LIVE QUESTIONS IN THE THERMAL LOAD AND THERMAL POLLUTION OF HUNGARIAN RIVERS

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Abstract

Power plants using fresh-water cooling introduce waste heat into rivers or pools with their heated up cooling water. This amount of heat exceeds the amount of electric energy produced. This *thermal laad* may cause changes in the water quality and eventually even *thermal pollution.*

This study deals with the actual questions of thermal load and thermal pollution in Hungary. First it treats the *elements and system of physical processes of thermal loading*, then it points out the correlation between dhysical processes (hydrological-hydraulical) and *water quality* (mainly hydrobiological aspects). The second part of the paper makes the reader acquainted with measurements concerning the thermal load of significant power plants in Hungary along Danube and Tisza, then it draws conclusions about the increasing thermal load of the Paks Nuclear Power Station on Danube, then it makes a guess about necessary measures in the future for the protection of water quality. Finally, it shows the importance of a necessary colaboration between experts of energy production and water protection.

The importance of the subject in Hungary

Among environmental effects on living waters, the *thermal load* increasing due to the development of electric energy industry has an ever growing importance.

Cooling water leaving the condensers of power stations with temperatures increased by 8—10 °C introduces an amount of waste heat equivalent to 150—200% of the electric energy produced into the environment of the power plant. This amount of heat leaves through a cooling tower or cooling pool directly into the atmosphere in the case of closed, recirculation cooling (Fig. 1a), whereas upon applying fresh water cooling, the total amount of heat gets into the surface water, generally into a river (Fig. 1b) with the cooling water heated up, and upon using a follow-up cooling tower also a significant part of the total amount is led into the receiver (Fig. 1c). We have to count on the economic *fresh water cooling* and thus on the thermal load of rivers originating from it not only at present, but also in the future.

The *amount of excess heat* introduced into rivers changes the original, natural temperature conditions of the river, as a consequence of which the chemical, physical and biological characteristics determining the quality of water may become unfavourable, the undesirable phenomenon of *thermal pollution* may take place [1, 2].

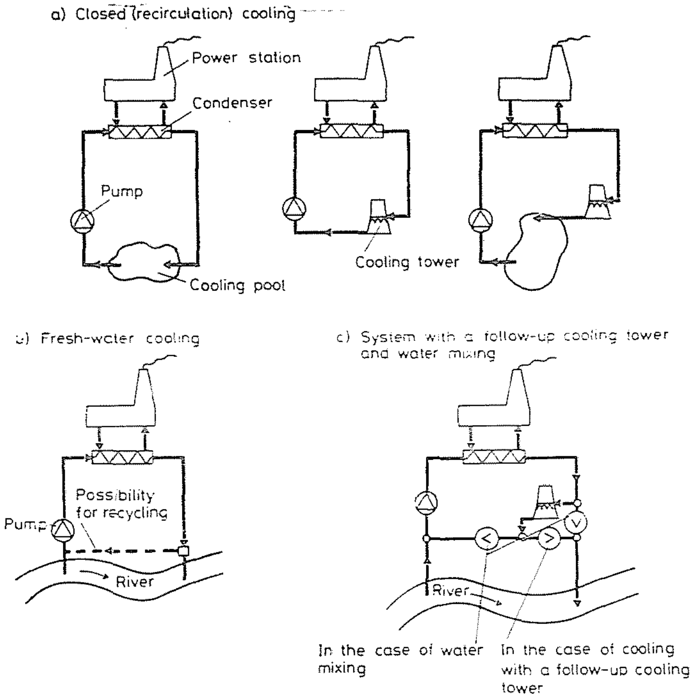


Fig. 1. Cooling systems

In Hungary, a danger of thermal pollution emerges at the Százhalombatta Power Plant and the Nuclear Power Station at Paks on the Danube, and at the Tisza Thermal Power Station on the Tisza river (Fig. 2).

According to present plans, heat reduction is realized by fresh water cooling in the condensers of the power plants. For the year 2000, hence these power plants would provide the vast majority of heat introduced into the rivers which would correspond to a water discharge of $Q = 300$ m^3/s heated up by $\Delta t = 9$ °C. Hence the commenced investigations were built upon the expected heat load increase. Due to the complex nature of the problem, the water intake, mixing, discharging and environmental effects of the waters heated up (as well as that of pollutants) are investigated by experts in different branches of science.

