

Simulation of convective-conductive-radiative heat transfer in a cooling basin

P. Vaitiekūnas, V. Vaišis, D. Paliulis

Dept of Environmental Protection, Vilnius Gediminas Technical University, Sauletekio al. 11, LT-10223 Vilnius-40, Lithuania

E-mail: vaitiek@ap.vtu.lt, vaisisv@adm.vtu.lt, daipal@mail.ru

2006 11 28

PHOENICS 3.6.1 VR (2004), PC PENTIUM 2

Abstract

The three-dimensional mathematical model of complex research of heat and mass transfer in water media was used. This allows examining the interaction of some transfer processes in the natural cooling basin (lake Drūkšiai): heat convection and conduction, direct and diffusive solar radiation, variable density of the water and heat transfer coefficient of the water-air interface. The combined effect of these natural and unnatural actions determines the heat amount that the basin is able to dissipate to the surrounding atmospheric media in thermal equilibrium (no change in the mean water temperature).

This article presents a number of most widely used expressions for vertical and horizontal heat transfer coefficients. Suggestions are made that the mixing rate at the water surface is caused by natural space. There is analyzed case when there is no wind – calm.

Mean temperature profiles measured and predicted in the cooling pond, as well as on their time variation. A comparison experimental and numerical result showed a qualitative agreement. Simultaneous measurements and mathematical simulating using the instantaneous boundary conditions could find a better quantitative approximation, because of their possible variations in longer period of time.

Content list

1. Objective of work
2. Description of phenomenon simulated
 - 1) Qualitative
 - 2) Mathematical
3. Presentation of results
4. Conclusions
5. Literature References
6. Nomenclature

1. Objective of work

In order to qualify the cooling pond as an adequate thermal dissipater for the heat expelled by the station, will be necessary a composed analysis of the geographical, solar and water characteristics. The varying atmospheric and solar conditions make the basin to be a different characteristics dissipater everytime. Each one of the atmospheric or solar factors cannot determine by itself the dissipating capacity of the basin. All the elements are highly bound and must be treated simultaneously. The main objective is to establish these influences and to balance them with the heat coming from the nuclear

power station. This analysis will provide us a base for establishing the capability of the basin to dissipate the heat completely or otherwise to calculate the net mean water temperature increase.

The water temperature at the station intake will be the solution to a dynamic flowing and heat transfer problem that may be treated with PHOENICS CFD codes [1–3]. We attempted to apply these codes in a simulation of two-phase mathematical model of the hydrothermal processes in a cooling pond, including the effects of three-dimensional (3D) structure features of the transport, power and direction of the wind, variable density of the water, heat conduction at the water-air interface, direct and diffuse solar radiation [4].

In this paper is presented simulation of mass and heat transfer in a cooling basin according [2] but without wind blowing.

2. Description of the phenomenon simulated

2.1 Qualitative

This work describes the thermal evolution of a natural mass of water submitted to several environmental conditions. The length of the basin is 14.3 km, its mean width is 5.3 km and depth is from 7 to 35 m, area is 61.5 km². The basin domain will be discretized in polar cells; the basin contour delimited with fully blocked sells and porous regions (fig.1).

