Indian J. Met. Hydrol. Geophys. (1977), **28**, 4, 459-464

556·552 : 536·2 : 621·311

Dissipation of heat from cooling ponds

R. S. D'SOUZA and T. P. SARMA

Bhabha Atomic Research Centre, Bombay

(*Received 20 May 1976*)

ABSTRACT. A mathematical model is proposed for the planning of cooling ponds used for dissipation of waste heat from heated discharge waters of Power Generating Stations. This dissipation of waste heat is found to be mainly dependent on wind speed and water temperature, negligibly influenced by air temperature and humidity and is independent of solar radiation. The model's special application is where the water resources are limited and need for recycling of water used for cooling the condenser waters of the power station is necessary. The models show that the acreage requirements of the cooling ponds of such types of the order of 1·0 to 2·5 acres/Mw (e) during the hotter months at Bombay. Data was also collected at Tarapur Atomic Power Station's discharge channel and the model calculations compared well with the actual temperature fall in the channel observed during low tide.

1. Introduction

The increasing demand for electricity has necessitated a proper evaluation and study of condenser cooling water sources to which rejected heat from Power Stations is added for ultimate dissipation. The advent of nuclear energy has permitted greater emphasis on nuclear power stations, which have their advantages over limiting resources of hydro and fossil fuel power stations. In nuclear power stations much more condenser cooling water is used compared to fossil fuelplants. Hauser (1971) has estimated annual heat rejection of magnitude 10×10^{15} calories for nuclear power plants, in U.S.A., a prime producer of electricity, by the year 2000, compared to 2×10^{15} calories by fossil fuel plants, which would have tapered off and decreased by that year. He has also indicated the several methods of supplying cooling water to condensers that are in use today and listed them by order of preference from operating and experience point of view :

(1) Once through Fresh Water Cooling ;

(2) Cooling Ponds and Reservoirs ;

(3) Coastal seawaters;

(4) Evaporative Cooling Towers ; and

(5) Non-Evaporative Dry Types of Cooling Towers.

Considerable interest is shown for cooling ponds because of its possible economic favourability and as well as the public awareness for cleaner environment. There are two types of cooling ponds which are used for dissipating waste heat. In one type the cooling pond is used for dissipating heat before it is permitted to flow into the lakes and rivers from which the water is drawn, thereby reducing the thermal effects on the environment. In the second type, the condenser discharge waters are allowed to dissipate heat in the cooling ponds and the cooled waters are again used for condenser cooling. Several mathematical and physical models have been developed to study the heat exchange across the water surface, both due to natural conditions and man's activity. Some of them pertinent to this study are those of Harbeck *et al.* (1959), Harbeck (1964), Federal Water Control Administration (1968), Parker and Krenkel (1969), Jobson (1971, 1975), etc. In the present model, an attempt has been made to estimate the excess temperature that would develop above the natural water temperature in the cooling pond due to recycling of heated waters, discharged at one end and taken into the station at the other end after natural cooling, and thereby also to estimate the minimum area required for the cooling pond for representative meteorological conditions in any particular region. However additional arrangements will have to be made for makeup requirements of waters lost due to evaporation in this kind of set-up. Corrollary to the model is, one can plan the size of the cooling pond, taking into consideration the maximum temperature the heated waters can have at the discharge point of the station taking into account the design of the condenser system.

2. Theoretical Model

The physical processes that are involved in the surface heat exchange in a cooling pond are radiation, evaporation, conduction and advection. The excess temperature above the natural water temperature, that would develop in a cooling pond having recycling water system, would solely depend on the heat discharge of the power station, and would be independent of the heat content due to natural conditions prevalent there. The transfer of heat in and out of natural water bodies has been studied exhaustively and appears in any relevant text books. The factors that govern the heat content of the cooling pond are : Q_s, the net heat flux due to incoming radiation of sun and sky after taking into consideration the reflection from the water surface and cloud cover ; Q_a, the net heat flux due to long wave radiation from the atmosphere ; Q_b, the net heat flux of long wave radiation emitted out of the water ; Q_e, the heat loss due to evaporation ; Q_{ea}, the heat advected from the water body by the evaporated water vapour ; Q_c, the heat loss due to conduction-convection of sensible heat ; Q_{bcs}, the heat due to biological, chemical processes and from the sediments ; Q_M, the heat radiated from the surrounding mountains, if any.

