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Pyflow Wellbore Simulator

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ABSTRACT

Matching wellbore measurements with reservoir model results is a challenging task. In case of a single feed zone system, pressure and temperature measurement may match without additional computational effort. However, in cases of multiple feed zones, reservoir and wellbore pressure do not necessarily match (even at the feedpoints) due to interzonal flow. AUTOUGH2 and TOUGH2 geothermal reservoir simulators assume a constant bottom hole pressure and therefore their accuracy will be limited. However, numerical stability of deliverability models (DELV generators) can be increased by simultaneously coupling them with a wellbore simulator and updating the flowing bottom hole pressure. To accurately deal with those issues, a multipurpose 1-D flow solver has been developed in Python, named Pyflow. Pyflow can be used to calculate flow properties along a well, with a selection of single or multiple feed zones. Well flow tests can be modeled directly to fit both pressure and enthalpy values. Quite good accuracy was achieved with a standalone version of Pyflow (well flow tests) and verified by data from the Reykjanes & Hellisheidi high temperature geothermal boreholes. Simulation results showed that enthalpy of the feed zones can be assessed by using Pyflow standalone.

1. INTRODUCTION

Geothermal system utilization can be divided into three focus areas; thermal energy stored under the crust (geothermal reservoir), interactions between reservoir and borehole (extraction), and direct use of thermal energy or electricity generation (exploitation). As can be expected, sustainable use of a geothermal reservoir is highly dependent on extraction and exploitation. Geothermal borehole flow modeling has a crucial role in utilization of geothermal resources, as the operation of the geothermal reservoir is done through the extraction of the geo-fluid. Changes in pressure gradient between the reservoir and the bottom of the well can be represented as a total pressure drop between the two. When the borehole has multiple feed zones, the pressure gradient is affected by each feed zone. In many cases, boreholes intersect with the reservoir in multiple locations and geofluid will be drawn from the reservoir at each of those locations. This results in increased complexity of the flow conditions in the wellbore. Consequently, it is necessary to have a wellbore model that is capable of analyzing the flow characteristics of multiple feed zones.

Demand for research of multiphase flow has increased due to the needs of the oil and gas industry and has subsequently been adapted to geothermal wells. One of the earliest calculations showing a model of pressure drop in a multiphase flow were addressed by (Martinelli & Nelson, 1948). Adaptation to geothermal systems was achieved by coupling pressure drop with heat transfer principles. The model was validated by data from the Wairakei and Broadlands geothermal fields of New Zealand by using four vertical slip correlations for multiphase flow (Gould, 1974).

Adaptation of non-condensable gases, dissolved solids, and specific liquid phases such as NaCl liquid solution to geothermal well models, integration of user-specified calculation point (top-down or vice-versa) and multiple feed-zones have been discussed by many authors (Aunzo et al., 1991; Barelli et al., 1982; Bjornsson, 1987; Freeston & Gum, 1993; Gunn & Freeston, 1991; Ortiz - Ramirez, 1983; Takahashi, 1988). Moreover, explicit coupling methods (well output curve, look-up tables) and implicit coupling methods (e.g., updating flowing bottom hole pressure based on calculated parameters from reservoir simulator for each time step) were applied to couple wellbore simulators, such as GWELL, GWNACL, HOLA, WFSA, WFSB, WELF, FLOWELL (Aunzo et al., 1991; Gudmundsdottir, 2012; Hadgu et al., 1993, 1995; Hadgu & Freeston, 1990), to reservoir simulators e.g. TOUGH, TOUGH2, AUTOUGH2 (K Pruess, 1987; Karsten Pruess et al., 1999; Yeh et al., 2012).

In this work,1-D wellbore simulator Pyflow has been developed for investigating pressure drop based on range of mass flow rate and diameter of the pipe. Various correlations of void fraction, friction and friction correction were added to Pyflow Standalone. Additionally, multiple feed zones are integrated into the Pyflow Standalone.

2. METHODOLOGY

In this section Pyflow and its model assumptions are described. The mathematical representation of the flow in the wellbore and the governing equations are taken by (Gudmundsdottir, 2012). Finally, the development of the standalone Pyflow computer code and the implementation of multi-feed zone is discussed.

