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Estimation and validation of models two phase flow from geothermal wells

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Abstract

The behavior of two phase flow is a difficult subject that has been studied extensively over the years. The main problems concerning the flow involve determining the type of flow, which is related to many parameters and also calculating the pressure drop in a pipe containing two phases of the same fluid.

The purpose of this paper is to evaluate two phase condition at various high temperature geothermal sites in Iceland and apply known models for two phase flow to these conditions. These models involve both the determination of flow regimes as well as pressure drops in horizontal pipes. Furthermore, measurements have been performed at Nesjavellir Power Plant in Iceland in order to compare the model results to real data.

Results show that some types of flow regimes are more common than others at the named geothermal sites, which simplifies and narrows the search further for suitable pressure drop models. Measurements at Nesjavellir show that modeling errors are generally high and the best models predict pressure drop with 30% error.

1 Introduction

Utilization of geothermal heat is a well known method for both heat and power production and its usage is still rapidly increasing. This utilization has traditionally been in the field of district heating where relatively low temperature geothermal fluid is used, either directly or indirectly by using heat exchangers. Geothermal heat is also used for power production in many countries but in order to achieve sufficient efficiency, high temperature geothermal fields are exploited in this case.

Two phase flow is very common in connection with high temperature geothermal areas where steam is used for power production and water is supplied to district heating systems. Consequently, it is of vital interest to be able to determine fluid behavior and pressure losses in surface pipes which are connected to the geothermal wells, in order to understand this primary part of a energy production system which involves both power production and district heating.

Much research has been conducted in the area of two phase flow and the subject is far from covered. In the field of analyzing flow regimes, a great number of flow maps have been proposed, see [1], [2], [3], [4] and [5]. The most recent publication by [6] proposed a universal flow regime map for a broader range of data than previous models.

When regarding pressure drops models, they can be divided into two types: 1) separate models for each flow regime and 2) general models. For references see [1], [2], [7] and [3]. In this paper a modified Harrison correlation ([8]) is amongst others used for comparison with measurements of geothermal pipes.

The subject of this paper is to analyze the two phase flow conditions that exist in the transport pipelines of Icelandic geothermal power plants. Secondly, to present measurements of pressure drop in the Nesjavellir geothermal power plant and compare the measurements to the pressure drop predictions of a suitable model for these conditions.

2 Methods and models

2.1 Two phase flow regimes

The complex interaction between the phases in two phase flow forms an overall outlook of the flow at each time, which is categorized into different flow regimes. The concept of a flow regime is a subjective and qualitative concept and therefore it is not possible to incorporate it into mathematical equations as a parameter. Predicted results usually show some discontinuity between different regimes which is related to uncertain prediction, see [3].

Figure 1 shows the Hewitt division of flow which is categorized as:

Stratified flow : The phases separate so that the liquid flows in the bottom of the pipe and the gas phase in the upper half.

Stratified-Wavy flow : With increased gas speed in stratified flow, waves start to form on the interface between the two phases, traveling in the direction of the flow.

Dispersed Bubble flow : Gas or vapor bubbles are distributed in the liquid phase. At low speeds the bubbles tend to collect at the top of the pipe due to low density of the bubbles.

Annular dispersed flow : The liquid flows in a film at the pipe wall and surrounds all of the gas phase which flows in the center. Usually a small fraction of the liquid phase is entrained in the gas phase as droplets. The film thickness is nonuniform because of gravity and is much thicker at the bottom.

Plug flow : With higher gas velocity the gas phase bubbles converge and form long plugs which flow near the top of the pipe in the direction of the flow. Sometimes also called elongated bubble flow.

Slug flow : Is defined as, frothy slug waves which reach the top of the pipe. The slug can cause much difficulty because of the sudden pressure pulses and vibrations of the tubes. In reality it is very difficult to distinguish between plug and slug flow.

Semislug flow : The slug waves do not reach the top of the pipe and pass through the pipe as waves. Similar to the wavy annular flow.