Studies reported here were aimed at the investigation of the *physical processes in thermal loading of rivers* [3, 4, 5]. The knowledge of physical processes and the *systematisation of hydrological-fluid mechanical experiences* are of basic importance for water-chemical, water-biological studies concerning the changes in water quality as well as for the determination of the maximum permissible limit of thermal load and thermal pollution.

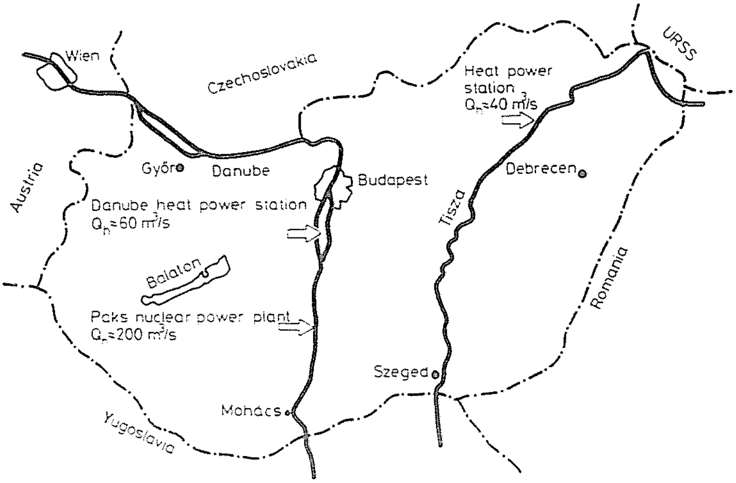


Fig. 2. Thermal load expected on Hungarian rivers in year 2000 Czechoslovakia, Soviet Union, Rumania, Yugoslavia, Austria

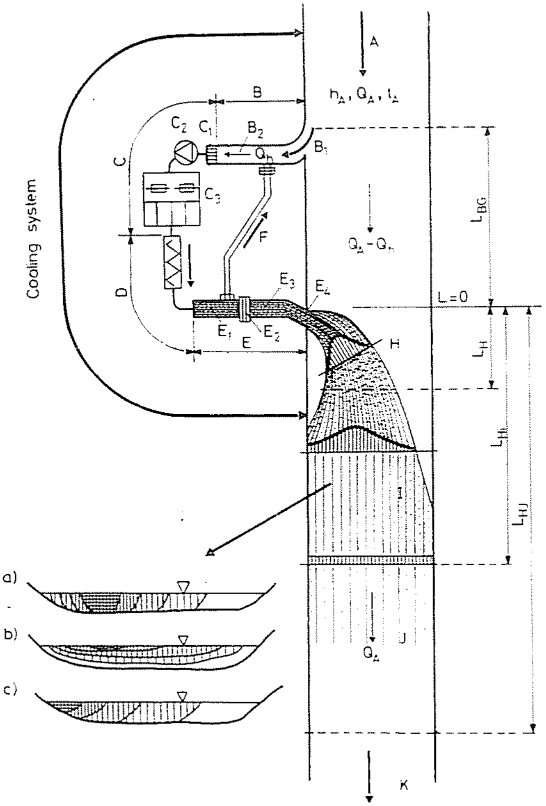


Fig. 3. Elements of physical processes in thermal loading

Thermal loading processes system

Composite processes of the overall process of thermal loading of rivers and heat reduction in power stations are shown in Fig. 3 [6].

In section A of the river *above the power plant* the water level, $h_{A(\tau)}$, and the mean velocity, $\bar{v}_A$, vary in time, corresponding to hydrological conditions. The heat transfer, Q_c, of the river is:

$$Q_{cA} = Q_A \varrho c_p t_A,$$

where

Q_A: water discharge,
ϱ: density of water,
c_p: specific heat of water,
t_A: temperature of water.

For absorbing the waste heat of the power plant, the cooling water discharge taken from the river, Q_h, goes through the processes of *cooling system* $B-E$. In ground state power plants Q_h is constant, whereas in peak plants it varies in time.

In process B of *water intake* the cooling water flows through a connection (engineering structure) to the river, B_1 and an open surface channel, B_2 towards the power plant with a water surface and mean velocity determined by the water level.

Process C of *water-lifting and purification* consists of grid filtration C_1, water-lifting (pumping plant) C_2 and water purification technology C_3. After the pumps, water proceeds through the process under pressure and has a practically constant velocity.

Cooling water passes along the power station through *heat exchange condensers* (process D). Heat transfer occurs during a flow of $v = 1.0$ m/s velocity through the 10—20 m long condenser tubing having a diameter of 22—38 mm. In the course of this process, cooling water is heated up in the average by $t_{\max} = 8-10$ °C.

