EXPERIMENTAL EVALUATION OF HEAT EXCHANGE BETWEEN WATER SURFACE AND ATMOSPHERE

by

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ABSTRACT

The heat balance of a water body mainly depends upon the heat exchange processes at the water surface. An experimental method has been developed for determining the heat exchange, the exchange coefficient and the equilibrium temperature. The measuring equipment consists of two similar, well insulated pools which are exposed to the meteorological conditions of the Lower Weser River, Germany. The water temperature of the first pool (T_1) is artificially adjusted to the actual river temperature either by cooling or heating. The temperature of the second pool (T_2) is held constant above the temperature T_1. The difference in power inputs required $W_2 - W_1$ is equivalent to the net rate of heat exchange due to the increase of temperature to ΔT above the river temperature.

1. INTRODUCTION

In order to protect the ecological system of a river the thermal load caused by heat discharge of power plants must be predicted and controlled. In many cases there is a mutual influence and superposition of several heat discharges.

In brackish zones of tidal rivers the ecology is especially sensitive. Therefore the permissible heating range in German tidal rivers is limited to $2^{O}K$. This limitation is relevant during periods with little heat exchange.

After the heated effluent is completely mixed with the receiving water, the decrease of water temperature mainly depends upon heat exchange processes between the water surface and atmosphere. Especially in tidal rivers, where a body of water repeatedly receives artifical heat and remains inside the region of discharge influence for a long time, the knowledge of the heat exchange at the water surface is fundamental for determining the cooling rate.

In a previous comprehensive study Kuhn (1972) established a heat exchange coefficient which is proportional to the cooling rate and computed as a function of water temperature and meteorological variables. But past experience has demonstrated that the computation of heat exchange coefficients on the basis of meteorological variables becomes efficient only when extensive and very exact measurements of these parameters are available. Therefore an experimental method has been developed by the Franzius-Institut measuring the rate of heat exchange directly.

2. BASIC THEORY

The net rate of heat exchange at the water surface consists of the following components (Kuhn, 1972):

$$H = H_W + H_G + H_S + H_V + H_K + H_N \qquad (1)$$

in which

H_W = net rate of heat exchange due to back radiation from the water to the atmosphere

H_G = net rate of heat exchange due to absorbed atmospheric radiation

H_S = net rate of heat exchange due to absorbed solar radiation

H_V = net rate of heat exchange due to evaporation and condensation at the water surface

H_K = net rate of heat exchange due to conduction at the water surface

H_N = net rate of heat exchange due to rainfall

Under the assumption that a body of water is well mixed the variation of temperature with time is determined by

$$\frac{dT}{dt} = \frac{H}{H \cdot \rho \cdot c} \qquad (2)$$

in which
h = water depths
ρ = water density
c = specific heat of water

Neglecting heat exchange due to rainfall, only the terms H_W, H_V and H_K are changing due to heating up by artifical heat. The atmospheric radiation and the solar radiation are not influenced by increasing water temperatures.

If the net heat flux directed into the water body is defined to be positive, an increase of water temperatures due to artifical heat will cause a decreasing net heat flux at the water surface, because back radiation from the water body and evaporation are increasing with higher temperature.

If there is a positive heat flux at a starting point, the temperature of the water will increase until the heat flux is equal to zero. This water temperature is defined as equilibrium temperature T^+. The equilibrium temperature is that temperature, a body of water exposed to a constant set of meteorological conditions would approach.

The equilibrium temperature only depends on meterological conditions, not on water depth. A change in meteorolocigal conditions leads to another curve, describing the relationship between heat flux and temperature. Kuhn established a heat exchange coefficient A, which is the derivation of that curve in the point of non heat flux. The coefficient is proportional to the cooling rate and can be calculated as a function of water temperature and wind velocity. Kuhn expressed the net rate of heat exchange at the water surface as

$$H = \frac{\partial H}{\partial T} \cdot (T - T^+) = A \ (T^+ - T) \tag{3}$$

in which
A = total heat exchange coeffient
T^+ = equilibrium temperature
T = water surface temperature

This equation shows, that the net rate of heat exchange is equal to the product of the heat exchange coefficient and the difference between the equilibrium temperature and the water surface temperature.

Combining Equation 2 and 3 gives

$$\frac{dT}{dt} = - \frac{A}{h \cdot \rho \cdot c} \ (T - T^+) \tag{4}$$

Assuming constant meteorological conditions, this equation is soluble and the solution shows the wellknown exponential course of temperature until reaching the equilibrium temperature.

$$T - T^+ = (T_O - T^+) \cdot \exp \ (- \frac{A}{g \cdot \rho \cdot c} \ t) \tag{5}$$

Besides the heat exchange coefficient, water depth is the essential parameter of the range of temperature variation with time. For example, in case of wind velocity of 2 m/s and water depths of 5 m the half-life-period amounts to 8 days. Normally constant meteorological conditions can not be expected throughout such long periods.

