Optimization of pipelines for transportation of geothermal two-phase fluid from well-head to power block

Paolo Maria Zanzucchi[1], Giampaolo Manzolini[2], Marco Del Carria[1], Claudio Pietra[1], Joseph Bonafin[1]

[1] Turboden SpA, via Cernaia 10, 25124 Brescia, Italy

[2] Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milano, Italy

paolo.zanzucchi@turboden.it

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ABSTRACT

Geothermal power plants require a so-called Resource Gathering and Reinjection system, to collect and deliver the geothermal fluid from the production wells to the power plant, and to give back the fluids to the reinjection wells. In many cases, at the well-head, geothermal flow consists of two phases: vapour (water steam + no-condensable gases) and brine. If two-phase flow is present, a separator is required, and its location has a significant impact on both pressure losses and costs. Different strategies can be adopted in terms of location of separation station. Main factors, which can influence the location of separation station, are:

- Space available on well pad vs space available on pad where the power plant will be built;
- Distances and elevation between well pad and power plant;
- Characteristics of the geothermal fluid extracted.

Subject of this study is the implementation of a model for the optimization of geothermal two-phase fluid transportation system. It will allow determining pressure and power losses along the two-phase pipeline and compare them with the ones of two single-phase lines. Knowing the power lost during transportation, the net power output will be computed adopting a simplified binary cycle. The model developed will be then validated with reference geothermal pipelines data. At last, a comparison between single- and two-phase pipelines will be carried out based on power producible, pressure losses and total costs.

1. INTRODUCTION

Optimization of resource gathering systems for the transportation of geothermal two-phase flows is a complex task depending on the assessment of the overall pressure losses along the pipeline. In literature, there is not an explicit method or general correlation that can always be adopted to calculate these losses. Indeed, pressure losses strongly depend on the flow regime inside the pipe, which relies on characteristic of the stream and of the pipeline. Determination of the flow regime is typically carried out using empirical flow pattern maps that can be found in literature (Lips and Meyer 2011). Unfortunately, most of the information available in literature refers to small diameter pipes and cannot be scaled up to be applied to large diameter ones, as the flow regime does not depend only on geometry (Archibong et al. 2016). Therefore, an accurate analysis of the correlations described in literature is required. Each one has its own ranges of applicability and constraints that dictate their use.

Few software are available to optimize two-phase pipeline, such as OLGA and MAST, which are based on empirical correlations. However, their complexity do not justify their use in a preliminary analysis. Hence, the need for this model.

Another significant difficulty that has to be addressed is the data collection for the model validation. For validating the model, both measurements taken in a two-phase pipeline and design data have been considered and analysed. When considering two-phase flows, pressure measurement alone is not enough. Characteristics of the stream, i.e. steam quality, composition and mass flow rate are required as well. This implies the need for specific equipment, other than manometers. Moreover, the condition of the pipeline has to be considered because fouling or corrosion could be present. Varying the surface finish or reducing the cross-sectional area available to the stream flow lead to higher pressure losses, and variation of the flow regime. Regarding designed data, the main problem to face is the absence of a precise procedure able to correctly predict two-phase pressure losses and safety margin to be considered. However, the aim of this work is the development a model able to compute results as close as possible to the ones available. For all this reasons, the validation of the model is a delicate step and will be described in more details in Chapter 4.

The procedure followed to develop the model is presented. Initially a literature analysis has been performed, collecting all the correlations that could be useful. It follows the implementation of the model itself and then its validation, with data of two-phase pipelines provided by Turboden. At the end, conclusions have been drawn (Zanzucchi 2018).

2. CORRELATIONS ANALYSED FOR TWO-PHASE FLOW

Two-phase flows encompass all those streams where two different phases are present simultaneously. As the objective of this project is the modelling of geothermal fluid gathering systems, the focus will be on liquid-vapour-NCG (Non-Condensable Gases) flows, particularly brine is considered for the liquid. Main variables are: pressure, enthalpy, velocity, density, void fraction and mass fraction. They are enough to describe the behaviour of the flow and allow the calculation of pressure losses. In principle, two-phase flow modelling could follow the same procedure as single-phase ones by applying the transport equations to each individual phase and setting appropriate boundary conditions. However, in this case a new closure relation is required at the interface between the phases. This results in a new additional model to describe the fundamental equation considering that the interface between phases is not stationary. This would be a very computational expensive process; therefore, simplified approaches are often used. Hence, simplified correlations must be adopted and implemented in the model. The different correlations evaluated in this work are reported in Table 1.