If H is defined as the heat content per surface area of the pond (cal cm^{-2}), then the change of heat content across the unit surface is given by

$$\frac{dH}{dt} = Q_s + Q_a(T_a) - Q_b(T_w) - Q_e(T_w) - Q_c(T_w) - Q_{ea}(T_w) - Q_{bcs} + Q_M \quad (1)$$

where T_w=water temperature of the cooling pond

T_a =air temperature

Generally Q_{ea} is neglected, since it is ordinarily small and is difficult to estimate (Hutchinson 1957). Two estimates of Q_{ea} by Anderson (1952) and Neumann (1953) show this value to be less than $1 \cdot 5$ per cent of Q_e.

The total heat content per unit surface area of pond H, can be expressed as the sum of the natural and man-induced processes, H_N and H_M respectively. Therefore we have

$$\frac{dH_n}{dt} = Q_s + Q_a(T_a) - Q_b(T_0) - Q_e(T_0) - Q_{ea}(T_0) - Q_c(T_0) - Q_{bcs} + Q_M \quad (2)$$

where, T_0=normal water temperature.

Subtracting Eq. (2) from Eq. (1) and neglecting Q_{ea} terms, we obtain

$$\left.\frac{dH_m}{dt}\right) = - Q_b(T_w) + Q_b(T_0) - Q_c(T_w) + Q_c(T_0) - Q_e(T_w) + Q_e(T_0) \quad (3)$$

The black body radiation from the water surface after correcting for reflection is given by (Hutchinson 1957).

$$Q_b(T_w) = \sigma\, 0.97 T_w^4 \quad (4)$$

$$Q_b(T_0) = \sigma\, 0.97 T_0^4 \quad (5)$$

where, $\sigma = 8 \cdot 244 \times 10^{-11}$ (cal cm^{-2} min^{-1} deg^{-4}); Stefan Boltzman constant.

The ratio of evaporation heat losses to sensible heat loss was first given by Bowen (1926) and is widely used in calculating the sensible heat term in the energy budget studies of water bodies.

$$Q_c = \gamma\, Q_e$$

where, $\gamma = \dfrac{0.64(T_w - T_a)}{(e_{Tw} - e_a)}$ (Bowen's ratio)

e_{Tw}=saturated vapour pressure of water at temperature T_w

e_a = vapor pressure of water in air at air temperature T_a

Another widely used empirical relationship is for Q_e, the heat loss due to evaporation and is given for lakes by Johnsson (1946)

$$Q_e = 0.018 L(e_{Tw} - e_a) U^{0.8} \text{ (cal cm}^{-2}\text{ day}^{-1})$$

where, $L = 734 \cdot 1 - 0 \cdot 51 T_w$ (latent heat of evaporation at T_w)

U= wind speed measured 6 m above lake surface in metres per second.

Therefore we obtain

$$Q_c(T_w) + Q_e(T_w) = 1.247 \times 10^{-5} U^{0.8} (734.1 - 0.51 T_w) \times [e_{Tw} - e_a + 0.64(T_w - T_a)] \text{ (cal cm}^{-2}\text{ min}^{-1}) \quad (6)$$

$$Q_c(T_0) + Q_e(T_0) = 1.247 \times 10^{-5} U^{0.8} (734 \cdot 1 - 0.51 T_0) \times [e_{T0} - e_a + 0.64 (T_0 - T_a)] \text{ (cal cm}^{-2}\text{ min}^{-1}) \quad (7)$$