Furthermore an applicable computation of heat exchange coefficients is only possible, if wellknown data about evaporation and condensation are available. This is one difficulty when using the exchange coefficient for computation of heat exchange between water surface and the atmosphere.

Another problem is the determination of the equilibrium temperature, because generally the actual water temperature is not equal to the equilibrium temperature. There may occur large differences between actual temperatures and equilibrium temperatures with time of a day or under consideration of daily averaged values all the year round.

Considering a period of one day, normally the maximum of the equilibrium temperature will occur at noon due to solar radiation and the minimum at night. The temperature T_W of a water body will follow the variation of the equilibrium temperature T^+ with a phase lag.

Considering the variation of temperature throughout a year there are similar curves with maximum in summer and minimum in winter. In spring and early sommer the actual water temperatures are normally lower than the equilibrium temperatures, whereas in autumn and winter the relation is contrary.

If the equilibrium temperature is higher than the temperature of a water body including already artificial heat water temperature will continue to increase and the artificial heat will even remain in the water body.

The application of the heat exchange coefficient under the assumption that water temperature without any artifical heat is equal to the equilibrium temperature leads to an easy calculation. This assumption, however, will only casually agree with real conditions. Therefore is was thought desirable to determine the heat exchange between water surface and atmosphere by experimental evaluations.

3. EXPERIMENTAL PROCEDURE

3.1 Measuring Equipment

The measuring equipment consists of two similar plastic pools with a free water surface, 2.00 m in diameter and 30 cm deep. They are well insulated on the sides and bottom and generally filled to the same depths to within 3 cm of the top of the pool sides. Water loss by evaporation is refilled automatically. Identical stirring devices placed in each pool keep the water well mixed.

The pools are placed on a platform above the water surface of the river. They are directly exposed to the climate of the river region investigated.

The measuring equipment further consists of thermo-couples for temperature sensing, water level gauges, a flowmeter, electrical heating elements, a refrigerator, heat exchangers and a 12-point recorder. The arrangement of the measuring equipment is shown in Fig. 1.

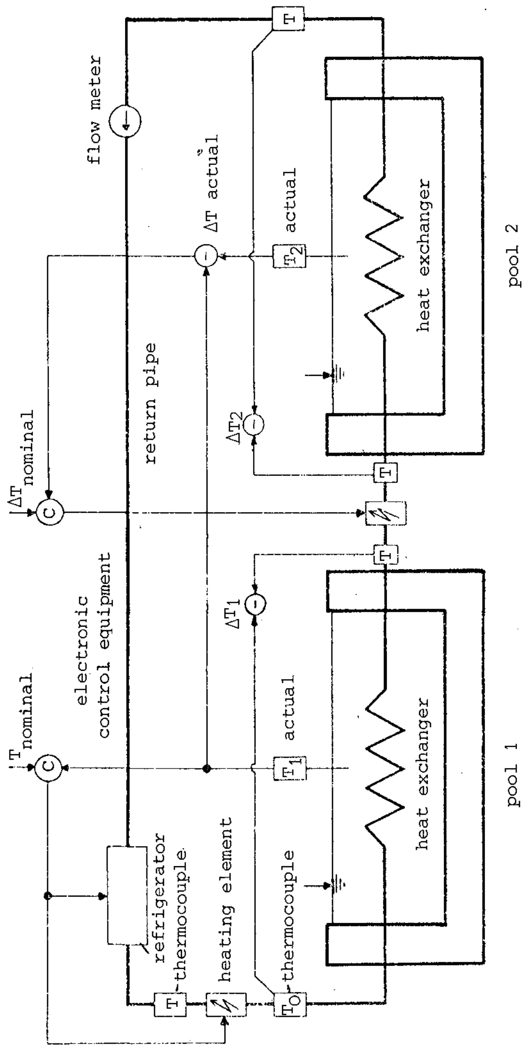

Fig.1
Scheme of the Measuring Equipment

Additionally all relevant meteorological data are registered on the platform and recorded.

The principle of the measuring equipment is that both pools have equal dimensions and that they are exposed to the same meteorological conditions.

By means of an electronic control unit the water of the first pool is cooled or heated corresponding to the actual river temperature T_1. The water of the second pool is also cooled or heated, but is controlled by a constant difference of temperature $\Delta T = 2.00^{\circ}C$ above the temperature of the first pool (tolerance $0.01^{\circ}C$). Water temperatures T_1, T_2, and the difference of temperatures ΔT are measured and recorded. The power inputs W_1 and W_2 are determined by measurements of initial and return temperatures at the heat exchangers and quantity of flow.

