Comparative analysis of computer programs for hydraulic calculation of steam-water mixture in pipelines

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Abstract. In the practice of developing geothermal fields, it is necessary to forecast the flow parameters of the well and the pressure drop in the pipeline and need to decide on the optimal design for stable operation of the pipeline. At domestic facilities of geothermal energy, the hydraulic calculation of the steam-water mixture pipelines was carried out using the computer program MODEL developed by the authors of this work. New challenges and the emergence of stability theory led to the creation of the mathematical model SWIP (Steam-Water Inclining Pipeline). This paper presents a comparative analysis of two options for implementing the new model.

1. Introduction

The use of the deep heat of the Earth is considered to be one of the most effective directions of the development of the fuel and energy complex, ensuring minimal harmful impact on the environment. For regions of the Russian Far East with thermal anomalies, such as Kamchatka and Kuril Islands, the development of geothermal resources is relevant and economically justified. In the world practice of the development of steam-hydroterm fields, which are the basis of modern geothermal energy, about 20 years ago, the use of two-phase transport of heat-transfer in surface pipelines from wells to group separators began. Among the first, this technology was used in the development of the Mutnovsky field (Kamchatka).

Pipeline of steam-water mixture connects wellhead of production well with inlet manifold of separator of power plant. The hydraulic calculation of the pipeline has problems associated with two-phase flow. An additional complication is that the flow parameters of the transported mixture depend on the wellhead pressure, which acts as an unknown.

Hydraulic calculation, depending on the tasks set, can be performed for an existing or projected pipeline. In the first case, the task is to predict the flow parameters of the well and the pressure drop in the pipeline when the plant operation mode changes. In the second – the choice of the optimal diameter of the pipeline and future predict. The second case should be considered as a general. In both cases, the only initially determined value is the pressure in inlet manifold of the plant (the pressure at the end-point of the pipeline). The remaining values, considering the dependence on wellhead pressure, shall be determined during the calculation.

In the practice of developing geothermal fields, the solution of the first of the set tasks involves finding a dependence of the pressure drop on phase flow rates, pipe diameter, and flow pressure. In addition, it is necessary to define conditions that ensure stable operation of the pipeline.
The choice of a rational pipeline diameter is an important problem of two-phase transportation. The small diameter creates large pressure losses, reducing the energy potential (flow rate and temperature) of the heat-transfer. The large diameter creates a risk of unstable operation of surface pipeline and the well-to-pipeline system as a whole.

2. Mathematical models of hydraulic calculation
At domestic geothermal power facilities, the hydraulic calculation of steam-water mixture pipelines was carried out using the computer program MODEL, developed by the authors of this work for JSC Geotherm, which develops the field and operates the Mutnovskaya Geothermal Power Plants. Calculations were performed to find optimal solutions for possible options of transportation and to determine the construction parameters for further project. The total length of pipelines built program by MODEL is more than 10 km. The exploitation of the pipelines confirmed the effectiveness of the calculations - pulsation modes were not observed, and pressure drops were close to the predicted ones. The calculation was reduced to determining the pressure drop in the pipeline for set initial pressure, flow rate and enthalpy of the mixture.

But the mathematical model on which the MODEL program is based is suitable for a narrow velocity range of 20–30 m/s, which does not meet modern challenges. In addition, practical experience has shown that the empirical criterion velocity for sustainable transportation in the MODEL program is too strict for pipelines that do not have upstream flows. It should be noted that production wells decrease productivity over time, and the velocity of the mixture in the pipelines falls below the nominal values. Also, in order to reduce costs for construction of pipelines, mixture flows from individual wells are combined into one main pipeline. At the same time, the decommissioning of one well leads to a decrease in the flow rate in the main pipeline, which should be taken into account when designing the pipeline structure. In addition, the emergence a new theory of stability [1] required taking into account the influence of the gravitational component of the pressure drop not considered in this model. All this prompted the creation of a new model.

Numerous attempts led to the creation of a mathematical model of the SWIP (Steam-Water Inclining Pipeline).

The internal pressure drop in the pipeline is expressed in terms of the components for friction, acceleration, gravity, and local resistances

\[ dp = dp_f + dp_m + dp_a + dp_g, \]

where \( dp \) – the total internal pressure drop in the pipeline, \( dp_f \) – the component for friction, \( dp_m \) – the component for local resistances, \( dp_a \) - the component for acceleration, \( dp_g \) – the component for gravity.