The excess heat taken up is:

$$Q_c = Q_h \varrho c_p \Delta t.$$

After the power plant, cooling water proceeds towards the receiver in process E of *warm water flowback*. At section E_1 of the open surface channel the water level is practically constant, in section E_2 being after the weir or E_3 after an overflow as well as in mouth E_4 it varies depending on the momentary water level of the receiver. A cooling back of the water may be started here, the temperature decrease being Δt_E.

Recirculation F is applied in winter operation if:

$$t_A < 8\ ^\circ\mathrm{C}$$

in order to hinder overcooling or for deicing cooling water channel.

The *flow pattern in mouth*, H is determined by the mode of introduction, the ratio of discharges of the river and the cooling water, velocity relations and the difference in specific gravity. The warm water discharged into the river thus takes up the motion state of the river only after covering a distance L_H.

In section I of the river, *turbulence* results in the levelling of temperatures in the transverse profile in a distance L_{HI} from the mouth.

Process J of *further cooling back*, or river length L_{HJ} needed for total cooling back probably exceeds the distance L_{HI} necessary for total mixing — especially for narrower rivers —, but for very broad rivers the case where

$$L_{HJ} < L_{HI}$$

is also imaginable.

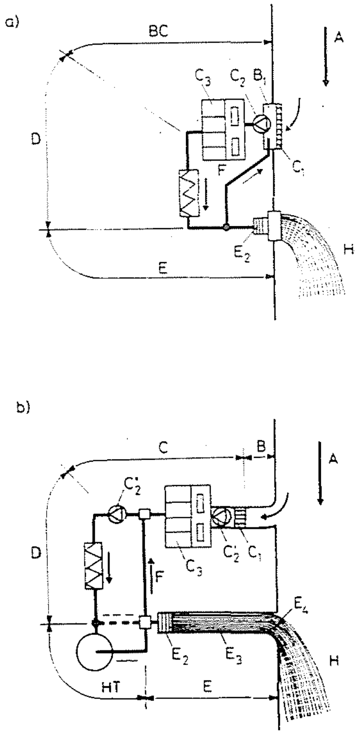


Fig. 4. Cooling system with coastal engineering structures (a) and two-step pumping (b)

The above correlation between mixing and cooling back is determined besides the nature of the flow pattern at the mouth and the geometric properties of the river also by the *characteristics of the temperature distribution in the transverse profile.* Figures 3. a, b and c show that in the transverse profile of the river isotherms form as a result of differences in specific gravities and turbulences.

After cooling back is finished, in section K of the river being after the thermal load, natural temperature relations prevail again.

The heat balance of section $A-K$ of the river thus may be given from the viewpoint of a water particle moving with a velocity of $\bar{v}_{AK}$ by neglecting temperature variations due to natural reasons as follows:

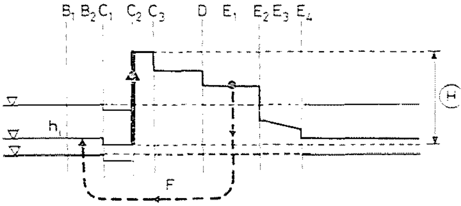
$$Q_{cK} = Q_{cA} + (\Delta t_{\max} - \Delta t_E)\, Q_h c_p\, \varrho W \,. \,.$$

Similar behaviour is observed for thermal loads of the cooling system or the river in cases shown in Fig. 4.

a) *Water intake and flow-back realized by coastal engineering structures* results in a similar process, only effects due to cool and warm water channels are left out.

b) *Two-step pumping* provides a possibility for the eventual application of follow-up cooling towers, e.g. is critical in summer from the point of view of thermal pollution. Part of the extracted waste heat can be transferred directly into the atmosphere in this way, naturally only by a significant excess coast in investment and operation.

a) One-step pumping



b) Two-step pumping

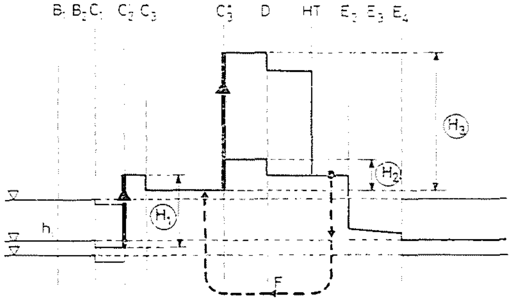


Fig. 5. Hydraulic longitudinal sections of cooling systems

This latter case may be illustrated by the hydraulic longitudinal profile of cooling towers operated by simple fresh water cooling and two-step pumping shown in Fig. 5. The manometric lifting heights of pumps are in the case of Hungarian rivers:

$H \approx 15$ m
$H_1 \approx 11$ m
$H_2 \approx 5$ m
$H_3 \approx 20$ m.