The difference of input $W_2 - W_1$, which is necessary to maintain the range of $\Delta T = 2.00^{\circ}C$ is equivalent to the net rate of the heat exchange between the water surface of a river artifically heated by $2.00^{\circ}C$ and the atmosphere.

In analogy to Kuhn the heat flux can be expressed as the difference between equlibrium temperature and water temperature multiplied with the heat exchange coefficient, now called α, because it is evaluted experimentally.

$$H_1 = \alpha_1 \ (T^+ - T_1) + W_1 \qquad H_2 = \alpha_2 \ (T^+ - T_2) + W_2 \tag{6}$$

in which

W_1 = power input to pool 1) (heating +, cooling -)
W_2 = power input to pool 2)
α_1, α_2 = experimental heat exchange coefficient
T^+ = equilibrium temperature

The constant difference of temperature implies, that the variation of temperature in pool 1 is equal to that of pool 2

$$\frac{dT_1}{dt} = \frac{dT_2}{dt} \tag{7}$$

and it follows, that the heat flux of pool 1 is equal to that of pool 2.

Assuming that for a low difference of temperature $\Delta T = 2.00^{\circ}C$ $\alpha_1 \approx \alpha_2 = \alpha$ Equation 6 produces

$$W_2 - W_1 = \alpha \ (T_2 - T_1) \tag{8}$$

and the heat exchange coefficient is

$$\alpha = \frac{W_2 - W_1}{T_2 - T_1} = \frac{W_2 - W_1}{\Delta T} \tag{9}$$

The equilibrium temperature can be determined by Equation 2 and 6:

$$H_1 = h \cdot \rho \cdot c \cdot \frac{dT_1}{dt} \stackrel{!}{=} \alpha \ (T^+ - T_1) + W_1 \qquad (10)$$

$$T^+ = \frac{1}{\alpha} \ (h \cdot \rho \cdot c \cdot \frac{dT_1}{dt} - W_1) + T_1 \qquad (11)$$

So the complex processes of heat exchange between water surface and atmosphere can be determined by measurements of temperature and power input.

3.3 Results of Measurements

The prototype of the measuring equipment described was installed on a platform above the water surface of the Lower Weser River, Germany, near by a nuclear power plant. The equipment was put into operation in April 1979 in connection with an already existing system of control points for water temperature in order to determine the cooling rate of river water artifically heated up by the discharge of cooling water.

Results of measurements are shown in Fig. 2 and 3, demonstrating the operation method of the measuring equipment. The water temperature of the first pool was controlled on the level of 18.3^{o}C corresponding to the actual river temperature. For that purpose it was necessary to heat the pools during the night and to cool it in the day-time.

The net rate of heat flux can be determined separately for each of the pools by the difference between the temperatures of forward and return flow (ΔT_1, ΔT_2) and quantity of flow in the heat exchanges. Furthermore the distance between the curves of ΔT_1 and ΔT_2 is proportional to the heat exchange coefficient α. Fig. 3 shows important meteorological data.

The results of the measurements have been compared with results of heat exchange computations which are conducted on the basis of meteorological measurements. This comparison yielded differences of a certain tendency, which requires further research. For example, measurements conducted during the night obtained better correspondence to the computations than those conducted in the day time.

4. CONCLUSIONS

The surface heat coefficient and equilibrium temperature can be evaluated using the experimental method described here. An advantage of this method consists in determining the complex processes of heat exchange at the water surface by simple measurements of temperature and power input.

