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Assessment of Natural Heat Loss by the Balance Method

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Abstract

Natural heat loss from geothermal systems is commonly assessed by measurements of individual discharge features (surface manifestation method). Results can be affected by systematic errors due to over-estimation of surface steam losses and under-estimation of concealed outflows. For systems discharging neutral pH chloride waters, such errors can be detected by the balance method if reliable data for the equivalent upflow rate of deeper fluids are available (chloride flux studies). Recently, heat losses have also been determined by simulation studies, i.e. modelling of fluid flow in the natural state.

Application of the balance method for the Yangbayain Field (Tibet) shows that too large values (between 215 and 485 MW) have been obtained by the surface method whereas the balance method indicates a total loss of about 90±30 MW, similar to that obtained by an independent simulation study (about 70 MW). Discrepancies are also indicated for the 1951/52 and 1954 surveys of the Tauhara and Wairakei Fields (NZ) where the balance method indicates total losses of about 350±70 MW whereas a significantly higher value (530 MW) was obtained by the surface method.

Introduction

Three different methods have been used to assess the natural heat loss of geothermal systems, namely:

1) integrated assessment of losses from individual surface discharge features (surface manifestation method or surface method);
2) assessment of losses from heat and mass balance considerations (balance method);
3) modelling of the reservoir in the natural and exploited state (modelling method).

The first method has been developed in New Zealand and various suitable techniques have been summarised (i.e. Dawson, 1964; Dawson and Dickinson, 1970; Allis, 1981). It has been used to assess losses of most high-temperature systems in the Taupo Volcanic Zone (NZ) and to monitor changes during exploitation. The method is well suited for prospects standing in rather flat terrain where hot fluids rise to shallow levels and where heat transfer by concealed outflows can be neglected.

The second method has been used for hot water systems discharging neutral pH chloride water collected by a draining creek or river; this method was also developed in New Zealand (Ellis and Wilson, 1955).

The third method has only been used recently to model simultaneously heat and mass transfer in hot water reservoirs, both in the natural and the exploited state. Estimates of natural losses can be obtained by such simulation (O'Sullivan, 1985).

Assessments by each method can contain errors which are rarely cited. In the case of the surface method, losses due to surface steam discharge (i.e. evaporation, steaming ground, discharge from steam vents) but also liquid losses can be overestimated as will be shown later. The balance method can give too low values if deeper outflows are present whereas the modelling method can contain errors which are directly proportional to uncertainties in the average permeability of the model.

It is the aim of this paper to show that by extending the balance approach, systematic errors can often be assessed.

Heat loss Of an intermediate-temperature system under exploitation (Tangbayain, Tibet)

The natural heat loss of the Yangbayain field was first determined by the surface method. A survey in 1975 (Scientific Reconnaissance Team, University of Beijing, 1976) indicated a loss of about 215 MW; the value was increased to about 485 MW as a result of later studies (Liao et al; 1980). The system is fed by an upflow beneath a high mountain range with hot water moving laterally at about 170°C into a shallow secondary reservoir beneath a broad valley. This reservoir is about 250 m thick and consists of partly silicified Quaternary fluvio-glacial deposits overlying almost impermeable granites. It is sealed at the surface and is surrounded by siliceous deposits. Hot water is only discharged along a narrow strip of the Zangbu River, the sink for all thermal water. A schematic diagram of the natural fluid discharge is shown in Figure 1; cross-sections of the reservoir have been given by Liao et al (1980) and Cappetti and Wu (1985).

The secondary reservoir has been explored and four pilot plants have been constructed between 1979 and 1986 with a total plant capacity of 13 MWe in 1935 in 1934 some pressure drop inside the reservoir was already noticed (average temperature of produced fluids being 150°C). A reservoir simulation study in 1985 indicated a long term capacity of about 12 MWe for the explored part of the reservoir. The simulation showed that a natural inflow rate of about 100 kg/s is required to model the secondary reservoir in its natural state (G. Cappetti, pers. comm.). With reference to a mean annual temperature of 2.5°C (the field lies at 4300 m), this points to natural losses of about 70 MW (simulation method).