Effects and consequences in the process of thermal pollution

The most important effects, processes and conditions for cooling water can be represented as shown in Fig. 6:

a) *Thermal effects* start with the sudden rise in the temperature of water in condensers D and they continue in channel E and in section H—J of the river.

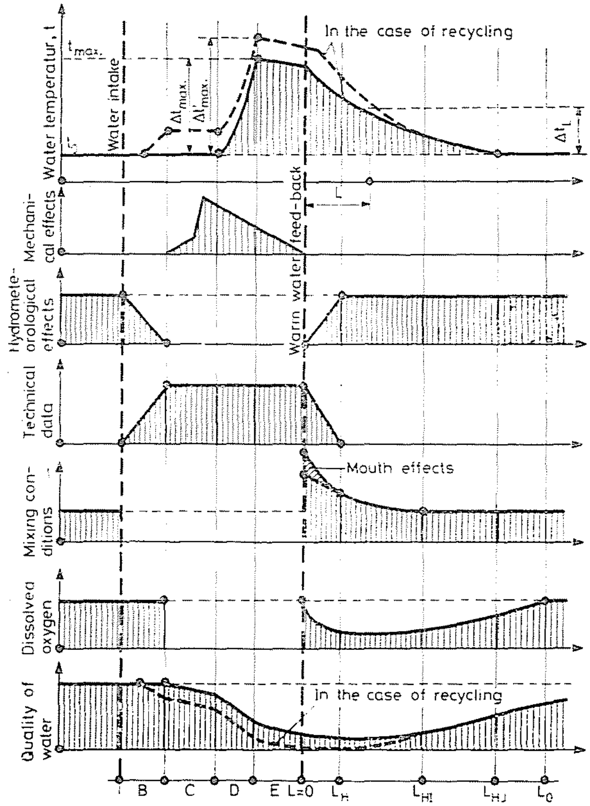


Fig. 6. Processes and effects of thermal pollution

b) *Mechanical effects* on the water and water organisms are caused by elements C_3, D and E_2.

c) The above effects and consequences are basically influenced by the

- hydrological-meteorological characteristics of the cooling system and the receiver,
- technical characteristics of the cooling system,
- hydraulic conditions in the river.

The hydrological-meteorological effects prevail in rivers with large surfaces and changing water levels, whereas they hardly or not at all appear in the individual elements of the cooling system. In the latter, the characteristics of water motion are determined by the *technological parameters* of the power plant.

Concerning research the complex process of thermal load — thermal pollution may be separated into *two sections different in their nature*:

- section *B—E of the cooling system*,
- processes *G—J in the river*.

The characteristic processes of the first section may be generalised to some extent, i.e. experience can be transferred to technologically similar systems of other power stations. To the contrary, phenomena in rivers are more complex, thus, results of researches are less to be generalised. This concerns mainly the mixing of the warm water, for this, *diffusion conditions and mouth phenomena are decisive*.

d) *The amount of dissolved oxygen* in the water is also determined by these processes. Based on the analysis of the physical processes it can be established that:

- Dissolved oxygen is influenced by the technical realization of the cooling system.
- In the river, it is the result of hydrometeorological conditions and biological activity.
- In the warm water the amount of dissolved oxygen can be expected to decrease owing to reaction kinetic reasons.
- The question is also related to the pollution of the given river, to the character and phase of biological processes taking place in it.

e) When the winter operational mode of warm water recycling is used, the discharge of cooling water led back, O'_h may decrease to

$$Q'_h = 0.2 - 0.5\ Q_h$$

whereas at mouth H even an excess temperature of

$$t'_{\max} = 14 - 16\ ^{\circ}\mathrm{C}$$

may appear, thus mixing is thereby modified in the river.

f) As a result, negative or positive changes in the water quality may occur already in section *C* (in the case of recirculation already in section *B*). In the case of an intensive thermal load, changes may last longer than necessary for reestablishing the original physical state of the river in distance L_{HJ}.

Considering the characteristics of thermal pollution and also results published in the literature, it is obvious that for the foundation of further theoretical and water quality evaluations field experiments are necessary.

