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GeoSteamNet: 2. STEAM FLOW SIMULATION IN A PIPELINE

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ABSTRACT

A computer program is developed to simulate steam flow in a pipeline as a part of "GeoSteamNet: a computer package for the simulation of steam flow in a geothermal power plant network". The fluid movement is governed by the following basic principles: the conservation of mass, the linear momentum principle (Newton's second law or Navier Stokes equations) and the first and second laws of thermodynamics. The second law of thermodynamics defines the direction of a spontaneous process, which is indirectly validated in the algorithm as steam flows from high to low pressure and heat flows from high to low temperature. The nonlinear equations are solved with the Newton-Raphson method.

A comparative study on the variation of temperature, pressure and heat loss in a pipeline of length 1000 m, inner diameter 0.3 m and thickness 0.005 m is presented. Three cases are discussed: a) no conduction-convection heat loss, b) an insulation of 0.05 m thickness on the pipeline and c) maximum heat loss (i.e. no insulation). The change in pressure is same in the three cases whereas there is appreciable temperature drop even in the case a. Similarly, there is 36% density change in the case b, which is a restriction to use the Bernoulli's equation for steam flow simulation.

INTRODUCTION

Knowledge of numerical simulation of steam flow in a pipeline network of geothermal system is vital for rationalization and optimization of steam used for electrical energy generation (Ruíz et al. 2010). Presently, we are working on two important aspects of the project: a) thermodynamic data of water and b) appropriate algorithm for steam flow in a pipeline. The second aspect will be discussed here.

The fluid flow is mostly analyzed by two equations: mass-balance (continuity equation) and momentum balance (Newton's second law of motion or Navier Stokes equations) in situations where the fluid may be treated as incompressible and temperature differences are small (Mazumdar, 2009). Bhave and Gupta (2006) presented a comprehensive textbook on the analysis of water distribution in a municipal network. The water flow in a pipeline network is successfully modeled with the Bernoulli's theorem and Hardy Cross method. In the circumstances when flow is compressible (density is not constant), or occurrence of heat flux (temperature is not constant), there is need of at least one more equation: energy balance. Smith and van Ness (1975) presented the derivation of all the three equations for fluid flow.

In this article an algorithm is developed to solve numerically the three equations: mass, momentum and energy balance for steam flow in a pipeline. An example is presented for steam flow in a pipeline of 1000 m long for three cases: a) no heat loss, b) heat loss for given characteristics of pipe and insulation of it and c) maximum heat loss (i.e. no insulation).

FUNDAMENTAL EQUATIONS

The movement of fluid in a system is governed by the following basic principles: conservation of mass, the linear momentum principle (Newton's second law or Navier Stokes equations) and the first and second laws of thermodynamics (smith and Van Ness, 1975). The second law of thermodynamics defines the direction of a spontaneous process. In the pipeline network of geothermal power plant the steam flows from high to low pressure and heat flows from high to low temperature. Thus the second law of thermodynamics is indirectly validated and will not be considered here.

Majumdar (1999) developed a general purpose computer program "Generalized Fluid System Simulation Program (GFSSP)" to compute pressure and flow distribution in a complex fluid network