Using an analogy approach, electric power potentials of 155 MWe (Guo Guoying et al., 1981) and 100 MWe (Lund et al., 1984) have been predicted based on the earlier heat loss studies. In 1986 estimates for the electric potential were quoted which differed by more than one order of magnitude. When I visited the field in 1986, I tried to estimate its natural losses from various surveys made between 1981 and 1982 using also a few observations made in 1986.

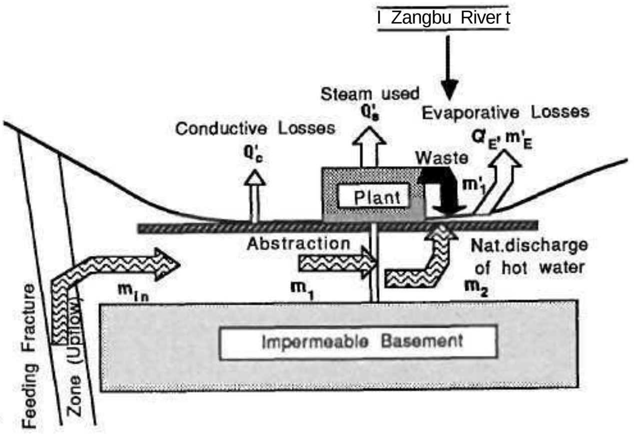

Fig.l: Heat and massflow components used to assess natural losses of the Yangbayain Field (Tibet) by the balance method.

Table 1: Assessment of mass flowrate of unmixed hot water discharged by the Yangbayain shallow reservoir into the Zangbu River (14.-15.4.1982).

	upstream site	upstream creeks	downstream site	mean of wells	mean of springs
flowrate (kg/s)	1107	<50	1356	-	-
Cl (mg/kg)	2.08	1.2	35.4	499	504
HBO_2(mg/kg)	0.61	0.3	14.6	233	213

NoterUpstream denotes a site about 19 km upstream from the power house, the downstream site was about 5 km downstream from the power plant. All concentrations refer to separation at ambient atmospheric pressure.The flowrate of the river was measured on 14.4.82; the chemical survey was made on 15.4.82 (data from Si Donxin et al.,1985).

Assuming that the natural losses did not change between 1981 and 1986, the following loss components are indicated:

a) Conductive losses at the surface Q'c, which were about 23 MW in 1981 (based on a regional temperature survey at 7 m depth cited in Yang Qilong, 1981); minor conductive losses into the underlying granites will be neglected. (Note: All parameters with a prime are those determined by surface measurements.)
b) Evaporative losses Q'g from warm lakes, hot pools, and minor steaming ground were about 10-15 MW in 1986; the largest contribution comes from a warm lake (ancient hydrothermal eruption crater) with a surface area of 7350 m^2 and a surface temperature of 20°C in 1986.
c) Significant losses are associated with the direct discharge of thermal water into the Zangbu River (component *mz* in Figure 1).

Some information about the natural discharge rate m2 can be obtained from a chloride and boron flux study of the river made on 15.4.82, one day after the river flow was measured (see Table 1). During both days a total of 48 kg/s of hot water was abstracted by a 1 MWe pilot plant which used 6.7 kg/s (Q's) of steam and discharged about 41 kg/s of waste (m'i) into the river at the local boiling temperature (about 85°C). Although no error for the river flow estimate has been quoted, the data indicate a maximum value for m'i +1112 (^ 200 kg/s) on the 14.4. whereas the chemical data indicate an input of only about 88.5 kg/s for both components on the 15.4. assuming a constant river flow during both days.