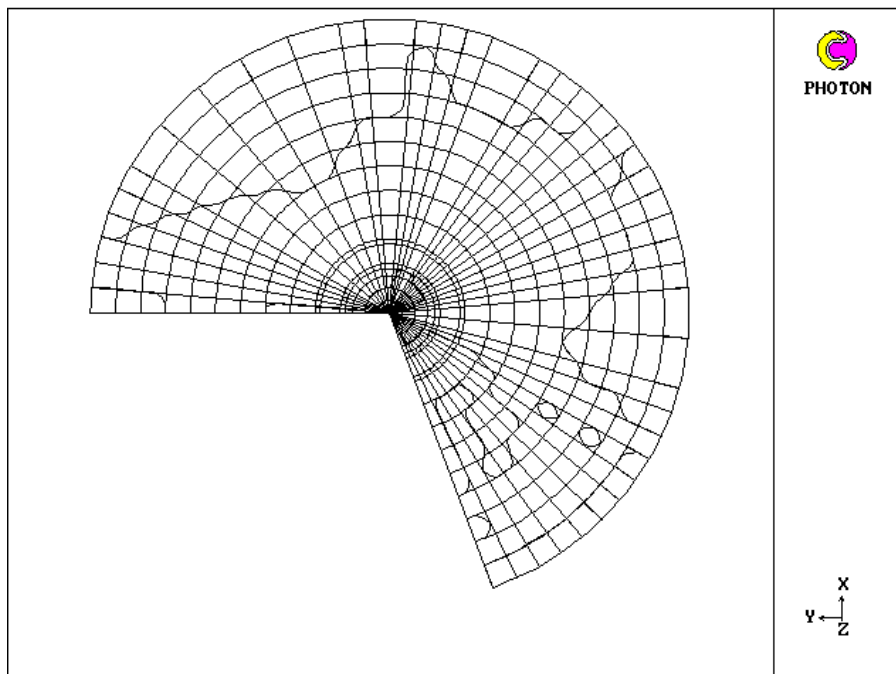


Fig. 1 Difference grid ($x \cdot y \cdot z = 41 \times 17 \times 9$). and contours of the lake Drukshiai

The taking of water at the station intake will be considered as an outlet boundary condition of the domain where outflow occurs. It will be a geographical fixed point. The outflow of the station will be an inlet boundary condition to the domain. It will present a heat and moment source constituting one of the main factors to be considered in the thermal analysis.

2.2 Mathematical

The dimension of the computational grid, distributed by a polar coordinates system, is (NX*NY*NZ = 41*17*9), that's to say, 6273 cells although some of them are fully blocked to the fluid and heat. Area discretisation is presented in the fig.1 (vertical coordinate is z).

Solution techniques and governing equations. In a general approach with recirculation of the streams and heat transfer, the problem is solved as the 3D set of the Navier-Stokes equations and energy equation for a two-phase theoretical model. The general expression is [2, 3]:

$$\text{div}(\rho V \Phi - \Gamma_{\Phi} \text{grad} \Phi) = S_{\Phi}. \quad (1)$$

The real properties of water will be implemented for accounting the existent links between its density, heat capacity, thermal conductivity etc. and the temperature (water in liquid state). These linking, and the establishment of conditions that simulates the action of the gravity, will establish the conditions for the possible formation of natural convection phenomenon and buoyancy forces.

The program codes used evaluate density of the water as a function of temperature [3]:

$$r = (999.83952 + 16.945176t - 7.9870401 \times 10^{-3} t^2 - 46.170461 \times 10^{-6} t^3 + 105.56302 \times 10^{-9} t^4 - 280.54253 \times 10^{-12} t^5) / (1 + 16.879850 \times 10^{-3} t) \quad (2)$$

The existence of a density gradient combined with a body force as the gravity action may cause a buoyancy force responsible of a free convection phenomenon, which may be important in the fluid motion. However, it will be a good approximation to consider constant other water properties, as the thermal conductivity or heat capacity, because of less effect of their respective gradients on the fluid motion.

Surface exchange. Considering adiabatic bottom and walls, the only capacity of thermal dissipation of the mass of water occurs by means of the heat exchange at the surface with the atmosphere. The main factors considered which will determine as much the global distribution of temperature as the amount of total dissipated energy. The addition of the net effects of these energetic factors will represent the amount of global energy that the basin surface is capable to dissipate.

We will study the distribution of temperature at the surface of the basin because, although the global mean temperature of the basin may increase, it doesn't mean that couldn't be appreciated certain change of the temperature at the station cooling water intake.

Forced convection exchange. The incidence of the hot water stream into the basin implicates the inclusion of a heat transfer forced convection factor in the near field zone and heat conduction in the water space.

Incidence of direct solar radiation. The incidence of solar direct radiation over the basin surface induces the heating of the water; its value depends on its specific heat at constant pressure ($C_p = 4183 \text{ J}/(\text{kg}\cdot\text{K})$), so that $Q_{sun} = C_p T$. The values of Q_{sun} in Ignalina (Lithuania) are picked up from the table 1.

