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A Comparative Evaluation of Steam Transport Simulation in Pipeline Networks of Los Azufres Geothermal Plants with PipePhase and GeoSteam.Net

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ABSTRACT

In the project of CeMIEGeo P14 (Mexican Center for Innovation in Geothermal Energy), the software "GeoSteam.Net" for the simulation of steam transport in geothermal power plants in the Web platform is developed. The simulator is useful to improve (i) design and construction, (ii) monitoring and operation, and (iii) decision making in updating and modifying geothermal power plants. Using the GeoSteam.Net simulator, a demo program was written in the Windows platform to simulate steam transport in the pipe networks of the Los Azufres geothermal power plants, U-07 and U-13. The first simulation of the entire steam transport pipeline networks of Los Azufres Geothermal Field (LAGF) was performed in 2007 using the commercial fluid transport simulators, PipePhase and Sim.Snet under a project financed by Comisión Federal de Electricidad (CFE).

A comparative evaluation of simulation results, obtained with PipePhase and GeoSteam.Net, of two scenarios: (a) fixed steam production (flow rate Q) of all the connected wells and (b) fixed pressure (P) of the wells, Az-02A, Az-06, Az-22 and Q fixed of other connected wells, indicates that the measured production parameters (P and Q) of a well influence the production of steam and its transport. In the first scenario (fixed Q), there is a considerable difference between the measured and calculated pressure of the wells, Az-02A, Az-35, and Az-37. Similarly, there is significant high vapor production if the pressures of the wells, Az-02A, Az-06, and Az-22 are set to fix. It is 17% higher for GeoSteam.Net while it is 9% higher for PipePhase. Thus, the precise measurements of P and Q of each well and the well-opening synchronization with the help of steam simulator are essential for better functionality of a geothermal power plant.

1. INTRODUCTION

In geothermal systems, the primary resource for generating electrical energy is steam to move the turbines (Verma and Torres-Encarnación, 2018). Most of the geothermal fields produce a mixture of liquid (water) and vapor (steam). Presently, the geothermal fluid gathering systems are of different types: centralized, satellite, or individual separation type. In the last two, the steam is separated in a separator at the wellhead. The separated steam is transported to the turbine through a steam-pipeline network consisting of tubes, manifolds, valves, expansion, reduction, etc.

The steam (fluid) flow in the geothermal pipeline networks is more complicated than that in any other type of system since the pressure, temperature, and flow-rate of fluid in geothermal wells are controlled by nature. Additionally, the considerable distance between the wells and their topographic settings in a geothermal field also complicates the steam flow in the pipeline networks. The conditions of well-opening (i.e., the control of pressure and flow-rate at the wellhead) produce the incrustation (mainly the deposition of silica and calcite) in both geothermal reservoir and pipeline network. Similarly, instability in the form of pressure fluctuations has been observed in the geothermal pipeline network (even sometimes in the wells) if the well-openings are not synchronized. Thus, knowledge of numerical simulation of steam flow in the pipeline network of a geothermal system is vital for rationalization and optimization of steam used for electrical energy generation (Ruíz et al. 2010).

Enormous efforts have been made to understand the mechanisms of vapor transport in the pipeline networks of several geothermal fields worldwide (Garcia-Gutierrez et al., 2009). Consequently, it has resulted in several computer codes: VapStat-1 (Marconcini and Neri, 1979), FLUDOF (Sanchez et al., 1987), Sim.Snet (TS & E, 2005), etc. There are numerous 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 (Cazarez-Candia and Váquez-Cruz, 2005), and fluid flow characteristics with uncertainty in a geothermal well (García-Valladares, 2007).