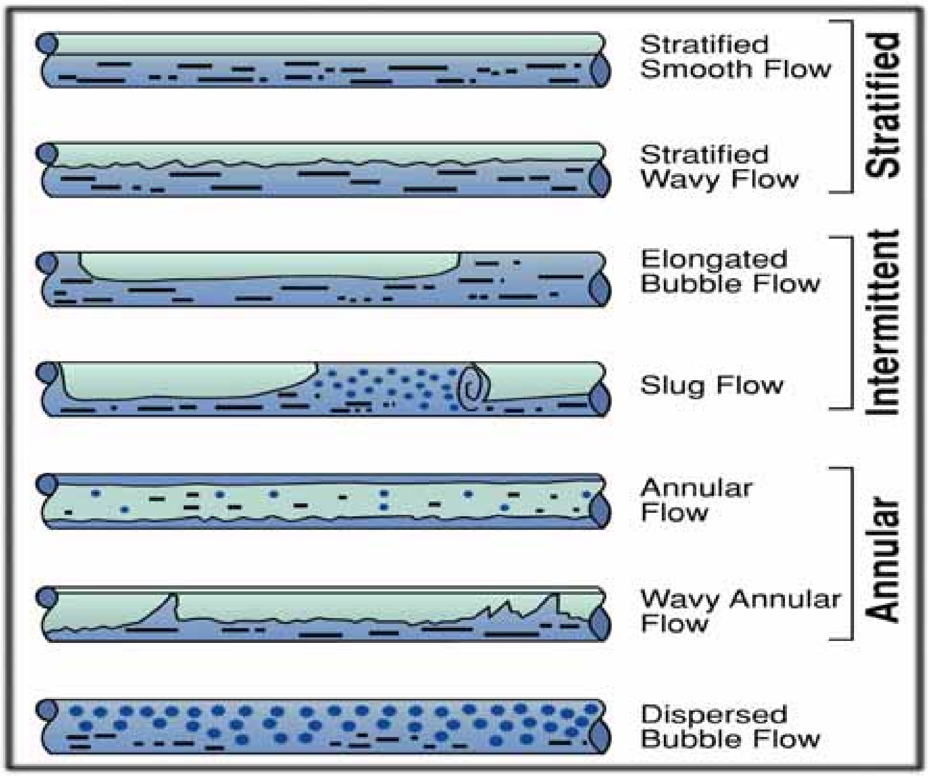

Figure 1: The main flow regimes

Many different methods have been proposed for the recognition of flow patterns ranging from visual inspection to characteristic fluctuation in hold up, conductivity and pressure by finding the range of fluctuation for each flow regime.

The use of only visual observations for determining flow patterns has the disadvantage of being subjective. Differences in interpretation of visual observations are with out a doubt a major reason for experimenters having recorded different flow patterns under essentially similar flow conditions, see [5]. The development of a simple qualitative means for distinguishing between flow patterns is therefore desirable.

2.2 Pressure drop models

The basic procedure used in predicting frictional pressure drop in two phase flow is developing a general correlation based on statistical evaluation of data. The main disadvantage of such correlations is choosing the appropriate weight for the data in each flow regime, i.e. deciding which combination of data for each flow regime gives the best fitted correlation for the whole dataset.

Another problem in using correlated pressure drop calculations is that the range of application is limited and a large number of constants are required in the correlation for larger data sets.

The flow regime in the transport lines is most likely a wavy stratified one and therefore models that have shown good agreement with pressure drop data for these flow regimes should give a better result.

Many different pressure drop models exists and can be classified as

- Homogeneous models, where the two phases are treated as a single fluid.
- Separate flow models, where phases are treated separately.
- Semi-analytical models, where the physical behavior of the flow is modeled thoroughly. An example of this are the so called mechanistic models, see e.g. [9].

The modified Harrison correlation, see [8], is based on a large data set from geothermal flow in a 10 cm diameter pipe. The first parameter to be determined is the void fraction, α, which is the ratio between the volume of the gas phase in the pipe and the total volume of the pipe.