Table 1. Values of the mean solar intensity (S^h) on horizontal in a mean day of every month in Ignalina

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
$S^h, \text{W}/\text{m}^2$	70	200	240	316	392	436	402	326	275	170	100	70

The effects of these incidences will be affected by the optical reflection over the surface, represented by a determined index (not all the incident energy is transmitted and absorbed). Only part of the net energy that impinges on the surface of the basin (table 2) is used for increasing the heat of the water. The residual energy is lost in form of reflected energy. This factor will depend on the incidence angle of the solar beam and the refraction index of the water $n=1.33$ (ignoring its wavelength dependence). Both contributions are related each other by means of the Fresnel laws. The incident radiation fraction that penetrates the basin surface (P), and is absorbed by the water for its posterior transformation in heat, is expressed in the Frenel formula:

$$P = 1 - \frac{1}{2} \left[\frac{\sin^2(z - \theta_r) + \operatorname{tg}^2(z - \theta_r)}{\sin^2(z + \theta_r) + \operatorname{tg}^2(z + \theta_r)} \right], \quad (3)$$

where θ_r is refraction angle on the water surface, z is zenithal solar distance ($90^\circ - \text{solar altitude}$). We will use too the Snell refraction law in order to determine θ_r as a function of the refraction index n and the solar zenithal distance z :

$$n \sin \theta_r = \sin z. \quad (4)$$

Incidence of diffuse solar radiation. The diffuse solar radiation is also an important factor since its value oscillates from a 13% of the direct radiation incidence for high solar altitude (90°) to a 150% or rather for smaller altitudes.

On clear days could be established the next experimental table which relates the solar altitude with the direct radiation fraction that constitutes the diffuse radiation, table 2.

Table 2. Percentages of direct radiation which constitutes the diffuse radiation as a function of the solar altitude

Solar altitude	I_{solar} , %	Solar altitude	I_{solar} , %
5	148	50	17,24
10	75,5	55	16,02
15	51,3	60	14,93
20	39,16	65	13,99
25	31,89	70	13,19
30	27,04	75	12,50
35	23,58	80	11,89
40	20,98	85	11,36
45	18,96	90	10,89

The data of the table 4 are fitted by means of an equation that relate the solar altitude and the percentage of direct radiation [1, 3]. The adjustment equation that we will used in the program in order to determine the diffuse radiation, is of the form:

$$I_{\text{solar}, \%} = a + b/h, \quad a = 2.807, \quad b = 727.1 \quad (5)$$

Particularizing for Ignalina, the values of the monthly solar altitude has been calculated from equation:

$$h = \arcsin(\cos \varphi \cos \delta \cos \gamma + \sin \varphi \sin \delta) \quad (6)$$

where h is solar altitude ($^{\circ}$), γ is solar hourly angle ($^{\circ}$), φ is geographical latitude ($^{\circ}$), δ is solar declination ($^{\circ}$): $\delta = 23.5 \cos(30K - 187)$ and K is number of month set (1, 2, ..., 12).

Consequently, we will introduce a source of additional radiation whose value will be a determined percentage of direct incident radiation and this will establish the effect of the diffuse radiation over the basin surface.

Radiative exchange atmosphere-water and water-atmosphere. The heat exchanges by the radiation between the atmosphere and the water or vice versa is produced by the mere fact that both mean possess a different temperature of the absolute zero. This quantity of energy is interchanged and transported by means of emissions of electromagnetic nature in a band of infrared emission. The global amount of energy is obtained by integration above all the wave longitudes of the band of emission, resulting in a numerical relation that relates the energy emitted by a body as function of its temperature. This relation is the Stefan-Boltzman law and will be applied to evaluate the effect that this exchange of energy on the water temperature:

$$Q_{rad} = 4\epsilon\sigma(T_{H_2O}^4 - T_{air}^4), \quad (9)$$

where ϵ is the emissivity ($0 < \epsilon < 1$), σ is the Boltzman constant $\sigma = 5.777 \times 10^{-8} \text{ W/m}^2\text{K}^4$. The emissivity ϵ is characteristic of each medium, and represents the effective difference of the radiant medium with a perfect black body emission at the same temperature. For Druksiai lake $\epsilon = 0.96$.

