Nordic Hydrology 4, 1973, 237–255
Published by Munksgaard, Copenhagen, Denmark

COOLING PROBLEMS IN THERMALLY POLLUTED RECIPIENTS

TODOR MILANOV

The Swedish Meteorological and Hydrological Institute, Sweden

The extension of the warm water plume in receiving waters used as recipients for thermal pollution has been studied using a meteorological approach. For some real cases the area of excess temperature has been examined and compared to the conditions when heat is transferred to the atmosphere only. Numerical values are given for the warm water areas for different localities in Sweden for cooling water discharge corresponding to 2 000 MW waste heat.

The rapidly increasing power demands and the technical progress have resulted in the need for building very large thermal power plants. Because of the large quantities of cooling water required, they are located, when possible, near large bodies of water. A nuclear power plant with a production of 1 000 MW electric energy needs approximately 50 cubic metres per second of cooling water, if the temperature rise of the water is 10 degrees Centigrade. The power plants in Sweden which are under construction (Ringhals, Barsebäck, Forsmark) will be of 3 000 MW size. At the same rise of temperature, as mentioned above, these power plants would need 150 cubic metres of cooling water per second.

When heat is supplied continuously or periodically to a recipient, the natural conditions of temperature will change, and this directly or indirectly affects the physical, chemical and biological conditions of the water. In the winter the discharged cooling water can affect ice conditions and also cause the formation of fog.

An unsuitable location of intake and discharge may cause recirculation of the cooling water, which will reduce the effective power of the station. In order to estimate the risks of environmental influence on the recipient and in order to find the best relative place for intake and discharge, the extension of the area of warm water plumes outside the discharge point must be known already at the projecting stage. Many authors have written about this theme: Becker (1965), Prichard & Carter (1965), Falkenmark & Milanov (1969), Ehlin (1970) and Prych (1972). In this report a meteorological approach has been used. A short introductory discussion is first given on the principles for the heat exchange between water and atmosphere. A model for the discharge of cooling water is discussed. This model is compared with empirical data on the distribution of excess temperature in various cases.

HEAT BALANCE EQUATION

The heat balance of a natural body of water is controlled by the processes supplying or abstracting heat. The predominant heat exchange takes place through the atmosphere at the water surface. Heat transfer between the surface and the inner part of the body of water takes place through advection, convection and turbulence and to a lesser degree through molecular heat transference. Heat is transferred from the water surface by long wave radiation, evaporation and convection. Heat is supplied to the water mainly by absorption of sun radiation, but also by turbulent and molecular heat transference from the atmosphere as well as by transformation of the kinetic energy of the currents to heat due to the inner friction of the water. Because of the transformation of the kinetic energy of currents, the molecular heat exchange, just like the heat supply, is negligible compared to other heat processes. The heat budget for vertical heat-exchange between water and atmosphere can be written in the following way:

$$Q_n \equiv R + E_v + K - Q_s \qquad (1)$$

where Q_n is net heat loss, R effective heat loss by long wave radiation, E_v heat loss by evaporation-condensation, K heat loss by convection and Q_s heat input by absorbed short wave radiation.

The first three terms on the right-hand side of the equation can be calculated from an empirical formula, if the temperature of the surface-water, the temperature of the air, the wind speed, the air moisture and the cloud cover are known.

There are many formulas for heat loss by evaporation and convection. The most general ones, however, which would give the best results, are not easy to use in practice as they have an exchange coefficient which can be estimated only with the greatest difficulty after comprehensive observations. Therefore, approximations are often used in which the coefficient of exchange is set to be a function of the wind speed at a certain level, independent of the wind profile and the temperature-gradient in the surface layer.

The following formulas by Hutchinson (1957) for heat release by radiation, and by Throne (see Milanov 1969) for release by evaporation and convection, are used for the calculation of the extension of the warm water area in recipients.

$$R = 8.26 \cdot 10^{-11} (0.97\tau^4 - T^4(1 + k_c B^{2.5}) (0.820 - 0.250 \cdot 10^{-0.126 P_w})) \quad (\mathrm{cal/cm^2 \cdot min}) \qquad (2)$$

$$E_V = 0.01046 (1.0 + 0.6V) (e_\tau - e_T) \quad (\mathrm{cal/cm^2 \cdot min}) \qquad (3)$$

$$K = 0.00534 (1.0 + 0.6V) (\tau - T) \quad (\mathrm{cal/cm^2 \cdot min}) \qquad (4)$$

where

τ = temperature of the water surface in °K
T = temperature of the air in °K
B = the fraction of the sky, in tenths, covered by clouds
k_c = factor depending on the nature of the cloud cover (see Hutchinson, 1957)
P_W = vapour pressure over water in mmHg
V = wind velocity in m/s
e_τ = saturated vapour pressure at the temperature of the water surface in mb.
e_T = vapour pressure of air in mb.

The heat input by short wave radiation Q_s can be measured by instruments or calculated from an empirical formula if the cloudiness and the elevation of the sun are known.

THE CHANGE IN THE HEAT LOSS

The heat transfer from a free surface of water to the atmosphere according to equations (2–4) can be regarded as a function of the temperature of the water surface τ, the temperature of the air T, the wind velocity V, the amount of cloud B, and the factor k_c or Q_n (τ, T, V, k_c, B).

Let us regard a part of the undisturbed water of the recipient. If the temperature of the water surface is τ_0, the temperature of the air T_0, the wind velocity V_0, the amount of cloud B_0, and the factor k_c, the equation will be

$$Q_n (\tau_0, T_0, V_0, k_c, B_0) = R (\tau_0, T_0, k_c, B_0) + K (\tau_0, T_0, V_0) + E_v (\tau_0, T_0, V_0) - Q_s \tag{5}$$

where Q_n is net heat loss, R heat loss by long wave radiation, K heat loss by convection, E_v heat loss by evaporation, Q_s heat input by short wave radiation.

