SIMPLE MODEL OF EVALUATION OF DAMBOVITARIVER HEAT RECOVERY POTENTIAL

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ABSTRACT

Nowadays usage of renewable sources of energies is increasingly required in order to reduce the greenhouse gas emissions,and a great deal of interest is shown by low temperature energy sources. These "new" resources are either residual energies from industrial processes, or they could be gathered from natural resources, as well.

Such is the case of the heat accumulated by the water of Dambovita's river during its crossing of Bucharest, especially in hot summer days, when river's water manifests high temperatures, with obvious not healthy consequences for its biotope. This creates the interest of studying the possibility of the heat recovery and usage in other municipal processes.

Present paper aims to define a simple model of assessing the thermal potential of river Dabovitza and its recovery possibilities using aheat exchanger sunk in Dambovitza at its exiting section from Bucharest.

KEYWORDS

heat recovery,river thermal pollution,rising river water temperature

1. STATEMENT OF THE PROBLEM

Water is the fluid with the highest thermal capacity in nature. Huge quantity of heat is accumulated by water for each degree Celsius, more precisely 1.16kWh for each cubic meter.
On the other hand, due to its dramatic negative impact over natural life, temperature increase of Dambovitza water, over a certain-admissible levels, is considered thermal pollution. On the other way around, water temperature increase indicates an important amount of energy /heat, accumulated from different sources, available as low temperature resource, and available for recovery and usage in different local processes.

2. OBJECTIVES

Definition of a simple model capable of predicting the amount of energy /heat available in Dambovitza water in one section of the river at its exit from Bucharest.

Assessment of recovery of the heat accumulated by Dambovitza water will be made considering the dimensioning of a simple heat exchanger sank in river's water, to be used in a surface water heat pump. Will be considered as limitations in the process first the needed riverbed space for the installation of the heat exchanger and second, the financial investment. For comparison will be considered two constructive types of heat exchangers.

DOI: 10.5121/aeij.2024.11401

3. METHODOLOGY

Involved methodology is the determination of the heat available budget of the rivers in a section at its exit from Bucharest. Thermal and hydraulic regime of Dambovitza's will be considered as data entry in the considered outline of the heat budget.

Scalability of the model should also be considered, if the amount of heat recovered makes sense from an economical perspective, and avoiding ecological disturbance.

4. CONSIDERED MODEL

The model boundary consists of Dambovitza channelized river-bed and sides in Bucharest. Aiming to assess the recoverability of accumulated heat in river's water within the defined boundary, were considered in the model only the assumed major heat contributor in the heat budget, responsible for water heating. First were the direct Sun radiations, both long-wave (LW) and short-wave (SW) radiations, and secondly, the direct water interaction and heat exchange with (hot) air (/winds blowing), determining water evaporation or/and condensation, phenomena accompanied by convective heating exchange processes between air and water. Perfect conduction in water body was considered, water stratification assumed as inexistent. On the other hand, were excluded from the river's heat budget, due to its channelized bad, any mass and heat exchange processes with underground waters, springs, rocks etc. Complete thermic equilibrium was also considered between the concrete river-sides and bed and river's water.

Assuming a constant channel's geometry along the considered boundary, a simplified energy balance equation could be written, re-interpreting Williams' equation: [1].

$$\frac{dQ_{tot}}{Ldx} = (Q_{Lw} + Q_{Sw}) + (Q_{air} - Q_{ev}) + Q_b + Q_{rs} + Q_s \qquad (1)$$

Where:

Q_{tot}-total water heat exchange on the balance outline [W]
L -Dambovitza's river bed width along Bucharest channel, considered constant [m]
Q_{Lw} -Long wave sun radiation [W/m^2]
Q_{Sw} -short wave sun radiation [W/m^2]
Q_{air} -convective direct heat exchange with air flowing at water surface [W/m^2]
Q_{ev} -heat extracted from water by wet saturated vapors during vaporization [W/m^2]
Q_b -convective heat exchange with the concrete river bed [W/m^2]
Q_{rs} -convective heat absorbed by concrete sides [W/m^2]
Q_s -convective heat exchange with concrete river sides [W/m^2]