TWO-PHASE CORRELATIONS		
Void Fraction		
Modified Dix (Woldesemayat and Ghajar 2007)		$\alpha = \dfrac{U_{SG}}{U_{SG}\left(1 + \left(\frac{U_{SL}}{U_{SG}}\right)^{\left(\frac{\rho_G}{\rho_L}\right)^{0.1}}\right) + 2.9\left[\frac{gD\sigma(1+\cos\theta)(\rho_L-\rho_G)}{{\rho_L}^2}\right]^{0.25}(1.22+1.22\sin\theta)^{\frac{P_{atm}}{P_{system}}}}$
Lockhart-Martinelli (Thome 2004)		$\alpha = \left[1 + 0.28\left(\frac{1-x}{x}\right)^{0.64}\left(\frac{\rho_g}{\rho_l}\right)^{0.36}\left(\frac{\mu_l}{\mu_g}\right)^{0.07}\right]^{-1}$
Friction Factor		
Swamee-Jain (Heimisson 2014)		$f = 0.25\left[log_{10}\left(\frac{\epsilon}{3.7D} + \frac{5.74}{Re^{0.9}}\right)\right]^{-2}$
Colebrook-White (Kiijarvi 2011)		$\frac{1}{\sqrt{f}} = -2Log_{10}\left(\frac{\epsilon}{3.7D}\frac{2.51}{Re\sqrt{f}}\right)$
Chen (Aakenes 2012)	$Re \leq 2000$	$f = \frac{16}{Re}$
	$Re \geq 4000$	$\frac{1}{\sqrt{f}} = -4 * Log_{10}\left[0.2698\left(\frac{\varepsilon}{D}\right) - \frac{5.0452}{Re} * Log_{10}\left(0.3539\left(\frac{\varepsilon}{D}\right)^{1.1098} + \frac{5.8506}{Re^{0.8981}}\right)\right]$
	Transition	$f = \frac{f_{lam}(4000-Re) + f_{turb}(Re-2000)}{2000}$
Friction Correction Factor (Awad and Muzychha 2004)		
Churchill		$\Phi^2 = \left(\frac{f_m}{f_l}\right)\left(1 + x\frac{\rho_l-\rho_g}{\rho_g}\right)$
Lockhart-Martinelli		$\Phi^2 = 1 + \frac{C}{X} + \frac{1}{X^2}$
HTFS		$\Phi^2 = 1 + \frac{C_c}{X} + \frac{1}{X^2}$

P. Sookprasong (Azzi and Friedel 2005)	$\Phi^2 = \frac{(\rho_l u_l + \rho_g u_g)(u_l + u_g)}{\rho_l u_l^2}$
Pressure drop caused by height difference	$\Delta p_H = g\rho_m \sin\theta\,(h_2 - h_1)$
Pressure drop caused by friction	
Darcy-Weisbach (Kiijarvi, 2011)	$\Delta p_f^{2-phase} = \Phi^2 \frac{f\rho L}{D}\frac{u^2}{2}$
Beggs-Brill (Beggs and Brill, 1973)	$\Delta p_f = \frac{2 f_{tp} u_m^2 \rho_{ns} L}{D}$
Pressure drops through different installation	
Chisholm (Chisholm 1983)	$\Delta p_{fi} = \Phi^2 K_{SP}\frac{G^2}{2\rho_{liquid}}$
Darcy-Weisbach (Heimisson 2014)	$\Delta p_{fi} = \Phi^2 \frac{f\rho_m \bar{V}^2 h}{2D}$
Sreenivas Jayanti (Jayanti 2011)	$\Delta p_{fi} = \Phi^2\left(\frac{1}{2} f\rho_l u^2 \frac{\pi R_b}{D}\frac{\theta}{180°} + \frac{1}{2}k_b \rho u^2\right)$