Consider now a part of the discharged water. If the temperature of the water is τ, the temperature of the air T_0, the wind velocity V_0 and the amount of cloud B_0, the equation will be

$$Q_n (\tau, T_0, V_0, k_c, B_0) \equiv R (\tau, T_0, k_c, B_0) + K (\tau, T_0, V_0) + E_v (\tau, T_0, V_0) - Q_s \tag{6}$$

The difference between equation (5) and (6) is

$$\begin{aligned} \Delta Q_n &= (\tau, T_0, V_0, B_0, k_c) - Q_n (\tau_0, T_0, V_0, B_0, k_c \equiv \\ & R (\tau, T_0, B_0, k_c) - R (\tau_0, T_0, B_0, k_c) + K (\tau, T_0, V_0) - \\ & K (\tau_0, T_0, V_0) + E_v (\tau, T_0, V_0) - E_v (\tau_0, T_0, V_0) \approx \\ &= ((\frac{\partial R}{\partial \tau})_{\tau_0} + (\frac{\partial K}{\partial \tau})_{\tau_0} + (\frac{\partial E_v}{\partial \tau})_{\tau_0}) (\tau - \tau_0) \end{aligned} \tag{7}$$

If the difference $\tau - \tau_0$ is great, $\partial R/\partial \tau$, $\partial K/\partial \tau$ and $\partial E_V/\partial \tau$ are calculated at a mean temperature of $(\tau + \tau_0)/2$ instead of τ_0.

In Fig. 1 the following function is shown

$$(\frac{\partial R}{\partial \tau})_{\tau_0} + (\frac{\partial K}{\partial \tau})_{\tau_0} + (\frac{\partial E_v}{\partial \tau})_{\tau_0} \equiv F (\tau_0) \tag{8}$$

This function is calculated from equations (2), (3) and (4) for varying V and τ_0.

As is seen, this heat-transfer increases linearly with increasing wind velocity.

A MODEL FOR THERMAL DISPERSION OF WARM COOLING WATER

The distribution of the temperature in warm water plumes can most easily be derived for a straight discharge (Fig. 2), i.e. a discharge which takes place within parallel walls, presuming that the warm water flows on the surface without mixing with the recipient water, and that we have a complete horizontal mixing

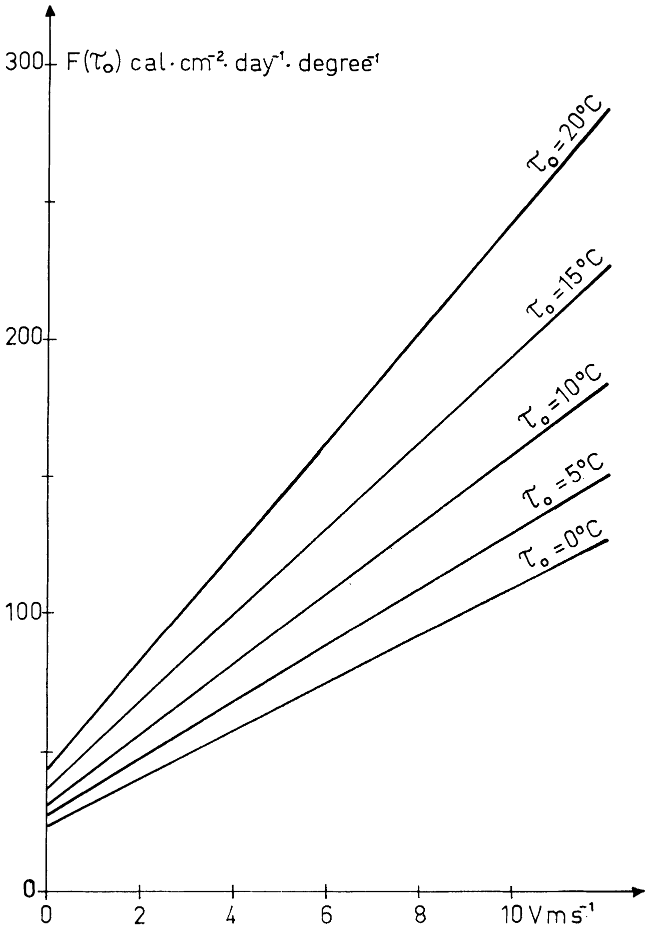

Fig. 1.
Heat transfer function $F(\tau_0)$ for different wind velocities V and temperatures of the water surface.

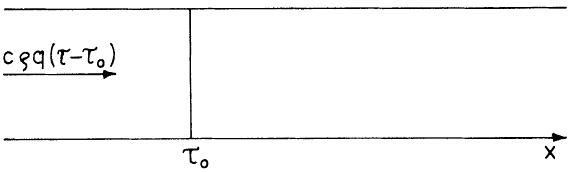

Fig. 2.
Definition sketch.

within this layer. Thereafter we study the change of the heat balance in relation to the natural state under staionary condiions.

If the cooling water discharge q is constant, the discharge of excess heat is $\varrho \cdot c \cdot q\ (\tau - \tau_0)$ where ϱ is density of water and c specific heat of water. The divergence of heat is

$$-\varrho \cdot c \cdot q \frac{\partial}{\partial x} (\tau - \tau_0)\ \delta x \tag{9}$$

This will be equal to the heat transfer from the horizontal water surface to the atmosphere according to equation (8).

$$F\ (\tau_0)\ (\tau - \tau_0)\ D \cdot \delta x \tag{10}$$

where D is the distance between the walls and $D \cdot \delta x$ the area.