All programs were written to solve a specific problem and do not yield satisfactory results for different production conditions, even in the same field. Garcia-Gutierrez et al. (2009) simulated the effect of superficial field topography on the steam transport in the pipeline network of Los Azufres geothermal field (LAGF) with using the commercial software packages PipePhase and Sim.Snet. 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. A group of NASA (National Aeronautics and Space Administration) developed a computer program, "Generalized Fluid System Simulation Program (GFSSP)" to calculate the pressure and flow distribution in complex networks of fluids (Majumdar, 1999). Verma and Arellano (2010) modified the algorithm

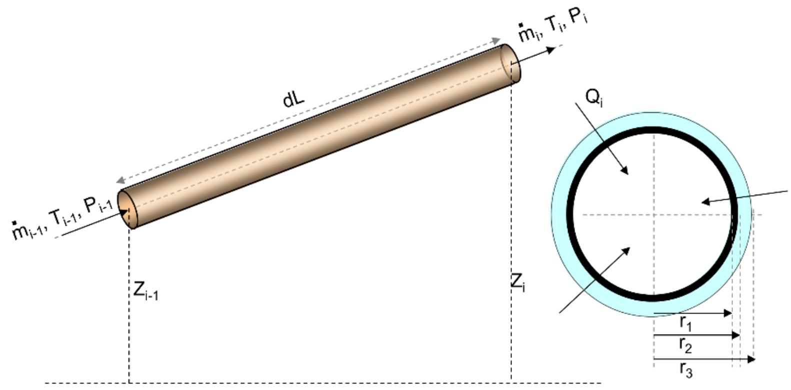

Figure 1: Schematic diagram of the i[th] control volume element of a pipeline. T, P, Z and $\dot{m}$ represent temperature, pressure, elevation, and mass flow rate at the node i-1 and i, respectively. The cross-sectional view of the element shows the positive heat flux Q_i. r_1, r_2, and r_3 are radii of the inner and outer part of the pipeline, and the outer part of the insulation over the pipeline, respectively.

of GFSSP for unidirectional steady-state steam flow in the geothermal power plant and wrote a computer program, PipeCalc in Visual Basic 6.0 for the steam flow in a pipeline. The numerical solution approach for the equations of conservation of mass, linear momentum, and energy is adapted from Patankar (1980) and Majumdar (1999).

In the project of CeMIEGeo P14 (Mexican Center of Innovation in Geothermal Energy), the first version of GeoSteam.Net was completed for the simulation of steam transport in geothermal plants in the Web platform (Verma and Torres-Encarnación, 2018). The numerical simulator is useful to optimize the use of geothermal resources through (i) design and construction of pipeline network, (ii) monitoring and operation of power plants, and (iii) decision making in the updating and modification of geothermal power plants. A functionality of GeoSteam.Net is illustrated for the design and construction of a geothermal pipeline network (Verma, 2019).

In this article, a demo program, LAGeoSteam.Net was written as an application of GeoSteam.Net for the simulation of steam transport in a pipe network of LAGF power plants, U-07 and U-13. A comparative evaluation of the simulation of two scenarios: (a) fixed production (flow rate Q) of all the connected wells and (b) fixed pressure of the wells, Az-02A, Az-06, Az-22 and Q fixed of other connected wells was presented. The results were also compared with the simulation results obtained by PipePhase (Garcia-Gutierrez et al., 2007) under the project financed by Comisión Federal de Electricidad (CFE). The results indicate that the measured production parameters of a well (i.e., separation pressure and steam flow rate) influence the production of steam and its transport. In the first scenario (Q fixed of all wells), there is a considerable difference between the measured and calculated pressure of the wells, Az-02A, Az-35, and Az-37. Similarly, there is significant high vapor production if the pressures of wells, Az-02A, Az-06, and Az-22 are fixed.

2. THEORETICAL ASPECTS OF STEAM TRANSPORT

The fluid transport equations are based on the three basic principles: conservation of mass, momentum, and energy. These equations were programmed slightly differently in the softwares: GeoSteam.Net and PipePhase.

2.1 GeoSteam.Net

Verma (2013) 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. 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 a validation of the second law of thermodynamics). The steam transport is assumed here as unidirectional steady-state flow.