Table 1: Matrix of correlations implemented

α	f	Φ^2	Δp_f	Δp_{bend}
Dix	Chen	HTFS	Darcy-Weisbach	Darcy-Weisbach
	Swamee-Jain	Churchill	Beggs-Brill	Chisholm
		Lockhart-Martinelli		Sreenivas-Jayanti

Table 2: Names of all the possible correlations for each parameter

3. MODEL IMPLEMENTATION AND OPERATING PROCEDURE

The development of the model required different steps to divide the overall objective in intermediate procedures. All the different steps followed for the implementation of the model are listed below:

- Implementation of single functions for the calculation t of pressure drop for two-phase pipelines, fixing all the other inputs;
- Implementation of an additional routine for the computation of power losses along the pipeline and updating the properties of the fluid considering the new thermodynamic conditions;
- Thermal expansion is considered by means of a function which add, when needed, expansion loops along the pipeline;
- Single-phase pipelines calculation is added considering the flash unit near well-head;
- Calculation of the net power output considering the fluid conditions at the plant inlet equal to the end of the RGS and adopting a simplified ORC;
- Implementation of the costs analysis, considering only those expenses strictly related to the pipeline, i.e. cost of materials, supports and welds.

The model discretises the overall length of the pipeline, dividing it into shorter sections of defined length. The user can select the grid size. A parametric analysis shows that a more refined grid significantly increase the computational time whilst the accuracy improvement is limited (approximately cents of bar per kilometre of pipeline passing from 50m/step to 20m/step). This variation is acceptable considering the uncertainties in the computation and the overall losses expected, which are generally much higher. The discretization of the pipeline allows the application of the equations without involving integral forms but using discrete equations. This both simplifies the procedure and provides quite accurate results with an uncertainty much lower than the expected one when calculating two-phase pressure losses with conventional correlations. The procedure to use the model is intuitive, after inserting the inputs required, regarding both the stream and the pipeline characteristics, the operator needs to select the best set of correlations which will be used in the calculations of two-phase pressure losses. The model will then provide results both of the two-phase and single-phase transportation systems suggesting the optimum one. The applicability of a particular set is related to the expected flow regime. However, as there is not an available flow pattern map for large diameter pipes, these are derived considering the mass flow rate, diameter and inclination of the pipe. The idea of variable sets of correlations depending on the flow regime gets confirmed in literature. It is explicitly said that there is not one single set of correlation able to correctly predict the pressure losses in a two-phase pipeline over all flow regimes, (Spedding et al., 2006) and (Lips and Meyer, 2011). Therefore, the need for variable correlation option.

Fig. 1 reports the flow chart of the model computation considering all the steps required in the optimal configuration choice.

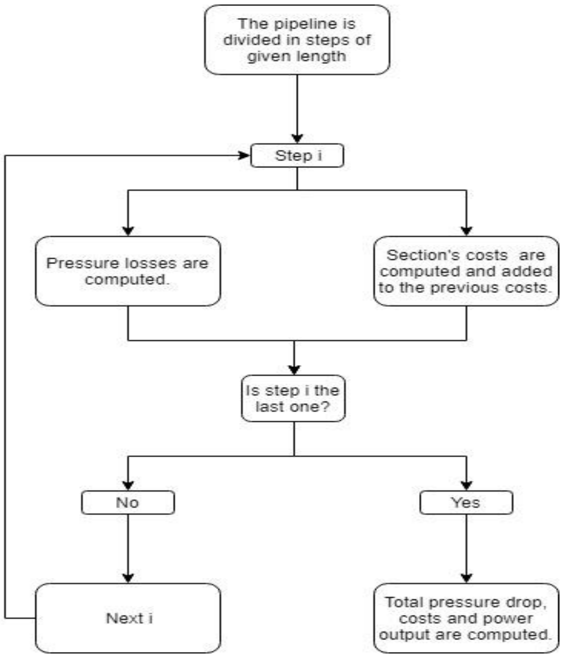

Figure 1: Flow chart of the model operating procedure

3.1 Power and cost analysis

Power and costs are computed in a simplified way in order to have a general indication of the trends and identify the optimal transportation strategy. As the objective of this work is the optimization of the RGS, these power and cost analysis are used only as common basis for the comparison between the two transportation strategies.

