GeoSteam.Net: Steam transport simulation in a three-reservoirs pipeline network

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Abstract. In the project CEMIE-Geo, the development of a steam transport simulator, GeoSteam.Net for a geothermal pipeline network is in progress. The steam-transportation algorithm considers the conservation of mass, linear momentum, and total (mechanical plus thermal) energy. The simulator is useful for the optimization of (i) design and contraction, (ii) monitoring and operation and (iii) decision making in the update and modification of the geothermal power plant. A demo program, DemoGeoSteam.Net for the solution of the well-known problem of three reservoirs (i.e. three pipes that connect two production wells and one power plant) is written in C# on the Windows platform, which can be downloaded from the website http://www.INEELGeoSteam.Net/WtrStmTbl. Similarly, an illustration is presented in defining the pipeline diameters of the above three reservoirs geothermal pipeline network.

1. Introduction

In geothermal systems, the main resource for generating electrical energy is steam, which is transported to a power plant to move the turbines [1]. The steam (fluid) transport in geothermal pipeline networks is complex than that in any other system due to natural control of pressure, temperature and flow rate of fluid in geothermal wells [2]. Additionally, the large distance between wells and their topographic settings in a geothermal field also complicate the steam flow in the pipeline networks [3]. The well opening (i.e., controlling pressure, temperature, and flow rate at the wellhead) produces incrustation problems (commonly known as silica and calcite deposits) in the geothermal reservoir as well as in the pipeline networks. Similarly, instability in the form of pressure fluctuation in the geothermal pipeline network (even sometimes in the wells) has been observed in the well-openings are not synchronized [4]. Thus, the knowledge of numerical simulation of steam flow in a pipeline network of a geothermal system is vital for the rationalization and optimization of steam used in the transformation of thermal energy to electrical energy [5].

Enormous efforts are in progress worldwide to understand the mechanisms of vapor transport in the geothermal pipeline networks [3]. Consequently, several computer programs are written: VapStat-1 [6], FLUDOF [7], Sims.Net [8], etc. There are many recent studies on the fluid and heat flow in pipeline networks; prediction of pressure, temperature and velocity distribution of two-phase flow in petroleum wells [9] and fluid flow characteristics with uncertainty in a geothermal well [10]. García et al. [3] simulated the effect of superficial field topography on the steam transport in the pipeline network of Los Azufres geothermal field by using the commercial software packages PipePhase and Sims.Net. They found that the transport of geothermal fluids from the wellhead to the power plant
through very long and complex pipeline networks directly affects the amount of electricity generated per unit of fluid produced.

Recently, the optimization of pipeline networks is a principal subject of studies: pipeline design for a least-cost CO\textsubscript{2} transport in the CO\textsubscript{2} sequestration cycle [11,12], finite volume method numerical model of transient pipeline network for steam transport [13]. In the project CEMIE-Geo, the development of a steam transport simulator, GeoSteam.Net for geothermal pipeline network is for the optimization of (i) design and contraction, (ii) monitoring and operation and (iii) decision making in updating and modification of the geothermal power plant. Presently, there is a web service, \texttt{http://www.INEELGeoSteam.Net/INEELGeoSteamNet.asmx} for steam transport in components, pipeline, and elbow.

The present paper describes the demonstration program, written in C# on the Windows platform to resolve the three reservoirs problem (i.e. three pipelines that connect two production wells and one power plant). Similarly, the program illustrates an application in defining the diameters of pipelines, which are connecting two production wells to a geothermal power plant.

2. Steam transport algorithm with total energy conservation constraint

Verma[2] presented the algorithm for steam transport in a geothermal pipeline, considering the conservation of mass and momentum (Newton’s second law) and the first and second laws of thermodynamics [14,15]. In the pipeline network of the geothermal power plant, the steam flows from high to low pressure and heat flows from high to low temperature (i.e., indirectly validation of second law of thermodynamics). The steam transport is assumed here as unidirectional steady state flow.

Figure 1 shows a schematic diagram of \(i\)th control volume element of a pipeline between nodes \(i-1\) and \(i\). The finite difference discretization of continuity equation in one dimension along the pipeline is written as

\[
\rho_i u_i = \rho_{i-1} u_{i-1}
\]  

where \(\rho\) is density and \(u\) is velocity. The subscripts \(i\) and \(i-1\) represent the values at the respective node and \(i=1, 2, \ldots, n\) (no. of segment).