Recommendations for the practical calculation of the individual components of formula (1) for two-phase environments significantly depend on the parameters of the environment and the conditions of its transportation. The steam-water mixture transported through pipelines in geothermal fields is characterized by the volumetric dominance of the vapor phase. An exception may be the mixture in the pipelines transporting the separator. For example, at the Pauzhetskoye field, separation is usually carried out near the wellhead. The water level in the separator is set by selecting extent of throttling at the gate valve along the water line. As a result of throttling, saturated water boils, and a steam-water mixture enters the main pipeline of the separator.

In order to maintain the temperature that determines the energy potential of the heat-transfer, during transportation it is necessary to minimize pressure losses. In order to maintain the temperature that determines the energy potential of the coolant, during transportation. Pressure drops are generally small, and the composition of the mixture at the beginning and at the end of the pipeline differs little. Such conditions make it possible to neglect the component of the pressure drop for acceleration, therefore:

\[ dp = dp_f + dp_m + dp_g, \]

According to classical representations, the component for friction is determined by the formula obtained from the analysis of the forces acting on the selected pipe element.
\[ dp_i = \frac{4\tau}{D} dl , \]  

(3)

where \( \tau \) - shearing stress on a pipe wall, \( D \) - diameter of a pipe, \( dl \) - length of element.

The total friction drop is determined by integration (3) over the entire length of the pipeline. The difficulties arise in determining the shearing stress. In [2], the most appropriate expression for the shearing stress in relation to the flow in the geothermal well was considered the upper section of the well, where friction has a significant effect and where the flow parameters are close to the conditions of surface transportation.

\[ \tau = (\rho_w v_1^2 (1 - \alpha) + \rho_g v_g^2 \alpha) \lambda / 8 , \]  

(4)

where \( \rho_w \) - the water density, \( \rho_g \) - the steam density, \( v_1 \) - is the water velocity, \( v_g \) - the steam velocity, \( \alpha \) - the true volume vapor content (ratio of the volume of the gas phase to the total volume of the consider element), \( \lambda \) - the friction coefficient.

Formula (10) represents the shearing stress of the mixture as the sum of the stresses created by the gas and liquid, taking into account their cross-section averaged (true) velocities and their part in the consideration volume. To determine the coefficient of friction, the Shifrinson formula is recommended [3]

\[ \lambda = 0.1 (\delta / D)^{0.25} , \]  

(5)

where \( \delta \) - the absolute equivalent roughness of the inner surface of the pipe.

The homogeneous model also provides a satisfactory agreement with the experimental data for large pipes [4]. For a homogeneous model

\[ \tau = \lambda \rho_m w^2 / 8 , \]  

(6)

where \( \rho_m \) - the density of the mixture according to the homogeneous model, \( w \) - is the velocity of the mixture according to the homogeneous model.

The total expression is obtained as the arithmetic mean according to the formulas (4) and (6)

\[ \tau = (\rho_w v_1^2 (1 - \alpha) + \rho_g v_g^2 \alpha + \rho_m w^2) \lambda / 16 . \]  

(7)

The heat-transfer state parameters, including the mass rate steam content, calculated by using the equations for pure water and water steam in the saturation state.

To determine the pressure drop at the local resistance, the MODEL program used a formula based on a homogeneous model, which can be represented in differential form

\[ dp_m = \frac{0.7 \zeta \rho_m w^2}{L} dl , \]  

(8)

where \( \zeta \) - coefficient of local resistance for a single-phase flow, \( L \) - pipe length.

This formula is designed for a wide range of velocity. Numerous calculations to justify the reconstruction of steam-water mixture pipelines at Mutnovskoye field regarding the elimination of non-functional local resistances, confirmed by practical results, make it possible to recommend this formula for a new model.

The following formula is used for the gravitational component of the pressure drop in the direction of flow

\[ dp_g = -\left(\rho_g \alpha + \rho_l (1 - \alpha)\right)g \sin \theta dl , \]  

(9)

where \( \theta \) - is the angle of inclination of the pipe axis relative to the horizontal plane.

Formula (2) for pressure drop is as follows

\[ dp = \frac{(\rho_w v_1^2 (1 - \alpha) + \rho_g v_g^2 \alpha + \rho_m w^2) \lambda}{4D} dl + \frac{0.7 \zeta \rho_m w^2}{L} dl - \left(\rho_g \alpha + \rho_l (1 - \alpha)\right)g \sin \theta dl , \]  

(10)

A significant difficulty lies in determining the true volume steam content on which the density of the mixture depends. A number of phenomena affecting this value do not have a strict theoretical description, so there is no universal theoretical formula for determining the true volume steam content based on flow parameters. Relevant practical problems are solved by means of correlations [5-8]
containing theoretically justified relationships and empirically established coefficients. Among them, there are correlations that claim to maximize the coverage of conditions in various experiments. However, there are no experimental data corresponding to the conditions of transportation of the steam-water geothermal mixture for such an important parameter as the pipe diameter. In experiments to determine the true volume gas content, the diameter of 0.15 m is considered large [9], while the pipelines of the steam-water mixture in geothermal fields have a diameter of 0.3 m or higher. In [10], an approach to determining the true volume content in the SWIP model is described in detail.