The calculation of net electric power that can be produced considering the flow at the end of the RGS considers the two phases separately. The Carnot efficiency is applied to the vapour phase, which is condensing, while for the liquid phase the Lorentz efficiency is considered, to better match the triangular profile. To improve the accuracy of the ORC approximation, an ideal to real efficiency is added as a variable input.

The values obtained are not representative of the actual power producible but are used only to understand which configuration will have higher power generation.

To determine the overall cost of the RGS, the model considers:

- The weight of the metallic pipe, with an input cost of metal;
- Total insulant outer area and not its weight because its cost is generally given as dollars per square metre;
- Supports, their cost is computed as a percentage of the metal weight and multiplied by the same cost of material. This is done in order to simplify the calculation. The percentage is an input variable; therefore, it can be varied considering that a pipe with larger diameter and thicker walls will be heavier, requiring more supports;
- The model computes the number of welds required considering a standard rod length and the number of bends. However, it is uncommon to have a cost per weld therefore their influence on the total cost of the pipeline is considered in the cost of material of the metal, which is also a variable input.

3.2 Comparison of single- and two-phase transport

Single- and two-phase transport are compared throughout a sensitivity analysis. The model compares pressure losses, power produced and total cost of both pipelines. To determine the best configuration of both viable solutions, the pipes diameter varies in a range of (+/-) 50 millimetres. This allows identifying the optimum condition of each possibility. Consequently, these are compared and the best one is identified.

To summarize, the comparison is based on total pressure drop and the economic analysis. The last one is based on the total investment costs and on the value attributed to the difference in power producible between the different cases, named added value. However, if two-phase pressure losses calculated are too high, than the proposed solution is the transportation of the different phases in two separated pipelines regardless the economic analysis. Otherwise, the best solution is identified considering the trade-off between total added value and the investment costs. However, as this cost analysis is not very accurate but gives an indicative value of what will be the costs related to the RGS and the power output, the obtained results are considered a screening and have to be analysed carefully. If the difference between the two economic results obtained is small, it is not certain that one choice is better than the other. In this case, a detailed analysis is required and the preliminary analysis requires a more accurate investigation with professional tools.

4. MODEL VALIDATION AND APPLICABILITY

4.1 Baseline data analysis

To validate this model and define the best set of correlation to be used a comparison with real measurements and with designed data from outsource studies of two-phase pipelines is required. All the results obtained are then analysed with the expected pressure drop and conclusions are extrapolated. The focus is set on the validation of two-phase pressure losses, as single-phase ones can be calculated quite accurately using equations described in literature.

Turboden provided design data (calculated with professional software tools) of pipelines still to be built in Olkaria, Kenya. Streams' compositions and pipelines characteristics are provided as well.

Pipeline	Mass flow rate [ton/h]	Inlet pressure [bar]	$\Delta p_{expected}$ [bar]
I	98	7	2,5
II	118	5,91	0,9
III	145	14	1,67

Table 3: Properties of reference two-phase pipelines in Olkaria, Kenya.

A wide range of data is required to get an accurate validation of the model. However, difficulties arise when actual measurements are considered. Streams quality and concentration of Non Condensable Gases (NCG) are required together with the pressure and flow rate measurements. Therefore, the only real data considered are the ones related to a two-phase pipeline in Latera VT, Italy, where appropriate instruments were installed. Data were collected at different inlet conditions of flow rates and pressures. The streams composition and pipeline characteristics do not vary, as the following measurements regard always the same pipeline and production well.

