HEAT LOSS FROM HIGH TEMPERATURE PONDS

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ABSTRACT

Heat loss from high temperature ponds is of interest for several reasons including to calculate heat fluxes for natural features or to determine cooling rates for engineering purposes, such as scaling prevention or to keep within material temperature ratings. However, most published data and correlations relate to moderate temperature ponds developed for power station cooling ponds or for spas and bathing pools. In this paper correlations for determining the heat loss from such cooling ponds and bathing pools are presented. The principles, important parameters and the differences from high temperature ponds are discussed. At moderate temperatures, environmental factors such as air temperature and humidity, solar radiation and particularly wind speed are very important. At higher temperatures the cooling rates are much greater and these factors become less significant. Experimental data from several high temperature ponds and cooling channels are compared. Cooling mechanisms are discussed. A correlation for high temperature ponds is suggested

1. INTRODUCTION

This work originated from a need to know the cooling rate of a well testing pond, so that the delay before the pond could be pumped out through a “plastic” MDPE pipeline could be calculated. A literature search showed that a number of correlations were available to estimate heat and water loss, however, these generally have been determined for warm ponds, up to temperatures around 35 or 40 ºC. Heat and evaporation losses calculated using different correlations, even over a limited range of pond temperatures, will give widely varying results. Heat loss and evaporation at higher temperatures are significantly greater.

Evaporation loss is related to heat loss and is an important parameter, particularly at high temperatures where it dominates. Evaporation also depends on water temperature as well as meteorological factors: wind speed, air temperature and humidity.

Early work was done at Wairakei to determine heat flows from natural features such as hot pools, geysers or fumaroles. Actual heat losses were measured and empirical correlations derived. (Dawson 1963). Dawson measured losses at about 13-kW/m^2 at 90ºC and 18-kW/m^2 at 98ºC. This information is very useful when checking other theoretical correlations.

This paper discusses some experimental work to try to derive better correlations for high temperature ponds.

Temperature measurements of two well testing discharge ponds at Tauhara, a separated water holding pond and channel at Ohaaki, a well test cooling channel, and separated water holding ponds at Tauhara and Wairakei were used to try to determine actual heat losses at higher temperatures. In most of these cases the data were gathered during normal operations so it was not generally possible to control input flows and temperatures. However, the most significant issue was in getting high enough temperatures to check the high end of the correlations.

2. POND COOLING RATES

2.1 Theoretical Heat Loss

Heat loss, or gain, is the sum of a number of factors:

- Gain from radiation: direct sun and atmospheric radiation, which depend on cloud cover, latitude, time of year, time of day, and so on.
- Loss to or gain from conduction: depending whether the pond is warmer or cooler than the air and its surroundings
- Loss to radiation
- Loss to evaporation
- Gain or loss from added water: depending on the temperature of the added water relative to the temperature of the pond.

Most of these factors depend on the pond temperature, but are also dependent on meteorological (weather) factors, particularly wind speed and humidity. Radiation loss and evaporative loss will dominate as the pond temperature increases.

A number of empirical correlations are available to calculate heat and evaporation loss, however they are generally derived for irrigation channels or surface water reservoirs or for cooling ponds, which have relatively low temperatures – up to about 35 or 40ºC.

An example of the contribution of the various factors is given in **Figure 1**. Note that these were calculated for still conditions and an air temperature of 10°C; they also assume a time span of days or weeks, so that diurnal or seasonal changes are not shown. Losses are shown as positive; gains as negative heat flows.

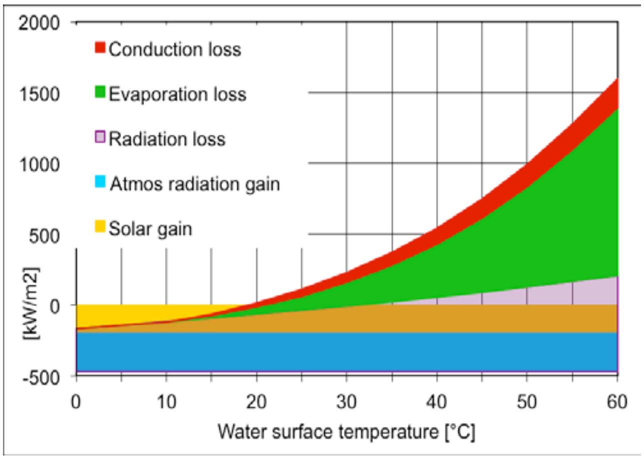

Figure 1: Heat losses after Ryan and Harleman

Typically correlations have been derived for moderate water temperatures and empirical values obtained that match the data under those conditions. Consequently the accuracy of the correlations when used beyond these limits is not known. The correlations give different results, even for the same assumed meteorological conditions. Theoretical heat losses for pools up to about 40ºC vary from about 500 to over 3,000 watts per square metre.

