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MODELING STUDIES OF THE NESJAVELLIR GEOTHERMAL FIELD, ICELAND

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ABSTRACT

This paper describes a series of numerical modeling activities aimed at the evaluation of the Nesjavellir geothermal field in Iceland for space heating and electrical power production. The first model of the field was developed in 1986, and since then the model was updated both in 1992 and 1998. The results of these modeling activities show that the model has generally predicted well the performance of the field. The initial model underestimated the global average permeability of the field, due to the short calibration history, and was therefore conservative in the initial estimation of the generating potential of the field. The subsequent models have predicted reliably the flow rates, enthalpies and pressure declines of all wells in the Nesjavellir field. These models have only required minor modifications in reservoir parameters in order to refine the matches with the well data between updates.

1. INTRODUCTION

The Nesjavellir geothermal field is part of the Hengill geothermal system in SW-Iceland. The field was developed during 1965 to 1990 to provide Reykjavik, the capital city of Iceland, and surrounding towns with hot water for space heating (Stefansson, 1985; Franzson et al, 1986). The first phase of the developments, a 100 MW_t thermal power plant was commissioned in September 1990. In the plant the geothermal fluids, separated water and steam, was used to heat up fresh water to 83°C in heat exchangers. The heated fresh water was then piped 27 km to the capital and distributed. Most of the water is discharged into the sea after use at a disposal temperature of 40°C (Gunnarsson et al, 1992). The Nesjavellir plant was expanded to 150 MW_t in 1992 corresponding to a production capacity of 850 kg/s of 83°C heated fresh water. Electric generation was not included in these early developments, but the city council of Reykjavik decided in 1996 to install 2x30 MW_e turbines at Nesjavellir, and increase the thermal power capacity to 200 MW_t. The expanded power plant started operation in October 1998.

A total of 20 deep (1-2 km) geothermal wells have been drilled at Nesjavellir. Thirteen of these wells are commercial producers, with an average thermal output of 60 MW_t per well or 9 MW_e per well. In the year 2000 two new wells are planned. The objective of the drilling now is to expand the production area to evaluate the feasibility of increasing the production from the field. The locations of the Nesjavellir power plant and the wellfield is shown on Figure 1.

A conceptual model of the field was proposed by Stefansson (1985). This model formed the basis for the development of a three dimensional simulation model of the field during the years 1984-86. The main objective of the modeling studies so early in the development phase of the field was to use the model to guide the exploration work, and to estimate roughly the generating capacity of the field. The model was calibrated against all available data up to the end of 1986 and matched well the initial temperature and pressure distribution of the system, measured pressure interference between wells and the short history data on well flow rates and enthalpies.

The response of the field to utilization has been carefully monitored since 1986 and the data obtained have been compared to the predictions of model. The first recalibration of the model was carried out in 1992 and the second recalibration in 1998 (Bodvarsson et al., 1993; Bodvarsson, 1998). In this paper we describe the three dimensional reservoir model of Nesjavellir and some of the model results. The performance of the model is discussed in terms of its consistency with the observed temperature and pressure conditions in the field and the accuracy of predictions compared to subsequent field data.

2. THE THREE DIMENSIONAL MODEL

The three dimensional numerical model which was developed during 1984 to 1986 consisted of four layers, three of which (layers U, M and L) were 400 m in thickness, while the bottom layer R was 800 m thick (Bodvarsson et al., 1990). The choice of the number of layers and their respective thicknesses were based on the thermodynamic conditions in the field and the locations of the major feed zones in the wells. This layering of the model has been maintained in later revisions of the model.