Test	Mass flow rate [ton/h]	Inlet pressure [bar]	$\Delta p_{measured}$ [bar]
IV	154	13	1,2
V	181	13,8	1,4
VI	292	14,7	3
VII	292	14,5	2,5
VIII	298	14,9	2,7
IX	300	13,9	2,6
X	188	9,4	2,2

Table 4: Properties of reference two-phase pipeline measured at difference conditions in Latera (VT), Italy

Not only actual measurements are relevant, but also the designed ones. Indeed, all the analysis of the plant layout and characteristics is based on the designed data. Therefore, the same weight has been given to both types of information provided.

4.2 Comparison of void fraction, friction factor and friction correction factor correlations

The first parameters that were analysed are void fraction, friction factor and friction correction factor as they are fundamental quantities for the calculation of pressure losses.

Analysing in detail the impact each of them has on the overall pressure drop in a pipeline, it was observed that:

- Void fraction correlations have a relatively small effect, the difference in the results obtained using the modified Dix correlation and the Lockhart-Martinelli's one was significantly lower than the total computed loss (around 0.05 - 0.1 bar difference on a two kilometres pipeline with an expected loss of 0.9 bar). The variability is related to the other correlations used, as the void fraction influences them. Therefore, the higher the pressure drop calculated, the higher the difference in the results obtained using the two correlations. Consequently, the modified Dix correlation is used.
- Friction factor has a strong influence on the calculated results. Switching from the Chen correlation to the Swamee-Jain leads to a significant loss increase, especially at high pressure drop values. This parameter is directly reflected on pressure losses due to friction. It is, therefore, reasonable that the increase in computed value between the two formulations available is higher for sets of correlations that predict higher losses. However, it is still too early to determine whether the first one is better than the other or vice versa.
- Friction correction factor influences both pressure losses due to friction, when using the Darcy-Weisbach correlation, and due to the stream flowing through different installations, i.e. bends. Keeping the same equations for all the other parameter and varying the first three correlations provided for this factor, the results obtained had a high variability without showing a particular trend. A comparison between this behaviour and the expected one, found in literature, was performed. It was observed that, with some correlation of pressure losses, it is not possible to use indifferently one equation of friction correction factor or the other. A new correlation for this factor was considered. Particularly, it was observed that in bends, peculiar friction correction factors were required. Therefore, it wasn't possible to vary it for the calculation of both frictional and bends losses. A new correlation was implemented, which is the Sookprasong (Azzi and Friedel 2005). By doing this, the results obtained at variable friction correction factor correlations, keeping constant all the other parameters, were more homogeneous and coherent with the expected behaviour.

4.3 Comparison of pressure drop correlations

Different correlations are available for the calculation of pressure losses due to height difference, friction and flow through different installations (mainly bends and valves). The model allows the choice of different correlations for each component of pressure losses, except for the one due to height difference. Indeed, it is directly dependent on the overall height difference and the density of the fluid considered. Therefore, this loss depends more on the liquid fraction than on the flow regime in the pipe.

Regarding the effects on the frictional pressure losses, the two equations provided quite different results. Particularly, when using the Beggs-Brill correlation, the losses were always much higher than the values obtained using the Darcy-Weisbach. The first correlation is purely empirical and, therefore, it is not possible to understand its physical meaning. In their paper, “A Study of two-Phase Flow in Inclined Pipes” Beggs and Brill (1973) explained that this correlation has a wide range of applicability, especially in terms of inclination of the pipe. However, its accuracy is too low for the calculation of geothermal two-phase flows. This reflects in an overestimation of the losses due to friction. This correlation finds its applicability field in the oil and gas industry. Here the higher computed loss is considered as a safety margin and the power and pressure losses are not as relevant as the mere transport of the fluid. However, when transporting geothermal fluid for power generation, these losses are fundamental. For this reason, the Beggs-Brill correlation was excluded from the analysis. The Darcy-Weisbach equation, instead, provided interesting results, when used in the comparison analysis. Therefore, it became the main correlation for the calculation of frictional pressure losses.

Considering the results obtained with the different correlations available for the calculation of pressure drop in bends, a strong relationship with the friction correction factor is observed. Keeping constant this factor and all the other parameters and applying one correlation or the others, the results obtained varied slightly. Applying the Darcy-Weisbach, the results obtained were the lowest one, while the Chisholm provided the highest. However, the variation can be considered negligible if compared with the overall calculated pressure drop (the value resulting from the Chisholm is around 4% higher than the one considering Darcy-Weisbach). This consistency of results can be seen as proof of the quality of the correlations. Therefore, the choice of the best correlation has to be found analysing friction factor and friction correction factor.