A common simplification is that heat loss is proportional to some function of wind speed and is zero when the wind speed is zero. This may be appropriate with low temperature ponds but is not applicable to high temperature ponds, particularly with low ambient temperatures, as thermal buoyancy will cause mixing of the warm moist air near the water surface with the cool relatively dry air above the pond – even in still conditions. This mixing will result in significant evaporation and consequent heat loss. Ryan at al (1974) commented that little work has been done in this area and most of that was in the laminar range, which is not applicable to field cases. That there is considerable evaporation under still conditions is obvious by the vapour plume above hot or warm water surfaces even under still conditions. Refer to **Figure 2**.

Figure 2: Steam plume from well testing pond

The correlations tend to be used over moderate time scales, that is, more than a few days and typically weeks, so diurnal changes are not considered – losses are averaged over day and night.

Although correlations that are linear with pond temperature may give acceptable results over the temperature ranges associated with bathing pools, they are unlikely to be correct over greater temperatures. Radiation heat loss is proportional to the fourth power of absolute temperature. Evaporative loss is proportional to the saturation pressure corresponding to the warm pond water: the saturation pressure also follows a power relationship with temperature. Hence, an appropriate heat loss correlation should show an increasing rate of heat loss with increased temperature.

EARLIER EXPERIMENTAL WORK: DAWSON

Dawson (1964) carried out a range of experiments on a small artificial pool (1-m deep, 6.5-m^2 in area) to derive correlations for determining heat and evaporation loss from natural geothermal features at high temperatures. The pool was heated by a series of steam pipes in the bottom and the energy input could be measured.

Dawson determined the total heat loss from the combination of evaporation, radiation and conduction and diffusion. His work was done in assumed calm conditions although he noted that wind speed was between 1 and 2-m/s during the experiments.

Dawson evaluated evaporation by measuring changes in pool water level directly, making allowance for losses by seepage and at ambient temperatures. From this he derived an experimental curve. He evaluated radiation heat losses assuming blackbody radiation and accounting for the reduced emissivity of the water surface.

SPECIFIC CORRELATIONS

The different correlations are reviewed in this section. Discussion is more detailed on the correlations of Shanahan and Lund, which appear to better match observed data.

Shanahan reviewed correlations from a number of authors for the different heat loss (or gain) components. He considers two correlations suitable for artificially heated ponds: those by Ryan & Harleman and by Meyer. The two correlations are quite similar except at very high temperatures where the R & H correlation drops markedly. As this is intuitively false (evaporative losses would be expected to continue increasing as the boiling point is reached) the Meyer correlation has generally been used here.

Although curves obtained using the Meyer function (Shanahan) follow an appropriate power relationship, they give significantly lower heat losses in the lower temperature range compared to the other correlations.

The Talati and Stenstrom correlation is proportional to wind speed; that is, for zero wind speed there is no evaporation. Intuitively this approximation is invalid as noted above. Further as it is linear with water temperature, it will underestimate higher temperature losses.

Dawson

Dawson describes the process that he used to determine his correlation, but does not give the actual correlation or development of the components.

A curve that closely matches that given by Dawson is:

φ = 0.20+0.0025*T+3E-5*T^2+7.5E-6*T^3+1.1E-7*T^4

in kW/m^2

where T = pond surface temperature [°C]

There is no scientific basis for the form of the equation or the constants beyond the close match with Dawson’s curve and experimental data.

Dawson goes on to note that heat loss increases greatly with boiling pools, as would be expected. He gives a correlation for that additional heat loss in terms of the height of the boiling zone. He correlates it with estimates of the heat output of WK204, the “rogue bore”.

Heat Loss From Hot Pools and Spas: Lund

Lund calculates both heat loss and evaporative loss from typical pools and spas, to enable designers and operators to calculate heating requirements. His calculations are for pools in the range of 15 to 40ºC and are based on American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) correlations. He notes that typical pool temperatures are around 27ºC so it might be expected that his correlations are specific to temperatures around that. He also notes that evaporative heat loss is typically 50 to 60% of the total heat loss for pools (in this temperature range). Evaporation depends on an activity factor, relating to the amount of splashing and the wetted area of adjacent surfaces. This ranges from 0.5 for residential pools (little activity) to more than 1.5 for wave pools.