3. Results and consideration

Therefore a variable-step grid was constructed, Fig 1. It covers only a certain part of the surface and the range of integration with respect to the normal covers a 10 m layer of water. Cross section of the intake and outflow channel is 150x2.5 m, intake velocity $U_0 \approx 0.2 \text{ m/s}$., discharge rate $G \approx 80 \text{ m}^3/\text{s}$.

In Fig 2 are presented mean temperature profiles predicted in the cooling pond at various time intervals.

Predicting the mixing of the hot and cool water in the lake is a complicated process. The predictions is in a good agreement with the measured results, Fig 3, because there are no wind blowing, only forced convection and conduction in the water, direct and diffuse solar radiation, radiative exchange atmosphere-water and water-atmosphere.

Measurements [5] and numerical prediction show a two-layer near field mixing structure, with the upper layer about of the 2.5 m thickness.

Performed numerical experiment to show solar radiation factor impact to the basin heat exchange. There were performed two numerical experiments with different heat exchange mechanisms. The results of 1st experiment with local temperatures (t °C) are presented in table 3, the location coordinates of the basin (see Fig. 1) are x_3, y_i ($i=1,2,\dots,17$), $z_9=\text{constant}$.

The coordinates are given for basin sector near the intake of water canal. The primary conditions of experiment are following: the calm air temperature 25.9 °C, inlet water temperature 36 °C, direct solar radiation intensity 500 W/m², diffuse solar intensity 100 W/m², air humidity 75 %, water discharge rate $G=80 \text{ m}^3/\text{s}$.