Connection between the physical and water-biological processes of thermal pollution

The elements of thermal load are expediently discussed from the viewpoint of the classification of aquatic life space [7] by considering the concrete thermal effects on individual water particles and organisms (Fig. 7).

— The water temperature in the *undisturbed section of the river* is the mean value t_A. All the living organisms in the transverse profile of the river are influenced by any change in this value.

— Grid and sieve filtration (composite process *C*) let only organims moving together with the water into *the cooling system*, thus mechanical and thermal effects affect here only these organisms. In condensers (composite process *D*), cooling water is heated up very rapidly, in about 6—12 s to the mean maximum temperature, t_{max}. However, part of the water particles and organisms are in direct contact with the tube walls of about 40 °C for a longer or shorter period of time, whereas other particles are heated up only by mixing, i.e. in an indirect way.

— In process *E*, i.e. *the discharge of warm water* (warm water channel), in general, temperature is the same for all organisms. The major part of cooling

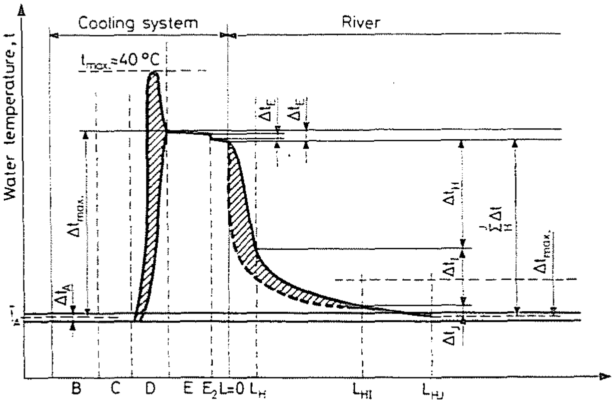


Fig. 7. Longitudinal change of water temperatures

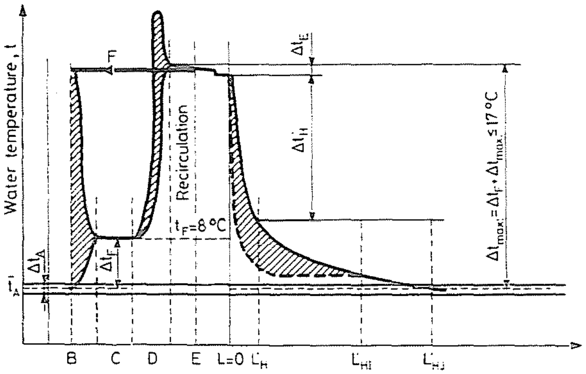


Fig. 8. Water temperatures in recirculation working mode

is provided here by the decrease in the temperature of the airing weir, Δt_{E_2} in which, however, the drifting organisms are subjected also to mechanical effects.

— In sections *I* and *H* of *mixing in the mouth and river*, the temperature of moving particles and thus that of the different types of biotopic communities is different, up to distance L_{HI} of temperature levelling in the transverse profile.

— In distance L_J of *temperature levelling*, again the whole of the water discharge of the river is influenced by the still existing elevated temperature t_J.

The above course of temperature change in the water can be influenced in winter by using a *recycling operation mode in the cooling system*. In this case (Fig. 8), the excess temperature of water entering the river may reach even

$$\Delta t'_{max} = \Delta t_F + \Delta t_{max} \approx 17 \text{ °C}.$$

In this case as well, organisms moving together with the recycled water reach the cooling system.

The load on aquatic living space described has different effects on individual biocoenoses:

— on *plankton* moving together with the water,
— on *benthon* living in or attached to the sea bottom,
— on *nekton* capable of own motion.

The most important biocoenosis of rivers is generally the *plankton* (7 determining the self-purification ability of rivers. Since they drift in the water and move together with it, on those existing in the cooling water, the thermal load has a direct influence. Therefore, following consequences are probable:

— *Mechanical damage* in the course of passing through the power plant and its equipments,

— *direct thermal effects* may cause the death of living beings or changes in their life processes (growth, proliteration, etc.), or they might even lead to a rearrangement of the ecosystem. For all species, a definite upper level (lethal) of direct thermal effects exists.

— In the case of *indirect thermal effects*, lack of oxygen, or as a consequence, lack of food, as well as unfavourable changes in life processes (e.g. in succession) of the living being may occur. From this point of view, the oxygen content of the river is of primary importance. Special care has to be taken of the sections of rivers impounded being deeper and poorer in oxygen.

— The *benthon* sitting on benthos is not moving together with the water, thus — in the case of continuous operation of the power plant with a practically constant thermal load — they are subjected also to a constant thermal load, hence it may be supposed that they are more heat-resistant than plankton.