The correlation that he uses is:

W_p = A*(pw-pa)*(0.089+0.0782*V)/Y

Where:

A	pool surface area [m^2]
pw	saturation vapour pressure at surface [kPa]
pa	saturation pressure at air dew point [kPa]
V	air velocity [m/s]
Y	latent heat of vapourisation [kJ/kg] (2,330 assumed).

For indoor pools, with very low air velocity (ventilation systems only), a low activity factor and assuming an air temperature of 20ºC and relative humidity of 40 to 60%, evaporation losses are up to about 0.3-kg/hour per square metre of pool for a 35ºC pool temperature, which is equivalent to about 7-mm per day of evaporative loss. It varies little with changes in humidity up to 90%.

Heat losses for some cases are plotted in **Figure 3**:

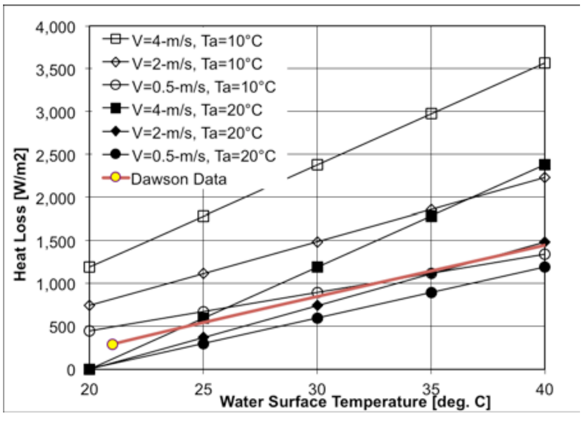

Figure 3: heat losses from Lund

Using the correlation, for a wind speed of 1-m/s, the loss almost doubles compared to still air; for 5-m/s it is over five times greater.

Assuming a low ambient temperature, 10ºC for example, even at 100% humidity, losses are similar for the same activity factor. For an activity factor of 1.0 losses double, for example at 35ºC pool temperature and still conditions, the water loss is about 14-mm per day, at 5m/s (18-km/h or a “light breeze” on the Beaufort scale) the loss is 76-mm per day. Back calculating the heat loss from the evaporation, shows that evaporative loss is between about 20% of the total heat loss (at low pool temperature and low wind speed) up to about 70% at 35ºC and 5-m/s.

However, the correlations fail at higher temperatures: evaporative heat loss becomes several times larger than the total heat loss.

Water Temperature Modelling: Shanahan

Shanahan (1984) uses a heat balance approach. The approach is similar to that of Ryan, Harleman and Stolzenbach (1974) whose work is referred to by Shanahan.

Shanahan gives metric equivalents to the basic English unit equations. However, the conversion factors that he provides appear to be incorrect in some cases.

The heat balance needs to include water inflows and outflows. Heat conduction to the earth through the bottom of the pond is small and is usually ignored.

Heat transfer through the water surface is the major effect. It comprises five components, typical values of which are given in Table 1.

Table 1: Pond Heat Loss Components

Component	Symbol	Unit	Range	
Net solar radiation	φ_{sn}	W/m^2	50	350
Net atmospheric radiation	φ_{an}	W/m^2	200	400
Back radiation	φ_{br}	W/m^2	250	500
Evaporation loss	φ_{e}	W/m^2	0	350
Conduction gain/loss	φ_{c}	W/m^2	-70	200

The water body is assumed isothermal, that is, it has a constant temperature throughout. This assumption can be inaccurate for deep lakes and flowing streams; it should be satisfactory for relatively shallow, small, static cooling ponds.

Solar radiation

Solar radiation, less an allowance for reflection, uses a correlation from Ryan and Harleman, 1973. It works well in nearly all situations, but can overestimate heat gain under hazy conditions.

$\varphi_{sn} = 0.94*\varphi sc*(1-0.65*C\hat{}2)$

where:

φsc	depends on latitude and time of year. It is averaged over the day and typical values at about 37º latitude (Wairakei) range from 140-W/m^2 in winter to 350-W/m^2 in mid-summer.
C	the fraction of cloud cover.

Atmospheric radiation

Atmospheric radiation uses a correlation from Brunt (1932) that was recalibrated and verified by Hatfield et al in 1984.