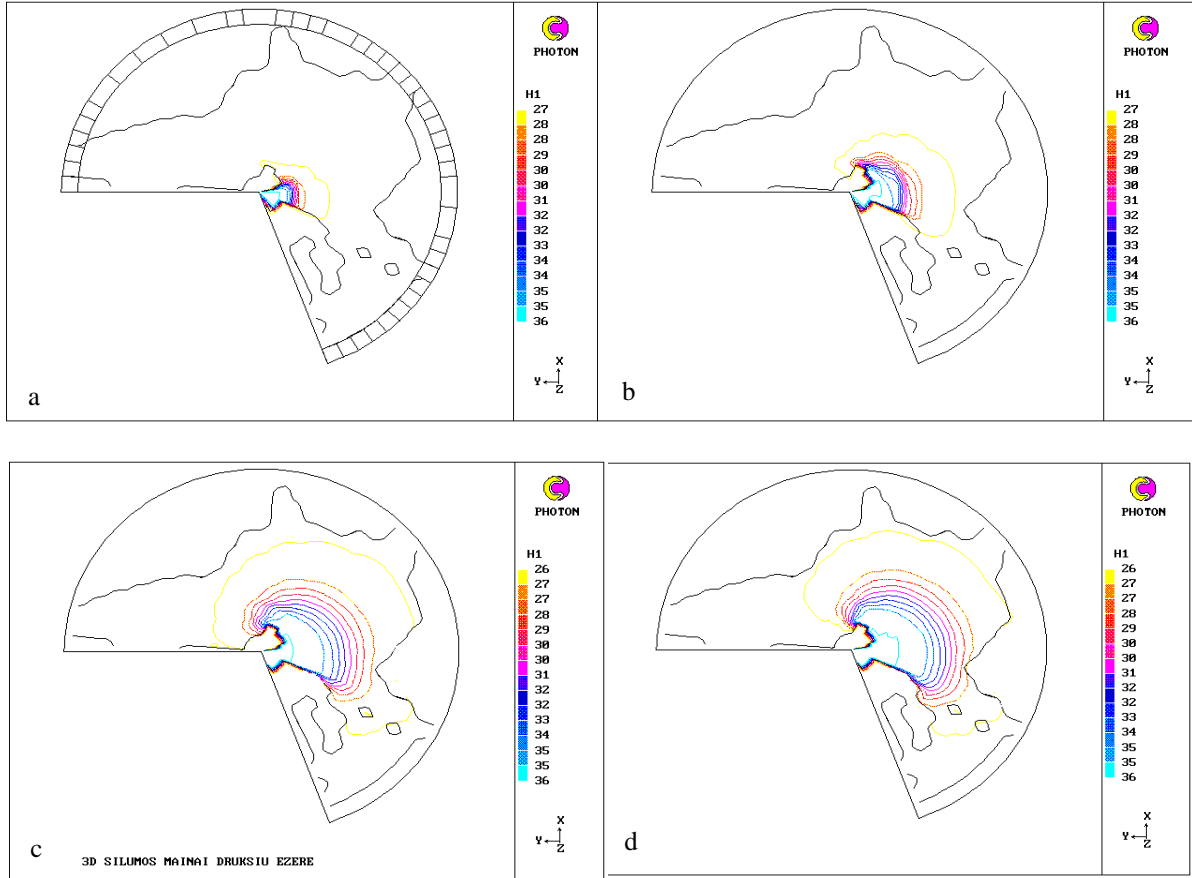


Fig 2. Heat transfer in the cooling pond at various time intervals: a) $t_1=0.5 h$, b) $t_2=h$, c) $t_3=2h$, d) $t_4= 2.5h$

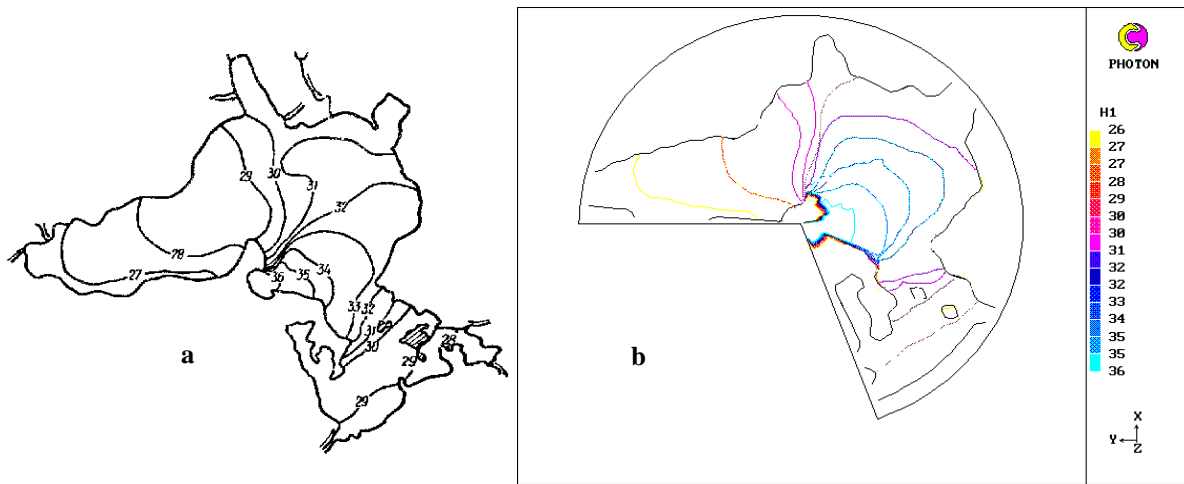


Fig 3. Temperature distribution on the water surface of the lake Drukshiai for wind velocity - 0 m/s): a - measured isotherms [5], b - predicted isotherms. The air temperature is 25.9°C

The results table 3, row 1, presents 1-th experiment which assesses all heat exchange mechanisms: by conductivity of water-atmosphere plus radiate exchange atmosphere-water and water-atmosphere, direct and diffuse solar radiation over the basin surface, in the row 2 – temperatures without direct solar radiation effects, 3 – without diffuse solar radiation effects, 4 – without estimation of radiate heat

exchange water-atmosphere, atmosphere-water. In row 5 are presented measured values [5], C^0 , and in 6-row – percentage declination predicted temperatures of row 1 from measured ones (5-row).