Introducing the terms AQ_S ,Ams and AQi ,Ami as error components associated with near-surface steam (s) and hot water (1) losses,the heat and mass balance equations are:

$$(1)\quad (Q'c + Q'E + AQ_S) + (Hm_2 + AQi) = Q_{nat}$$

$$(2)\quad (me + mE + Am_s) + (m_2 + Ami) = m_{na}t,$$

where Qn_{at} and m_{nat} are the total heat and mass flowrates of fluids respectively . Since the discharged hot water is practically unmixed, as indicated by the concentration of non-reactive constituents in wells and hot springs (Table 1), it can be assumed that all hot chloride water is discharged at or near the surface at boiling temperature ,i.e. enthalpy H = (356-10) kJ/kg.It is also assumed that conductive losses are maintained mainly by condensation of vapour and that the average enthalpy of steam, discharged directly or by evaporation at the surface with temperatures between 30 and 85°C, is about 2600 kJ/kg. Using the numerical data listed previously, this gives:

$$(1b)\quad 52\ MW + AQ_S + AQi= Q\wedge.and$$

$$(2b)\quad 61\ kg/s + Am_s + Ami = m_{nat}.$$

The four unknown parameters are restrained by the condition:

$$(3)\quad (Qnat/^{m} nat) = const.$$

The constant in (3) is the mean enthalpy of fluids rising to the surface in the secondary reservoir which lies within the range of (630-10) kJ/kg and (720-10) kJ/kg; the lower value relates to fluids as produced from wells, the upper one to fluids entering the secondary reservoir. It is assumed initially that (Q_{nat} / m_{nat}) = 620 kJ/kg.
The unknown parameters in (lb) and (2b) can be assessed using limiting values for AQs or Ami; resulting values for Q_{nat} and m_{nat} can be obtained either by linear programming or by using a graphical method (see Fig.2).The following limiting cases are indicated:

A: Ami = 0 ; (i.e. m_2 = 47.5 kg/s). This gives:
AQs = - 18 MW; Am_s = - 7 kg/s; Q_{Mt}~ 34 MW; m_{nat} ≈ **54** kg/s.

B: Am_s = 0; (i.e. steam losses are accurate).This gives:
AQi = 16.5 MW; Ami = 48 kg/s; Q_{nat}- 68.5 MW; m_{nat}- 109 kg/s.

C: m_2= $m_{m}ax$; (i-e. $m_{ma}x$ ≤(200 - 41) kg/s). This gives:
AQi ≤ 37 MW; Ami £ 107 kg/s;
AQs ≤ 21 MW; Am_s ≤8 kg/s; Q_{nat} ≤ 110 MW; m_{nat} ≤ 176 kg/s.

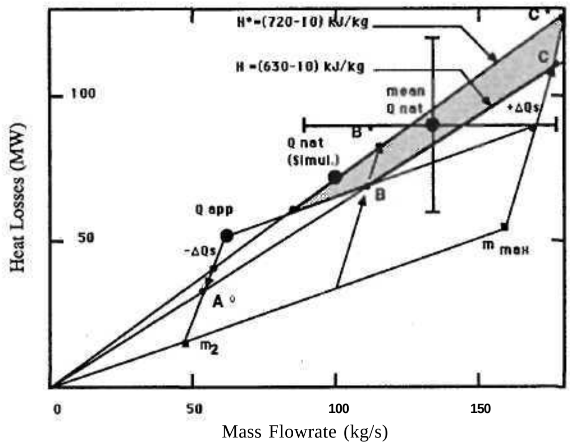

Fig.2: Mass flowrates and surface heat losses indicated for the Yangbayain Field (Tibet) by the balance method.

The likely value of Q_{nat} can be assessed from a discussion of the limiting cases.The heat loss indicated by case A is too low since the estimated total vapour losses are too low (only about 17.5 MW) insufficient to maintain the actual conductive losses; hence, Q_{nat} > 34 MW. The loss given by case C is an upper limit since the value of m_2, as indicated by the difference between up- and downstream river flowrates on the 15.4.82 , is based ort the assumption that the input of non-thermal water by several small creeks between the gauging sites can be neglected. In spring and early summer this input can be as high as 50 kg/s; hence, Q_{nat} < 110 MW. It is likely that total losses given by case B are also a minimum since assessment of steam losses in 1986 were not accurate because minor losses of steaming ground near the river were not taken into account; if for case B the component AQs > 0, then Q $_{nat}$ > 68.5 MW.
If the average enthalpy of thermal fluids transferred to the surface were 720 kJ/kg, this would imply Q $_{nat}$ > 60 MW in case B and < 128 MW in case C (see Fig.2). Any point wthin the shaded field of Fig.2 is a solution for Q_{nat}. A mean of about 90 ± 30 MW is probably the best estimate for the natural heat losses of the Yangbayain prospect which can be given at this stage. These losses can be sustained by a natural upflow of about 135 kg/s of hot chloride water; similar values were obtained by the simulation study, namely about 70 MW and 100 kg/s respectively.