The equation of the conservation of energy is expressed as

\[
\Delta \left( H + \frac{u^2}{2} + gZ \right) = Q - W_f
\]  

where \(Q\) is the amount of heat per unit mass given to the control volume element from surroundings. \(W_f\) is shaft work per unit mass which is zero here. \(H\) is enthalpy per unit mass, \(Z\) is the elevation from the reference datum line, and \(g\) is the acceleration due to gravity. Figure 1 also presents a cross-sectional view of the pipeline. The rate of heat-transfer to the control volume element from the surroundings[16] is given by

\[
H_T = \frac{2\pi DL(T_{in} - T_{out})}{\frac{1}{h_Lr_L} + \frac{\ln \left( \frac{r_2}{r_1} \right)}{k_A} + \frac{\ln \left( \frac{r_3}{r_2} \right)}{k_B} + \frac{1}{h_{out}r_3}}
\]  

where \(r_1\), \(r_2\), and \(r_3\) are radii as shown in Figure 1. \(k_A\) and \(k_B\) are thermal conductivities of pipeline and insulation over it, respectively. \(h_L\) is the convective heat transfer coefficient between steam and inner part of the pipeline. Similarly, \(h_{out}\) is the convective heat transfer coefficient between the outer part of insulation and surrounding air. \(T_{in}\) and \(T_{out}\) are the temperature of the inner steam and the outer air, respectively.

For the steady-state flow, the heat transferred to the control volume element from the surrounding is the heat transferred to the inflowing fluid. Thus, the heat added (given) to per unit mass of inflowing fluid is
Figure 1. Schematic diagram of $i^{th}$ control volume element of a pipeline. $T$, $P$, $Z$ and $\dot{m}$ represent temperature, pressure, elevation and mass flow rate at the node $i-1$ and $i$, respectively. The cross-sectional view of the element shows the positive heat flux $Q$. $r_1$, $r_2$ and $r_3$ are radii of inner and outer part of the pipeline, and outer part of the insulation over it, respectively [2].

$$Q = \frac{H_T}{\dot{m}} \times \left(1 + \frac{dL}{2u}\right)$$

The multiplying factor $(1 + \frac{dL}{2u})$ is the time required to pass the fluid through the control volume element. Thus the discretization of the energy equation is

$$H_i - H_{i-1} + \frac{u_i^2 - u_{i-1}^2}{2} + g(Z_i - Z_{i-1}) = Q_i$$

where $Q_i$ is the amount of heat per unit mass given to $i^{th}$ control volume element. The conservation of linear momentum is

$$V dP + u du + g dZ + dF = 0$$

For both laminar and turbulent flow, the energy loss due to friction is expressed with the Darcy-Weisbach equation

$$dF = \frac{f u^2}{2D} dL$$

The Moody chart provides the value of friction coefficient $f$. The discretization of momentum equation is

$$\left(\frac{1}{\rho_i} + \frac{1}{\rho_{i-1}}\right)(p_i - p_{i-1}) + \frac{u_i^2 - u_{i-1}^2}{2} + g(Z_i - Z_{i-1}) + \frac{f u_i u_{i-1}}{4r_1} dL = 0$$

The system of nonlinear equations is solved with the Newton-Raphson method.

3. Description of DemoGeoSteamNet Computer Program

The computer program DemoGeoSteamNet is written in C# on the Windows platform and can be downloaded from the website [http://www.INEEL.GeoSteam.Net/WtrStmTbl](http://www.INEEL.GeoSteam.Net/WtrStmTbl). Figure 2 shows the main interface form of the demonstration program. Two geothermal wells are contacted to a power plant with three pipelines; it is a well-known problem of three reservoirs. The problem is solved here with the constraint of the total (thermal and mechanical) energy conservation instead of the mechanical energy conservation (i.e., Bernoulli theorem). The wells have pressure values of 1.2 and 1.0 MPa, respectively. The geothermal power plant runs at pressure 0.8 MPa. The length of each pipeline is
1000 m. The diameters are 0.5, 0.6 and 0.7 m, respectively. The question to answer is the total amount of vapor reaching to the power plant from each well.

The user has to select the highest pressure well as the starting well. In this case, that is well 1. Similarly, the user has to provide the guess values of vapor flow rate for each well. The program uses the Newton-Raphson method to solve the nonlinear equation system; so, the guess values play an important role in the execution time and the convergence of solution of the equations. The execution starts with pressing the button, Calc. The total vapor which will reach the plant is 113.9 kg/s (i.e. 68.8 kg/s from well 1 and 45.1 kg/s from well 2). It also calculates the parameter values at the junction node as shown in Figure 2.

