ASSESSMENT OF TOTAL HEAT AND MASS TRANSFER OF A LARGE HOT POOL USING THE BALANCE METHOD (OHAAKI POOL, BROADLANDS-OHAAKI GEOTHERMAL FIELD, NZ)

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Introduction

Hot pools and hot lakes with minor discharge of chloride water can often be found over large hot water systems. These pools are fed by deep thermal fluids which usually have been mixed with less mineralised shallow water and which ascend along deep reaching fracture zones. In most cases these pools and lakes occupy an older hydrothermal eruption crater. The water in the pool is clear and deposition of silica occurs at the margin often forming overhanging deposits. In New Zealand the Ohaaki Pool (Broadlands-Ohaaki), the Champagne Pool (Waiotapu), and the Waimangu Hot Lakes (Waimangu) are examples of such pools and lakes.

Evaporative heat losses are high because of the high surface temperature but natural overflow is usually small. The concentration of chemical constituents of the hot water is almost constant over long periods indicating that the total upflow is significantly greater than the total mass flow given by evaporation and natural overflow.

In this paper the likely total heat and mass transfer of the Ohaaki Pool in the Broadlands-Ohaaki geothermal field will be assessed; for locality of pool and wells cited refer to Browne (1986) and Henrys (1986).

The Ohaaki Pool heat transfer problem

The Ohaaki Pool occupies an ancient hydrothermal eruption crater (evaporating surface area about 850 m^2) and taps deeper, hot chloride water which has been mixed with CO_2-rich steam-heated, deeper groundwater containing some condensate. There is good evidence that mixing occurs at a depth of 200 to 300 m where bicarbonate waters at temperatures of 140 to 180°C occur throughout the field which have caused external corrosion of wells (Hedenquist and Stewart, 1985). After mixing, fluids ascend as two-phase mixture to the surface causing a cone-shaped, anomalous seismic velocity structure beneath the pool down to about 200 m depth (Henrys, 1986).

The evaporative losses at the pool surface are on the average about 18±2 MW using the algorithm of Ryan et al. (1974)for the range of temperature data observed between 1929 and 1984 (see Table 1). The loss indicates an average mass flow rate of 6.7 kg/s for steam escaping from the pool which is of the same order as the average overflow rate of chloride water (about 10 kg/s) prior to 1967. When the first deep wells were tested between 1967 and 1971, the pool level dropped by 9 m (in 1971); the overflow stopped in 1969. Discharge tests of nearby well BR 3 and the immediate response of the pool level indicated a common deep feed. Analysis of later level changes showed that the pool responded to reservoir pressure changes (Grant, 1982).

Chemical analyses listed in Table 1 show that concentration of chemical constituents remained almost constant between 1929 and 1977, even after the overflow of the pool stopped. The unchanged concentrations of non-reactive constituents, like Cl and B, indicate that a large concealed outflow of mixed water must have occurred. Smaller changes in concentration were only observed after waste fluids from well BR22 had been discharged into the pool between 1981 and 1982; after this episode, the pool started to overflow again.

Heat and mass balance considerations

Approximate solutions can be obtained from the heat-, mass-, and chloride flux balance equations for a setting as shown in Figure 1; since:

(1) $m_E + m_o = m_c + m_d$ (mass balance)

(2) $Q_E + H'_p m_o = H_c m_c + H_d m_d$. (energy balance),

and (3) $Cl'_p m_o = Cl_c m_c + Cl_d m_d$ (chloride flux balance).

For an explanation of the symbols and subscripts, see legend in Figure 1.

These equations can be solved with respect to the mass flow rate m_d of deeper chloride water entering the "mixing box" in Figure 1, since:

$$m_d = \frac{Q_E(Cl'_p - Cl_c) + m_E Cl_c (H'_p - H_c)}{[(H_d - H_c)(Cl'_p - Cl_c)] - [(H'_p - H_c)(Cl_d - Cl_c)]} \cdot \tag{4}$$

Equation (4) is not directly suitable for numerical solution since it contains more unknown than known parameters. However, with suitable assumptions covering extreme cases of vapour transfer between the mixing box and the surface and two additional limits restraining the enthalpy range of fluids entering the mixing box, a range of values can be found for the mass flow rate m_d and, hence, for all other unknown parameters.