Errors in the earlier heat loss assessments could have been avoided if balance checks similar to those shown in Fig.2 had been applied. For the 1975 study a value of about 21.5 MW is quoted for all liquid surface losses, i.e. m2 about 62 kg/s, pointing to steam losses of no more than 30 MW in contrast to the anomalously high value of about 193 MW inferred from the surface method. Although the surface losses of the field were somewhat larger in 1975 because of transient phenomena (the surface temperature of the large hot lake was as high as 44.5°C), the balance study indicates that surface steam losses were overestimated using the surface method..

Heat loss assessment by surface and balance methods of the Tauhara and Wairakei high temperature system (NZ).

The natural heat loss from the Tauhara and Wairakei Fields was assessed by the surface method during several surveys between 1951 and 1958. There is good evidence that both fields represent upflow centres of one large geothermal system, the Wairakei-Tauhara system (Allis, 1981). Because of the documented details, the results published by Fisher (1964, 1965) have been accepted as the best values describing the natural losses of both fields prior to exploitation (i.e. 1951/52), namely about 105 MW for the Tauhara Field and about 430 MW for the Wairakei Field. The relative errors are about 20 to 25% (Allis, 1981).

A separate study of the discharge rate of equivalent chloride water entering the Waikato River which drains both fields was made in 1954 by Ellis and Wilson (1955) when waste fluids (178 kg/s) from a few Wairakei bores were already discharging into the river. Ellis and Wilson deduced that a total of about 340 MW were discharged from both fields . They also used a simple mass balance approach to infer that the difference between their value and that obtained by the surface method at that time (about 600 MW cited in Grange 1955) could be caused by an overestimate of steam losses in the surface method.

Since satisfactory results had been obtained with the balance method at Yangbayain, the same method was also applied to the Tauhara and Wairakei data. Unfortunately, the natural losses of both fields have not yet been assessed by the simulation method; no reservoir model has been constructed for the Tauhara Field and the presently used Wairakei reservoir model was set up by using the heat loss assessed by the surface method as input data (M. O'Sullivan, pers. comm.). Any discrepancy between data given by the surface and balance method can therefore not be resolved with reference to data obtained by the simulation method. The natural fluid flow model is similar for both fields. In the pre-exploitation state deep hot chloride waters ascended to a level of about 500 m depth where $T \approx 250°C$. The average chloride concentration of these waters was about 1.9 g/kg at 1 bar separation when produced in 1954 (Ellis and Wilson, 1954); the average enthalpy of fluids from producing wells in 1955 was about 1070 kJ/kg (Henley et al., 1984). The average chloride concentration of the very deep hot water is greater, about 2.225 g/kg according to Youngman (1988). In the following discussion it will be assumed that ascent of the very deep water was quasi-adiabatic and that its effect upon the heat balance can be neglected.

From about 500 m depth, fluids ascended to higher levels as a two-phase mixture with vapour being separated at higher levels; vapour spread laterally and was often discharged away from low lying centres where hot chloride water escaped. Mixing with steam-heated groundwater was common, as is indicated by the lower chloride contents of hot water in shallow wells at Wairakei (that for WK1, 8A, 9, 14 was only about 1.4±0.3 g/kg in 1954), whereas most shallow wells at Tauhara encountered steam heated waters (Henley and Stewart, 1983; Henley et al., 1984). Discharge of almost unmixed chloride water was rare (only at Geyser Valley, Wairakei). The near-surface chloride flux varied seasonally and was a maximum during the winter when more chloride water was flushed (Ellis and Wilson, 1955). Such seasonal variations were neglected at Yangbayain because of the very low rainfall there.

Before applying the extended balance method, one has to decide whether heat loss data obtained by the 1951/52 and 1954 surveys can be compared.