The seventh power law is used to derive an equation for the void fraction

$$\frac{1-\alpha}{\alpha^{7/8}} = \left[\frac{(1-x)}{x}\frac{\rho_G}{\rho_L}\frac{\mu_L}{\mu_G}\right]^{\frac{7}{8}} \quad (1)$$

where ρ is the density, μ is the viscosity and L and G denote the liquid and gas phases, respectively. The average liquid phase velocity is found from

$$\overline{V}_L = 1.1(1-x)\frac{\dot{m}(1-x)}{\rho_L(1-\alpha)A} \quad (2)$$

where x is the mass fraction of gas, $\dot{m}$ is the mass flow and A is the cross sectional area of the pipe. The average velocity of the equivalent single-phase flow, $\overline{V}$, is found from

$$\frac{\overline{V}_L}{V} = \frac{\left(1-\sqrt{\alpha}\right)^{8/7}\left(1+\frac{8}{7}\sqrt{\alpha}\right)}{1-\alpha} \quad (3)$$

The average equivalent velocity is then used to find the friction factor and the wall shear stress, τ_w.

The pressure gradient is finally calculated from the shear stress

$$\frac{dp}{dz} = \frac{4\tau_w}{d(1-AC)} \quad (4)$$

where d is the pipe diameter and the acceleration correction factor AC is given as

$$AC = \frac{\dot{m}_G}{\rho_G P A^2 \alpha} \quad (5)$$

where P is the pipe perimeter. This method has given a good agreement with experimental data for geothermal two phase flow.

3 Results

3.1 Flow regimes in icelandic geothermal power plants

An attempt was made to find the most likely flow regime in the two phase flow of steam and water in Icelandic geothermal power plants from the operating conditions of each pipeline.

The Baker map for horizontal two phase flow, published in 1955, is plotted with G/λ against $L\psi$ where G and L are the mass fluxes of the gas and liquid phase respectively and λ and ψ are found from

$$\psi = \left(\frac{0.0724}{\sigma_L}\right)\left(\frac{\mu_L}{0.0009}\left(\frac{1000}{\rho_L}\right)^2\right)^{\frac{1}{3}} \tag{6}$$

and

$$\lambda = \left(\frac{\rho_G}{1.2} \cdot \frac{\rho_L}{1000}\right)^{\frac{1}{2}} \tag{7}$$

where σ_L is the surface tension of the liquid. The Baker map in figure 2 indicates that the most common flow regimes in geothermal pipelines are annular flow and wavy flow. It not unlikely that the Baker map is underestimating the gravity force in larger pipes.