4.3 Results

Applying the model to the pipelines whose data have been provided, different results were computed. All the possible sets of correlations were used to understand the trends each of them has and to identify the ranges of applicability.

Regarding the estimation of pressure losses emerged that there is not a single correlation which could be applied every time and in every condition. The results obtained varied depending on the flow conditions and geometric characteristics of the pipe, particularly mass flow rate and diameter. What relates these two quantities is the flow regime. Varying one and/or the other, the flow regime changes and therefore the pressure losses computed with the different sets of correlations vary accordingly. In those pipelines with big diameters and low flow rates, the flow is most probably segregated while in smaller diameters pipes with high flow rates the flow could be distributed. As the frictional losses, in a two-phase flow, is strictly related to the friction between phases, this is expected to be higher in distributed flows instead of the ones in segregated stream. Therefore, the identification of the best set of correlation to be used did not converge on a single set for all the cases but on one for each estimated flow regime.

The idea of variable sets of correlations depending on the flow regime gets confirmed in literature. It is explicitly said that there is not one single set of correlation able to correctly predict the pressure losses in a two-phase pipeline over all flow regimes, (Spedding et al. 2006) and (Lips and Meyer 2011). Therefore, it is possible to conclude that there is a strong relationship between pressure losses and flow regime. In the estimation of the flow regime, the height difference has been neglected. Analysing the results obtained, emerged that, in certain ranges of pipe inclination, the model was able to estimate the losses with good approximation. The altimetry profile of the pipelines considered presented many different conditions, only downhill pipeline, only uphill and uphill/downhill alternating continuously. Therefore, the only parameters considered are mass flow rate and diameter.

In the application field of geothermal flow transport, the diameters of the pipelines are generally big. However, the flow pattern maps that have been studied and described in literature refer only to small diameter pipes (order of magnitude of one inch). As the difference is so high, it is not possible to apply these to the flow in big diameter pipes maintaining a good accuracy. Therefore, it is difficult to identify precisely the flow regime and therefore automatically obtain the best correlation and the correspondent pressure drop to be expected. For this reason, a critical analysis has to be made, at least until the database for the comparison is limited to few cases. However, with the available data it was possible to identify some correlations that works best under certain circumstances, results are displayed in Table 8 and Figure 2:

- If the pipeline is characterised by relatively small diameters and low mass flow rates, the set of correlation suggested is reported in Table 5.

Set 1		
Void fraction	α	Dix
Friction factor	f	Chen
Friction correction factor	Φ^2	HTFS
Friction pressure loss	Δp_f	Darcy-Weisbach
Pressure losses in bends	Δp_{bend}	Chisholm

Table 5: Best set of correlations for small diameter pipelines and low mass flow rates

This is the case of pipeline I, which has DN250 and mass flow rate around 98 ton/h.

- If the pipeline is characterised by big diameters and medium-low mass flow rates, the set of correlations suggested is reported in Table 6

Set 2		
Void fraction	α	Dix
Friction factor	f	Swamee-Jain
Friction correction factor	Φ^2	Lockhart-Martinelli
Friction pressure loss	Δp_f	Darcy-Weisbach
Pressure losses in bends	Δp_{bend}	Chisholm

Table 6: Best set of correlations for big diameter pipelines and medium-low mass flow rates

The results obtained in this case were relatively accurate for pipelines as II and III, IV and V.

- If the pipeline is characterised by big diameters and high mass flow rates, the set of correlations suggested is reported in Table 7. This provided good results in all the pipelines, which respected the above conditions, such as Latera Tests VI, VII, VIII, IX and X.

