Supersaturated solar ponds for enhanced thermal insulation by the spontaneous formation of a thin film gas at the bottom

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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In this work the novel approach of supersaturated solar ponds to enhance thermal insulation of the pond by the spontaneous formation of a thin film gas blanketing its bottom which is covered by active nucleation sites is discussed. Utilizing a simplified physical model an expression for the heat transfer and the increase of temperature at the bottom of the solar pond was derived.

Keywords. *Solar-pond; Solar energy; Film-boiling heat transfer*

I. INTRODUCTION

The global squeeze on energy supply are exacerbating chronic energy shortages not only in Europe and the United States but are wreaking havoc around the world. According to the head of the International Energy Agency, the world has never witnessed such a major energy crisis in terms of its depth and its complexity, and like the oil crises of the 1970s, which prompted huge gains in fuel efficiency the world may see faster adoption of government policies that speed the transition to cleaner energy such as wind or solar energy. Among solar technology alternatives, a salinity-gradient solar pond SGSP is one such technology which seems to be both relevant and promising for many countries. A salinity-gradient solar pond is a body of water that collects and stores solar energy and consisting basically in three regions, namely: surface zone (Upper Convective zone), main gradient zone (Non-convective zone), and bottom zone (Lower Convective Zone) as sketched in Fig. 1. Solar energy is collected and accumulated in the bottom zone causing the temperature to increase. The insulating properties of the gradient zone, combined with the high heat capacity and large volume of water make the solar pond both a solar thermal collector and a long-term thermal storage device. Due to its intrinsic attractiveness several aspects in solar ponds have been researched in the last years, for example, new novel working fluids to prevent convection, [1]; buoyancy-driven flow effects, [2]; desalination process, [3],[4]; two-dimensional transient analysis, [5], or thermoelectric conversion, [6], just to name a few. For a comprehensive up-to-day in solar ponds technology the review from Alibakhsh Kasaeian et al, (2018), [7] is highly recommended to the interested reader.

* Corresponding author: tel.: +34 648 039 039; francisco.javier.arias@upc.edu

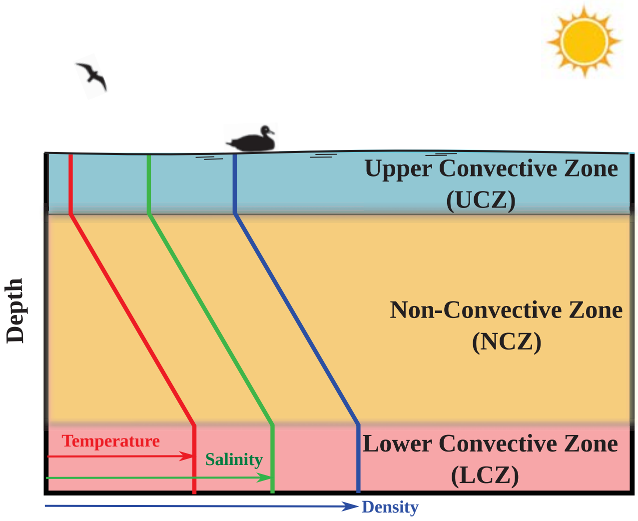

FIG. 1. Schematic view of the solar pond and the respective temperature, salinity and density profiles.

The object of this work was a first assessment for a novel approach in which the traditional solar pond is now supersaturated with a given inert gas which precipitates upon contact with active nucleation sites covering the bottom of the pond. The precipitation of the gas translates into the formation of a gas thin film which thermally isolate the bottom of the pond in a similar fashion to the well known film boiling regime.

II. METHODS AND MATERIALS

A. The supersaturated solar ponds

The strong thermal effect of a gas film covering the surface of heaters is a well known phenomena in heat transfer technology. Indeed, when the heater attains a certain critical heat flux (CHF) the liquid boils at the surface with the formation of a vapor film blanketing the surface which result into an abrupt rise of temperature

because the dramatic reduction of heat transfer owing to the insulating power of the thin film, a heat transfer regime known as *film boiling*.
By aforementioned, it is reasonable to think that thus phenomena could be interesting in application to the solar pond project, because the formation of a gas film covering its bottom will result into an increase in the thermal insulation of the solar pond which is, of course, desired. However, because boiling is not possible for application to solar pond /among other things because the destruction of its stratified stability, [8], the gas film should be promoted in other way. In fact, the gas film may be generated from the precipitation of a pond which is supersaturated with a certain inert gas (for example CO_2) upon contact with the bottom when it has been deliberately covered with active nucleation sites.