Using Classius-Clapyeron equation for the change of saturated vapour pressure with temperature and approximating it by taking the first three terms of the expansion of the power series, we have

$$e_{T_w} = e_{T_0} (1 + \alpha T_e + \alpha^2 T_e^2/2) \quad (8)$$

where, $T_e = T_w - T_0$

$\alpha = 18(734.1 - 0.51\, T_o)/R T_o^2$

e_{T_0} = saturated vapour pressure at T_0

$R T_0 T_w \approx R T_0^2$

The error introduced by the above approximations is found to be not more than one percent, Substituting Eq. (8) in Eq. (6) and then substituting Eqs. (4), (5), (6) and (7) in Eq. (3) and approximating $(T_e + T_0)^4 = T_0^4 + 4T_0^3 T_e$, we obtain:

$$\left(\frac{dH_m}{dt}\right) = 3\cdot 19867\times10^{-10}\, T_0^3 . T_e + K_3(0.64\, T_e + \alpha e_{T0} . T_e + \alpha^2 e_{T0} . T_e^2/2) - K_4 . T_e\, [0.64\, (T_0 + \alpha\, T_e - T_a) - e_a + e_{T0}\, (1 + \alpha T_e + \alpha^2 T_e^2/2)\,] \tag{9}$$

where, $K_3 = 1.247\times10^{-5}\,(734.1 - 0.51T_0).U^{0\cdot8}$

$K_4 = 0.51\times1\cdot274\times10^{-5}\, U^{0\cdot8}$

Letting

$$B_1 = 3.19867\times10^{-10}\, T_o^3 + K_3\,(0.64 + \alpha\, e_{T0}) - K_4[\,0.64\,(T_o - T_a) + e_{T0} - e_a\,]$$

$$B_2 = K_3 e_{T_o}\, \alpha^2/2 - K_4\,(0.64 + \alpha e_{T_o})$$

$$B_3 = -K_4 e_{T_o}\, \alpha^2/2$$

then Eq. (a) is a differential equation of the form.

$$\left(\frac{dH_m}{dt}\right) = T_e\,(\,B_1 + B_2 T_e + B_3 T_e^2\,) \tag{10}$$

For a well mixed pond, one can write

$$\left(\frac{dH_m}{dt}\right) = \frac{\rho c_p P a}{b}\left(\frac{dT_e}{dx}\right) \tag{11}$$

where,
ρ=density of water

c_p=specific heat of water

p=electrical power of the station

$a=r/p$

r=condenser flow rate

b=breadth of the channel

x=distance from the discharge point

If AR is defined as the cooling pond area per unit power of the station and τ as the temperature gained by the cooling water in the station and ϵ as the excess temperature at the intake point over natural temperature, then substituting the R.H.S. of Eq. (11) for dH_m/dt in Eq. (10) and integrating we obtain AR

$$AR = \frac{\rho c_p a}{2B_1}\ln\left|\frac{(\tau+\epsilon)^2\,(\,B_1 + B_2\epsilon + B_3\epsilon^2\,)}{[B_1 + B_2\,(\tau+\epsilon) + B_3(\tau+\epsilon)^2]\epsilon^2}\right| + \frac{\rho c_p a B_2}{2B_1 W_1}\ln\left|\frac{(W_2 - W_1)\,(2B_3\tau + W_2 + W_1)}{(W_2 + W_1)(2B_3\tau + W_2 - W_1)}\right| \tag{12}$$

where,

$$W_1 = (\,B_2^2 - 4B_1 B_3\,)^{\frac{1}{2}}$$

$$W_2 = B_2 + 2B_3\epsilon$$

If in the final Eq. (10), $B_3 T_e^3$ term is neglected then we obtain a more simplified solution

$$AR = \frac{\rho c_p a}{B_1}\ln\left|\frac{W_3\,(\,\tau+\epsilon\,)}{(\,W_3 + B_2 \tau\,)\epsilon}\right| \tag{13}$$

where,

$$W_3 = B_1 + B_2\,\epsilon$$

Finally, solving Eq. (13) for ϵ, we obtain

$$\epsilon = \frac{-\,(\,B_1 + B_2\,\tau)\left[(B_1 + B_2\,\tau)^2 + \dfrac{4B_1 B_2\,\tau}{K_5 - 1}\right]^{\frac{1}{2}}}{2B_2}$$