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

$$\rho_i u_i = \rho_{i-1} u_{i-1} \tag{1}$$

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

The equation of the conservation of energy is expressed as

$$\Delta\left(H + \frac{u^2}{2} + gZ\right) = Q - W_s \tag{2}$$

where Q is the amount of heat per unit mass given to the control volume element from surroundings. W_s 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 is given by

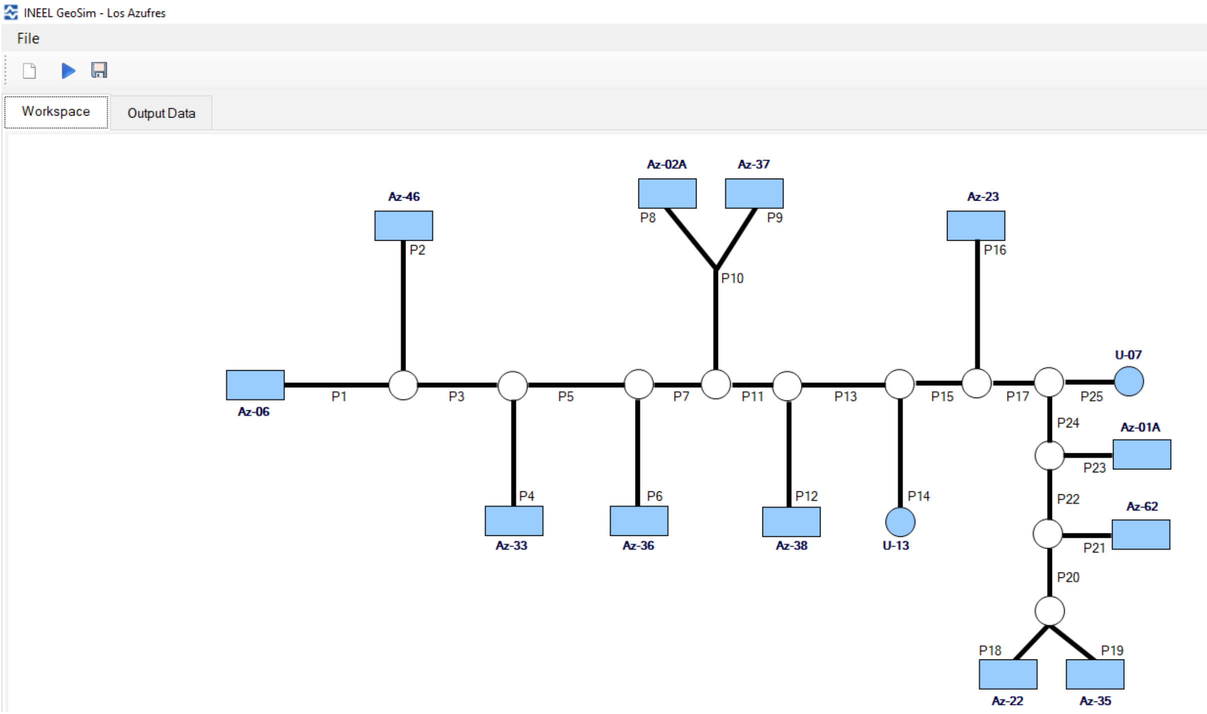

Figure 2: Principal interface of LAGeoSteam.Net representing the schematic diagram of the pipeline network of south region of LAGF. It consists of 12 production wells and two electrical energy generation units.