The central part of the grid used in the simulations is shown in Figure 2. The grid was designed to allow for modeling of each well individually and the element numbers for elements 2 through 20 correspond to the number of the well located within the element. The total grid extended 12 km in all directions in the original model in order to avoid boundary effects. The grid was extended to 100 km when the model was recalibrated in 1992. The only other changes that have been made to the grid since 1986 concern the gridblocks containing wells 17 and 18 drilled in 1986 and wells 19 and 20 drilled in 1999 (Bodvarsson et al., 1993; Sigurdsson et al., 1999). The upflow zone was assumed to be located in a gridblock which geographically is located underneath the Hengill volcano (Figure 3), in agreement with the conceptual model (Gunnarsson et al., 1992). The upflow is believed to be located in a two phase zone which explains the vast differences in vertical pressure potential shallow in the southern part of the well field.

Various reservoir parameters have been adjusted during the simulations and recalibrations of the model, including permeabilities and porosities, production indices for wells and the mass recharge rate and enthalpy of the upflow zone. Most other parameters used are well known for geothermal systems or did not affect the simulation results significantly. The computer code MULKOM (Pruess, 1982) has been used throughout this work.

3. NATURAL STATE MODELING AND HISTORY MATCHING. THE 1986 MODEL

The 1986 model was calibrated against all available data up to the end of 1986. The basic grid shown in Figure 2 was used for the main reservoir layers (layers L and R) corresponding to the depth interval 800 to 2000 m. Because of conductive heat transfer from the two shallow layers (layers U and M), many of the gridblocks shown in Figure 2 were not needed in those layers. The conductive heat losses were computed for different areas based on observed temperature data from wells and convective heat losses to surface springs were estimated from visual comparison to well steam discharges.

The three dimensional model was also calibrated against flow rates and enthalpies of the wells and observed pressure decline. This work started after a coarse match was obtained with the natural state conditions. The calibration with the production history required many changes in the permeability and the porosity distribution especially in the production layers. This, in turn, required recalibration of the natural state calculations and vice versa (Bodvarsson et al., 1990).

A comparison between computed values for the 1986 model and measured data is shown on three figures. Figures 4 and 5 show the computed temperature in the R layer and the pressure distribution in the U layers with observed values from the wells given in parentheses. The solid hatched lines indicate the presence of impermeable barriers. As shown on the figures the model matches the temperature and pressure distribution fairly well and the computed two phase zone extends around wells 6, 8, 9 and 19, in good agreement with the observed data. A similar match was also obtained for the other layers. Figure 6 is an example of the match between observed and calculated flow rates and enthalpies. The match is for well 6 one of the wells that had the longest production history when the history matching of the 1986 model was carried out. Well 6 shows considerable variations in flow rate and enthalpy. Some of the variations are caused by mobility effects, but the rise in the enthalpy in 1984 has been explained as interference with well 9 that started producing at that time.

The final 1986 model estimated the recharge rate of the upflow zone under the Hengill volcano to be 65 kg/s with an enthalpy of 1850 kJ/kg corresponding to an energy input of 120 MW_t. Mass and heat losses to surface springs only amount to some 20 MW_t. The rest of the energy losses are due to conductive losses to the ground surface as well as lateral conductive and convective heat losses. The permeabilities of the system varied between 1- 50 md. The highest values were assigned to the area close to the Kyrdalur volcanic fracture. The effective porosities in the upper part of the reservoir were estimated to be 5 % and 3.5% in the lower part.

The 1986 model was used to study the various exploitation cases for Nesjavellir in order to determine the generating capacity of the reservoir (Bodvarsson et al., 1991). The result of those studies were that the Nesjavellir field could supply a 300 MW_t power plant at full load for 30 years without reinjection. A 400 MW_t power plant could only be operated at full load for 15 years. To operate a plant of that size reinjection would be necessary as the factor limiting the capacity of the field seemed to be the gradual pressure drop in the reservoir due to production.

