions*, **14**, (1990), 1279-1286.

Laurien, E.: Influence of the model bubble diameter on three-dimensional numerical simulations of thermal cavitation in pipe elbows. *Proceedings*, *3rd International Symposium on Two-Phase flow modeling and experimentation*, Pisa, Italy, 22-24 September (2004).

Laurien, E., and Giese, T.: Exploration of the two fluid model of two-phase flow towards boiling, cavitation and stratification, *Proceedings: The 3rd International Conference on Computational Heat and Mass Transfer*, Banff, Canada, may 26-30, (2003).

Liao, Y., and Lucas, D.: Computational modeling of Flash Boiling Flows: A Literature Survey, *International Journal of Heat and Mass Transfer*, **111,** (2017), 246-265.

Liao, Y., Lucas, D., Krepper, E., and Rzehak, R.: Flashing evaporation under different pressure levels, *Nuclear Engineering and Design*, **265,** (2013), 801-813.

Maksic, S., and Mewes, D.: CFD-calculation of the flashing flow in pipes and nozzles, *Proceedings of ASME FEDSM´02*, Montreal, Quebec, Canada, 14-18 july (2002).

Marsh, C.A., and O´Mahony, A.P.: Three-dimensional modelling of industrial flashing flows, *Progress in Computational Fluid Dynamics*, **9,** (2009), 393-398.

Mimiouni, S., Boucker, M., Lavieville, J., Guelfi, A., and Bestion, D.: Modeling and computation of cavitation and boiling bubbly flows with the NEPTUNE_CFD code, *Nucl. Eng. Des*., **238,** (2008), 680-692.

Orkiszewski, J,: Predicting Two-Phase pressure Drop in Vertical Pipes. *Journal of Petroleum Technology*, **19**, (1967), 829-838.

Pinhasi, A., Ullmann, A., and Dayan, A.: Modeling of flashing in two-phase flow, *Rev. Chem. Eng*. **21**, (2005) 133-164.

Ranz, W.E., and Marshall, W.R.: Evaporation from drops-Part I. *Chem. Eng. Prog*., **48**, (1952), 141-146.

Wallis, G.B., Critical two-phase flow, *International Journal of Multiphase flow*, **6,** (1980), 97-112.