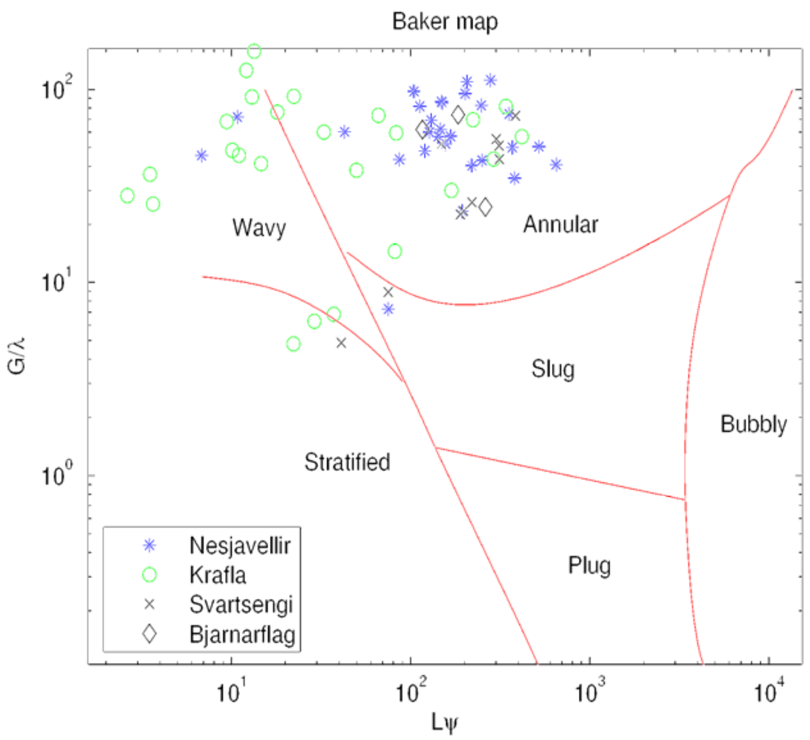

Figure 2: Baker flow regime map for horizontal flow

The Mukherjee and Brill map, see [10], for horizontal two phase flow is based on several measurements for different inclination of pipes. The map is plotted for the so called liquid phase velocity number as a function of the gas phase velocity number. The map predicts that only stratified flow persists in the transport pipelines of the selected geothermal power plants, as seen in figure 3.

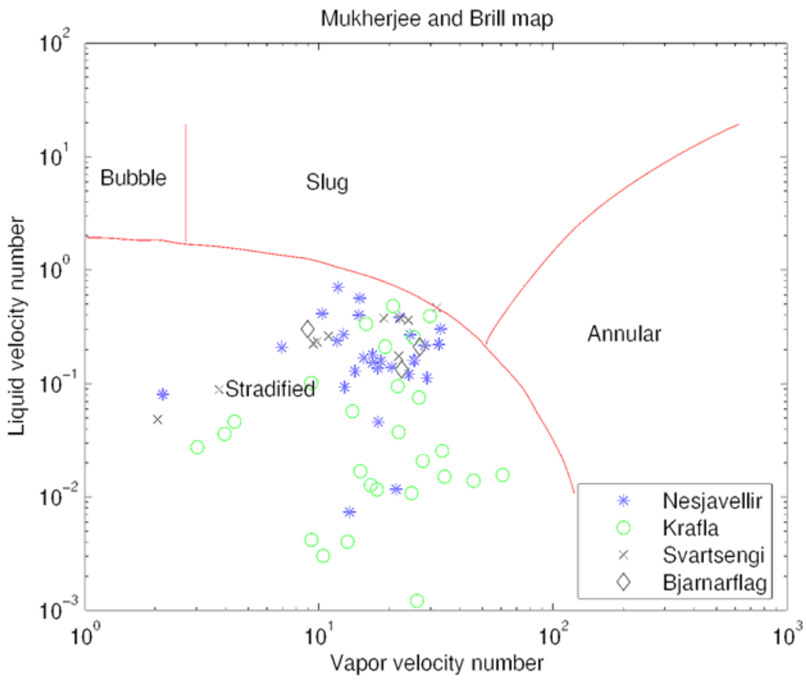

Figure 3: The Mukherjee and Brill map for horizontal flow

The final map considered here is the Spedding and Nguyen map, see [10]. The operating conditions are shown in figure 4 and the map clearly predicts that wavy stratified flow is the most common flow regime.