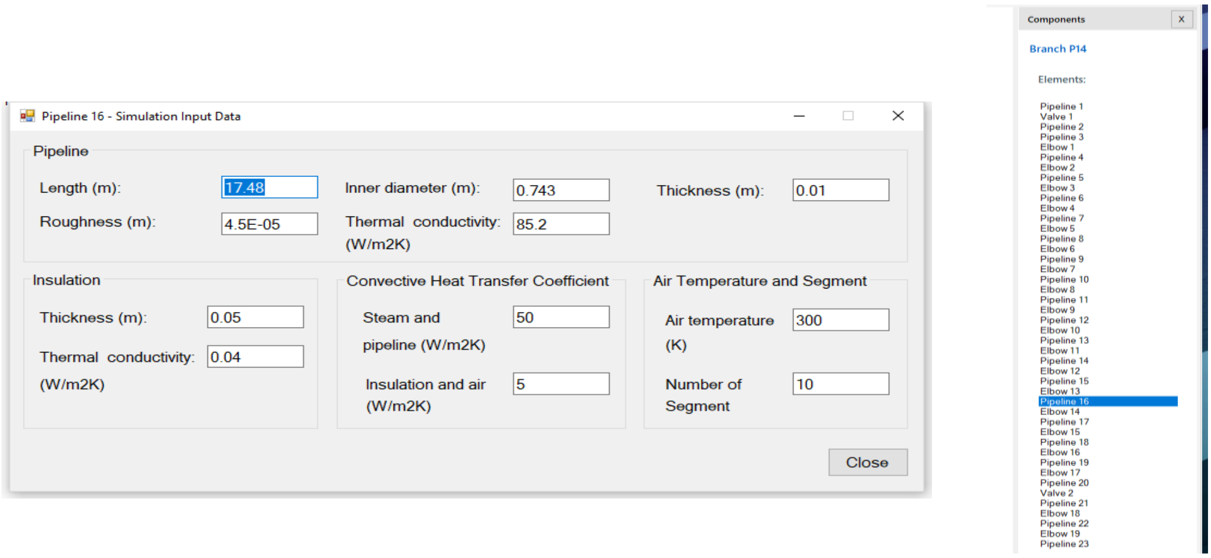

Figure 3: List of components of Branch P14, obtained by a double-click on P14 in Figure 2 and characteristics of pipeline 16, visualized by a double-click on Pipeline 16 from the list of components of Branch P14.

$$H_T = -\frac{2\pi\, dL\, (T_{in} - T_{out})}{\left[\frac{1}{h_{in} r_1} + \frac{\ln\left(r_2/r_1\right)}{k_A} + \frac{\ln\left(r_3/r_2\right)}{k_B} + \frac{1}{h_{out} r_3}\right]} \tag{3}$$

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_{in} 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

$$Q = \frac{H_T}{\dot{m}} \times \left(1 + \frac{dL}{2u}\right) \tag{4}$$

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

$$H_i - H_{i-1} + \frac{u_i^2 - u_{i-1}^2}{2} + g(Z_i - Z_{i-1}) = Q_i \tag{5}$$

where Q_i is the amount of heat per unit mass given to i[th] control volume element.

The conservation of linear momentum is

$$V\,dP + u\,du + g\,dZ + dF = 0 \tag{6}$$

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

$$dF = \frac{fu^2}{2D} dL \tag{7}$$

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

$$\left(\frac{\frac{1}{\rho_i} + \frac{1}{\rho_{i-1}}}{2}\right)(p_i - p_{i-1}) + \frac{u_i^2 - u_{i-1}^2}{2} + g(Z_i - Z_{i-1}) + \frac{f u_i u_{i-1}}{4r_1} dL = 0 \tag{8}$$

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

2.2 PipePhase

The algorithm used to solve the equations of the conservation of mass, momentum, and energy in PipePhase is described in Garcia-Gutierrez et al. (2009) and will not be presented here.

3. STEAM TRANSPORT SIMULATION IN LOS AZUFRES GEOTHERMAL PIPELINE NETWORK

Los Azufres geothermal field (LAGF) is located in the Mexican Volcanic Belt of central Mexico, 250 km west of Mexico City, and 90 km northeast of Morelia, capital of Michoacán state. The field is hosted by the Sierra de Los Azufres, a high mountain range that houses a dense pine forest and numerous hot springs, fumaroles, and boiling mud pools. The wellhead elevations range from 2750 m to 3000 m above sea level (masl). The LAGF is divided into two well-defined productive zones: Maritaro in the north and Tejamaniles in the south, with a few kilometers between them.

Garcia-Gutierrez et al. (2007) performed the first simulation of the whole steam transport system of LAGF under the project financed by Comisión Federal de Electricidad (CFE) using two commercial fluid-flow simulators, PipePhase and Sim.Snet (Steam Transmission Network Simulator). PipePhase is a robust simulation tool for steady-state, multiphase flow in wells, pipes, and pipeline networks transporting oil and gas, water, and steam. It has a friendly Graphical User Interface (GUI) that facilitates the assembly of hydraulic models and viewing of results and has an optimization module for pipeline networks. PipePhase is a relatively expensive proprietary code and includes several pressure-drop models. Sim.Snet is a general-purpose steady-state steam transport simulator that couples wells, pipes, reservoirs, sources, and sinks, including power plants. It computes pressure, temperature, mass flow rates, and enthalpy, heat losses, and condensate at each node or pipe segment. Unlike PipePhase, it has only a pre-processing module based on MS Excel for creating input files and employs the Bernoulli equation for carrying out pressure drop calculations.

