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Flow Rate Estimation Modelling in a Transmission Pipeline Using Response Surface Methodology (RSM)

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ABSTRACT

The source of geothermal energy to be used for district heating systems is, in most cases, located some distance from the heating market, although geothermal water may also be found within the market area. A transmission pipeline is therefore needed to transport the geothermal fluid from the geothermal field to the end users. Geothermal fluids can be transported over fairly long distances in thermally insulated pipelines. Transmission pipelines of even 60 km length have been built with acceptable heat loss values, though shorter transmission distances are much more common and clearly more desirable. At flowing conditions, the temperature drop in insulated pipelines is in the range of 0.1 to 1.0°C/km, while in uninsulated lines it is 2 to 5°C/km (in the range of 5 to 15 l/s flow for 15-cm diameter pipe).

In addition to a group of parameters, which are almost constant, such as the length, diameter, thickness, thermal insulation properties and material type of the pipeline, whether above ground or buried and so on, temperature drop rate in transmission pipelines is strongly affected by flow rates. At low flow rates, the temperature drop is higher than that of greater flow rates. The temperature drop depending on the flow rate becomes more apparent for relatively long pipelines.

In this study, the temperature drops in the transmission pipeline of the Bigadiç geothermal district heating system (GDHS), a buried 18 km long pipeline, is investigated for varying flow rates. Response Surface Methodology (RSM) is then used for modelling and estimating the flow rate depending on the temperature drop in the pipeline. The results show that the flow rates given by the model (with R^2, coefficient of determination, of 96.67%) are in a good agreement with those measured by the flowmeter.

Keywords: District heating system; Flow rate; Response Surface Methodology (RSM); Transmission pipeline.

1. INTRODUCTION

Geothermal energy, which is considered as one of the most promising alternative among renewable energy sources, has proven to be sustainable, clean, and safe. Therefore its worldwide applications are increasing steadily. Turkey is one of the top five countries for the direct geothermal applications [1]. Direct use of geothermal energy in Turkey has focused mainly on district heating. Over 8.5 million m^2 of indoor space is heated using geothermal energy in more than 20 district heating systems [2]. The total installed capacity of these systems (805 MW_t) accounts for 12% of the estimated worldwide capacity of the geothermal district heating systems (6725 MW_t) [3].

The distance of the geothermal resource from the potential heating market is a very important parameter as regards the technical and economic viability of the heating system. However, geothermal fluids can be transported over fairly long distances in thermally insulated pipelines. Transmission pipelines of even 60 km length have been built with acceptable heat loss values (i.e., the Akranes project in Iceland), though shorter transmission distances are much more common and clearly more desirable [4, 5]. The heat loss occurring in a transmission pipeline, whether above ground or buried underground, constitute one of the main sources of total energy loss in a district heating system, and thus a loss in revenue.

In addition to a group of parameters, which are almost constant, such as the length, diameter, thickness, thermal insulation properties and material type of the pipeline, whether above ground or buried and so on, temperature drop rate in transmission pipelines is strongly affected by flow rates. At low flow rates, the temperature drop is higher than that of greater flow rates. The temperature drop depending on the flow rate becomes more apparent for relatively long pipelines. At flowing conditions, the temperature drop in insulated pipelines is in the range of 0.1 to 1.0°C/km, and in uninsulated lines, it is 2 to 5°C/km (in the approximate range of 5 to 15 l/s flow for 15-cm diameter pipe) [6]. It is less for larger diameter pipes. For example, less than 2°C loss is experienced in the new aboveground 29 km long and 80 and 90 cm diameter pipeline (with 10 cm of rock wool insulation) from Nesjavellir to Reykjavik in Iceland [7]. The flow rate is around 560 l/s and takes seven hours to cover the distance. Uninsulated pipe costs about half of insulated pipe, and thus, is used where temperature loss is not critical. Pipe material does not have a significant effect on heat loss; however, the flow rate does. At low flow rates, the heat loss is higher than as greater flows.