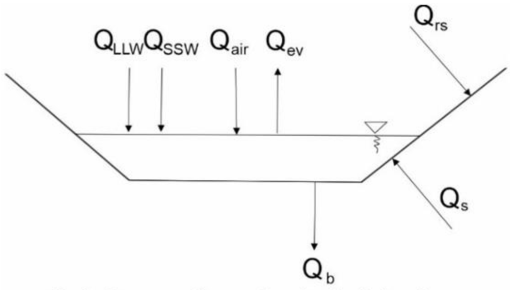

fig.1 -Cross section on the riverbed showing heat flows considered to affect the energy budget of the river

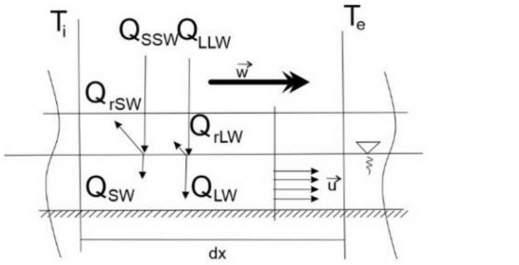

fig.2 Vertical section over river's channel, showing reflected and absorbed solar radiation flows, affecting river's heat budget.

4.1. Solar Radiation

Q_{Lw} and Q_{Sw} are, respectively, the heat absorbed by water due to solar long wave (LW) and solar short wave (SW) direct radiations [2]. Not all incident sun radiation is absorbed by Dambovitza. But absorbed short wave radiations will contribute to water heat balance right under the water surface, (in some cases contributing to temperature stratification, neglected here), while long wave sun radiation is absorbed in river depth, causing temperature increase. Depending on wave length, water surface smoothness and Sun azimuth, part of solar incident radiation is reflected back in the air, (Q_{rSW} and Q_{rLW} respectively).

Considering the sun short wave radiation data from measurements available on [2], direct short wave solar radiation absorbed by the water could be calculated [3] as

$$Q_{sw} = (1 - a_1) * S_w \qquad (2)$$

Where:

a_1 -the radiation reflection coefficient of water surface (albedo). Typical albedo average values for water surfaces range 0.1-1.0, for low solar altitude [3]

S_w -Short wave solar radiation. [W/m^2]

Total direct/incident long wave radiation, infrared radiation, is responsible for water bodies heating. The total flow of net long wave radiation is composed by the direct radiation from atmosphere, the total radiation reflected by nature (land, vegetation etc.) incident to the water surface, and the back-ward/ radiation reflected by river's water [4].

$$Q_{LW} = Q_{atmLW} + Q_{rLW} + Q_{landLW} \qquad (3)$$

Where:
Q_{atmLW} -long wave energy flow from atmosphere [W/m^2]
Q_{rLW} -long wave reflected /backed from water [W/m^2]
Q_{landLW} -land/concrete cover long wave radiation [W/m^2]

$$Q_{atmLW} = 0.96 * \varepsilon_a * \sigma * (T_a)^4 * f$$

$$Q_{rLW} = -0.96 * \sigma * (T_w)^4 \qquad (4)$$

$$Q_{landLW} = 0.96 * \sigma * (T_a)^4$$

Where:

σ -Boltzmann constant 5.695 E-8 [W/m^2/K^4]
ε_a -emissivity constant of air
T_a -air temperature [K] [2]
T_w -mean value of water temperature [K] [5]
f -view-to-sky factor [2]

Q_{atmLW} was calculated in conditions of view-to-sky factor of 1. Indeed, Dambovitza's river sides are not shaded by any vegetation or tall buildings that could diminish the solar radiation. On the contrary, the channel's section, with its trapezoidal shape, expose Dambovitza directly to the Sun, the critical hour interval from 10:00 hours to 16:00 hours having a major impact on temperature increase.