Set 3		
Void fraction	α	Dix
Friction factor	f	Swamee-Jain
Friction correction factor	Φ^2	HTFS
Friction pressure loss	Δp_f	Darcy-Weisbach
Pressure losses in bends	Δp_{bend}	Chisholm

Table 7: Best set of correlations for big diameter pipelines and high mass flow rate

Whilst the last two cases could be considered validated in a more complete way, as the data available for comparison are a few, for the first one this is more delicate. Indeed, the pipelines available for the comparison were only one, pipeline I. Further comparison with new data will prove to be useful for a better validation and for the identification of the best sets of correlations at different condition. From the sensitivity and cost analysis emerged that for the pipelines II, III and Latera two-phase transport is suggested and the best pipe's diameters are the one written in the above figure. Instead, for the pipeline I, single-phase transport is suggested due to the high-pressure loss there would be, especially compared to the inlet pressure. The overall loss was more than one third of the inlet pressure, 2.5 bar lost over 7 bar at well-head. The choice of the best transportation strategy and of the optimum pipe diameter made by the implemented model were always coherent with the solution suggested by external engineering consultant companies that studied the same pipelines. In the case of Latera, this choice is coherent with the pipeline built. This demonstrate that the model is able to predict quite accurately the optimum configuration of a pipeline.

4.3 Industrial application

The implemented model can be used during the initial analysis of a geothermal project to understand whether it could be possible to use a single pipeline transporting the two-phase flow or not. This will be useful to have a preliminary idea of the cost of the pipeline. It will allow to have reasonable results, especially regarding the transport strategy, when needed. Moreover, the procedure required to use the model is not highly time consuming. As said the model will be useful in an initial analysis, therefore to have a more detailed and precise information, a professional calculation is still required. However, the data that will be provided can be used to improve the model, continuously validating it. This will increase steadily its accuracy and range of applicability. The more it will be used, the better it will become.

5. CONCLUSIONS

Estimation of two-phase flow pressure losses and, in general, definition of the best arrangement of RGS, in terms of pipeline routing, is of crucial importance in the design of geothermal power plants. Until now very few software are available for the design of pipelines for the transportation of two-phase flow and, in literature, there is not a simple and general procedure to do it. Hence the need for a model able to compute pressure losses and compare the different possibilities for the transport of geothermal fluid. With the model implemented, it is possible to do so under certain conditions. As there is not a single set of correlations applicable to streams flowing in all possible regimes and due to the difficulty in finding and defining a flow pattern map, it is difficult to automate the choice of correlations. Therefore, this tool has to be used critically and applying the best correlations suggested in Chapter 4.3 depending on the flow and pipe characteristics. If these conditions are met, the model is able to provide interesting results on which a preliminary analysis of the geothermal power plant could be based. Moreover, the transportation strategy suggested by the model has been observed to be coherent with the provided one. This allows having a better idea of what the cost of the RGS will be, hence its impact on the total cost of the plant.

Pipeline	Diameter	Flow rate [ton/h]	Set of correlation	$\Delta p_{calculated}$ [bar]	$\Delta p_{expected}$ [bar]	Percentage variation [%]
I	250	98	1	2,51	2,5	0,4%
II	400+500	118	2	0,92	0,9	2,4%
III	400	145		1,53	1,7	-8,2%
IV	450	154		1,05	1,2	-12,3%
V	450	181		1,36	1,4	-2,8%
VI	450	292	3	2,65	3,0	-11,6%
VII	450	292		2,72	2,5	8,7%
VIII	450	298		2,69	2,7	-0,2%
IX	450	300		3,07	2,6	18,2%
X	450	188		2,28	2,2	3,7%