4. RECALIBRATION OF THE THREE DIMENSIONAL MODEL

Several of the Nesjavellir wells have produced continuously since 1986 and more wells have been put into production as the power plant has been expanded. A monitoring program was set up in 1986 in order to observe changes in reservoir parameters caused by the mass extraction from the reservoir. The pressure monitoring consists of downhole pressure logging once a year in all idle wells and weekly water level measurements in the ones with zero well head pressure. The producers are sampled at least once a year, and more often when changes are observed. The flow rate and fluid enthalpy of all producing wells were measured weekly until 1990 when the power plant started production. Since then productions wells are flow tested, either during annual maintenance stops or when wells are off-line for other reasons. These monitoring data can be found in various internal reports of Orkuveita Reykjavikur and Orkustofnun.

4.1 The 1992 model

The predictions of the 1986 model were compared with the monitoring data every year. After only few years it became obvious that there was some discrepancy between the predictions and the observed data. This was not surprising as the history matching of the 1986 model was based on only few years production from the field. It was therefore decided in 1992 to investigate the performance of the three dimensional model and recalibrate it against all new data. These were mainly the monitoring data but also included information from wells 17 and 18 drilled in 1986, but not included in the 1986 model.

The evaluation of the predictive capabilities of the 1986 model was obtained by prescribing the actual flow periods for the wells and then comparing the calculated flow rates and enthalpies of the flowing wells with those observed up to 1992. In addition, the computed pressure decline at all the observation wells were compared to the observed values (Bodvarsson et al., 1993). As an example, Figure 7 shows the comparison between observed and calculated flow rates and enthalpies for well 6 up to 1992. The predictions overestimate the flow rate decline of well 6, but the enthalpy prediction for well 6 is acceptable. The 1986 model, however, overestimated the enthalpy of the produced fluids for some of the other wells. The conclusion of the comparison was that the model predictions were in remarkably good agreement with the observed data, especially since the prediction period was considerably longer than the calibration period of the 1986 model.

The 1986 model predictions for the pressure decline in the reservoir from 1984 to 1991 were, however, not as accurate

as the flow parameter predictions. The model predicted the pressure decline for well 7 reasonably well but overpredicted the pressure decline for wells 10, 14 and 15 by a factor of 2-4. The model predicted practically no pressure decline in well 12, as observed. This well is separated from the main producing field by faults acting as permeability barriers.

The pressure decline predictions strongly suggested that the 1986 model was based on too low permeabilities. The 1986 model was therefore recalibrated until acceptable match was obtained for all the data. The new model was called the 1992 model. In order to reproduce the actual pressure decline in the reservoir, the permeability had to be ten times larger that in the 1986 model. The porosity distribution was, however, not significantly changed. By maintaining the permeability contrast between the different blocks in the model the overall natural state temperature and the pressure distribution was maintained. Therefore, only minor changes had to be made on the basic grid (Figure 2). The most important one was that in the vicinity of the "new" wells 17 and 18 it was necessary to infer local barrier to the model in order to explain why these wells are relatively colder than other wells at Nesjavellir. The 1992 model estimates the recharge in the upflow zone as 73 kg/s or little higher than in the 1986 model. The upflow enthalpy is however the same, or 1850 kJ/kg

The most important consequence of the recalibrations of the model concerns the generating capacity of the reservoir as the 1992 model predicted that the reservoir could supply a 400 MW_t power plant for 30 years.

4.2 The 1998 model

The second update of the Nesjavellir model was carried out in 1998 (see Bodvarsson, 1998). During the period from 1992-1998 wells 5, 6, 7, 11, 13 and 16 were flowing near continuously and well 9 from 1994. Wells 7, 10, 14 and 15 were flow tested for a few months in 1996. The performance of the model was evaluated as in 1992 by prescribing the correct flow periods for all the wells and then comparing the model results with actual changes in flow rate, enthalpy, pressure and temperature decline. An example of this work is shown on Figure 8 where the observed and calculated flow rates and enthalpies for well 6 up to 1998 are depicted. In general the 1992 model predicted very well most of the field behaviour during this period. The main calibrations needed on the model were; (1) to obtain more rapid simulated enthalpy decline for wells 11 and 16 and the associated increases in flow rate due to mobility effects; (2) to obtain 1-2 bar more simulated pressure decline in well 18 in the NW-part of the well field and (3) to evaluate the apparent temperature decline, of some 15°C, observed at 1000-1500 depth in well 7.