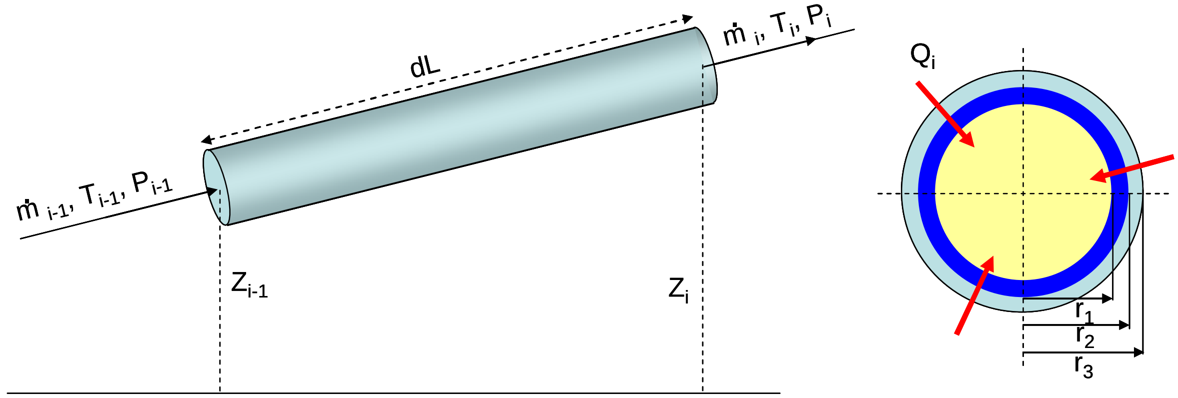

Figure. 1. Schematic diagram of i^{th} control volume element of a pipeline. The steam flow rate at the node i-1 and i are $\dot{m}_{i-1}$ and $\dot{m}_i$, respectively. Z is elevation. T and P represent temperature and pressure, respectively. The cross-sectional view of the element shows the positive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

including unsteady state and angular flow. In the geothermal power plant we are interested in unidirectional steady state steam flow. The following equations will be considered for steam flow in a pipeline (Smith and van Ness, 1975):

Continuity Equation

The continuity equation (conservation of mass) for steady state flow is

$$\nabla \cdot \rho \bar{u} = 0 \quad (1)$$

where ρ is density and $\bar{u}$ is velocity. Figure 1 shows a schematic diagram of i^{th} control volume element between nodes i-1 and i. The finite difference discretization (Patanker, 1980) of continuity equation is expressed as

$$\rho_i u_i = \rho_{i-1} u_{i-1} \quad (2)$$

The subscript i and i-1 represent the values at the respect node.

Conservation of Energy

The equation of the conservation of energy is expressed as

$$\Delta\left(H + \frac{u^2}{2} + gZ\right) = Q - W_s \quad (3)$$

where Q is the amount of heat per unit mass given to the element from surroundings. W_s is shaft work per unit mass. H is enthalpy per unit mass and Z is the elevation from the reference datum line. Figure 1 also presents a cross-sectional view of pipeline. The rate of heat transfer to the control volume element from the surroundings is given by

$$H_T = -\frac{2\pi\, dL(\mathrm{T_{in}} - T_{out})}{\left[\frac{1}{h_{in} r_1} + \frac{\ln(r_2/r_1)}{k_A} + \frac{\ln(r_3/r_2)}{k_A} + \frac{1}{h_{out} r_3}\right]} \quad (4)$$

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 outer part of insulation and surrounding air. T_{in} and T_{out} are the temperature of inner steam and outer air, respectively.

We are interested in the steady state flow. So, the heat transferred to the control element will be transferred to the inflowing fluid. Thus the heat added (given) to per unit mass of inflowing fluid is

$$Q = \frac{H_T}{\dot{m}} \times \left(1 + \frac{dL}{2u}\right) \quad (5)$$

The discretization of energy equation is

$$H_i - H_{i-1} + \frac{u_i^2 - u_{i-1}^2}{2} + g(Z_i - Z_{i-1}) = Q_i \quad (6)$$

Conservation of Linear Momentum

The conservation of linear momentum may be written as

$$VdP + udu + gdZ + dF = 0 \quad (7)$$

For both laminar and turbulent flow the energy loss due to friction is expressed with the Fanning equation

Table 1: Data used for the present modeling of steam flow in a pipeline.

Parameter	Value
Pipeline	
Length (m)	1000.0
Inner diameter (m)	0.3
Thickness (m)	0.005
Thermal conductivity (W/m^2 K)	80.2
Roughness (m)	$2x10^{-7}$
Insulation	
Thickness (m)	0.05
Thermal conductivity (W/m^2 K)	0.043
Convective heat transfer coefficient	
Steam and pipeline (W/m^2 K)	30.0
Insulation and air (W/m^2 K)	6.0
Inflow saturated steam	
Temperature (K)	450.0
Mass flow rate (kg/s)	10.0
Air temperature (K)	300.0
Horizontal pipeline (Z=0)	

$$dF = \frac{2\,fu^2}{D}dL \tag{8}$$

Thus the discretization of momentum equation is

$$\left(\frac{\dfrac{1}{\rho_i}+\dfrac{1}{\rho_{i-1}}}{2}\right)(p_i - p_{i-1}) + \frac{u_i^2 - u_{i-1}^2}{2} + g(Z_i - Z_{i-1}) + \frac{2\,fu_iu_{i-1}}{D}dL = 0 \tag{9}$$

The idealizations imposed in the derivation of these equations are described in the Chapter 10 of book by Smith and van Ness (1975). A comprehensive and systematic numerical solution approach is adapted from Patanker (1980) and Majumdar (1999). The system of nonlinear equations is solved with Newton-Raphson method.