Equation (9) and (10) give

$$\frac{\partial\ (\tau - \tau_0)}{\partial x} = - \frac{F\ (\tau_0)\ D}{c \cdot \varrho \cdot q}\ (\tau - \tau_0) \tag{11}$$

or

$$\tau - \tau_0 \equiv (\tau - \tau_0)_{max}\ e^{-\frac{F\ (\tau_0)\ D}{\varrho \cdot c \cdot q}\ x} \tag{12}$$

or

$$S = \frac{\varrho \cdot c \cdot q}{F\ (\tau_0)} \ln \frac{(\tau - \tau_0)_{max}}{\tau - \tau_0} \tag{13}$$

which give the excess temperature as a function of x and where $(\tau - \tau_0)_{max}$ is the difference of the temperature in the discharge ($x = 0$). $S = D \cdot x$ is the surface.

Equation (13) also applies to the extension of warm water plumes on the surface of a lake or the sea, assuming that there is no mixing of recipient water and that the warm water extends homogeneously on the surface. As a rule the extension of warm water does not take place parallelly as in a channel form but rather in the form of a plume. Consequently, the size of the warm water plume, i.e. the area in which the warm water has an excess temperature, can be calculated from equation (13), but not the form of the plume as it can fluctuate considerably with the direction and the velocity of the wind and the currents.

COMPARISON WITH EMPIRICAL DATA

Measurements of the distribution of excess temperature have been carried out in the area of cooling water discharge from the power plant of Karlshamn. The measurement of the surface water temperature at a depth of 0.5 m was carried out by sensitive temperature measuring devices tugged by a boat moving in sections over the area. The quantity of cooling water discharged from the power station was 10.5 m^3/s and the temperature increase in the station fluctuated between 8.3 and 10.5°C.

The observed distributions of the temperature are shown in Figs. 3–6. The Figures show that the distribution model of the warm water plume is determined

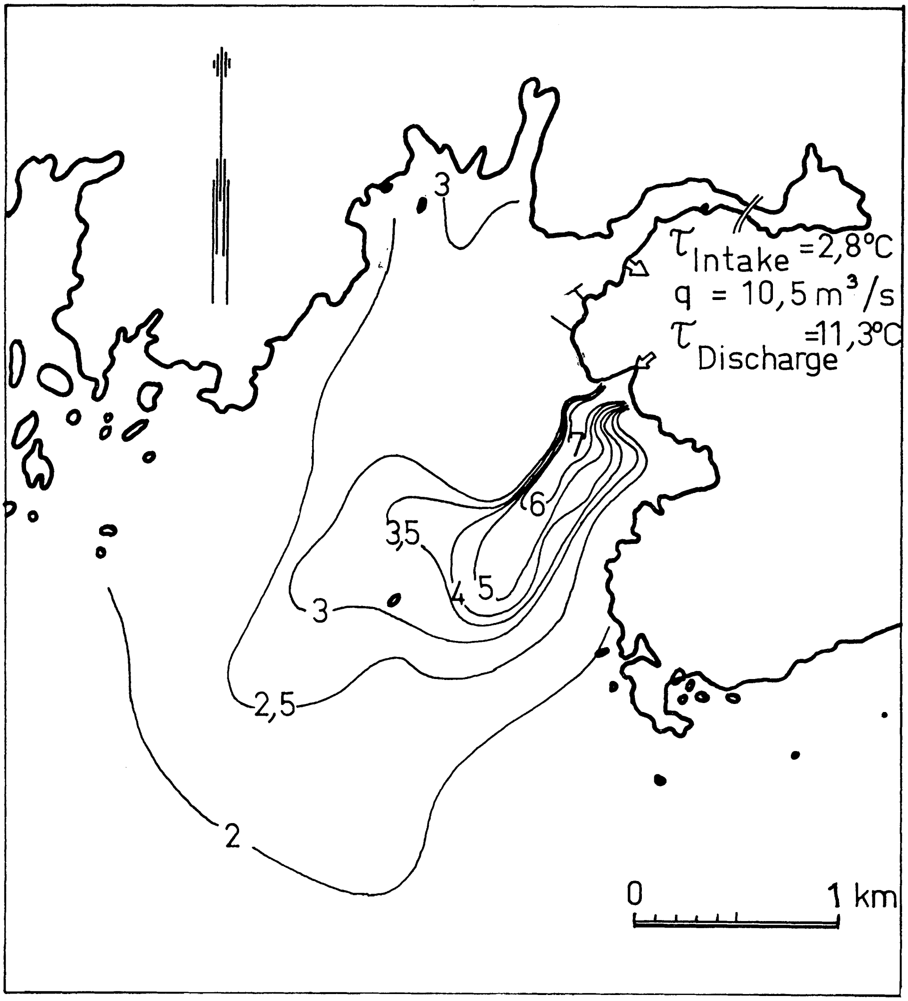

Fig. 3.
Temperature distribution off the Karlshamn power station, April 15, 1970, 0.5 m depth, wind: NNW 1-2m/s.