3. The realization of mathematical model SWIP and verification

The simplest realization of mathematical model of SWIP was performed in the form of a computer program SWIP-S for short pipes, where all values and their gradients were determined for a single nodal point and were considered unchanged throughout the calculated interval. In practice, this did not cause significant difficulties – when calculating the pipeline was divided into sections, usually 100-150 m long, within which this simplification is acceptable. Nevertheless, the task was set to implement SWIP with the ability to perform calculations for long pipelines consisting of heterogeneous sections with different pipeline geometries (different lengths and inclines: ascending, horizontal and descending), without fixing intermediate calculations in order to enter the data obtained as the source for the next section. In addition, the new program is supposed to calculate the differences in individual sections not by a single nodal point, but by numerical integration of equation (10). This realization was the computer program SWIP-L for long pipes, in which the parameters are calculated for each point with an interval of 10 cm.

There are very few experimental data for verification of the developed model. The rich experience of successful application of the MODEL program for the calculation of pipelines at the Mutnovskoye and Pauzhetskoye fields allows using the MODEL program under typical conditions of its application to verify a new model.

To carry out calculations using MODEL and SWIP-S and compare the results obtained, a horizontal pipe with a length of 100 m, an internal diameter of 0.4 m, enthalpy of the mixture 1200 kJ / kg, and pressure at the wellhead 7.5 bar were taken. Since the MODEL program does not take into account the gravitational component, and local resistances are determined in the same way as in the new model, the verification was carried out without the presence of local resistances. The calculated pressure drops are shown in Figure 1. There is good agreement in the nominal cost range.

Figure 1. The calculated pressure drops: 1 – MODEL, 2 – SWIP-S
Figure 2 shows the calculated pressure drops depending on the flow rate made according to SWIP-S and SWIP-L with the same pipe configuration and source data as in figure 1. Visible deviations are observed at flow rates of more than 60 kg/s. In particular, at $G = 60$ kg/s, SWIP-S understate the result by 1.6%, and at $G = 80$ kg/s by 2.9%.

**Figure 2.** The calculated pressure drops by SWIP.

For comparative analysis of the calculation of parameters for various versions of SWIP (S-version and L-version), a typical conditional pipeline of the Mutnovskoye field was taken: length 1 km, diameter 400 mm, pressure at the initial point 7 bar, enthalpy 1200 kJ/kg, height difference 25 m, local resistance coefficient 5, distributions of height difference $s$ and local resistance are uniform.

For SWIP-S calculations, the pipeline was divided into five sections of 200 m each, with a height difference of 5 meters and a local resistance coefficient of 1 due to the uniformity of the distribution. Performing the calculations at the next step, the pressure at the initial point of the previous section is reduced by the amount of the drop. No such partitioning is required for SWIPL calculations. The results of the calculations are presented in Table 1. The calculations by SWIP-L do not require such a divide. Results of calculations are presented in Table 1.

**Table 1.** S- and L-version calculation pressure drop by SWIP model.

| Mass rate, kg/s | Pressure drop SWIP-S, bar | Pressure drop SWIP-L, bar | Percent of understating by S-versions relative to L-versions, % |
|----------------|---------------------------|---------------------------|-------------------------------------------------------------|
| 30             | 0.5416                    | 0.5493                    | 1.4                                                         |
| 40             | 1.1529                    | 1.1857                    | 2.8                                                         |
| 50             | 2.0347                    | 2.1495                    | 5.3                                                         |

The analysis of the results reveals the sensitivity of the calculated values to the integration step at high flow rates. The higher the flow rate of the mixture and the pressure drop, the greater the deviation of the pressure drops calculated according to the S-and L-versions. In practice, the SWIP-S version is based on a single integration step (10) using gradients calculated for the initial pressure. If friction dominates in the pressure drop, and as the flow proceeds, the pressure along the length of the pipe decreases, the phase velocities increase and the pressure gradient increase, this approach reduces the calculated pressure drop.