The air emissivity was determined according to [4] using the equation:

$$\varepsilon_a = 0.172 * \left(\frac{p_{va}}{T_a - 273.15}\right)^{\frac{1}{7}} * (1 + 0.22 * C_L^2) \quad (5)$$

Where:

P_{va} -actual vapor pressure at air temperature [kPa]
T_a -air temperature [K]
C_L -cloudiness constant, with value 0 for clear sky, as considered in the project, and 1 to full covered sky.
P_{va} in equation (5) is the actual vapor pressure, for the determination of which was preferred Antoine equation, due to simplicity and accuracy:

$$\log_{10}(p_{va)} = 0.133 * (A - \frac{B}{C + T_a - 273.15}) \quad (6)$$

With:

pv_a -actual vapor pressure at air temperature [kPa]
T_a -air temperature [K]

A, B and C in equation (6) are coefficients specific to the nature of the fluid of which partial pressure will be determined. For water were considered values: A=8.07131, B=1730.63, C=233.426 according to [6], [7]

4.2. Air-River Heat Exchange

The total energy exchanged by river's water and the air, (Q_{ev} – Q_{air}) is the difference between the heat transferred from the air to the water, as a result of simple convective processes, and the heat consumed or added by evaporative or condensing processes taking place at water surface.

Liquid evaporative processes taking place at river's surface are determined not only by direct solar (short wave) radiation and heating-cooling processes at water surface, but mainly by the pressure gradient of the saturated vapors formed at water surface. In still air, the difference between saturated pressure at water temperature and partial vapor pressure at air temperature is the main evaporative ingredient. Meaning that even if water molecules have the necessary energy for evaporation, the process will not occur if air is already saturated with water vapors; it will evaporate from the water the needed mass to saturate the air with vapors, at the respective air temperature (the water vapor molecules evaporating from water surface will diffuse among the existing water vapor molecules already exiting in the air), taking off the water the correspondent latent evaporation energy. In natural environment the above-described process is directly influenced by the movement of air, which is responsible for the decreasing of water vapor concentration in the air. Wind is the natural factor that modifies the concentration of vapors at liquid surface. A higher (turbulent) wind speed will decrease the vapor concentration and so, will sustain evaporative processes. On the other hand, if temperature in the air decreases in such an amount that the correspondent vapor partial pressure is higher than correspondent saturated pressure, condensation will occur until the two pressures equalize, and bringing in the water the correspondent condensation energy.

The evaporative rate could be determined using a simple derivative equation from the Dalton's law presented in [8], [9] and [10]:

$$m_{ev} = 0.1333 * k * (p_{sw} - p_{vd}) * f(w) \quad (7)$$

where:

m_{ev}-water volume evaporated daily [mm/m^2]
k -constant, assimilated with mass-transfer coefficient, dependent on the water flow condition (level of turbulence) and atmospheric stability.
p_{sw} -vapor's saturated pressure at water temperature [kPa]
f(w) -is wind speed function [m/s]
p_{vd} -partial vapor pressure at dew point temperature [kPa]

Mass-transfer coefficient k in (7) is difficult to determine, and not a constant value, due to the specificities of water course and weather conditions. Dambovitza's flow rate being relatively slow, around 0.074 m/s, could makes possible its assimilation with a pond or a lake. This assumption could make possible the use in the model, of a simpler, empirical, equation based on measurements made on small water surfaces and lakes surrounded by dry spaces, as described in [11]. Valid for water bodies with Sun exposed area respecting the condition: 50m<$A^{0.5}$<100km, the daily evaporative rate could be calculated with eq (7'):

$$m^*_{ev} = 2.909 * A^{-0.05} * (p_{sw} - p_{vd}) * w \quad (7')$$

where

m^*_{ev} -is the evaporated daily rate [mm/m^2]
A -water course surface [m^2]
P_{sw} and p_{vd} with the same representations, [kPa]
w -wind speed, [m/s]

In both equations (7) and (7') the considered wind speed is considered at 2m above the water surface.

Partial vapor pressure at dew point temperature will be determined with equation:

$$p_{vd} = \varphi * p_{sw} \quad (8)$$

with:
φ- relative humidity

Saturated vapor pressure at water temperature will be calculated using Tetens formula [12], [13]

$$p_{sw} = 0.611 * \exp(19.83 * \left(1 - \frac{273}{T_a}\right)) \quad (9)$$

With:

T_a -air temperature [K]
p_{sw} -vapor saturated pressure at water temperature [kPa].