2.1 Physical Data Model of the Model

Pyflow was constructed using the programming language Python 3 (Van Rossum & Drake, 2009). By using numerical integration (without consideration of flow regimes) the continuity, energy, and momentum equations are solved along the well direction. To evaluate the differential equations, a built-in function of SCIPY is used, namely solve_ivp. The computation is performed by explicit Runge-Kutta (Bogacki & Shampine, 1989) method of order 3(2) to obtain solution.

The main core of Pyflow consist of a few fundamental functions which calculate thermodynamic conditions, a friction factor, a friction correction factor, a void fraction correction, and the differential equations based on the state of the fluid. Returned values of the functions are based on the depth interval specified by the user. To run Pyflow, input parameters are required. These parameters can either be wellhead conditions of the wellbore or bottom hole conditions. Thus, Pyflow can be run from wellhead to bottom of the well or vice versa. The architecture of the main core is illustrated in Figure 1. In addition to the main core, Pyflow has multi diameter, multi mass flow, multi feed zones, single feed zone, and coupling functions that can be selected by the user. The result can be plotted or saved in a csv file. Multi diameter and multi mass flow functions are coded to investigate pressure drop of the wellbore profile over a range of mass flow rates and liner diameters. A multi feed zones function is implemented to simulate boreholes that have multiple feed zones.

In the development phase of Pyflow, few assumptions were made to calculate fluid flow in the wellbore. These are:

- The flow in the wellbore is assumed to be in steady state and one dimensional.
- Phases are in thermodynamic equilibrium.
- Existence of dissolved solids and non-condensable gases are ignored.
- The fluid is assumed to be pure substance, and revised release on the IAPWS97 (IAPWS, 2007) is used to calculate thermodynamic properties of the fluid. Revised release of IAPWS 2006 (IAPWS, 2009) formulation is used to calculate the dynamic viscosity of the pure substance.

The continuity, energy, and momentum equations are assembled in the matrix system and embedded into the code. Numerical integration to the system of ordinary differential equations is implemented into the standalone version with the following capabilities:

- Modelling of superheated steam flows.
- Modelling of user specified number of multi feed zones and input parameters.
- Selection of casing and slotted liner diameter.
- Selection of roughness of the pipe based on depth.
- Performing wellbore calculation from wellhead to bottom hole or vice versa.
- Various selection of friction factor, friction correction factor and void fraction.
- Selection of ODE solver method (RK45, RK23, DOP853).
- Experimental module for investigating wellbore pressure drop profile as a function of various mass flow rates and well diameter.

To run the simulation by using Pyflow, the following input parameters are needed:

- Initial conditions at the wellhead or at the bottom of the well.
  - Pressure, enthalpy, and total mass flow
- Geometry of the well.
  - Casing depth
  - Casing inner diameter
  - Slotted liner depth
  - Slotted liner inner diameter

- Additional parameters (based on user selection).
  - Distribution parameter of void fraction (Rouhani & Axelsson, 1970)
  - Roughness of the well

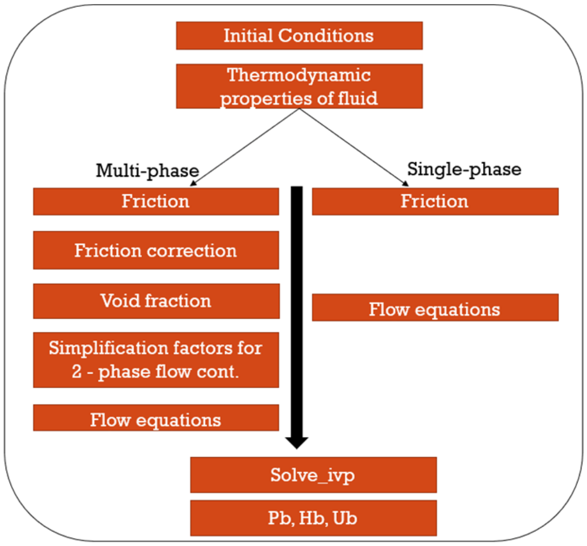

Figure 1: The main core architecture of Pyflow: the fundamental functions of the code to compute the pressure at wellhead or at the bottom hole of the well.

