SELECTION OF ALTERNATIVE COASTAL LOCATIONS

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ABSTRACT

Factors of importance in power plant site selection for once - through cooling water systems situated on sea coasts are reviewed. Principles of recirculation management are indicated and briefly discussed in view of the implications of this approach on the environmental aspects of the problem. The need to recognize that the waste heat problem is not solved by prescribing zero recirculation is stressed.

INTRODUCTION

Selection of coastal sites for large power plants must consider the recirculation aspects as well as the possibility of environmental side effects.

All heat rejected from power plants is ultimately dissipated to the atmosphere which is achieved by raising the water temperatures above their natural ambient level over a substantial area. Hence, for a given site and heat load the excess temperature distribution can only to a limited extent be managed by engineering design.

Recirculation resulting from the rise of ambient temperature in the vicinity of the intake can be made subject to a rational management. Investments in marine installations should be adjusted, not necessarily to minimize recirculation, but to minimize the total cost of power loss due to recirculation and costs of marine installations.

An approach based on recirculation management principles does not appear to be in conflict with considerations with respect to the question of thermal impact on the acquatic environment at a given site.

MANAGEMENT PRINCIPLES

In general terms the objective of waste heat management is to minimize the sum of construction and plant operation costs and possible damages to the equatic invironment. Consequently a possible objective function is:

$$F = R + D + C \tag{1}$$

where R is the cost of a decreased plant efficiency due to recirculation, D is the cost of damages imposed on the environment, and C is the cost of construction of the marine installations of the cooling water system.

The term D is controversial and quantification in terms of money is elusive, if at all possible. Nevertheless this aspect of the waste heat problem plays a major role in plant site selection considerations. For power plants located at rivers this is understandable since waste heat disposal can cause temperature barriers, whereas it is less obvious for coastal locations where the influence of the waste heat disposal is of a local character.

Another characteristic feature of the term D is that there are strict limits as to the extent by which the environmental impact can be managed by the lay-out of the cooling water system for a given plant site and a given rate of heat rejection.

The term R which represents the power loss due to recirculation can be influenced to a great extent by a proper determination of the positioning of intake and outfall.

Recirculation Optimization

It appears worthwhile to consider the objective function

$$F = R + C \tag{2}$$

to investigate the consequences of this approach, and to raise the question of a possible conflict between a recirculation optimization and a total optimization (equation (1)).

This approach is clearly applicable to cooling ponds where environmental damages to the equatic environment need not be considered. With the numerical modeling techniques available today the elements necessary to perform a recirculation optimization are available.

Differentiation of the reduced objective function leads to the simple result that a total cost minimum is found when the marginal costs of decreasing the intake temperature equals the marginal cost of efficiency loss due to recirculation:

$$\frac{dR}{d\Delta Ti} = \frac{dC}{d\Delta Ti} \qquad (3)$$

where ΔTi is the water temperature above its natural equilibrium at the intake.

It should be noted that apart from the hydraulic complexity of the problem, a rigorous analysis is difficult to perform since the cost of efficiency loss can be evaluated in numerous ways. Furthermore, the effect of a certain degree of recirculation can to some extent be catered for in the design of the steam condensers. Regardless of the difficulties inherent in the problem it seems appropriate to perform an analysis of this type rather than to rely on arbitrary criteria with respect to the acceptable level of recirculation.

Note that the term recirculation designates indirect recirculation (intake located in the far-field). Direct passage of heated water from outfall to intake is assumed to be nonexistent.

PLANT SITE SELECTION

In principle, all terms in the objective function should be evaluated to provide a proper basis for a decision with respect to selection of potential sites. This in turn would require a full investigation of hydraulic and biological aspects at each site. However, a general knowledge with respect to flow patterns of the site is often sufficient as a basis for preliminary excess temperature field computations and subsequent evaluation of biological effects. In this way the various sites can be given priority, and a few be selected for detailed hydraulic and biological studies.

In the following, the main features of a site selection are discussed, and a sample computation of the optimum recirculation is given.

Total Energy Budget

The ultimate sink of waste heat is the atmosphere. Under equilibrium conditions, or as an average over a sufficiently long period of time, the total rate of heat dissipation over the influenced water surface area therefore must equal the rate of heat supply.