Balıkesir is one of the geothermal energy-rich provinces of Turkey with several geothermal fields. These sources are all appropriate for direct use such as space and greenhouse heating, industrial processing and balneology. In addition to individual heating, district heating is a common use of geothermal energy in the city. An estimation of nearly 10000 equivalent residential heating is provided in Balıkesir through five GDHSs, namely Gönen, Edremit, Bigadiç, Güre and Sındırgı. However, almost in all systems, the total amount of geothermal fluids produced cannot be determined correctly during the operation due to the lack of flow meters. Instead of this, the geothermal energy produced by the systems is estimated by taking a group of system parameters into account. These parameters are constant initial flow rate of the wells, operating characteristics of the well pumps, some system related temperatures, and etc.

The above mentioned basic incapability has encouraged the authors to develop a mathematical model to estimate the flow rate of geothermal fluids. Thus, the temperature drop rate in the transmission pipeline of the Bigadiç (GDHS), a buried 18 km long pipeline, is investigated for varying flow rates. Response Surface Methodology (RSM) is then used for modelling and estimating the flow rate depending on the temperature drop in the pipeline. The results show that the flow rates given by the model (with R^2, coefficient of determination, of 96.67%) are in a good agreement with those measured by the flowmeter.

2. MATERIAL AND METHODS

2.1. Bigadiç geothermal district heating system

System description. The Bigadiç geothermal district heating system (GDHS), projected for 3000 equivalent residential heating, is located 38 km south of the city of Balıkesir which is in the west of Turkey. Being one of more than 20 GDHSs in Turkey, it began operation for 300 users in 2004-2005 heating season and reached 1548 equivalent residential heating as of 2016. The heat source of the Bigadiç GDHS, Hisarköy geothermal field, is located 23 km east of Bigadiç, and extends over an area of more than 1 km^2. The reservoir temperature is taken as 110°C (Figure 1).

Figure 1. General view of Hisarköy geothermal field.

The Bigadiç GDHS has 8 production wells in total ranging in depth from 307 to 750 m. However, only two of them, namely HK-2 and HK-8, are operative while the rest are out of service due to the effects of pressure drops in the geothermal fields, precipitation in the wells and the interactions of the wells. Therefore, a peak power unit (an auxiliary heating support) has to be operated in most cases, almost 70% of the heating period, due to the wells which subsequently became inoperative. Lineshaft pumps are used in both geothermal wells. The pumps are driven by frequency converter to regulate the flow instead of just turning the pump on and off. The mean temperatures and flow rates of the HK-2 and HK-8 wells are 95°C and 100.5°C; 10 kg/s and 15 kg/s, respectively (Figure 2).

Figure 2. Views from the HK-8 well (left) and main gas separator and collection lines (right).

The Bigadiç GDHS consists mainly of three circuits: (a) energy production circuit (EPC), (b) energy distribution circuit (EDC), and (c) energy consumption circuit (ECC). The schematic diagram of the system is given for the heating period in Fig. 3. In the EPC, the thermal water at an average temperature of 95°C and a flow rate range of 20-25 l/s drawn from the production wells in the Hisarköy geothermal field is transported to the heat exchangers located in the heat centre of the system. A buried transmission pipeline of 18 km is used for the transportation. The geothermal water moves itself in the transmission pipeline since the elevation difference between the inlet and outlet of the pipeline is approximately 200 m, good enough for a natural flow of 25 l/s water.

The EDC is a closed-loop system with three pairs of independent supply and return pipes in which a secondary fluid circulates in order to transfer the heat to the ECC. The supply/return temperatures for the secondary fluid obtained during the winter operation conditions are on average of 56/44°C. The supply temperature of 56°C is reached in two stages: the return temperature (44°C) is first raised up to 50°C using three flat heat exchangers; Heat Exchanger-I (HE-I), Heat Exchanger-II (HE-II) and Heat Exchanger-III (HE-III), which transfer the heat from the geothermal fluid to the secondary fluid in the heat centre. The secondary fluid is then transferred to the peak power unit, which consists of two liquid fuel boilers, each of which has a nominal power of 2326 kW. The final temperature, 56°C, can be therefore achieved. This auxiliary heating support is provided for only two distribution lines, for HE-2 and HE-3 lines. The buildings which are heated by the HE-1 line are located in high altitudes. This disables the connection of the HE-1 line with the boilers since the high static pressure will act on the boilers. After its heat is transferred, some part of the geothermal fluid is pumped to the hotels for the hot spring and thermal therapy purposes, while the remainder is discharged to the river. The discharge temperature varies between 40°C and 46°C during the heating period (Figure 3).