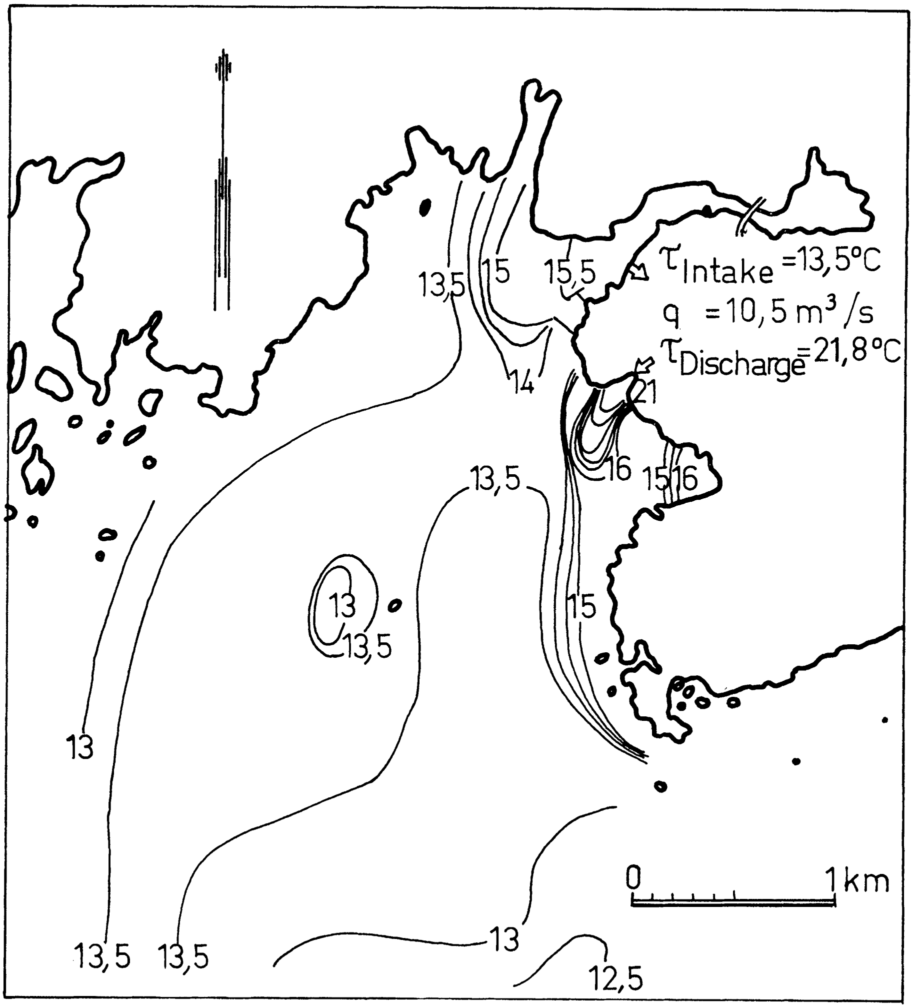

Fig. 4.
Temperature distribution off the Karlshamn power station, June 12, 1970, 0.5 m depth, wind: NNW 10–15 m/s.

mainly by the winds. From the Figures it can also be seen that a certain degree of recirculation to the intake takes place.

Figs. 7–10 show the relation between the decrease of the excess temperature and the warm water plume areas. The broken lines represent excess temperatures calculated from equation (13). The diagram in Figs. 7–10 shows that here the ex-

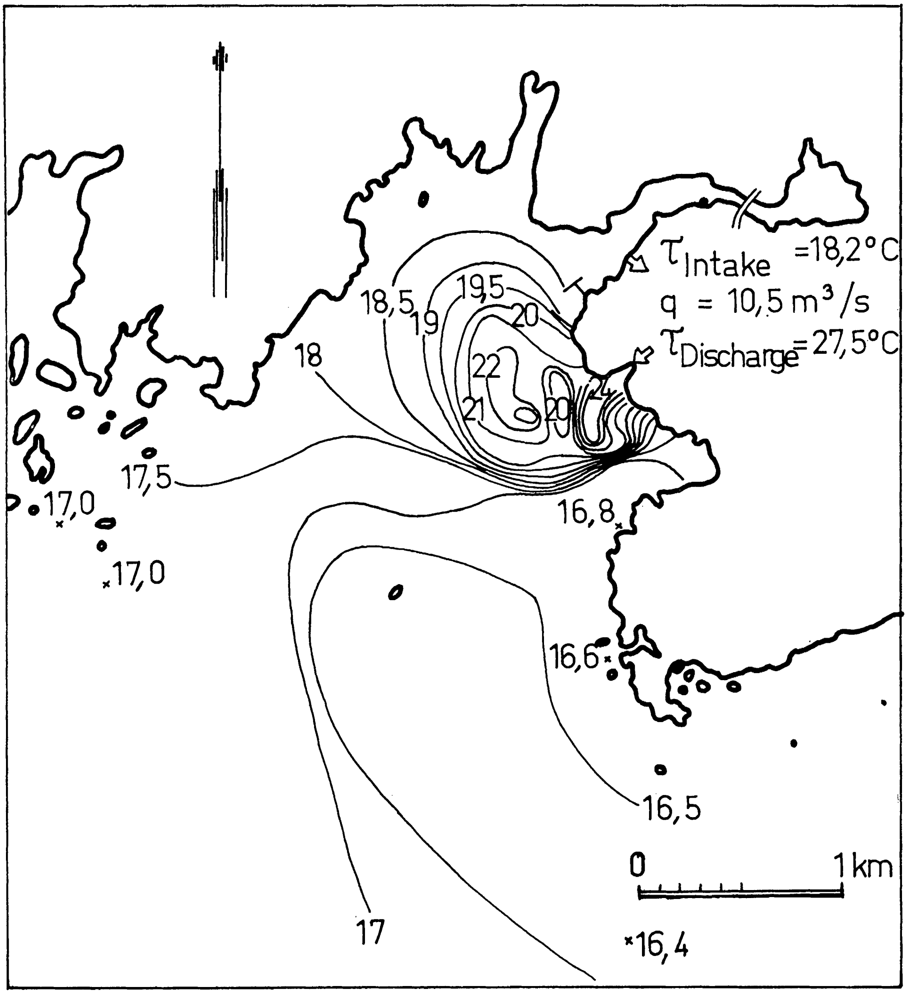

Fig. 5.
Temperature distribution off the Karlshamn power station, September 1, 1970, 0.5 m depth, wind: SSW 2-4 m/s.

