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The use of solar thermal energy for self and passive control of sedimentation in large reservoirs

Francisco J. Arias^a and Salvador De Las Heras^{a*}

^a Department of Fluid Mechanics, Polytechnic University of Catalonia,
ESEIAAT C/ Colom 11, 08222 Barcelona, Spain

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Solar thermal energy and its possible role with regard to self and passive control sedimentation in large reservoirs behind dams is discussed. It is known the impact caused by large reservoirs because the drastic reduction of the natural water flow velocity of rivers and the consequent sediment trapping. Sediment trapping in the reservoir has not only an environment impact because reducing the sediment transported to the deltas of rivers but also limits the useful lifetime of the dam for flood control, water supply, and hydropower generation. However, because the large surface of the reservoir together with the free available solar insolation a self and passive sedimentation control method may be possible. The idea is simple, namely. Likewise solar ponds take advantage of the ultraviolet solar energy in deep waters, then in the bottom of the reservoir the ultraviolet radiation could be collected by deliberately furrowing the reservoir floor. The mild heating of the floor will result into mild convective currents which can recirculate the sediment continuously. Utilizing a simplified physical model a first assessment of the idea is performed.

Keywords. Solar energy applications; Dams sedimentation problem.

I. INTRODUCTION

It is known the impact caused by large reservoirs because the drastic reduction of the natural water flow velocity of rivers and the consequent sediment trapping. Sediment trapping in the reservoir has not only an environment impact because reducing the sediment transported to the deltas of rivers but also limits the useful lifetime of the dam for flood control, water supply, and hydropower generation. Today, methods of managing sediment fall under three general categories: those that divert sediment around or through the reservoir, those that remove deposited sediments, and those that minimize the amount of sediment reaching the facility in the first place. Many successful implementations of these strategies are documented, however, all of them, as active strategies, have an important economic cost and as a result the search for new reservoir management concepts is an open field of research [1], nevertheless, all of the current methods are active meaning that surveillance is required as well as energetic inputs to be implemented and then are costly strategies.

The aim of this work is to explore a new alternative method which among other features it could be the only passive approach so far proposed, as far as the authors know. The idea is inspired in the solid underlying principle behind solar pond technology.

FIG. 1. Schematic diagram of the principles behind a non-convecting solar pond.

II. METHODS AND RESULTS

In a solar pond as pictorially depicted in Fig. 1 advantage is taken in the fact that the absorption phenomena depend on the specific wavelength of the radiation. In fact, when solar radiation enters a pond, while the infrared component is absorbed near the surface (a few centimeters from the surface) because water is opaque to long-wave radiation, however, the ultraviolet radiation component- as well as visible in less degree, can penetrate clear water to a depth of several meters. These

* Corresponding author: Tel.: +93 73 98 666; francisco.javier.arias@upc.edu

FIG. 2. Schematic of furrowing the soil of a dam with the aim of absorb ultraviolet radiation and generating convective current.

radiation components can be absorbed at the bottom of the pond by a dark-colored surface and as consequence the lowest layer of water is then hottest [2]. Because this thermal gradient the lowest layer of water become lighter and the convective currents will appears if measures are not taken to prevent it. Inspired in the same principle a novel passive solar approach to tackle the problem of sedimentation in large reservoirs behind dams seems at least feasible from a theoretical point of view. In this concept the bottom of the large reservoir is furrowed as pictorially sketched in Fig. 2. The aim of such furrows is to absorb the ultraviolet radiation arriving from the surface and the causing a mild heating of bottom waters which can set mild convective currents but enough to recirculate small particles of sediment.

A. Momentum considerations

Let us consider a furrow of infinite extension as depicted in Fig. 2 which is formed by two vertical parallel plates with a plate spacing b and length L and located at the floor of the reservoir at a depth H in which a flux of

FIG. 3. Physical model of the solar furrow with infinite extension.

solar radiation q is entering the furrow and is absorbed (by the bottom or the vertical plates either by direct or indirect absorption after multiple reflections inside the walls). As a result, the temperature inside the furrow will rise and set a free-convective motion. Fig. 3 shows the physical model used in the analysis.

With a turbulent regimen, fully developed and assuming a two dimensional flow between parallel plates, the pressure drop is given by

$$\left. \frac{dp}{dx} \right|_{loss} = -\frac{f\bar{\rho}v^2}{2b} \quad (1)$$

where p is pressure, x the length coordinate; f is the friction factor; b is spacing plate; $\bar{\rho}$ is average density of water and v is the velocity.

On the other hand, for natural convection, the above drop pressure must be balanced by the buoyant potential expressible as

$$\left. \frac{dp}{dx} \right|_{buoy} = -\rho_o \beta g (\bar{T}_f - T_o) \quad (2)$$

where ρ_o is the reference density; β is the coefficient of thermal expansion; g is acceleration due to Earth's gravity; and $\bar{T}_f$ and T_o the average and reference water temperature, respectively. A rough upper limit can

be estimated for the increase of temperature $\bar{T}_f - T_o$ by assuming that the furrow absorbs the total ultraviolet radiation going inside. Then by heat transfer we have

$$\rho_o v c_p (\bar{T}_f - T_o) \approx q \quad (3)$$

where v is the velocity of the fluid; c_p the heat capacity; and q the heat flux penetrating the furrow. Then, inserting Eq.(3) into Eq.(2) one obtains

$$\left. \frac{dp}{dx} \right|_{buoy} = - \frac{\beta g q}{v c_p} \quad (4)$$

Equating Eq.(4) and Eq.(1) and solving for the fluid velocity yield

$$v = \left[\frac{2b\beta g q}{f c_p \bar{\rho}} \right]^{\frac{1}{3}} \quad (5)$$