The ECC comprises of many closed-loop systems constructed under each building which connect the consumers with the EDC. In the ECC, the closed-loops are designed to have one or two heat exchangers for each building. One heat exchanger is for heating, and the other is for hot water requirements. The supply/return temperatures for the ECC obtained during the winter operation conditions are on average of 43/39°C (Figure 3).

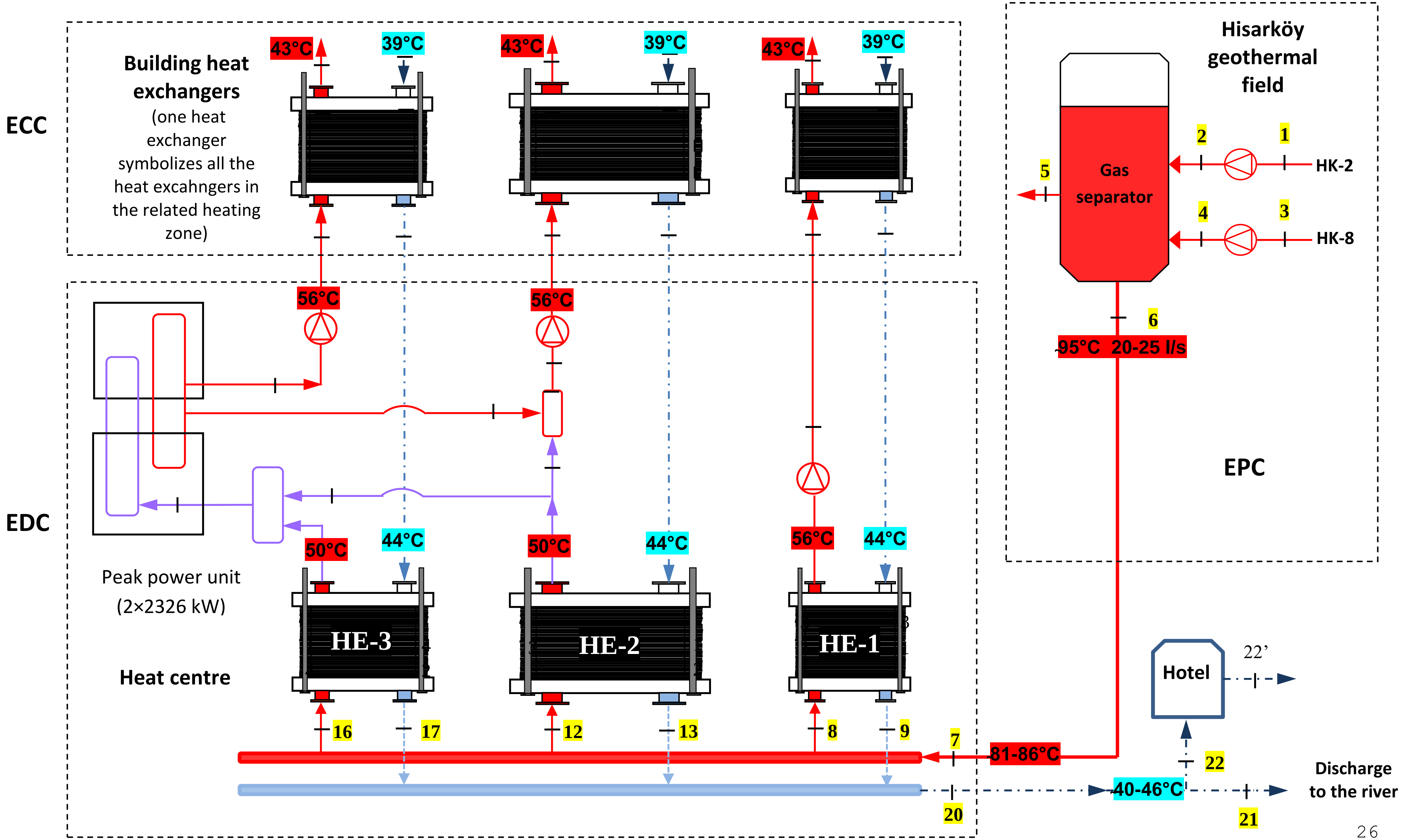

Figure 3. Schematic diagram of the Bigadiç GDHS for winter season.