The most difficult calibration activity turned out to be getting the desired enthalpy decline in well 11 and the temperature decline in well 7. After much thought it was decided to make an important change in the conceptual model of the field. In the 1992 model, it was assumed that well 7 was in very good hydrological communication with well 16. It was felt that the relatively large observed pressure decline in well 7 was due to a good hydrological connectivity with one of the producing wells, and well 16 was picked for lack of a better choice. Based on the data for 1982 to 1998 it was decided that well 11 was a better candidate to provide the required pressure decline in well 7. It was also hypothesized that cooler fluids invade the wellfield at depth from the north-east. These fluids flow past well 7 causing the observed cooling in that well, and the rapid enthalpy decline in well 11. This relatively major change in the conceptual model allowed much better match to the observed data. In addition, relatively minor adjustments were made in the permeability and porosity distribution within the wellfield.

5. SUMMARY AND CONCLUSIONS

The three dimensional numerical model of the Nesjavellir field was developed in 1986, based on a bulk of exploration data for the field but limited production histories of all the available wells. This model was updated in 1992, after significant production history of several of the first 18 wells had been obtained. In 1992 it was found that the 1986 model predicted the flow rate and enthalpy histories reasonably well but overestimated the observed pressure decline for most of the wells. The main change from the 1986 model to the 1992 model was that significantly higher reservoir permeability was required to match the production and pressure decline data, which was in fact promising for the performance of the reservoir.

The second update of the model in 1998 showed that the predictions of flow rates, enthalpies and pressure decline data using the 1992 model matched very favorably the measured data up to 1998 for practically all of the Nesjavellir wells. The most important data, which are the pressure decline data from idle wells, were accurately predicted for most wells, but the model underestimated the enthalpy decline in some wells. The recalibration of the 1992 model led only to few changes within the main well field and no changes in the reservoir parameters outside the production area, which in fact means that all the long-term predictions made by the 1998 model are identical to predictions of 1992 model.

The 1998 update of the Nesjavellir project has been used for various performance predictions. It is the conclusion of these studies that the Nesjavellir field can easily sustain the present power production of 60 MW_e and the associated thermal power capacity (200 MW_t) for thirty years, as only a total of about four (4) make-up wells will be required. A total pressure decline of less than 10 bars (from initial values) is predicted for all observation wells. However, enthalpy declines will make some of the peripheral wells less productive.

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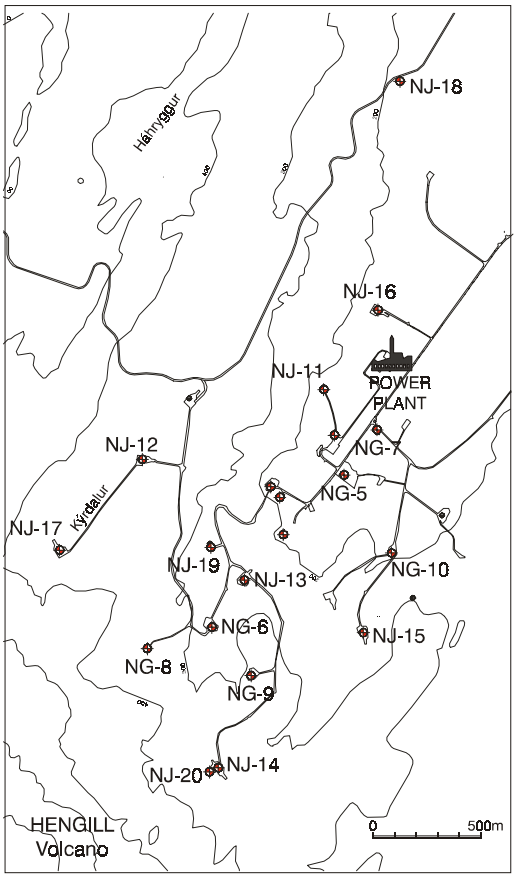