Timing and locality effects: The first survey using the surface method was made during 1951/52; the chloride flux was measured in 1954. Fisher repeated his survey in 1958 and found unchanged values at Tauhara; at Wairakei hot water losses had declined (probably by about 10% in 1954) but steam losses had remained almost the same neglecting changes which occurred after 1954 (steam discharge around well WK 201 drilled in 1958). The chloride flux survey only gives the total flux of both fields between the upstream site of the Lake Taupo outlet and the downstream site at Aratiatia Rapids (about 4 km downstream from the centre of the Wairakei Field). Flux measurements at an in-between site (Huka Falls) cannot be used to separate the chloride input from the Tauhara Field.

Effect of steam-heated water: The balance method only allows a check of heat losses associated with chloride waters. The combined chloride flux of hot water discharged into the Wairakei, Waiora, and Waipouwerawera streams which drain the Wairakei Field was about 210 g/s in 1954; the surface method gave a subtotal of 73 MW for the heat transferred by the streams in 1951/52. The chloride flux indicates a mass flow rate of about 110 kg/s of equivalent unmixed chloride water which, if discharged at boiling point temperature, would only account for 40.5 MW using an enthalpy of (415-50) kJ/kg. The rest, i.e. about 32.5 MW, must have been added by steam-heated groundwater which constitute steam losses. A significant portion of the losses associated with hot water and seepage (total of 147 MW for both fields cited by Fisher) is therefore associated with steam loss. Hence, results of the surface surveys cannot directly be compared with results from the chloride flux study; for the same reason balance checks applied in the past to liquid and steam losses to obtain the mean enthalpy of deeper fluids (Fisher 1964, 1965) are open to criticism.

Concealed outflow effects: Neither survey allowed for the possibility of concealed outflows of mixed chloride waters.For example, a minor outflow from the Tauhara Field enters for example Lake Taupo (Waipihi outflow); the low liquid losses (about 5 MW) and the low chloride content of these fluids encountered in wells near the Terraces Hotel indicate that the contribution of this outflow, which occurs upstream from the Lake outlet site, was minor. Both surveys also were not extended below the Aratiatia Rapids where extinct manifestations occur (P.R.L. Browne, pers. comm.) which were probably fed by an ancient outflow from the Wairakei Field. Since possible losses downstream from the Rapids were not considered by either survey, this does not affect the comparison. In the absence of any documented losses outside.it will be assumed that all chloride water supplied by the two upflow centres entered the Waikato River between the Lake outlet and the Rapids.

In order to apply the extended balance method, it will be assumed (as for Yangbayain) that steam losses associated with conductive losses (19.2 MW) and evaporative losses (122.5 MW), as given by the surface method for both fields, contain the least error and that mass flow rates can be obtained by using a mean enthalpy of 2625 kJ/kg (covering a wide range of surface steam temperatures between 40 and 99°C). Since additional steam losses from steaming ground are significant, the components AQs and Am_s in equations (1) and (2) are > 0. As for liquid losses, it will be assumed that the chloride flux values of Ellis and Wilson can be used for this component, the mean annual chloride input of both fields was in 1954 about 412±120 g/s, which indicates a mass flow rate of about 217 kg/s for unmixed chloride waters discharging about 79 MW. An upper limit for the total losses can be obtained by using the upper limit for the chloride flux, i.e. 532 g/s, corresponding to maximum liquid losses with a mass flowrate $m_{max} = 280$ kg/s.

According to equations (1) and (2) one obtains for the combined losses from the Tauhara and Wairakei fields:

(lc) 221 MW + AQs + AQi = Q nat, and

(2c) 271 kg/s + Am_s + Ami = Qnat-

It can be assumed that the enthalpy of the ascending hot fluids (equation 3) lies within the range of (1000 - 50) and (1100 - 50) U/kg as indicated by fluid characteristics of test wells discharged in 1954 adding waste fluids at a rate of 178.5 kg/s to the river (Ellis and Wilson, 1955). If one uses the same approach as for Yangbayain, one obtains the diagram shown in Fig.3. Since in equations (lc) and (2c) the unknown parameters AQ_S and Am_s are > 0, only two limiting cases are of interest, namely:

case B: Ami = 0, and

caseC: mi = m max (280 kg/s).