φ_{an}=2.69E9*(1+1.29*$\sqrt{e_a}$)*(1.8T_a+492)^4*(1+0.17*C^2)

where:

e_a	vapour pressure [mbar].
T_a	air temperature [ºC]

(both measured at two metres above the water surface).

Back radiation

Back radiation is proportional to the fourth power of the absolute water temperature:

$\varphi br = 5.5e\text{-}8*(T_s+273)\hat{}4$

T_s is the temperature of the water surface [ºC].

This is the same equation in Ryan, Harleman and Stolzenbach.

Evaporation

Shanahan comments that calculation of evaporation is the most uncertain of the five components. Evaporative heat loss is directly proportional to the rate of evaporative water loss:

$\varphi e = \rho * L_v * E$

where:
ρ water density [kg/m^3]
L_v latent heat of evaporation [J/kg]
E evaporation rate [m/s].

Shanahan further notes that there is an extensive literature relating to calculations of evaporative loss. The general form of equation is:

$E = F(W)*(es\text{–}ea)$

Where:
F(W) some function of wind speed (2-m above surface)
es saturation vapour pressure of air [mbar]
(at the water surface temperature)
ea vapour pressure of the air (2-m above surface).

The two equations can be combined to give:

$\varphi e = f(W)*(es\text{–}ea)$

where
$f(W) = \rho * L_{v*} F(W)$

Both ρ and L_v are functions of the water temperature, although Shanahan notes that they are often taken as being constant. The error over normal environmental ranges would be small, but it would be larger for high temperature ponds.

There are many correlations for the wind speed function, usually of the form:

$f(W) = a+b*W$

Where a and b are constants.

The preceding analysis is very similar to Ryan et al, who comment that the best database for this form is the Lake Hefner formula, and that it performed well at Lake Mead, Lake Eucumbene in Australia and that a very similar form was derived for a study of Russian lakes.

Shanahan also confirmed that a commonly used equation is known as the Lake Hefner equation; it is recommended for natural conditions, that is not artificially heated. It is:

$f(W) = 17*W_2$

Where W_2 is the wind speed at 2-m above the water surface (this equation is in English units, despite the “2-m”).

Ryan et al (1974) refer to a formula for artificially heated water surface from a study of ponds in Texas and Louisiana (Brady et al 1969) that is of the form:

$f(Wz) = a+b*W_z^2$

They then compare the two forms with measured data from Brady, Lake Hefner and Hazelwood, Australia. Both formulae consistently underestimate the heat loss. Ryan et al note that Harbeck (1962) had concluded that the constant b is weakly correlated to lake area; a modification that improves the match, but that the predicted heat loss is still too low. They then go on to add in the effect of evaporation by free convection, firstly giving the theoretical basis. Refer to notes on Conduction, below.

For artificially heated conditions Helfrich et al (1982) recalibrated various evaporation correlations using field data from several cooling ponds. Shanahan does not record the temperatures of these ponds, but it is likely that these were less than 40ºC. Consequently the calibrations would be of doubtful use at higher temperatures. Helfrich recommends the Ryan and Harleman equation:

$f(W) = 2.12*\Delta\theta v^{1/3}+2.44*W_2$

The uncalibrated equivalent is:

$f(W) = 2.68*\Delta\theta v^{1/3}+3.08*W_2$

Where:
$\Delta\theta v$ is the difference between the “virtual air temperature” at the water surface and in the air 2-m above the water surface [ºC]. (It is required to account for the buoyancy of the moist air above the water surface).
The “virtual air temperature” is defined as the temperature of dry air with the same density as moist air. Ryan and Harleman define it as:

$\theta v = (T+460)/(1+0.378*e/p)-460$ (in English units)

where:
T air temperature [ºF]
e air vapour pressure [mm Hg]
p atmospheric pressure [mm Hg]

In metric units the equivalent (not given by Shanahan) is:

$\theta v = (T+273)/(1+0.378*e/p)-273$

Where T is in ºC
e and p are in mbar.

This has the effect of increasing the wind effect with increasing temperature, but only by a small amount. Over about 60ºC the wind function decreases again as the density of the water laden warm air approaches the density of cold dry air. At temperatures over 90ºC it decreases to zero, implying that there is no evaporation at these temperatures: intuitively this is incorrect.

This modification is particularly important in hot pools, where the buoyancy created by the hot surface will have a significant effect on evaporation rates and hence heat loss. Some correlations, such as the Lake Hefner equation, show that evaporation is zero under still conditions. This is clearly not the case for hot or even warm ponds.