When running a simulation, Pyflow executes the following components in consecutive order:

1. Validation of the user provided data. If a necessary input is missing, Pyflow raises an error, and assumes default value.
2. Based on input parameters, Pyflow computes the thermodynamic condition of the fluid for a given interval.
3. If the fluid is in multi-phase, friction, void fraction, and simplification factors will be calculated and fed into the function that calculates ΔP, ΔH, and ΔU for a given interval. If it's not, same routine will be followed but friction correction and void fraction are ignored.
4. The system of ordinary differential equations (the calculated ΔP, ΔH, ΔU) are numerically integrated by solve_ivp. The solutions for pressure, enthalpy, and velocity are saved for each interval.
5. Validation of the energy balance for multi feed zones simulation. If the energy balance of the wellhead (or the bottom of the well for the reverse simulation) is not equal to the overall energy balance at the multi feed-zones, Pyflow raises an error message to check the energy balance.

2.2 Development of the Computer Code

This section contains the main work frame of Pyflow Standalone. Flow charts of the module are represented with the additional features of Pyflow.

<u>2.2.1 Pyflow Standalone</u>

Main purpose of the standalone version is to match with measured pressure and temperature values during the discharge of the well. Call is made from standalone version to main core of Pyflow where necessary functions to solve the flow in borehole are imported. Standalone version has built in functions. Those are:

- From_top_to_bottom
  - Run_single_feed
  - Run_multi_feed
- From_bottom_top

- Run_single_feed
- Run_multi_feed

Flow chart of Pyflow Standalone is represented in Figure 2. To run the code, functions that represent the type of the calculation (e.g., bottom to top, top to bottom, single feed, and multi feed) must be imported. By calling the functions mentioned above with the necessary input parameters simulation will be run.

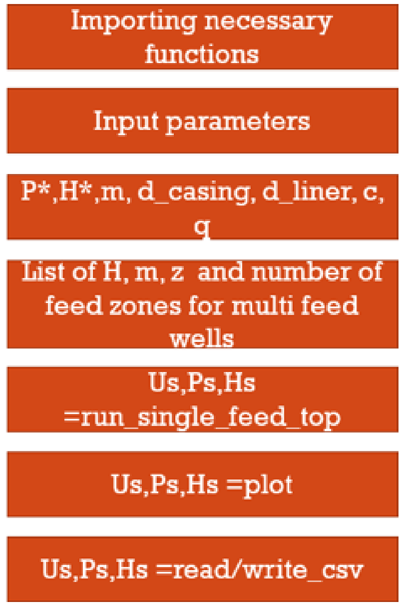

Figure 2: The main workflow of Pyflow Standalone. Same input parameters apply for multi-feed simulations except, list of enthalpies, mass flows, and depth intervals. P* and H* represent wellhead or bottom hole pressure & enthalpy, and depend on the type of simulation.

Pyflow is capable of simulating wells with multiple feed zones. Lists of the mass flow rates, enthalpies, depth intervals of the feed zones, and number of feed zones are the additional input parameters for the multi feed zone module of Pyflow. Flow chart of the multi-feed zone module is illustrated in Figure 3. Simulations are divided into intervals between the feed zones, casing, and liner. If the simulation is run from top to bottom, then Pyflow:

1. Calculates the thermodynamic variables of the fluid from wellhead to the end of the casing. Simulation continues until it reaches the first feed point.
2. Saves the calculated point pressure above the feed zone.
3. Updates changes in the mass flow at the feed zone.
4. Calculates the energy balance of the mixture based on mass and enthalpy of the feed zone.
5. Runs the simulation with the new inputs (3, 4) and the saved point pressure (2)
6. Continues simulation until it reaches a new feed zone or the end of the well.

If the user wishes to run a simulation from bottom to top, the routine mentioned above will be the same, but in a different order:

1. Calculates the thermodynamic variables of the fluid from bottom hole to first feed point.
2. Saves the calculated pressure point below the feed zone.
3. Updates changes in the mass flow at the feed zone.
4. Calculates the energy balance of the mixture based on mass and enthalpy of the feed zone.
5. Runs the simulation with the new inputs (3, 4) and the saved point pressure (2).
6. Continues the simulation until it reaches a new feed zone or the end of the liner.