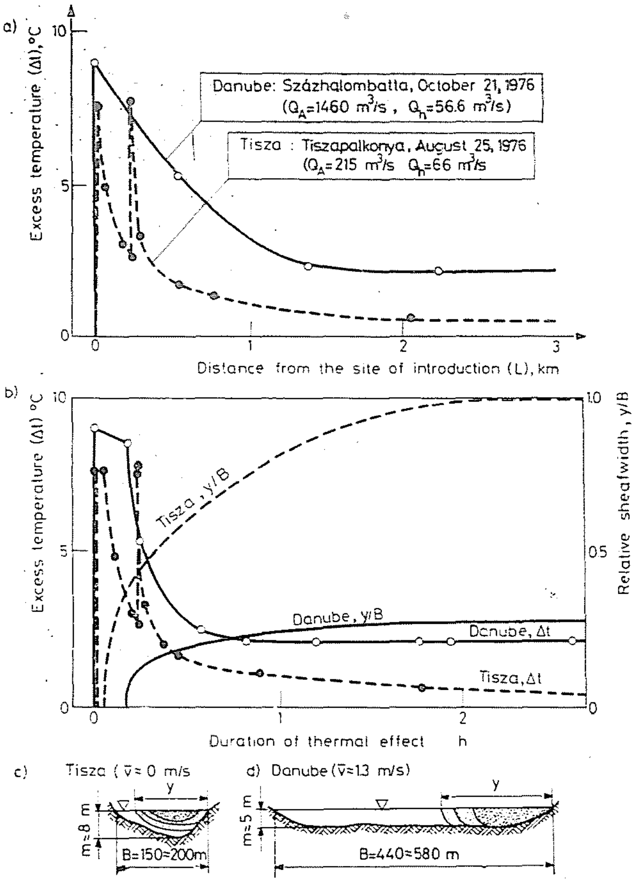


Fig. 9. Characteristics of thermal load on Danube and Tisza

— The effect of temperature changes is best known for fish belonging to the *nekton*. For fish, a small uniform elevation in the temperature is of minor importance, however, a longer residence in the warm neighbourhood of the mouth or in the warm water channel may be dangerous.

The above effects and dangers on biocoenoses of rivers can be judged only on the basis of the concrete thermal load of a given river.

Characteristic processes of thermal loading in Hungarian rivers

First detailed field experiments were carried out in the period of 1975—1978 in the Százhalombatta section of the *Danube* and the Tiszapalkonya section of *Tisza* (Fig. 2) in cooperation with colleagues from the *Research Institute of Electric Energy* (VEIKI) [3, 4]. A comparison of thermal loading on the Danube and Tisza is possible on the basis of Fig. 9 representing the measurements [8]. The discharge of cooling water introduced, Q_H was about 3% of the discharge of the river, Q_A in both cases, thus the differences are due to the individual characteristics of the rivers and of warm water introduction and not to a difference in thermal load.

For the longitudinal change in excess temperature Δt, a rapid decrease is observed in both cases.

However, there are significant differences in the spatial position of the warm water sheaf in the transverse profile. This is mainly due to the difference in the hydraulic characters of the two rivers. The subsiding of warm water in the Danube is determined by the relatively small depth and higher mean velocity ($\bar{v} \approx 1.0$ m/s), whereas in the dammed section of Tisza by the higher relative depth and significantly smaller velocity ($\bar{v} \approx 0.3$ m/s). Thus

- in Danube a narrow sheaf near the bank
- in the dammed section of Tisza a rapid spread of the sheaf and its vertical temperature layering is the most important characteristic.

Correspondingly, the thermal effect on the characteristic ecocoenoses of the two rivers is also different.

— Thermal effects on *plankton* are significantly different mainly in the initial, "thermal shock" period. In Danube, excess temperature exists even after several hours of residence time, whereas in Tisza, a more rapid temperature decrease and due to the "floating up" of warm water an increased load of surface layers are to be expected.

— In Danube, the temperature of *benthos* is practically the same as that of surface layers, thus benthon is influenced by thermal effects in the same way as plankton in the same vertical section. To the contrary, in Tisza the thermal effect of the sheaf floated up is felt at the (sea) bottom only in a distance of about 1—2 km from the mouth.

— From the point of view of *nekton:* the section of the warm water sheaf with a higher temperature spread over the whole width of the river in Tisza, whereas in Danube, the transverse profile outside the sheaf provides an undisturbed "channel" for the fish.