Another correlation recommended by Helfrich, after he recalibrated it, for natural ponds is the Meyer function:

$f(W) = 68+8.5*W_2$ (in English units)

In metric units this is:

$f(W) = 6.68+1.87*W_2$

It can be seen that this does not specifically allow for the buoyancy of air over a warm pond, but it does have a constant function so allows for some evaporation at zero wind speed. It gives quite similar results to the Ryan and Harleman function, except that it does not reduce at very high temperatures.

Helfrich records two other wind speed correlations used for warm pools, Rimsha and Donchenko (1957) and Throne (1951). Rimsha and Donchenko include a factor with the difference in temperature between the water and air:

$f(W) = 61+1.47*(Ts–Ta)+13.3*W_2$ (In English units)

These constants are not recalibrated by Helfrich. In metric units:

$f(W) = 5.99+0.260*(Ts–Ta)+2.92*W_2$

The Rimsha and Donchenko function is significantly larger than the R&H function: about 50% higher at 20ºC and over three times as great at 90ºC.

The Throne correlation is in the same form as the Meyer function but the wind speed constant is over eight times greater. It was not recalibrated by Helfrich, presumably if it had been it would have been similar to the re-calibrated Meyer function. This illustrates the wide variation in calculated heat losses. The un-recalibrated Throne function is:

$f(W) = 67+7.1*W_2$ (in English units)

The appropriate wind function is then used to calculate the evaporative heat loss. Including the latent heat of evaporation gives the evaporative heat loss as:

$\varphi e = (L/2466)*f(W)*(es–ea)$

Where 2466 is the latent heat at 15ºC (60ºF), the assumed constant value used by Ryan and Harleman. Either the R & H or the Meyer wind functions can be used. As the two correlations give similar results over most of the temperature range, but the R & H function drops to zero at very high temperatures, the Meyer function is the more realistic.

Conduction

Shanahan notes that, as conduction is driven by a similar heat diffusion process to the moisture diffusion that drives evaporation, then the equations will be of a similar form:

$\varphi_c = k*f(W)*(Ts–Ta)$

Where k is a constant, = 0.255 in English units. In metric units the equation is:

$\varphi_c = 0.61*f(W)*(Ts–Ta)$

Ryan, Harleman and Stolzenbach use the same assumption, but attribute it to Bowen (1926) and write the equation as:

$\varphi_c / \varphi_e = C*((Ts–Ta)/(es–ez))$

Where:
C a constant, = 0.61 [bar.ºC] or 0.26 [mm Hg. ºF];
es saturation vapour pressure of water at temp. Ts
ez vapour pressure of air at 2-m height and temp. Ta.

The theoretical basis for φ_e is given:

$\varphi_e = \lambda*((Tsv–Tav)^{1/3}*(es–ez))$

Where λ is a constant.

Tsv and Tav are the virtual water and air temperatures. The authors report that the formula gave excellent evaporation predictions when correlated with laboratory work on a heated 1.1-m by 1.1-m tank and a 7-m by 12-m basin. They observe that the correlation fails for the small tank for small virtual temperature differences (about 5ºC).

Other Correlations

Aeration Basin Heat Loss: Talati and Stenstrom

Talati calculates heat balances for aeration basins; the calculation determines evaporative heat loss separately using a method attributed to Novotny and Krenkel (1973). No specific limits are put on applicability. However, the method is likely to be incorrect for warm or hot pools as there is no allowance for increased evaporation and heat transfer from buoyancy induced by the warmer water. In particular, the evaporation is zero for still conditions.

Sludge Pond Heat Loss: Makinia et al

Makinia correlates heat transfer and heat loss in sludge ponds. Although the form of the heat loss equations used is universal, his temperature range of interest is very limited – the effluent temperature range is between 19 and 20ºC.

Ryan, Harleman and Stolzenbach

Ryan, Harleman and Stolzenbach's paper presents a technique for evaluating the contribution of free convection to evaporation, in contrast to forced or wind-driven evaporation. The paper summarises the means of heat loss or gain and draws on earlier work by Ryan and Harleman, as referenced by Shanahan.

Weisman and Brutsaert

Weisman and Brutsaert's paper presents a numerical solution for evaporation over long reaches (more than 100-m) over periods of a few weeks or more, where atmospheric conditions will average to near neutral. It is not therefore useful for the relatively small ponds and short time frames reviewed here.