Multi-feed zone simulations are performed with Pyflow by simply looping the single feed zone simulations according to each feed zone characteristics and applying the mass and enthalpy balance. Due to the complexity of the two-phase flow, mass flow rate and the enthalpy of the liquid & gas phases are assumed uniform. Therefore, energy balance is calculated based on a mixture of the enthalpies and the mass flows. Energy balance equation for bottom to top can be represented as:

$$\dot{m}_u h_u + \dot{m}_{in} h_{in} = \dot{m}_{ab} h_{ab} \quad (1)$$

Where, $\dot{m}_u h_u$ is flowing mass flow and enthalpy of the fluid under the feed zone. $\dot{m}_{in} h_{in}$ represents mass flow and enthalpy of the feed zone and $\dot{m}_{ab} h_{ab}$ represents mixture of the mass flows and enthalpies above the feed zone. Therefore, calculated $\dot{m}_{ab}, h_{ab}$ can be used as mass flow rate and enthalpy inputs for the simulation.

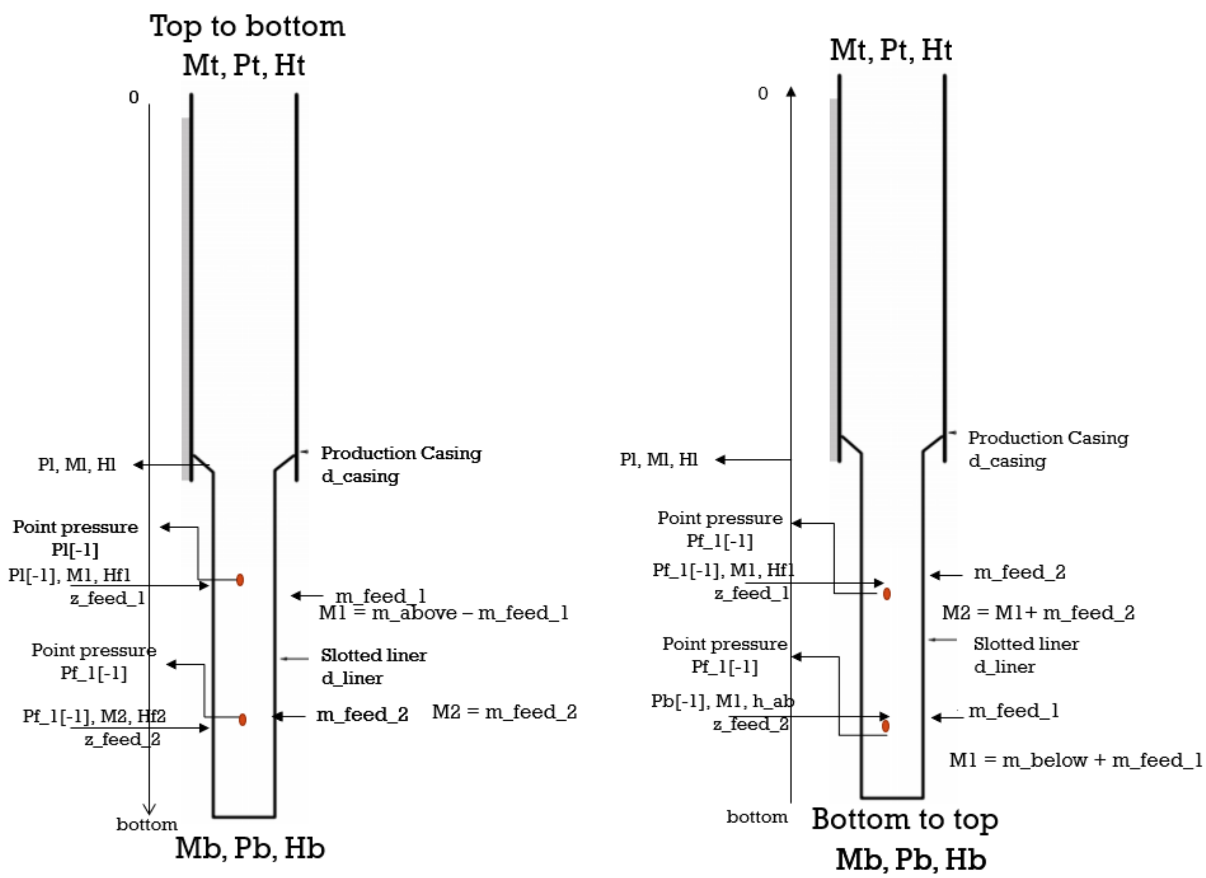

Figure 3: Flow diagram of Pyflow multi_feed_zone module for top to bottom & bottom to top. Subscript "l" represents slotted liner, "b" bottom, "t" top, and "f_1" feed zone one. From top to bottom, "Pl[-1]" represents point pressure to be used for the feed zone pressure.

3. RESULTS

To validate the Pyflow standalone, well discharge test records from two geothermal fields, Reykjanes and Hellisheidi, are used. Vertical and directional boreholes with multi-feed zones are simulated by Pyflow standalone.