III. FILM-GAS HEAT TRANSFER

Because in almost every respect the theoretical treatment of the heat transfer for a gas film is similar to that of film boiling including the stability criteria being, perhaps, the most important difference at least from a thermal point of view that the heat removal is not by latent heat (boiling) but rather by sensible heat of the precipitated gas. Following the classical theoretical derivation for the heat transfer coefficient of a film boiling given by Berenson, (1961), [14], it is easy to derive an approximated adapted expression for the film-gas. Consequently, if the heat transfer for a film boiling is given by,[14]

$$h_{fb} = 0.425 \left[\frac{\kappa_v^3 \Delta h_v \rho_v g(\rho_l - \rho_v)}{\mu_l \Delta T \sqrt{\frac{\sigma}{g(\rho_l - \rho_v)}}} \right]^{\frac{1}{4}} \qquad (1)$$

where κ is the thermal conductivity; Δh the average enthalpy difference between vapor and liquid; ρ density; μ the dynamic viscosity; g gravity; ΔT the difference of temperature, and σ the surface tension, the the subscripts: l and v stand for liquid and vapor, respectively. Then for a gas film the heat is now remove by the sensible heat transported by the gas, i.e., $c_{pg}\Delta T$ being c_{pg} the isobaric specific heat capacity of the gas, and ΔT the difference of temperature between the wall and the media. Thus, the term Δh_v in Eq.(1) should be modified according with the new situation and becomes

$$h_{fg} = 0.425 \left[\frac{\kappa_g^3 c_{pg} \rho_g g(\rho_l - \rho_g)}{\mu_l \sqrt{\frac{\sigma}{g(\rho_l - \rho_g)}}} \right]^{\frac{1}{4}} \qquad (2)$$

where the superscript g stands for gas. Eq.(2) represents the heat transfer coefficient for a film-gas (no boiling) which is governed by Taylor-Helmholtz instabilities valid for horizontal surfaces.

In order to compare the effect on the heat transfer at the bottom of the solar pond by promoting the gas film, it must be considered also the expected heat transfer coefficient when there is not gas film, i.e., by the convection between the bottom wall and the *lower-convective zone* of the pond. Many semiempirical formulations for natural convection heat transfer between horizontal plates are available; but in view of the uncertainty, the following simplest expression seems preferable,[9]

$$h_c = 0.54 \frac{\kappa_l}{l} \left[\frac{\rho_l^2 c_{pl} \beta g l^3 \Delta T_c}{\mu_l \kappa_l} \right]^{\frac{1}{4}} \qquad (3)$$

being β the thermal expansion coefficient; l the distance between plates (which in our case is the thickness of the *lower convective zone* $l = l_{lcz}$); and c_{pl} is the specific isobaric heat capacity of the liquid.

• Discussion

If we call ΔT_f and ΔT_c are the temperature drop between wall and the quiescent temperature of the liquid with and without film, respectively, then forma balance of energy we have

$$\frac{\Delta T_f}{\Delta T_c} = \frac{h_c}{h_{fg}} \qquad (4)$$

where ΔT_f and ΔT_c are the temperature drop between wall and the quiescent temperature with and without film, respectively. Inserting Eq.(2) and Eq.(3) into Eq.(4) yields

$$\frac{\Delta T_f}{\Delta T_c} = 1.27 \left[\frac{\kappa_l^3 \rho_l^2 c_{pl} \beta \Delta T_c \sqrt{\frac{\sigma}{g(\rho_l - \rho_g)}}}{\kappa_g^3 \rho_g c_{pg} (\rho_l - \rho_g) l_{lcz}} \right]^{\frac{1}{4}} \qquad (5)$$

IV. RESULTS AND CONCLUSIONS

In order to obtain some idea of the shape of the curve predicted by Eq.(5), we assume some typical values of the parameters: Considering air as the dissolved gas and a temperature for the non-convective zone 80 ^{o}C and at 1 atmosphere of pressure: $\kappa_g = 3 \times 10^{-2}$ W/mK; $c_{pg} = 1000$ J/kgK; $\rho_g = 1.1$ kg/m^3; $g = 9.8$ m/s^2; $\sigma \approx 71.7$ mN/m; and for the water: $\kappa_l = 0.64$ W/mK; $\rho_g = 1000$ kg/(m^3); $c_{pl} = 4200$ J/kgK; $\beta = 7 \times 10^{-4}$ /K and a *lower-convective zone* thickness $l_{lcz} = 0.1$ m,[11]. The resulting curve is shown in Fig. 2. It is seen, that, equally than a film boiling, the effect of the film-gas has a very strong effect on the heat transfer and then increasing dramatically the temperature of the wall, and form this fact an interesting possibility raise for the solar pond, namely, because the heat transfer of the solar