For simplicity the rate of additional heat loss which takes place to the atmosphere when the temperature is raised ΔT above its natural equilibrium is assumed to be given by:

$$H = f \, \Delta T \text{ Watt/m}^2 \qquad (4)$$

Conservation of energy requires that the surface rate of heat loss integrated over the entire excess temperature field equals the rate of heat supply:

$$Q \Delta T o \rho \, Cp = f \int_A \Delta T dA \qquad (5)$$

where Q is the cooling water discharge, ΔTo is the temperature increase over the condensers, ρ is the density of water and Cp is the specific heat.

Evidently, the magnitude of the integral in equation (5) is fixed for a given heat supply and completely independent of the currents , the mixing processes of the receiving water body and the mode of discharge. Furthermore, the integral is independent of the vertical distribution of the excess temperature. These factors only affect the shape of the temperature field. Thus, in discharge areas with a considerable tidal activity the excess temperature distribution will tend to attain a more uniform distribution that in areas where the natural energy available for the spreading is lower. The result will be that the excess temperatures in receiving waters with a high level of mixing in the vicinity of the outfall will be relatively low, whereas the excess temperatures further away will be relatively high. Thus, the area encircled by lines through equal low excess temperatures will increase with increasing tidal and mixing intensity of the receiving water.

It is worthwhile to note that the shape of the excess temperature field is determined to a very high extent by the ability of the tidal currents to yield an initial spreading of the source. This appears to be a factor of considerable importance as compared to the effect which can be obtained by a submerged diffuser.

If a high velocity surface jet is utilized the jet momentum can induce a current pattern which can be of considerable importance for the shape of the entire temperature field in situations where the tidal currents are weak.

Contrary to the distribution of the surface excess temperatures, the total amount of heat stored in the water depends on the transport and mixing characteristics of the receiving water as well as the mode of discharge. The heat storage is reduced by floating the heated water onto the receiving water. In this way the surface heat loss may not be significantly altered but the heat storage can be reduced considerably and temperature changes at the bottom of the receiving water avoided.

The Relevance of Initial Dilution

A considerable attention has previously been given to the question of the so-called near field, i.e. the zone in the vicinity of the outfall where outfall conditions significantly affect the temperature field. This is especially relevant for small discharges as far as evaluation of the risk of direct recirculation is concerned. However, for cooling water discharges from large power plants heat stored in the discharge area can easily attain a significant level whereby the entraining water is already heated.

The statement above especially applies to a situation in which the heated water is discharged through a diffuser in a receiving water characterized by an oscillating tidal flow. In this case discharge may take place over a diffuser length of a few hundred meters while the tidal current provides a spreading of the source equal to the tidal excursion which may be several kilometers. Furthermore, since the diffuser jets entrain water which is already heated the dilution obtained could be illusory.

If, on the other hand, the heated water is discharged as a horizontal surface jet with an initial velocity comparable to the tidal velocity the momentum of the jet will induce a circulation pattern which may have a considerable effect on the temperature distribution. The temperature field is then stretched in the direction of the jet and thus distorted as compared to the diffuser situation. However, regardless of the mode of discharge the surface heat loss integrated over the whole warm water surface remains the same.

Thermal regulations which prescribe maximum surface temperature differentials can on the grounds above be said to have little meaning for large cooling water discharges. In this connection it should be emphasized that this aspect is only to a limited extent manageable by the design of the intake and outfall structures.

In order to make reliable predictions of the temperature field in the vicinity of the outfall the practising engineer is faced with the problem of predicting the effect of the interaction between the near- and the far-field. A computation based on the assumption that water unaffected by the discharge is available for dilution will inevitably lead to erroneous results.

The Effect of Tidal Currents and Mass Injection

An idealized example in which heat is injected to a semi-infinite region of open and shallow water is considered. It is furthermore assumed that the excess temperature is uniformly distributed over the depth d. The effect of a tidal current becomes apparent when the water is considered to remain at rest and the heat source to move sinusoidally over the tidal excursion, J.M. Williams [1] . The heat can in this situation be assumed to take place over a line source with a distribution and a resulting excess temperature field shown in principle in Fig. 1.

An approximate solution with respect to the temperature distribution in the center line of the oscillating temperature field can be obtained by considering the one-dimensional conservation of heat equation:

$$\frac{d^2\Delta T}{dx^2} - \frac{Q}{edD}\frac{d\Delta T}{dx} - \frac{f}{dD\rho Cp}\Delta T = 0 \qquad (6)$$

where the symbols not previously defined are:

x is the coordinate in the direction perpendicular to the coast, D is the dispersion coefficient in the direction perpendicular to the coast and e is an equivalent tidal excursion.