Vapour which separates during ascent between the mixing box and the surface, when the enthalpy of the fluids decreases from H_m to H'_p, can be assessed for two extreme cases:

Case I: **Vapour is condensed and enters the bottom of the pool, i.e $Q_E=Q'_E$,**
Case II: **escapes elsewhere and heats up groundwater, i.e. $Q_E=Q'_E+\Delta Q_E$.**

There are also limits for the enthalpy H_m of fluids in the mixing box:

Limit A: **the enthalpy H_c of the CO_2-rich heated water is almost the same as that of the deeper chloride water, i.e $H_c=H_m=H_d$,**
Limit B: **H_c is lower than H_d but can be assessed from temperatures at the same level in nearby wells, i.e. $H_c<H_m<H_d$.**

Since mixing occurs within a large volume, as indicated by the mixed fluids from the 350 m deep well BR33 which lies about 700 m to the west of the pool (Table 1), quasi-equilibrium conditions probably exist in the mixing box; for Limit A the value of H_m should be close to that indicated by SiO_2 geothermometer of the pool water ($T_{mix}\approx200°C$); hence, for Limit A we can use $H_m\approx850$ kJ/kg. The CO_2-rich heated waters might constitute a lateral flow which can be recognised in the stable temperature profile of nearby well BR3 where T at 240 m depth is about 170°C; for Limit B we used $H_c\approx720$ kJ/kg. Appropriate values for H_m and H_d can be obtained from the chloride-enthalpy diagram (Figure 2).

Numerical example (Case I)

With data listed in Table 1 and values (Limit A) discussed above, one obtains the following input data:

Cl'_p=1.06 g/kg; Cl_c=0.03 g/kg; Cl_d=1.44 g/kg;
H'_p=400 kJ/kg; $H_c=H_d$=850 kJ/kg;

this gives m_0=40 kg/s; m_c=18 kg/s; m_d=29 kg/s.
The concealed outflow rate (m_0-m'_0) is therefore (40-10) kg/s. This also constitutes a minimum value for m_0; for all other cases slightly larger values of m_0 were obtained. If for Case I the enthalpy H_c=H_m is lowered to 720 kJ/kg, one obtains, for example, m_0=43 kg/s, m_c=19 kg/s and m_d=32 kg/s. The total heat loss is not much affected by these changes and lies between 37 and 38 MW for both examples cited. Similar results can be obtained if one uses boron values listed in Table 1.

Numerical example (Case II)

If one introduces $\bar{H}=(H_2+H_3)/2$ for the mean enthalpy of vapour between the mixing box and the surface, one obtains an approximate value for the energy Q_E transferred since:

$$(5) \qquad Q_E = \frac{\bar{H}(H_m - H'_p)(m_o + m_E)}{(\bar{H} - H'_p)} \ .$$

Using as starting values m_0 and m_E from Case I, approximate values for ΔQ and Δm can be obtained since $\Delta Q_E/\bar{H} = (Q_E - Q'_E)/\bar{H} = \Delta m_E$. The value of Δm can be added to the mass flow rate of the CO_2-rich water to avoid an imbalance in the heat and chloride flux balance equations of the mixing box .By iteration best fit values for m_0, m_c, and m_d can be found.

For Limit B with 720 kJ/kg<H_c<850 kJ/kg a range of values for m_0 was obtained which all lie between 48 and 54 kg/s. A sensitivity analysis showed that errors of all parameters are dominantly affected by the error in Q'_E.

Summary

The study has shown that the total heat and mass transfer of the Ohaaki Pool is significantly greater than that given by surface losses (about 21.5 MW) and that a large concealed outflow of hot water (between 30 and 44 kg/s) is required to explain the unchanged chemistry of this pool in its natural state. The total heat transferred (37-41 MW) is about 2 times greater than that assessed from surfaces losses.

The same findings should also apply to other clear hot pools including those with no natural overflow but for which constant concentration of chemical constituents is documented. Constant chemistry of hot pools and hot lakes implies that there is always a large concealed outflow of hot water associated with these features.

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Mr G. Caldwell (now Geophysics Division, DSIR) introduced the concept that the total heat and mass transfer of a hot pool can be assessed from balance equations. The data listed in Table 1 were provided by Chemistry Division, DSIR (Geothermal Research Centre, Wairakei); their permission to publish the data is gratefully acknowledged.