The total heat needed for water evaporation will be determined by the general law.

$$Q_{ev} = \frac{\rho}{1000} * m_{ev} * \lambda \quad (10)$$

With:

Q_{ev} -sensitive heat gained by water [W/m^2]
ρ -water density [kg/m^3]
m_{ev} -evaporated volume [mm/m^2]
λ -latent heat of water vaporization [J/kg]
Q_{air}, the second major component is the energy transfer process between air and water. It is the sensible net heat gained or lost by the river due direct convective heat exchanged between river's water and air. Due to the difficulty of determination of a convective coefficient for the heat transfer between water and the air at water surface, it was preferred the Bowen ratio, [14]:

$$B = \frac{Q_{air}}{Q_{ev}} \quad (11)$$

Bowen ratio is calculated, according to [14] as:

$$B = 1.46 * \frac{1}{\varphi} * \left(\frac{T_a}{273}\right)^2 * \exp(-19.83 * (1 - \frac{273}{T_a})) \quad (12)$$

where

T_a -air temperature [K]
Q_{air} and Q_{ev} were previously calculated

5. MODEL INTERPRETATION AND RESULTS

Based on the described model an algorithm was developed in order to simulate the river behavior in a summer hot day. Studying the measurements obtained in the project [5] a hot day was picked and calculations were performed for a time interval of 24 hours. Accuracy of the model was verified determining, based on water temperature at entrance section in Bucharest, the temperature of the water at its exit from Bucharest.

The results obtained after applying the model indicates that solar radiation is the major contributor for increasing river's water temperature. Total available heat flows revealed may vary in a range between 48 to 500 W/m^2 in a sunny day, with a total maximum value of 204MW for whole heat budget boundary. This amount is the one whose recovery, as a source of green energy, this paper investigates.

First observation is that, as an absolute value, this amount of recoverable energy it is huge. Second observation is that daily variation range of the total heat budget is huge also. It must be added that a natural year (summer-winter) cyclicity is also present, even if not investigated in this paper. Due to this high variability of natural parameters and cyclicities, the heigh heat potential attractiveness may be diminished.

During summer, especially in hot days, the lack of vegetation and natural shading of Dambovitza's channel, both short-wave and long wave radiations, Q_{SW}, and Q_{LW} become the major contributors in the heat balance, with picks in interval 9:00-15:00, when Sun radiation is critical. All other processes taken into account in this investigation have minor impact to the overall heat balance of the river. Fig.3 bellow is the representation of heat flows contributions in total heat-balance of the river, on a time interval of 24 hours.

As observed, evaporative and convective heat exchange processes between water and air are not determinants in heat balance. An interesting phenomenon that could be observed is that Q_{air}, the convective heat contribution in rivers temperature increases after midday, when air temperature increases as well. It might be assumed that, due to low river flow rates that conduct to low to inexistent water turbulences, formation of vertical currents is inexistent and, consequently, low vertical circulation and mixing of water is not present. So Dambovitza is behaving like a large heat "battery", which might conduct to the assumption of water temperature stratification. Even in these conditions sensitive heat exchange by the river with the atmosphere together with that generated by evaporation are neglectable, with low values per square meter.

During the night, due to the heat accumulated, the river becomes itself a LW radiation generator, together with the rest of environment. In the interval 0-5:00, before sunrise, the model reveals a negative difference between the diffuse LW radiation received by the river (from the environment) and the LW radiation returned /emitted back by the river in surrounding atmosphere, which contributes to water temperature decrease. In fact, river's water temperature decreases during the night by 1-1.5 ^{0}C in the interval 0:00-9:00, revealing the rivers temperature inertia, and the inexistent /insufficient Sun radiation to compensate the heat loss of the river.

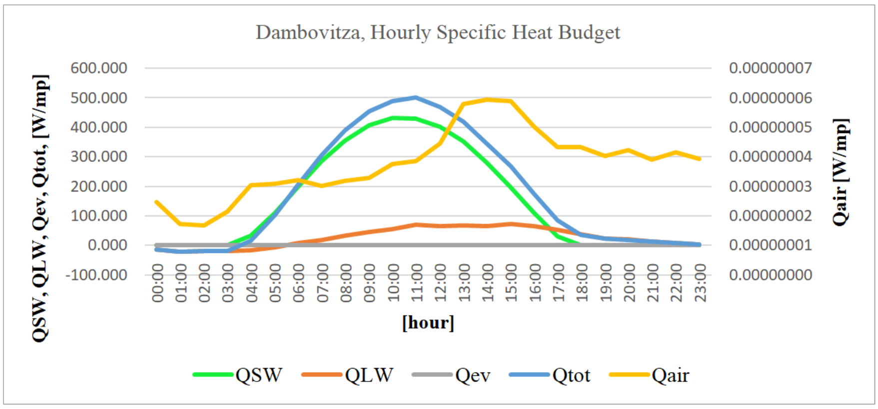

Fig. 3 Heat flows variations, responsible for Dambovitza's water temperature increase