Figure 1. The Nesjavellir wellfield

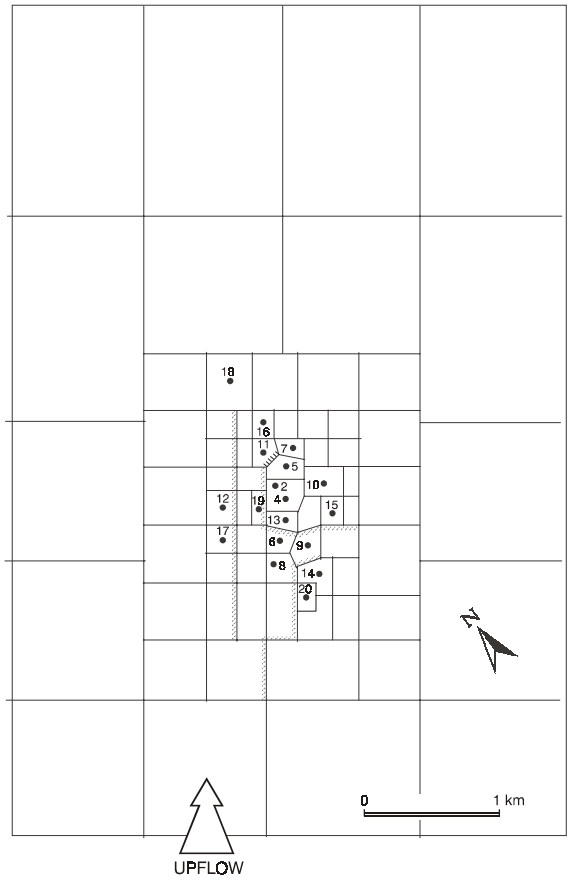

Figure 2. Areal view of the central part of the numerical grid, showing well numbers and inferred low permeability barriers.

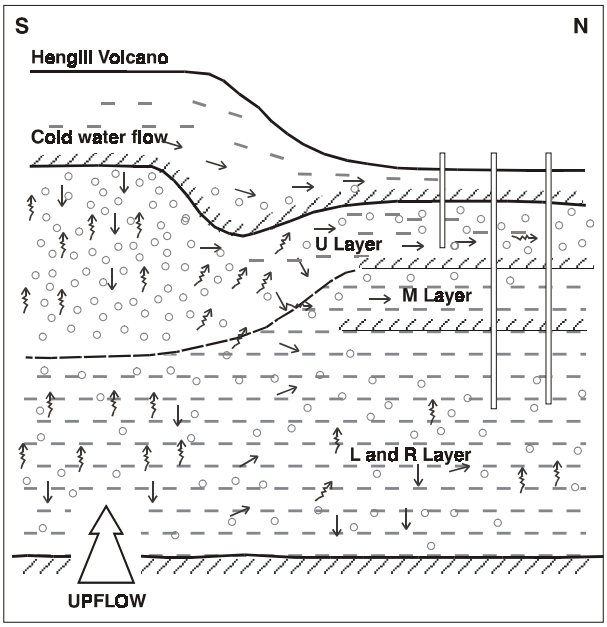

Figure 3. A model of the upflow zone and flow patterns for various layers. Straight arrows indicated liquid flow and wriggled arrows vapor flow.