Detailed information on boreholes and input parameters for the Pyflow standalone are illustrated in Figure 4. Depth of the feed zones are assigned based on formation temperature measurements. Mass flow rate of the feed zones is selected to achieve better matches. Same applies to enthalpies, therefore, the entered input parameters may differ to determine the enthalpy of the feed zone.

RN-13b		H006		H007		H054	
Pwh	41 bar	Pwh	15.33 bar	Pwh	30.33 bar	Pwh	65.78 bar
Hwh	1400 kj/Kg	Hwh	1258 kj/Kg	Hwh	1512.75 kj/Kg	Hwh	2078 kj/Kg
d_casing	0.315 m	d_casing	0.315 m	d_casing	0.315 m	d_casing	0.315 m
d_liner	0.178 m	d_liner	0.178 m	d_liner	0.178 m	d_liner	0.178 m
m_f1	7 kg/s	m_f1	25kg/s	m_f1	20 kg/s	m_f1	5.1 kg/s
m_f2	7.8 kg/s	m_f2	5.1 kg/s	m_f2	30 kg/s	m_f2	15.81 kg/s
m_f3	3.5 kg/s	m_f3	0.1 kg/s	m_f3	0.1 kg/s	m_f3	13.1 kg/s
m_f4	3.5 kg/s	h_f1	1294 kj/Kg	h_f1	1990 kj/Kg	m_f4	0.1 kg/s
h_f1	1387.7 kj/Kg	h_f2	1130 kj/Kg	h_f2	1210 kj/Kg	h_f1	2400 kj/Kg
h_f2	1300.0 kj/Kg	h_f3	1029 kj/Kg	h_f3	1050 kj/Kg	h_f2	2400 kj/Kg
h_f3	1254.4 kj/kg	z_f1	-1000m	z_f1	-950m	h_f3	1550 kj/kg
h_f4	1350.0 kj/kg	z_f2	-1450m	z_f2	-1450m	h_f4	1375.0 kj/kg
z_f1	-1150m	z_f3	-2250m	z_f3	-2050m	z_f1	-1000m
z_f2	-1700m	z_casing	-750m	z_casing	-750m	z_f2	-1490m
z_f3	-2100m	-	-	-	-	z_f3	-2000m
z_f4	-2495m	-	-	-	-	z_f4	-2500m

Figure 4: Characteristics of the boreholes to simulate well discharge test with Pyflow standalone.

Simulated pressure profile of the RN-13B borehole is illustrated in Figure 5. Interval between -1150 m and the bottom of the well successfully matched with the measured well discharge test. Intervals between the wellhead and right below the casing (-1100 m) showed an average of 5 bar deviation.