Before carrying out a required simulation scenario in PipePhase, a pre-processing is needed to test the hydraulic model performance and select the pressure drop model for the topographic and operating conditions of the LAGF pipeline network. It was performed through the simulation of the network of plants U-07 (50 MWe) and U-13 (25 MWe) in the South Zone of LAGF, by considering the fixed flow rate of all wells and plant U-13, while the pressure of U-07 was fixed. A best-fitting between the simulation results and the field measurements of pressure and flow rate by the calibrated manometers and pressure transducers at various points along the main steam collector pipeline (diameter 1.07 m (42 in.)) of power plants U-07 and U-13 were to define the right pressure drop model. It was found that the pressure-drop model described by Mukherjee and Brill (1983; in Garcia-Gutierrez et al., 2007) was the most suitable for the simulations of LAGF pipeline network with PipePhase, taking into account the rough topography of the area and the possibility of two-phase flow in the network.

In 2018, the beta version of the steam transport simulator, GeoSteam.Net, was completed to simulate a geothermal pipeline network. In addition, a specific program, LAGeoSteam.Net, was written on the Windows platform to simulate the transport of steam in the pipeline network of geothermal power plants, U-07 and U13 plants of LAGF South Zone. The validation of results was carried out by comparing the measured parameters, pressure, and steam flow rate of each producing well, and with the simulation results obtained by PipePhase in 2007 (Garcia-Gutierrez et al., 2007).