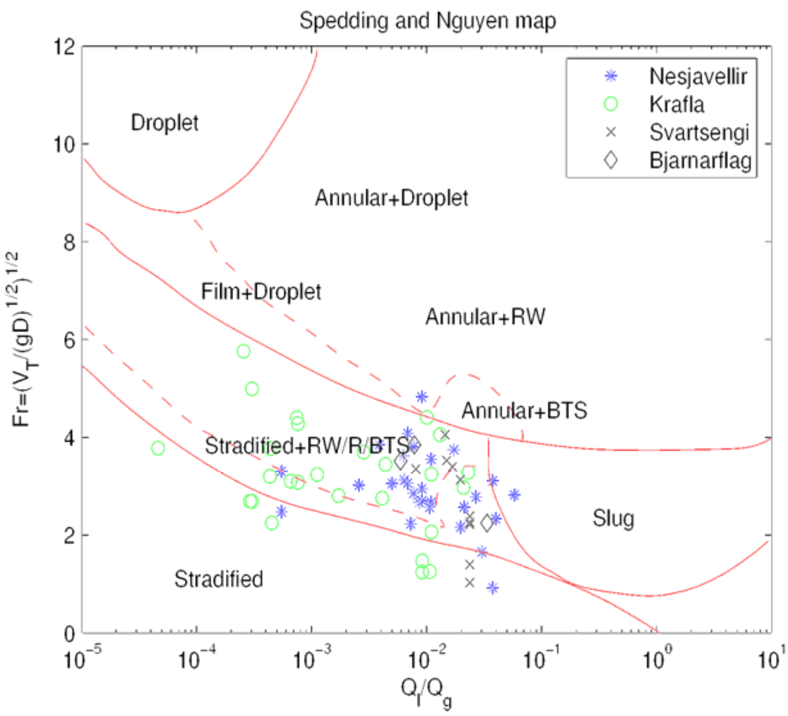

Figure 4: Modified Spedding and Nguyen map for horizontal flow

The maps indicate that very similar flow pattern exists in all of the transport pipelines, which is most likely a wavy stratified flow. This means that the two phases flow separately, gas phase at the top and liquid phase at the bottom, and the interface between the phases is wavy.

3.2 Measurements of pressure losses

Measurements of pressure drop were performed on geothermal pipes at Nesjavellir power plant in Iceland. A conventional manometer was used to determine pressure difference between points at a distance up to 300 meters from each other.

The manometer setup is shown in figure 5, where small pipes are connected to the geothermal pipelines with the manometer in between. The base fluid in the manometer is carbon dioxide which has the same pressure as the geothermal fluid and the manometer is therefore a liquid-gas one.

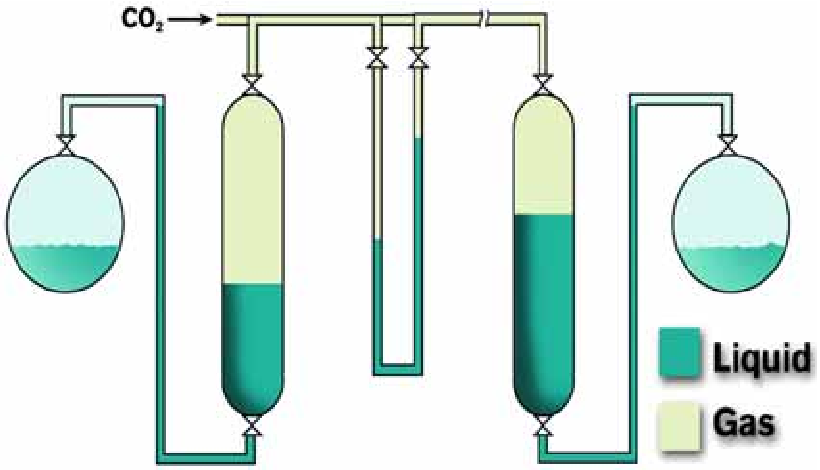

Figure 5: The manometer setup

Only few metering points were available at Nesjavellir and figure 6 shows the different connections of the manometer that were used in the study.