where,

$$K_5 = \exp\left[\frac{AR.B_1}{\rho\, c_p\, a}\right]$$

3. Results and Discussions

In order to arrive at the effects of the various parameters used in the model, computations are made using BESM-6, varying one parameter and keeping other parameters constant. Further, for given set of values, we have calculated cooling pond acreage requirements, using Eqs. (12) and (13) and these are given in Table 1. It is found that the values are agreeing within $0\cdot1$ per cent (Table 1). As such the simplified Eq. (13) can be used for all practical purposes. The effects of wind speed on the cooling pond acreage are calculated, keeping others parameters constant. The results are given in Fig. 1. It is seen from this figure, wind speeds more than 4 m/sec give acreages less than $2\cdot0$ acres/Mw(e). This is expected, as higher wind speeds lead to higher evaporation rates, thereby increasing the disipation of heat. The effect of humidity and air temperature are studied and these have been found to have negligible effect on the overall cooling. On the other hand higher water temperatures do have some influence on heat dissipation though much less than wind speeds (Fig. 1). Hence, the model shows that wind speed and water temperature do influence the dissipation of heat from the cooling pond whilst humidity and air temperature have negligible influence. These observations are in conformity with the conclusions arrived by Jobson (1971) in his study of dissipation of heat from water surfaces.

TABLE 1

Cooling pond areas by Eqs. (12) and (13)

Time hr. min)	T_o (°C)	Ta (°C)	U (m/sec)	Humidity (%)	Cooling Pond Acreage acre/Mw(e) by Eq (12)	Eq (13)
0800	27·6	27·6	2·92	79·0	1·1087	1·1069
0930	29·2	30·5	4·17	76·0	0·9850	0·9837
1215	32·4	30·8	2·57	63·0	2·0155	2·0143
1350	33·2	32·5	2·85	66·0	2·1719	2·1709
1600	32·3	29·0	2·71	66·0	1.9152	1.9140
1800	32·3	28·0	2·01	76·0	2.3317	2·3307
2000	31·1	25·5	2.15	91.0	1.8653	1.8637
2200	30·5	24·1	1.00	91.0	2.8049	2.8026
2400	30·0	25·7	5·97	83·0	0.8242	0·8232
0200	29.6	25·8	3·96	83.0	1.0618	1·0605
0400	22.0	24·5	2.36	86.0	1.4301	1.4283
0600	28·7	25·5	2.36	86.0	1·3932	1·3913

Limiting discharge water temperature 110°F (43·3°C)

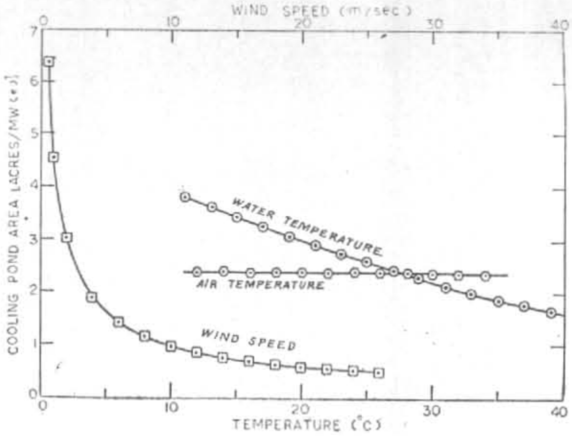

Fig. 1. Effect of the various physical parameters on cooling pond area

TABLE 2

Physical parameters measured at the cooling pond at different times

(a) 7 March 1975

Time (hr-min)	23-20	01-30	03-30	05-30	07-20	09-20	11-25	13-20	15-20	17-20	19-15	21-15
T_o °C)	24·50	23·50	23·00	23·00	22·00	24·00	25·20	27·40	29·70	27·70	25·20	25·20
Ta (°C)	20·80	21·60	19·60	18·40	18·30	24·90	28·00	31·00	26·80	25·30	24·50	23·00
Wind speed (m/sec)	12·22	8·33	3·33	5·21	5·42	4·31	5·42	3·33	7·15	9·03	8·13	0·83
Humidity (%)	72·00	85·00	91·00	93·00	91·00	66·00	62·00	48·00	61·00	57·00	59·00	62·00