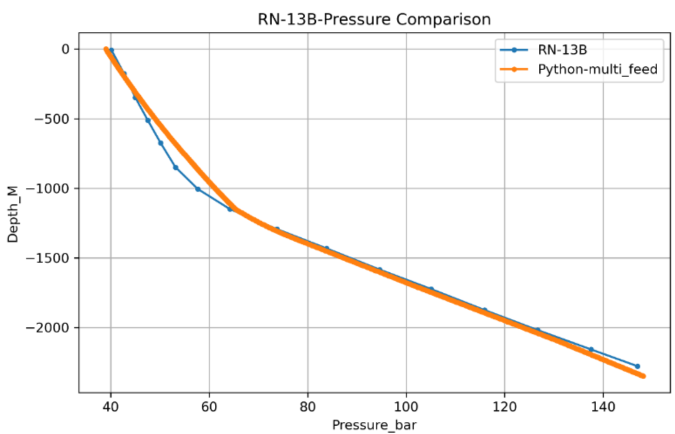

Figure 5: Discharge test of the RN-13B vs simulated pressure profile.

The simulated temperature profile of the RN-13B is illustrated in Figure 6. The temperature graph simulated with Pyflow achieved a very successful temperature profile with a deviation of 5°C compared to the measured values.

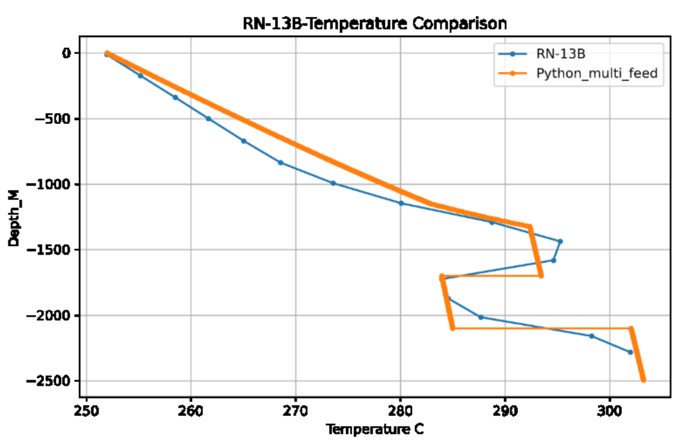

Figure 6: The simulated temperature profile of the RN-13B.

The simulated pressure profile of the H-006 is illustrated in Figure 7. Pyflow single feed zone module and multi feed zone results were compared with the measured data from the Hellisheidi. The pressure profile calculation results from the multi feed module are slightly better than for the single feed module. The calculated bottom hole pressure from the single feed module was the same as measured bottom hole pressure from the field, while the multi feed zone module deviated by 8 bar.

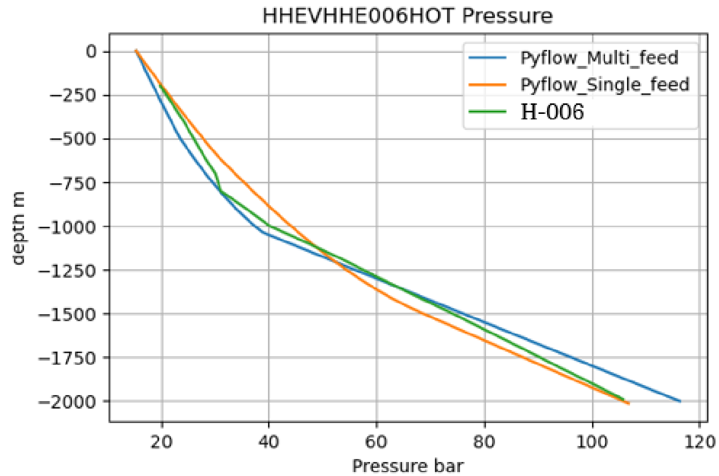

Figure 7: The discharge test of H-006 vs Pyflow single & multi feed zone.

The temperature calculation of the H-006 is illustrated in Figure 8. The temperature profile found by the single feed module was 50°C more than the measured temperature profile. Pyflow multi module results followed the same trend as the measured temperature profile of the borehole.