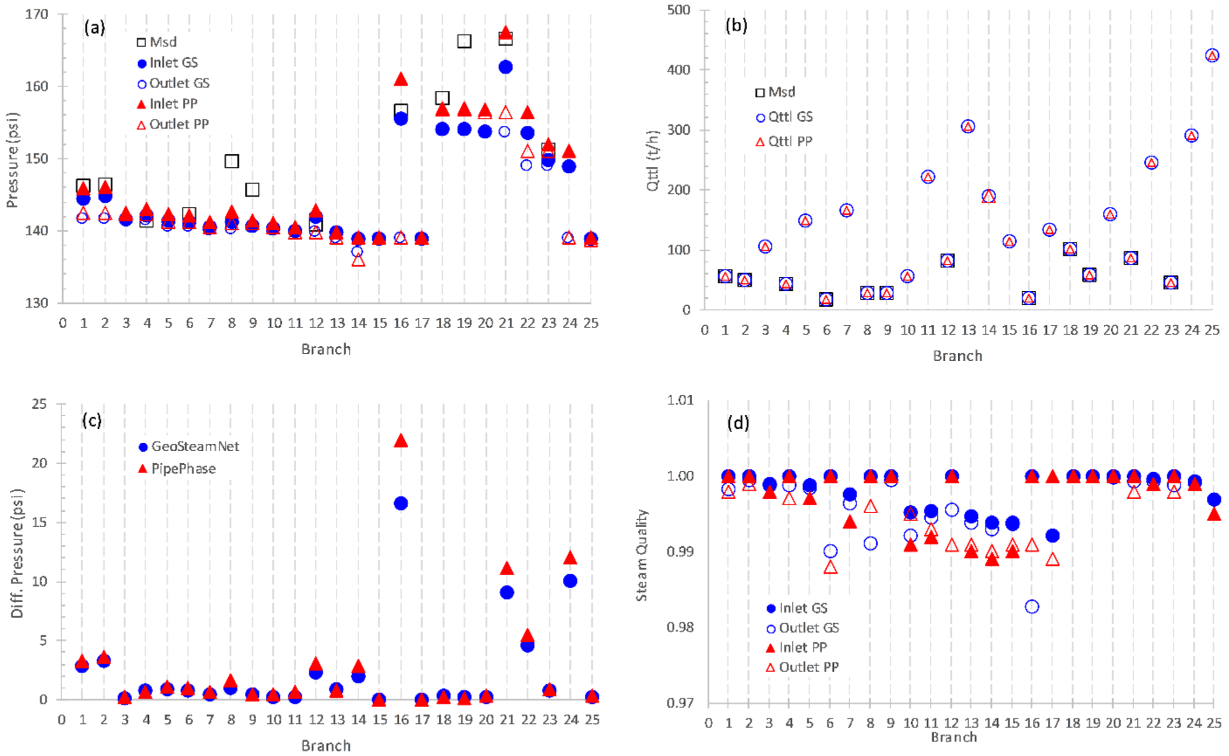

Figure 4: Simulation results for the scenario when all Q fixed for well and U-13 and P fixed for U-07: (a) comparison of inlet and outlet pressure of each branch, (b) comparison of flow rate in each branch, (c) pressure drop along each branch, and (d) steam quality change along each branch.

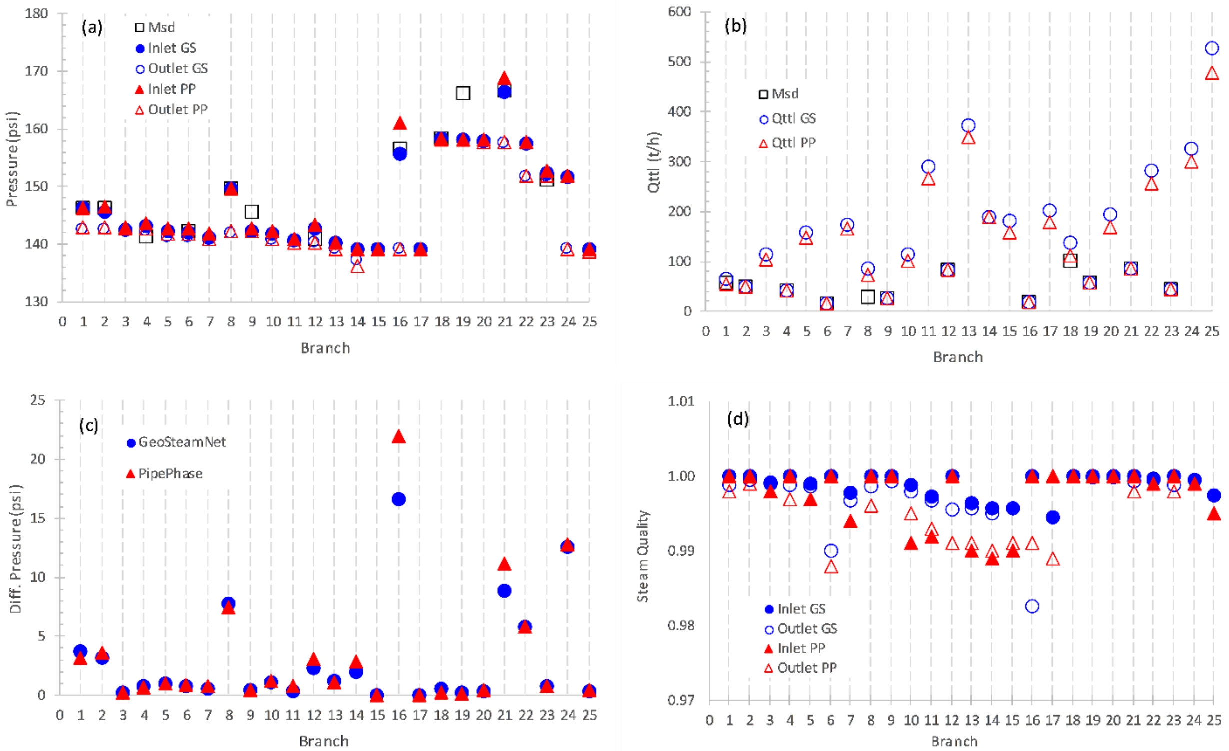

Figure 5: Simulation results for the scenario when the pressure P of wells Az-02A, Az-06, and U-07 are fixed, and the flow rate Q of other wells and U-13 are fixed: (a) comparison of inlet and outlet pressure of each branch, (b) comparison of flow rate in each branch, (c) pressure drop along each branch, and (d) steam quality change along each branch.