Transmission pipeline. In the Bigadiç GDHS, a buried, 18-km-long transmission pipeline at an average depth of 1 m is used to link the Hisarköy geothermal field and the distribution network in Bigadiç town (Figure 4). The transmission line consists of the steel pipes of 250 mm nominal diameter, insulated with 3.54 cm thick polyurethane foam and covered by a protective high density polyethylene layer. The insulation thickness is considerably lower than in similar pipes. Therefore, the pipeline constitutes one of the main sources of the heat losses accounting for 18-24% of the total energy losses. The heat loss rate in the transmission pipeline obtained by applying the energy balance equation varies between 900 kW and 1400 kW depending on the operating conditions in the heating season. This means that 8-12% of the total energy input to the system is lost in the line [8].

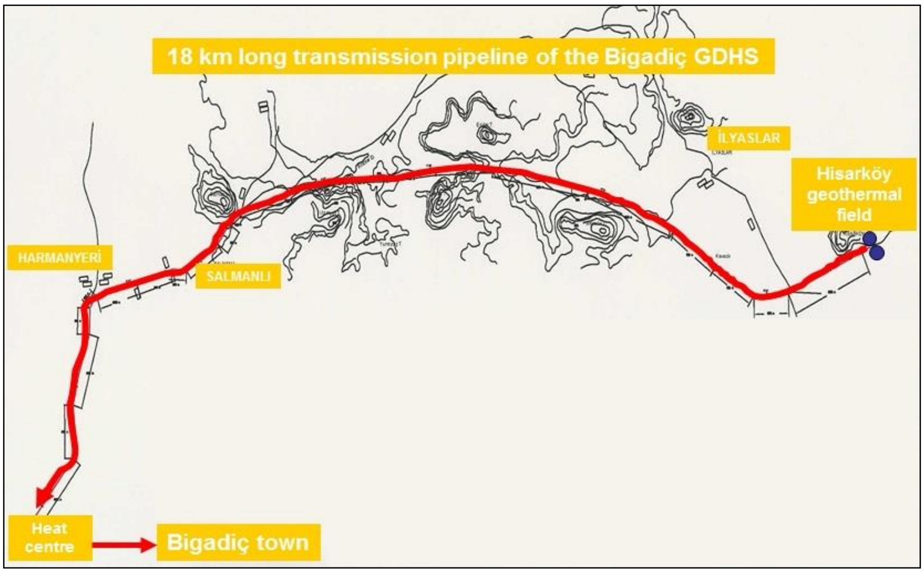

Figure 4. Transmission pipeline of the Bigadiç GDHS.

The high heat losses in the transmission pipeline result in high temperature drops throughout the pipeline. The temperature drop rate, that is, the temperature difference between the inlet and the outlet of the transmission pipeline varies between 9°C and 14°C in the heating season. It takes peak values particularly when the temperature of the ground in which the pipeline lies is the lowest and at lower flow rates (e.g., below 10 l/s) when a single well works. However, the temperature drop rate is below 9°C at relatively high flow rate conditions which are rarely experienced in the system (e.g., 7.45°C at flow rate of 31 l/s and ground temperature of 10.6°C). The well operators take care that the maximum geothermal flow rate produced in the system does not exceed 25 l/s for a long time in order to prevent any failure in the wells. The operation frequencies of the well pumps are therefore kept in the related limits.