WATER LOSS RATES

Water will evaporate from the pond: the rate will depend on the pond water temperature and on ambient air temperature, humidity and wind speed.

As with calculations of heat loss, there are several evaporation loss correlations available. And as with the heat loss correlations, particularly those for irrigation channels or reservoirs, these were derived in relatively arid climates, hence evaporation loss is greater than in temperate climates like Taupo. For example, one such correlation has a base evaporation loss of 3-mm per day – considerably greater than the average evaporation expected here.

An alternative to a direct evaporation loss calculation is to back calculate from known heat loss. If the evaporative heat loss is known, then the evaporation rate can be calculated assuming all the heat has gone into evaporating water, knowing the latent heat of evaporation. However, unless the split between evaporative heat loss and conductive and radiant heat loss is known the evaporation determined as described will be an upper bound.

Shanahan and Lund give direct calculations for evaporative water loss. Shanahan gives separate correlations for the various heat flow components, as described above.

Lund notes that evaporative heat loss is typically 50 to 60% of the total heat loss for pools, in a temperature range up to about 40ºC. However, it appears that Lund is only considering heat losses, not radiant or conductive gains. Lund considers recreational pools hence evaporation depends on an activity factor, relating to the amount of splashing and the wetted area of adjacent surfaces.

Calculated evaporation loss rates, for different water temperatures, are given in **Figure 4**.

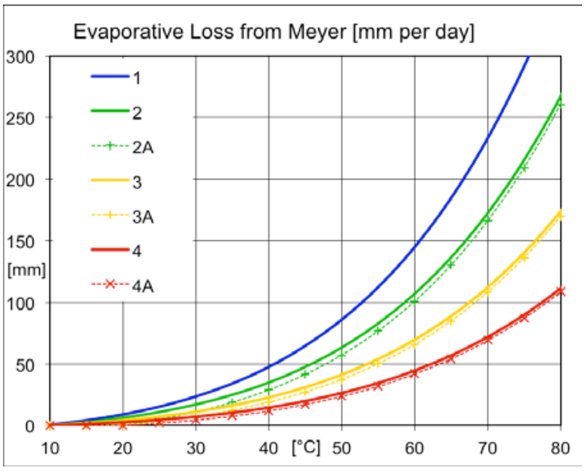

Figure 4: Evaporation Loss Rates

The parameters for the curves shown are:

Curve number	wind speed [m/s]	air temp. [°C]	vapour press. [m-bar]
1	8	5	12
2	5	10	12
2A	5	20	23
3	2	10	12
3A	2	20	23
4	0	10	12
4A	0	20	23

It can be seen that the critical factors are the water temperature and the wind speed; other environmental factors such as air temperature and humidity have less effect.

EXPERIMENTAL WORK

Well Testing Ponds in The Tauhara Geothermal Field

Two test ponds were constructed, referred to as the TH2 and the TH6 ponds. There were constructed in natural ground and lined with a bentonite filled geotextile to reduce leakage. Each pond was approximately rectangular with side slopes of 3 horizontal to 1 vertical, accordingly the ratio of surface area to pond volume varied according to the depth of water in the pond.

The TH2 pond base dimensions are nominally 15-m by 10-m, with a maximum depth of 3.2-m, giving a maximum nominal volume of about 1,800-m^3. The TH6 pond base dimensions are nominally 40-m by 20-m, with a maximum depth of 2.6-m giving a maximum nominal volume of about 3,600-m^3.

Temperatures were measured in the ponds after discharge testing to determine the rate of cooling and to compare it with theoretical cooling rates. The cooling rate and consequently temperature drop will vary with pond depth: shallower ponds will have a greater surface area compared to the heat content of the pond, so will cool more rapidly. The measured temperature drops confirmed this.

Theoretical and measured temperatures for the TH6 pond are shown in **Figure 5** and for the TH2 pond in **Figure 6**. Note that as the TH2 pond had approximately 1.4-m of cold rainwater in it at the time the discharge test was carried out, the time from the "start of the test" has been adjusted to give a best match with the "2-m deep" curve. The same heat loss versus pond temperature correlation was used as had been used for the TH6 pond.

Meteorological conditions varied through the tests, although being winter, air temperatures were generally low. Wind speed varied from near still conditions to moderate breezes. No allowance has been made for the varying weather conditions in calculating the theoretical heat loss. Varying weather conditions may account for the variation of the measured from theoretical temperatures. Because environmental factors have been excluded, the heat losses at temperatures below 30 or 40°C are likely to be incorrect.