Similarly, we can see the calculated values of all the parameters for each pipeline by pressing the corresponding button near the three pipelines (i.e., buttons 1, 2, and 3). It calculates the following parameters at each node: temperature, pressure, liquid flow rate, vapor flow rate, total energy, thermal energy, kinetic energy and potential energy, and in each pipeline segment: heat loss due to conduction-convection-radiation and fractional energy loss. The fractional energy is not a lost energy rather it corresponds to the conversion of mechanical energy to thermal energy, which is due to the friction between fluid layers and the fluid and wall of the pipeline. Thus, it is within the system and is taken into account in the energy balance equation.

3.1. Design of Pipeline Network

The designing of a pipeline network of geothermal power plants is a challenging task. It demands to include various factors like production well characteristics, the distance between wells and power plants, and field topography, which are difficult to manage and predict. Similarly, the production well characteristics may change with time. So, there is need to keep in mind a tolerance in the characteristics of production in designing the pipeline network for a geothermal power plant. An illustration of GeoSteam.Net is presented here for defining the pipeline network for the above three reservoirs problem.

Let the well 1 produces 80 kg/s steam at the pressure 1.2 MPa, while the Well 2 also produces 80 kg/s but at the pressure 1.0 MPa. The question is to define the diameter of each pipeline such that the
total vapor 160 kg/s reaches to the plant at the pressure 0.8MPa. In this example, there may be many solutions; we will present a procedure to obtain a solution. There is need to calculate the outlet pressure of individual pipeline with varying the diameter.

Figure 3: The form for well 1 for input parameters and calculated results, which is visualized by pressing the button 1 in Figure 2.
Figure 4: Calculated results for pipeline 1 with diameter 1.0 m obtained by pressing the button, Calc in Figure 3. The calculated outlet pressure is 1.191 MPa.

Figure 5: Variation of outlet pressure with diameter of pipelines 1, 2 and 3.
Figure 3 shows the input form for the characteristics of pipeline 1, which is visualized on pressing the button 1 in Figure 2. All the characteristics of pipelines except the diameters are same as considered in the above example. There are three parameters, inlet pressure $p_{in}$, outlet pressure $p_{out}$, and mass flow rate $(Q_{liq} + Q_{vap})$; out of which two are independent and the third one is dependent. Thus, there are three buttons, “Calc $P_{out}$”, “Calc $Q_{in}$” and “Calc $P_{in}$” for each calculation possibility in Figure 3. For example, if the inlet pressure and flowrate are given, the outlet pressure is calculated by pressing the button, “Calc $P_{out}$”.

Figure 4 shows the calculated results. The outlet pressure will be 1.191 MPa. The procedure is repeated with varying the diameter. Similarly, the same procedure is applied to the well 2. Figure 5 shows the variation of outlet pressure with diameter for well 1 and well 2. Let we decide that the inlet pressure of pipeline 3 be 0.900 MPa. It means that the diameter of pipeline 1 and pipeline 2 should be $D_1$=0.516 m and $D_2$=0.650 m. Now, the variation curve of outlet pressure with diameter for pipeline 3 at inlet pressure =0.900 MPa is calculated and plotted in Figure 5. It shows that the outlet pressure of pipeline 3 will be 0.800 MPa at the diameter $D_3$=0.878 m. Thus, if the diameter of pipelines 1, 2 and 3 are 0.516, 0.650 and 0.878 m, respectively, the 160 kg/s vapor will reach to the plant from the two wells, producing 80 kg/s vapor each.

4. Conclusions

The computer program DemoGeoSteamNet is written in C# on the Windows platform and can be downloaded from the website http://www.INEELGeoSteam.Net/WtrStmTbl. The steam transport simulator, GeoSteam.Net for a geothermal pipeline network is under development in Angular for the web platform. Presently, it simulates the steam transport in the branch which is formed by pipelines and elbows, considering the conservation of mass, momentum and total energy. The fluid mixing model at the junction node is also based on the conservation of total energy.

The algorithm for iteration during the simulation of steam transport in a pipeline network is accurate, but it is currently slow. We are still working on it. The empirical relations based on the correlation of experimental data in fluid mechanics require the calibration of a numerical model for real study system (e.g. the value of convective heat transfer coefficient). Additionally, the present algorithm is constrained for the simulation of steam transport only due to the limitations of internal consistency in the thermodynamic properties of water. The energy balance at any point in the pipeline network validates the varsity of present algorithm for steam transport in the geothermal pipeline networks.

A functionally of GeoSteam.Net is presented for the design and construction of a geothermal pipeline network. Currently, the calculations were made manually; we are working on the automation of these calculations for a complex network.

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