2.2. Temperature and flow rate measurements

The rate of temperature drop in the transmission pipeline was clearly determined by taking the difference between the entering and leaving temperatures of the geothermal water. Thermal resistive probes were used for the temperature measurements. Since the pipeline had no flowmeter, a bypass line consisting of 150 mm diameter steel pipes was constructed at the inlet of the pipeline. An electromagnetic flowmeter, appropriate for the bypass line, was also mounted on the bypass line to measure the volumetric flow rate of the geothermal fluid flowing in the pipeline (Figure 5). The bypass line was not designed to work constantly and therefore kept closed except during the flow measurements. This resulted in a relatively few number of flow rate measurements which were used for the RSM modelling. The daily average soil temperatures at a depth of 1 m were obtained from a meteorological station located near the transmission pipeline. The technical data of the measuring instruments used in the study is given in Table 1.

Figure 5. Temperature measurement at the inlet of the transmission pipeline (left), flow rate measurement at the outlet of the transmission pipeline (right).

Table 1. Properties of measuring instruments used in the study.

	Instrument	Technical data		Intended use
Temperature	Thermal resistive probes	Measuring range Sensor Accuracy	*–50 to +180 °C* *Pt100, class A, 4 wires* *± °C ± Ohm* *-50 °C 0,25 0,1* *0 °C 0,15 0,06* *100 °C 0,35 0,13*	The inlet and outlet temperatures of the geothermal water flowing in the transmission pipeline.
Flow rate	Electromagnetic flowmeter	Accuracy Lining Pipe dimension Process temperatures	*≤ ± 0,3 % or 0,2 % of MV* *Polypropylene* *DN150* *-5 to 90°C*	Total volumetric flow rate of the transmission pipeline.

2.3. RSM modelling

RSM is a statistical technique that is used for modelling the relationship between the factors and responses. By this way, results of the unpracticed combinations of different factor levels can be predicted. Equation (1) presents the general full factorial response surface mathematical model for the experimental design which is composed of linear, square and interaction terms [9]:

$$Y = \beta_0 + \sum_{i=1}^{n} \beta_i X_i + \sum_{i=1}^{n} \beta_{ii} X_i^2 + \sum_{i<j}^{n} \beta_{ij} X_i X_j + e \qquad (1)$$

where Y is the response (volumetric flow rate of the transmission pipeline in l/s), X_i are coded values of the ith input parameters in °C (daily average soil temperature, T_{soil}, and temperature drop throughout the pipeline, ΔT), terms,β_0, β_i, $\beta_{ii}$and β_{ij} are the regression coefficients and e is the random error term which is the difference between observed and predicted responses. In this study, because of the uncontrollable factors namely T_{soil} and ΔT (which are selected for the predictor of the flow rate) RSM is not used for designing the experiments. Modeling and predictions are performed by using the data that is observed in different dates instead of using a data set obtained from an experimental design. The data set which was obtained in different operation conditions of the transmission pipeline (for different flow rates and soil temperatures) is used for the RSM modelling (Table 2).

Table 2. Flow rate, temperature drop and soil temperature parameters used in RSM modelling.

Date of measurement	Measured flow rate (l/s)	Temperature of the geothermal water entering the pipeline (°C)	Temperature of the geothermal water leaving the pipeline (°C)	Temperature drop, $\boldsymbol{\Delta T}$, (°C)	Daily average soil temperature $\boldsymbol{T_{soil}}$, (°C)
14.10.2011	25.5	95.27	85.76	9.51	17.8
10.11.2011	23.5	94.52	84.37	10.15	13.9
23.11.2011	22.8	94.61	84.06	10.55	12.2
18.12.2011	22.0	92.92	81.42	11.50	10.0
02.01.2012	26.0	95.48	83.87	11.61	7.8
12.01.2012	25.4	94.70	81.50	13.20	7.2
20.02.2012	24.5	94.44	80.38	14.06	4.4
25.12.2011	10.0	89.42	74.70	14.72	9.4
21.03.2012	9.8	93.50	78.12	15.38	10.6