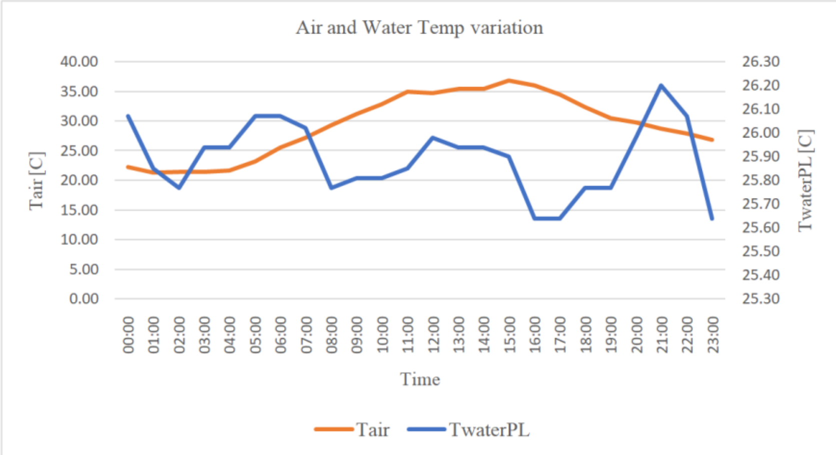

Fig 4. Cyclicity of water and air temperature during one day

6. HEAT RECOVERY

The first remark that must be made running the model and observing the variations, is the fact that during one hot summer day, the total river's heat budget is not the result of a stationary process, but a cyclical one, with its highest heat values available in the interval 7:00 – 16:00, as revealed in Fig.3. Was picked the hottest day in the measured interval available in [5] and the variations of water and air temperatures were depicted in Fig. 4. On top of that a yearly cyclicity process of heating-cooling of river's water must be considered as well. A larger time interval in the year for measuring temperatures would show clearer the heating-cooling process during the year, important also from the recovery process point of view.

As the objective of the present paper was to investigate the possibilities of recovery the river's heat, in order to consequently decrease its temperature, from a technical point of view, this aim points to the installation of a heat exchanger on the riverbed, delivering the recovered heat to a heat-pump.

Where chosen two constructive types of heat exchangers. Both implementations were considered, with Dambovitza's water as primary /hot fluid and a 15% glycol-water mix secondary /cold fluid. The heat exchangers mentioned before were considered to be mounted in a section near the river's exit section from Bucharest. Both constructive types were considered with no external shield, and the heat exchange surface directly sunk in river's water.

In normal cooling industrial processes, design of a heat exchange equipment is made considering stationary /nominal running regimes, with flow rates and entrance temperatures of both hot and cooling fluids as constant values. Not this being the case in this investigation, further determinations were made in order to better understand the available heat and variations, coupled with the external parameters' variations. The above-described model was run using the parameters available on several days, spread from July to September. For the heat exchangers dimensioning process most important was to determine the variations boundaries of the main parameter. The model revealed that maximum power is to be recovered in interval 6:00 to 18:00 with variations from a minimum of 56MW in September to a maximum of 204MW in August and hot water temperatures from 22ºC in Sep to 31ºC in August.

In both cases, the design calculations were conducted according to *F correction factor method* [15], aiming to determine the total heat exchange surface needed, and the temperature variation range of the secondary /cold fluid.