(b) 26 March 1975

Time (hr-min)	00-00	20-10	04-30	06-10	07-55	09-45	12-10	14-30	16-15	18-15	20-125	21-15
T_o (°C)	22·30	21·60	21·50	20·80	20·90	23·30	25·40	28·20	27·00	24·50	24·00	22·50
Ta (°C)	28·50	18·70	17·70	18·70	22·60	26·50	32·30	31·70	29·80	26·50	23·50	21·00
Wind sped (m/sec)	1·76	3·33	4·79	4·38	2·26	3·06	1·94	2·71	2·64	6·88	7·08	2·43
Humidity (%)	51·00	51·00	42·00	33·00	36·00	26·00	12·00	15·00	31·50	36·50	49·50	51·00

(c) 30 April / 1 May 1975

Time (hr-min)	08-00	09-30	12-15	13-50	16-00	18-00	20-00	22-00	24-00	02-00	04-00	06-00
T_o °(C)	27·60	29·20	32·40	33·20	32·30	32·30	31·00	30·50	30·00	29·60	29·00	28·70
Ta (°C)	27·60	30·50	30·80	32·50	29·00	28·00	25·50	24·10	25·70	25·80	24·50	25·50
Wind speed (m/sec)	2·92	4·17	2·57	2·85	2·71	2·01	2·15	1·00	5·97	3·96	2·36	2·36
Humidity (%)	79·00	76·00	63·00	66·00	66·00	76·00	91·00	91·00	83·00	83·00	86·00	83·00

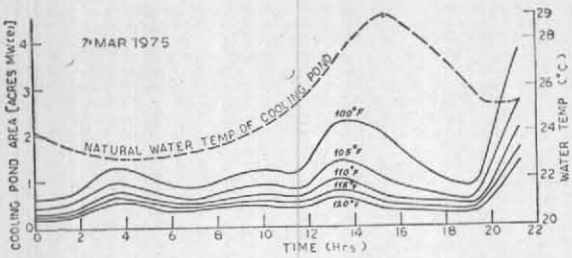

Fig. 2. 6/7 March 1975

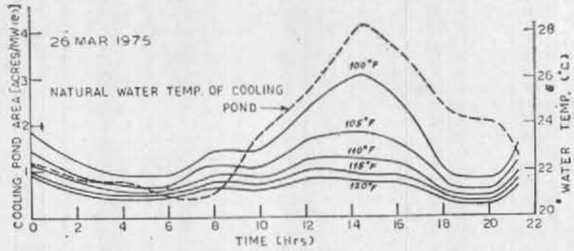

Fig. 3. 26 March 1975

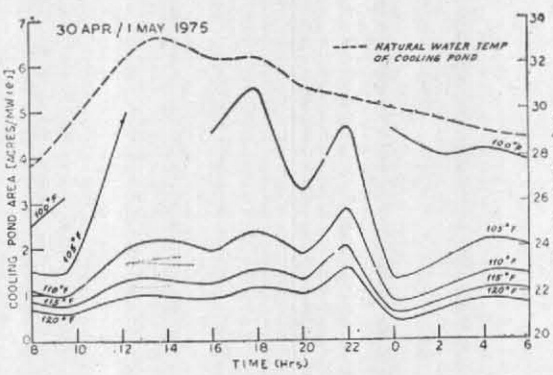

Fig. 4. 30 April/1 May 1975

Figs. 2-4. Cooling pond area requirements on limiting the temperature of discharged waters of the station

To illustrate the usefulness of the model measurements of air temperature, water temperature, wind speed and humidity (Table 2) are made at a pond of area approximately 1 acre situated at Trombay, Bombay, for 24 hours, at two-hour intervai on 7 March, 26 March and 30 April 1975. These months are chosen for measurements, because of higher water and air temperatures in these months in this region. The cooling pond requirements computed for this period are likely to be on the higher side compared to other times of the year. On these three days, Table 2 shows that the water temperature varies from 20·8° to 33·2°C ; air temperature from 18·3° to 32·3°C ; wind speed from 0·8 to 12·22 m/sec and humidity from 12.0 to 93·0 per cent. Further, whilst the water and air temperatures vary sinusoidally during the day, the maximum air temperature being two hours later than the maximum water temperature, the wind speed varies randomly during the day.