cess temperature of the surface water decreases according to two different exponentials: the former a very rapid one, the latter a slow one, which is parallel to the theoretically calculated curve. The decreasing of the temperature during the initial stage occurred very rapidly, which is mainly due to the initial mixing, which in its turn is a result of the excess kinetic energy of the discharged water compared to the ambient water. After the consumption of the kinetic energy of

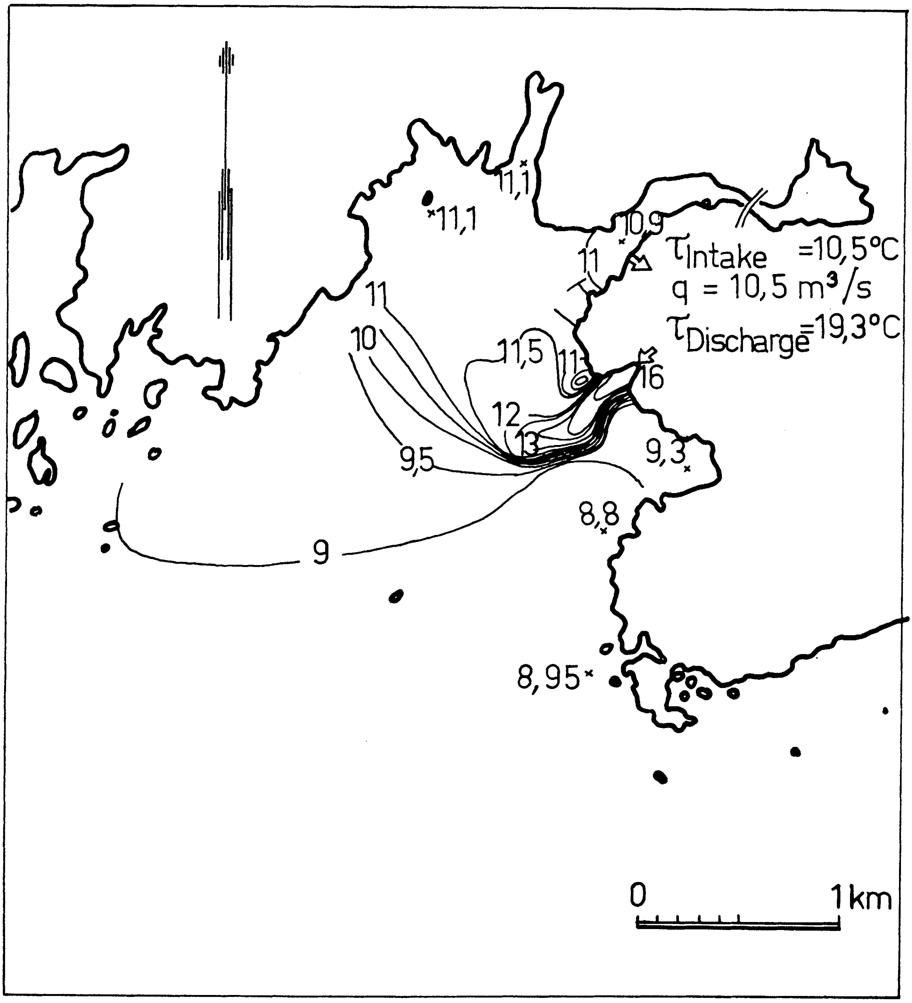

Fig. 6.
Temperature distribution off the Karlshamn power station, September 30, 1970, 0.5 m depth, wind: SSE 2–3 m/s.

the cooling water flow the temperature decrease is caused mainly by heat transfer to the atmosphere.

Table 1 gives numerical values of the heat loss function $F(\tau_0)$ off the Karlshamn power station, calculated partly from observed data from equation (13) and partly from the actual meteorological conditions according to equation (8).

The experimentally calculated values of F(τ_0) diverge considerably from those obtained from heat loss formulas. This difference may depend on the fact that the assumption on which the theoretical model is based, i.e. that the effect of the mixing with the recipient can be ignored, does not represent the real conditions.

CALCULATION OF THE MIXING EFFECT

The mixing of the recipient water with the discharged cooling water is a complicated physical process, because it is dependent upon the static and dynamic characteristics of the recipient, the discharge device and its design, the wind

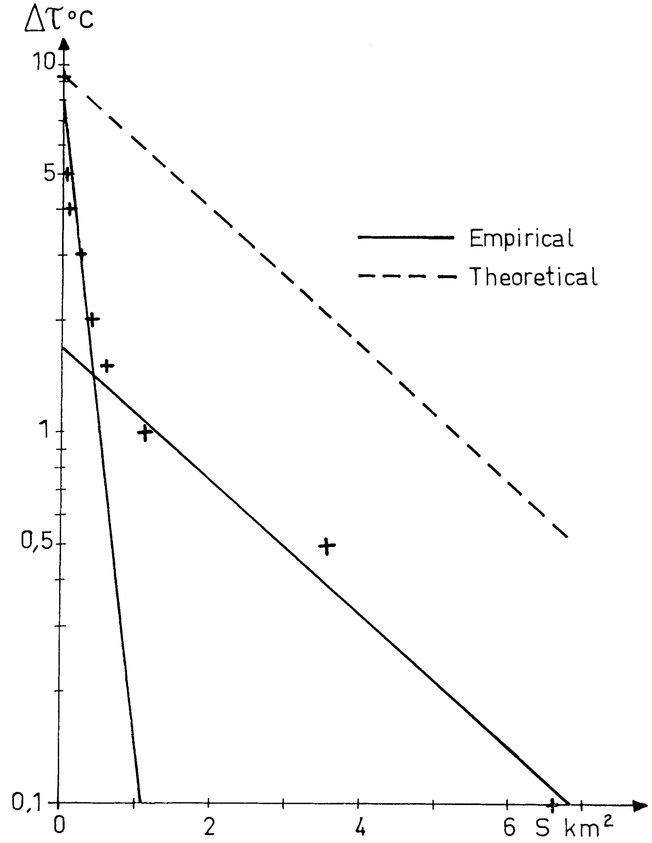

Fig. 7.