A detailed study of hydrobiological consequences based on the above characteristics of thermal load has been carried out by the Research Institute for Water Economics [5].

Thermal load on Danube originating from the Paks Nuclear Power Plant

The above aspects in the study of thermal load can be successfully applied also to the present and future effects of the Paks Nuclear Power Plant being presently built, which uses the largest amount of cooling water.

Surface studies were started in 1982, before the operating of the Nuclear Power Plant by surveying the initial state with the determination of the hydrological and hydraulic characteristics on this section of the river. In 1983, following the starting the operation of the first 440 MW block of the plant, the subsiding of the relatively small amounts of warm water on the Danube, in the period of 1984—85 the mixing and subsiding of the water from the two blocks

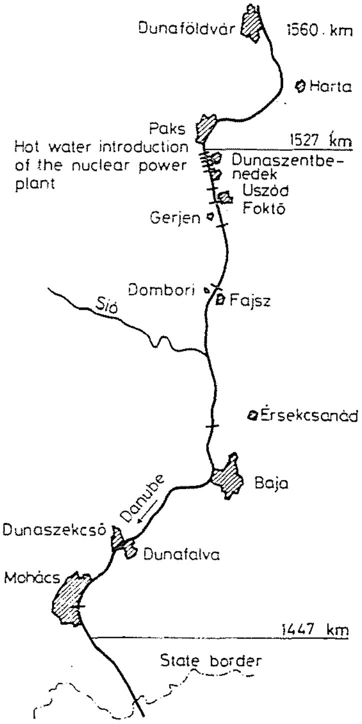


Fig. 10. Section of Danube studied in 1985

being in operation were studied on the whole section of Danube below Paks as ar as Mohács (Fig. 10), in accordance with observations concerning the quality of water which were carried out by other institutions.

Some results:

— The 50 m^3/s cooling water with an excess temperature of 8—10 °C of the Nuclear Power Plant enters the Danube as a warm water sheaf near to the bank, and correspondingly to this special section of the river, the *excess temperature decreases rapidly at the beginning.* Figure 11 illustrates this phenomenon at the lowest water level. In this case, even at extremely low levels of water, the excess temperature, Δt does not exceed 3 °C at the cross dam being about 500 m far from the site of warm water introduction.

— The excess temperature of the warm water sheaf decreases only very slowly *in the further sections of the river* (Fig. 12) but everywhere remains below the preestimated value. Excess temperature near to the right-side bank varies presently proportionally to the water discharge and thermal load in a length of