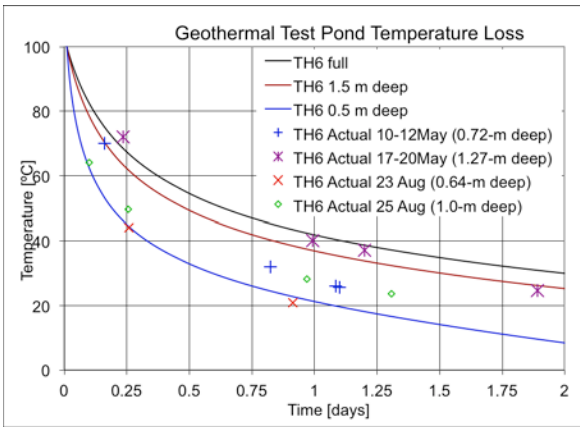

Figure 5: TH6 Test Pond Temperature Drop

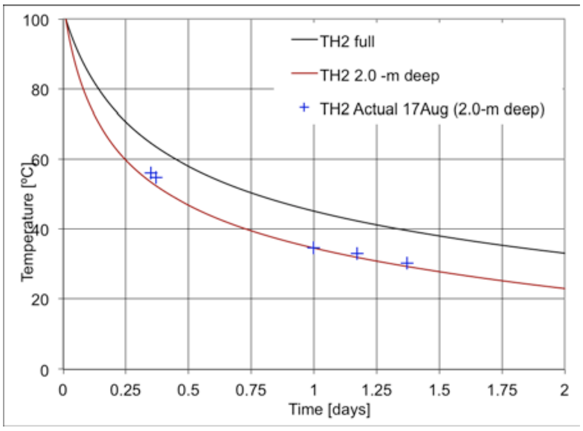

Figure 6: TH2 Test Pond Temperature Drop

The test results indicate that the shape of the measured curves generally follows the theoretical curves. However, insufficient readings were taken, particularly at the early stages and very high temperatures. The Dawson correlation is unlikely to be accurate below about 40°C, where other environmental factors dominate; very few data points were above these temperatures.

The data gathered from the TH2 and TH6 ponds is inadequate to accurately confirm evaporation loss correlations, however, it appears that evaporative losses are in the range of those predicted by Lund or Shanahan. Losses at moderate temperatures are high: predictions are of the order of 100 to 150-mm per day for temperatures around 50 to 60ºC. Measured losses, including leakage, when the ponds were first filled and were around these temperatures were up to 190-mm/day.

Separated Water Holding Ponds in the Ohaaki Geothermal Field

Observations were made in the Ohaaki West and East Holding ponds with the close assistance of Contact Energy; water was discharged into the ponds at different times to enable data to be gathered. A meteorological station was set up by GNS beside the East Pond and a number of temperature probes were installed in the Pond. These were logged automatically with data being downloaded every few weeks. Contact Energy provided the station records of discharges to and from the pond, and records of the pond water levels.

Three button dataloggers were attached to floats set out on a line strung across the pond to measure surface temperature. Two sets of three were mounted on 6-m poles laid down the pond side to measure temperatures at two different depths with one floating, and at different points around the pond to get an idea of the lateral temperature distribution. Another was set up at the inlet to measure the inlet temperature. Of course when the pond is low, some loggers were above water level so gave irrelevant readings.

The experiment did not achieve the required outcomes, as temperatures in the pond were too low to calibrate the high end of correlations.

A further experiment was attempted in the channel leading to the holding pond. The channel comprises sections of shallow channel about 2-m wide, some culverts and a pond about 42-m long and 17-m wide. Dataloggers were set up at various points along the channel and in the small pond.

The measurement concept was different from the pond measurements: in that case heat loss was determined by measuring temperature drop from an initial temperature in the one mass of water. In the channel the temperature was measured at points down the channel. As the heat rate (energy/time) lost between successive points down the channel is the mass flow rate times the temperature difference, the heat loss can be calculated directly.

The match of modelled to actual results was not convincing, possibly because of the varying channel geometry and the effect of the culverts. Another problem is that the channel is no longer a large pond so heat loss patterns will be different.

Cooling Channel

A cooling channel was set up to cool water from a geothermal well before disposal. As with the Ohaaki channel, dataloggers were set up at stations along the channel and the temperatures were correlated with flow down the channel. Temperature data are shown for one flow in Figure 7. It can be seen that the temperatures reached a steady state reasonably rapidly, so the data could be used to check heat losses. (In the first part of the trial the flow had been diverted into Pond 1 so missing the section of channel immediately upstream of Pond 2).