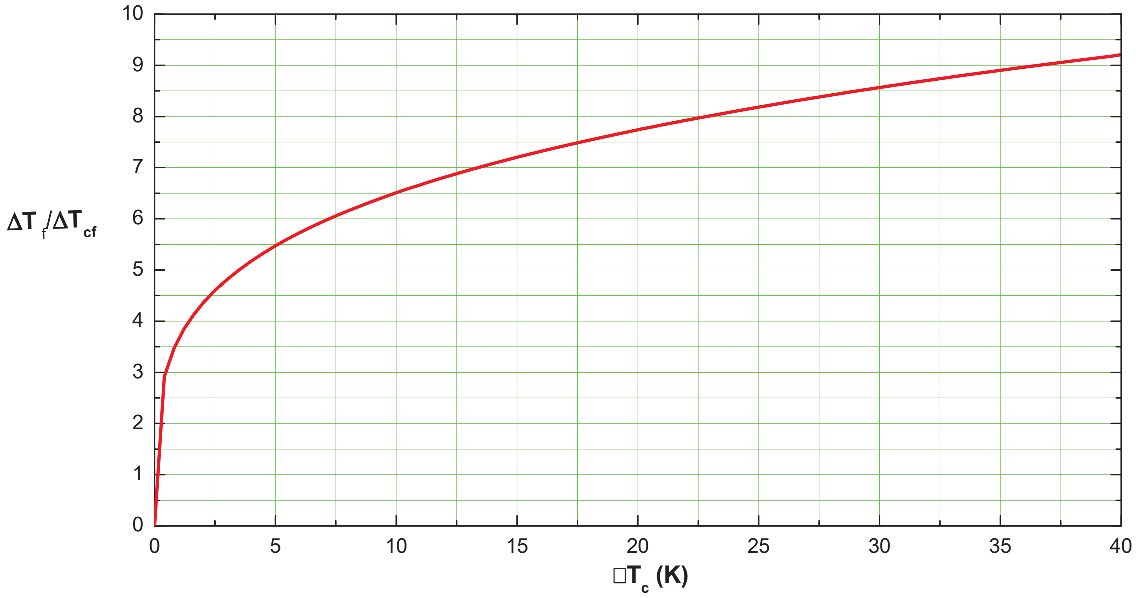

FIG. 2. The increase of temperature ratio $\frac{\Delta T_f}{\Delta T_c}$ as function of the initial difference by the presence of the film-gas predicted by Eq.(5).

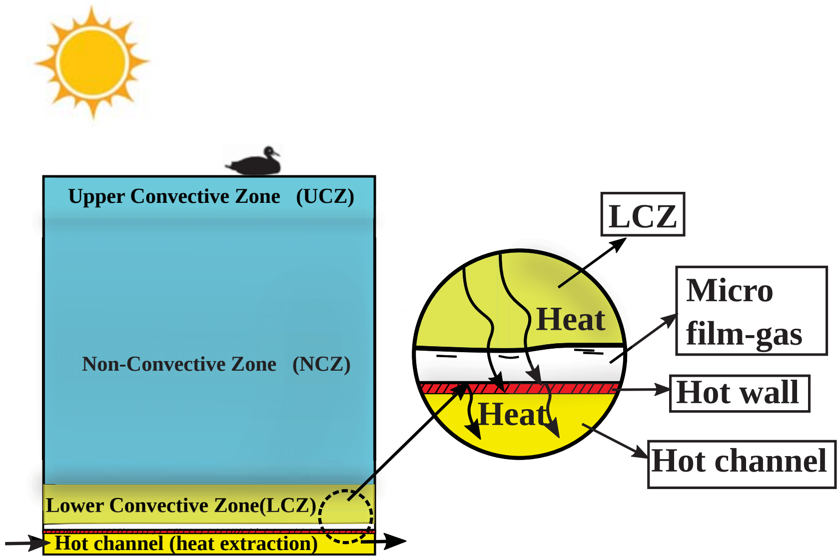

FIG. 3. Because the very reduced heat transfer due the film-gas, heat can be transported from the *non-convective zone* to a hot channel where the heat can be extracted and then eliminating the need of disturbing the *non-convective zone* and creation of a lower convective region as classical approach.

heated bottom-surface of the solar pond is strongly impeded upwards by the presence of the film, then the heat of the wall can be transferred to a second channel locate below, more or less as depicted in Fig. 3. This possibility could eliminate the need of disturbing the main body of water by the direct extraction of heat from the lower convective zone, as in current approaches. [8].