Finally, the heat flux arriving at the bottom of the dam can be calculated as function of the heat flux at the free surface q_o by means of the absorption coefficient, a

$$q = q_o e^{-aH} \quad (6)$$

where H is the depth of the dam. Thus, Eq.(5) can be rewritten as

$$v = \left[\frac{2b\beta g q_o e^{-aH}}{f c_p \bar{\rho}} \right]^{\frac{1}{3}} \quad (7)$$

• Sedimentation control

Sedimentation control may be performed by the convective current in two ways, namely. First by preventing the sediment falling in the soil, and secondly by re-suspending the sediment already settled in the soil. Because the most restrictive criteria is the re-suspension of sediment already settled, we assess the capability of the convective currents to handle sedimentation by assessing the capability for re-suspension. For a fluid to begin transporting sediment that is currently at rest on a surface, there must be a critical shear stress τ_c for the initiation of motion of grains at the bed which is given by, [3]

$$\tau_c = 0.03(\rho_s - \bar{\rho})gD \quad (8)$$

where ρ_s and D are the density and diameter of particle sediment, respectively. On the other hand, the Reynolds analogy gives

$$\tau = \frac{f \rho v^2}{2} \quad (9)$$

Thus, inserting Eq.(9) into Eq.(8) yields

$$v_c = \left[\frac{2\tau_c}{\bar{\rho}f} \right]^{\frac{1}{2}} \quad (10)$$

where v_c is the critical velocity of the fluid for the initiation of motion of grains at the bed.

Finally, a first estimation of the capability for sedimentation control by the convective currents can be reckoned by dividing Eq.(7) with Eq.(10) yielding

$$\frac{v}{v_c} = \left[\frac{2b\beta g q_o e^{-aH}}{f c_p \bar{\rho}} \right]^{\frac{1}{3}} \left[\frac{\bar{\rho}f}{2\tau_c} \right]^{\frac{1}{2}} \quad (11)$$

where it is a necessary condition for control of sedimentation $\frac{v}{v_c} \geq 1$. By using the expression for the critical shear stress Eq.(8), Eq.(11) can be rewritten as

$$\frac{v}{v_c} \simeq 5.1 \left[\frac{b\beta q_o e^{-aH}}{c_p \bar{\rho}} \right]^{\frac{1}{3}} \left[\frac{f}{g} \right]^{\frac{1}{6}} \left[\frac{\bar{\rho}}{(\rho_s - \bar{\rho})D} \right]^{\frac{1}{2}} \quad (12)$$

• Discussion

Eq.(12) provides a rough first assessment which is not intended to provide definitive estimates and then nor should be misconstrued as an attempt to generate a definitive mechanistic analysis. For example, it is noted that in Eq.(12) the depth of the furrow L (see Fig. 3) is absent in the calculations and then one may tempted to think that the depth of the furrow could be simply disregarded. However, it is not the case. In fact, in assuming that the main mechanism for heat transport is by convection and neglecting conduction implies that the furrow must be deep enough. Also, it was assumed that the total ultraviolet radiation penetrating the furrow is absorbed inside which although can be more or less assumed for deep furrows, however, certainly is untrue for the general case.

III. RESULTS

In order to obtain some idea of the shape of the curves predicted by Eq.(12), we assume some typical values of the parameters: $q_o = 200 \text{ W/m}^2$; $a = 0.032/\text{m}$ for ultraviolet radiation, [2]; a friction factor $f = 0.03$; a typical quartz-rich sediment with a density $\approx 2650 \text{ kg/m}^3$; $\bar{\rho} \approx \rho_o = 1000 \text{ kg/m}^3$; $c_p = 4180 \text{ kJ/(kgK)}$; $\beta = 2.0 \times 10^{-4}/\text{K}$; and a reasonable furrow spacing $b = 2\text{m}$. The resulting curves are shown in Fig. 4. It is seen that the convective currents induced by the furrow may handle particles with diameters smaller than $20 \mu\text{m}$ and for dams from 10 meters depth. This result is encouraging further research if one considers that typical sediment profile are around ($\approx 60\%$) mostly 2-to-50 μm while coarse sediment ($> 50\mu\text{m}$) accounted for 23.09%, [4].

FIG. 4. Ratio between the free convection velocity and the sediment critical shear velocity, Eq.(12) as a function of the depth of the dam and several diameters of the sediment particles .

IV. SUMMARY AND CONCLUSIONS

A novel passive solar approach to tackle the serious problem of sedimentation in reservoir and large dams was proposed. In this concept the bottom of the dam or large reservoir is deliberately furrowed. The aim of such furrows is to absorb the ultraviolet radiation arriving from the surface. The principle which although keep certain resemblance with the well known solar pond technology in which ultraviolet radiation is harnessed, however, here is not intended to hamper natural convection but rather to promote this in the furrow. Utilizing a simplified physical model an analytical expression for the convective currents and capability for sedimentation control was derived. The preliminary results are highly encouraging and show that passive solar thermal energy is an interesting option for passively control the sedimentation in dams and harnessing the free-solar irradiation.

NOMENCLATURE:

a = absorption coefficient
 b = plate spacing
 c_p = heat capacity
 D = diameter of particle sediment
 f = friction factor
 g = gravity
 H = depth of the dam

L = length of the furrow
 q = heat flux
 T = temperature
 $\bar{T}_f$ = average temperature inside the furrow
 v = velocity
 x = the length coordinate

Greek symbols

ρ = density
 μ = dynamic viscosity
 β = coefficient of thermal expansion
 τ_c = critical shear stress

subscripts

c = critical
 f = fluid
 o = reference, surface

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