Figure 3 indicates that for these cases, within the inferred enthalpy range:

$$280 \text{ MW} < Q_{nat} < 420 \text{ MW}.$$

Again, any point within the shaded field shown in Fig.3 is a solution for Q_{nat} which satisfies observed data and assumed restraints. A mean value of 350 ± 70 MW is probably the best estimate for the natural losses (between 1951 and 1954) of the combined Tauhara and Wairakei Fields. These losses would have been sustained by an upflow of about 350 kg/s of hot fluids of which about 250 kg/s would be discharged as unmixed hot water (at boiling point) at or near the surface, transferring about 92 MW of heat. It is likely that these liquid losses had already decreased by about 10% in 1954; any such temporal changes lie, however, within the error of the

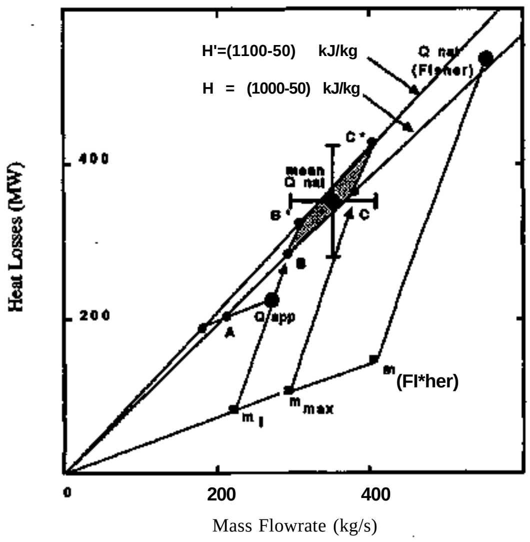

Fig.3: Mass flowrates and surface heat losses indicated for the Wairakei and Tauhara Fields (New Zealand) by the balance method.

best estimate cited above.

If one compares our values with those cited in Fisher (1964,1965), one can infer that both liquid and steam losses cited for the earlier surveys were over-estimated by about one third. In case of the liquid losses it is likely that the error was caused by the inclusion of steam-heated waters; as for the discrepancy in steam losses, it is possible that the area of steaming ground was overestimated (R.Allis,pers.comm.). Errors in evaporative losses, however, were small since an independent check of evaporative losses of various Tauhara features cited in Fisher (1965) by using the algorithm of Ryan et al. (1974) gave similar values except for ebullition effects.

If the same types of error had occurred during the earlier surveys both at Tauhara and at Wairakei, it is possible that the natural losses from the Wairakei Field were no greater than about 280 MW and those of the Tauhara Field no more than about 70 MW during 1951 to 1954. Although surface steam losses increased later both at Tauhara and at Wairakei as a result of the pressure drop induced by the production at Wairakei (Allis, 1981, Henley and Stewart, 1983), it is unlikely that steam losses between 1951 and 1954 exceeded steady state losses associated with the natural upflow of hot chloride water. Until independent assessments are produced by the simulation method, one can only state that the total losses of both fields were somewhere between 280 and 530 MW in the undisturbed state; the balance method, however, allows the prediction that the actual value was at the lower end of this range.

Summary:

Application of the balance method to natural hot water and steam losses from three hot water systems which discharge neutral chloride waters at the surface has shown that unknown or poorly known loss components can be assessed by the heat and mass balance equations.This shows that surface steam losses assessed previously by the surface method have been significantly overestimated pointing to a probable systematic error in steam loss assessments of surface manifestations.

Natural heat loss data published for similar systems might contain the same types of error. If balance checks were applied to data obtained by the surface method, one should be aware that losses associated with hot water and seepage discharges may contain a component coming from steam-heated waters which has to be separated from losses due to discharge of hot chloride waters.

Problems can arise if natural losses which have been overestimated are used to infer the power potential of a certain reservoir using the method of analogy or if a reservoir model were used for a simulation study which is calibrated by using natural upflow rates based on overestimated natural losses.

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