Figure 2 shows the schematic diagram of the pipeline Network of geothermal power production units, U-07 and U-13 of LAGF, as documented in LAGeoSteam.Net. It consists of 12 production wells and 2 electrical power generation units. It is the main interface of the program, LAGeoSteam.Net. If one double-clicks on a well (shown by a filled rectangle) or a production unit (shown by a filled circle), it shows an interface to visualize and change the characteristics of the well or unit. Similarly, if one double-clicks on a branch (indicated by a solid thick line), it shows a window with the list of all the components of that branch. For example, Figure 3 shows the list of components of branch P14.

Further, the characteristic of a component is obtained by double-click on it from the list. Figure 3 also shows the characteristics of pipeline 16. Thus, the program is user-friendly. On pressing the triangular button in the toolbar in Figure 2, it starts the execution of the program. The simulation result can be stored in an XML file.

3.1 Simulation Results for Scenario when Q of All Wells Fixed

Figure 4 shows the simulation results of the scenario for fixed measured flow rates of all the wells and plant U-13, fixed pressure for plant U-07. For this scenario, Figure 4b shows the input values of the flow rate of each well, so the calculated flow rates for all the wells and power plants with both simulators, PipePhase and GeoSteam.Net are in agreement with the measured flow rates. If we look at Figure 4a,c, the calculated inlet and outlet pressures with both simulators agree except for the branches, P16, P21, and P24. The branch P16 is of the well Az-23, and it has 215 components and approximately 1.7 km long. Additionally, the diameter of the branch P16 is small (i.e., 25.4 cm (10 in.)); so, the slight differences in the calculation algorithms of GeoSteam.Net and PipePhase may produce large differences in the pressure drop. The maximum change in steam quality along the branches is 0.02 and is for the branch P16. It is again associated with its length and diameter of the branch.

It can be observed in Figure 4a that there are substantial differences in the measured and calculated pressures of wells, Az-02A, Az-22, and Az-37. It could be interesting to simulate the pipeline network for the scenario when these wells' pressure is fixed. Garcia-Guiterrez et al. (2007) performed the simulation of the scenario of fixed pressure of wells, Az-02A, Az-06, and Az-22 with PipePhase; so, the same scenario was carried out here with LAGeoSteam.Net for the comparison purposes.

3.2 Simulation Results for Scenario when P of Wells, Az-02A, Az-06, and Az-22 Fixed

Figure 5 shows the simulation results of the second scenario for the simulation of the pipeline network, considering the fixed pressures of wells, Az-02A, Az-06, and Az-22. The simulation results of both simulators are in agreement. GeoSteam.Net calculates a slightly higher flow rate for each well (Figure 5b); however, both simulators calculate a higher total flow rate than the measured flow rate. It is 17% higher for GeoSteam.Net while it is 9% higher for PipePhase. Thus, the precise measurements of P and Q of each well and the well-opening synchronization with the help of steam simulator are essential for better functionality of a geothermal power plant.

4. CONCLUSIONS

The steam transport simulator for a network of geothermal pipes is suitable for the real-time understanding of fluid flow mechanisms in the pipeline network of geothermal power plants. GeoSteam.Net simulates the steam transport in branch, which is formed by pipelines and elbows, considering the conservation of mass, momentum, and total energy. The mixing model of fluid at the junction node is also based on the conservation of total energy. The algorithm of iteration during simulation of the steam transport in a pipeline network is precise, but it is presently slow. We are working on it. The demo program LAGeoSteam.Net is user friendly, and the results are in agreement with the results of PipePhase and the measurement values of pressure and flow rate of production wells in the field except for the measured pressure of wells, Az-02A, Az-22, and Az-37.

Since the steam transport models are based on the empirical relations obtained from the correlation studies of experimental data in fluid mechanics, it demands the calibration of a numerical model for the real study system (e.g. the value of coefficient of convective heat transfer). 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 functionality of the present algorithm for steam transport in the geothermal pipeline networks.

The precise measurements of pressure and flow rate of production wells are essential for monitoring and operation of a geothermal power plant according to the prediction of steam transport simulators.

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