Equation (6) ignores the effect of heat dispersion in the direction of the current, and will for this reason give conservative estimates of the excess temperatures. This will particularly be the case for the lowest excess temperatures. However, the longitudinal dispersion effect can to some extent be catered for by using a tidal excursion which is somewhat greater than the true excursion.

The soulution to equation (6) is:

$$\Delta T = \Delta Tm \exp (\alpha x) \qquad (7)$$

where

$$\alpha = \frac{1}{2} \frac{Q}{edD} \left[1 - \sqrt{1+4 \frac{fe^2 dD}{\rho C_p Q^2}} \right] \qquad (8)$$

and ΔTm is the maximum temperature along the coast subject to the condition that the total rate of heat dissipation is equal to the rate of supply:

$$\Delta Tm = \frac{Q\rho C p \alpha}{ef} \Delta To \qquad (9)$$

where ΔTo is the excess temperature at the point of discharge and Q is the cooling water flow.

For large cooling water discharges Q and a small tidal excursion equation (8) can be approximated by:

$$\alpha = \frac{fe}{\rho C_p Q} \qquad (10)$$

in which case equation (7) is modified to:

$$\Delta T = \Delta To \exp \left(- \frac{fe}{\rho C_p Q} x\right) \qquad (11)$$

For conditions normally encountered, the approximation used to derive equation (11) becomes good when the discharge exceeds 50-100 m^3/s corresponding to 1000-2000 MW nuclear power plants. Thus, for plants of this size the injection of mass becomes the dominating heat transport mechanism in the oscillating flow situation considered above. Note that equation (11) represents the solution to equation (6) when omitting the diffusive term.

Clearly, the idealized example above contains too many approximations to provide a proper basis for a determination of the positioning of intake and outfall. On the other hand, a useful insight with respect to orders of magnitude and parameter sensitivity can be gained with a very limited effort.

Another idealized example which is useful to consider refers to the situation in which heat is injected over a vertical line source in an infinite region of shallow water with horizontal and isotropic diffusion. The conservation of heat equation is in this case:

$$\frac{d^2\Delta T}{dr^2} + \left(1 - \frac{Q}{2\pi dD}\right) \frac{1}{r} \frac{d\Delta T}{dr} - \frac{f}{\rho C_p dD}\Delta T = 0 \qquad (12)$$

where r is the radial coordinate with origin at the source.

The solution to this general equation contains the modified Bessel function of second kind and of order $-\frac{1}{4}\frac{Q}{\pi dD}$.

For the special case when Q equals $2\pi dD$ the solution becomes:

$$\Delta T = \Delta To \exp \left(-\sqrt{\frac{f}{\rho CpdD}}\, r\right) \qquad (13)$$

For very large flows the solution is approximated by:

$$\Delta T = \Delta To \exp \left(- \frac{\pi f}{\rho C_p Q} r^2\right) \qquad (14)$$

Note that the temperature at the source in this case, where no tidal activity is assumed to be present, becomes equal to the temperature of the source itself for relatively low discharges. For conditions normally encountered this is the case for discharges in the order of 20 m^3/s and above.

The Effect of a Residual Drift

The idealized examples above will rarely apply without modifications to real situations. For a more refined analysis, two-dimensional time-dependent numerical models based on flow patterns generated by hydrodynamic models should be applied. Techniques applied in numerical modeling of this type is described in a paper presented by G.S. Rodenhuis at this Conference [2].

One of the reasons for the need for numerical modeling is the inability of analytical methods to incorporate the effect of irregular flow patterns, irregular topographies and the combined effect of the mass injection effect and the important effect of a residual current.

Clearly, the presence of a residual drift current is of decisive importance for the shape of the temperature field, and hence for biological assessments and positioning of intake and outfall. A residual drift current of, say, 3 cm/s would be about one magnitude greater than the advection velocity caused by the mass injection considered in the oscillating flow example above. This will clearly have the effect of transforming the temperature field into a relatively narrow plume along the coast in the direction of the drift current. Furthermore, since unaffected water is continuously fed into the plume, a considerable decrease of maximum excess temperatures and a corresponding increase of temperatures further downstream will take place.

The recognition of the effect of a drift current should be duely reflected in the planning of field measurements and the subsequent data processing.

In areas where the wind is a dominating factor in the generation of the flow pattern which therefore is of a stochastic nature, a deterministic model approach is less suitable. As a compromise, deterministic numerical models can be run over a period long enough to contain the characteristic statistical features of the natural conditions in order to produce results which can be interpreted accordingly. Another possibility is to perform a number of model runs using parameter-sets which combine into a known frequency of occurrence.