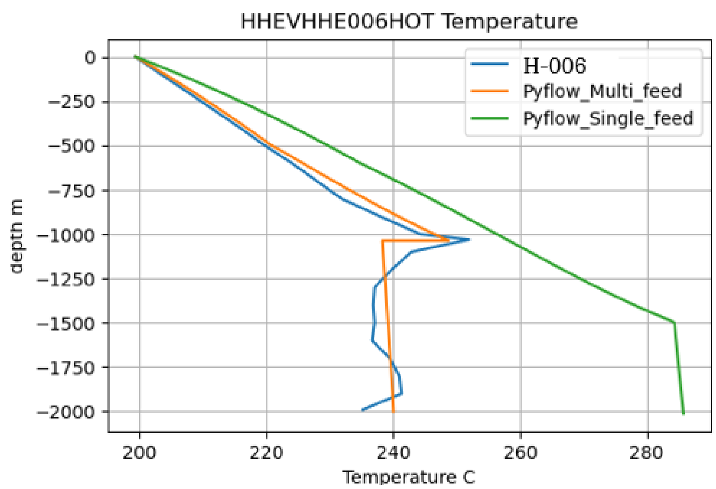

Figure 8: The temperature discharge test of H-006 vs Pyflow modules.

The calculated pressure profile of H-007 is shown in Figure 9. Apart from a 4 bar deviation between -250 m and -800 m, the pressure profile calculation results from Pyflow multi module had the same trend as the measured data from the field.

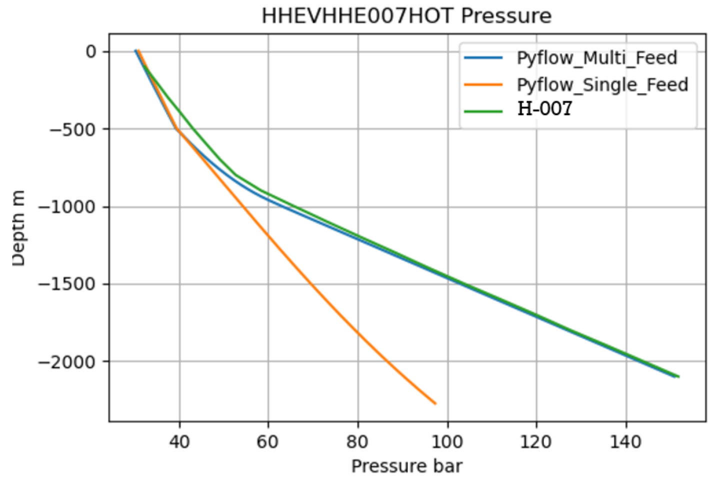

Figure 9: The simulated pressure profile of H-007 vs Pyflow modules.

The calculated temperature profile of the H-007 is shown in Figure 10. Results from Pyflow single module were 50°C higher than the measured data from the field. Same as in the previous case, calculated temperature profile from multi feed module had the same trend as the measured data from the field.

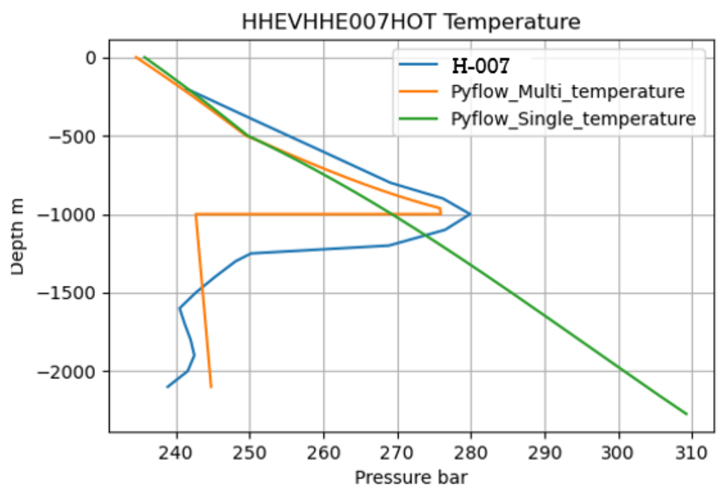

Figure 10: The measured temperature profile of H-007 vs Pyflow modules.

The simulated pressure profile of the H-054 is illustrated Figure 11. The Pyflow multi module achieved a good pressure profile with only a deviation of 7 bar at the bottom of the well.