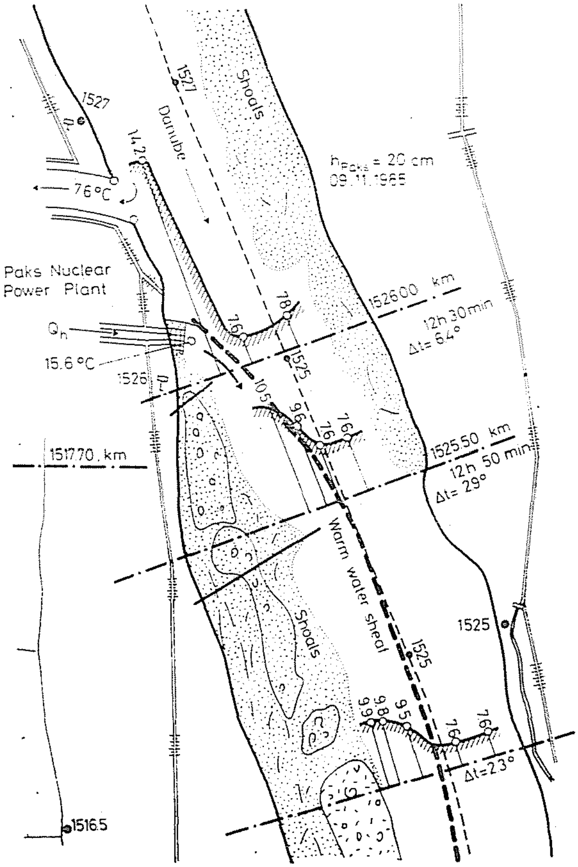


Fig. 11. Initial section of warm water sheaf

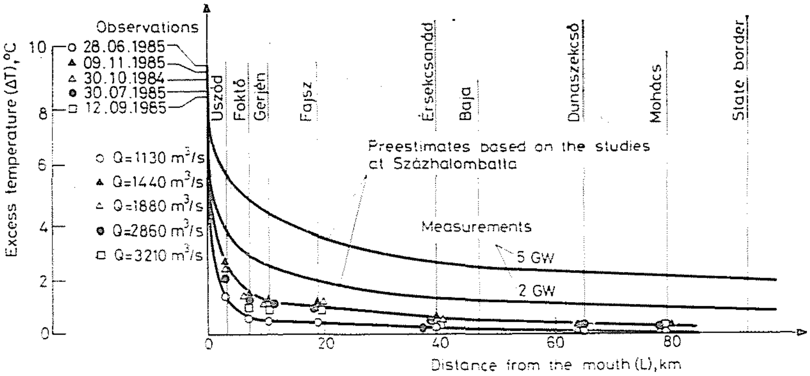


Fig. 12. Decrease of excess temperature to the frontier at an output of 880 MW of the Paks Nuclear Power Plant

40 km, whereas excess temperatures of 0.1—0.3 °C observed in further sections are probably at least partly due to local effects.

From these observations it seems that the thermal load of the totally built out 4-block Nuclear Power Plant will remain below the preestimated value and thus it will not cause harmful changes in water quality in form of thermal pollution. In spite of this, the increase in the thermal load should be followed carefully, since the *initial quality of Danube*, previously unknown, may be decisive, it may influence the limit to which the present, unlimited use of *fresh-water cooling* may be maintained. Above this limit, the increasing demand on cooling water and the protection of water quality may necessitate some regulation.

Regulation — similarly to the practice of other countries — will probably occur by establishing *temperature limits*. According to hydrological studies, mainly plankton organisms moving through the cooling system together with cooling water, and microorganisms living in the mud of the warm water sheaf have to be protected. Summarising the results it seems that: [17]

— *the upper temperature limit allowed for a longer period* will be about 30 °C after the discharge of warm water,

— a permissible *temperature step* in $\Delta t \approx 15$ °C will be accepted relative to the natural temperature of the river, eventually with a seasonal variation,

— measures cannot be excluded concerning the *mechanical effects* on the microorganisms which move together with the cooling water.

If we want to estimate the *character and extent* of regulation in advance, then starting from hydrobiological demands and considering the present and future capacity of the Nuclear Power Plant, reasonable working conditions can be chosen:

The "*summer* and *autumn*" state represent maximum water temperature of the Danube and usually low water level, respectively (maximum temperature and highest relative thermal load). If temperature step Δt may also be dangerous from the hydrobiological point of view, then the so-called "winter" state, operation with *continuous warm water feed-back* should be realized. The same should be done in the case of very low water level and water temperature (the case of largest temperature step).

If we *estimate the modes and steps of future regulation* at the level of our present knowledge and based on the analysis of working states, the following can be established:

— up to the total performance of 1760 MW of the four blocks being built, fresh-water cooling may be maintained with practically no restrictions, because it will not cause any harmful effect on water quality.

— A certain enlargement of the power, eventually up to *3000—4000 MW* may be realized also by fresh-water cooling, but probably only with restrictions and with a controlled operation, in the case of an unfavourable water level or water quality with a *technical intervention for decreasing the temperature*. Among these, cessation of summer operation, letting the pump operate further after stopping the blocks, eventually planning and operation of excess pumping capacity, or in the worst case the decreasing of the output seem to be the possible solutions.

— In the case of *further extension*, fresh-water cooling might be applicable, but exact limits can only be set in the possession of the operational results for the first 4 blocks. Therefore, the necessity for a forced cooling cannot be disregarded, neither other technical-economical solutions for decreasing the temperature of cooling water. An important aspect is that the follow-up cooling tower in the warm water feed-back is not the only and best solution indeed. As far as no power plant series are built on the Danube, the primary problem is not the temperature increase in the total water mass in the river, rather the protection of the part of water passing through the cooling system. Thus every technical solution ensuring a rapid decrease in the temperature of water leaving the condensers (e.g. mixing with cold water, weir, a mouth ensuring laster mixing, etc.) may be equivalent to the cooling tower solution which requires high investments and operational costs and, at the same time, causing also mechanical effects. Thus an important task of future research is to search for such solutions and to utilize local resources.

Considering all this we mean that in the future an *efficient, elastic cooperation between experts of energy production and water protection possibilities will be necessary* rather than well-defined but rigid requirements and limits. By all means, limits determined with care and soundness will be needed also in the future, but the elaboration of a plan ensuring the application of limits in such a way which serves simultaneously economic energy production and water protection will also be necessary.

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