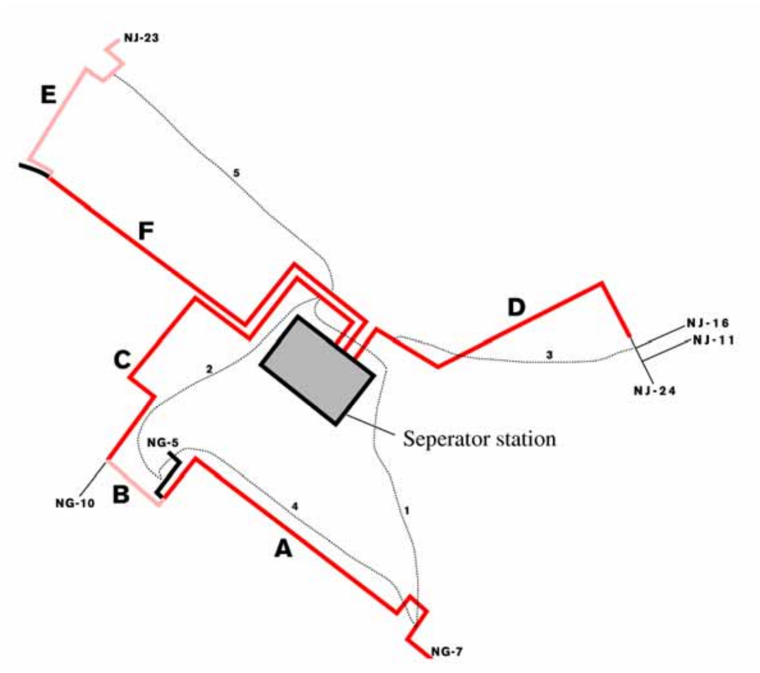

Figure 6: Measurement points at Nesjavellir

Table 1 below shows the results of the measurements for the five points available.

Measurement	Δp [mbar]	L [m]	$\dot{m}_{total}$ [kg/sek]	Inner diameter [mm]	Number of bends
1	164	-	-	-	-
Pipe A	-	272	25	344	4
Pipe B	-	75	42	394	1
Pipe C	-	299	69	693	5
2	62	-	-	-	-
Pipe B	-	75	42	394	1
Pipe C	-	299	69	693	5
3 (Pipe D)	246	230	114	693	2
4 (Pipe A)	123	272	33	344	4
5	442	-	-	-	-
Pipe E	-	138	23	394	4
Pipe F	-	332	125	693	2

Table 1: Measurements at Nesjavellir

During measurements it was observed that the maximum pressure fluctuation was around 10-15 cm per second, i.e. around 5–8 millibars per second so the average value of several measurements was taken as the pressure drop. It was also concluded that the average error of each measurements was about 10 cm of water height, which corresponds to 10 millibars.

In order to include the effects of bends in the pipe, a model by Chisholm, see [11], was used as a correlation, resulting in an equivalent pipe length for a given bend.

3.3 Comparison of models and measurements

The measurements were compared to several models for pressure drop and the results are shown in table 2, where the error is relative to the experimental results and the spread denotes the standard deviation of the error from the average value.

	Avg. error [%]	Spread [%]
Harrison model	36	52
Simple model	27	49
Mechanistic model	117	111
Martinelli Nelson	43	60
Lockhart Martinelli	83	7
Baroczy	92	105
Friedel	32	43

Table 2: Comparison of models and measurements

The lowest combined prediction error and spread is seen in the prediction of the model by Friedel, which is a relatively old model. This is followed closely by the Harrison model, described in this paper. Nevertheless, the results show large errors for most of the models, indicating the difficulty in predicting pressure drop in larger geothermal pipes.

4 Conclusions

In this paper, models for determining two phase flow regimes are applied on conditions in Icelandic geothermal pipelines, in order to determine the most common flow regime present. Also pressure drop models are compared to actual measurements at Nesjavellir power plant in Iceland.

It is apparent that the most common flow regime is a stratified wavy flow, which is somewhat dependent on flow velocity and void fraction, but in general the void fraction is very large in plants that utilize steam for electricity production. This would not be the case in district heating pipes where only the water phase is present.

Results for the pressure drop measurements show large pressure drop for a relatively short pipes with large diameter. The reason is most likely the braking effect of the wavy flow as well as the large difference between gas and liquid velocity in the pipes (gas velocity being much larger).

When models are compared to the measurements, the resulting errors are very high for most of the models, up to about 120%. The best models turned out to be the Friedel model and the Harrison model, with an average relative error of about 30%.

The results clearly show that there is a need for a better model for the pressure drop calculation in geothermal power plants. There is a need for a correlation based on measurements in actual geothermal power plants, which could include among others the effect of the surface roughness on the frictional pressure drop. The correlations could then be used to replace the small pipe correlations in the existing analytical or semi-analytical models intended for stratified wavy flow

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