V. SUMMARY OF RESULTS AND CONCLUSIONS

(a) The thermal insulation from the formation of a gas film at the bottom of a solar pond when the pond is supersaturated with a certain gas was discussed.

(b) An analytical expression, Eq.(2), was derived which predicts then heat-transfer coefficient for film-gas pool from a horizontal surface.

(c) An analytical expression, Eq.(5), was derived which compares the temperature rise at the wall with the presence of the film-gas.

(d) Additional R&D is required in order to explore the possibilities of the Leidenfrost effect in solar ponds and to arrive at a practical design promoting the insulator film.

NOMENCLATURE:

c_p = isobaric specific heat capacity, J/kgK
h_c = convective heat transfer coefficient, W/m^{2}K
h_{fb} = film boiling heat transfer coefficient, W/m^{2}K
h_{fg} = film gas heat transfer coefficient, W/m^{2}K
l = thickness, depth, m
l_{ncz} = thickness of the *upper convective zone*, m
p = pressure, Pa
T = temperature, K
Δ = difference

Greek symbols

β = coefficient of thermal expansion, 1/K
σ = surface tension, N/m
κ = thermal conductivity, W/mK
μ = dynamic viscosity , Pa s
ρ = density, kg/m^3

subscripts

b = boiling
g = gas
l = liquid
lcz = *lower convective zone*
ncz = *non-convective zone*

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VI. REFERENCES

[1] Yakubu, M., Shuja, S.Z., Yilbas, B. S., and Al-Qahtani, M, 2020, "Influence of working fluid on a novel solar pond coil," J. Energy Resour. Technol. 143(4)

[2] Derakhshan S., Mirazimzadeh S.E; Pazireh S, 2018, "Study of buoyancy-driven flow effect on salt gradient solar ponds performance," J. Energy Resour. Technol. 140(10. 101203.

[3] Farahbod, F., and Farahmand, S, 2014, "Experimental study of solar-powered desalination pond as second stage in proposed zero discharge desalination process." ASME. J. Energy Resour. Technol. 136(3): 031202

[4] Farahbod, F., Mowla, D., Jafari Nasr, M. R., and Soltanieh, M, 2012, "Investigation of Solar Desalination Pond Performance Experimentally and Mathematically," ASME. J. Energy Resour. Technol. 134(4): 041201.

[5] Verma, S., and Das, R, 2022, "Wall energy loss and entropy generation in solar ponds using one-dimensional and two-dimensional transient analyses," ASME. J. Energy Resour. Technol. 144(10): 101305

[6] Goswami R; and Das R, 2020, "Experimental analysis of a novel solar pond driven thermoelectric energy system," J. Energy Resour. Technol. 142(12)

[7] Alibakhsh Kasaeian, Shakiba Sharifi, Wei-Mon Yan, 2018, "Novel achievements in the development of solar ponds: A review," Solar Energy, Volume 174, p.p. 189-206.

[8] Goswami D.Y; Kreich F; Kreider J.F. Principles of Solar Engineering, Second Edition 2nd Edition. Taylor & Francis

[9] Cengel Y.A; Ghajar A.J, 2020, McGraw-Hill Global Education Holding, LLC. Heat and mass transfer: Fundamentals and Applications. 6a edition.

[10] Punyasena, M.A., Amarasekara, C.D., Jayakody, J.R.P., Perera, P.A.A., Ehamparam, P, 2003, "An investigation of rain and wind effects on thermal stability of large-area saltpan solar ponds," Sol. Energy 74, 447-451.

[11] Khadije El Kadi, Sherine Elagroudy, Isam Janajreh, 2019, "Flow simulation and assessment of a salinity gradient solar pond development, Energy Procedia," Volume 158. p.p. 911-917

[12] Rohsenow W.m; Griffith P, 1956, "Correlation of aximum heat transfer data for boiling of saturated liquids," Chem. Eng. Pro. Symp. Series, vol. 52, no. 18. p.p. 47

[13] Zuber N, 1959, "Hydrodynacmic aspects of boiling heat transfer. USAEC rept. AECU-4439. doctoral dissertation, University of California at los Angeles

[14] Berenson P.J, 1961, "Film-boiling heat transfer from a horizontal surface," Journal of Heat Transfer. . p.p 351-358,

[15] IAPWS Release on Surface Tension of Ordinary Water Substance, International Association for the Properties of Water and Steam", September 1994.

[16] Chen H; Li Z; Wang F; Wang Z; , and Li H, 2017, "Investigation of surface properties for electrolyte solutions: measurement and prediction of surface tension for aqueous concentrated electrolyte solutions," J. Chem. Eng. Data 2017, 62, 11, 3783-3792