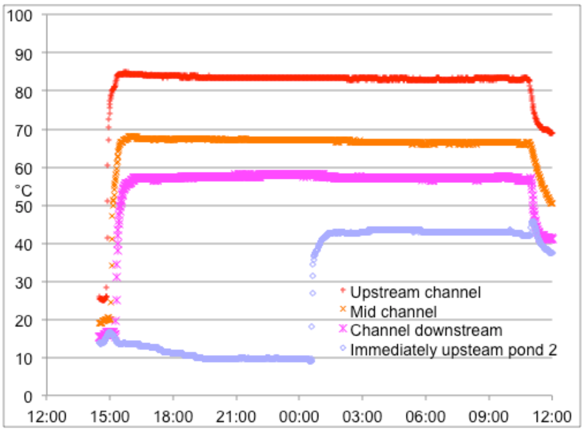

Figure 7: Well test cooling channel temperatures

The theoretical temperature drops for the various lengths down the channel were calculated using the formula based on the Dawson experimental data. These are plotted in Figure 8, along with measured temperatures. The correlation was reasonable, possibly over-estimating heat loss. However, further trials at different flow rates would be necessary to confirm the suitability of the formula.

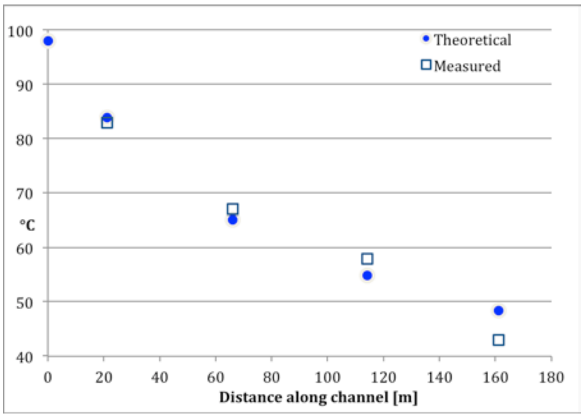

Figure 8: Heat loss along cooling channel

As noted above, during the first part of the trial, the water was diverted into Pond 1; for the second part, not all the water was directed to Pond 2. This may explain the discrepancy for the last point in the channel: the theoretical heat losses were calculated assuming that all the flow continued through to Pond 2; if the flow were lower the temperature drop would have been higher so bringing the theoretical temperature closer to that measured.

Wairakei Separated Water Holding Pond

Contact Energy constructed a large (80,000-m^3) separated water holding pond in the East Wairakei Steamfield. The pond is intended to hold separated water when reinjection fails, so that the station can continue to generate until the reinjection system is repaired.

The pond is lined with a composite system, with HDPE lining being used on the sides. The manufacturer's recommended maximum temperature for this material is 60°C. The material loses strength at higher temperatures. Dataloggers were set up at various points around the pond and at the inlet and outlets to determine maximum temperatures The data showed that pond temperatures were generally less than 60°C, with slightly higher temperatures only for a short period during initial stages of pond filling.

Good calibration data was not obtained, as the size and shape of the pond meant that significant cooling occurred as the pond floor was first covered and while the pond was relatively shallow.

Tauhara Te Huka Power Station Holding Pond

Contact Energy constructed a 4,000-m^3 separated water holding pond for the Te Huka Power Station in the Tauhara field. The pond holds separated water discharged at station start up and shut down; the water is then pumped into the reinjection system. Temperatures were measured at various points during station commissioning, the main purpose being to determine the likely range of temperatures at the suction of the discharge pumps: the pump discharge line had a relatively low maximum temperature-pressure rating.

Good correlations for heat loss could not be obtained as the commissioning resulted in discharges of varying length and flow rate. Consequently it was difficult to isolate satisfactory heat loss data. The maximum temperature recorded near the water inlet was about 75°C; the maximum temperature at the pump suction, at the opposite end of the pond on the invert, was just over 40°C.

CONCLUSION

The commonly used correlations for cooling ponds and bathing pools do not extrapolate well for high temperature ponds. For high temperature heat losses environmental factors are less significant than for the lower temperature ponds. A correlation developed by Dawson in 1964 appears to match observed cooling of high temperature ponds and channels. This correlation depends only on the temperature of the water body. It is only likely to be useful above about 40°C.

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