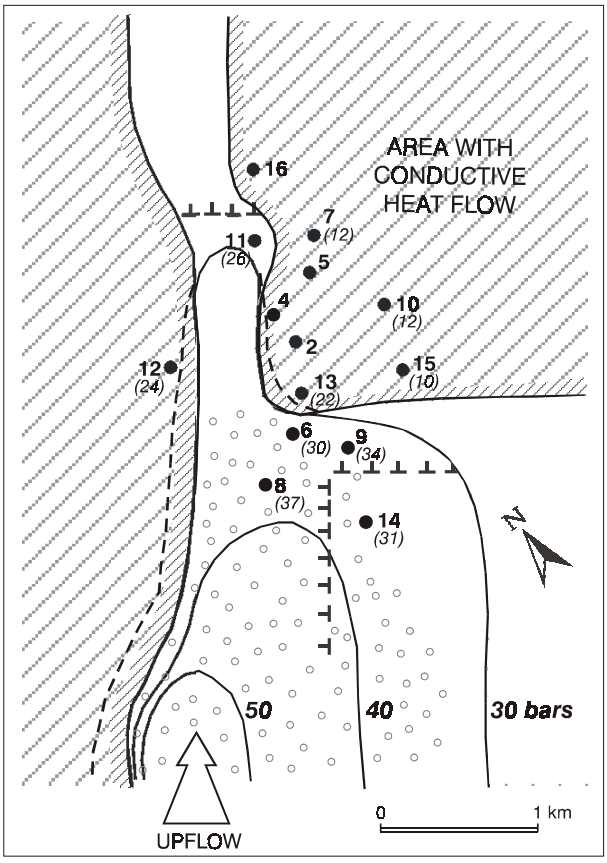

Figure 5. The computed pressure distribution for layer U. Observed values for each well are given in parenthesis; dotted area represents two-phase zone.

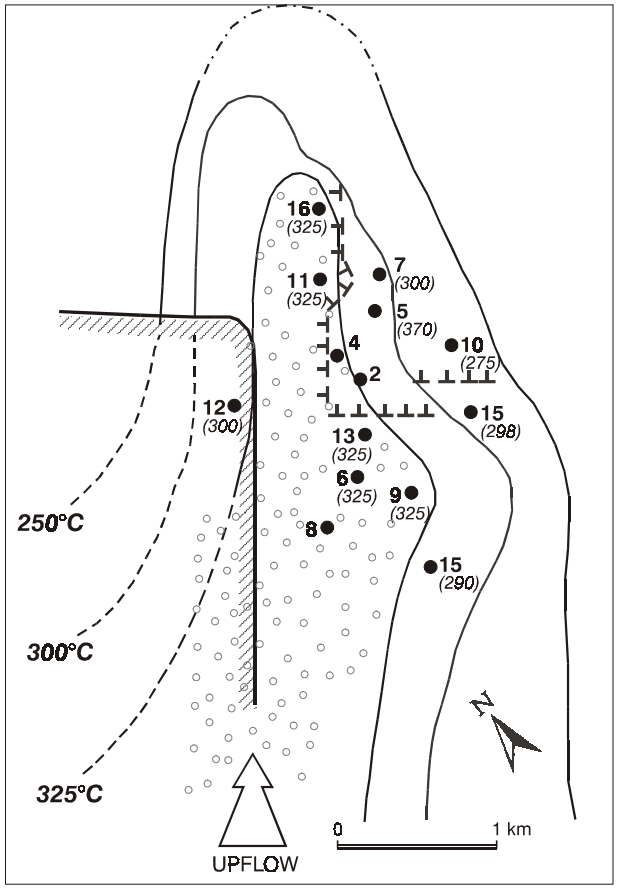

Figure 4. The computed temperature distribution for layer R. Observed values for each well are given in parenthesis; dotted area represents two-phase zone.