Relations between the decrease of the excess temperature and the warm water areas off the Karlshamn power station, April 15, 1970.

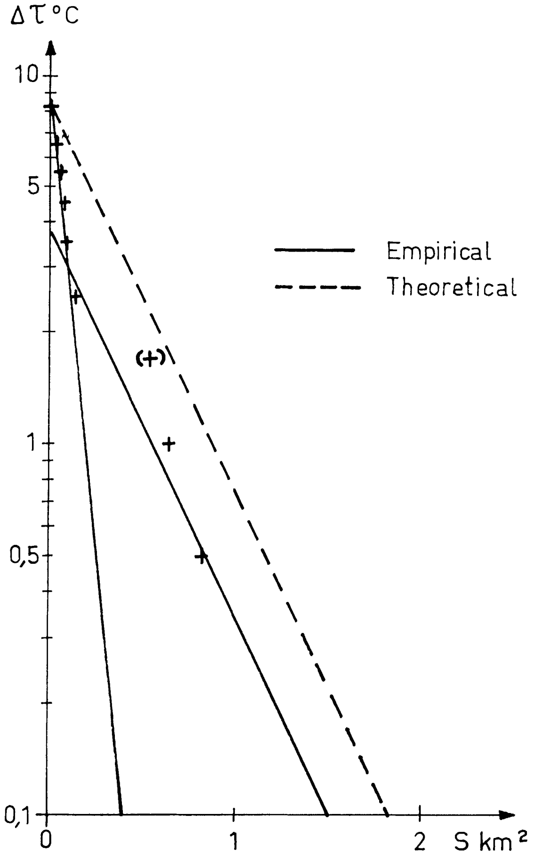

Fig. 8.

Relations between the decrease of the excess temperature and the warm water areas off the Karlshamn power station, June 12, 1970.

velocity, etc. For a theoretical analysis of the initial mixing process at small underwater discharges into recipients, see Cederwall (1968). In the following, attempts will be made to estimate the mixing effect by means of the above mentioned empirical data.

Figs. 7–10 show the effect of the heat transport when mixing. Obviously the mixing of recipient water causes a more rapid decrease of the temperature than what is due to the heat transfer to the atmosphere. This decrease of temperature through mixing is denoted $\Delta F(\tau_0)$.

Since the mixing gives a direct reduction of the heat input, we calculate $\Delta F(\tau_0)$ from the difference between $F(\tau_0)$, calculated from the experimental data and $F(\tau_O)$, calculated from the equations of heat loss on the basis of the meteorological conditions, Table I. This mixing is a factor of great importance, about which further investigations are being made.

THE HEAT BALANCE OF THE WARM WATER PLUME AREA

The warm water plume area S is in heat balance when the following processes are in balance with each other:

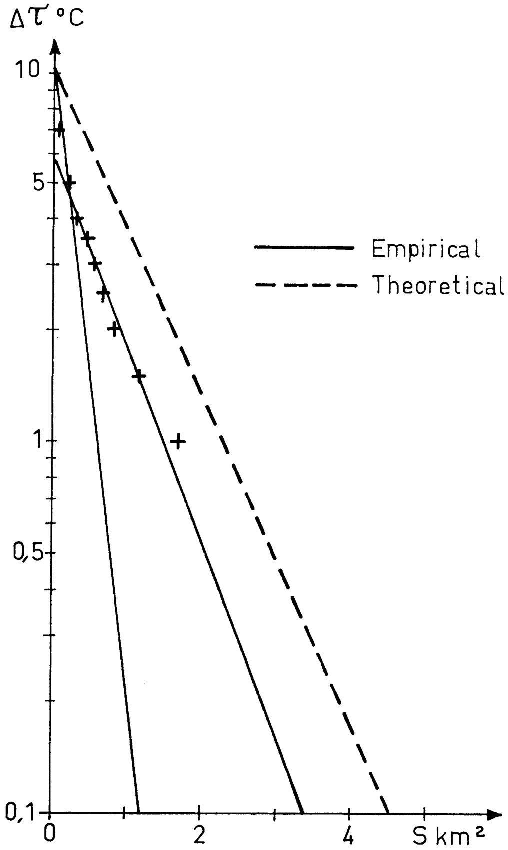

Fig. 9.

Relations between the decrease of the excess temperature and the warm water areas off the Karlshamn power station, September 1, 1970.