Starting from the available heat potential determined earlier, and using the general heat exchange duty calculation:

$$Q_{rec} = K * A * F * \Delta T_{ML} \quad (13)$$

where:

Q_{rec} -Heat potential to be recovered [W]
K -global heat exchange coefficient /factor [W/m^2/K
A -needed heat exchange surface [m^2]
F -correction factor
ΔT_{ML} -logarithmic average temperature [^{o}C]
Mean temperature is determined with equation [12]:

$$\Delta T_{ML} = \frac{\Delta T_1 - \Delta T_2}{\ln(\frac{\Delta T_1}{\Delta T_2})} \quad (14)$$

With:

ΔT_1 -Dambovitza's temperature variation in heat exchanger [^{o}C]
ΔT_2 -cooling fluid temperature variation in heat exchanger[^{o}C]

First heat exchanger, was considered of consisting in a battery of blade-heat-exchangers, of type Nuenta3k4 [16] mounted along the river. According to its Technical Fact Sheet (TFS), a single heat exchanger has a minimal footprint on river's bed, consists of 4 blades pitched 0.2m, with total length of 3m, wide of 0.6m, and height of 0.4m. The total heat exchange surface is of 11.8m^2 as described in TFS [16] and heat power transferred valued between 8-20kW (typical power transferred being 15kW). The heat exchanger is made in stainless steel, and the total flow rate of the secondary fluid is 1.2 lit/sec.

Considering the above input data, with a 300 W/m^2 global heat exchange coefficient, the resulted needed heat exchange surface of Nuenta3k4 heat exchanger is of 29.4E3m^2.

The second heat exchanger implementation was considered to be based on closed-loop HDPE 100 2" pipe. Even if this implementation is mostly advised in lakes and ponds applications, due to the low values of river's flow rate, combined with the low depth of the river in the considered section of implementation, this second version of heat exchanger was considered applicable in the specific case of Dambovitza river.

For the implementation, the heat exchanger is made of coils of 1m diameter, made of 2" (50mm) HDPE 100 pipe. The resulting set-up is of 24 coils per row across the river, and a number of 52 rows up-down the river. Input data for the design calculations of this implementation were the same as in the first case. A lower global heat exchange coefficient resulted, of only 80W/m^2/K, given by the low conduction coefficient of HDPE 100 2". The heat exchange surface calculated resulted in a value of 98.3E3m^2, much higher than the firs implementation

The cost calculations made for the two heat exchangers implementations and maintenance demonstrate that a low-cost implementation could give hope. A 697kEur investment in the HDPE

100 2" pipe vs 13.15 mEur in case of Nuerta3k4 speaks by itself. But the definition of an industrial /local process may be decisive for further investigations due to the fact that leads the calculations of the rates of investment recovery (IRR) and total cost of ownership TCO.

7. Conclusions and Discussions

Although heat potential results are in big numbers, temperature availability in Dambovitza's water is low and fluctuating in mean values, indicating a difficult heat transfer, as defined in the paper. More, the river temperature during the day, and during the year, has a cyclical variation, which create supplementary recovery difficulties. The results, as calculated, conduct to huge heat transfer surfaces, in order to capture this heat potential. From a usage point of view, it is also interesting to observe that, if during summer heat losses are not an issue, (air temperature is higher than river's water temperature) and consequently the distances between the location, on the river, of such a heat recovery system and the economical beneficiary process, during the cold periods of the year, heat losses could be important and jeopardize the whole concept.

From an ecological point of view, due to low river flows/speeds, the development of algae deposits on heat-exchange surface is eminent, with the consequence of further decrease of heat recovery efficacity. On the other hand, plastic (HDPE) presence in rivers' water could be subject of further ecological discussions being translated, on the long run, in potential sources of microplastics in river's water, with undesirable repercussions.

Results obtained are not indicating a feasible implementation, huge classical heat recovery equipment being needed. In author's opinion the huge heat potential of Dambovitza river continues to be interesting for a recovery processes, but by using different technologies, as Organic Rankine Cycles of working fluids with high-molecular mass and low vaporization temperatures, by one hand, or in local implemented adsorption heat pumps, by the other hand. In first case a number of supplementary investigations are mandatory for further definitions of the working fluid, due to low temperature heat transfer involved processes. In the second case, adsorption heat pumps should be coupled with heating-cooling storages.

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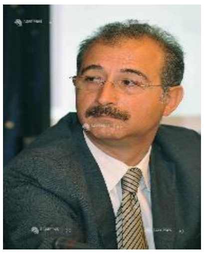

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