Table 8: Comparison of results obtained with the expected ones

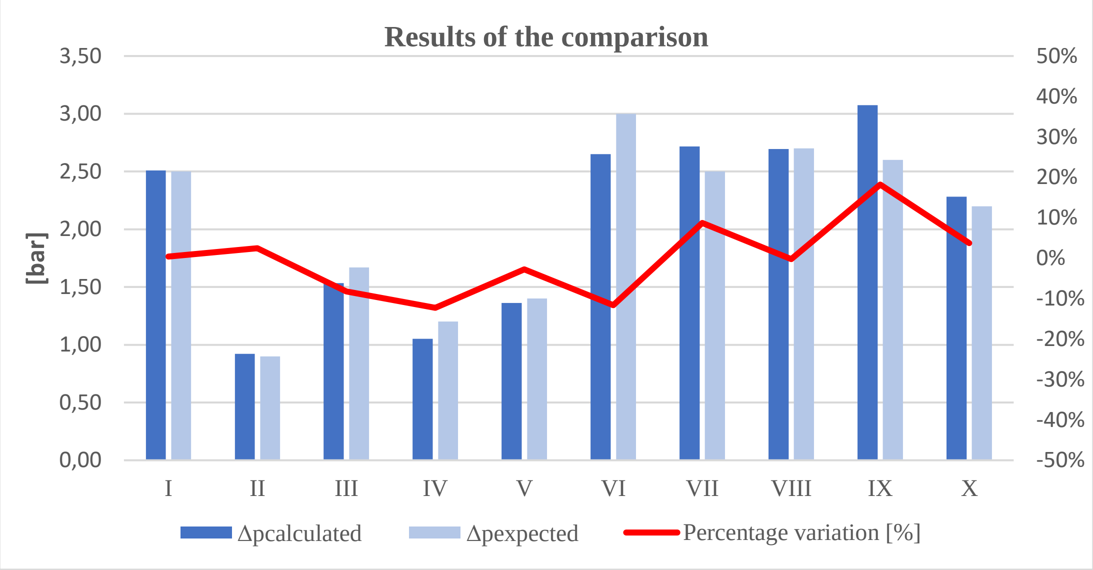

Figure 2: Comparison of expected pressure drop and calculated one

REFERENCES

Aakenes F. *Frictional pressure-drop models for steady-state and transient two-phase flow of carbon dioxide*. Norwegian University of Science and Technology (2012).

Archibong-Eso, Yahaya Baba, Edem Nsefik-Eyo, James Enyia, Ini Ikpe: A Study of Two-Phase Air-Water Flow in Horizontal and Inclined Pipelines, *International Journal of Scientific & Engineering Research* (2016), Volume 7, Issue 12.

Awad M., Muzychha Y. *A simple asymptotic compact model for two-phase frictional pressure gradient in horizontal pipes*, ASME International Mechanical Engineering Congress and Exposition (2004).

Azzi A. and Friedel L., Two-phase upward flow 90° bend pressure loss model, Forschung im Ingenieurwesen Springer-Verlag, *T. Bertram ; S. Kabelac ; T. Schmidt ; K. Steel*, 69, pp. 120–130, (2005).

Beggs, D. H., & Brill, J. P. A Study of two-Phase Flow in Inclined Pipes, *Journal of petroleum technology*. (1973), 25(5), pages: 607-617.

Chisholm D. Two-phase flow in heat exchangers and pipeline, *George Godwin in association with the Institution of Chemical Engineers*, London (1983).

Heimisson, I. *Headloss in two phase ow of water and steam in geothermal gathering pipe systems*, University of Iceland (2014).

Kiijarvi, J. *Darcy Friction Factor Formulae in Turbulent Pipe Flow*. Lunowa Fluid Mechanics (2011) Paper, 1–11.

Lips, S., & Meyer, J.: A review of two-phase flow in inclined tubes with specific reference to condensation, *International Journal of Multiphase Flow*, (2011), Volume 37(8), pages: 845–859.

Spedding P. L., Benard E., Donnelly G. F.: *Prediction of Pressure Drop in Multiphase Horizontal pipe Flow*, International Communications in Heat and Mass Transfer, Queen's University Belfast, (2006), 33 (9)(9), 1053-1062.

Thome, J. R. Void Fractions in Two-Phase Flows. *Engineering Data Book III*, (2004), 1–33.

Woldesemayat, M. A., & Ghajar, A. J. Comparison of void fraction correlations for different flow patterns in horizontal and upward inclined pipes. *International Journal of Multiphase Flow* (2007), 33(4), 347–370.

Zanzucchi Paolo Maria, *Optimization of pipelines for transportation of geothermal two-phase fluid from well-head to power block,* M.Sc Thesis, Politecnico di Milano (2018).