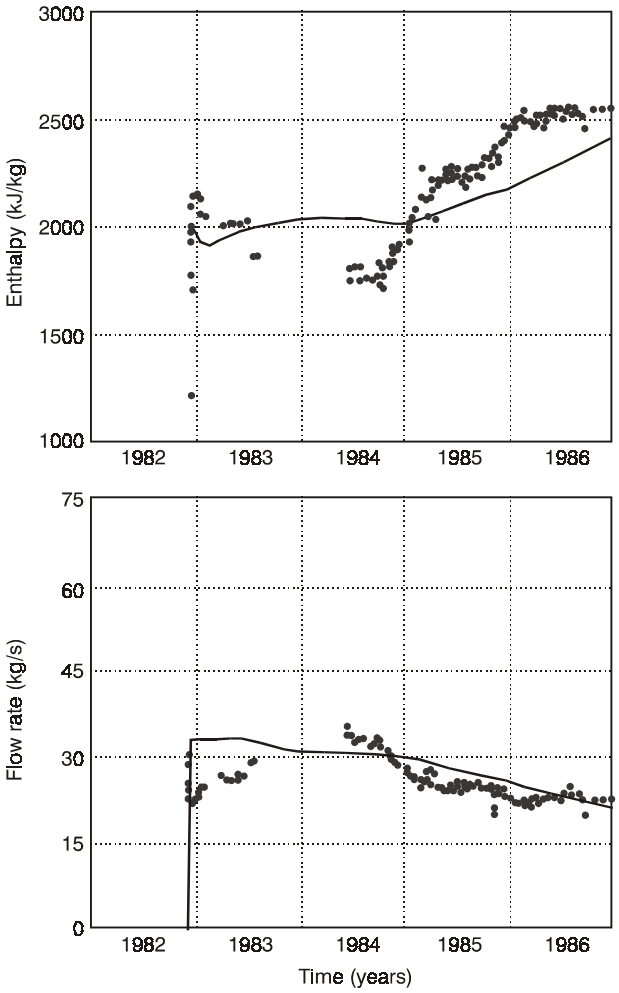

Figure 6. Comparison between computed and observed flow rates and enthalpies for well 6.

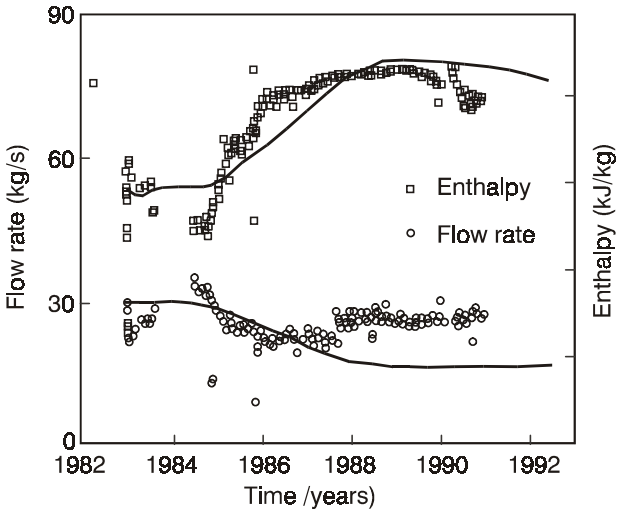

Figure 7 Comparison between predicted and observed flow rates and enthalpies for well 6 up to 1992 (the 1986 model).

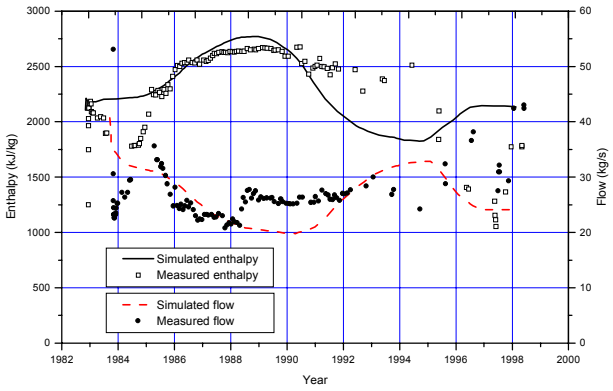

Figure 8. Comparison between predicted and observed flow rates and enthalpies for well 6 up to 1998 (the 1992 model).