Figure 3 shows graphs of the dependence of the percent understating of the pressure drop calculated by S-versions relative to L-versions on the flow rate for different pressure values at the initial point of the pipeline.
Figure 3: The dependence of the percent understating of the pressure drop calculated by S-versions relative to L-versions on the flow rate for different pressure values.

Note that for the pipeline under consideration, the transport of the mixture at an initial pressure (at the inlet) of 7 bar with a flow rate of 70 kg/s, according to the calculation according to SWIP-L, is no longer possible - in the process of calculating down-flow, pressure becomes impossible values (pressure in principle can not be negative).

For SWIP verification in conditions of inclined pipes, pipeline data from the Geo-1 well at the Mutnovsky field was used. This pipeline has the largest height difference of the currently operating steam-water mixture pipelines in Kamchatka. Data on the pipeline: length 1050 m, height difference from the beginning to the end 110 m, internal diameter 0.406 m, total coefficient of local resistances 8. For verification, data obtained on 16.09.2011 and 11.09.2019 were used. The parameters at the entrance to the pipeline (wellhead) and the results of calculations are shown in Table 2.

Table 2. The parameters at the entrance to the pipeline (wellhead) and the results of calculations.

| Date          | Mass rate, kg/s | Enthalpy, kJ/kg | Wellhead pressure, bar | Calculated pressure drop by SWIP-S, bar | Calculated pressure drop by SWIP-L, bar | Experienced pressure drop, bar |
|---------------|-----------------|-----------------|------------------------|-----------------------------------------|------------------------------------------|-------------------------------|
| 16.09.2011    | 65.0            | 1221            | 11.3                   | 1.52                                    | 1.49                                     | 1.5                           |
| 11.09.2019    | 65.3            | 1121            | 8.9                    | 1.76                                    | 1.78                                     | 1.8                           |

To calculate the total pressure drop according to SWIP-S, the pipeline was divided into 7 sections. For SWIP-L, this partitioning is not required. The error in determining the test pressure drop is estimated at ±0.2 bar.
4. Conclusions
Despite the introduction of approximate values for some coefficients into the model, a good agreement was obtained between the calculated and measured pressure drops (Table 2). Note that the MODEL program was used in the design of this pipeline.

Thus, the proposed SWIP model under typical conditions of transportation of a steam-water geothermal mixture is in good agreement with the calculation according to the MODEL program, which in these conditions is in good agreement with the experimental data. For atypical conditions (a significant incline of the pipeline, low velocity of flow), the new model is preferable.

This model should not be considered as universal, suitable for all conditions. The model does not take some effects influencing at parameters of flow, for example, such as changing regimes the two-phase flow. As new data is obtained, the model is expected to be improved.

A comparative analysis of the computer programs SWIP-S and SWIP-L shows that the use of a program focused on short pipelines can distort the results due to the chosen procedure for solving equation (10) at high flow rates that provide high pressure drops.

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References
[1] Shulyupin A N 2018 Stability of the Operation Mode of a Steam-Water Well (Khabarovsky: "Amurprint")
[2] Shulyupin A N 1992 Flow in a geothermal well: model and experiment Volcanology & Seismology 13(4) pp 426-34.
[3] Theoretical Foundations of Heat Engineering. Heat Engineering Experiment: reference book 1988 ed V A Grigoriev and V M Zorin (Moscow: Energoatomizdat)
[4] Rizaldy and Zarrouk S J 2016 Pressure drop in large diameter geothermal two-phase pipelines Proc. 38th New Zealand Geothermal Workshop pp 1-5
[5] Waldeemayat M A and Ghajar A J 2007 Comparison of void fraction correlations for different flow patterns in horizontal and upward inclined pipes Int. J. of Multiphase Flow 33 pp 347–70
[6] Bhagwat S M and Ghajar A J 2012 Similarities and differences in the flow patterns and void fraction in vertical upward and downward two phase flow Experimental Thermal and Fluid Science 39 pp 213–27
[7] Xu Y and Fang X 2014 Correlations of void fraction for two-phase refrigerant flow in pipes Applied Thermal Engineering 64 pp 242–51
[8] Bhagwat S M and Ghajar A J 2014 A flow pattern independent drift flux model based void fraction correlation for a wide range of gas-liquid two-phase flow Int. J. of Multiphase Flow 59 pp 186–205
[9] Deng Z, Yang Z, Yang X and Ishii M 2019 Experimental study on void fraction, pressure drop and flow regime analysis in a large ID piping system Int. J. of Multiphase Flow 111 pp 31–41
[10] Shulyupin A N and Varlamova N N 2021 Determining the void fraction in the hydraulic design of geothermal steam-water mixture piping Therm. Engin. 68(5) pp 395–9