Finally, pure stochastic models can be employed. This approach is rarely used in this context, even though it would appear probable that this would be appropriate both for purposes of recirculation management and for assessments of biological effects. The advantages with respect to elucidation of both aspects appear to be self-evident, although it is unconceivable to apply a stochastic model without resort to some type of deterministic approach.

RECIRCULATION MANAGEMENT - AN EXAMPLE.

According to equation (7) the optimum recirculation is found by equating the marginal costs of power loss and construction costs:

$$\frac{dR}{d\Delta T_i} = \frac{dC}{d\Delta T_i}$$

Cost of Power Loss Due to Recirculation

Harlemann [3] indicates the following relation for the change in basic plant efficiency for a typical boiling water or pressurized water reactor plant:

$$\frac{\Delta E}{E} = \frac{T_d - T_1}{T_2 - T_d} \qquad (16)$$

where $T_d - T_1$ is the deviation in (^oF) from the design steam condensing temperature, T_2 is the maximum operating temperature of the plant, and T_d is the design steam condensing temperature. Equation (16), which qualitatively is correct [3] , shows that there is a nearly linear relationship between power loss and deviations from the design temperature. Consequently, the present value of power loss due to the presence of temperatures increased ΔT_1 over the natural equilibrium at the intake can be written as:

$$R = \Delta E \; f \; \Delta T_1 \; PVF \qquad (17)$$

where ΔE is the power loss per degree increase in intake water temperature, f is the cost of 1MW year, PVF is the present value factor.

These factors are tentatively evaluated as follows:

$\Delta E = 0.0035\,E$ MW $^oC^{-1}$

$f = 20$ \$ $(MWh)^{-1} = 175{,}000$ \$ $(MW\ year)^{-1}$

PVF $\simeq$ 14 for a 5% discount rate and a period of 25 years.

For a 2000 MW power plant the marginal present value of power loss is estimated at 17 million dollars per degree centigrade.

Construction Costs.

In the example considered above it is assumed that the plant's required 100 m^3/s of cooling water is conveyed through large submerged conduits from an intake structure several hundred meters from the shore, see Fig. 1. The outfall is assumed to be located at the shore. For simplicity it is furthermore assumed that the construction and pumping costs can be expressed as:

$$C = Px \tag{18}$$

P is the cost per unit lenght and x is the distance between intake and outfall.

The time averaged excess temperature distribution in the outfall-intake line is assumed approximated by an exponential decay, equation (7). The marginal cost of construction and pumping can then be computed as:

$$\frac{dC}{d\Delta T_i} = \frac{P}{\alpha \Delta T_i} \tag{19}$$

Substitution of equation (17) and (18) in (3) leads to the optimal excess temperature at the intake:

$$\Delta T_i \text{optim} = \frac{P}{\Delta E \ f \ PVF \ \alpha} \tag{20}$$

from which the optimal distance between outfall and intake is readily computed using equation (7).

The cost of the marine installations (including pumping) of the type considered is estimated at 80,000 US $ per meter.

The exponent α in equation (7) is assumed to be increased by the action of a residual tidal drift current as compared to the value one would obtain in the case of a purely oscillating flow. The magnitude of the exponent is estimated at 0.003 m^{-1}.

With the above cited figures the optimum recirculation becomes

$$\Delta T_i \text{optim} = \frac{80\ 10^3}{17\ 10^6\ 3\ 10^{-3}} \simeq 1.6\ ^\circ\text{C}.$$

Because of the exponential decay of the excess temperature with distance from the outfall and because of the considerable construction costs involved, deviations from the optimum temperature will inevitably lead to a considerable increase in the total cost.

The choice of magnitude of the various parameters involved in the analysis above can of course be discussed and a sensitivity test would in an actual case be required. Furthermore, the effect of increased ambient temperatures in the far-field can to some extent be catered for in the design of the steam condensers. However, in any case, the analysis stresses the importance of a reliable prediction of the excess temperature distribution.

As a practical comment to the example considered it should be noted that it would appear to be advantageous to discharge in the off-shore position using a high velocity jet, and to take water in close to the shore. Furthermore, a position of the intake upstream relative to the outfall conduits should be considered. Thus, in order to perform a complete analysis, two dimensions for determination of the optimum intake position would need be considered.