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Table 1: Chemistry of fluids from Ohaaki Pool and of surrounding wells

Date ddmmyy	Well	pH	T °C	Na	K	Ca	Mg	Cl	SO_4	HCO_3	SiO_2	B	Comments
000029	Ohaaki	8.0	94	926	84.5	12	0.5	1049	63	769	305	29.3	overflow
151058	Pool	-	98	860	92.5	-	-	1078	-	-	-	30.1	"
230159	"	-	-	920	82.5	-	-	1078	10.2	771	-	31.2	"
160665	"	7.0	95	860	82	8.5	0.2	1060	100	680	339	32.1	overflow (12 kg/s)
150477	"	8.2	96±3	946	55	11.8	-	1047	159	703	226	30.1	no overflow
281079	"	7.4	-	929	75	11.6	0.6	1051	119	771	250	30.3	"
mid 81 -mid 82	"	-	-	-	-	-	-	1200 -1250	-	-	-	-	input from BR22
100184	"	7.5	93	973	81	12.1	0.5	1161	90	740	296	32.5	overflow
020384	"	7.9	-	969	85	8	0.4	1136	77	680	273	33.9	no overflow
080884	"	-	92.5	833	77	9.9	0.42	1137	84	774	-	32.8	"
						Unmixed waters							
260368	BR03	8.3	-	975	194	-	-	1603	6	386	555	49.0	inferred deep water
080283	BR22	8.4	-	1058	234	24	0.02	1721	6	165	840	49.9	"
						Steam heated CO_2 -rich groundwater							
041267	BR06	7.4	-	435	39	180	-	28	15	2204	180	1.2	inferred steam heated water
						Shallow mixed water							
050184	BR33	8.8	-	938	105	1.2	0.05	1158	68	621	427	35.3	T=180° at 350 m depth

Note: All concentrations are in mg/kg and analyses refer to separation at atmospheric press.

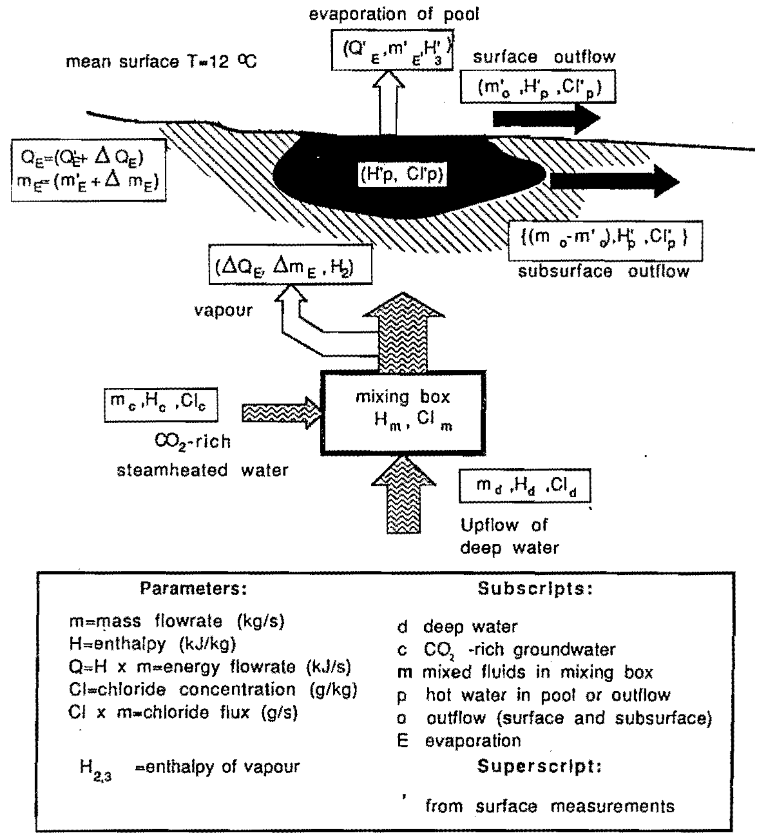

Figure 1. Diagram showing heat and mass flow components of fluids involved in the total heat and mass transfer of the Ohaaki Pool.

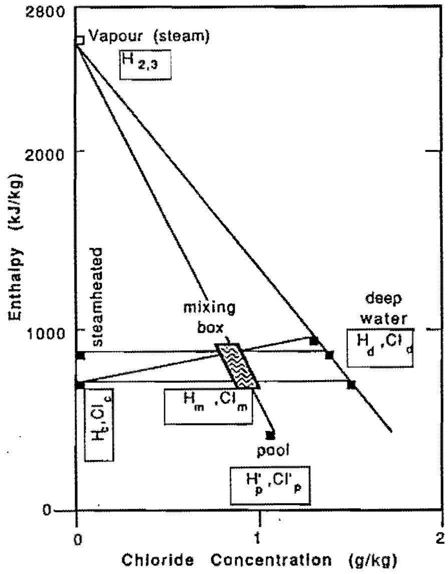

Figure 2. Chloride-enthalpy diagram showing control of mixed fluids discharged by the Ohaaki Pool.