PROGRAM DESCRIPTION

The computer program, PipeCalc is written in Visual Basic 6.0. The thermodynamic data of water are calculated from an ActiveX control, *SteamTablesGrid* (Verma, 2010) instead of ActiveX component, *SteamTables* (Verma, 2003).

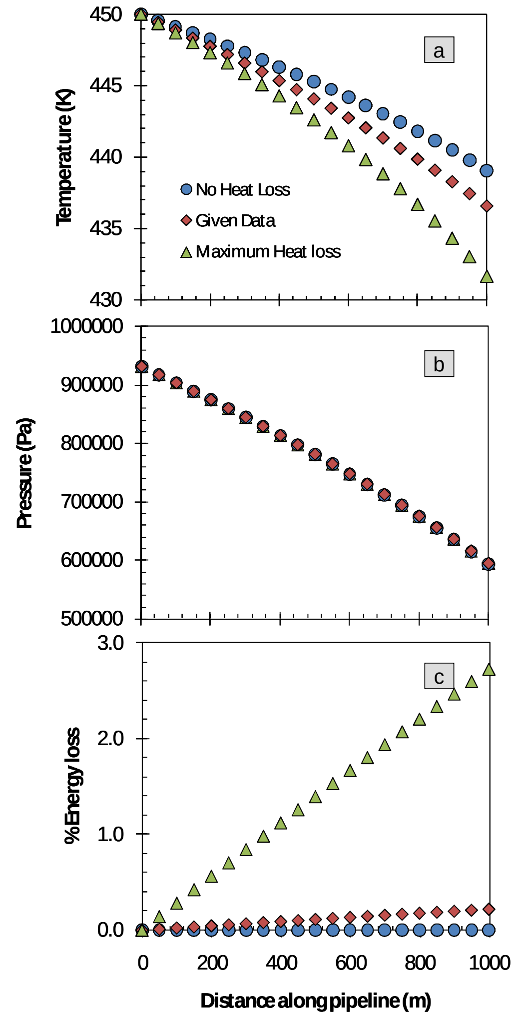

Figure. 2. Calculated values of temperature, pressure and energy loss for three cases: a) no conduction-convection heat loss, b) an insulation of 0.05 m thickness on the pipeline and c) maximum heat loss (i.e. no insulation).

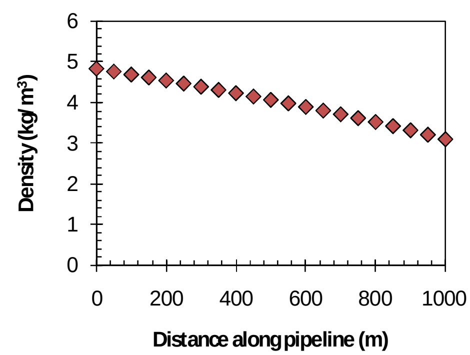

Figure. 3. Variation of density for case b, when there is insulation over the pipeline. The change in density is 36% which is a restriction to use the Bernoulli's equation for steam flow simulation.

A structured variable is defined as pipe, which stores all the input and calculated parameters in it. The advantage of this approach is that it is straight forward to create ActiveX control. Our final goal is to create ActiveX controls for every component of a pipeline network of geothermal system and a graphic user interface. This way the program will be a general purpose computer code for analyzing steady state flow in any geothermal pipeline network.

AN EXAMPLE

To illustrate the applicability of PipeCalc an example is presented here. A horizontal pipeline of 1000 m is considered. All the input parameters are given in Table 1. The pipeline is divided into 100 elements (i.e. the length of each segment is 10.0 m). We performed preliminary calculations for the segment length of 1.0, 10.0 and 100.0 m. The results were in agreement for the segment length 1.0 and 10.0 m.