3. RESULTS AND DISCUSSION

According to the experiments presented in Table 2, mathematical model based on RSM (presented in Equation (2)) for the responses has been established with 95% confidence (type-I error (α)=0.05) by using Minitab Statistical Package. R^2 (coefficient of determination) is calculated as 96.67% which means that ΔT and T_{soil} explain 96.67% of the change in the flow rate while the rest, 3.33%, is affected by other variables which are not included in the model. According to the results of analysis of variance (ANOVA), P-value for the regression model including lines and quadratic terms is calculated as 0.003, less than α=0.05, which means that the given mathematical model is significant.

$$Flow\ Rate = -148.100 + 33.902(\Delta T) - 4.554(T_{soil}) - 1.456(\Delta T^2) + 0.204(\ T_{soil}{}^2) \quad (2)$$

The experimental flow rates are compared to those estimated by RSM model in Table 3. As seen in the table, the difference between the model and measured values is on average of 4.31%. The test set and corresponding model responses are given in Table 4 and Fig. 6. The difference between the model and measured values is calculated less than 10%.

Table 3. Comparison table of the experimental and model flow rates.

Flow rate (measured, l/s) (Y_i)	Flow rate (obtained from the model, l/s) ($\hat{Y}_i$)	Prediction error (%) ($e_i = \lvert Y_i - \hat{Y}_i \rvert / \hat{Y}_i$)
9.8	9.5	3.16
10	10.7	6.54
22	24.1	8.71
22.8	22.3	2.24
23.5	22.1	6.33
24.5	24.6	0.41
25.4	23.5	8.09
25.5	26.2	2.67
26	26.1	0.38

Table 4. Test set for confirmation and corresponding model responses.

Date	Temperature drop in the pipeline, ΔT, (°C)	Daily average soil temperature, T_{soil}, (°C)	Flow rate (measured, l/s) (Y_i)	Flow rate (obtained from the model, l/s) ($\hat{Y}_i$)	Prediction error (%) (e_i)
17.12.2011	10.52	10.0	21.4	22.3	4.21
10.01.2012	12.54	7.80	25.5	25.0	1.96
02.04.2012	12.55	11.1	20.7	22.6	9.18

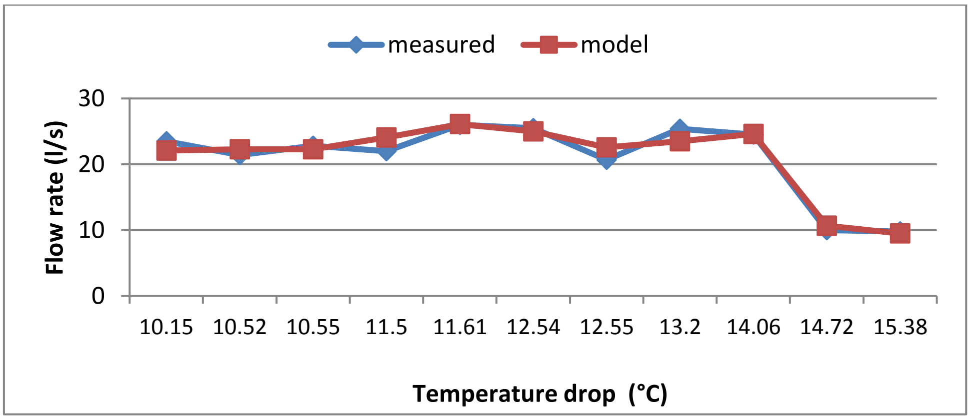

Figure 6. Comparison of the experimental and model flow rates.

4. CONCLUSION

In this study, the transmission pipeline of the Bigadiç GDHS is investigated and a mathematical model based on RSM has been established with R^2 of 96.67% which gives the volumetric flow rate of the geothermal water flowing in the pipeline depending on the rate of temperature drop and soil temperature. The results show that the flow rates given by the model are in a good agreement with those measured by the flowmeter. A test set was used for the model validation. The error rate for the given model is calculated less than 10%. As justified above, the flow meter used in this study, was not appropriate to operate continuously or to collect a wide range of flow rate data. This caused an insufficient number of flow rate measurements used for the RSM modelling and therefore led to high deviations in the model responses from the experimental results. However, the model can be improved considerably and more accurate responses can be obtained by using extensive data set which will better explain the flow characteristics in the pipeline.

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