Table 4. Numerical 1st experiment results of basin heat exchange

		y_i					
		14	12	10	8	6	4
1	$^{\circ}C$	27.77	27.96	27.56	26.12	26.08	26.20
2	$^{\circ}C$	27.59	27.56	27.36	26.04	25.90	25.96
3	$^{\circ}C$	27.73	27.91	27.51	26.10	26.03	26.15
4	$^{\circ}C$	27.77	27.96	27.55	26.12	26.08	26.20
5	Experimental, $^{\circ}C$	27.5	27.6	28.2	28.1	27.1	27.2
6	Deviation, %	+0.6	+0.85	-1.9	-4.0	-3.8	-3.7

Table 4. Numerical 2nd experiment results of basin heat exchange

		y_i					
		14	12	10	8	6	4
1		25.92	25.92	25.97	25.92	25.91	25.91
2		27.73	27.91	27.51	26.10	26.03	26.15
3		27.59	27.75	27.36	26.04	25.90	25.96
4		25.92	25.92	25.97	26.03	25.90	25.91

The results in the table 4 row 1 presents heat exchange mechanism by conductivity of water-atmosphere surface, 2 – conductivity plus direct solar radiation, 3 – conductivity plus diffuse solar radiation, 4 – conductivity plus radiate heat exchange water- atmosphere, atmosphere- water.

4. Conclusions

1.The code of elliptic equations was used to construct a numerical model of hydrothermal dynamics in lake Druksiai, in the region of the hot-water discharge and heat dissipation in the whole basin. The CFD codes were applied for the numerical solution of 3D mathematical model of the flow and heat transfer. The solutions can evaluate the effect of temperature-dependent water density, of water-air heat conduction, of water mixing and of the ground geometry.

2. Measurements and numerical simulations show a two-layer near field mixing structure, with the upper layer of the 2.5 m thickness [4].

3. An analysis of the numerical solutions for the hydrothermal processes in lake Druksiai, and their comparison with the test points suggest an influence of the water-air heat conductivity, of the variable density of water, of water mixing, and partially of the geometry of the shore-line on the results of simulation, which are qualitatively similar to the test points. To approach the prediction to the actual state, the possible time-dependent boundary conditions should be included.

5. Nomenclature

ρ – water density, kg/m^3 ;

Φ – dependent variable: 1 for continuity eq., U, V, W impulse in directions x, y and z respectively, $m/s, H$ enthalpy (temperature);

\vec{V} – velocity vector, m/s ;

Γ_{Φ} – exchange coefficient of variable Φ ;

S_{Φ} – source term in the flow for variable Φ ;
 p – pressure N/m²;
 x, y, z – polar co-ordinates, x , radians, y, z , m.

6. Literature References

1. Montenegro H. S., Choucino M. A. (1994). Thermal dissipation in natural Basin The PHOENICS Journal of Computational Fluid Dynamics & its applications. Vol.7, No. 3. P.14–36.
2. Vaitiekūnas P., Petkevičienė J., Katinas V. (1998). A Numerical Simulation of Three-Dimensional Hydrothermal Processes in a Cooling Pond. The PHOENICS Journal of Computational Fluid Dynamics & its applications. Vol. 11, Nr. 3. P. 348–354.
3. Vaitiekūnas P., Petkevičienė J., Katinas V. (2000). Numerical simulation of hydrothermal processes in lake Druksiai. Computational procedure. ISSN 0235-7208. Energetika. Nr.4. P. 42–52.
4. Vaitiekūnas P., Petkevičienė L. (2003). Two-phase numerical modeling of heat exchange in a natural basin. In: Advances in Heat Transfer Engineering, Ed. B. Sunden and J. Vilemas. 4th Baltic Heat Transfer Conference, 25 – 27 August 2003, Kaunas, p. 435–440.
5. Ecosystem of the cooling pond of the Ignalina NPP in the initial period of its operation. T. 10. D. 1. Vilnius. Akademija. 1992. 246 p.