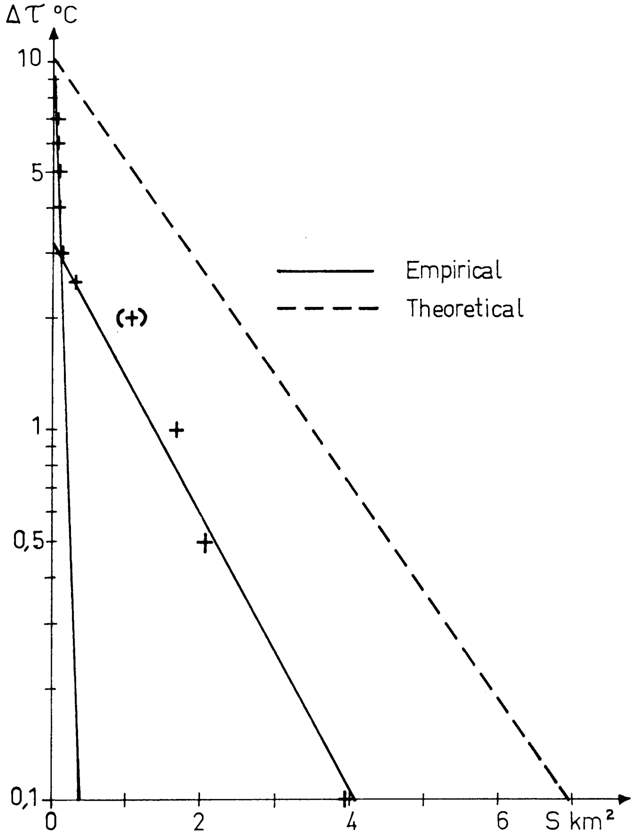

Fig. 10.
Relations between the decrease of the excess temperature and the warm water off the Karlshamn power station, September 30, 1970.

(A) The heat input of cooling water to the recipient Q_{in} (cal/day)

(B) The heat transfer to the atmosphere $\Delta Qn \cdot S$ (cal/day)

(C) The heat loss from the warm water plume area through mixing $Q_{mix} \cdot S$ (cal/day)

At balance the following is true

$$(A) + (B) + (C) \equiv O$$

where (A) is calculated from data concerning the discharge

$$Q_{inp} \equiv c : \varrho : q \cdot \tau_0$$

Table I.
The heat transfer function and calculated mixing effect.

Date	Cooling water discharge, q (m³/s)	Temp. of the cooling water, τ (°C)	Temp. of the surface, τ_0 (°C)	Excess temp. $(\tau\text{-}\tau_0)_{max}$ (°C)	Warm cooling water areas, S (km²)	Wind velocity, S (m/s)	Heat transfer function, $F(\tau_0)$ (cal/m² day)		Mixing effect $\Delta F(\tau_0)$ (cal/m² day degree)
							Empirical	Theoretical	
15.4.70	10.5	11.3	2.0	9.3	6.6	1.5	1) $374 \cdot 10^4$	$38 \cdot 10^4$	$336 \cdot 10^4$
							2) $39 \cdot 10^4$	$38 \cdot 10^4$	$1 \cdot 10^4$
12.6.70	10.5	21.8	13.5	8.3	1.4	12.5	1) $1160 \cdot 10^4$	$215 \cdot 10^4$	$945 \cdot 10^4$
							2) $220 \cdot 10^4$	$215 \cdot 10^4$	$5 \cdot 10^4$
1.9.70	10.5	27.5	17.0	10.5	3.4	3.0	1) $384 \cdot 10^4$	$92 \cdot 10^4$	$292 \cdot 10^4$
							2) $99 \cdot 10^4$	$92 \cdot 10^4$	$7 \cdot 10^4$
30.9.70	10.5	19.3	9.0	10.3	4.0	2.5	1) $995 \cdot 10^4$	$60 \cdot 10^4$	$935 \cdot 10^4$
							2) $63 \cdot 10^4$	$60 \cdot 10^4$	$3 \cdot 10^4$

(B) is calculated from equations (2–4) of the heat transfer from water to atmosphere.

(C) is calculated from empirical data.

As long as there is no mixing with recipient water, the size of the warm water plume is determined by (A) and (B). The addition of (C) causes a reduction of the warm water plume. Table 2 gives the heat balance data from all experiments. The Table shows that between 23 and 53 % of the supplied heat energy was emitted to the atmosphere and the rest by heat loss through the mixing with recipient water. This caused a great reduction of the real warm water plume area.

Table 2.
The heat budget data.

Date	A (cal/day)	B (cal/day)	C (cal/day)	$\frac{B}{A}$ %	$\frac{C}{A}$ %
15.4.70	$8.44 \cdot 10^{12}$	$-1.97 \cdot 10^{12}$	$-6.47 \cdot 10^{12}$	23	77
12.6.70	$7.53 \cdot 10^{12}$	$-4.00 \cdot 10^{12}$	$-3.53 \cdot 10^{12}$	53	47
1.9.70	$9.53 \cdot 10^{12}$	$-4.71 \cdot 10^{12}$	$-4.81 \cdot 10^{12}$	49	51
30.9.70	$9.34 \cdot 10^{12}$	$-2.50 \cdot 10^{12}$	$-6.76 \cdot 10^{12}$	27	73

THE SIZE OF THE WARM WATER PLUME AREA IN THE SWEDISH CLIMATE

By using the normal values of air temperature, wind, air moisture and cloud cover during different seasons as well as the normal water temperature of lakes and seas, the theoretical size of the warm water plume area has been calculated for various places in Sweden. The calculation of the normal values of the air temperature, cloud cover and air moisture is based on thirty-year monthly mean values from climate stations of the Swedish Meteorological and Hydrological Institute (SMHI, 1932–1962). Temperature values are taken from Svinbådan, Karlshamn, Simpevarp, Nyköbing, Stockholm, Västerås, and Finngrunden (Melin 1938 and Fishery Board of Sweden (1951–1965)). The calculation refers to the wind velocity of 5 m/s, which is the most common during the year.