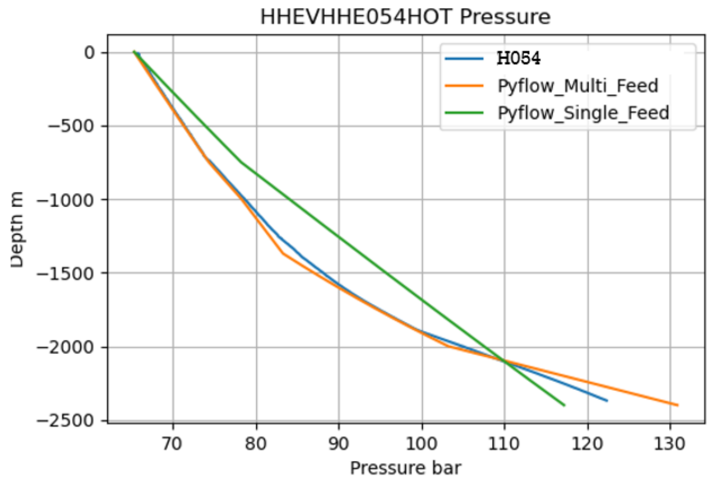

Figure 11: The measured pressure profile of H-054 vs Pyflow modules.

The calculated temperature profile of the H-054 is illustrated Figure 12. Pyflow multi module achieved a quite similar temperature profile compared to the borehole. Deviation of 3°C was detected at the bottom of the well.

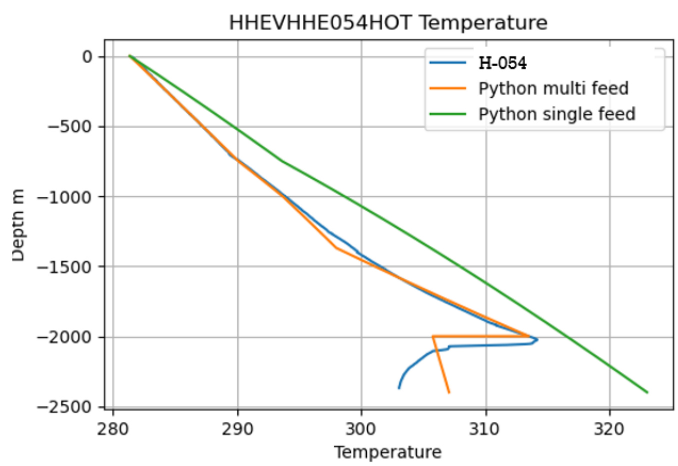

Figure 12: The measured temperature profile of the H-054 vs Pyflow modules.

4. DISCUSSION

Accurate results were obtained in simulated wells using the Pyflow multi feed module. In the calculations, it was seen that the multi-phase flow was dominant in the upper sections. For instance, RN-13B borehole is liquid dominated in the interval between -2500 m to -1150 m. After this interval, phase change is occurring rapidly.

It may be possible to obtain better results by re-establishing the energy balance mentioned in 2.2.1 Pyflow Standalone. Steam flow rate can be calculated by taking advantage of steam velocity and the void fraction. Therefore, energy balance can be calculated based on steam flow rate & enthalpy and liquid flow rate & enthalpy.

Hybrid explicit and explicit coupling procedures can be easily implemented to Pyflow Standalone. Well lookup tables can be prepared, and hybrid explicit coupling can be done via F-type (TOUGH2) WFLO-type (AUTOUGH2) sources of the reservoir simulators. Explicit coupling can be done via the subroutine, which includes stopping criteria, multi feed zones, and compatible reservoir source. DELV type source (productivity index against constant bottom hole pressure) might be useful for the explicitly couple Pyflow to TOUGH2 and AUTOUGH2.

5. CONCLUSION

The focus in this paper is to develop a wellbore model that represents multi feed zone boreholes and to determine the enthalpy values of the each feed zones. More than 20 different wells that have multi feed zones were used to validate the standalone version of Pyflow. The pressure and temperature distribution provided by Pyflow were quite promising. Consequently, the Pyflow Standalone module can detect the enthalpy values of multiple feed points and simulate geothermal wells where the geofluid is pure water with a high accuracy.

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