A small segment length increases the accuracy in the calculated values, but it also increases the execution time. So, one has to perform always some preliminary calculation to optimize the values of different input parameters according to confidence limits of their measured data. This can speed up the further calculations to obtain reliable results.

Figure 2 shows the variation of temperature, pressure and energy loss along the pipeline for three cases: a) no conduction-convection heat loss, b) an insulation of 0.05 m thickness on the pipeline with parameters given in Table 1 and c) maximum heat loss (i.e. no insulation).

The decrease in temperature is highest for case c. There is a formation of liquid water from the point entrance of steam into the pipeline and the conditions of temperature and pressure are along the saturation curve. There is no formation of liquid water in cases a and b and the system is in the superheated steam region.

The velocity of steam flow is approximately 30 m/s. It means that the steam flows from one end to other within 35 s. Figure 2c shows the loss energy for the three cases. It can be observed that there is about 3% energy loss within 35 s when there is no insulation on the pipeline (case c).

One more point to be emphasized is that there is substantial decrease in temperature (11 K) even when there is no heat loss (case a). This decrease in temperature is associated with the expansion of vapor during its flow through the pipeline.

Figure 3 shows the variation in the density of steam for case b. It is 36 %. It means that the Bernoulli's equation has limitations to model steam flow in a pipeline.

CONCLUSIONS

The program PipeCalc is written in Visual Basic 6.0. The algorithm is based on the conservation of mass, the linear momentum principle (Newton's second law or Navier Stokes equations) and the first law of thermodynamics. The second law of thermodynamics defines the direction of a spontaneous process. In the pipeline network of geothermal power plant the steam flows from high to low pressure and heat flows from high to low temperature. Thus the second law of thermodynamics is indirectly validated. The nonlinear equations are solved with the Newton-Raphson method.

The results obtained from a numerical simulation of steam flow in a pipeline for the three cases: a) no conduction-convection heat loss, b) an insulation of 0.05 m thickness on the pipeline and c) maximum heat loss (i.e. no insulation) may be stated as:

- There is decrease in the temperature and pressure of steam along the pipeline even when there is no heat loss. It is associated with the expansion of steam during its flow.
- A decrease of 36 % in the density of steam indicates that the use of Bernoulli's equation for steam flow simulation has certain limitations.
- Steam flow in pipeline is very fast. It takes about 35 s to travel 1000 m.
- In fluid mechanics many empirical relations are used which are based on the correlation studies of experimental data. Therefore, the calibration of a numerical model for the system to be studied is crucial. We performed the simulation for a hypothetical case. For a calibration we need to consider real measurements.

Presently, we are working on the implementation of this numerical approach for a geothermal pipeline network. It consists of including all the components like valve, expansion-reduction, joint, etc.

ACKNOWLEDGEMENTS

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REFERENCES

Bhave, P.R. and Gupta, R. (2006), "Analysis of Water Distribution Networks" Narosa Publishing House, India.

Majumdar, A. (1999), "Generalized Fluid System Simulation Program (GFSSP) Version 3.0", Report No. MG-99-290, NASA, USA.

Patanker, S.V. (1980), "Numerical Heat Transfer and Fluid Flow", Hemisphere Publishing Corporation, USA, 197p.

Ruíz, A., Mendoza, A., Verma, M.P., García, A., Martínez, J.I. and Arellano, V. (2010), "Steam flow Balance in the Los Azufres Geothermal System, Mexico", Proc. World Geothermal Congress, in press.

Smith, J.M. and Van Ness, H.C. (1975), "Introduction to Chemical Engineering Thermodynamics", 3rd Ed., McGraw-Hill Kogakusha, Ltd., 632p.

Verma, M. P. (2003), "Steam Tables for pure water as an ActiveX component in Visual Basic 6.0", *Computer & Geosciences*, **29**, 1155-1163.

Verma, M.P. (2010), "GeoSteamNet: 1. Thermodynamic data for steam flow in a pipeline network of geothermal system" This volume.