RECIRCULATION AND BIOLOGICAL EFFECTS

The question whether or not decisions based on recirculation management principles could be in conflict with biological demands is difficult to assess. Apart from the very limited effect of the efficiency decrease due to recirculation, the same quantity of heat is rejected to the environment. The fact that recirculation is present only means that the excess temperature field is "concentrated" to a higher extent in the area between outfall and intake than would be the case if no recirculation was present at all.

Additionally, it appears that a recirculation management analysis would always tend to yield solutions which are preferable from a biological point of view as well since sites and intake-outfall lay-out solutions causing relatively small areas to be subject to high excess temperatures would be preferred for both reasons.

There may,however,be coastal sites which for biological reasons should not be used. It should be noted that as far as decimation of marine organism due to entrainment in the cooling water system is concerned, this aspect is independent of the question of the distribution of an excess temperature field. This and other biological aspects can be assessed using a numerical modeling technique described in the paper presented by B. Møller and K.I. Dahl-Madsen at this Conference [4].

DISCUSSION

The aim of the considerations presented in this paper has been to elucidate some of the important elements in the analysis of the waste heat management problem. Therefore, the methods indicated above do by no means represent a state-of-the-art of modeling techniques but should be regarded as tools which can be used for purposes of quick approximations, sensitivity analyses and systems analysis.

The main object of this paper is that it addresses the genuine need to recognize that the waste heat problem is not simply solved by prescribing maximum surface temperature differentials in the receiving water and requiring zero recirculation.

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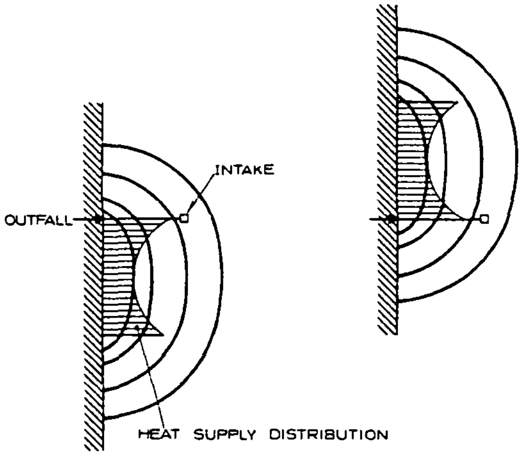
IDEALIZED TEMPERATURE DISTRIBUTIONS AT THE SLACK TIDES OF AN OSCILLATING TIDAL FLOW FIELD



ILLUSTRATIONS OF THE RECIRCULATION MANAGEMENT EXAMPLE

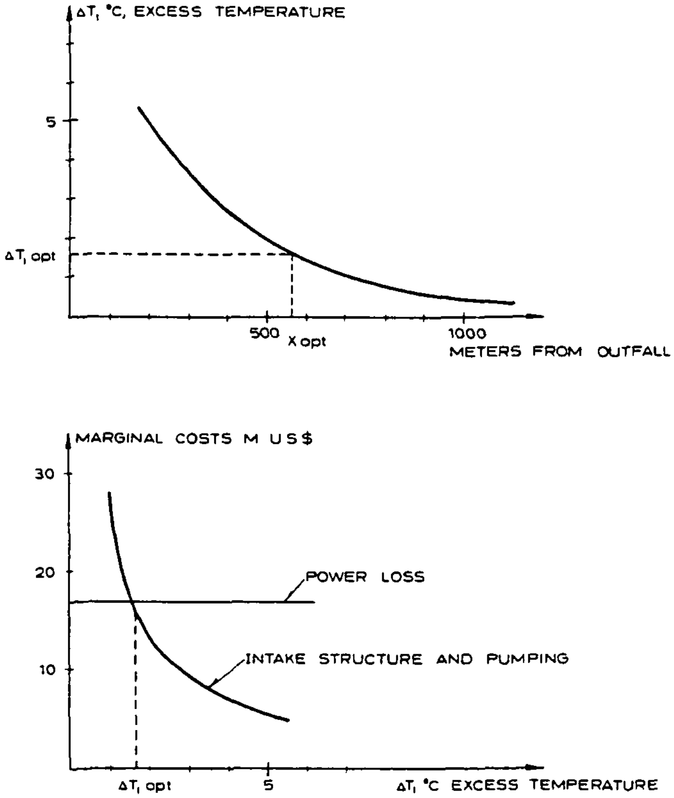


Fig 1 Idealized temperature distribution and marginal cost analysis