Having the above data in hand, computations are then made for the three days of cooling pond acreage requirements per megawatt electrical power with an added restriction that the discharge water temperature of the station should not exceed specified values of 100°F (37·8°C), 105°F (40·7°C), 110 °F (43·3°C) , 115°F (46·1°C) and 120°F (48·9°C). These values are plotted in Figs. 2, 3 and 4 for the different days. As seen from Fig. 2, on 7 March, if the discharge temperature is restricted to 110° the cooling pond area required does not exceed 1·0 acre/Mw(e), except for a two-hour duration when it exceeds 1·5 acre/Mw(e). On 26 March (Fig. 3) the calculations show that the acreage requirents did not exceed 1·25 acre/Mw(e). Whilst, on 30 April (Fig. 4), for more than 90 per cent of the time, 2·0 acre/Mw(e) is sufficient for 110°F discharge water temperature, whereas for the rest of the time it goes up to 2·5 acne/Mw(e). Further, the computations show that for higher water temperature and low wind speeds, the cooling pond area requirements are higher. This is because that for higher water temperature, the margin allowed for ϵ by the restriction of discharge water temperature is small requiring greater amount of dissipation of heat, whilst small wind speed lowered the losses of heat from cooling pond due to lower evaporation rate.

Finally, data was also collected of various parameters required for testing the reliability of the model at the discharge channel system of Tarapur Atomic Power Station. This station is situated on a minor promontory projecting into the Arabian Sea on the west coast of India, and uses once through seawater cooling system for its condensers. The seawater is drawn into an intake pool and after circulation in the station is discharged as heated water into a double discharge channel system having two channels running along the coast on either side of the intake pool. Each channel has length of 3300 ft and width of 53ft. Observations are made of the various parameters during the three low tides, when the mixing of incoming seawater in the discharge channel is minimum. During these low tides, a temperature fall of ·1° to ·2°C was noticed between the discharge point of the station and the discharge point of the channel into the sea for wind speeds varying from 7 to 15 m/sec. This is in quite good agreement with the predicted values of fall of ·15° to ·22°C by the model for the same wind speeds.

Acknowledgements

The authors are greatly indebted to Dr. A. K. Ganguly, Director, Chemical Group, Bhabha Atomic Research Centre for useful discussions and Shri S. D. Soman, Head, Health Physics Division for his keen interest.

REFERENCES

Anderson, E. R.	1952	U.S. Geog. Surv. Circ. Tech. Rep. **229**, p. 71.
Bowen, I. S.	1926	*Physical Review*, **27**, p. 785.
Federal Water Control Administration	1968	'Industrial Waste Guide on Thermal Pollution', U. S. Dep. of Interior, Pacific Northwest Water Laboratory, Corvallis, Oregon.
Harbeck, G.E. (Jr.), Koberg, G.E. and Hughes, G.H.	1959	U. S. Geol. Surv. Professional Paper, **272-B**, p. 7.
Harbeck, G. E. (Jr.)	1964	*J. Power Div. ASCE*, **90**, PO3, p. 1.
Hauser, L. G.	1971	*Ibid.*, **97**, PO1, p. 79.
Hutchinson, G. E.	1957	*Treatise on Limnology*, **1**, Chapman & Hall Ltd., London.
Jobson, H. E.	1971	*J. Power Div., ASCE*, **97**, PO1, p. 89
	1975	Proc. Symp. on Modelling Techniques, ASCE, San Francisco, Calif, Sep. 3-5, 1975, p. 729.
Johnsson, H.	1946	*Geogr. Ann., Stockholm*, **28**, p. 1.
Neumann, J.	1953	*Bull. Res. Coun.*, Israel, **2**, p. 71.
Parker, F. L. and Krenkel, P. A.	1969	'Thermal Pollution Status of the Art' Rep. No. 3, Dept. of Environment and Water Resources Engineering, Vanderbilt, Nashville, Tenn.