Fig. 11 gives calculated warm water plume areas for cooling water discharges

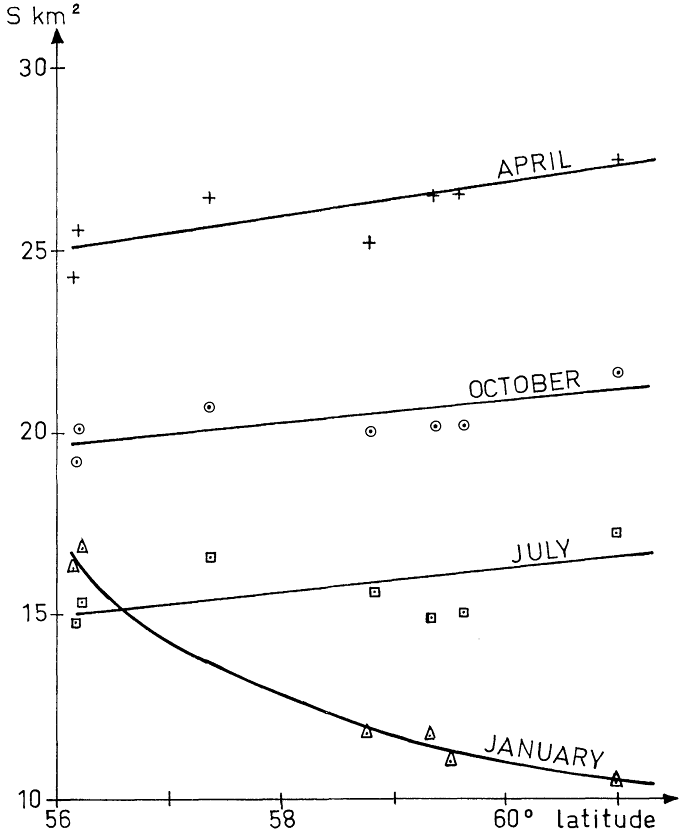

Fig. 11.
Warm water areas for different localities in Sweden for cooling water discharge corresponding to 2 000 MW waste heat, excess temperature 10°C, limit excess temperature 0.1°C, wind velocity 5 m/s.

corresponding to 2 000 MW waste heat. The excess temperature is assumed to be 10°C and the limit temperature 0.1°C. The months selected represent the different seasons of the year. The Figure shows that the warm water plume area decreases with latitude in January, a phenomenon which is connected with the influence of the air temperature, and increases with latitude in April, July and October, which, implying larger warm water areas in the north than in the south of Sweden during these months, is due to the influence of the water temperature.

CONCLUSIONS

When cooling water is discharged, heat is transferred to the recipient. Because of its high temperature, as compared to the recipient, the cooling water normally spreads in the surface layer of fresh water, causing an area of excess temperature. In saline water, where the density depends upon both temperature and salinity, the cooling water spreads in other layers of the recipient. Excess heat is transferred to the atmosphere by radiation, evaporation and convection. The warm water plume attains a maximum area, the size of which depends upon the excess heat being transferred from this surface to the atmosphere. The mixing of colder recipient water implies the presence of a supplementary process with temperature reducing effect, which makes the warm water plume area smaller than the theoretical one, calculated from meteorological data.

For some real cases the area of excess temperature has been examined and compared to the conditions when heat is transferred to the atmosphere only. The decrease of temperature has taken place according to two exponential parts. Thereby, the less steep part corresponds only to heat transfer to the atmosphere, the steeper one to the same heat transfer in combination with another process with temperature reducing effect, which is mixing of colder recipient water. In all cases the effects of mixing have been observed at the very point of discharge, which is to be expected in the presence of an initiating mixing caused by kinetic energy in the discharged cooling water. A comparison between experimentally observed warm water areas and the corresponding areas calculated from meteorological data, shows that the reduction of temperature because of mixing has been relatively great. Therefore, when forecasting the size of a warm water area for a planned plant location, it seems reasonable to consider that not only heat transfer to the atmosphere but also mixing into recipient water, causing a decrease of temperature, will occur.

REFERENCES

Becker, A. (1965) Die thermische Belastbarkeit der Binnengewässer und die bei Durchflusskühlung eintrentenden Nutzungsverluste. – Besondere Mitteilungen zum Gelwässerkundlichen. *Jahrbuch der Deutschen Demokratischen Republik,* Berlin.

Cederwall, K. (1968) *Hydraulics of Marine Waste Water Disposal.* Hydraulic Division, Chalmers Institute of Technology, Göteborg, Sweden, Report No. 42, January.

Ehlin, U. (1970) Effects of large cooling-water discharges. *Proc. Conf. World, Water and We, Jönköping.*

Ehlin, U. (1971) Cooling water discharges to lakes and seas. SMHI HBF/HBO PM No. 151, September 1971.

Falkenmark, M & Milanov, T. (1969) Om kylvattenutsläpp i recipienter. SMHI, Meddelande Serie D Nr. 13, Stockholm.

Fishery Board of Sweden (1951–1965) Series Hydrography Report Nos. 1–15, (Hydrographical observations on Swedish lightships).

Hutchinson, G. E. (1957) *A Treatise on Limnology,* Vol. 1.

Melin, R. (1938) *Yttemperaturen i Svenska Vattendrag.* SMHI, Stockholm 1938.

Milanov, T. (1969) Avkylningsproblem i recipienter vid utsläpp av kylvatten. SMHI, Notiser och preliminära rapporter, Serie Hydrologi, Nr. 6, Stockholm.

Pritchard, D. W. & Carter, H. H. (1965) On the predication of the distribution of excess temperature from a heated discharge in an estuary. Technical Report 33, February. Chesapeake Bay Institute, Johns Hopkins University.

Prych, A. (1972) A warm water effluent analyzed as a buoyant surface jet. SMHI, Notiser och preliminära rapporter, Serie Hydrologi, Nr. 21, Stockholm.

SMHI (1932–1962) Meteorologiska iakttagelser i Sverige 1932–1962. SMHI, Stockholm.

Received: March 10, 1973.

Address:
Water Balance Section,
The Swedish Meteorological and
Hydrological Institute,
Box 12108,
S 102 23 Stockholm,
Sweden.