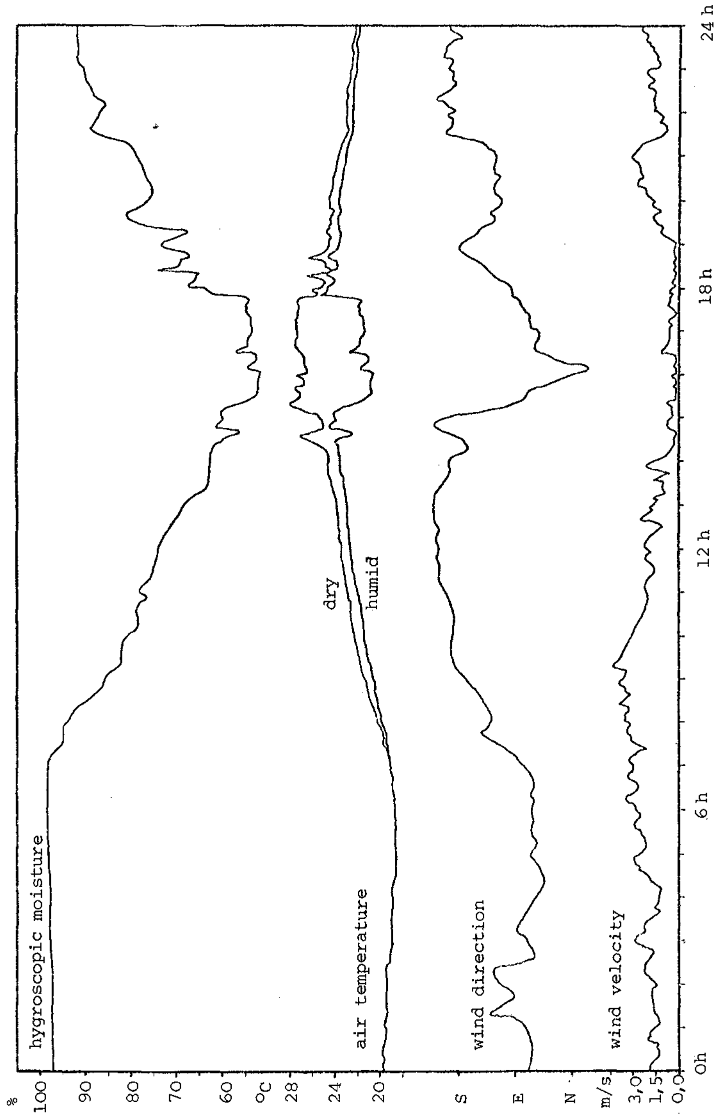

Fig. 2
Meteorological Measurements on 28.7.1979

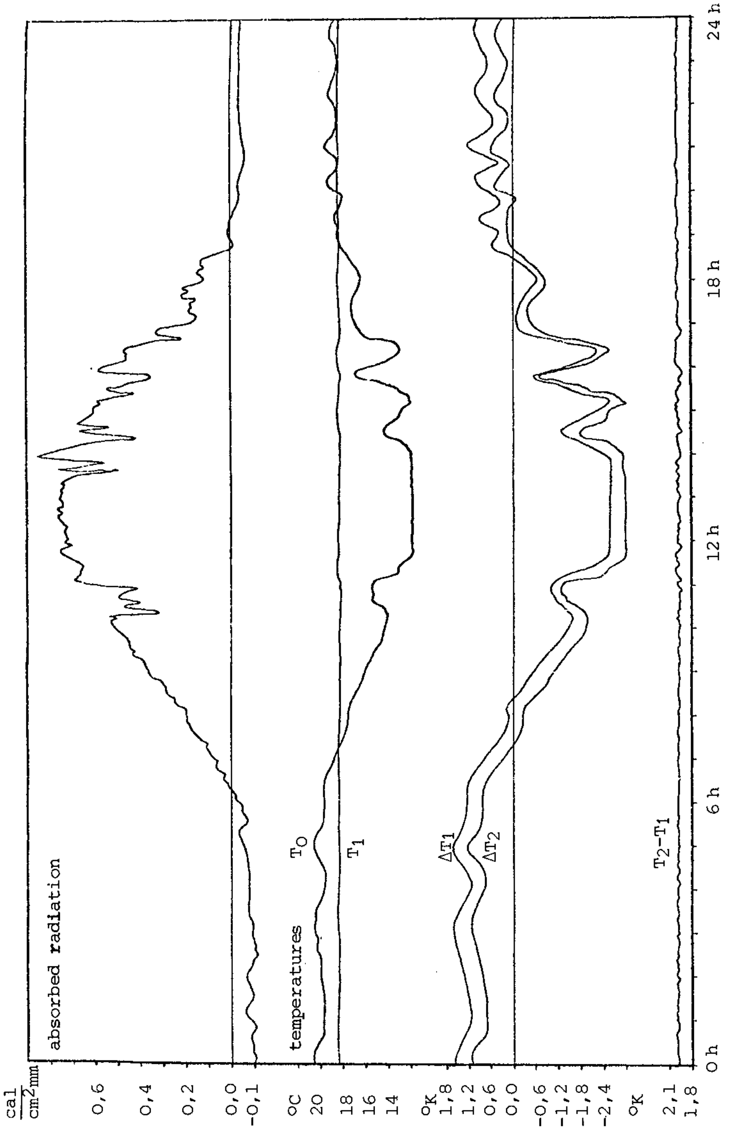

Fig. 3
Measurements of Heat Exchange on 28.7.1979

Because the physical actions of heat exchange at the pools are in principle similar to those at the river surface, different results are only imaginable as a consequence of different boundary conditions (wind, waves). Thus it is important to expose the pools as near the water surface of the river as possible.

Finally, a functional relation has to be found which allows to apply the results of pool measurements to the actual exchange at the river water surface.

5. REFERENCES

KUHN, W. (1972). Physical and Meteorological Considerations on the Use of Waters for Cooling Purposes. Arch. Met. Geoph. Biokl., Switzerland, Ser. A, 21, pp. 95 - 122